Interreg 2 Seas Mers Zeeën
ISHY
European Regional Development Fund

Implementation of Ship Hybridisation

Output 3

Toolbox (business cases & carbon saving potentials) for retrofit and new build vessels of low carbon propulsion technologies

Project No. 2S06-015

With the financial support of

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Output 3

Toolbox (business cases & carbon saving potentials) for retrofit and new build vessels of low carbon propulsion technologies

1. Introduction

To meet the 1.5C Paris Agreement climate goals, a minimum of 70% of the global shipping fleet must convert to low-carbon propulsion technology by 2035. Widespread adoption of alternative propulsion technology in the maritime sector is highly complex and beset with challenges requiring multinational responses and coordination of multiple actors across the whole value chain. Reflecting these challenges policymakers including the International Maritime Organisation (IMO), and governmental authorities including in the US and the EU to further tighten limits on emissions of Carbon Monoxide (CO), Hydrocarbons, Particulate Matter (PM), Nitrogen Oxides (NO_x), Sulphur Oxides (SO_x) and greenhouse gases (GHG) from the maritime sector. The IMO has adopted an ambitious GHG reduction strategy of at least 50% reduction in GHG emissions from shipping by 2050 against a 2008 baseline, reducing the average carbon intensity (CO_2 per tonne-mile) by at least 40% by 2030, and 70% before mid-century.

These increasing environmental pressures and availability of alternative low-carbon propulsion technologies are driving the popularity of alternative propulsion systems. Fuel cell and hybrid propulsion systems have potential to reduce environmental impacts from vessels. Rapid development in alternative propulsion technologies has led to a diverse and complex market, presenting increasingly difficult requirements for vessel owners and operators to identify suitable technologies. The wide range of assessment criteria to be considered and the complexity requires a toolbox to provide knowledge and maximum benefit on investment for vessel operators and owners.

The ISHY project aims to develop, testing and validate the tools and socio-economic models, for the implementation of low-carbon hybrid and hydrogen technologies in vessels and ports; and to demonstrate the feasibility of these technologies through retrofit, new build, and infrastructure development. The outputs and increased understanding from the project will increase the likelihood and pace of adoption of these technologies. The project seeks to deliver the following key demonstrations:

- **Construction of CTV with a hydrogen propulsion system.**
- **Construction of a new passenger vessel (400 pax) with a full hydrogen propulsion system.**
- **Development of a hydrogen fuel cell module, to be used in different types of vessels**
- **Validation of hydrogen bunkering facilities to meet the identified needs of the market.**
- **A methodology to retrofit small craft vessels.**
- **Integrated business cases for the retrofitting of vessels or to build new vessels, utilizing hydrogen propulsion systems.**
- **Supporting tools for certification hydrogen vessels and bunkering facilities.**

This report presents the compiled deliverables of Output 3 '*Toolbox (business cases & carbon saving potentials) for retrofit and new build vessels of low carbon propulsion technologies*', including specifically:

- **D 1.7.1 Literature review report on environmental performance of options for low carbon propulsion systems***
- **D 1.7.2 Workshop on the selection and use of low carbon propulsion systems**
- **D 1.7.3 Guidelines for the establishment of baseline to judge the CO2 footprint and environmental benefits****
- **D1.8.1 Report on the economic performance and cost/benefit of options for low carbon propulsion systems. ***
- **D1.8.2 Workshop on the selection and use of low carbon propulsion systems**
- **D1.8.3 Report to establish baseline to judge the economic cost/benefit low carbon propulsion technologies****

* **Reports D1.7.1 and D1.8.1 are presented as a single combined report.**

**** Reports D1.7.3 and D1.8.3 are presented as a single combined report.**

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Implementation of Ship Hybridisation

Deliverable 1.7.1 & 1.8.1

Review of environmental and economic performance of low carbon propulsion systems

Project No. 2S06-015

With the financial support of

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1.0	21/10/19	Parakram Pyakurel	Solent University	Version 1
1.1	19/04/2021	L Wright	Solent University	Conversion to ISHY template
2.0	05/11/21	Y Wang & L Wright	Solent University	Updates throughout. Note of related publications.

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2. Introduction

In 1997 Kyoto Protocol delegated responsibility to limit GHG from international shipping to the International Maritime Organization (IMO) (UNFCCC, 1997). The Paris Agreement, adopted December 2015 under the United Nations Framework Convention on Climate Change (UNFCCC) recognises climate change as an urgent global threat and sets mitigation goals of limiting temperature increases to well below 2˚C, and ideally below 1.5˚C (UNFCCC, 2015). Rapid and deep cuts to global emissions of greenhouse gases (GHG) are required to meet these targets, whilst global emissions continue to rise (Le Quéré et al, 2018). It is against this backdrop that the significant and increasing GHG emissions of the international shipping sector are coming under increasing scrutiny. The maritime industry emits about 940 million tonnes of CO_2 annually (International Maritime Organization, 2015). These emissions are likely to increase significantly unless substantial mitigation measures are undertaken. A business-as-usual scenario would see an increase of 50% - 250% emissions by 2050. Meeting the 1.5 or the 2-degree target will require a significant and fundamental shift in the global maritime industry.

This report presents the rationale and background to the reduction of GHG and pollution emissions through changes in fuel and propulsion systems in the maritime sector. It then presents a review of low-carbon and zero-carbon propulsion systems in the maritime industry. Uptake and implementation of such systems are necessary to achieve the long-term decarbonisation required by the shipping industry to deliver mitigation in line with the Paris Agreement (Traut et al., 2018).

2.1. Related publications

For further information please see the related publication(s):

- Wang Y, Wright LA. A Comparative Review of Alternative Fuels for the Maritime Sector: Economic, Technology, and Policy Challenges for Clean Energy Implementation. *World*. 2021; 2(4):456-481. https://doi.org/10.3390/world2040029

1. Rationale for alternative fuels and propulsion systems

Maritime transport is a significant contributor to atmospheric pollution and to climate change. The majority of merchant and other civilian maritime transport activities use liquid fossil fuels often marine diesel oils (MDO) or heavy fuel oil (HFO) in deep sea shipping applications. As a result, the industry is the single largest emissions source for Nitrogen Oxide (NO_x), Sulphur Oxide (SO_x), and Particulate Matter (PM) in the transport sector. The sector further contributes 2.5% of global GHG emissions.

In recognition of the damage being caused by the levels of pollution the IMO implemented MARPOL (the International Convention for the Prevention of Pollution from Ships) Annex VI in 1997. This is the air pollution element of its environmental convention. The annex requires increasingly progressive restrictions to SOx, NOx, and PM; and the introduction of emission control areas to further reduce those pollutants in designated sea areas. In 2011 the IMO implemented modifications to Annex VI by including an Energy Efficiency Design Index (EEDI) for new ships. The index is a technical measure which sets minimum requirements for new vessels in energy efficiencies per capacity mile, for different ship types and sizes. Promoting the development and use of more energy efficient and less polluting engine technology. Also, a Ship Energy Efficiency Management Plan (SEEMP) provides a mechanism to improve the energy efficiency of ships currently in operation. However, these modifications fail to fully recognise the emissions arising from the absolute growth of the shipping industry (Gilbert *et al*, 2017). In 2018 the IMO Marine Environment Protection Committee (MEPC) adopted resolution MEPC.304(72) Initial IMO Strategy on reduction of GHG emissions from ships. The strategy presents an ambitious target to reduce total annual GHG emissions by at least 50% by 2050 compared to a 2008 baseline. It presents a framework to develop measures to reduce emissions, including development for the use of alternative low-carbon and zero carbon fuels, technological interventions, and policy directions.

Within the European Union shipping emissions represent about 13% of emissions from the transport sector, and 4% of the EU total GHG emission (European Union, 2019). Within the previous two years (2018) the maritime transport sector has been recognised as being underrepresented in EU member states GHG inventories. From 1 January 2018, under Regulation (EU) 2015/757, large ships over 5000 gross tonnage, loading or unloading cargo or passengers at ports in the European Economic Area (EEA) are to monitor and report their related CO_2 emissions and other relevant information. Furthermore the EU 2020 Climate and Energy Package introduced a goal of a 20% reduction in total GHG emissions, compared to a 1990 baseline; this goal was further supplemented in November 2018 with the Commission's adoption of a strategic long-term vision for a climate neutral economy by 2050, in line with the Paris Agreement objective of keeping global temperature increase below 1.5C.

Various policy drivers have been adopted at the member state level to drive the decarbonisation in the maritime sector. Including, but not limited to:

- United Kingdom - Climate Change Act 2008: is a long-term, legally binding framework to reduce carbon (CO_2) emissions. The Act requires total GHG reductions of at least 34% by 2020 and 80% by 2050 (from 1990 levels).
- Belgium - Flemish policy: The Climate Plan of the Flemish Government intends to reduce the CO_2-emissions by 40 % and increase the renewable energy production by 27% before the end of 2030. The Flemish government 'Vision 2050: a long-term strategy for Flanders' has a transition priority focused on green mobility. Europe defined the "Clean Power for Transport' directive, which has been implemented in Flanders and has led to the definition of several goals which need to be met by 2020. For hydrogen (H_2) transport, 20 public fuelling stations should be built by then.
- Netherlands - On a national level the set-up of an H_2 infrastructure is stimulated and co-funded. Regional use of H2 for shipping is necessary to support the realisation of the necessary port infrastructure. Energy transition and CO_2 reduction are focus points on regional and national agendas. Regional initiatives are stimulated by 2 programs:
    - Duurzaamheidsambitie 2030 (2016); agreement between port authorities, port companies, regional government and environmental organisations to reduce CO_2emissions by 40% in 2030
    - Zeeuwse Energie Dialoog (2017); public – private agreement about regional contribution to Paris agreements.

- French national policy for the CO_2 -reduction in the transportation sector, marine and inland transportation is driven by the 2014/94/EC directive. The strategy is to: develop GNV for marine and inland. Develop installations of electricity for ships so they do not consume fuel when waiting at the dock. For marine the objective is to have a GNV station at least for each inland "axis" by 2030 develop H2 charging station for captive fleet & specific usage. French laws in terms of energy transition invite Ports to find and set up new solutions. Ports consider it as their mission to propose a new approach for sustainable energy distribution system.

The implementation and uptake of low carbon propulsion systems and fuels largely depends on economic cost-benefit. Low carbon fuels and associated propulsion technologies currently represent <1% market share. It is difficult to estimate the uptake of these fuels, the economies, and the interlinked consideration of future market share. Low carbon fuels production technologies and efficiencies are likely to change in the near to longer term future and since these affect the cost of low carbon fuels, their economics can be uncertain. However, low carbon fuel technologies that have potential to be economical include hydrogen, methanol, ammonia, Bio-LNG, low carbon shore power, batteries for electricity storage onboard, electric engines and wind propulsion. For the UK, hydrogen and ammonia production technologies have higher competitive advantages than methanol and bio-LNG production technologies (frontier economics, 2019).

