Department of Mechanical and Aerospace Engineering

Hydrogen in the maritime sector: An evaluation of hybrid renewable systems for decarbonising ferry ships

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Abstract

This dissertation aims to contribute to the existing literature for the marine industry by implementing hybrid renewable energy systems (HRES) combined with hydrogen as energy carrier to mitigate the Greenhouse gas (GHG) emissions of the sector and synchronously cover the demand of certain ferries that operate in the United Kingdom.

The literature review indicated the current situation in the maritime globally and nationally along with the future targets towards sustainability. It revealed that green hydrogen production could be a game changer regarding transition to alternative technologies.

Two ferries were studied that operate in Belfast-Cairnryan and the Douglas-Heysham domestic routes, the most popular ones regarding the number of passengers in the recent years. These ferries were Stena Superfast VII and Ben-my-chree, with an annual fuel consumption of 13,958,818.8 L/year and 5,862,298.32 L/year respectively. The methodology was carried out by the creation of two HRES with harness of renewable energy sources (RES) available close to the ports of these ferries, which were tidal and offshore wind energy. The former system investigated the utilisation of 1 SeaGen-S 2MW tidal turbine and the later the offshore wind farm of West of Duddon Sands that utilises 108 Siemens 3.6 MW wind turbines.

The configuration of these systems was optimised using HOMERPro software tool. The results highlighted that, 5 tidal turbines combined in a HRES were able to meet the fuel demand of the ferry and generate 94 thousand kg more than the initial annual demand of the it and on the other hand the offshore wind-hydrogen HRES was able to not only cover the energy demand of the ship but also to produce excess hydrogen of 696,640,105 kg/year and at the generate electricity for almost 139,064 households .

A financial analysis estimated the Net Present Value for each system revealed that both would return profit to the investors making them cost-effective. All in all, this research contributed to the extension and deployment of the already literature by proving that these systems could be feasible and significant towards the targets of 2050.

Acknowledgements

As this journey comes to an end, I feel the need to acknowledge a few people that contributed to this dissertation. To begin with, I would like to express my gratitude to my supervisor Dr.Stephanie Ordonez-Sanchez , your guidance and positiveness helped me accomplish my goals , I am honoured that I had the opportunity to work with you . I would like to thank Dr.Sofoklis Makridis for introducing me to the field of hydrogen and its potentials and always believing and supporting me since my early stages in my academic career .

I cannot forget my family, that supported me through ups and downs so I can follow my dreams, without you I would not be who I am until this day.

Chris thank you for standing by my side, if I have you along the way I am sure that I can accomplish many dreams. My friends, you kept me sane and strong even by distance, you are the family I chose to have, and I will always be grateful that I was lucky enough to have you in my life. My grand mom , my bestie , giagia , you are my role model and I wish when I grow old to be half at least of how strong you are . My grandad, I hope that you can see me and I hope that I am making you proud. And last but not least, my Odin ,you brought me smile even in the darkest of days .

To my granddad and to Rusty , you will be missed , always in my heart ..

Table of Contents

1.0 Introduction 12
1.1 Statement Gap 14
1.2 Significance of the study 15
1.3 Scope of the study 16
1.4 Objectives 17
1.5 Thesis structure 17
2.0 Literature Review 19
2.1 Background Study 19
  2.1.1 Hydrogen as an element 19
  2.1.2 Hydrogen Categories 21
  2.1.3 Green Hydrogen 23
2.2 Maritime Sector Emissions 25
  2.2.1 Maritime Sector in UK 29
2.3 Strategies and Regulations 30
  2.3.1 European Energy Strategy and current Regulations 30
  2.3.2 United Kingdom’s strategy and Regulations 32
2.4 Hydrogen Production 36
  2.4.1 Electrolysis 38
2.5 Hydrogen Storage 46
2.6 Hybrid Renewable Energy Systems 48
3.0 Methodology 49
3.1 Introduction 49
3.2 Background Data Collection 52
  3.2.1 Ports 52
  3.2.2 Shipping Routes 54
  3.2.3 Ship Emissions 58

3.2.4 Fuel Consumption ... 59
3.2.5 Hydrogen Consumption / Demand ... 62
3.2.6 Renewable Energy Sources ... 65
3.3 Simulation Tools ... 73
4.0 Results ... 81
4.1 Hybrid Systems ... 82
4.1.1 Tidal energy → Hydrogen ... 82
4.1.2 Offshore Wind Energy → Hydrogen ... 84
4.2 Financial Analysis ... 88
5.0 Discussion ... 92
5.1 Contribution of the study to Academia ... 92
5.2 Limitations ... 92
6.0 Future Work ... 93
7.0 Conclusions ... 94
8.0 References ... 97

List of Figures

Figure 1 Hydrogen Pathway (Source: [5]) ... 13
Figure 2 Hydrogen illustration properties (Source: [23]) ... 20
Figure 3 Hydrogen state diagram (Source: [22]) ... 21
Figure 4 Different colours of hydrogen (Source : [30]) ... 22
Figure 5 Approximate GHG emissions per kWh of engine power for various fuels (Source:[7]) ... 27
Figure 6 Projected fuel marine demand for 5 and 10 years (Source: [42]) ... 28
Figure 7 UK's carbon dioxide emissions , 1990-2016 (Source: [15]) ... 29
Figure 8 Illustration of HyNet Project (Source: [65]) ... 35
Figure 9 Illustration of Gigastack project configuration (Source:[67]) ... 36
Figure 10 Renewable hydrogen production technologies schematic (Source: [6]) ... 37
Figure 11 Alkaline electrolysis (Source: [77]) ... 41

Figure 12 PEM Electrolysis (Source: [77]) 43
Figure 13 Comparison ranges for current density/voltage curves foe PEM and Alkaline electrolysis (Source: [77]) 44
Figure 14 Illustration of NEL’s PEM electrolyser facility (Source:[80]) 46
Figure 15 Methodology’s Schematic 51
Figure 16 Short Sea Crossings around UK (Source : [97])) 54
Figure 17 Stena Line Superfast VII on duty (Source: [99]) 55
Figure 18 Ben-my-chree ferry (Source: [104]) 57
Figure 19 Available Wind and Tidal energy sources around the UK (Source : [118]) 66
Figure 20 SeaGen – S 1.2 MW (Source : https://www.power-technology.com/projects/strangford-lough/) 67
Figure 21 Illustration of SeaGen -S 2MW underwater (Source: [122])......... 69
Figure 23 West of Duddon Sands offshore wind farm ([124]) 71
Figure 26 Tidal Energy-Hydrogen HRES schematic (Source: HOMERPro) 75
Figure 24 Offshore Wind – Hydrogen HRES schematic (Source : HOMERPro) 77
Figure 25 Wind Profile (Source: HOMERPro)... 78
Figure 27 Hydrogen production of the Tidal- Hydrogen HRES (Source: HOMERPro) 83
Figure 28 Hydrogen production of the offshore wind-hydrogen HRES (Source : HOMERPro).. 85
Figure 29 Electrical Load of the offshore wind-hydrogen HRES (Source: HOMERPro) 86
Figure 30 Gamesa 4.5MW -hydrogen HRES electrical load production(Source : HOMERPro) 87
Figure 31 Gamesa 4.5MW-hydrogen HRES hydrogen production (Source: HOMERPro) 87

List of Tables

Table 1: Hydrogen properties.. 19
Table 2: Comparison of water electrolysers.. 44
Table 3 National Sea Crossing around UK from 2017-2019......................... 52

Table 4 Characteristics of Stena VII/VIII 55
Table 5 Ben-my-chree characteristics 57
Table 6 Operational days of Stena Superfast VII 61
Table 7 Operational days of Ben-my-chree 61
Table 8 Stena Superfast VII and Ben-my-chree fuel consumption 61
Table 9 Stena Superfast VII and Ben-my-chree hydrogen demand & total consumption 64
Table 10 Specifications of SeaGen-S 2MW tidal turbine 68
Table 11Offshore Windfarms close to Heysham port 70
Table 12 Characteristics of Siemens 3.6MW offshore wind turbine 72
Table 13 Summary of the components of both HRES 80
Table 14 Results for various numbers of tidal turbines 82
Table 15 Cost outputs of the HRES systems 89
Table 16 Offshore Wind-Hydrogen HRES components' costs 89
Table 17 Tidal turbine -Hydrogen HRES components' costs........................ 90

List of Graphs

Graph 1 Passengers annually for National Sea Crossing From GB to Northern Ireland 53
Graph 2 Passengers annually for National Sea Crossing From GB to Isle of Man 53
Graph 3 Emissions of Stena Superfast VII and Ben-my-chree for 2018-2020 59
Graph 4 Annual Emissions per distance 59
Graph 5 Power Curve of SeaGen S 2MW 69
Graph 6 Power Curve for Siemens 3.6MW offshore wind turbine............... 73
Graph 7 The start up point of the excess electricity production 84

Nomenclature

Symbol	**Description**	**Units**
ATR	Auto Thermal Reforming	
AWE	Alkaline Electrolysis	
EEDI	Energy Efficiency Design Index	
GHG	Greenhouse Gas	
HER	Hydrogen Evolution Reaction	
HRES	Hybrid Renewable Energy Systems	
HFO	Heavy Fuel Oil	
IMO	International Maritime Organisation	
IPCEI	Important Project of Common European Interest	
MARPOL	International Convention for Prevention of Pollution from Ships	
MEC	Microbial Electrolysis Cells	
MGO	Marine Gas Oil	
MDO	Marine Diesel Oil	
MCT	Marine Current Turbines	
OER	Oxygen Evolution Reaction	
ODS	Ozone Depleting Substances	
PEM	Polymer Electrolyte Membrane	
RES	Renewable Energy Sources	
SMR	Steam Methane Reforming	

SOE	Solid Oxide Electrolysis	
SWP	Siemens Wind Power	
TCA	Trade and Cooperation Agreement	
VOC	Volatile Organic Compounds	
SR	Standard rate of fuel consumption	kg/kWh
mcr	Maximum continuous rating which equals with the maximum output (MW) that can be produced under normal circumstances	(%)
P	Engine's power	kW
ρ	Density of the fuel	Kg/m^3
S	Speed of the ship	knots
U_{H2}	Lower Heating Value of Hydrogen	MJ/kg
U_{fuel}	Heat Value of fuel	MJ/kg
n_{ic}	Efficiency of internal combustion engine	
n_{fc}	Efficiency of fuel cells	
D	Distance	Km

1.0 Introduction

Recently, a considerable literature has grown around a variety of environmental concerns, such as the global climate change, which have been originated to the anthropogenic emissions due to the production, transformation, and utilization of energy [1],[2]. The constant demand for energy, resulted for the numbers to increase, in 2019, with the average global atmospheric carbon dioxide concentration to reach 409.8 ppm [3]. This is the highest it has been in at least 800,000 years [3].

Consequently, several potential remedies to the present environmental issues caused by hazardous pollutant emissions have emerged [1]. One of the most successful options appears to be hydrogen energy systems as they seem prominent to play a significant part in improving the environment and ensuring sustainable equilibrium [1].

International organizations such as International Partnership for Hydrogen and Fuel Cells in the Economy, the European Commission, and the International Partnership for Hydrogen and Fuel Cells in the Economy predict that the world will soon be oriented toward a zero-carbon economy, with hydrogen technology taking the lead regarding transportation, distribution of power generation along with micro applications [4],[5] as it is illustrated in Figure 1.

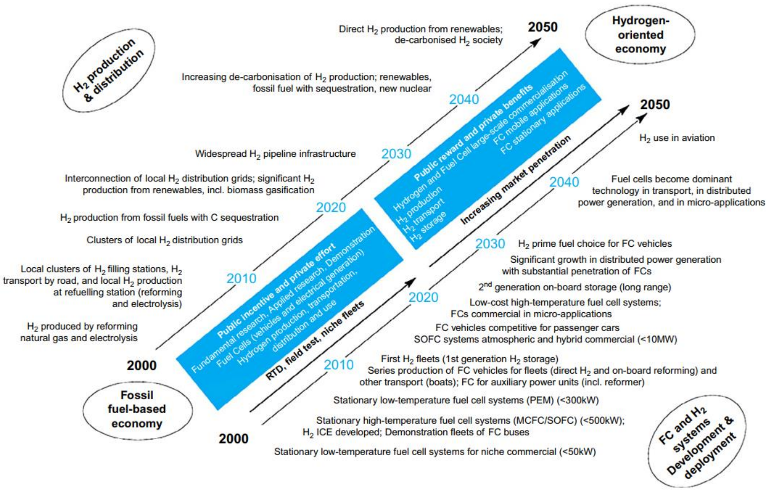


Figure 1 Hydrogen Pathway (Source: [5])

Hydrogen is widely assumed to be among the universe's most plentiful elements [6]. Its heat emission per unit mass is estimated to be 3 times that of gasoline [6]. It may be generated from a range of resources, including biomass, natural gas, nuclear power, and renewable energy sources (RES) as sun and wind [4]. It is a renewable energy source that creates only oxygen and water vapor when burned, creating zero emissions [6]. So, undoubtedly it can be considered as a clean energy carrier that is prominent to be fundamental in the worldwide energy transition scheme.

The transportation sector accounts for half of all liquid fossil fuel usage [7]. Nowadays, globally, the sector consumed 2523 million tonnes of oil equivalent (Mtoe), making it responsible for approximately 30% of total global energy consumption amongst all end-use industries [7]. Shipping was associated for approximately 2.8 % of total annual GHGs on a CO_2-equivalent scale between 2007 and 2012, according to the Third IMO GHG assessment [8]. The percentage of worldwide anthropogenic emissions attributed to shipping has grown from 2.76 % in 2012 to 2.89 %t in 2018 [9].

The production of hydrogen can be deployed in a variety of applications. This dissertation will focus into the transportation industry and specifically the decarbonisation of domestic shipping routes by the development of hybrid systems that utilise different forms of renewable energy to produce green hydrogen.

Renewable Energy appeals to have the ability to convert the maritime sector at all scales, including international and domestic [10]. A clean energy-based sector necessitates a constraint of the fossil fuel -powered vessels and more of energy-efficient designs and renewable energy technology, among other things.

Due to advancements in renewable energy technologies, innovative solutions such as hybrid renewable energy systems (HRES) are becoming day by day more prominent for power production applications [11].

This paper will examine the feasibility of such systems by utilising the main renewable energy sources of the UK that currently are offshore wind and tidal energy with them to be approximately 14.8% and 2.7% respectively for the electricity generation for 2020 [12].

Renewables’ contribution to the energy mix of the maritime industry, might be still relatively new regarding developments and is expected to be as such in the short term [10]. Nevertheless, according to technology suppliers in the sector, innovation, and research efforts on the use of alternative renewable energy powered systems, along with efficient designs, are providing positive outcomes for immediate energy reductions for a variety of certain applications [10].

All in all, the sooner this transition takes place the merrier, and even though it may seem challenging, it is fundamental if the world aims to achieve a sustainable future.

1.1 Statement Gap

Various sectors some more than others opt to mitigate their environmental footprint and transit in a net-zero network. Transportation sector is one of them with a contribution of almost 2.8% of emissions [8]. During recent years, the maritime industry of the UK implemented a series of targets to be fully decarbonised until 2050 [7].

For these goals to attain, innovative techniques need to be adopted to the existing energy scheme. These methods include the harness of renewable sources that could eliminate pollution and at the same time provide the much-needed energy. Although, such technologies are developing rapidly, they still must confront several obstacles. One major issue that they need to face is the cost-competitiveness and the efficiency that they are lacking contrary with conventional energy sources. The introduction of hybrid renewable energy systems to the energy pattern could be a benchmark towards decarbonisation and environmental equilibrium.

The core of this research is to evaluate on a theoretical, technical, and financial scale the aspects of optimised hybrid renewable energy systems by exploiting the most prominent sources in the United Kingdom; offshore wind and tidal energy and intercorporate them with green hydrogen for the decarbonisation of domestic routes. Even though numerous studies have addressed the deployment of such systems they are only on the early stages of development. Consequently, a gap in the literature remains as there is a lack of investigation regarding the adoption of them in the marine agenda, and the few research that exist assess larger ships that travel in an international scale [145] and not in a national. Additionally, there are yet to be inspected the combination of HRES systems in existing operating vessels. Hence this study aims to contribute to these gaps by optimising HRES systems configuration combined with electrolysers and hydrogen with the assess of HOMERPro, to inspect how they could be utilised and provide alternative solutions for the decarbonisation of the marine industry by covering its energy demand on specific routes.

1.2 Significance of the study

Essentially, this thesis aims to contribute to Hydrogen’s prospect of decarbonising a part of a specific sector while respecting the environment. The decisive reasons behind this research and at the same time to the point studies along with an eagerness to create ways of developing renewable hydrogen production technologies from hybrid systems have created a patchwork of this study.

Meanwhile, such investment would assess the enhancement of the European and British economy by creating new “green” jobs and unquestionably the “fight” against climate change and the long run to the 2050 pan-European target. Inter alia, this was one reason out of the many that this thesis emerged for the creation of the optimum way to exploit excess hydrogen in a way that would return to the grid for enormous financial and at the same time environmental benefits.

Finally, this dissertation is a transition to the era of zero-carbon, taking part in the race of rapid technological developments.

1.3 Scope of the study

For someone to understand the scope of this study the boundaries of the research need to be addressed along with the aspects that will be excluded. As green hydrogen gains ground in the energy transition, it would be interesting to be evaluated regarding a specific sector such as the shipping industry which is a major contributor to the UK's economy. Even though this sector is not responsible for an equal amount of emissions in comparison with other industries it still provides a negative footprint towards the climate change and atmospheric pollution.

Whereas, hydrogen has a variety of categories, in this thesis the focus will be turned towards the possibilities that green hydrogen might have.

By deploying two different renewable energy sources from existing power plants such as the offshore wind farm, West Duddon of Sands and SeaGen-S tidal turbine (it was successfully decommissioned in 2019, but for the progress of this study it will be assumed all the data as if it was still operating), the aim is to confirm if it is feasible or not certain domestic routes; the most popular ones in terms of passenger transportation, to be fully decarbonised and at the same time produce electricity to cover the energy demands of British households.

One of the objectives of this study is to address the technical process for these systems to be operational, by evaluating the components that are necessary to be implemented.

It also aims to project the feasibility of these systems regarding the financial aspects and highlight if they would be profitable for potential investments.

