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Hydrogen as marine fuel source and energy carrier for ships power production and propulsion

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Abstract

At present, the shipping industry's energy demands are covered satisfyingly with traditional fossil fuels. However, the global effort to prevent climate change has led the International Maritime Organization (IMO) to impose ambitious decarbonization goals and regulations to the shipping industry. Achieving carbon-free operations is today of concern for the entire shipping industry. One of the emerging and most promising options as fuel and energy carrier, are hydrogenous solutions.

This study reviews three hydrogenous solutions as fuel and energy carrier onboard ships: Liquefied hydrogen (LH_2) in low temperature cryogenic tanks with pressure up to 12 bar, ammonia (NH_3) in tanks with pressure up to 18 bar, and lastly, liquefied organic hydrogen carrier (LOHC) in tank at atmospheric pressure.

Firstly, the study is done through an informal pre-study which includes informal interview with experts on the field, and secondly with a formal academical Systematic Literature Review (SLR). The results of these two are combined and compared to elaborate on which of the three hydrogenous alternatives presents the most potential when considering feasibility, safety, and sustainability.

The goal of this thesis is to provide a practical summary of the existing operational and technical knowledge so that actors in the shipping industry can easier decide which hydrogenous solution they would want to move forward with in the future.

This study shows that hydrogen loaded up into NH_3 is the most feasible and sustainable large-scale present solution for ocean going vessels. LOHC might have a future for local trades. LH_2 seems neither safe enough with present technology, nor feasible for a large global scale implementation.

However, without a sustainable blue or green energy source for production, the transition into hydrogenous solutions become counterproductive to its original purpose of reducing CO_2 emission footprint and air pollution. Sufficient capacity and availability of green or blue energy must emerge to satisfy the global transition. One solution for producing enough non carbon energy, can be contented by nuclear power.

The two parts of this study did not show any contradictory, but rather complimentary information. What the research work did show was that few big actors have published most of the articles on the subject, and that some countries are much more involved in this research than others. It is crucial for the success of the energetic energy transition of the shipping industry that research effort become amplified and diversified.

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List of Abbreviations

IMO	International Maritime Organization
SOx	Common notation for Sulphur Dioxidgmentes
NOx	Common notation for Nitro Dioxides
CO2	Carbon Dioxide
GHG	Greenhouse Gasses
LNG	Liquefied Natural Gas
SLR	Systematic Literature Review
NSD	Norwegian Center for Research Data
LPG	Liquefied Petroleum Gas
NH3	Ammonia
TTW	Tank To Wake
WTW	Well to Wake
SECA	Sulphur Emission Controlled Areas
HFO	Heavy Fuel Oil
SEEMP	Ship energy efficiency management plan
ICE	Internal Combustion Engine
FC	Fuel Cell
DME	Dimethyl Ether
RQ	Research Question
H2	Hydrogen diatomic molecule
H	Hydrogen
K	Degree Kelvin
C	Degree Celsius
LOHC	Liquefied Organic Hydrogen Carrier
MJ/Kg	Energy density gravity megajoule over kilograms
MJ/l	Energy density volumetric, megajoule over a litre
CIMAC	International Council on Combustion Engines
HB	Haber-Bosch Synthesis
SOEC	Solid Oxide Electrolysis Cell

PRU	Pressure Regulating Unit
CCS	Carbon Capture System
CH2	Compressed Hydrogen, typically 2-700 bar.
LFF	Low Flash Fuel
LHV	Lower Heat Value
GJ/m3	Gigajoule / cubic meter
t/m3	Ton/cubic meter
CapEx	Capital Expenditure
Marpol	The International Convention for Prevention of Marine Pollution for Ships
SECA	Sulphur Emission Controlled Areas
DO	Diesel Oil
DFE	Dual fuel engine
ZES	Zero emission ship
SOFC	Solid Oxide Fuel Cell
CI	Compression ignition
SI	Spark ignition
PEMFC	Proton exchange membrane fuel cell
EMS	Energy management system
SCR	Selective catalytic reduction
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EEOI	Energy efficiency operational indicator
BOG	Boil Off Gas
IEA	International Energy Agency

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Chapter 1. Introduction

1.1 Background

The worldwide ongoing population growth brings about a simultaneous rise in energy demand that creates considerable pollution impacts. These impacts again create problems concerning the environment globally and locally. In addition to global warming, they are other environmental challenges that we face, like shifting weather patterns, and local pollution of air, soil, and water. All those problems require new technology to meet the challenges they bring about. Reduction of emissions to the air is crucial. Those issues need to be solved by all sectors of the industry and economy.