3. Low carbon propulsion systems and technologies

Considering the predicted growth in shipping volumes to 2050, greenhouse gas emissions from ships must be cut by 75%-85% per ton-mile to meet the goals of the Paris Agreement. The third International Maritime Organisation (IMO) GHG Study forecasts under a business-as-usual scenario with no further mitigation, GHG emissions from international shipping would increase between 50% and 250% by 2050 (International Maritime Organization, 2015). Alternative low-carbon fuels will be essential to achieving decarbonisation in international shipping. However, there is no one technology or fuel to deliver the needed emissions reductions, and the effectiveness of these fuels vary widely. Fuels utilising a carbon-intensive production pathway will not deliver decarbonisation, instead shifting emissions elsewhere in the supply chain (Wang and Wright, 2021). The following review considers the environment and economic costs-benefit of a range of low carbon propulsion solutions, including renewable technologies (wind, solar), low carbon fuels (biofuels, LNG, Ammonia, Methanol, Nuclear), energy storage technology (electric, hydrogen cells, hybrids), efficiency improvements (slow steaming, hull coatings, heat recovery, exhaust systems, resistance), and carbon offsets.

3.1. Renewable propulsion technologies

The viability of 'renewable' propulsion (in this context, wind and/or solar) for applications any vessel greater than very small inshore vessels is limited due inherent limitations in available space and capacity for power generation. As such wind and solar power systems are only viable for auxiliary and supplementary power – whilst important for carbon reduction, in the context of this review they are not considered a primary solution for propulsive power.

3.1.1. Wind

Wind powered hybrid ships utilize the available wind to propel the ship in addition to traditional fuels. Different types of these ships include traditional sails on masts, Flettner rotors, turbosails, kites, and structural propulsion unit (Kindberg, 2015). Most of these propulsion systems are limited in use by the velocity and relative angle between the apparent wind flowing over the vessel and the ship direction; sails on mast and Flettner rotor and turbosail can still be used to efficiently propel a vessel at most angles other than around 45 degrees each side of the wind direction, all the others need to have significantly larger angles and as such limit the effectiveness.

A common problem and therefore limiting factor to this kind of propulsion system is the stability of the vessel. The force created by the sails creates a force moment which acts to heel the vessel over, which is counter-acted by a righting moment generated on the hull. If the righting moment of the ship is not sufficient to counterbalance the heeling moment from the sails then ship could heel to excessively large angles, creating a risk of a cargo shift and a loss of control. The additional weight from sailing equipment and rigs, usually located relatively high on the vessel, also have the effect of raising the centre of gravity of the vessel and further reducing the stability, which on some commercial vessels can result in the vessel no longer complying with regulations for stability. As regard the angle, kites could be used only with broad reaching angles and require special running rigging system to manoeuvre the sail. This is a particular problem for ships which run on the same route; it is likely that a prevailing wind system (historically known as a trade wind from the original era of sailing cargo vessels) could contribute to the propulsion in one direction but not in the other.

Another limiting factor which reduces the field of application of these additional propulsion systems is the intensity and the direction of the wind. Aerodynamic forces from sails and kites are broadly proportional to wind speed squared. Low wind velocities result in small forces which do not noticeably contribute to the propulsion (in fact, the additional mass from the sails and rigging will increase drag and hence increase emissions , whereas too much wind could limit the use of the system for structural or stability problems.

The ship Viking Grace that cruises between Finland and Sweden utilizes wind for propulsion and claims to be the only wind powered LNG hybrid ship (Bryce, 2018) in the world. This ship uses Flettner rotors for propulsion. Flettner rotors are vertical cylinders which spin and develop lift due to the Magnus effect as the wind blows across them.

Vessels fitted with assistive wind technologies (i.e. supplementing traditional propulsion technologies) could, depending on routes and wind availability, reduce fuel consumption and associated costs by 5-12%.

3.1.2. Solar

Application of solar assistance, including solar PV and hybrid sail systems which utilise both sunlight and wind to preserve limited deck area, for ship propulsion have been explored by several carriers. Deck space is required large enough to install sufficient solar energy systems and the panels need to be sturdier than for terrestrial use given the harsh marine environmental conditions to which they are to be exposed. Examples include, Eco Marine Power, which is in the process of developing cargo ships that utilise solar panels and also has solar sails to harness wind power (figure 6) (Eco Marine Power, 2019) and the UT Wind Challenger hybrid freighter with nine solar sails.

The energy generation capacity of these systems is only likely to be sufficient to augment auxiliary power demands (Balcombe et al., 2019). Potential CO2 reduction estimates from a range of studies for solar energy generation suggests savings from 0.2 to 12% (Bouman et al., 2017); with wind-solar hybrid systems potentially increasing savings to 10 to 40% (Balcombe et al., 2019).

The use of solar panel is more suitable in application where auxiliaries are powered by batteries. In this case the panels are not used to directly power the system but only to keep the battery charged. In this configuration small leisure and commercial boat could not use fuel to run their auxiliary systems.

3.2.'Low-carbon' fuels

3.2.1. Biofuels

Biofuels are produced from contemporary biomass rather than produced from fossil sources, including from renewable biomass or waste sources. The American Society for Testing and Materials defined biofuel as mono-alkyl esters of long-chain fatty acids resulting from edible oils, non-edible oils, and waste oils. Biofuels may offer significant GHG reductions across the fuel life cycle in some cases, it also contains no sulphur and more free oxygen than conventional fossil diesel fuels. The greater level of free oxygen results in more complete combustion with fewer emissions of CO, PM, and unburnt hydrocarbons. They may be used a 'drop-in' fuel in, necessitating little or no engine modification. Maritime transport is still in the early stages of biofuel adoption. Liquid biofuels that can be used in conventional diesel engines with very limited modifications appear promising for use in the maritime industry. Biodiesels may provide advantages when blended with marine diesels as it biodegradable, non-toxic, and essentially free of sulphur. Recent attention is also being given to lignin (algal) derived marine fuels for the development of a fuel the meets the industry requirements on price, performance, and emissions. Although this, so-called forth generation biofuel is typically not yet market ready or widely commercially available.

Production costs of biodiesel are largely attributed to the chemical technology employed in the production plant and the costs of feedstock. Typically, costs are comparable with existing fossil diesels ranging 0.92-1.93 of the average MGO prices in the top global 20 ports between 2018 and 2021 compared on a $/MJ of energy content (Wang & Wright, 2021).

3.2.2. Liquefied Natural Gas (LNG)

Typically, a mixture of 95% methane (CH_4), and less than 5% mix of other hydrocarbons (ethane, propane, and butanes) and nitrogen, LNG ships utilize LNG as fuel to power the ship. There exist ships that only utilize LNG for propulsion and hybrid ships that utilize LNG along with conventional fossil fuels such as fuel oil and diesel. There are currently around 120 LNG-powered ocean-going ships, with another 130 on order (Newman, 2019).

It has been estimated that LNG has the potential to reduce shipping GHG emissions between 20%-30% (Thomson et al, 2015). However, as the dominant component of LNG is methane any rogue methane emissions, commonly known as 'methane slip', because of incomplete combustion or storage escape can wipe out the advantage of LNG in GHG emission reduction. Methane is estimated to have 28 times GWP of CO_2 over 100 years (IPCC, 2015).

LNG can be obtained from fossil gas and biomass. Biogas is mainly produced through gasification and anaerobic digestion, there is an emerging trend to capture waste gas from waste by gasification (Wang & Wright, 2021). However, biogas produced in this manner contains a large CO_2 fraction and must be purified before use as a marine fuel. Costs associated with this process are relatively high, presenting a barrier to widespread adoption (Li, H., et al., 2017).

In comparison with oil fuels, the major impacts of LNG fuel on ship design concern storage, tank location, size of tank, hazard protection and boil-off of fuel. LNG is highly flammable in its gaseous state and must be stored at cryogenic temperatures. Consequently, storage tank and handling units of LNG require greater planning and engineering compared to conventional fuel oils. Furthermore, LNG requires four times more volume storage on-board than fuel oil for the similar energy value (Newman, 2019). This means that the size of fuel tank required is much larger for LNG based ships. LNG ships also have potential boil-off gas (BOG) issues also exist LNG ships. Although LNG carriers are designed to carry natural gas in liquid form at a temperature below its boiling point, even a small amount of heat causes evaporation of LNG which is known as the boil off gas problem (Tu, 2018).

The use of LNG as fuel is increasing in the 4-stroke medium speed engine. In fact, some manufacturers started to produce a range of engines able to use diesel or LNG; these engines are called dual fuel. The engine is designed to have two fuel supplies and so can equally run on diesel or LNG. Although the use of dual fuel engines poses different problems in terms of systems on board and fuel storage, it allows the ships to run NO_x and SO_x free when running on LNG and this solution is particularly useful when approaching some emission restricted areas.

LNG represents a directly comparable price point as traditional fossil fuels. Considering the complete life cycle of a vessel and the requirements for alternative design functions LNG performs closely. The LNG market, however, is more volatile than the traditional fuel markets, as evidenced with a recent price crash in 2018.

3.2.3. Ammonia

Ammonia (NH3) powered propulsion is considered one of the most efficient ways to decarbonize the shipping sector along with hydrogen and battery-based propulsion systems (Transport & Environment, 2016). Ammonia is a carbon free chemical compound, which can be produced in an environmentally benign method, presenting a promising clean energy carrier with an energy density nearly double that of liquid hydrogen (Service, 2018). The concept is to utilize renewable electricity to produce ammonia which is an energy rich gas. The ammonia is then used as fuel to power ships. Ammonia is a very versatile fuel which can be used in many forms. It can be used in internal combustion engines instead of fossil fuel with minor modifications and can also be used in gas turbines (Hofstrand, 2009) or in ammonia fuel cells (Brown, 2019).

The greatest advantage of ammonia compared to hydrogen in particular, is the easier storage requirements. Similar to propane ammonia, at standard temperature (25C) ammonia is required to be pressurised to 8.6 bar vapour pressure to maintain its liquid form, with an energy density of around 22.5 MJ/kg with 17.8% hydrogen content by weight. As such, ammonia can be stored as liquid at higher temperatures than liquid hydrogen which could potentially make it a more attractive option than hydrogen fuel cells (Cruise & Ferry, 2018).

The majority of ammonia supply is currently produced using the Haber Bosch to combine atmospheric nitrogen (N2) and hydrogen to form ammonia (Aziz et al, 2019). The primary production process utilizes Steam Methane Reforming with a natural gas feedstock or a coal gasification process. Although with increasing interest in the potential of ammonia for emissions reduction, alternative sustainable ammonia production pathways are under investigation including electrochemical and biological routes.

The main concern regarding ammonia as a marine fuel is its high toxicity and hazardous nature. Exposure to high concentrations of ammonia can result in serious health issues including blindness, lung damage, brain damage, and even death. However, procedures for safe handling of ammonia have been widely developed through the use of ammonia in various sectors especially in agriculture, chemicals, and refrigeration. Furthermore, incomplete combustion of ammonia when used in ICE systems, can lead to an increase in NO_x emissions. Although this can be mitigated where the ammonia is decomposed prior to injection in the engine system.