Lastly, as wind and tidal sources are dominant regarding energy around the United Kingdom [18], the focus of this study would be only in these power sources excluding other types of renewable energy.

1.4 Objectives

The general idea behind this dissertation is the combination of the maritime industry with innovative hybrid renewable systems; wind / tidal energy to produce green hydrogen.

The objective is to investigate if existing plants can cover demands on domestic routes that ferries operate and at the same time provide electricity as well.

This study aims to highlight how feasible is for British ports to adopt the hydrogen technology and exemplifies what are the main requirements for this to be achieved. To deploy this possibility, a combination of different renewable energy sources with hydrogen is made to create a hybrid system. Additionally, the investigation of the current legislation on a global and national scale have been taken into consideration and how they affect the shipping industry regarding innovation and alternative fuels Finally, for the proposal of this study to be feasible, the financial aspects need to be addressed.

This dissertation was conducted to assess specific objectives that will contribute to the already existing literature. A summary of these includes :

1. The evaluation of the potentials that energy sources such as wind and tidal have to offer to the decarbonisation of specific routes in the UK by the production of hydrogen.

2. Use of software tools such as HOMERPro for the optimisation of hybrid renewable energy systems (HRES).

3. The investigation of the financial aspects of these systems to showcase if they are profitable as technologies.

1.5 Thesis structure

This dissertation is distributed into six sections, with each having a unique contribution to this research.

The first section is the introductory of the study, a brief description regarding the importance of green hydrogen in the shipping industry along with hybrid renewable systems configuration to produce it.

In the literature review, a more excessive approach is given regarding hydrogen. The different types of it and why green hydrogen can be the key factor in terms of sustainability are investigated. Furthermore, the current scheme in the marine industry globally and nationally, along with the regulations that are applied are discussed.

The methodology section incorporates two sub-sections. The first is the background study that was needed to be made for the selection of the routes to be decarbonised, the appropriate renewable sources that will assess this aim and the description of them more specifically. The second sub-section includes how the modelling of those systems was appraised with the selection of HOMERPro as an optimisation tool, the calculations for the energy/hydrogen demand of the ferries and the excessive analysis of the components of each system.

In the results section, the outputs of the systems are analysed along with their feasibility. A financial analysis then is discussed to project the future Net Present Value (NPV) for both systems and if they could be attractive for potential future investments based on the cashback.

The discussion section will address the contribution of the study along with the limitations that were faced through the process. Whereas future work will be suggested based on the findings.

The last section will outline the outcome after the process of this dissertation. Concluding and highlighting the feasibility of the study.

2.0 Literature Review

2.1Background Study

2.1.1 Hydrogen as an element

Hydrogen can be described as a non-toxic, tasteless, odourless, and colourless gas [5]. It has several appealing qualities as an energy carrier, including its high energy is estimated around 120 to 140 (MJ/kg) which is almost double than that of conventional solid fuels (50MJ/kg), additionally its interaction with oxygen only generates water [5],[21]. A variety of its properties in 25°C and 1 atm pressure are outlined in the following Table

Table 1: Hydrogen properties: [22])

Hydrogen Properties	
Specific Volume (m^3/kg)	12.1
Density of gas at atmospheric pressure (kg/m^3)	0.082
Density of liquid at atmospheric pressure (kg/m^3)	71.0
Density of solid at atmospheric pressure (kg/m^3)	76.0
Critical pressure (MN/m^2)	1.30
Critical temperature (°C)	-240
Critical Volume (m^3/kg)	0.033
Combustion heat (kJ/kg)	144,000
Combustion heat to water (g)	-57.796 (kcal/mol)
Thermal conductivity (W/m°C)	0.182
Specific heat ratio ,cp/cv	1.405

Specific heat ,cp (kJ/kg K)	14.310
Boiling point – saturation pressure 1 atm (K)	20.4

Between the elements around the universe, hydrogen is the most abundant one, accounting for almost 90% of the quantity of atoms and 75 % of total matter [21]. Nevertheless, because of its intense reactivity on planet along with its low weight, it is mostly found in bound forms, such as vital organisms, water, or hydrocarbons [21]. In the atmosphere, approximately only 100 ppm may be found as gaseous molecules in the form of H_2 [5].

Figure 2 Hydrogen illustration properties (Source: [23])

Under standard conditions, hydrogen's form is gaseous, whereas at high pressures and extreme temperatures, it transforms into a solid or a liquid. The diagram below [Fig.3] [22] illustrates the phase swift when the temperature and the pressure change.

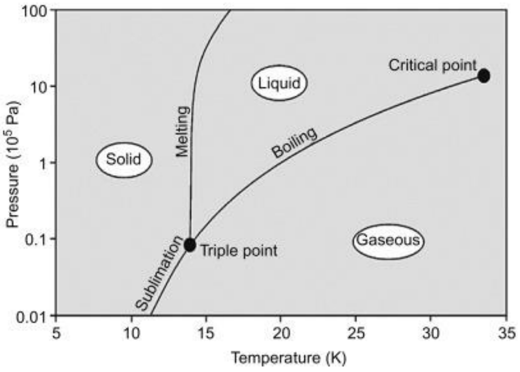


Figure 3 Hydrogen state diagram (Source: [22])

The curve between the tripe and critical point depicts the hydrogen's boiling point as pressure varies along with the saturation pressure when temperature changes [22]. It is worth mentioning that after the critical point the state does not face any changes.

It is widely established that, for energy applications or industrial use, hydrogen must be generated from other feedstocks using primary energy [5]. Currently the total global hydrogen production estimated to be approximately 500 billion cubic meters (b m^3) annually [21] in gaseous form. A report published by the Department of Energy U.S (2020), revealed that the current price for hydrogen production from PEM electrolyser, that will be discussed more thoroughly in the following sections, is approximately $ 5-6 USD/ kg and the capital cost of the electrolysis reaches the amount of U $ 1500 USD /KW [24], Bloomberg [13], additionally, predicts that the price of gaseous green hydrogen will drop to $0.7-1.6 USD until 2050, making it more cost competitive in the contrary of fossil fuel produced which has a price of $ 6-12 USD/MMBtu [13].

2.1.2 Hydrogen Categories

The fundamental knowledge of hydrogen as an energy carrier extents from its atomic wight to its final use, but in order to grasp the principles, it must be distinguished as a carrier rather than an energy source [25]. This implies that it must be powered by primary source of energy, for instance, electrical, hydro, solar or nuclear power [Fig. 4] [25]..

And the characteristics of the manufacturing process, particularly the energy source used, influence whether hydrogen is labelled green or blue. When in reality, it may be as well brown, grey, or pink [25].

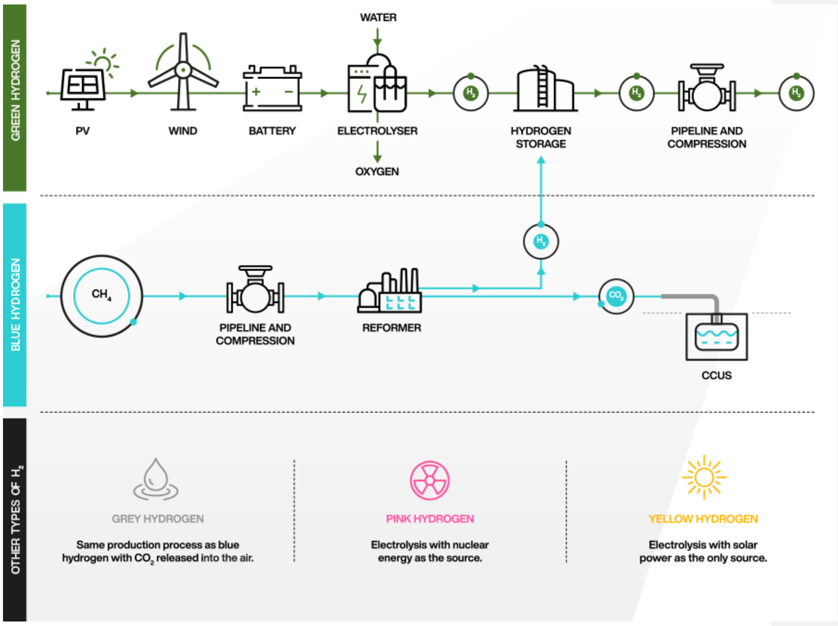


Figure 4 Different colours of hydrogen (Source : [30])

Blue Hydrogen:

It is produced either from fossil fuels [7] or when natural gas is divided into hydrogen and CO_2 using either Auto Thermal Reforming (ATR) or Steam Methane Reforming (SMR) , and then the CO2 is collected and stored [25]. The capture of GHG mitigates the environmental footprint of the earth [25],[26].

Green Hydrogen:

It is created by electrolysis of water splitting, with the use of renewable energy, which creates hydrogen and oxygen [25]. The outcome of this production is, oxygen which can be released back to the environment without harmful consequences [25].

Grey Hydrogen:

For many years, this form has been developing [26]. Methods such as SMR or ATR are used to divide natural gas or petroleum [27] into hydrogen and carbon dioxide (CO_2), basically similar pattern is followed as with the blue hydrogen except in this case CO_2 is not captured and it is released back to then environment [25].

Pink Hydrogen

Like green hydrogen, it is produced by electrolysis powered by nuclear energy, it also can be referred as red or purple [25],[28].

2.1.3 Green Hydrogen

Green hydrogen connects renewable energy to a variety of applications, serving as a supplement to electricity, renewable energy utilisation or biofuels [29],[31]. Hence, it has higher potential than fossil fuels as it could surpass world’s energy consumption at present and in the future [29].

Most crucially, in terms of decarbonisation, green hydrogen could be considered as the sole non-carbon alternative for hydrogen generation, as carbon capture in CCS is only 85 percent to 95 percent at best, and much lower so far [29].

Hydrogen can be used as a fuel in fuel cells, for instance as an electrochemical system that generates energy by combining hydrogen and oxygen from air; but it also can be ignited in turbines and engines [29],[32].

A variety of applications has been developed for fuel cells such as microgrids, large-scale power plants and back-up generation systems, as well as for numerous of transportation operations such as small-scale vehicles, fuel cell electric vehicles buses, ships, and ferries [33],[34].

Green hydrogen, as a chemical, has the ability to decrease the GHG emissions in industries that currently use hydrogen from fossil fuels, such as methanol, oil refining, and ammonia manufacturing [1],[29].

Like any other form of energy production, green hydrogen, encounters challenges. These factors include: the absence of existing transportation and storage infrastructure; its present high cost across the global value chain, from electrolysis to transportation and fuel cells the absence of existing transportation and storage infrastructure; and significant energy losses (which necessitate larger wind/solar deployment ratios); as well as the lack of value for the key advantage that green hydrogen may provide (e.g. decreased GHG emissions [1],[29],[35].

Renewables are rapidly becoming the most cost-effective source of power throughout the world, with substantial opportunity for cost reductions in the future [13],[36].

This raises the possibility of trading cost-competitive green hydrogen from renewable resources to places with lack of available land or renewable potential in the long-term scheme [29].

This exchange can be done directly with liquid hydrogen, using hydrogen carriers that enhance energy density for transportation, or through commodities [29]. The electrolyser, which will be evaluated in future chapters, is the main equipment for converting renewable energy into green hydrogen.

Even though it is cost-competitive in areas where all the ideal circumstances align, they are still areas distant from demand centres which could be challenging for the distribution of it [29],[37],[38], although plans project that this scheme is about to change in the near future. Wind energy, for instance, has a capacity factor of more than the half, in Patagonia, with the cost of electricity to be around USD 25-30/MWh [29],[40]. That could be sufficient to reach the production cost of green hydrogen at USD 2.5/kg, which is comparable to the current cost value of blue hydrogen. Nevertheless, in most places, blue hydrogen remains 2-3 times cheaper than green hydrogen [29], making it less attractive for investments on projects with it.

The cost is determined by electricity costs, operational and maintenance costs, investment expenses that may arise and the operating hours of the electrolysers [29]. Consequently, as the number of the hours rises, so does the cost of power. Countries such as the United States have installed solar projects with energy prices as low as USD 13.5-20/MWh because of supporting policy tools such as funds, which provide a decreased investment risk and a steady payment [27],[29].

This appraisal motivates policies to be implemented in the market of green hydrogen to create a “safety” umbrella for potential investors along with governments, deploying an environment for innovative technologies configuration.

2.2 Maritime Sector Emissions

The transportation sector accounts for half of all liquid fossil fuel usage [7]. Throughout the last 150 years, the energy source for ship propulsion has experienced major transition, beginning with sails to power the trips instead of actual fuel and progressing via the usage of coal to heavy fuel oil (HFO) and marine diesel/gas oil (MDO/MGO), which is now the primary fuel for this sector [10][40]. Nowadays, globally, the sector consumed 2523 million tonnes of oil equivalent (Mtoe), being responsible for almost 30% of total energy consumption worldwide amongst all end-use industries [7]. Shipping was associated for approximately 2.8 % of total yearly GHGs on a CO_2-equivalent basis between 2007 and 2012, according to the Third IMO GHG assessment [8]. The percentage of worldwide anthropogenic emissions attributed to shipping has grown from 2.76 % in 2012 to 2.89 %t in 2018 [9].

In the mid-2000s, hydrogen was introduced to be the fuel of the future in shipping, and it is still anticipated that it would provide a long-term answer [10],[41]. The use of hydrogen as a fuel in existing conventional marine engines could be viable only at low levels of mixing without posing substantial engine damage concerns [10]. The advancement of hydrogen fuel cell technology has resulted in substantial advancements and a great degree of interest, particularly in the offshore supply vessel, cruise, and passenger ship sectors [10]. This method uses an electrochemical process in fuel cells to transfer energy held in fuels directly to electricity which powers electric motors. Depending on the fuel used, there are several fuel-cell developments with varying levels of technological development, electrical efficiency, and consequent pollutants [34],[40].

Renewable Energy appeals to be promising for the transition of the shipping industry at all levels, including international and domestic transportation; fishing; and other maritime activities [17],[41]. A substantial transition away from conservative fossil-fuel transport toward an efficient designs renewable energy technology, among other things, could be crucial for a net-zero shipping sector [10]. The significance and extent to which renewable energy technologies will be adopted by the shipping industry may vary considerably depending on the size, purpose and location of the vessels which seems challenging but nevertheless fundamental towards the accomplishment of the targets [10],[41]. According to suppliers in the sector, innovation, and research efforts on the use of renewable energy alternatives, along with efficient designs, are already producing significant outcomes for immediate and near-term energy reductions for a variety of selected applications [10].

Renewables' contribution to the maritime industry in regards of energy, is still relatively constricted and is expected to remain as such in the short term [10],[41]. Nonetheless, developers are rapidly presenting designs and proof-of-concept patents proving significant savings in particular applications, suggesting that renewables have the potential to make a reasonable contribution in the medium term [10].

Hydrogen indicates enormous possibilities, as a renewable energy pathway for transportation, but the sustainability of the energy source utilised to produce hydrogen, as well as a lack of reliable low-pressure storage and cost-effective solutions for the fuel, are main concerns that must be addressed soon [10],[41].

Any effort aimed to eliminating GHG emissions by mitigating the use of fossil fuels must take into account the whole life cycle emissions of alternative renewable choices [7]. This is since upstream emissions may restrict or even cancel out the overall reductions obtained via the use of alternative fuels [7]. Figure 5 exemplifies the comparison between GHG life cycles for different fuel types.

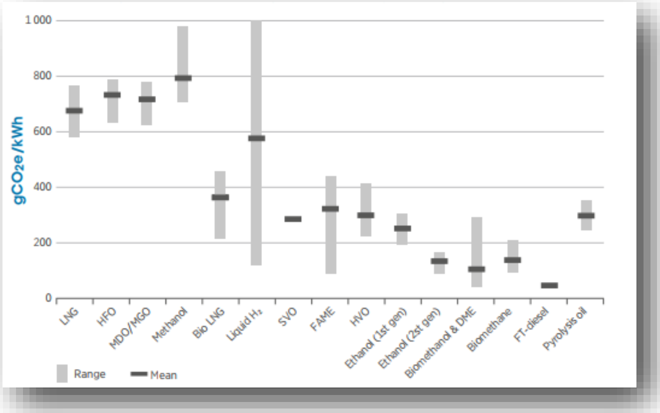
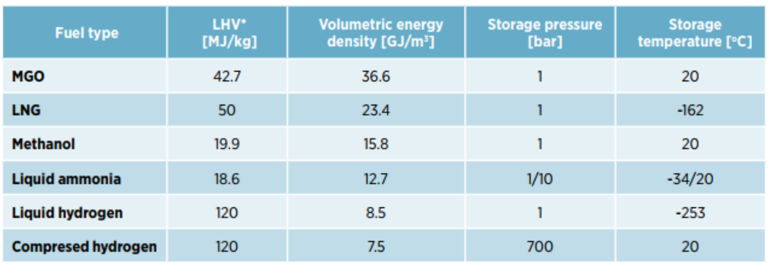


Figure 5 Approximate GHG emissions per kWh of engine power for various fuels (Source:[7])

The above figure exemplifies a comparison between GHG life cycles for different fuel types. Methanol and hydrogen, are notable compared to other fuels as their entire life cycle GHG emissions have the ability to surpass those of fossil marine fuels, depending on the production technique, feedstock type and electricity source [7].

Another important consideration is, the volumetric density, the energy density and the storage pressure and temperature of the various fuel options as they are equally essentials since they have a significant influence on the technoeconomic feasibility of each fuel [7].



Fuel type	LHV* [MJ/kg]	Volumetric energy density [GJ/m³]	Storage pressure [bar]	Storage temperature [°C]
MGO	42.7	36.6	1	20
LNG	50	23.4	1	-162
Methanol	19.9	15.8	1	20
Liquid ammonia	18.6	12.7	1/10	-34/20
Liquid hydrogen	120	8.5	1	-253
Compresed hydrogen	120	7.5	700	20

Figure 3 Comparison of marine fuels (Source : [7])

Additionally, the scheme of the fuel demand is expected to transition towards alternatives as illustrated in the following Figure 6.