One such important sector is the shipping industry. This industry is a significant driver of the world's economy, the marine transport sector, and the ports around the world. The global network of merchant ships provides one of the most important modes of transportation and provides 90% of the world's transportation and trade (Kaluza et al. 2010). The shipping industry accounts for a limited percentage of 2.89% of total air CO_2 emission (Ada Ezgi Başer 2020). However, the industry now needs to hasten and establish countermeasures to achieve control of the negative environmental evolvement (Gibbs et al., 2014). The International Maritime Organisation (IMO), together with the flag states, impose strict rules and regulations onto the shipping industry's fleet of vessels. As an example, from the 1. January 2020, the limit of Sulphur in marine fuels was reduced from 3.5% to 0.5% Sulphur by the IMO. Those new regulations apply for all ships above 400 GT, without scrubber treatment onboard as described in The International Convention for Prevention of Marine Pollution for Ships (MARPOL) Annex. V1 rule 4.1 and 3.2, and for ships trading within defined Sulphur Emission Controlled Areas (SECA) according to the IMO (Ada Ezgi Başer 2020). Figure 1 illustrates sulphur emission limits imposed by IMO, impact, and present levels.

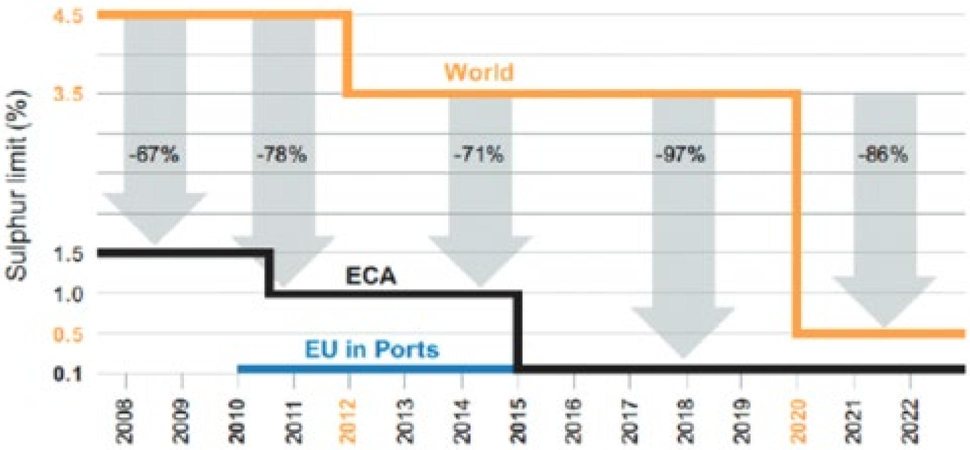


Figure 1: Sulphur limit regulation by IMO (Ada Ezgi Başer 2020, p. 2)

There is also a strategy regarding the reduction of greenhouse gases (GHG), by 30% 2025, and 50% by 2050 (International Maritime Organisation, 2020). These levels compare to limits raised in the Montreal and later Kyoto agreement (Shi, 2016). The recent new regulations laid down by the IMO, contains measurable and reportable levels from each ship that recognize the convention. The EEDI (Energy Efficient Design Index), and the EEXI (Energy Efficiency Existing Ships Index) secure control of the released CO2 and represent the equivalent amount of CO_2 that each ship emits, in relation to the amount of cargo carried per mile sailed. Under operation the EEOI (Energy Efficiency Operational Indicator), is explained as the annual fuel consumption divided by transported work. This can be considered as the annual average carbon intensity of a ship in real operational condition. Figures are calculated in a formula with relevant operational data, fuel types and qualities. It is now implemented onboard and managed by the Ship Energy Efficiency Management Plan (SEEMP). New technical solutions to cut GHG emissions from the global fleet of vessels are continuously under revision and of utmost concern (International Maritime Organisation, 2020).