Cost of ammonia in the current market vary widely from 0.66-2.57 that of typical MGO prices on a $/MJ basis for fossil derived fuel, and 1.50-2.64 that of typical MGO prices on a $/MJ basis for ammonia produced using a zero-carbon wind production pathway. However, it should be noted that the technology and the market for ammonia production at a scale required for shipping is in its infancy, and it is difficult to predict the economics or uptake of the technology at this stage.

3.2.4. Methanol

Methanol (MeOH), the simplest alcohol, also known as methyl alcohol or wood alcohol, is receiving increasing attention as a potential marine fuel. It is a toxic, light, volatile, and flammable liquid at standard temperature and pressure. Compared to typical MGO, methanol has a higher H/C ratio, oxygen, and octane number. The high oxygen helps produce a more efficient clean burn in ICE systems, with near zero SO_x, and reduced CO_2 and PM emissions (Zincir, 2019). Test data from the world's first methanol powered ship *Stena Germanica* resulted in a reduction of SOx emissions by 99%, PM emissions by 95%, NO_x by 60% and CO_2 by 25% from the ship operation compared to equivalent MGO operation (ETIP Bioenergy, 2015).

Methanol can be produced from numerous sources including from carbon-containing feedstocks, biomass, and non-bio renewable energy. In the current market most methanol is produced rom catalytic conversion of synthesis gas (CO and H_2) from natural gas reforming or from the gasification of coal (Dalena, F. *et al*). To realise methanol as a alternative low-carbon fuel production routes must be shifted to low-carbon alternatives, such as low carbon feedstock or the implementation of carbon capture storage technologies.

Lower production cost is reported as one of the benefits of Methanol (AFDC, 2019). Typical price estimates compared with average MGO market prices range from 0.43-1.57 for fossil production methods, and 1.50-2.64 for biomass-based production. The key challenges of using methanol in vessels include its low energy content compared to petroleum fuels, its highly corrosive nature and volatilely than other fuel sources.

There are today two leading engine manufactures developing large marine engines compatible to run on methanol. The first is Wartsila who are focused on developing four-stroke diesel cycle engines. The second company is MAN Diesel Turbo which is focused on remodelling their two-stroke diesel cycle engines to be methanol compatible (Live Bunkers, 2019).

3.2.5. Nuclear

Nuclear power in ships works on the same principle as steam powered ships, with the heat source being provided by a small nuclear reactor. The heat from the reactor produces steam, which is used to drive a turbine, connected to either a generator or through a gearbox to provide direct propulsion. Compared to traditional liquid or solid fuelled propulsion systems, nuclear power offers several advantages. Nuclear power offers high power density and stable fuel prices, with very low greenhouse gas and other air quality affecting emissions. Vessels can operate for extended periods without the need to refuel. All fuel is contained within the reactor, with no space required for additional fuel tanks. The requirement for supporting infrastructure is limited with no need for complex exhaust and scrubber systems. Local exhaust pollution is significantly reduced compared to traditional oil-based fuels and there are minimal emissions associated with reactor operations. However, there are supply chain emissions associated with extraction and processing of fuel, and re-processing of spent fuels (Gilbert *et al.*, 2018).

The disadvantages emerge as high costs for operation and maintenance, and concerns regarding safe operation. While nuclear power has been used extensively in military applications including in warships and submarines, only a handful of civilian craft have ever been built. Development of civilian nuclear-powered craft encounters many barriers with public perception and politics, legislation, nuclear non-proliferation, safety, and security. For these reasons most nuclear-powered vessels are military and/or icebreaker industries, with only a handful of commercial vessels ever being built.

3.3. Energy Storage & Fuel Cells

3.3.1. Shore power and plug-in battery-powered ship (Electricity)

Shore power is an emission mitigation strategy replacing the use of fossil fuel with electricity supplied from shore. These ships could be either fully or partly powered by renewable energy fuels. In terms of direct emissions, battery-powered ships with electricity could eliminate emissions resulting from the operational stage. However, the strategy is not truly zero-carbon as the provided shore-power is drawn from the local power grid. The effectiveness of emissions mitigation is strongly tied to the carbon intensity of local power generation (Wang & Wright, 2021). Worldwide, electricity generation is still mainly based on fossil fuels. Acceding to the IEA, coal and natural gas are major electricity generation sources. Electricity generation in 2018 from coal was 38.8%, natural gas was 23.1%, nuclear 10.6% and hydro 16.4% (IEA, 2019). The mix of electricity production varies between countries and very much depends on the availability of sources and the demand of each region.

Shore-side power can be utilised primarily in two modes – for the purpose of cold-ironing, providing power when vessels are in dock, or to provide battery power for propulsion. The vessel *MF Ampere Ferry* is an example of fully battery powered boat that operates between Lavik and Oppedal, Norway (Corvus, 2015). This boat is powered by 1040 kWh battery modules and has charging station at each shore of size 410 kWh (Corvus, 2015).

Supplementary electrical power can be provided by onboard renewable generation. Common renewable energy sources used are wind (briefly discussed in 'Wind powered hybrid ship' section), and solar photovoltaics (PV) (Mofor et al, 2015). Most renewable systems installed on ships currently in operation are supplementary with these electrical energy sources only used to power a part of the propulsion or provide supplementary systems power. For instance, use of solar PV charged lead-acid batteries to provide auxiliary propulsion has been planned for 220 gross tonnage freighter Greenheart (Mofor et al, 2015).

A study (Wu and Bucknall, 2016) demonstrated that annual cost decrease from battery-electric propulsion systems can significantly reduce cost, under the assumption of battery lifespan (i.e. use time before replacement) is 5 years. Lifetime of the ship was assumed to be 30 years and three scenarios (annual battery cost decrease of 6%, annual battery cost decrease of 15%, and battery lifespan increase of 5% and annual cost decrease of 6%) were considered by Wu and Bucknall (2016).

3.3.2. Hydrogen

Hydrogen is the simplest and lightest element, considered one of the most promising alternative clean energy sources. There are several distinct advantages to hydrogen as an energy source. Firstly, the sole by-products of hydrogen are water and small amounts of NOx. Second, it is possible to produce hydrogen from a variety of renewable sources including biomass, nuclear power, and non-bio renewable energy such as wind and solar photovoltaics (PV). Thirdly, hydrogen has a high energy-to-weight storage ratio, with the energy density of hydrogen is between 120 and 142 KJ/kg.

Hydrogen is normally found in compound form; therefore, it can be extracted from a range of sources including water, biomass, or fossil fuels. The production of hydrogen can be achieved through several techniques, including reforming (steam, partial oxidation, autothermal, plasma, and aqueous phase), gasification, and pyrolysis and water electrolysis. Most hydrogen in the current market is derived from fossil fuel sources through steam methane reforming. Utilising hydrogen produced under this pathway risks increasing overall GHG emissions compared to traditional MGO, due to the carbon intensive production pathway. Electrolysis using renewable energy can provide low-carbon hydrogen, however it currently only account for 3.9% of global production.

Hydrogen can be primarily utilised in two modes – direct combustion or in hydrogen fuel cell systems. Hydrogen fuel cells convert hydrogen to electricity in order to propel ships and also supply electrical power on-board. A fuel cell power pack consists of a fuel and gas processing system and a stack of fuel cells that convert the chemical energy of the hydrogen to electric power through electrochemical reactions (Marex, 2017). Simple layout showing the working principle of hydrogen fuel cell is shown below (MSUM, 2019).

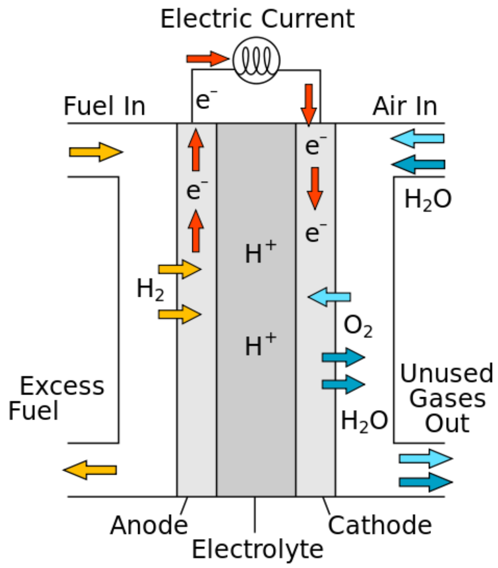

Figure 1 Schematics of hydrogen fuel cell

A fuel cell is composed of an anode, a cathode, and an electrolyte membrane. The cell works by passing hydrogen through the anode and oxygen through the cathode. At the anode site, the hydrogen molecules are split into electrons and protons. The protons pass through the electrolyte membrane, while the electrons are forced through a circuit, generating an electric current and excess heat. At the cathode, the protons, electrons, and oxygen combine to produce water molecules (FCHEA, 2019).

Swiss technological giant company ABB and Norwegian research institute SINTEF are collaborating (Ship Technology, 2019) to develop hydrogen fuel cell powered ships. Some main barriers to this technology are high initial and fuelling costs and safety concerns given high flammability of hydrogen gas (Klippenstein, 2015).

Cost benefit analyses of a hydrogen fuel cell powered ship has been conducted for different scenarios (Saito, 2018). Containership of 2400 Twenty-foot Equivalent Unit (TEU) traveling to and from ports of Rotterdam and Antwerp was considered. Table below shows the payback periods for fuel cell sizes of 500 kW, 1000 kW, 1500 kW and 2000 kW for Proton-Exchange Membrane Fuel Cell (PEMFC), Molten Carbonate Fuel Cell (MCFC) and Solid-Oxide Fuel Cell (SOFC) calculated by Saito (2018):

	Payback period (year)		
Fuel cell sizes	**PEMFC**	**MCFC**	**SOFC**
500 kW	-	-	-
1000 kW	-	-	-
1500 kW	-	11.59	>25
2000 kW	-	4.01	6.02

Table 1 Payback periods for fuel cells of different types and sizes

It can be seen from Table 2 that 500kW and 100kW systems do not have payback period at all indicating that these systems are economically not feasible. Economically feasible systems are 2000 kW MCFC and SOFC as they have payback periods of 4.01 and 6.02 years respectively. MCFC type fuel cells appear to be the most economically viable option according to Saito (2018). Capacity of 1500 kW is feasible for MCFC as it has payback period of 11.59 years but not for SOFC as the payback period is greater than 25 years.

Cost benefit analysis on hybrid ship power by diesel, batteries (lithium ion) and supercapacitor packs has been carried out by Kim et al (2019) assuming the ship lifespan of 25 years. Their study shows that payback period can depend upon cargo handling time and that lower payback period can be achieved if the cargo handling time is larger. Payback period ranging from 10.2 years to 4.2 years was found in their study.

3.4.Hybrid systems

Hybrid systems are propulsion systems that use more than one power source to propel the vessel. The propeller shaft is connected to shafts driven by more than one power source in hybrid ships. Hybrid systems can use a mixture of the power sources discussed above or other potential fuel and power sources.

Special attention should be paid to hybrid propulsion technologies, it has been argued that, even in the near term, immediate and rapid exploitation of available mitigation measures is of critical importance (Traut et al., 2018) and low carbon propulsion systems enabled ship hybridization is one potential mitigation measure.