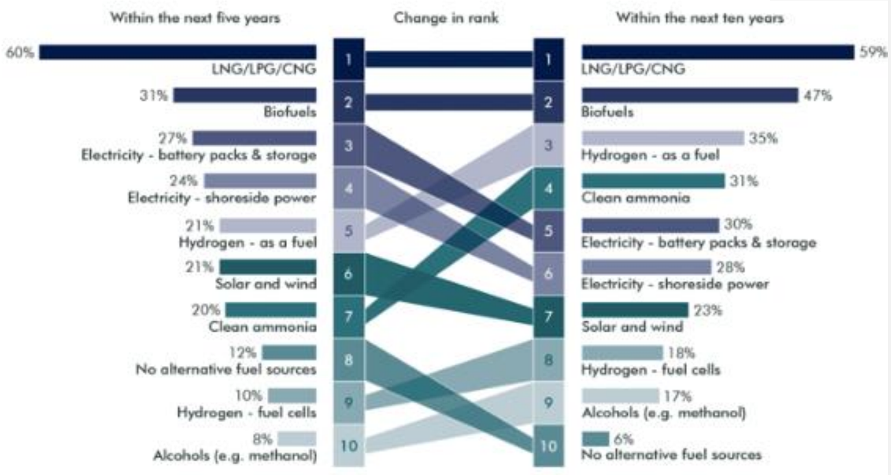


Figure 6 Projected fuel marine demand for 5 and 10 years (Source: [42])

Undoubtedly, the reason behind LNG remaining on top, originates due to the fact that certain fuels can be more challenging than others to manage due to particular storage requirements and safety concerns (i.e. hydrogen), whereas , fuels like methanol , have properties similar to traditional fossil fuels , but their cost is currently uncompetitive [7],[41]. Ergo, while selecting an alternative fuel, the consequence for infrastructure, safety and logistics must be evaluated. To verify this theory, for instance, ammonia has 2/3 the volumetric density compared to LNG, thus, extra storage is required [7].

The realisation of the potentials that renewables have to offer for the maritime industry, necessitates an integrated system engineering tactic that also tackles hurdles to implementation [10]. Thus, the development of hybrid renewable systems [43] is evaluated recently, to achieve the optimum results for the maximum exploitation of the available sources around the world along with the production of alternative energy carries that will ensure the elimination of emissions in the atmosphere.

2.2.1 Maritime Sector in UK

The UK could be described as one of the pioneers globally regarding the maritime sector. It suffices to say that, for the UK to keep its position it has to evolve by adapting into the new industry scheme. Thus, the government partnered with the marine industry in 2015, to manifest a development strategy that sets goals for innovation and zero emission plans until 2050 [15],[16]. This strategy highlights what are the future steps, in terms of innovation, environmental and social-economic impacts. With this plan, the UK aims to strengthen the relationships towards Europe and the world in general.

Shipping industry is a key factor in the economy of the country, it contributes more than £5 billion pounds [15] to the national fund. Additionally, the leisure and tourism field benefits the country by adding up almost £3.12 billion (in 2017) [15].

To keep the competitive advantage, it also needs to tackle the environmental impacts and reduce the footprint of the industry; following the lead of Europe and the transition patterns towards sustainability, as this would mitigate the implications that might affect the sector [15]. The UK among other countries that have a strong maritime power, contribute to the GHG Emissions [Fig.7]

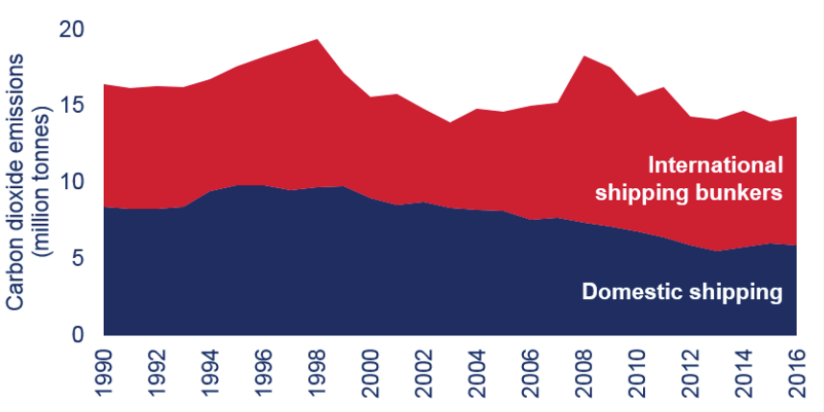


Figure 7 UK's carbon dioxide emissions , 1990-2016 (Source: [15])

Despite the fact that, the amount of the total GHG emissions is relatively low, almost 3.4% [44], scientists predict that this percentage will increase approximately to 52% [45] in the future years unless immediate actions are taken.

Following up IMO Strategy [46] until 2050 it aims to accomplish a transition to a net-zero maritime sector, complying with international regulations and be regarded as a role model in the field [15], to achieve these goals partnerships with government bodies, industry and other contributors of the supply chain have to be established [15]. A project that is needed to mentioned is; Maritime Research and Innovation UK (MarRI-UK) [15] which will combine sources from the academic field along with companies of the shipping industry to deploy inter alia, the existing research and the innovation of the sector , creating contemporary methods and systems for the marine sector [47].

2.3 Strategies and Regulations

2.3.1 European Energy Strategy and current Regulations

The European Commission has defined the molecule as a key factor of the energy transition and one of the «Green Deal» objectives [31],[48]. For instance, under its 2020 published hydrogen plan, the EU aims to increase by doubling up the existing hydrogen market until 2030 with 80 GW of electrolysis production capacity, half of which will be located outside of the Union (Eastern Europe, North Africa) [31],[48]. By 2030, 400 billion € (~ £ 4,137,338.17) in investment is planned m with the eventual goal of making Europe a leader in hydrogen production competing with the United States and China [48].

European legislations are encouraging the large-scale development of hydrogen production plants with sustainable business models [31],[48]. The ‘Red II’ directive is the best evidence of this; it sets a target of 14% renewable energy in transportation fuels, necessitating significant investments in green hydrogen for the generation of synthetic fuels such as renewable methanol or refineries [49].

The deployment of public funding is also created to enable large-scale energy transition developments, such as the innovation fund, which will be sponsored by carbon market profits of 1 billion Euros annually for at least the next 10 years, deeming projects which emerging from Green Deal, declining the risk of the first projects by covering partially or utterly the initial project financial gaps [48].

Also, there is the under-development process of a committed Hydrogen IPCEI (Important Project of Common European Interest) that, if approved by the Commission [50], will allow exemptions from government support ceilings to finance significant integrated projects at European level, supporting continent's reindustrialisation [48].

In April 2018, the IMO embraced a vision for the reduction of the shipping sector's GHG emissions, in line with the Paris Agreement, the United Nations 2030 Agenda for Sustainable Development and the Sustainable Development Goal (https://sdgs.un.org/topics/climate-change), which suggests: ''Urgent actions to be taken towards the climate change and its implications''[7],[46]. This stipulates that by 2050, emissions must be reduced by at least 50% from 2008 levels [7].

The vision, in further detail, establishes three levels of commitment [46]:

1. The carbon intensity of ships to decrease when EEDI (Energy Efficiency Design Index) for vessels are implemented.
2. International shipping's carbon intensity is expected to decline.
3. International shipping's GHG emissions will rise and the decrease.

Albeit, the implementation of targets for the decline of GHG emissions in the maritime is relatively new, the IMO has been operating on restricting airborne emissions of volatile organic compounds (VOC), ozone depleting substances (ODS), Nitrogen oxides (NOx), Sulfur oxides (Sox) and shipboard incineration since 1960, especially after the adoption of Annex VI-Prevention of Air Pollution from Ships in 1997 [7],[51].

The IMO proposes the following ways in order to achieve these goals [46]:

1. Utilisation of a fuel with a low sulphur concentration (less than 0.5% m/m)
2. In case of the concentration of sulphur exceeding 0.5%, apply an appropriate cleaning method, such as an exhaust sulphur scrubber.
3. During docking periods, use onshore power supply.
4. Substitute alternative fuels, such as LNG, hydrogen, methanol, and others.

For what is worth, Brexit will have no impact in terms of the UK's climate change targets, which are established by the Climate Change Act of 2008 [52]. The Trade and Cooperation Agreement (TCA), on the other hand attempts to guarantee that neither the EU nor the UK will reduce their commitments to emissions and removals of GHG and ozone depleting chemicals to levels lower than those in effect at the conclusion of the implementation period [52].

2.3.2 United Kingdom's strategy and Regulations

Over the next few decades, hydrogen is projected be a major asset in the decarbonization of the UK's energy sector. By 2050, total hydrogen consumption in the United Kingdom is anticipated to rise from 0.7 million tonnes (Mt) that was in 2020 to approximately 3 to 19 million tonnes [14]. Currently almost all hydrogen is utilised as an industrial supply in oil refineries [53] and chemical sector, but there are possibilities for a transition towards green hydrogen use in a variety of more applications [54].

While batteries are vital in the decarbonisation of passenger vehicles, hydrogen is considered as a possible alternative for maritime and rail transport and larger scale vehicles that require longer range and refill periods equivalent to internal combustion engines [54],[55]. A variety of government supported projects in the UK are investigating the perspective of hydrogen use in transportation [55].

The hydrogen market is still in its early stages, nevertheless it seems promising for the upcoming years [55],[56]. According to the Committee on Climate Change [14], hydrogen will be a major asset for accomplishment of the net-zero goals that UK has set [55]. Aligned with this aspect, a proposal for a £90 million fund was established by the government to tackle emissions [57] that accrue from households and heavy industry, in early 2019. Inter alia, a portion of the funds will be used to develop technologies to exploit offshore wind for electrolysis generation and creation of hydrogen [55].

Processing and production of hydrogen is rather expensive than current techniques that produce grey hydrogen [55],[58]. Consequently, a crucial necessity for decreasing total costs is the production of hydrogen at scale [13],[55]. According to current estimations the price of hydrogen in the UK by 2050 will reach approximately £428 billion, whereas the global market value would be at least £380 billion [55],[59].

To build profitable hydrogen projects, it is necessary to overcome existing pricing uncertainty and a lack of demand prediction [55],[59]. Long-term contract certainty is considered as essential in this respect for reducing some of the perceived dangers [55]. The United Kingdom, along with many other countries, lacks a well-defined regulatory framework for hydrogen initiatives in different industries [55],[59].

This creates a series of uncertainties and loopholes that must be filled before the hydrogen economy can thrive [55]. Unfortunately, to date, there is a limited amount of regulations relating to hydrogen in particular. H2 projects, on the other hand, must overcome the current legal framework, which applies to gases in general [55].

Hydrogen is defined as a “gas” in the Gas Act of 1986 (the “Gas Act”) and is thus regulated as part of the gas network [60]. The Gas and Electricity Markets Authority, which operates via the Office of Gas and Electricity Markets, regulates the UK gas market [55].

Anyone who engages in gas supply, transportation or shipping , or takes part in gas interconnectors operations, or who offers smart monitoring regarding gas, must be authorised under the Gas Act [55],[60]. The licenses include safeguards to ensure the safe functioning of the gas network as well as price control clauses [55]. An entity hoping to transfer hydrogen (or carry out another action controlled by the Gas Act) with the use of particular pipelines may be required to obtain a licence, along with the demonstration of a credible plan to begin activities and allow Ofgem to conduct a risk assessment as part of the licensing process [55].

A gas license must also follow many industry regulations, including [55]:

1. Independent Gas Transporter Uniform Network Code
2. The Uniform Network
3. Retail Energy Code
4. Supply Point Administration Agreement

The maximum quantity of allowed hydrogen injected into the UK gas network is 0.1 %, according to the Gas Safety Regulations 1996 [61]. Although efforts are made, for this amount to raise the hydrogen blend to up to 20% [61]. If these efforts attain, the regulations will need to be modified for the allowance of this greater mix.

Hydrogen, similarly, to other gases, is tightly restricted in terms of safety and health. The Health and Safety Executive mandates that it has to comply to the following regulations [55],[60],[61],[62]:

1. Pipeline Safety Regulations (1996)
2. Gas Safety (Management) Regulations 1996
3. Depending on the quantities involved, the Planning Regulations 2015 and/or the Control of Major Accident Hazards Regulations (‘COMAH’) 2015 hydrogen storage .

5. Permission is necessary under the Hazardous Substances Regulations to store two or more tonnes of H_2, and a permission is as well required, when there is a need for storing five and above tonnes of H2.

6. The Dangerous Substances and Explosive Atmosphere Regulations 2020 establishes criteria for the utilisation of equipment and safety systems in possible hazardous settings.

Until now, there is no regulatory agency in charge of overseeing hydrogen initiative. Instead depending on the activity, a number of regulators would be in charge [55]. According to the UK Taskforce on Innovation, Growth and Regulatory Reform, establishing a governmental agency for hydrogen may assist the advance of the UK’s hydrogen industry [63]. The introduction of a national hydrogen regulatory framework within the Department for Business, Energy, and Industrial Strategy, as well as the establishment of a new hydrogen could motivate investment and innovation in this market [63].

Lastly, over the course of 2020, several hydrogen projects have been developed [55]. Specifically, the following organizations have succeeded in obtaining financing to advance demonstrations of the hydrogen in the UK's energy, industrial, transportation, and heating sectors [55].:

1. HyNet: Progressive Energy Limited in partnership with three other companies; Johnson Matthey, Essar Oil and SNC Lavalin, entails the construction of a hydrogen production plant in north western England as part of the UK's pioneering net-zero district storage technology and carbon capture [64] .

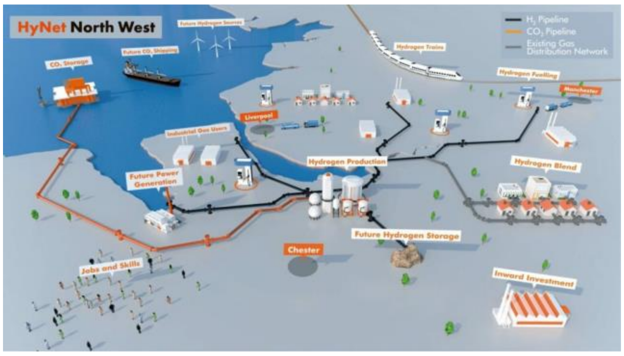


Figure 8 Illustration of HyNet Project (Source: [65])

2. Dolphyn Project: coordinated by Environmental Resources Management, is designing a 2 MW prototype of a technology that integrates seawater with offshore wind power for the generation of “green” hydrogen that can be pumped back to land. Underdevelopment plans incorporate a 10MW floating

offshore wind turbine, and as well electrolysers and a water treatment facility for regional hydrogen generation [66].

3. Gigastack: Orsted, Phillips 66, and Element Energy in partnership with ITM Power Trading Ltd, will demonstrate the delivery of large quantities of zero-carbon, cost efficient hydrogen using gigawatt-scale PEM electrolysers. It will create sustainable hydrogen for the Phillips 66 Humber Refinery using energy supplied by Orsted's Hornsea One offshore wind farm [67].

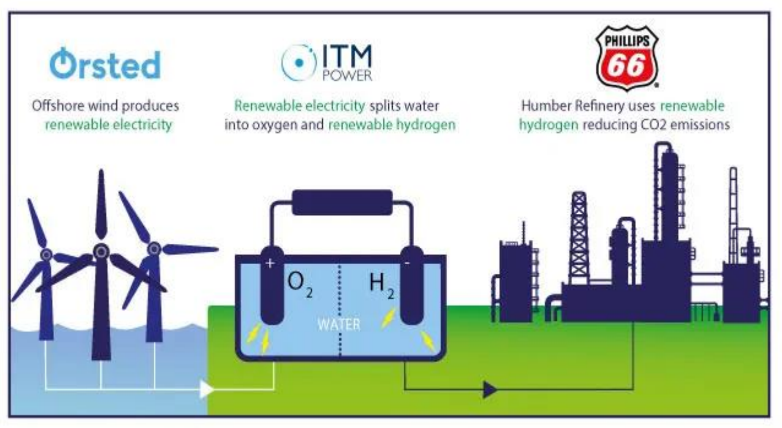


Figure 9 Illustration of Gigastack project configuration (Source:[67])

2.4 Hydrogen Production

Hydrogen can be generated through numerous technologies; it could be either produced by clean energy sources or biomass energy [6]. With that being addressed, hydrogen can be produced from water, including water thermolysis, thermochemical water splitting, photocatalytic water splitting and water electrolysis [6],[56],[68]. Albeit these approaches can be carried out effectively utilizing RES such as solar, wind and nuclear energy [6] [Fig.10], the former three are limited by low conversion efficiencies, whereas , water electrolysis is well established and can convert power to hydrogen at a 70-80% efficiency [26]. Additionally, hydrogen can also be produced by utilising biomass, but this will not be addressed in this dissertation as it can be considered as out of scope .

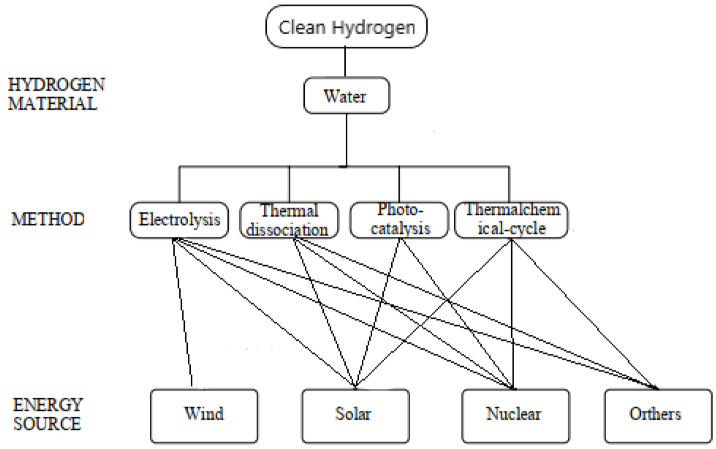


Figure 10 Renewable hydrogen production technologies schematic (Source: [6])

Wind powered hydrogen production

Using a wind farm’s electricity to create hydrogen can increase the plant’s total resource usage, therefore increasing grid-connected wind power production [6]. This abandoned wind farm electricity, particularly, may be transformed into direct current via rectification utilising power electronic control systems, and then be used to create hydrogen in electrolytic cells [6]. The hydrogen produced by these may later be separated and purified, which afterwards can be compressed and stored in specific storage tanks [6].

A variety of scientists [69],[70] have conducted a series of assessments regarding the range of GHG emissions comparing different methods of hydrogen production , as summary of their conclusions, they highlighted that the range for GHG emissions for systems powered by wind could vary from 600 to 970 gCO_2/kgH_2 [69],[70] .