The entire shipping industry will need to be altered to meet the new requirements imposed. The first step of this process means at least, but not limited to, a significant increase of engine and propulsion efficiency, new building should be adapted, new optimised ship designs done by improving hull, propeller, rudder, and resistances optimization. Planning of ship course, routing, and positioning of vessel within a defined pool is crucial for cargo hauling, optimization and minimization of ballast voyages, speed, and tracking, as well as big data utilisation will be taken into consideration for achievement of the utmost sustainability of overall operational picture (Bouman et al. 2017).

However, this study work will focus on the decarbonization by applying different hydrogenous solutions for power production and for propulsion onboard. All major engine and power system makers who engage in the maritime power and propulsion industry have already analysed different energy sources with hydrogen tied up into adaptable solutions for the maritime industry (Herdzik 2021). For the shipping segments, different hydrogenous solutions as energy carriers are considered, and they are at present time favourable compared to other carbon-based alternatives in respect to environmental matters. These hydrogenous solutions are now in a phase of becoming implemented into the business. Hydrogen as an energy carrier and a fuel alternative into the shipping segment is now growing rapidly. Feasibility studies have shown that no single form of a hydrogenous solution is necessarily superior to another (Ashrafi, Lister, and Gillen 2022). Results are highly dependable on type and trade of the ship. Today, the maritime hydrogen-specified operational experiences and competence are still very limited among crew, yards, and authorities worldwide. Those considerations will not be of concern further in this work. Although research and study of hydrogen in different forms and shapes need to be further elaborated, hydrogen has now been recognized by the industry as a promising alternative among other sustainable alternative fuels with an ultra-low total CO_2 –footprint (Fernández-Ríos et al. 2022). There is no CO_2 formation during combustion of pure hydrogen, only during grey or descaled production lines. This adds to global CO_2 emissions but reduces the local pollution, since today's fuel alternatives also consider and reduce local emissions such as nitrogen oxides (NOx), sulphur oxides (SOx), and particulate matter (PM) into the air. Therefore, in the future, with blue or green production lines, we will be able to produce large scales of different hydrogenous solutions for marine fuel applications with no CO_2 footprint from production, meaning there will be neither local nor global pollutant emissions. Hydrogen will therefore be superior to other marine fuels such as Liquified Natural Gas (LNG) among others, which still are fossil based. The fluctuation and diversity of parameters depend on which of the hydrogen and energy carriers we have concentrated on. The different forms of hydrogenous solutions named: LH_2, NH_3, and LOHC, shall be further elaborated during this thesis work.

The shipping industry has challenges complying with and imposing new sustainable technical solutions to reach IMOs requirements. The entire industry needs now to oblige to the rules and regulations the political decision-makers and contributors form in respect to local and global emissions. There is a wide spectrum of possibilities to reduce global emissions and footprints, but still no single pathway that guarantees to be the best solution for all sectors (Bouman et al., 2017).

When the total picture is considered, as the below illustrated figure 2 indicates, a promising solution comes to light when involving nuclear power into hydrogenous production lines. For example, we could use the Haber–Bosch reactor process to produce NH_3 driven by nuclear power (*Haber-Bosch Process - an Overview | ScienceDirect Topics*, n.d.). This method is most promising in respect to the total CO_2 footprint in well to tank (WTT) estimates. However, in this study, research work will concentrate on the tank to wake (TTW) and elaborate on onboard technical challenges, operational issues and the onboard applied rule and regulations for the selected hydrogenous alternatives. The figure below should therefore only be considered as a visualised indication of the total emissions, depending on the energy source utilised in the production line, viewing the different possibilities and total CO_2 footprint from the different alternatives of producing NH_3, as an energy carrier and fuel alternative for the shipping segments (Philibert, n.d.).