3.5.Efficiency improvements

3.5.1. Slow steaming

Speed is a key variable in maritime transportation. Comparatively ships travel slower than other modes of transport, but there is wide agreement that there is inherent value in a ships speed. As trips may last significant periods of time, up to several months for deep-ocean transits, the economic benefit of faster delivery and increased throughput are significant. However, changes in the economic climate, including a significant downturn in transport demand from 2009, operators have been adopting 'slow steaming' approaches as an operational technique to downsize their capacity and utilise idle capacity (Woo & Seong-Hyeok Moon, 2014). Initially proposed by Maersk post-2007, vessels are operated significantly below design speed to reduce fuel consumption. Due to the close to exponential relationship between speed and increasing resistance, hence power requirements, where full speed might typically utilise 85-90% of installed vessel engine capacity, slow steaming significantly reduces this demand. Research suggests wide uptake of this approach among operators with a reduction in the average operational speed of container vessels from 2006 to 2012 (Tezdogan *et al*, 2016). Maersk suggest a voyage speed reduction of 20% can result in a reduction in bunker fuel consumption, and CO_2 emission of more than 40% and 20% respectively (Woo & Seong-Hyeok Moon, 2014).

3.5.2. Hull coatings

Increases in hull roughness can add considerably to fuel consumption and propulsive requirement. Biofouling, the accumulation of microorganisms, plants, algae, or animals on wetted hull surface increases a vessel drag coefficient slowing it down and requiring increased fuel consumption. Slime adds 1-2% to drag, weed up to 10%, and heavy fouling can increase fuel consumption by 40-50% (Bouman *et al,* 2017). Paints and hull coatings can minimise skin friction and assist in preventing flora and fauna attaching to the hull. Importantly biocides may prevent biofouling of the hull but may also impact on the marine environment. Technologies are developing in silicone and controlled release biocides, but these are relatively expensive and do not have the same durability of biocide counterparts.

3.5.3. Heat recovery

Typically, about half the energy produced by the powertrain is lost as waste heat (Senary *et al*, 2016). Waste heat is part of the heat generated in the fuel ignition process, dumped into the ambient area with no useful propulsive power generated from it. Waste Heat Recovery Systems (WHRS) convert heat from exhaust and coolant systems into useful power for energy generation or further mechanical power. The usefulness of waste heat sources is dependent on the temperature of the heat, with the most attractive sources being the exhaust gases, engine jacket cooling water, lubrication system cooling water, and turbocharger cooling (Senary *et al*, 2016). Depending on the efficiency of the systems employed estimates for fuel saving range from 4-16% (Balcome *et al*, 2017).

3.5.4. Exhaust treatment

Exhaust scrubbing technologies are widely employed to reduce NO_x and SO_x emissions from vessels burning residual fuel oils. Technology is in early stages of application for CO_2 emissions scrubbing and some experimentation has been undertaken with methane oxidation catalyst technologies.

3.5.5. Resistance reduction

To reduce the power used to move the ship, some systems were developed to try to lower resistance of the hull. Once a hull has been designed, its wave resistance cannot be modified, therefore only the friction resistance could be reduced; this is due to the contact between the water and the hull.

Some attempts to create an air cushion between the water and the hull have been developed. The biggest problem is to have a constant layer of air which is difficult to achieve due to the fact that the air naturally floats so as soon as it is pumped under water, it tends to run toward the surface. Also, in order to create a uniform layer of air there must be many injection points along the length and breadth of the hull which create a lot of technological problems under the structural and productive point of view.

3.6. Carbon offsets

3.6.1. Carbon offsets

Carbon offsets are a reduction in emissions of carbon dioxide or other GHGs made to compensate for emissions elsewhere. The Clean Development Mechanism (CDM) established under the Kyoto Protocol, validates and measures projects to ensure genuine carbon benefits recognises over 200 types of offset. Broadly these can be grouped as renewable energy, methane abatement, energy efficiency, reforestation and fuel switching. Offsets provide a convenient 'alternative' to actual reduction of one's own GHG emissions. There is however criticism of the practice – from questions on the benefits of certain types of offset, to relocation of emissions to other economies and areas.

4. Conclusions

This report presents a review and highlights the range of technologies and options available for carbon reduction in maritime transport. Whilst a range of options and technology exist with varying degrees of potential for carbon reduction, not all are suited the vessels and pilots encapsulated within the ISHY project, nor are they within the scope of the project. Technologies considered within the ISHY project include hydrogen fuel cells and electric hybrids. However, other options for carbon reduction are clearly not without merit and are recognised as having strong potential to achieve decarbonisation.

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Implementation of Ship Hybridisation

D1.7.2 and D1.8.2

Report of Workshop Activities and Discussion: Review of environmental performance of options for low carbon propulsion systems

Project No. 2S06-015

With the financial support of

Author

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Revision history

REVISION	DATE	AUTHOR	ORGANISATION	DESCRIPTION

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6. Introduction

The ISHY project aims to develop, testing and validate the tools and socio-economic models, for the implementation of low-carbon hybrid and hydrogen technologies in vessels and ports; and to demonstrate the feasibility of these technologies through retrofit, new build, and infrastructure development. The outputs and increased understanding from the project will increase the likelihood and pace of adoption of these technologies. The project seeks to deliver the following key demonstrations:

- **Construction of CTV with a hydrogen propulsion system.**
- **Construction of a new passenger vessel (400 pax) with a full hydrogen propulsion system.**
- **Development of a hydrogen fuel cell module, to be used in different types of vessels**
- **Validation of hydrogen bunkering facilities to meet the identified needs of the market.**
- **A methodology to retrofit small craft vessels.**
- **Integrated business cases for the retrofitting of vessels or to build new vessels, utilizing hydrogen propulsion systems.**
- **Supporting tools for certification hydrogen vessels and bunkering facilities.**

This report details the workshop activities and discussion held Solent University, 12th September 2019 on the subject of 'review of environmental performance of options for low carbon propulsion systems' (in fulfilment of the ISHY project deliverables D1.7.2 and D1.8.2).

7. Attendees

Laurie Wright – Solent University

Vittorio Boccolini – Solent University

Isobel Francois- WatersofNet

Erwin Salemink – Impuls Zeeland

Nico Bolleman - OTD

Jeeroen Dieleman - YES

Frans Claeys – Geoxyz GeoAqua

Sam Schotte – Vives University

Thijs Verstraete - Parkwind

Reddy Devalapalli – Lloyds Register

Carlos Armenta - University Polytechnics Hauts-de-France

Wim Stubbe – Port of Ostende

Sebastien Delprat - University Polytechnics Hauts-de-France

Henk Polinder – TU Delft

Udai Shipurkar – TU Delft

Jan Bot – Zepp Solutions

Graeme Hawksley – Hybrid Marine

Adriaan Schuller - Zilvermeeuw

Parakram Pyakurel – Solent University

Maarten Herman – Solent University

Wim Van Hooff – Frop en Advishauem

Katie Stickland – Solent University

8. Overview

A presentation was given by Dr Laurie Wright and Dr Vittorio Boccolini with the participants involved by answer questions through mentimeter using their mobile devices, this allowed the responses to be seen by all and invoked a general discussion within the room.

Following the presentation, the participants were invited to split into three thematic ('operational', 'technical', 'societal') breakout groups to consider the key questions from the technical, operational and image and perception point of views. Halfway through the participants were asked to move to a different group.

Figure 2 Breakout discussion groups, Solent University

9. Group discussion

Following the initial presentation, the following discussion points were posed to the group with responses recorded using the Mentimeter application.

- What are the options for low carbon propulsion?
- What is the rationale for low carbon propulsion?

After this initial group discussion exercise participants were asked to join their groups to consider the following the points.

- What are the most suitable, cost-effective?
- What are the barriers to other technologies?
- Are there other options?
- What are the opportunities and the threats?
- What does the future look like?

4.1.Responses from mentimeter:

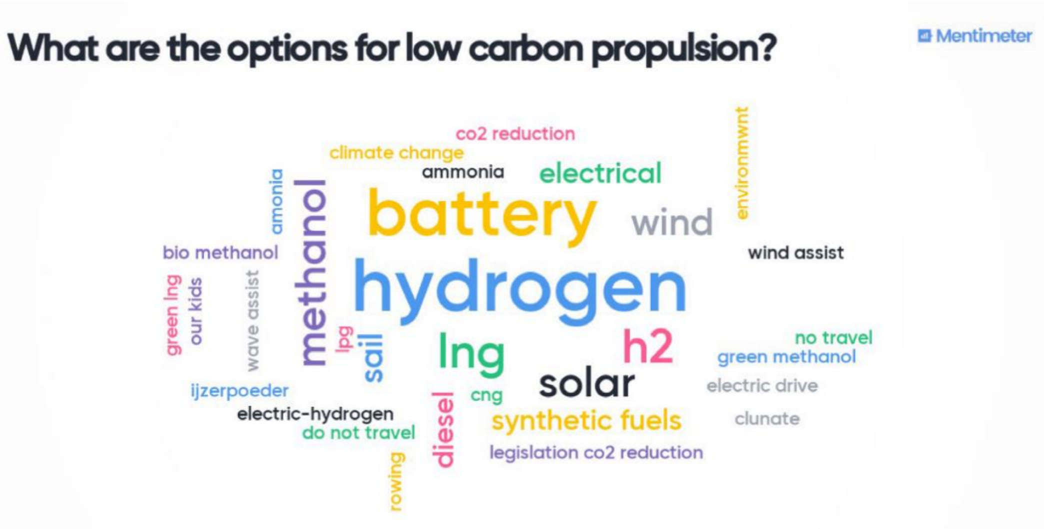

Figure 3 Mentimeter 'word cloud' responses to the question 'What are the options for low carbon propulsion?'

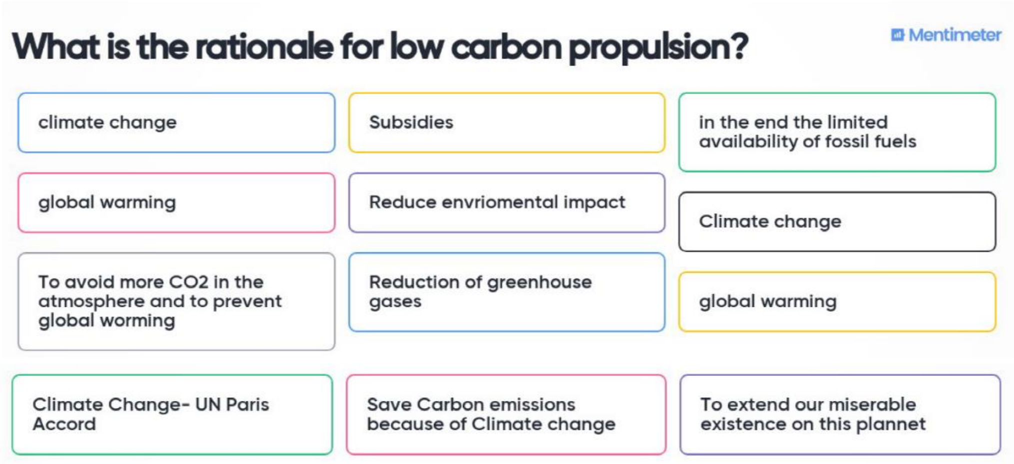

Figure 4 Mentimeter responses to the question 'What is the rationale low carbon propulsion?'