Tidal energy powered hydrogen production

Another renewable source that can be used to produce hydrogen is tidal energy. To the best of the author’s knowledge, similar to the wind turbines, tidal turbines use the power that tides produce to create electricity. United Kingdom, and in particular England is among the countries with the highest tides’ range in global scale [71] Therefore, when it comes to energy sources after wind it could be considered as one of the most popular. Tidal energy can be challenging as the tides can vary from time to time and unpredictable based on the weather circumstances.

The first time that green hydrogen was produced globally was in 2017 by European Marine Energy Centre (EMEC). Prototype tidal energy converters supplied electricity into an electrolyser by harnessing the tidal power [72],[73].

2.4.1 Electrolysis

Hydrogen could be generated in an ecologically beneficial and CO^2-neutral manner by electrochemical water splitting, which could use electrical energy supplied from renewable energy sources such as wind or hydro power generators [5],[21]. Water is split to H_2 and O_2 in an electrochemical cell employing a direct current in this process known as water electrolysis, as shown in the [Equation 1] [5] or more detailed in [Equation 2] [5],[74]:

$$2H_2O(1/g) \rightarrow 2\ H_2\ (g) + O_2\ (g)\ \text{[Equation 1]}$$

$$1\ H_2O + \text{Electricity (237.2 kJ/mol)} + \text{Heat (48.6 kJ/mol)}\ H_2 + 1/2\ O_2$$
[Equation 2]

External energy is required for this endothermic process, and the reaction can occur only at sufficiently high voltages [5].

The electrolyser can be developed as part of the grid or independent system [21]. If H_2 production is the only objective, the system does not require any electric loads, fuel cells, or short-term energy storage such as batteries [21],[74].

Nevertheless, not only the off-applications of water electrolysers attract interest [21]. Because of the rising installation capacity of renewable energy plants, their inclusion into the electrical grid might be profitable [21],[74]. Electrolysis devices can therefore serve to bridge the gap between the power provided by variable resources and the energy consumption at multiple times of the day [21].

However, as a result of the increased fluctuations generated by tidal wind sources, an efficient power control is essential for operating the electrolyser at optimal circumstances and achieving maximum hydrogen conversion [21],[74].

The unpredictable working circumstances place a tremendous strain on the electrolyser, thereby decreasing its service life significantly [21],[74].

The combination of an electrolyser with a battery could be considered as a reasonable approach for the utilisation of excess power beyond the electrolyser's operational limitations, particularly in case when currents outside of the electrolyser's operating range are required to be applied [21],[74].

Unfortunately, due to rapid energy demand and the restricted hydrogen development ratio, the efficiency of hydrogen generation by water electrolysis is too low to be economically viable [21],[74]. As a result, many researchers have worked on the creation of alternative financially competitive electrocatalysts, to enhance efficiency, and energy reduction [21],[74].

2.4.1.1 Water Electrolysis

One of the most competent methods for the production of hydrogen is water electrolysis since it harnesses renewable H_2O and delivers only pure oxygen as a subsequent product [21],[74],[75]. Furthermore, this process makes use of direct current (DC) electricity from RES such as solar, wind, and biomass [21].

Although the use of renewable energy is projected to rise soon, the European Energy Directive has set a target of achieving the utilisation of 14 % of the energy requirements from RES until the end of 2021 and thus water electrolysis could be an asset for the success of it [21],[74],[75].

Moreover, water electrolysis has several advantages, including high cell efficiency and a higher rate of hydrogen generation with high purity (99.999%) , which is advantageous for further conversion into electrical energy using low temperature fuel cells [21],[74],[75].

The water molecule is the reactant in the electrolysis process, and it is dissociated into hydrogen (H2) and oxygen (O2) under the effect of electricity [21],[74],[75].

Water electrolysis is divided into four categories established on the electrolyte, circumstances during the operation, and ionic agents (OH, H+, O_2) used; nevertheless, the operational principles are the same in all the situations [21],[76] :

1. PEM water electrolysis
2. Alkaline water electrolysis (AWE)
3. Microbial electrolysis cells (MEC)
4. Solid oxide electrolysis (SOE)

The last two categories are in primary stages of development and after the examination of the available literature it was encapsuled that the levels of hydrogen production are insufficient through these technologies [21],[76].. Consequently, this dissertation will focus on the comparison of alkaline and PEM water electrolysis .

2.4.1.1.1 Alkaline Water Electrolysis

Alkaline water electrolysis for hydrogen generation is a matured and advanced technique with commercial applications up to the megawatt range among the available water electrolysers [5],[76].

During the cathode side of the alkaline electrolysis process, two molecules of alkaline solution (KOH/NaOH) turn to one molecule of hydrogen (H_2) and two hydroxyl ions (OH-) [5],[76].

The H_2 that is produced then escapes from the cathode surface to reform in a gaseous state, and the hydroxyl ions (OH-) transfer to the anode under the influence of the electrical circuit between anode and cathode through the porous diaphragm, where it is discharged to 1/2 molecules of oxygen (O_2) and one molecule of water (H_2O) [5],[76].

The O_2 is rearranged at the electrode surface and exits as hydrogen via the following process [Fig.11]

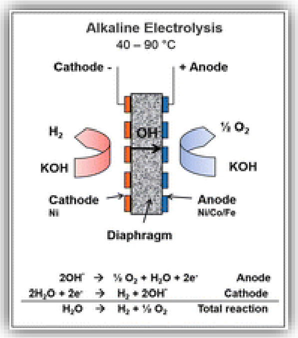


Figure 11 Alkaline electrolysis (Source: [77])

At this technique, aqueous mixtures of sodium or potassium hydroxide with strong ionic conductivity are often used as the electrolyte in concentrations ranging from 20–40 wt % [5],[21],[77]. Alkaline electrolysis operates at temperatures ranging from 40°C to 80°C [5],[21],[77].

Steel grids are used as anode and cathode in the alkaline water electrolysis process, and they can be plated with nickel as a catalyst [5],[77]. They are arranged near to each other as feasible to decrease ohmic losses [5].

Nonetheless, due to its low-cost and durable components, scalability, and extended life-cycle (approximately 30 years) [69],70], this technology has found applications in a variety of industries, with investment prices ranging from \$1000 to \$5,000 per kW, depending on system size [5],[77].

Operating current densities vary from 200 to 500 mA/cm^2, resulting in cell potentials ranging from 1.8 to 2.4 V [5],[21],[77]. Furthermore, because of the low densities, the result is low energy efficiency along with low operating pressure [5],[21].

When the density of the current is 450 mA cm^2, approximately 4.1–4.5 kWh of electrical load is required per m^3 H_2 [5],[21],[77]. In industrial applications, amounts of 50–485 $m_{H2}{}^3$ /h are generated with an almost 99.9% pure gas [5],[21]. Higher efficiencies of 78–80 percent are achieved in current systems utilizing the zero-gap design due to a decreased energy input of around 3.6–3.8 $kWh/m_{H2}{}^3$ (at 200 mA/cm^2 and 90–120°C) [5],[21],[77].

Even though, a significant number of large-scale alkaline electrolysers has been manufactured over the years; material improvement including the enhancement of the separator’s stability and catalysts, remains the focus of scientific efforts [5],[76].

Polymer-based anion exchange membranes evolution, particularly, has intrigued numerous research organizations [5],[76].Their primary advantage is the simplification of the system by the replacement of the liquid electrolyte, which could be described as highly erosive and may leak out of the stack [5],[76]. The accessible solid electrolytes are often nobbled with alkaline electrolytes, this resonates to the fact that the levels of hydroxide ion remain low [5],[76].

Among others the stability of different oxide catalysts and no noble metals, is a major benefit when it comes to alkaline water electrolyser as it reduces the total cost of the system [5],[35].

Platinum, for instance, has the greatest known activity towards hydrogen evolution reaction (HER); however, nickel is mostly used because of its much cheaper cost [5],[76].

The OER catalyst has a greater influence on system efficiency as its strong oxidative currents cause corrosion and deterioration of the support material as well as the catalyst itself [5],[76].

2.4.1.1.2 PEM Electrolysis

The first PEM water electrolysis was developed in the early 1950s, and in 1966 the disadvantages from alkaline water electrolysis were addressed [21],[35].

Solid polysulfonated membranes were utilized as an electrolyte in PEM water electrolysis technology, which is comparable to PEM fuel cell technology [21],[35]. These proton exchange membranes provide a number of benefits, including decreased gas permeability, reduced thickness (Σ 20–300 μm), high-pressure operations and high proton conductivity (0.1 ± 0.02 S cm^{-1}) [21],[35].

Water is electrochemically divided into hydrogen at the cathode and oxygen at the anode at their respective electrodes in this type of electrolysis [21],[35]. Water is pumped to the anode, where it is split into oxygen (O_2), electrons (e-) and protons (H+) which generate this technology [21],[35]. The protons are transported to the cathode side [21], the electrons escape the anode via the external power circuit, which produces the reaction’s force (voltage). And they recombine at the cathode to generate hydrogen [21],[35]. A schematic of this process is presented below:

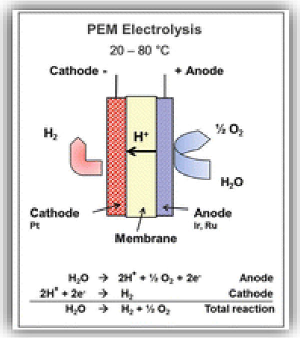


Figure 12 PEM Electrolysis (Source: [77])

One of the most environmentally friendly technologies to date is PEM water electrolysis as it offers the ability of the conversion of renewable energy to high purity hydrogen in terms of sustainability [21],[74].

Another advantages that PEM electrolysis system features is the unique design, high current density (over 2 A/cm^2) [Fig.13], rapid response, high efficiency, mitigated footprint, and the ability to operate at low temperatures (20–80 °C) [21],[35].

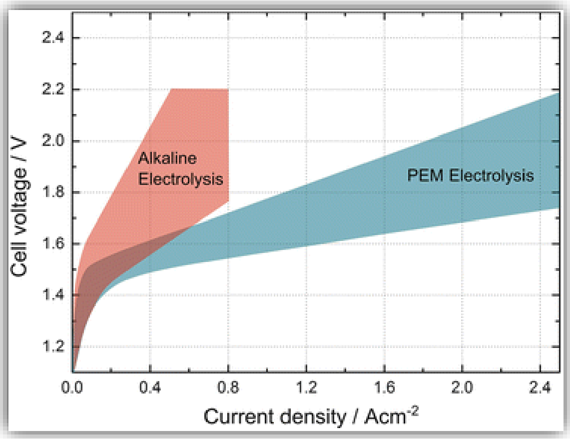


Figure 13 Comparison ranges for current density/voltage curves foe PEM and Alkaline electrolysis (Source: [77])

In addition, PEM electrolysis facilities can be considered as easy to balance, making them more appealing for industrial applications [21].

Iridium dioxide (IrO_2) or Ruthenium dioxide (RuO_2) as the OER at the anode and platinum (Pt) or Palladium (Pd) noble metals as the HER at the cathode are the electrocatalysts for PEM electrolysis process making it more costly than alkaline water electrolysis [21],[76].

Consequently, one of the most fundamental problems in PEM water electrolysis is the mitigation of manufacturing costs while maintaining high efficiency [21]. In spite of that, as year 2050 is approaching, more and more researchers [78] along with companies are putting a lot of work into improving the PEM water electrolysis' components, and consequently , this technique is getting closer to commercialization.

The following table encapsulates the properties for both electrolysers.

Table 2: Comparison of water electrolysers (Source:[29],[79])

	PEM	Alkaline
Electrolyte	Proton exchange ionomer	Aqueous KOH (20-40 wt%)
Cathode	Pt-Pd, Pt	Ni-Mo alloys
Anode	IrO_2 , RuO_2	Ni-Co alloys , Ni
Cell Separation	Nafion 117	Diaphragm
Current Density (A/cm^2)	0-6-2.0	0.2-0.4
Cell Voltage (Volt)	1.8-2.2	1.8-.2.4
Cell Area (m2)	<3	<4
Operating Temperature	50-80	60-80

(Celsius)		
Operating Pressure (bar)	30-76	1-30
Production Rate (Nm^3 /h)	<40	<760
Gas Purity (vol%)	>99.9999	>99.5
System Response	Milliseconds	Seconds
Lifetime (hours)	20-60k	60-100k
Development Status	Commercial	Mature
Costs (stack) minimum for 1 MW , for 2020	$ 400 USD/kW	$ 270 USD/kW
Estimating costs (stack) minimum 1 MW , for 2050	< $ 200 USD/kW	< $ 100 USD/kW

For this study the PEM electrolyser was chosen rather the alkaline. Even though the latter is an established method of production compared to PEM which is developing [5],[21], the former provides the ability of better production rate along with purity of the produced products almost close to 100% [5],[21]. These advantages overcome the alkaline, making PEM the best candidate for the project.

Hence, after research on the market for the proposed hybrid models that are going to be evaluated , PEM electrolysers manufactured by NEL were chosen. NEL is one of the leading companies, regarding hydrogen production with more than 3500 installed electrolysers in a global scale.

The M series [Fig.14] that the company manufactures is ideal when it comes to green hydrogen production, as it can generates from 2000 to almost 5000 Nm^3/h of pure H_2 [80]. For instance, the deal that Iberdrola [81] sealed with NEL for the manufacture of a 20MW electrolyser for a green project in Spain confirms the reliability of NEL.

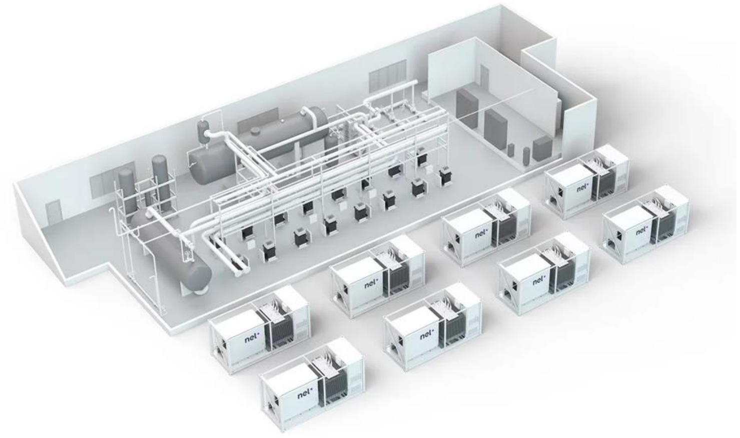


Figure 14 Illustration of NEL's PEM electrolyser facility (Source:[80])

2.5 Hydrogen Storage

Hydrogen storage is significant regarding the implementation of its technology in terms of power and transportation development. Compared to any fuel that is used to date , hydrogen has the highest energy per mass [82].Conversely , due to the low density that characterises it, low energy levels are created , emerging in the urgent need for development of advanced storage approaches and technologies.

Since, hydrogen is present in three available forms , it can also be stored as [83]:

1. cryogenic liquid;
2. pressurized gas;
3. solid fuel in combination with various materials

Thus, the conditions that it needs to be stored vary. When liquid, it is stored in cryogenic tanks as its boiling point at 1 atmospheric pressure is -253ºC [83]. When it is in gaseous form the pressure needs to increase and taking into account factors as, the infrastructure investment , the consumption of energy and the driving range it is confirmed that ideally it can be stored in tanks with high pressure of 350-700 bar and lastly, when solid it can be absorbed by specific surfaces [82],[83].

One of the main components is the storage vessels, which are divided in three categories [83]:

1. Bulk Transportation
2. Vehicular
3. Stationary .

A limitation of these vessel is the high density of hydrogen that needs to be fulfilled, and remains a crucial challenges in several transport applications [82].

Gaseous hydrogen storage is the most mature and widely established, and as for now is the most cost effective one. The reason for this is that, the liquefaction of LH_2 is an energy consuming process as it demands 30-40% of the low heat value (LHV) of hydrogen , in contrast of GH_2 that can be compressed using only 5-20% of LHV [83]. Moreover, LH_2 requires cryogenic conditions to be maintained on the contrary, GH_2 can be stored in ambient temperatures.

Because hydrogen has a low boiling point, it may be kept as a cryogenic liquid, compressed gas, or chemically bonded when used as a fuel in ships. Other than NOx, which is always a by-product of combustion in a combustion engine, using hydrogen with internal combustion engines might remove the greenhouse impact [84],[85]. Hydrogen has roughly three times the energy density of HFO, although it has a far lower volumetric density [84],[85].

Commented [SO1]: Not entirely sure why you jump from diesel to hydrogen so abruptly, maybe I didn't get the idea.

As a result, liquid hydrogen takes up roughly five times the space that the same amount of energy in the HFO takes up when stored [84],[85]. The same ratio grows to 15 times the volume of HFO when hydrogen is kept as compressed gas [84],[85]. Due to limited demand, there is presently no hydrogen supply infrastructure for ships anywhere in the globe. Electrolysis hydrogen generation technology is well-known and widely available; thus, it may be used in ports if there is enough carbon electric power to keep the process running [84],85].

Commented [EG(2]: Storage

Regarding the volume of hydrogen 1 kg of gaseous hydrogen can occupy more than 11 cubic meters in a space under standard conditions (temperature/pressure) [87]. Hence, in order for the storage to be financially beneficial, the density needs to increase [87]. Therefore, different approaches have been developed to handle this challenge evaluating a variety of inputs regarding the energy demand [87].

Consequently, the aim of storage is either to be utilised as a backup source in a number of purposes or the equilibrium of supply and demand considering the cost effectiveness [86].

All in all, even though liquid hydrogen (LH_2) is more expensive as it has to be maintained in lower temperatures, studies indicated [88] that is preferable longer trips as larger quantities of it can be transported contrary to gaseous hydrogen. In addition , comparing both states with the same volumetric amount , LH_2 overcomes GH_2 as it has higher density :

LH_2 : 8.5 MJ/L > 7.2 MJ/L : GH_2 [22]

Lastly, as gaseous hydrogen necessitates to be compressed making it more unstable to be contained, instead LH_2 is more prominent in terms of safety [88] .

2.6 Hybrid Renewable Energy Systems

As it was on the previous sub-sections, renewables have potentials to be part the solution in the climate change that the planet is facing. Hence, a variety of new innovating technologies is underway to assess this issue.