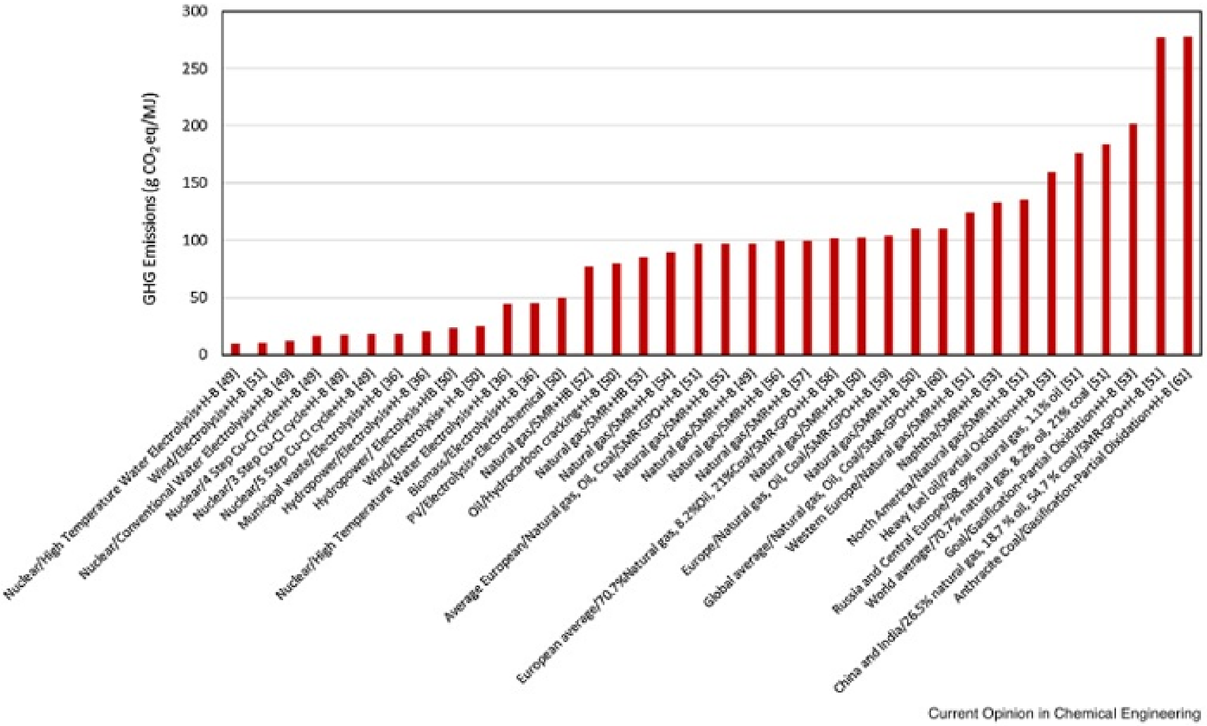


Figure 2: CO2 emission, clustered well-to-tank emissions data (Al-Aboosi et al., 2021, p. 6)

1.2 The motivation and intention of this study

Discussions are ongoing by all participants within the industry. Short term, in a window of 5-10 years, the industry aims to cut emissions through a combination of new technologies and operational developments. However, in the long term, a permanent switch to an alternative fuel will be required to fulfil obligations imposed by regulations already in place today. Amongst possible options, hydrogenous options, and solutions in different forms, can be used as a fuel for Internal Combustion Engine (ICE) and Fuel Cell (FC) (Fernández-Ríos et al. 2022). At present hydrogenous alternatives appear to be among the most promising long-term permanent solutions for the shipping industry. This master thesis aims to study and elaborate on the different possibilities and challenges, related to hydrogenous solutions as an energy carrier and fuel onboard. It will include considerations such as hydrogen as an energy carrier, utilisation onboard through different states, consumption options, handling, bunkering, and storage possibilities. The thesis will explore deeper into the pros and cons of when the product is used onboard as an energy source for the combustion engine and fuel cell. The life cycle sustainability of equipment and applications required for the nominated hydrogenous solutions will be considered. The intention is to include research and mapping of factors directly contributing to emission from the combustion, storage, and handling of hydrogen in different forms and states on board ships, basically tank to wake (TTW) considerations.