10. Summary of breakout discussions

5.1.Operational

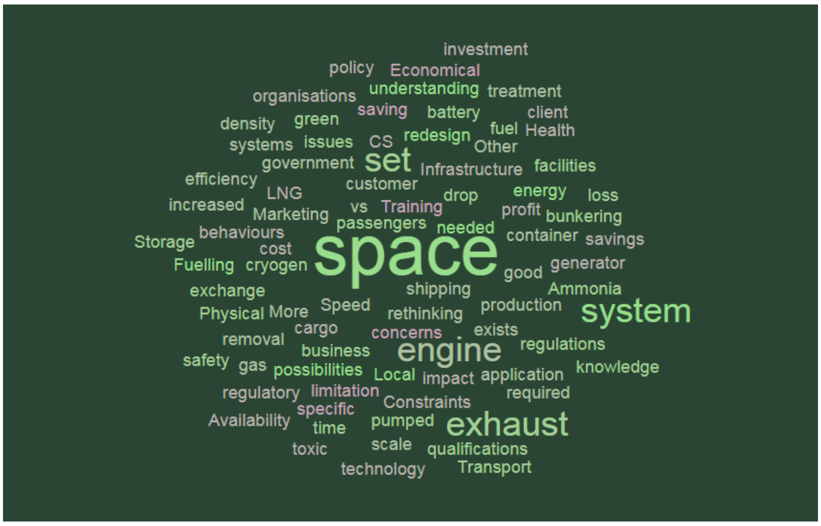

Figure 5 Summary 'word cloud' of the operational group discussions

The first point raised was regarding the space available on board for the hydrogen and battery. This requirement was viewed as loss of space for cargo or passengers and the consequences for cost or profit. This was countered by the space saving for shipping organisations, with increased space from removal of the exhaust systems. Without the exhaust system, no engine system and gas treatment is required, no generator set or engine set, so there is space saving with hydrogen.

Best use of the change in technology requires a redesign or rethinking of the ship concept by naval architects.

Economic issues included production, transport and scale. This would be tied into supply and demand and the availability of storage, infrastructure, bunkering and facilities.

Fuelling time was a consideration with a considerable difference expected between container exchange and pumped hydrogen using cryogen. This raised health and safety concerns as cryogen requires high pressure and can reach minus two hundred degrees. Using cryogen would require two management systems, one for the hydrogen and one for the cryogen.

Investment in high quality training is required to cover several aspects, including handling the hydrogen, maintaining and using the vessel (e.g., how to use the equipment, how to maintain the engines which don't have moving parts). There is a need to develop qualifications and technological awareness.

Local government regulations and policy will have a big impact in promoting and potentially preventing growth of the hydrogen market. There are also physical constraints at the ports and harbours. However, a growing awareness of the need to reduce the speed of climate change brings the possibility of marketing to customers who are "green" aware or green focussed.

This led the group to discuss the need to understand different client behaviours and requirements. For example, where speed it not important, reducing the speed brings efficiency savings which in turn requires less fuel to be used during the voyage, either lower energy density or lower volume.

There was a discussion around general operational changes with the introduction of AI and autonomy and the impact on crewing.

Other possibilities for fuel include ammonia, the positive is a drop in fuel which doesn't require refitting or redesigning vessels and it has good energy density, but it is toxic and there is less information available about the wider impacts of its use. It was agreed more knowledge is needed.

The uptake for LNG is due to the existing technology and there is no limitation from certification services.

Figure 6 'Operational' thematic disucssion group, Solent University

5.2. Technical

Figure 7 Summary 'word cloud' of the technical group discussions

This group had an in-depth discussion around the measurement of the efficiency of hydrogen in the context of the Rankine cycle. Considerations of the economy as a market driver, with hydrogen having a lower energy density yield than ammonia or LNG.

Figure 8 Technical thematic breakout group, Solent University

Other constraints included the lack of knowledge and technical training available in the industry, from the design of vessels with hydrogen as the main energy source, to the specifics of creating hybrid engines or hydrogen batteries. With investment in hydrogen only now starting to gather pace the cost due to low demand is an obstacle to greater use.

Similarly, the lack of regulation and the current standard requirements could be refined once there is more technical knowledge available. This would include the classification of different fuel storage and resulting design requirements.

It was thought that classification would help with economic viability as there is a structure and reference point for buyers and sellers to use.

Over short distances where speed was required it was agreed that hydrogen batteries were the best option. Some consideration was given to the requirements of decoupling and recoupling.

This led to a debate over the ethics or ethical issues involved in reducing energy consumption.

Overall, the group believed the biggest limitation and requirement for using hydrogen was cost.

5.3.Societal

Figure 9 Summary 'word cloud' of the societal group discussions

Figure 10 Societal thematic breakout group discussions, Solent University

This group were keen to maximise the opportunities of the ISHY project as having a visible impact in the industry. There was an agreement to lead by example in particular considering choosing how to travel and where to meet based on the lowest CO2 footprint. The partnership could choose ambassadors for each area to involve policy makers and stakeholders into the wider conversation with dissemination plan to make governments and policy makers bring about change.

In the wider context there was a discussion around the opportunities for government subsidies to stimulate developments and create a route to mass production of hydrogen products as has already been done with solar panels and offshore wind turbines.

Penalties could also be used to ensure there is an opportunity to develop technical and commercial viability.

Direct customer relations, ownership throughout the whole supply chain can contribute to a better understand of the potentials of using hydrogen. There needs to be more promotion of a risk-based analysis to prevent propagation of myths.

Having the knowledge behind a risk-based analysis will also allow the setting up of standards and will allow governments a clear platform to underpin the policy development.

1.1.1. Conclusions

The workshop provided valuable insights into the role of hydrogen and hybrid propulsion systems in the transition to a low carbon maritime system. Barriers were identified by participants in the economics of installations of these systems, stemming from a lack of available infrastructure for fuelling, high fuel pricing, and complications from loss of on-board space due to complex installations. Although, the group did also highlight the need for further investigation into the likely scenarios for fuel pricing, and vessel design to accommodate alternative low carbon propulsion systems. Further points were raised around the technical feasibility of these systems and the current state of standardisation in the industry. It is unlikely that mass take-up will be observed until these issues are resolved and thus, they represent priority area for investigation.

Clearly there are areas for further investigation to allay concerns and highlight the potential benefits of hydrogen and hybrid propulsion systems. Importantly an early activity is to dispel myths or misinformation surrounding some of these solutions, prior to more detailed investigations. Developing standardised approaches and an agreed risk-based analysis is vital to progress the implementation and uptake moving forward.

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Implementation of Ship Hybridisation

Deliverable 1.8.3 & 1.7.3

Multi-criteria decision-making model (Fuzzy TOPSIS method) to establish optimum economic and environmental benefit of low carbon propulsion systems

Project No. 2S06-015

With the financial support of

Interreg
2 Seas Mers Zeeën
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11. Introduction

Increasing environmental concerns have led global policymakers such as the IMO, and governmental authorities including the US and the EU to continually tighten limits for diesel exhaust emissions of Carbon Monoxide (CO), Hydrocarbons, Particulate Matter (PM), Nitrogen Oxides (NO_x), Sulphur Oxides (SO_x) and greenhouse gas (GHG). In the coming few decades, special attention will be paid to the issue of shipping decarbonisation. The Paris Agreement sets out a global framework to avoid dangerous global climate changes and limiting global warming to below 2 degrees Celsius (°C) and pursuing efforts to limit it to 1.5°C. To reach this aim, global net anthropogenic CO_2 emissions should decline by around 45% by 2030, from 2010 levels, and reaching net-zero by around 2050 (IPCC, 2018). In response to the Paris agreement, the IMO adopted an ambitious GHG reduction strategy aims to reduce with at least 50% total GHG emissions from shipping by 2050 in compared to the 2008 level, while at the same time reducing the average carbon intensity (CO_2 per tonne-mile) by at least 40% by 2030, and 70% before mid-century.

Increasing environmental requirements and improving availability of alternative low-carbon propulsion systems are increasing the popularity of alternative propulsion systems. Fuel cell and hybrid propulsion systems have potential to reduce environmental impacts, in particular, GHG emissions from vessels. These trends are clearly observable in current research literature and the developing market for fuel cell and hybrid systems,: notably, the project of FellowSHIP – Viking Lady (2003-2011), RiverCell (2015-2022), ZemShip - Alsterwasser (2006-2013), Nemo H2 (2012-present).

Rapid development in alternative propulsion technologies has to a diverse and complex market, and increasingly difficult decisions for vessel owners and operators to select suitable technologies. The environmental and economic performance of different systems varies from across its life cycle, from manufacturing, to fuel supply, operational profiles and maintenance, to end of life characteristics and options. The array of assessment criteria to be considered and the complexity necessitates a decision support methodology` to provide maximum benefit and return on investment for vessel operators and owners. In this context, a multi-criteria decision making (MCDM) analysis of fuel cell and hybrid systems is proposed in this study. The method enables consideration of economic, environmental, and technical aspects, to provide solid support to decision-makers to make robust and favourable choices.

12. Background

The methods developed are designed to evaluate the feasibility of the implementation of hybrid and hydrogen fuel cell technologies in vessels, supporting the identification of optimum solutions for economic and environmental performance. This method will provide a holistic view of the strengths and limitations of the hybrid and hydrogen fuel cell systems, exploring their lifetime performance from the environmental, economic and technical aspects, and scoring the available options using a multi-criteria decision-making technique. In particular, Life Cycle Assessment (LCA), Life Cycle Cost Analysis (LCCA), fuzzy analysis, axiomatic design are combined under multi-criteria decision-making technique fuzzy TOPSIS (Technique for Order Preference by Similarities to Ideal Solution).

13. Method

13.1. Overview of multi-criteria decision making (MCDM) and Fuzzy TOPSIS

The need to make complex decisions with multiple, often conflicting, assessment criteria are a common issue for decision makers. The techniques of Multi-Criteria Decision Making (MCDM) are applied across many subject domains to support decision making in these types of complex decisions, including in economics, social sciences, and medical sciences. When dealing with MDCA problems, the decision-makers have to carefully select, assess or rank the alternatives in decision making according to the weights of the criteria.

In the last two decades, MCDM techniques have become an important branch of operations research (Nadaban, Dzitac, and Dzitac, 2016). In general, MCDM techniques provide a framework to help decision makers to map and systematically assess the MCDM problem and critically evaluate and scoring the available options to make informed choices. Various MCDM techniques across disciplines have been proposed and the application of these techniques have been discussed in the literature, including classic MCDM approaches, Analytic hierarchy processes, Base-criterion methods, Analytic network processes, Weighted product model, and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

In many real-world situations, it is very common that the problems of decision making are subjected to constraints (e.g. financial, technological), objectives are not fully defined, and consequences are not accurately known at the time of decision; which impacts the accuracy of decision-making techniques. To solve this problem, Bellman and Zadeh (1970) introduced fuzzy theory into the MCDM problem. Fusing MCDM techniques with fuzzy theory, the decision theory and decision-maker model can deal with incomplete and uncertain knowledge and information.