When these sources are incorporate to a common system, they are widely referred as hybrid renewable energy systems (HRES) [43],[89],[90] with the main goal to be the cover certain energy demands. The energy sources that connect these systems could be alternative, conventional, and as well storage components; along these lines, a balance is achieved since these components complement each other and cover possible deficiencies [89],[90].

Additionally, they could be financially effective, stable sources of constant power supply under all the possible load scenarios contrary the single power plants and that the same time maintain the environmental equilibrium [89].

Despite of this, a few systems face obstacles when it comes to their operation. For instance, due to the increased price of the electrolysers available in the market and at the same time the low levels of efficiency to the production, set hydrogen as a not economically viable option [91],[94]. Hence, when these systems are in the designing planning process, the optimisation challenge is frequently solved by the assessment of the Net Present Cost (NPC) mitigation. Although it has to be kept in mind that the optimisation of such systems is a hard task to be accomplished due to the number of variables and complexity of them [91].

As the power generation from renewables is not constant and unpredictable due to multiple circumstances, an optimised energy flow coordination is required when planning HRES [92]. The energy strategy has to ensure the reliability at the minimum possible cost along with the optimum systems' efficiency [92].

Due to the constant need of improvement of these systems, a variety of software tools has been developed to cover certain needs of different systems. Shinha and Chandler [93], carried out a research which compared a variety of available software tools, and revealed that HOMERPro among others is a widely established technological asset regarding the modelling of hybrid systems as it provides the maximum options for the user for all the possible renewable combinations [92],[93],[94].

HOMERPro will assess the investigation of the hydrogen production process that is going to be evaluated in the upcoming sections and it will be evaluated excessively in the Methodology section.

3.0 Methodology

3.1 Introduction

The main goal of this research is to evaluate the case study of hydrogen deployment for the decarbonisation of the most popular domestic ferry routes in the United Kingdom by exploiting available renewable energy sources of the study areas.

To investigate this case, different scenarios were considered with the utilisation of both offshore wind energy and tidal energy. The models that were investigated were simulated through HOMERPro, the software tool that was firstly introduced in Section ; this software will assess the hydrogen production along with electrical outputs of each system.

As literature review examined such systems are referred to as HRES, it was revealed that for these systems to be successful the design of the is fundamental.

For this reason, a thoroughly explanation of how each system was created, from A to Z, to result positive outcomes to fulfil the aims of this dissertation.

This section indents to describe how the research was conducted from the collection of the data to the results and it is divided into three main sections:

1. Background Research to assess the data collection;
2. Wind Energy Simulations in HOMERPro;
3. Tidal Energy Simulations in HOMERPro.

As this study tries to evaluate the decarbonisation of two ferries with the use of different types of renewable energy, each subsection would be divided in two parts, one for the Belfast to Cairnryan route and the second for the Heysham to Douglas route.

For that to be more clear, the following schematic was created that outlines how this methodology was conducted for the optimisation of the HRES for each route :

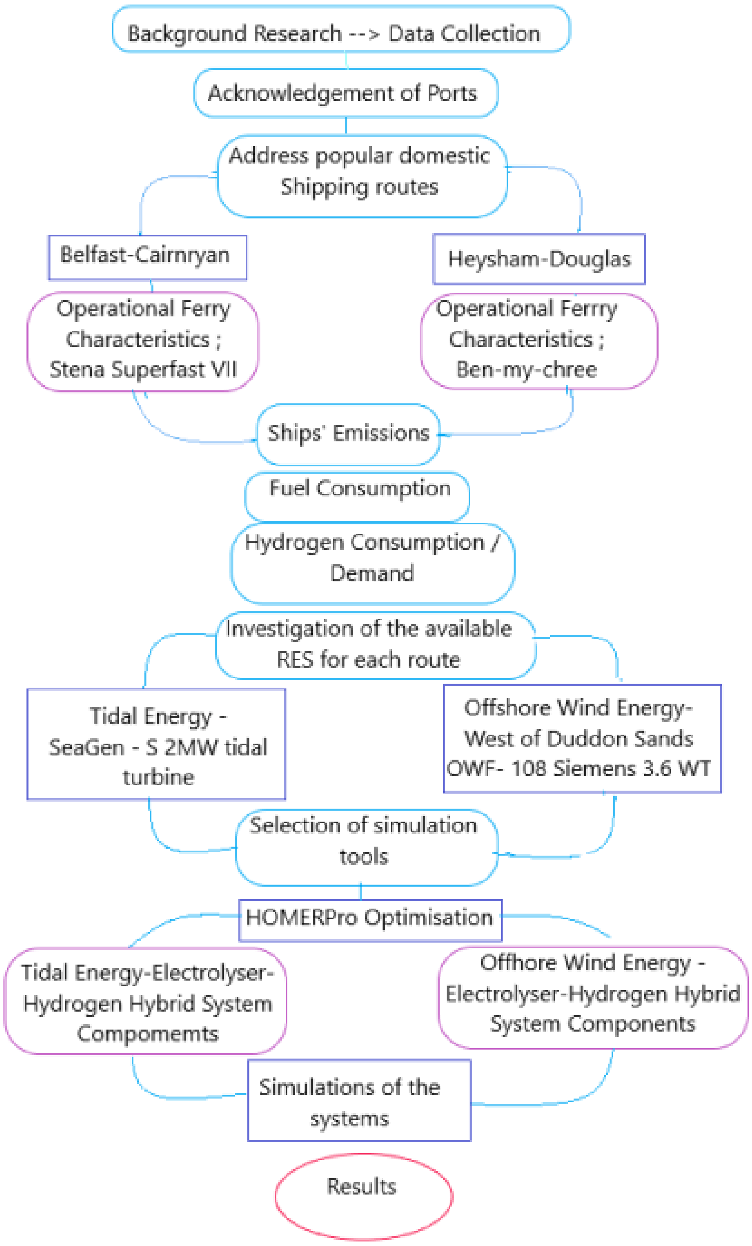


Figure 15 Methodology's Schematic

3.2 Background Data Collection

3.2.1 Ports

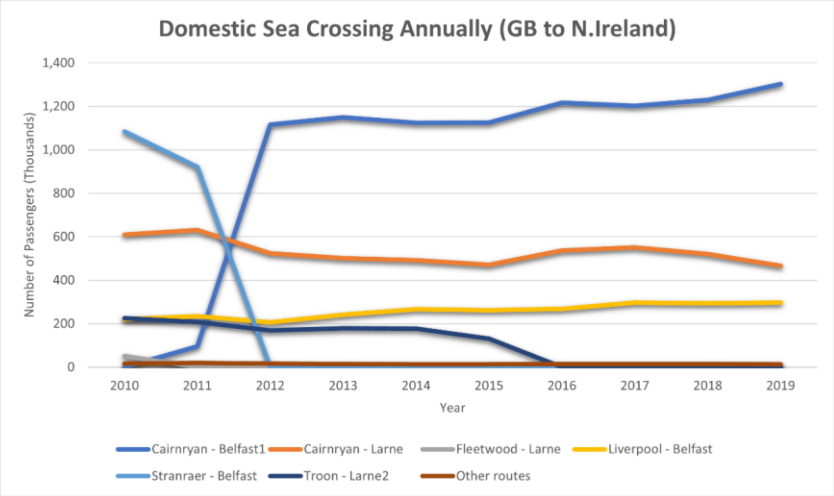
An investigation was conducted through the marine data of the UK in order to find the most popular routes that have been made for the time period of 2010 until 2019 [95]. By these findings, the ports with the most attraction to passengers would be the ones that this dissertation would focus to study . The routes that were investigated were the ones between Great Britain to Northern Ireland and Great Britain to Isle of Man as the routes from Great Britain to Channel Islands, Great Britain to Orkney and Shetland Islands along with other sea routes had fewer passengers compared to the former two [Table 3]. The year of 2020 would be excluded, due to the pandemic of Covid-19 , some of the routes that were regularly operating were either cancelled or eliminated in few routes per month . With that being said, the data for that took place during 2020 are not representative for numbers that would usually be calculated if the ships would operate under normal circumstances.

Table 3 National Sea Crossing around UK from 2017-2019 (Source: [95])

Routes	**2017**[1]	**2018**[1]	**2019**[1]
GB – Northern Ireland	2064	2058	2082
GB – Isle of Man	551	519	537
GB - Channel Islands	253	239	208
GB – Orkney/Shetland	457	467	526
All other Sea Crossing	183	234	132
Total	3509	3517	3484

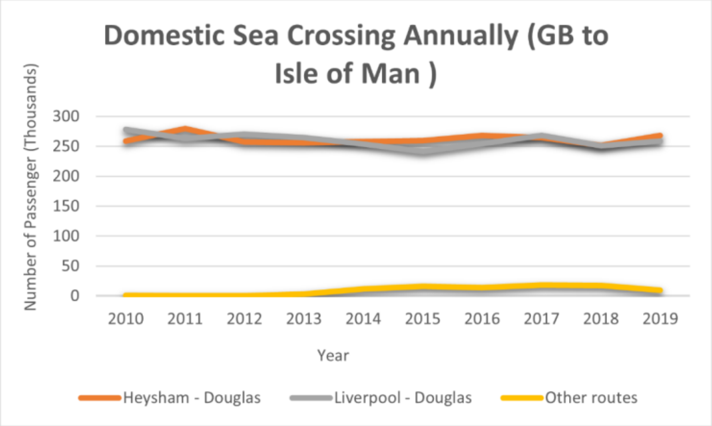
[1] Number of Passengers that travelled around UK (in thousands)

What is striking in the following Graph 1, is the rapid increase of preference in terms of the passengers for the route from Belfast (Northern Ireland) - Cairnryan (Scotland) since 2011 until 2019 .



Graph 1 Passengers annually for National Sea Crossing From GB to Northern Ireland . (Graph was made with the use of Excel . Data Source: [96]).

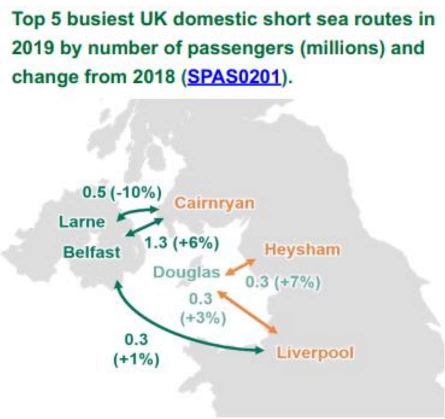
What can be clearly seen in Graph 2, is the difference between the two dominant routes from Great Britain to Isle of Man, is minor for the last decade, with the Heysham to Douglas, having a slightly higher attraction to passengers compared to the Liverpool to Douglas itinerary.



Graph 2 Passengers annually for National Sea Crossing From GB to Isle of Man. (Graph was made with the use of Excel . Data Source: [96]).

The Department for Transport released the Statistics od 2019 for short trips around the UK, which stated that Cairnryan – Belfast and Heysham – Douglas had faced an increase of the passengers with the former to have 1.3

million more in 2019 than 2018 with an increase of 6% and the later an increase of 7% [97].



Top 5 busiest UK domestic short sea routes in 2019 by number of passengers (millions) and change from 2018 (SPAS0201).

Figure 16 Short Sea Crossings around UK (Source : [97]))

3.2.2 Shipping Routes

Based on the finding on section 1.2 , the ports of interest to be decarbonised and become hydrogen hubs are the Belfast along with the Douglas harbour , since these are the locations from where the ships will depart on the itineraries that will be investigated.

3.2.2.1 Belfast to Cairnryan

Belfast Harbor is a major center for commodities exportation and importation, as well as passenger ferry transportation services. Stena Line is the only company that currently operates Belfast ferry port, which offers frequent passenger ferry crossings to Cairnryan in Scotland [98].

The ships that sail for this route are two sister ferries: Stena Superfast VII and Stena Superfast VIII, which travel six times per day and the duration of each trip is approximately 2 hours and 15 minutes [99].

Figure 17 Stena Line Superfast VII on duty (Source: [99])

3.2.2.1.1 Stena Line Ship Characteristics

As presented on the Table 4, both ships have minor differences, with the only noticeable one to be the engines as Stena Superfast VII sails with HFO in contrary Stena Superfast VIII which operates with MDO.

Table 4 Characteristics of Stena VII/VIII (Source :[100],[101],[102]))

Characteristics	Stena Superfast VII	Stena Superfast VIII
IMO	9198941	9198953
Flag	British	British
Operator	Stena Line Irish Sea	Stena Line Irish Sea
Type	Ro-Ro Ferry	Ro-Ro Ferry
Port of Registration / Departure	Belfast	Belfast
Port of Arrival	Cairnryan	Cairnryan
Initial Year of Service	2001	2001
Ship Builder	Howaltsweke Deutsche Werft AG,Kiel,Germany	Howaltsweke Deutsche Werft AG,Kiel,Germany

Length (m)	203.3	203.3
Width (m)	30.3	25
Clearance in Height (m)	5.05	5.05
Clearance in Width (m)	4.5	4.5
Gross Tonnage (t)	30285	30285
Beam (m)	25	25
Draught (m)	6.60	6.60
Engines	4 x Wärtsilä-Sulzer 12ZAV40S	4 x Wärtsilä-Sulzer 12V40S Diesel
Engine Power (Max/P_{me} @75%)	46000kW/36000kW	46000kW/36000kW
Speed	23 knots (42.60 km/hour)	23 knots (42.60 km/hour)
Capacity of Passengers	1300	1200
Price (Approximately)	$80.9 millions	£80.9 millions

3.2.2.2 Heysham to Douglas

Similarly to Belfast – Cairnryan, the route that connects the mainland of England from the Heysham port to the Douglas ;Isle of Man, has only one operational ferry company; Steam Packet [103]. Albeit, the frequency of the trips depends on the season, it remains one of the most popular in terms of ferry transportation around UK.

The ships that sail are Manannan and Ben-my-chree, After thorough research on the company's timetable [104] , it was noticed that through the years Ben-my-chree was the ship that operated the most for this specific route compared to Mannanan which mostly sails from Isle of Man to Belfast. For that reason, for the purposes of this dissertation the focus on the simulations would only be for Ben-my-chree.

Figure 18 Ben-my-chree ferry (Source: [104])

The duration of the itinerary is approximately 3 hours and 45 minutes, for four times daily, four times weekly [104]. The characteristics of the ship are represented below :

Table 4 Ben-my-chree characteristics (Source: [105],[106])

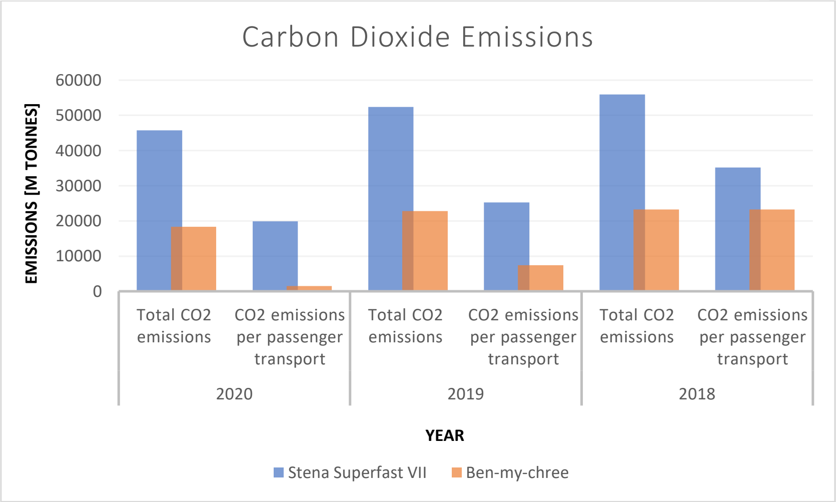
Characteristics	Ben-my-chree
IMO	9170705
Flag	United Kingdom (Isle of Man)
Operator	Isle of Man Steam Packet Company
Type	Ro-Ro Ferry
Port of Registration / Departure	Douglas
Initial Year of Service	1998
Ship Builder	Van der Giessen de Noord ,Rotterdam
Length (m)	125.2

Width (m)	23.4
Gross Tonnage (t)	12747
Beam (m)	23.4
Draught (m)	5.6
Engines	2 x MaK 9M32 Diesel
Engine Power (Max/Pme @100%)	8640 kW
Speed	19 knots (35.19 km/hour)
Capacity of Passengers	500 (636 max)
Price (Approximately)	£ 24,500,000 million

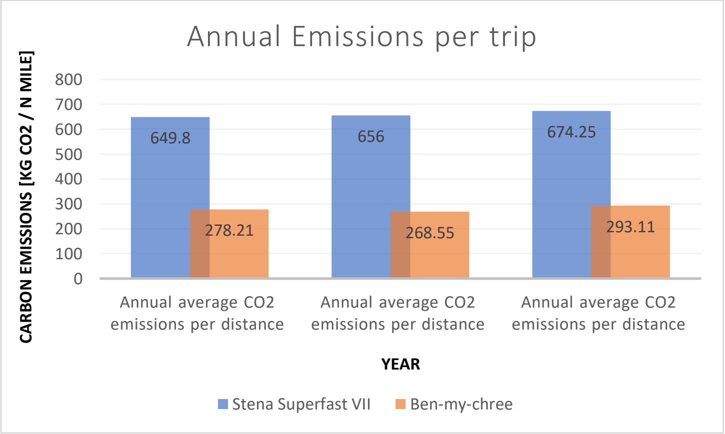
Because both Stena Superfast VIII and Ben-my-chree operate with MDO , only the case of Ben-my-chree will be evaluated as the same methodology is applicable for both vessels.

3.2.3 Ship Emissions

One of the many reasons these ships are being investigated, is since they contribute to the climate change and constant increase of the environmental pollution by creating GHG emissions every time they sail. By turning renewable energy into green hydrogen, they will be fully decarbonize, with the aim of eliminating their environmental footprint close to 0 g CO_2/ t nm. As it can be observed [Graphs 3,4] for the last couple of years the emissions of Stena Superfast VII are significantly higher than Ben-my-chree an assumption is that the later uses MDO which emits 20% GHG less than the HFO [107]. Albeit, these emissions compared to larger ships for instance; chemical tanker ships that operate for longer distances, are minor, this does not equals that they are negligible , and thus they also have to been taken into consideration as significant pollutants .



Graph 3 Emissions of Stena Superfast VII and Ben-my-chree for 2018,2019,2020 (Created by Excel , Source : 108])



Graph 4 Annual Emissions per distance (Created by Excel , Source : [108])

3.2.4 Fuel Consumption

The consumption of the fuel can vary depending on several parameters, such as the freight/passenger that carries per trip, along with (extreme) weather conditions , the demand , how many engines are used during the operation of the trips and many more [107].

The equation that can estimate the fuel consumption of a ferry is [107]:

$$\mathbf{Fuel}_{\mathbf{consumption}} = \frac{SR * \%mcr * P}{\rho * S} \text{ [Equation 3]}$$

Where :

- **Fuel**$_{\mathbf{consumption}}$ **:** HFO/MDO consumption (L/km)
- **SR** : standard rate of fuel consumption (kg/kWh)
- **%mcr :** maximum continuous rating which equals with the maximum output (MW) that can be produced under normal circumstances (%)
- **P :** the ship's installed engine power
- ρ_{HFO} **:** the density of the fuel
- S : speed of the ship

For the purposes of this research, the speed that was taken into account during the calculations was assumed to be constant, average speed that was given by the manufacturer), however, under real-time circumstances the speed changes depending on weather conditions or water changes. In addition, the generators that are installed on-board were excluded as well.

Assumptions:

1. For the estimation of the annual fuel consumption, it was assumed that during the year, no interruptions on the standard schedule of the ship occurred, as in reality maintenance issues or extreme weather conditions can impact the trips. Thus, the days that the ships were assumed to operate were:

   Stena Superfast VII: 360 days (as it operated five times daily, six times per week)

   Ben-my-chree: 288 days (as it operates four times daily, six times per week)

   As a validation for this assumption the report of the EU-Thetis [108] revealed that the days for the previous three years varied for several reasons, for instance 2020 had fewer operational days compared to other years, due to the pandemic of Covid-19 that decreased the daily trips, as it is illustrated on the following Tables :

Table 5 Operational days of Stena Superfast VII (Source: [108])

Year	Operating Days
2020	183 days
2019	222 days
2018	231 days

Table 7 Operational days of Ben-my-chree (Source: [108])

Year	Operating Days
2020	162 days
2019	212 days
2018	189 days

2. The fuel consumption per route was calculated by multiplying the distance that each ship implements per trip:

   Stena Superfast VII: 77.24 km

   Ben-my-chree: 103.64 km

3. Contrary to Stena Superfast VII , Ben-my-chree is operating with MDO, thus the density and the temperature difference that can be observed about the two ships in the Table .

Table 6 Stena Superfast VII and Ben-my-chree fuel consumption

Values	Stena Superfast VII	Reference	Ben-my-chree	Reference
SR (kg/kWh)	**0.2**	[107]	**0.2**	[107]
% mcr	**75**	[100]	**90**	[106]
P (kW)	**36,000**	[100]	**8,640**	[106]

ρfuel (kg/m^3)[3]	**1,010 at** 15°C	[109]	**900 at** 60°C	[109]
S (km/h)	**42.60**	[100]	**35.29**	[106]
Fuel Consumption per km (L/km)	**125.5**		**49.10**	
Fuel consumption (L/route)[1]	**125.5x77.24km = 9693.62**		**49.10x103.64 =5,088.724**	
Fuel consumption daily (L/day)	**48,468.1**		**20,354.89**	
Fuel consumption weekly (L/week)	**290,808.6**		**122,129.37**	
Fuel consumption annually (L/year)[2]	**13,958,812.8**		**5,862,298.32**	

3.2.5 Hydrogen Consumption / Demand

One of the essential factors for the feasibility of this research , is balance of the production rate with the demand of hydrogen , taking into consideration the components required for the distribution along with the energy demand. To determine how much H_2 would be required, the variation in calorific value between H2 and HFO was estimated, outlining an average mass of hydrogen ready to be utilized.

The equation that was used to transform the volumetric consumption into the mass consumption was estimated by multiplying it with the fuel's density , modifying the mathematical equation of density [110]:

$$F_{fuel\text{-}m} = F_{fuel\text{-}v} * \rho_{fuel} \quad \text{[Equation 4]}$$

Where :

$F_{HFO\text{-}v}$: volumetric fuel consumption

ρ : the density of the fuel

FHFO-m : mass fuel consumption

To estimate the mass of the hydrogen that is being consumed , the following formula could be used , which is also consists of the efficiency of potential fuel cells with the efficiency of the internal combustion [112]:

$$\mathbf{F_{H2\text{-}m}} = \frac{F_{HFO/MDO-m}}{\frac{u_{H2}}{u_{HFO/MDO}}} * [\mathbf{1} - (\boldsymbol{n_{Fc}} - \boldsymbol{n_{Ic}})] \text{ [Equation 5]}$$

Where :

$F_{fuel\text{-}m}$: Fuel (HFO/MDO) mass consumption

U_{H2}: Lower Heating Value of Hydrogen

u_{fuel}: Heat Value of fuel (HFO/ MDO)

n_{ic}: efficiency of internal combustion engine

n_{Fc}: efficiency of the fuel cell

The total hydrogen consumption is calculated including the maximum range for one trip as for this study an assumption was made that indicated that the tanks that will be installed on board to store the hydrogen will not exceed the area that the tanks for the existing fuel occupy. Therefore, for the estimation a formula was formed that incorporates the range of the trip is the distance multiplied by the safety factor for fuel reserve. And so :

$$\mathbf{T_{H2}} = \boldsymbol{F_{H2-m}} * \boldsymbol{D} * \boldsymbol{k} \text{ [Equation 6]}$$

Where :

$F_{H2\text{-}m}$:hydrogen mass consumption

D: distance (of the trip)

k: safety factor for fuel reserve

Assumptions :

1. For the safety factor an assumption was made in accordance with the safety and environmental standards regarding fuel storage [112], therefore k=1.2.
2. The values that are going to be used for the following estimations are highlighted with pink.

Table 7 Stena Superfast VII and Ben-my-chree hydrogen demand & total consumption

	Stena Superfast VII	**Reference**	**Ben-my-chree**	**Reference**
F_{fuel-v} (kg/km)	125.5		49.10	
Ffuel-m (kg/km)	126.7		44.19	
U_{H2} (MJ/kg)	120	[22]	120	[22]
u_{fuel} (MJ/kg))	40.9	[113]	42.7	[113]
n_{ic}	40%	[114]	40%	[114]
n_F	45%	[115]	45%	[115]
Fh_2-m (kg/km)	43.20			
D (km)	77.24	[98]	106.34	[103]
k^1	1.2	[112]	1.2	[112]
TH2	3,458.33		1,969.62	
TH2 daily (kg/day)	17,291.63		7878.44	
TH2 weekly (kg/week)	103,749.75		47,270.67	

TH2 annually (kg/year)[2]	1,792,795		2,268,991.895	

3.2.6 Renewable Energy Sources

After the establishment of the ports and which ships would be decarbonized to become future hydrogen hubs, the renewable sources that will produce the necessary power for this purpose need to be addressed .

3.2.6.1 Tidal Energy

One interesting finding is that close to Belfast port there is no offshore wind farms available. According to BBC (2019), the coastline of Northern Ireland is not eligible for off-shore wind farm developments due to potential aesthetic concerns [116],[117]. The findings were presented in a report issued by the Department of Economy [63], it stated that the “visual impact” on possible locations within 13 kilometers of the coast would be a “major concern” [116]. As a consequence, the Crown Estate, which controls the seabed, has excluded Northern Ireland from participating in 2019 lase round [116],[117].

For this particular reason, for the needs of the study alternative renewable energy sources had to be found. Inter alia, in the UK tidal energy has potentials as researches indicated that it possesses approximately half of Europe’s tidal energy supply [117].

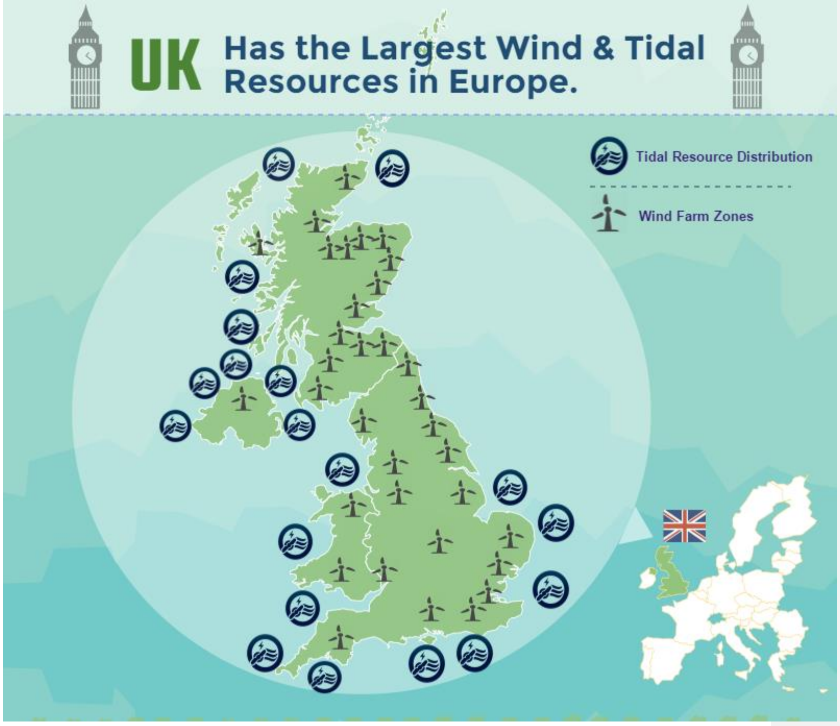


Figure 19 Available Wind and Tidal energy sources around the UK (Source : [118])

Strangford Lough, located on Northern Ireland’s east coast, is among the biggest maritime sites in terms of tidal energy [119]. The tidal stream averages 3.3 m, and there is a typical diel cycle, with the confined fetch limiting wave action [119].

As a reference for the optimisation of HRES that took place in this dissertation, SeaGen Turbine would be considered. The Strangford Lough Tidal Turbine, SeaGen 1.2MW is the first commercial-scale tidal energy facility in the world. Marine Current Turbines (MCT) designed it, and it was installed in Northern Ireland's Strangford Lough in July 2008, and it was successfully decommissioned in 2019 [119],[120],[121].

The SeaGen-S 2MW tidal stream turbine technology was chosen as the foundation for the calculations of this project. SeaGen-S 2 MW system is a development of the extremely successful 1.2 MW SeaGen – S turbine [120],[121],[122]. MTC was able to optimize the system design using the knowledge and expertise obtained from the initial project, delivering 2MW at a reduced cost with higher availability [122]. The production of energy from tidal flows necessitates the use of reliable, established, and cost-effective technologies [120],[121],[122]. The SeaGen-S 2 MW is the one of the pioneering technologies on the market of tidal energy to date. MCT has invented and patented essential key features that provide commercially feasible power production as the pioneer in the tidal energy industry [120],[121],[122].

These system features have been field-proven since installation in 2008, of the commercial scale, SeaGen – S 1.2 MW grid connected system. By 2012, SeaGen - S had delivered ten times the amount of electricity to the grid than all other tidal devices combined [120],[121],[122. Following MCT's acquisition by Siemens, SeaGen-S 2MW is being developed and tested to the highest production standards, benefitting from Siemen's world class, delivery of renewable energy technologies to worldwide utilities [120],[121],[122].

Figure 20 SeaGen – S 1.2 MW (Source : https://www.power-technology.com/projects/strangford-lough/)

A variety of the characteristics of SeaGen-S 2 MW are summarised in the following Table 10 along with an illustration of the turbine underwater in Figure 21:

Table 8 Specifications of SeaGen-S 2MW tidal turbine (Source: [122])

Characteristics	
Rotor	
Diameter (m)	20
Swept Area (for 2 rotors) (m^2)	628
Speed (rpm)	4-11.5
Generator	
Type	Asynchronous
Power	<= 1000 kW
Voltage (V)	690
Operational Details	
Cut-in tidal speed (m/s)	1
Rated Power (m/s)	2.5

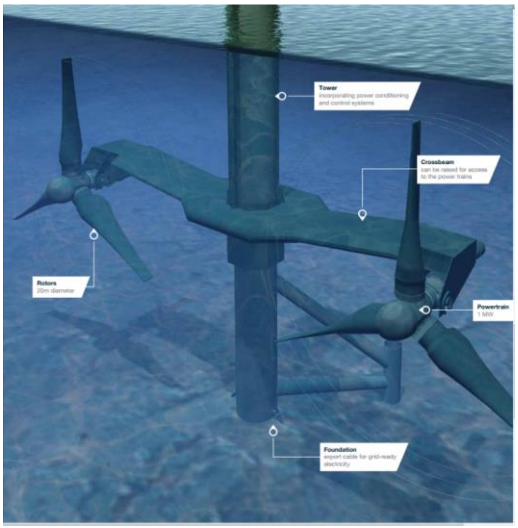
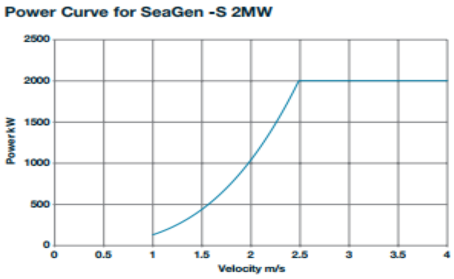


Figure 21 Illustration of SeaGen -S 2MW underwater (Source: [122])

Graph 5 shows that when the turbine reaches the peak velocity at 2.5 m/s it produces the highest power of 2 MW.



Graph 4 Power Curve of SeaGen S 2MW (Source: [122])

3.2.6.2 Offshore Wind Energy

Between Heysham and Douglas ports , there are five operating offshore wind farms that were found through an interactive map given by the Wind Europe data base [123],[124] as exemplified in the Table :

Table 9Offshore Windfarms close to Heysham port (Source: [123],[124])

Site Name	Barrow	Ormonde	Walney 3	Walney 1 &2	West of Duddon Sands
Number of turbines	30	30	47	102	108
Capacity	90 MW	152.3 MW	329 MW	367 MW	388.8 MW
Manufacturer	MHI Vestas	Senvion	Siemens	Siemens Wind Power	Siemens Wind Power
Owner	Orsted	Vattenfall & AMF	Orsted & PKA & PFA	Orsted & SSE & Ampere Fund & PGGM	Iberdrola Renovables & Orsted
Year of operation	2006	2012	2018	2012	2014

The plants are located in the East side of the Irish sea as shown in Figure 22 :

Figure 22 Operational Offshore Wind Farms around Heysham (Source: [124])

Figure 22 West of Duddon Sands offshore wind farm ([124])

One interesting finding in the literature review, is that in order to produce hydrogen increased energy is required [21] for that particular reason the offshore wind plant that is going to be evaluated is the West of Duddon Sands , as in terms of capacity it can produce almost 389 MW annually [125],[126].

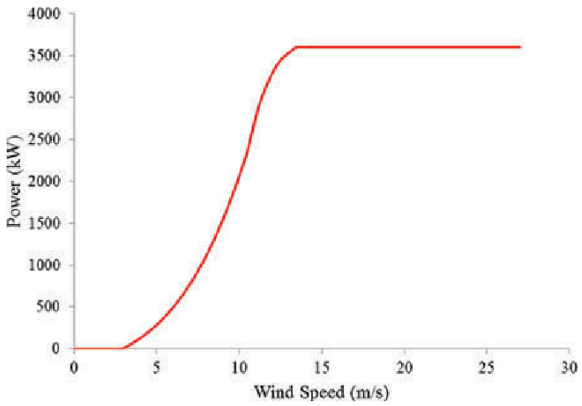
West of Duddon Sands Offshore Wind Farm is located in the West Coast of England specifically in the East side of Irish Sea close to Walney Island. It fully operates 108 turbines ; SWP 3.6MW with a 120m rotor diameter [125],[126] . The owners of the project are Scottish Power Renewables (50%)

and Orsted (50%). The total area covered is 67 km^2 [125],[126]. The power generated by the plant is estimated to cover the needs for almost 340,000 households annually [125],[126].

Table 10 Characteristics of Siemens 3.6MW offshore wind turbine ([125],[126])

Characteristics	
Rotor	
Diameter (m)	20
Swept Area (m^2)	67,000
Speed (rpm)	4-11.5
Hub height (m)	30
Generator	
Type	Asynchronous
Power	3600kW
Operational Details	
Cut-in speed (m/s)	4
Cut-out speed (m/s)	25
Rated Power (MW)	3.6
Capacity (MW)	389

The power curve of the wind turbines [Graph 6], encapsules that when the wind velocity exceeds 15m/s that is the point that the wind turbines achieve their maximum capacity.



Graph 5 Power Curve for Siemens 3.6MW offshore wind turbine (Source: [127])

3.3 Simulation Tools

As mentioned in the Literature Review, when a system combines two or more energy sources, it is widely referred as a hybrid energy system [20]. It is widely acknowledged that these systems several times can have reduced costs and inclined reliability rather than systems that only utilise one source of energy [20]. Although, for these systems to be feasible in terms of cost competitiveness reliability in the market [17],[92],[128], the optimal design is significant.

As the world in recent years tries to achieve net-zero goals and create a low emission environment, HRES are attracting more interest, including hydrogen and battery energy storage [128].

In this regard, for the past couple of years a variety of software tools has been developed to assess them and create the optimum expected outcome [19],[20],[92]. Inter alia, the National Renewable Energy Laboratory (NREL) (US) created the Hybrid Optimization Model for Electric Renewable (HOMER) , a simulation tool widely utilised in the performance evaluation of hybrid energy systems [19],[20].

The HOMER analysis tool allows comparison of a variety of system alternatives [94]. This feature enables a user-friendly investigation of the financial and technical benefits of several power system configurations [94].

HOMER simulates alternative system configurations using inputs such as diverse technical possibilities, component/equipment costs, available resources , weather data and many more , and provides as outputs findings as a list of viable options ranked be net present cost [91],[94].

3.3.1.1 HOMER Pro Optimisation

The simulations were conducted in HOMERPro, and the optimum energy system was evaluated for a period of one year, to assess the variety of elements of the HRES, such as the environmental (i.e weather conditions), technical (i.e design) and financial (i.e cost of components) considerations .These parameters were set in order to investigate the feasibility of the HRES systems ; wind-hydrogen , tidal-hydrogen .