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a classic multi-criteria decision analysis method, which was originally developed by Ching-Lai Hwang and Yoon (1981) for solving MCDM problems. The TOPSIS method is developed based on the concept that the chosen alternative should have the shortest geometric distance from the positive ideal solution (PIS) and the longest geometric distance from the negative ideal solution (NIS). In the process of TOPSIS, the performance ratings and the weights of the criteria are given as crisp values. The classic TOPSIS method has been further developed by Chen-Tung Chen in 1997 to extended multi-person, multi-criteria TOPSIS method into a fuzzy environment. Until now, the fuzzy-based TOPSIS method is still one of the most promising and most frequently used methods in MCDM (Rudnik and Kacprzak, 2017). Palczewski and Sałabun (2019) reviewed the application of fuzzy TOPSIS in published research in the past decade, the result shown that fuzzy TOPSIS today has been extensively applied to research in various aspects include policy-making, sustainable energy, engineering, automobile manufacture, supplier selection, and as well as risk assessment, point out the increasing popularity of fuzzy TOPSIS methodology.

When extended classic TOPSIS to a fuzzy environmental Chen (2000) introduced a vertex method to calculate the distance between two triangular FNs. According to Chen (1997), if $\breve{m}$ = (m1, m2, m3), $\tilde{n}$ = (n1, n2, n3) are two triangular FNs then:

$$\mathrm{d}(\tilde{m}, \tilde{n}) = \sqrt{\frac{1}{3}[(m1 - n1)^2 + (m2 - n2)^3 + (m3 - n3)^2}$$

The procedure of fuzzy TOPSIS can be expressed in Figure 1.

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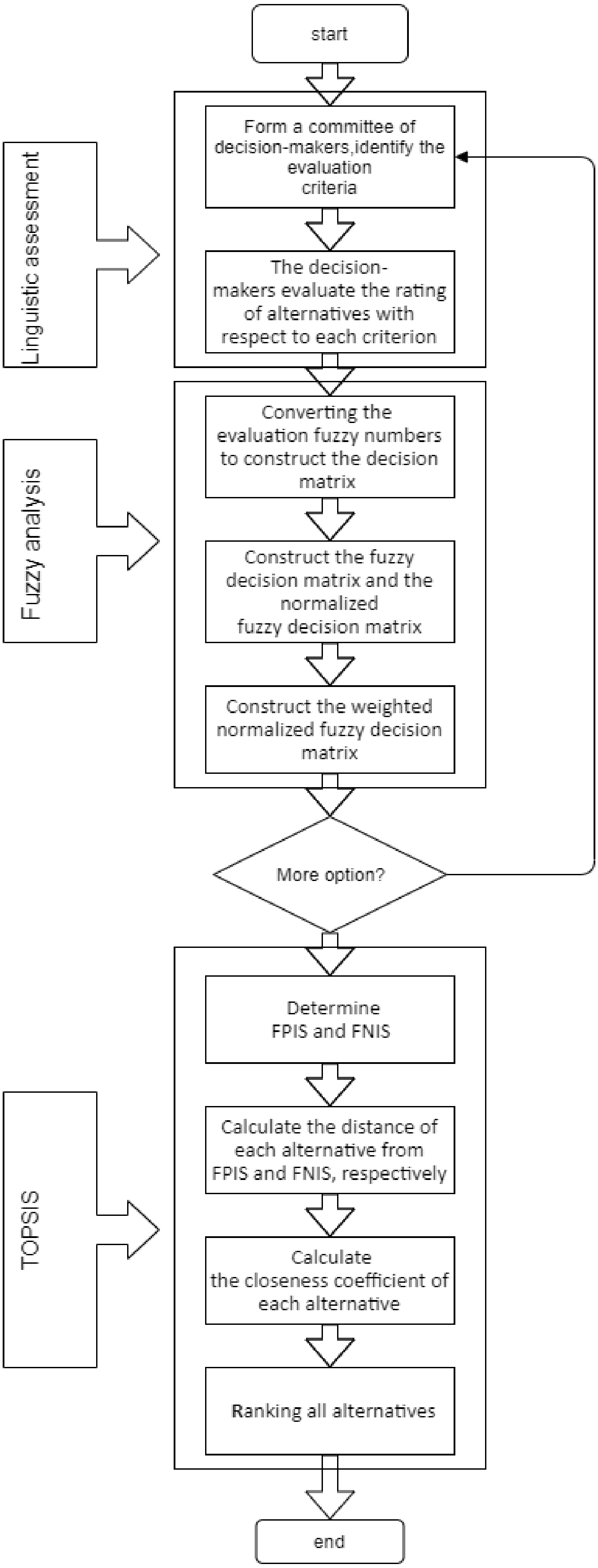

FIGURE 11. OUTLINE OF FUZZY TOPSIS APPROACH

Step 1: Form a committee of decision-makers, then identify the evaluation criteria.

In the study, the importance weights of various criteria and the ratings of qualitative criteria are considered as linguistic variables, and these linguistic variables can be expressed in positive triangular fuzzy numbers as shown in Table 1 and Table 2.

Very low (VL)	(0; 0; 0:1)
Low (L)	(0; 0:1; 0:3)
Medium low (ML)	(0:1; 0:3; 0:5)
Medium (M)	(0:3; 0:5; 0:7)
Medium high (MH)	(0:5; 0:7; 0:9)
High (H)	(0:7; 0:9; 1:0)
Very high (VH)	(0:9; 1:0; 1:0)

TABLE 2 LINGUISTIC VARIABLES FOR THE IMPORTANCE WEIGHT OF EACH CRITERION

Very poor (VP)	(0; 0; 1)
Poor (P)	(0; 1; 3)
Medium poor (MP)	(1; 3; 5)
Fair (F)	(3; 5; 7)
Medium good (MG)	(5; 7; 9)
Good (G)	(7; 9; 10)
Very good (VG)	(9; 10; 10)

TABLE 3 LINGUISTIC VARIABLES FOR THE RATINGS

Step 2: The decision-makers use the linguistic rating variables (shown in Table 2) to evaluate the rating of alternatives with respect to each criterion as presented in Table 3.

Criteria	Candidates	Decision-makers		
		D1	D2	D3
C1	A1	VG	VG	VG
	A2	G	G	VG
	A3	MG	G	F
C2	A1	VG	VG	F
	A2	G	VG	VG
	A3	F	G	G
C3	A1	VG	MG	G
	A2	G	VG	G
	A3	MG	MG	MG

TABLE 4 EXAMPLE OF THE RATINGS OF THE THREE CANDIDATES BY DECISION-MAKERS UNDER ALL CRITERIA

Step 3: Converting the linguistic evaluation into triangular fuzzy numbers to construct the fuzzy decision matrix and determine the fuzzy weight of each criterion.

A fuzzy multi-criteria group decision-making problem which can be concisely expressed as:

$$\widetilde{D}=\begin{bmatrix} \widetilde{X11} & \widetilde{X12} & \widetilde{X13} \\ \vdots & \vdots & \vdots \\ \widetilde{Xn1} & \widetilde{Xn2} & \widetilde{Xn3} \end{bmatrix}$$

$$\widetilde{W} = [\widetilde{W1}, \widetilde{W2}, \cdots \widetilde{Wn}]$$

Step 4: Construct the fuzzy decision matrix and the normalized fuzzy decision matrix.

To avoid the complicated normalization formula used in classical TOPSIS, the linear scale transformation is used here to transform the various criteria scales into a comparable scale. Therefore, we can obtain the normalized fuzzy decision matrix denoted by $\tilde{R}$:

$$\tilde{R} = [r_{ij}]_{mxn},$$

Where B and C are the set of benefit criteria and cost criteria, respectively, and

$$\widetilde{r_{ij}} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), j \in B$$

$$\widetilde{r_{ij}} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right). j \in C$$

Step 5: Construct the weighted normalized fuzzy decision matrix.

Considering the different importance of each criterion, we can construct the weighted normalized fuzzy decision matrix as:

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{mxn}, \text{ i= 1,2,.......,m, j=1,2,.......,n}$$

Step 6: Determine FPIS and FNIS.

According to the weighted normalized fuzzy decision matrix, the elements $\tilde{v}_{ij}$, j are normalized positive triangular fuzzy numbers and their ranges belong to the closed interval [0; 1]. Then, we can define the fuzzy positive-ideal solution (FPIS,A^*) and fuzzy negative-ideal solution (FINS, A^-) as:

$$\boldsymbol{A}^* = (\tilde{\boldsymbol{v}}_1, \tilde{\boldsymbol{v}}_2, \tilde{\boldsymbol{v}}_3 \dots . \tilde{\boldsymbol{v}}_n),$$

$$\boldsymbol{A}^- = (\tilde{\boldsymbol{v}}_1^-, \tilde{\boldsymbol{v}}_2^-, \tilde{\boldsymbol{v}}_3^-, \dots \tilde{\boldsymbol{v}}_n^-).$$

Step 7: Calculate the distance of each alternative from FPIS and FNIS, respectively.

The distance of each alternative from $A^*$and A^- can be currently calculated as:

$$d_i^* = \sum_{j=1}^{n} d\left(\widetilde{v_{ij}}, \tilde{v}_j^*\right), \text{ i= 1,2,...., m}$$

$$d_i^- = \sum_{j=1}^{n} d\left(\widetilde{v_{ij}}, \tilde{v}_j^-\right), \text{ i= 1,2,...., m}$$

Step 8: Calculate the closeness coefficient of each alternative.

The closeness coefficient of each alternative is calculated as:

$$CC_i = \frac{d_i^-}{d_i^* - d_i^-}, \text{ i=1,2,....,m}$$

Step 9: According to the closeness coefficient, the ranking order of all alternatives can be determined.

14. Fuzzy TOPSIS model designed for this study

The underlying idea placed on the fuzzy TOPSIS model proposed in this study is that to quantitatively evaluate and weight the available low-carbon emission fuel cell and hybrid system options from various perspectives and help decision-makers make the right decision with high confidence. The overall process of fuzzy TOPSIS model designed for this study is outlined in Figure 2.

In this principle, the environmental performance of the available option is evaluated through the LCA, the economic performance of the options is evaluated through the LCCA, and the fuzzy axiomatic design is used to critically assess the available options from technique aspect. Thereafter, the impact of each criterion on a subject option is integrated and compared to those obtained from alternative options by using the fuzzy TOPSIS. The process is believed to make the decision-making process more reliable and extensive. The fuzzy TOPSIS model in this study will be tested using a case study to evaluate the feasibility of the implementation of hybrid and hydrogen fuel cell technologies for the selected types of ships working within the 2 Seas area and identifying the option that ultimately outperformance the others under the demand of decision-makers.