Both of these hybrid systems face their own challenges, so this section will be divided in two main parts; how the methodology processed in terms of the optimisation of the :

1. Tidal energy -Hydrogen production hybrid system
2. Offshore wind energy – Hydrogen production hybrid system

HOMERPro needs certain inputs in order to deploy the simulation for each system, hence, these inputs would be described thoroughly in the following section as well.

3.3.1.1.1 Tidal energy – Hydrogen hybrid system

A schematic of the systems is illustrated below [Fig.26]:

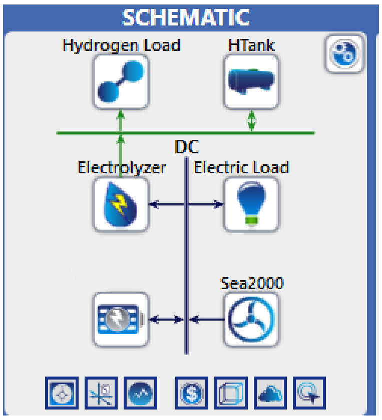


Figure 23 Tidal Energy-Hydrogen HRES schematic (Source: HOMERPro)

Tidal Data

HOMERPro as an input to optimise the hybrid system needs the monthly water speed for a period one year from the location that the plant is placed. After extensive literature research on multiple data bases, unfortunately, there was a lack of available data that did not cover the needs of the simulation. The velocity of the water can be unpredictable, and it has to be constantly monitored to have specific data, to proceed with the simulation an assumption was made that the velocity is constantly 2.5 m/s per month. The justification of this assumption emerges from the fact that a mean spring peak velocity greater than 2.25-2.5 m/s is generally required for cost-effective stream power generation [132], besides as shown on Graph 5, when the turbine has a 2.5 m/s is the time when it produces the maximum power. Hence, as the goal is to create the optimum system this assumption was taken into consideration.

Components of the system

Electrical Load

The electrical load is set to be negligible in this case scenario.

Electrolyser

The electrolyser that was chosen for this system was considered based on the same criteria as the one for the tidal-hydrogen HRES. The demand of the ferry was estimated at **7878.44kg/day** and so the electrolysers will require the same capacity and an additional 100 %t backup capacity (by HOMERPro outputs).

After repeating the same steps as with the former hybrid system, M2000 remained to be the ideal one for this model as well.

Battery

In order for the model to be simulated via HOMERPro a battery is needed as storage but it will not be evaluated further in this dissertation.

Hydrogen

As input the hydrogen demand was taken into consideration, which is;

the hourly hydrogen load: 720.50 kg/h

the daily hydrogen load: 17,291.63 kg/day

Tidal Turbine

The system was modelled with the use of 1 SeaGen tidal turbine with a capacity of 2MW.

Two components determine the energy of the tides, the kinetic and the potential [71]. For the calculation of this energy the following formula is needed [71]:

$$E=g*\rho*A*\int zdz = 0.5*g*\rho*A*h^2 \text{ [Equation 9]}$$

Where :

E : energy

g: acceleration of gravity

ρ : density of seawater

A : is the area of interest

z: vertical coordinate of the ocean surface h : tide amplitude

Using a seawater average ; g*ρ= 10.15 kNm^{-3} , the tidal cycle per m^2 of the water surface can be estimated as [71],[133] :

$$E= 1.4h^2 \text{ ,Watt-hour or } E= 5.04h^2\text{, kilojoule [Equation 10]}$$

Hydrogen Tank

The volume of the hydrogen tank was examined manually based on the outputs that HOMERPro provided.

3.3.1.1.2 Offshore wind energy -Hydrogen hybrid system

A schematic of the components of the hybrid system is illustrated [Fig.24] .

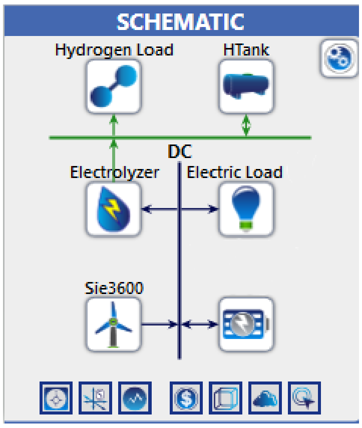


Figure 24 Offshore Wind – Hydrogen HRES schematic (Source : HOMERPro)

Inputs and components that were taken into account for the simulation success:

Wind data

The Figure below highlights the wind data that were obtained by the NASA Prediction of Worldwide Energy Resource (POWER) database [129]. As it can be observed, every month varies due to meteorological conditions, for instance May, June and November are the months that the wind has the higher average speed (m/s).

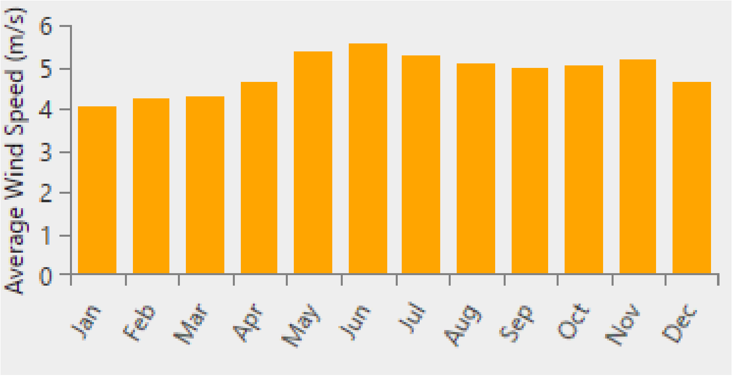


Figure 25 Wind Profile (Source: HOMERPro)

Wind Turbines

The number of the wind turbines is 108 , the model is 3.6MW Siemens with 120 meters rotor and a capacity of 389MW.

The power of the offshore wind turbine can be calculated by the following [130]:

$$P= 0.5 * \rho * A * Cp * V^3 *Ng * Nb \text{ [Equation 7]}$$

Where :

ρ: Air density (kg/m^3)

A: Swept area (m^2)

Cp: Coefficient of performance

V: wind velocity (m/s)

Ng: generator efficiency

Nb: gear box bearing efficiency

It is worth mentioning that, Betz law has to be taken into account which indicates that the wind turbines efficiency can never exceed the 59.3% of performance [130]

The power coefficient can be found by the equation [131]:

$$Cp = \frac{Pe}{Pt} \text{ [Equation 8]}$$

In addition, HOMERPro highlighted that the Cut-in speed is 4m/s (Power Outpout:127kW) , Cut-out speed is 25 m/s and the wind speed is 15-25m/s when the wind turbine reaches the maximum capacity output of 3600kW.

This means that this specific wind turbine is not able to produce electricity when the speed of the wind is <4m/s which is because of lack of torque and if the wind exceeds >25m/s , the wind turbine will face negative implications and even severe damages.

Components of the system

Electrical Load

The electrical load is set to be negligible in this case scenario.

Electrolyser

A PEM electrolyser was chosen (the reason regarding of the choice is explained on Section 2.4.1.1.2). The production of hydrogen is directly proportional to the Electrolyser's rated capacity. With the demand for the ferry estimated at **17,291.63** kg/day electrolysers will require the same capacity and an additional 100 %t backup capacity (justified by the HOMERPro outputs). The electrolysers were selected by the available options on the market as the system that is simulated Is based on real-life data.

A series of criteria was set for the selection of the optimum option:

1. Energy consumption

2. Capital Cost

3. Efficiency

4. Number to be used

As described on Section 2.4.1.1.2 NEL is one of the most reliable manufactures regarding electrolysers to date. Thus, after reviewing the available NEL models, M2000 was found to be ideal for the purposes of this dissertation The fundamental reason for this decision was that, regardless the energy consumption along with the cost, it is preferable for power systems to harness more electrolysers with lower capacity rather a large one for them to work on their rated capacity, assessing the prosperity of the system by extending their lifetime for a longer period of time.

Battery

In order for the model to be simulated via HOMERPro a battery is needed as storage, but it will not be evaluated further in this dissertation.

Hydrogen

As input the hydrogen demand was taken into consideration, which is ;

the hourly hydrogen load: 328.27 kg/h

the daily hydrogen load: 7878.48 kg/day

Wind Turbines

The model as mentioned previously will simulate 108 existing offshore wind turbines;

A summary of the components of both HRES is outlined below [Table 13]:

Table 11 Summary of the components of both HRES

		$OFW\text{-}H_2$ *	$T\text{-}H_2$ *
Turbines	Initial Number	108	1 (with double rotor)
	Capacity (MW/turbine)	3.6	2
Hydrogen	Per hour (kg/h)	328.27	720.50

Load	Per day (kg/day)	7878.48	17,291.63
Electrolyser		M2000	M2000
Electrical Load		Negligible	Negligible
Battery		4hr 1MW Li-on	4hr 1MW Li-on
Hydrogen tank (kg)		40.000	20.000

** The acronyms of the table stand for :*

OFW-H_2 : Offshore wind -hydrogen system , T-H_2 : Tidal -hydrogen system

4.0 Results

The literature review revealed that although innovative technologies are becoming more attractive over time, they remain under development, and they cannot adapt easily to the existing industry mostly due to the cost variables.

This dissertation's objective is to contribute to the already evaluated HRES by adapting them to the marine sector. Most of the studies that were inspected are implementing this type of systems for powering remote areas [90] or the generation of electricity by the combination of solar and wind HRES [11] but to date, these systems have not been excessively evaluated for their contribution to the shipping industry.

Thus, the methodology that has been followed for the selection of optimum systems for the decarbonisation of ferries could shed light on the existing literature by contributing to the enhancement of further research towards the adoption of these systems in the maritime as well, and the investigation of the financial outcomes which could be considered as benchmarks in the investment of such systems.

As it was introduced to the Methodology section, two HRES were modelled and thus, this sector will be divided into two categories. Moreover, after the explication of the technical results, the financial results would be discussed.

4.1 Hybrid Systems

4.1.1 Tidal energy → Hydrogen

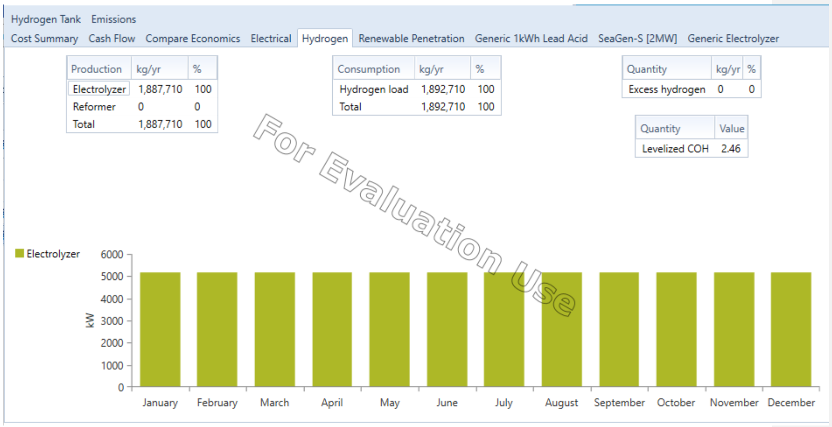
For the route of Belfast to Cairnryan, Stena VII’s demands for hydrogen annually are estimated to be 1,792,795 kg/day. The tidal – case scenario proved to be challenging as there were limitations that had to be solved due to the lack of data. Additionally, a series of simulations had to be run multiple time as the outcome of them were not the results that were expected.

The root of this problem was unfortunately, that 1 SeaGen 2MW is not suitable to attain the cover of the ferry’s demands for it to be fully decarbonised. Therefore, several simulations had to be implemented, adding manually more tidal turbines, as only one was able to cover approximately 20% of the total hydrogen demand. The summary of the results is encapsuled in the following Table

Table 12 Results for various numbers of tidal turbines (Source: HOMERPro)

	1 Turbine	2 Turbines	3 Turbines	4 Turbines	5 Turbines
Hydrogen Production (kg/year)	377,536	1,132,623	1,510,167	1,886,710	**1,887,170**
Electricity Production	1,752,000	35,040,00	52,560,000	70,080,000	87,600,000
Excess Electricity	0	0	0	0	0

By the addition of 5 tidal turbines with double rotors each, the results were refreshingly adequate. The hydrogen that was produced was estimated to be 1,887,170 kg/year, 94 thousand more than the initial demand. This could be a major advantage for the hybrid system as it could either stored as a back-up or be sold providing extra additional profit to the investment.



Production	kg/yr	%
Electrolyzer	1,887,710	100
Reformer	0	0
Total	1,887,710	100

Consumption	kg/yr	%
Hydrogen load	1,892,710	100
Total	1,892,710	100

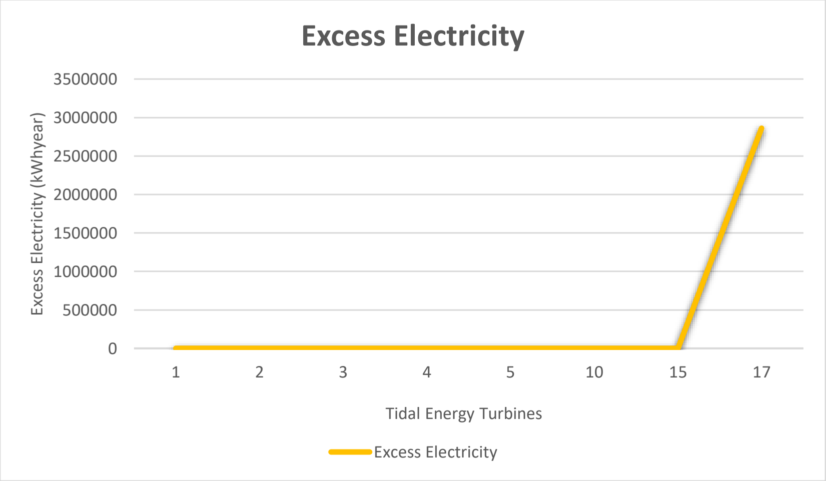
Quantity	kg/yr	%
Excess hydrogen	0	0

Quantity	Value
Levelized COH	2.46

Figure 26 Hydrogen production of the Tidal- Hydrogen HRES (Source: HOMERPro)

Albeit more tidal turbines equalled the increase of the hydrogen production along with the electricity production, the excess electricity remains zero constantly.

The optimisation of the system was assessed respectively until the point of the system to start producing excess electrical load. HOMERPro confirmed that after the extension of the system up to 17 tidal turbines [Figure] the excess electricality would start to be produced, a case scenario that is not feasible yet, as by the literature to date the largest tidal plant globally has 10 bulb tidal turbines operating [133],[135].



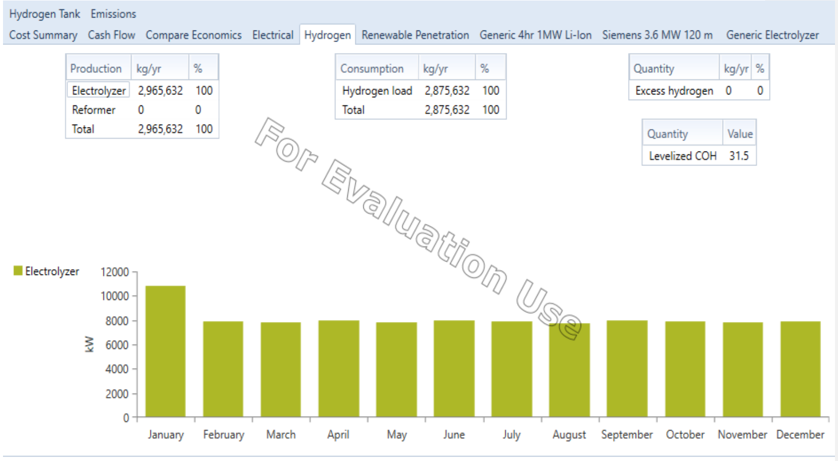
Graph 6 The start up point of the excess electricity production (Source: Made in excel using data that were extracted from HOMERPro)

However, these results can be food for thought to the academic and industry communities as there are still uncharted territories in terms of tidal energy that need to be addressed. Even though the tidal energy could be considered a mature technology there are still challenges that need to be tackled as the cost of them along with the maintenance remain high compared to other alternative RES, as it will be discussed on the following sub-section. If the British government could create opportunities for future investments of the sector, this alternative source could contribute even more to the climate change equation.

4.1.2 Offshore Wind Energy → Hydrogen

After simulating an existing offshore wind farm (West of Duddon Sands) with 108 3.6MW wind turbines and considering the hydrogen demand of the ferry; Ben-my-chree that operates from Douglas to Heysham, the results indicated that in terms of feasibility this model is not only able to produce the hydrogen demand of the ship but also create excess electricity in order to keep covering the demand of a variety of households that the initial wind farm provides electricity too.

As it is encapsuled in the following Figure the amount of hydrogen that is being able to be deployed is: 2,965,632 kg/year and the annual demand of the ship was estimated to be: 2,268,991.895 kg/year . So the excess amount of produced hydrogen is: be 696,640.105 kg/year which can either be stored as a backup plan in case of an unexpected fault on the system or either could be sold in potential hydrogen stations or buyers that could enhance the national trade as well.



Production	kg/yr	%
Electrolyzer	2,965,632	100
Reformer	0	0
Total	2,965,632	100

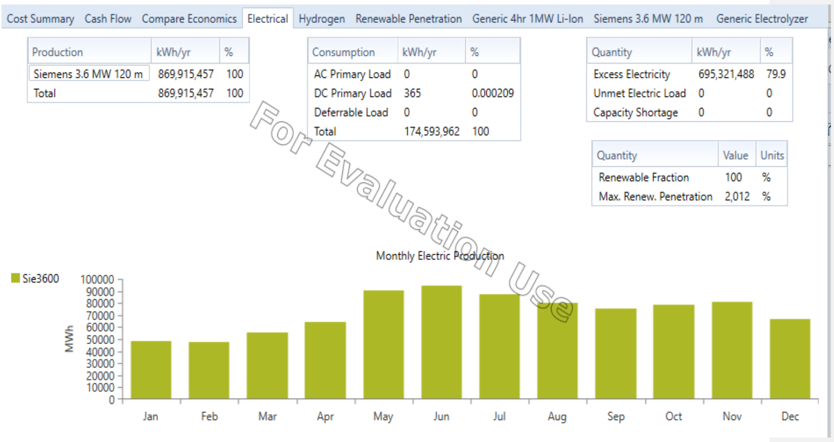
Consumption	kg/yr	%
Hydrogen load	2,875,632	100
Total	2,875,632	100

Quantity	kg/yr	%
Excess hydrogen	0	0

Quantity	Value
Levelized COH	31.5

Figure 27 Hydrogen production of the offshore wind-hydrogen HRES (Source : HOMERPro)

Regarding electricity the model can produce excess electricity of 695,321,488 kWh [Figure] per year being able to support almost 139,064 houses if the assumption that the average household in the United Kingdom consumes approximately 5MWh per day [136].



Production	kWh/yr	%
Siemens 3.6 MW 120 m	869,915,457	100
Total	869,915,457	100

Consumption	kWh/yr	%
AC Primary Load	0	0
DC Primary Load	365	0.000209
Deferrable Load	0	0
Total	174,593,962	100

Quantity	kWh/yr	%
Excess Electricity	695,321,488	79.9
Unmet Electric Load	0	0
Capacity Shortage	0	0

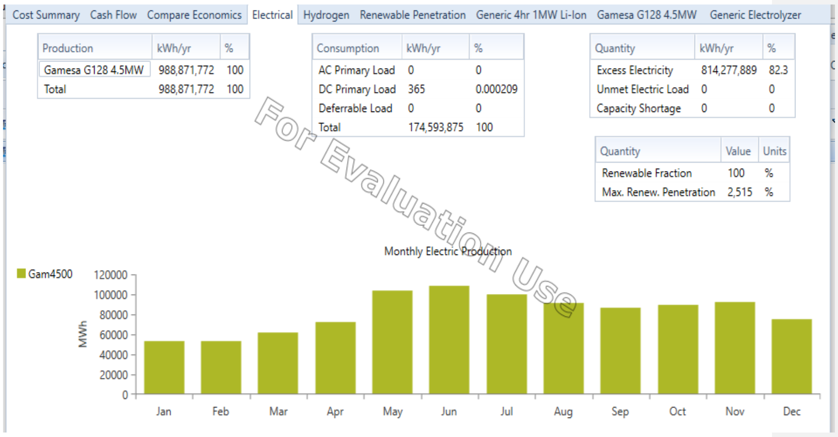
Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	2,012	%

Figure 28 Electrical Load of the offshore wind-hydrogen HRES (Source: HOMERPro)

Additionally, recent research addressed the possible scenario of retrofitting [137],[138] existing offshore wind turbines after the end of their lifetime instead of decommissioning them. This could be feasible if the monopile foundations that Siemens 3.6MW utilise during their operation, would remain in their initial place and only the tower would be replaced by larger wind turbines that could have longer tower and wider rotor.

In line of that, an additional scenario was investigated through this dissertation; the case of retrofitting the existing turbines of the West of Duddon Sands wind farm after their completion of their lifetime by bigger ones within a reason, such as the Gamesa 4.5MW turbines with 128m rotor [139], produced by the same manufacturer, could be able to generate more than the existing ones and if so, the amount that would be produced would have a significant difference to justify this possibility. In that scenario, the results seem promising as there is potential of decarbonising larger ships than Ben-my-chree and at the same time produce more electricity to provide to almost double number of households as the electricity reaches 814,277,889 kWh/year.

Despite that, retrofitting of offshore wind farms is in early stage of development [137],[138] and a challenge that it has to tackle is the gaps that exist in the literature review. Although, with the contribution of the results of this dissertation further evaluation of this method could be addressed as it was outlined that it can be profitable for both the decarbonisation of specific sectors and at the same time generation of the households' energy demand.



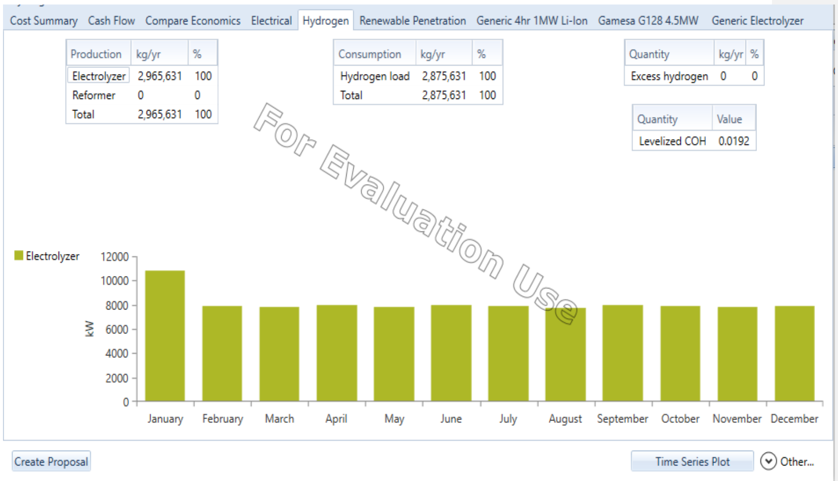
Production	kWh/yr	%
Gamesa G128 4.5MW	988,871,772	100
Total	988,871,772	100

Consumption	kWh/yr	%
AC Primary Load	0	0
DC Primary Load	365	0.000209
Deferrable Load	0	0
Total	174,593,875	100

Quantity	kWh/yr	%
Excess Electricity	814,277,889	82.3
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	2,515	%

Figure 29 Gamesa 4.5MW -hydrogen HRES electrical load production(Source : HOMERPro)



Production	kg/yr	%
Electrolyzer	2,965,631	100
Reformer	0	0
Total	2,965,631	100

Consumption	kg/yr	%
Hydrogen load	2,875,631	100
Total	2,875,631	100

Quantity	kg/yr	%
Excess hydrogen	0	0

Quantity	Value
Levelized COH	0.0192

Figure 30 Gamesa 4.5MW-hydrogen HRES hydrogen production (Source: HOMERPro)

These results highlighted that in terms of the technical aspects of such systems the outcome could be feasible and contribute to the decrease of the GHG emissions and at the same time cover the energy demands of ferries and households.

Driven by that, future research might analyse the potential that the other forms of renewable sources might have towards the production of hydrogen and the tackle of zero emissions transport sector. Many countries especially the ones that the core of their economy is based on national and international transport could benefit from the transition and selection of these type of innovations.

As in order for these techniques to be established and adapt to the current market not only the technical but also the financial aspect needs to be addressed. Hence, HOMERPro released certain value considering the

4.2 Financial Analysis

For every proposal one of the main factors to define if it is feasible or not is the financial factor. Many methods have been created through the years to estimate the costs of energy plants as it is essential to for the investors to have a feedback of potential projects.

LCOE is the term that defines the cost of a power plant due to through its lifetime and is dominant when it comes to financial costs as it shows the comparison values between different generation sources , it can be estimated by the following formula [140],[141] :

$$\text{LCOE} = \frac{C_{Capex} + \sum_{t=1}^{n} C_{opex}\,(1+k)^{-t}}{\sum_{t=1}^{n} Et(1+k)^{-t}} \quad \text{[Equation 11]}$$

Where:

LCOE : levelized cost of energy ($/MWh)

Ccapex : Capital expenses (General costs) ($)

Copex : operation expenses ($)

Et : production of energy (kWh = years of production)

HOMERPro after the simulation provided a series of costs based on the inputs that were inserted . These numbers are approximate as for such projects years of planning and development are necessary.

For the hybrid systems the costs are :

Table 13 Cost outputs of the HRES systems (Source: HOMERPro)

	OFW-H_2	*T-H_2*
Total Net Present Value (NPV) (£)	918,842,400	111,679,200
LCOE (£/MWh)	230,446.50	23,688.15
Operating Costs (£)	5,090,895	25,817.38

For this study, to determine the price of each of the hybrid systems that were evaluated it is of the components that consisted of each systems was taken into account. Conversely, due to the lack of data about prices for specific components, a few of the values were found in the literature. An assumption was made considering that hydrogen will be stored in its liquid form. Thus, the amount of cost that is needed is the hydrogen storage with the addition of the liquefaction process.

Table 14 Offshore Wind-Hydrogen HRES components' costs

Components	Costs	Reference
Wind Farm	1.6 billion pounds	[142]
Electrolyser	122.03 million pounds	[143]
Batteries	10.16 million pounds	[144],[145]
Storage	26.67 (+ 84) million pounds	[146]

An assumption was made that hydrogen will be stored in its liquid form. Thus, the amount of cost that is need is the hydrogen storage with the addition of the liquefaction process.

Similar process was deducted when collecting the financial data for the tidal turbine.

Table 15 Tidal turbine -Hydrogen HRES components' costs

Components	Costs	Reference
Tidal turbine	12 million pounds (x5 as this is the quantity for the project to be feasible)	[132]
Batteries	10.16 million pounds	[144],[145]
Electrolyser	122.03 million pounds	[143]
Storage	26.67 (+84) million pounds	[146]

The existing offshore wind is estimated to have a 25-year lifecycle, until now it is fully operating for 7 years leaving 18 years remain operation lifetime. Additionally, the SeaGen – S has been successfully decommissioned in 2019 but in order to address if the model is feasible the years that it was operating would be taken into account.

If the hybrid systems will be assumed to start producing hydrogen immediately, the additional cost for the unit needs to be calculated and a plan for future investors needs to be presented as a reference for future similar projects .Hence , the Net Present Value (NPV) can be used as a guide towards similar innovative developments and examine the feasibility of them .

NPV illustrates the value of the cashflow of the company in a certain period of time [147]. One of the disadvantages that it may have is that it cannot predict the changes that the market will may obtain [147].

The formula that estimates the NPV is [147] :

$$\text{NPV} = \Sigma_{t=0}^{n} \frac{Rt}{(1+i)t} \quad \text{[Equation 12]}$$

Where :

Rt : the cashflow for a certain period

i : the returned rate that could possibly returned (assumed to be 2% [150],[151] t: period of operation

For the tidal turbine-hydrogen model the NPV is :

$$\text{NPV} = \Sigma_{t=0}^{n} \frac{Rt}{(1+i)t} \quad \text{[Equation 14]}$$

Where :

Rt = 302,860,000 £ (estimated by adding all the components of the system)

i = 0.02

t = 11 years . (The tidal turbine was fully operating for 11 years ; from 2008 since 2019 , thus the lifetime of the hybrid model would have a lifecycle as such)

So , NPV = $\Sigma_{t=0}^{n} \frac{302860000}{(1+0.02)11}$ = 243,579,104 £ is the amount of money that will be returned to the company after the end of its lifetime making it a profitable investment.

For the offshore wind farm-hydrogen model the NPV is :

$$\text{NPV} = \Sigma_{t=0}^{n} \frac{Rt}{(1+i)^{t}} \quad \text{[Equation 13]}$$

Where :

Rt = 1,842,860,000 £ (estimated by adding all the components of the system)

i = 0.02

t = 18 years (remaining years of the lifetime of the wind turbines)

So , NPV = $\Sigma_{t=0}^{n} \frac{1842860000}{(1+0.02)^{18}+}$ = 1,290,295,706 £ is the amount of money that will be returned to the company after the end of its lifetime making it a profitable investment.

Another factor that needs to be taken into consideration is the price of the hydrogen . Last year , the Department of Energy (US) published a report that revealed that the current price of the hydrogen produced by electrolysis

(PEM) varies from approximately from 5 to 6 U.S. dollars per kg [148] and is projected to decline if the market turns its interest towards it.

The comparison of results both from the HOMERPro outputs and the NPV formula estimations had a deviation due to different inputs, although they are approximately close with a positive outcome, providing that these systems if planned properly to be adapted to the current market, could be profitable for potential investors and shareholders.

5.0 Discussion

5.1 Contribution of the study to Academia

The initial contribution of this dissertation is a generic method to optimise two hybrid renewable energy systems. This was demonstrated by scenarios of covering ferries' hydrogen fuel consumption based on realistic data along with proposals for the reduction of their current emissions.

Furthermore, the scenario of retrofitting the existing offshore wind farm after the end of its lifetime was optimise providing positive outcomes in terms of energy and hydrogen production, enhancing the motivation for further research on this aspect.

Moreover, a feasibility analysis was performed for both systems in terms of technical and financial aspects, using the HOMER software tool to identify the optimum system.

Secondary objectives include the Net Present Value (NPV) of each system, as well as the estimated costs of existing fuels compared to green hydrogen, to project a holistic picture for potential future investments in innovative technologies.

5.2 Limitations

Through the evaluation of this dissertation, a variety of limitations arose. As ships were studied one of the main assumptions to be taken into account was the operational days, even though the ships operate under a certain timetable, due to extreme circumstances such as weather conditions this could be affected.

Regarding the hybrid systems, an amount of data had to be assumed. For instance, one major limitation for the hydropower-hydrogen was the lack of data regarding the velocity of the tides per month and annually for the location of the tidal turbine as the majority of the available databases provided only the mean spring peak. This created an issue to the study as HOMERPro to simulate the system has to have as an input of the monthly average velocities of the location of the system. Thus, an alternation was found, as tidal turbines were found in the literature to have 2.5m/s velocity when they produce the highest power, the system was estimated to have a constant velocity of 2.5m/s per month.

An additional limitation was the unavailability of the costs of the systems' components from the manufactures. The majority of these costs, in this dissertation, was estimated based on the available sources in the literature. Hence, these costs require further validation and adjustment when they become available for evaluation. Last but not least, the proposed investment, operational and maintenance costs along with the cashback is a rough estimation, although this could be improved by the conduction of a more thorough real-life project to obtain the specific costs.

6.0 Future Work

From this research a variety of possible proposals for future work have arisen. Firstly, a case study could be conducted that would implement hybrid renewable energy systems that could utilise other types of renewable energy sources based on the availability of the location for the decarbonisation of maritime. For instance, Greece and Spain are countries with uncountable amount of solar power and at the same time a recognisable presence in the shipping industry [149], thus the investigation of such systems could be profitable for the nations.

Another alternation that could be taken into account would be integrated systems that combine both wind and tidal energy and produce hydrogen. By that, a full network of ultimate renewable energy could be created.

As the progress of retrofit is only at its early stages of development, a proposal about the further appraise of existing offshore wind farms that are close to the end of their lifetime along with the potential of transforming into hybrid renewable systems could be analysed.

A future work that came as an outcome of this study is the further reduction of the costs of PEM electrolysers, as with that HRES could be more cost-competitive to the current renewable technologies of the market.

Moreover, these systems are meant to be applied to cover the fuel demand of ferries, hence the investigation for the application on-board and the conversions that need to be done could carry out further research.

Lastly, this study aims to cover the possibility of green hydrogen production for ferries, that could be a leading example for researching if these methods could be applied as well on larger scale ships.

7.0 Conclusions

Undoubtedly, hydrogen seems to be the key factor when it comes to alternative fuels for the reduce of gases to the atmosphere, as its only products are water vapours and oxygen, compared to other conservative fuels that are used in the market , a great amount of challenges need to be tackled in order to be more attractive and competitive for both investors and governments. The investment to green hydrogen along with innovative projects may entitle potential risks, yet the urgency for reducing GHG emissions is crucial is the world does not wish for the climate change to incline its implications.

Offshore wind energy is more mature and powerful technology compared to tidal, nevertheless both have the ability to create large amounts of hydrogen with the exploitation of their produced power and the combination of water electrolysis. The result of this study exemplified an amount of great possibilities that these hybrid systems have, such as the decarbonisation of the marine sector and at the same time the production of enough electricity to cover the demands of households.

A detailed summary of these conclusions is presented below as:

1. The literature review confirmed that the transition towards alternative technologies is urgent.
2. The optimal system for both scenarios does not emit any GHGs as hydrogen is exploit as a fuel which when burned only produces water and oxygen. Thus, these systems could bring closer the United Kingdom to its target for reduction of emissions for a net-zero future until 2050.
3. The Heysham-Douglas route could be fully decarbonised with the utilisation of the existing offshore wind farm; West of Duddon Sands, consisted of 108, Siemens 3.6 MW 120m rotor wind turbines. The plant is able to generate 695,321,488 kWh/year excess electricity which was estimated to cover almost 139,064 households' energy demand around the United Kingdom. Additionally, the simulation of the hybrid renewable system indicated that the plant would be able to produce 2,965,632kg/year hydrogen covering both the fuel demand of the ferry; Ben-my-chree, that operates on this route and at the same have excess hydrogen of almost 696,640.105 kg/year, that could either be stored and used as a back-up or be sold.
4. An alternative proposal was implemented that suggested the feasibility of retrofitting of those wind turbines after the end of their lifetime, by exploiting their monopile foundations and replace them with larger wind turbines such as the Gamesa 4.5MW 128m rotor. Consequently, HOMERPro, illustrated that a plant would be able to generate even more excess electricity around 814,277,889 kWh/year covering more households' demands and at the same time producing enough hydrogen to decarbonise the route and have excess amount of it.
5. The optimum system for the decarbonisation of Belfast-Cairnryan route is a hybrid renewable system consisted of 5 SeaGen-S 2MW tidal turbines as they have the ability to cover the hydrogen demand of Stena Superfast VII annually and produce almost 94 thousand kg/year more which could either be stored as a back-up or could be sold. Despite of this, there was no excess electricity generation, thus after optimising multiple systems the result highlighted that it needs 17 tidal turbines and more to achieve that. However, the literature review revealed that to

date, the largest power plant for tidal energy is consisted of 10 tidal turbines, making this proposal not feasible just yet.

6. The Net Present Value (NPV) estimation for the hybrid renewable energy system of Offshore Wind Turbines-Electrolyser-Hydrogen outlined that the project has a positive outcome of £ 1,290,295,706 trillion pounds after 18 years of operation, making the project profitable and so feasible.
7. The tidal energy-electrolyser-hydrogen hybrid system’s Net Present Value is projected to be £ 243,579,204 million pounds for a period of 11 years. This appraisal revealed that this project regarding its financial aspects could be feasible as a potential investment on the energy sector.
8. While components’ costs limited the precision of the results, the approach of the prices based on the literature data provided a new insight on hybrid energy systems that harness offshore wind and tidal energy and their application on the marine industry for the generation of alternative fuels. Despite this, further research is needed for the costs and the evaluation of prices on real-life large-scale projects under development is recommended.

All in all, the general conclusion that can be extracted from this study is that “green hydrogen opens the pathway towards an ecotone towards a more sustainable future from a conservative past”.

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