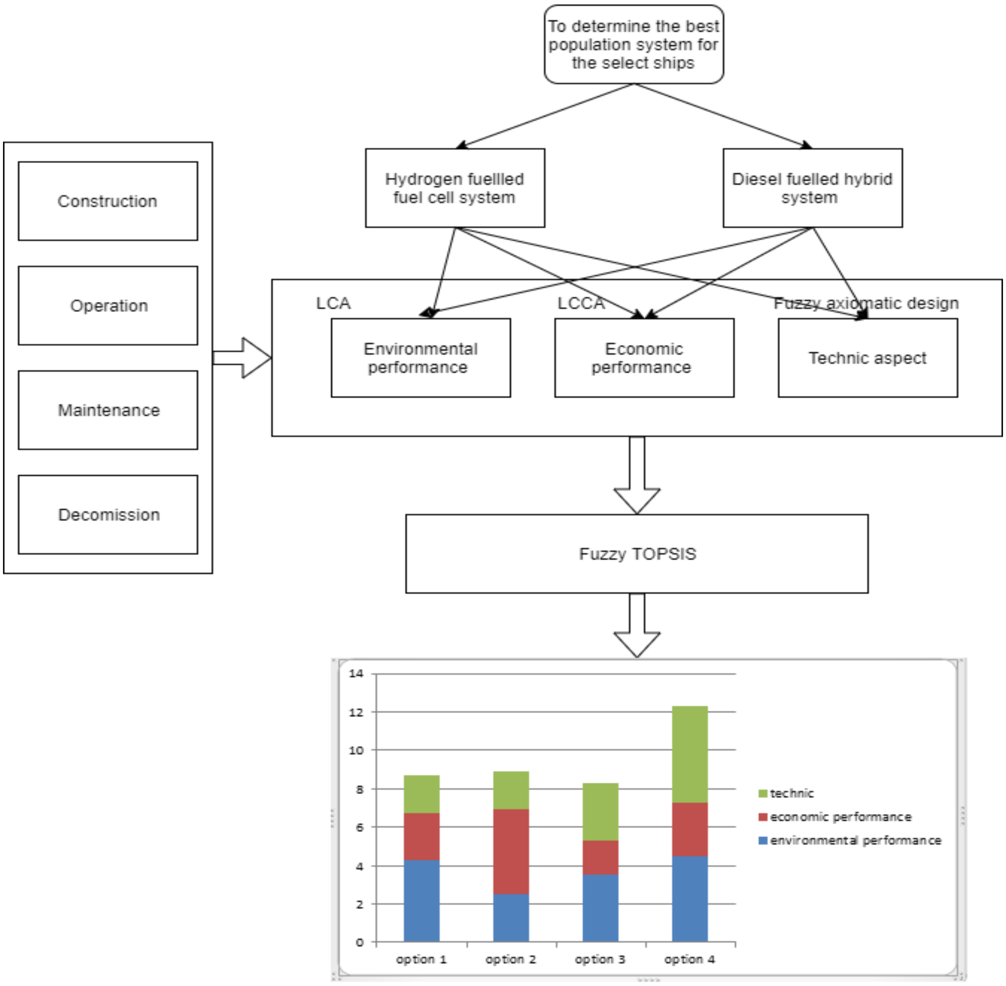

FIGURE 12 OUTLINE OF THE PROPOSED FUZZY TOPSIS APPROACH

15. Life Cycle Assessment (LCA)

The environmental impact of the fuel cell and hybrid fuelled ships in this study will be investigated through a consolidated LCA approach which guided by the standards of International Organisation of for Standardisation (ISO) 14040 serious (ISO 14041, ISO 14042, ISO 14043 and ISO 14044). The LCA structure defined by the ISO standards is shown in Figure 3.

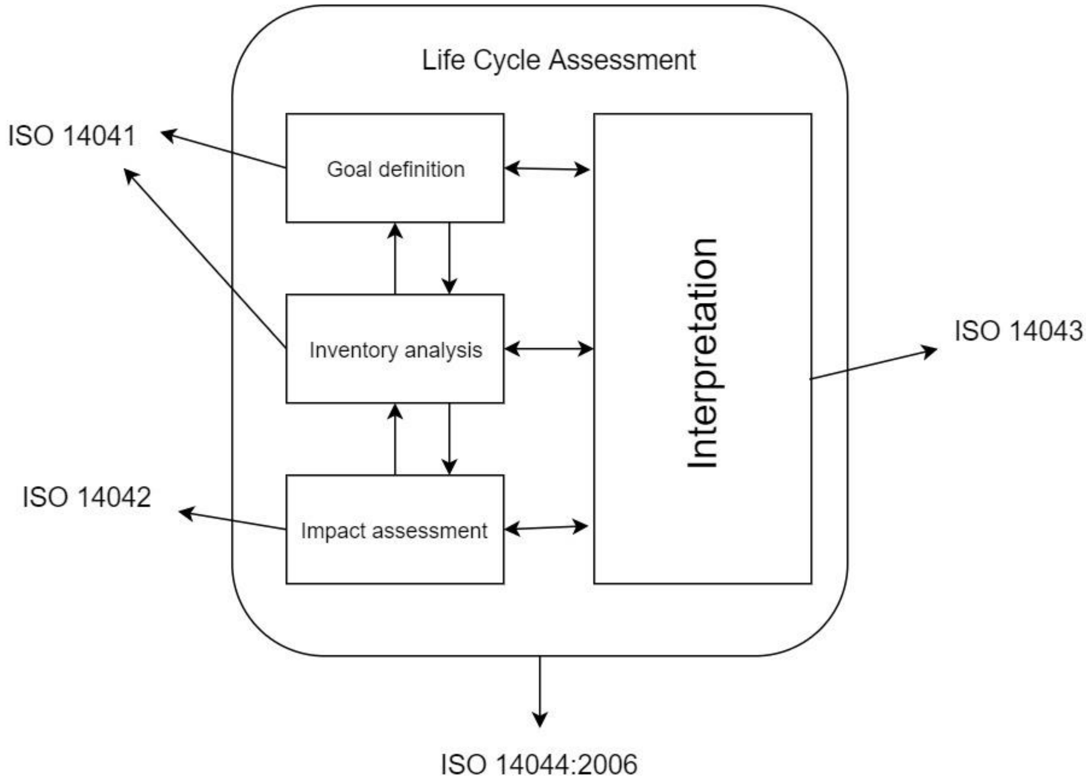

FIGURE 13 LCA FRAMEWORK

As illustrated in Figure 3, the elaboration of an LCA is based on the four phases:

1. **Goal definition:** To identify propose of the study, the function unit and as well as the scope of the study.
2. **Inventory analysis:** Includes the data collection and the assessment of the procedures for the calculation of the inlet/outlet fluxes from/to the system.
3. **Impact assessment:** to evaluate the effects of the compounds identified in the inventory phase on specific impact categories.
4. **Interpretation:** the phase of combined the results obtained from the inventory phase and in the impact assessment phase, to draw conclusions and formulate recommendations.

In order to apply LCA to the selected system, methodological choices are required, whose definition must consider the comparability among different studies. Therefore, common and harmonised calculation rules should be adopted to ensure that similar procedures are used for data collection and handling. In applies, for instance, the objectives, scope, and boundaries should be clearly defined in the first phase and as well as the methods for evaluating and calculate the impact in environmental aspect. The potential lifetime environmental impact assessment is performed in phase 3 with the data derived from the phase 2 inventory analyses. The evaluation methods and impact categories should be selected based on the purpose of the study. The impact categories often considered in the research include, for example, global warming, ozone layer depletion, acidification, eutrophication, consumption of resources, and waste production.

Focusing on the case study tested in this research, one important feature of hydrogen fuel is that the total emissions generated from hydrogen production largely depend on the resources and methods used. Life cycle environmental impact related to hydrogen fuel may vary significantly from one production pathway to another, even though they produce almost the same amount of emissions in ship activities. The LCA in this study, therefore, is focusing on the environmental impact associate with ship activities and fuel production.

In this research, the LCA in this study will calculate the lifetime environmental impact of the selected ships from the upstream process and core-module as shown in Figure 4.

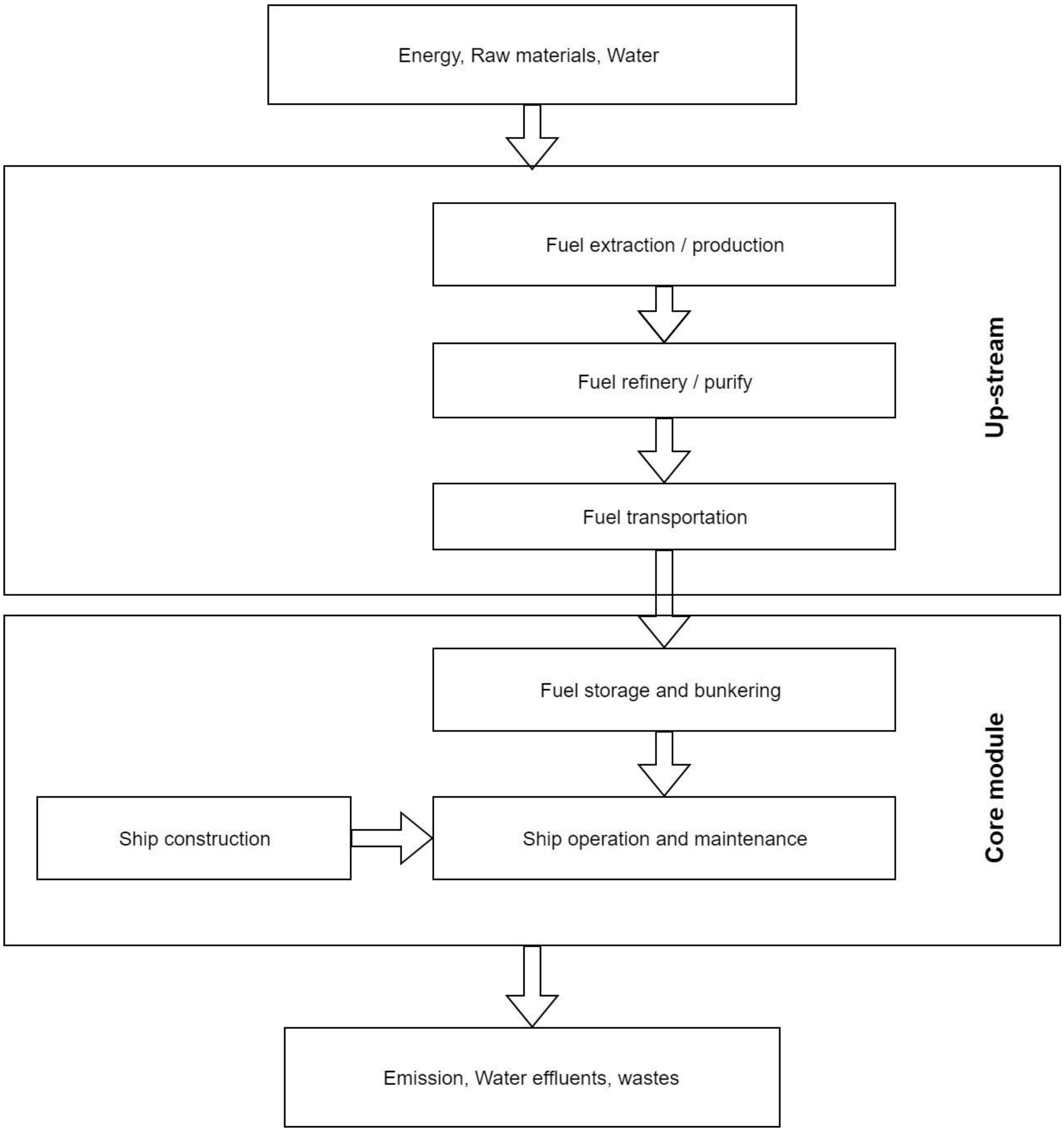

FIGURE 14 THE SYSTEM BOUNDARIES FOR LCA STUDY

16. Life Cycle Cost Analysis (LCCA)

The performance of selected ships in this study can be critically evaluated through the LCCA approach. As illustrated in Figure 5, the economic impact can be expressed by combing the total costs generated over the lifetime period of the ships. The economic impact has negative influence on decision making, which means ship with higher life cycle costs is a worse choice for decision-makers. Following the existing LCCA standard in ISO-15868, LCCA approach in this study contains six basic procedures, which are: 1. Establish alternative cases and select analysis period; 2. Determine performance periods and activity timing; 3. Estimate life cycle costs; 4. Develop cash flow stream diagrams; 5. Calculate net present value; and 6. Analysis of results and sensitivity analysis. Taking into account the ship lifetime stage, ship's life cycle costs in evaluation have been broken into four categories according to the life cycle cost structure provided in BS-ISO 15686-5 (2008), which include initial construction costs; operation costs; maintenance costs and end of life costs.

The LCCA approach in this study is designed as a selective-design analysis; ships with fuel cell or hybrid systems are recognised as 'alternative' cases, and conventionally fuelled ships are set as 'baseline' cases, with cost factors remaining the same for all cases. The LCC model proposed in this study will compare all differences of the direct cost factors identified in the CBS between the alternatives and the chosen baseline.

In this study a ship's LCC is calculated as based on the formula:

$$\sum LCC = \sum_{i=1}^{nCi} C_{ci} + \sum_{i=ni+1}^{nOi} C_{Oi} + \sum_{i=nOi+1}^{nMi} C_{Mi} + \sum_{i=nMi+1}^{nELi} C_{ELi}$$

Where C_{ci} is the construction costs of the ship in its lifetime

C_{Oi} is the total operation costs of the ship in its lifetime

C_{Mi} is the total maintenance costs of the ship in its lifetime

C_{ELi} is the total end-life costs of the ship

The overall economic impact of the proposed system can be expressed based on the formula:

$$\text{NPV} = \sum_{i=1}^{n} PV(R_t)$$

Where NPV ……. is the present value of LCC

R_t……is the operating earnings of the ship in the period t

r …….is discount rate

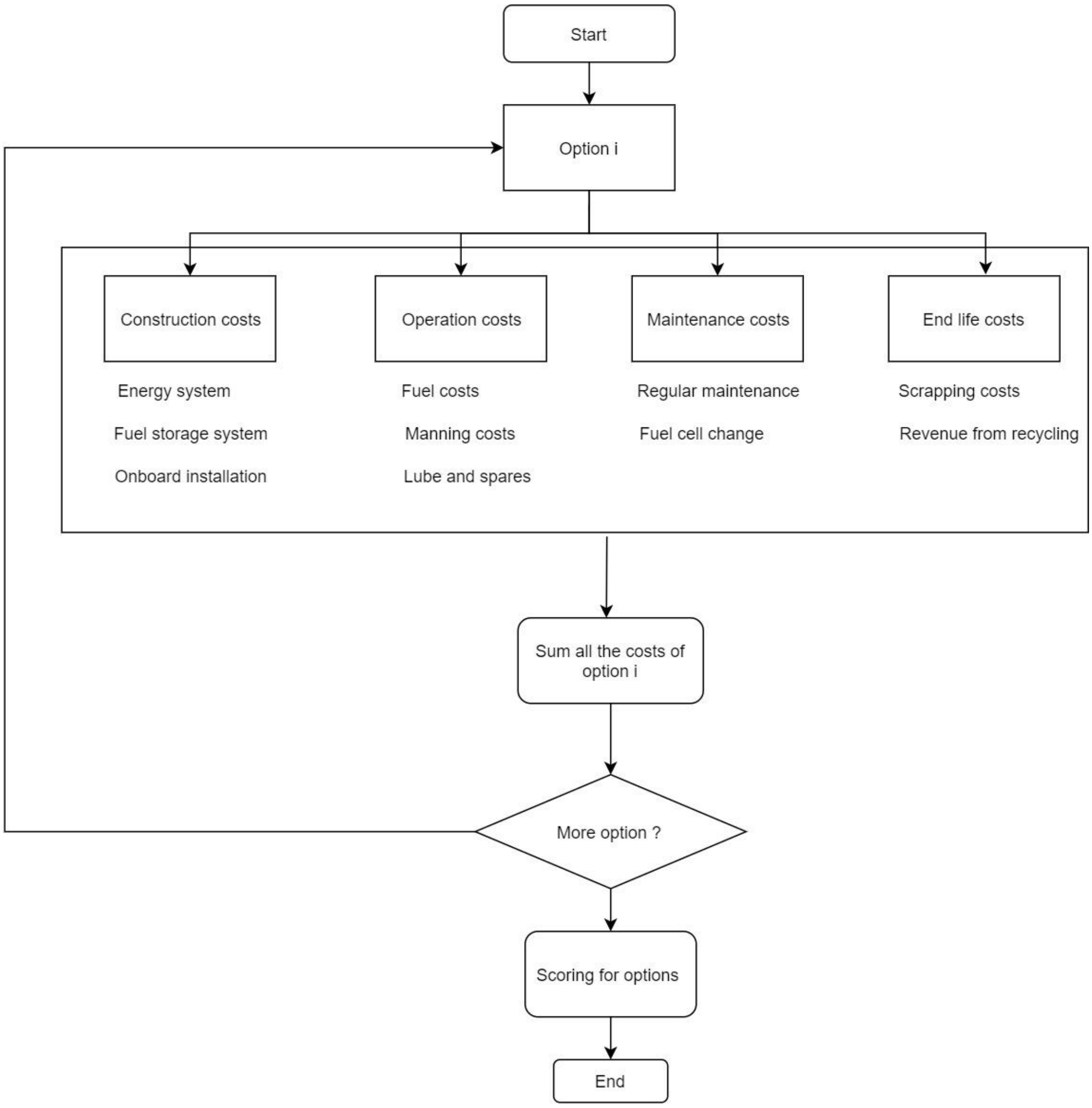

FIGURE 15 OUTLINE OF LCCA APPROACH IN THIS STUDY

17. Technical impact

To investigate the technical impact of the selected ships the approach of fuzzy Axiomatic Design (FAD) has been adopted. Axiomatic Design (AD) is a widely used MCDM tool in engineering which designed to establish a scientific basis to improve design activities by providing the designer with a theoretical foundation based on logical and rational thought process and tools (Suh, 2001). AD principles allow for the selection of not only the best alternative within a set of criteria but also the most appropriate alternative

The most important concept in Axiomatic Design is the “design axioms”. The first design axiom is the Independence Axiom; the second axiom is the Information Axiom. The axioms are stated as follows:

(1) The Independence Axiom: Maintain the independence of FRs

(2) The Information Axiom: Minimize the information content

The first axiom, Independence Axiom, states that the independence of FR_s should always be maintained to characterise the design goals. The $FR_s$are defined as the minimum set of independent requirements. The second axiom, Information Axiom, states that among those designs that satisfy the Independence axiom, the design which has the smallest information content is the best design. Then, the information is defined in terms of the information content I_k, that is related in its simplest form to the probability of satisfying the given FR_s. I_k determines the design with the highest probability of success is the best design.

Information content I_k for a given FR_k is defined as follows:

$$I_k = \log_2 \frac{1}{P_k}$$

Where P_k is the probability of achieving the functional requirement FR_k and log is the logarithm in base 2 (with the unit of bits).

$$P_k = \frac{common\ range}{system\ range}$$

In the process of design, the probability of success is given by what designer wishes to achieve in terms of tolerance (i.e. design range) and what the system is capable of delivering (i.e. system range). As shown in Figure 6 the overlap between the designer-specified "design range" and the system capability range "system range" is the region where the acceptable solution appears.

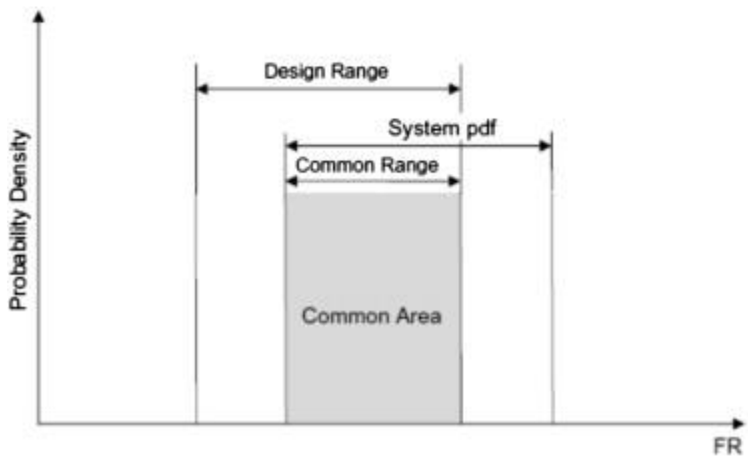

FIGURE 16 DESIGN RANGE, SYSTEM RANGE, COMMON RANGE AND PROBABILITY DENSITY FUNCTION OF AN FR

The proposed approach consists of following framework of the model as:

Step 1 the evaluation starts from the criteria selection, there are tangible and intangible criteria.

The crisp set can easily define tangible criteria but it cannot easily define intangible criteria. Therefore, linguistic terms will be used for intangible criteria. Experts are required to provide their judgments on the basis of their knowledge and expertise for each factor.

Step 2 The linguistic terms of the experts' opinion are transferred to triangular fuzzy numbers (TFNs) as per the linguistic scale information.

Step 3 Aggregate individual TFNs into group TFNs.

The aggregation of TFN scores is performed by applying the fuzzy weighted trapezoidal averaging operator, which is defined by the equation:

$$\widetilde{S_{ij}} = \frac{1}{K}\left(\tilde{s}_{ij}^1 + \tilde{s}_{ij}^2 + \cdots \cdots + \tilde{s}_{ij}^K\right)$$

Step 4 Define the FRs, the minimum sets of independent requirements that characterize the design goals for each criterion.

To represent FRs, triangular fuzzy numbers can be used.

Step 5 Calculate Information Contents. The decision area of each criterion and each alternative is evaluated with respect.

The information content is calculated by using the system range and the common range which is the intersection area between system range and design range. Where:

$$\mathrm{I} = \log_2 \frac{TFN\ of\ system\ design}{common\ area}$$

Step 6 Select the best alternative.

The alternative has the minimum total information content value is considered as the best choice under the given standard. The selection can be conducted using the equation:

$$I_i^t = \sum_{j=1}^{n} I_{ij}$$

In the technical impact analysis, experts were subject to offer the performance rating on the selected different attributes across the lifecycle of the ships. The attributes tested in this study include 1. Reliability, 2. Training required, 3. Operability, 4. Management commitment, and as well as 6. Safety.

18. References

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