The motivation for this study is to reveal pros and cons, advantages and disadvantages and characteristics of the selected hydrogenous solutions. By so doing giving the readers insight and meaningful know-how about the products. This will be achieved through elaborating on available white papers, practical knowledge, as well as gathering information and knowledge from academical papers. The total well to wake sustainability in respect to the environmental footprint, globally and locally will briefly be mentioned. After mapping and consideration of the scope, at this stage of the evolutionary phase of those concepts, a preferred study and elaboration approach and methodology solution appear to be a systematic literature review (SLR), the predominant reason for this is related to the facts that very limited operational experiences are accumulated and gained into the industry yet. The study aims to introduce, attain knowledge, and compare the hydrogenous alternatives selected. The result will give prime answers to which alternatives are the preferred one according to the context of the research question later formed. The result will also give an explanation and a brief adaptable inside view for stakeholders and others, to be of interest and considered before decision makers select alternatives for decarbonization of new building or retrofit for prime mover or power production system onboard ships.

1.3 Thesis and study work introduction, hydrogenous solutions for energy transition

The energy transition is happening as we speak, and present fossil fuels are being phased out and replaced with environmentally friendly and sustainable alternatives. Hydrogen related technologies as of today appear expensive and demanding. Hydrogen as an energy carrier has challenges in respect to storage, bunkering, and handling, ashore and onboard ships compared to traditional fossil fuel. In general, environmentally friendly fuel alternatives prove to be more complex than traditional fuels for all shipping segments (Lindstad, 2020). The purpose of this research is therefore to investigate and elaborate on which of the hydrogenous alternatives appears to be the most promising alternative for the near future.

This study's main methods adapted and established will be weighed individually against one another for pros and cons. The intention is to form a solid understanding of the complexity of using hydrogenous solutions as energy carriers. Studies and academic work excluded from deeper elaboration or extensive considerations are shore industry consumption and activities, such as production lines, transportation, economy, and some sectors of the total sustainability picture that are not considered as the core of this work. This picture is narrowed as we proceed first with the pre-study, and then with defining research questions and the study's objectives.

1.4 Structure of the thesis work

The thesis and its structure will aim to divide the work into six main chapters: Introduction and background, literature review, research method, results and finding, data analysis and conclusion.

The first chapter is defined as the introduction and background, this section describes and explains motivation and reason for the chosen thematic. The second chapter described the research and elaboration methods utilized during the work, the research review with the study of elements relevant for the thesis, the systematic literature separation and study, research questions, objectives, and structure. The third chapter intends to present the thesis research strategy and methodology. This includes the systematic literature review and interview of technical persons for retaining an expert opinion from shipping business companies. The fourth chapter will give a view of finding from the analysed data pros and cons of the three elaborated hydrogenous solutions. Comparison of advantages and disadvantages retracted from pre-study and the SLR study. Withdrawal from selected publication source and dispersion relevant for the research. Limitation and study level of the thesis is also discussed. Results and relevant findings will be explained and documented. The fifth chapter will hold the discussion part that will explain complexity and possibilities, own learning benefits and motivation throughout the work. It will also discuss weaknesses, and eventual missing parts for further work, as well as a suggestion for wider elaboration into practical implementation and operational experiences retained.The sixth chapter holds the final conclusions, recommendations, and will hint at new and upcoming relevant evolutionary possibilities about decarbonization in the shipping business.

Chapter 2. Literature review

2.1 Alternatives fuels for the shipping industry

The new fuels and energy carrier alternatives aimed for the shipping industry give significant reduction in emissions into the air, compared to any of all the traditional fuel alternatives available only a few years ago. Besides hydrogen, several very promising and exciting alternatives are evoked as we speak. The most advertised alternative for both the deep and short sea segment is liquefied natural gas (LNG), biofuels (including bio-methane), liquefied petroleum gas (propane), dimethyl ether (DME), and ammonia (NH_3) together with bio-hydrogen (Chiong et al., 2021). There is no clear answer as to which solution is seen as the most feasible, because it depends largely on the trade and segment and the ships size and shape.

The solution to reducing the environmental impact and raising the sustainability, including the economic consequences and impact, depends on several factors, some of which are uncontrollable elements for the industry itself. The most significant differences in sustainability between the energy sources are where and how the new fuel is produced, into which shipping segment it is aimed to be added into, and how it is consumed onboard (Law, Foscoli, Mastorakos, & Evans, 2021). Figure 3 gives a view of the tank to wake (TTW) relative energy picture of alternative fuels, compared to the traditional Heavy Fuel Oil (HFO) relative energy.

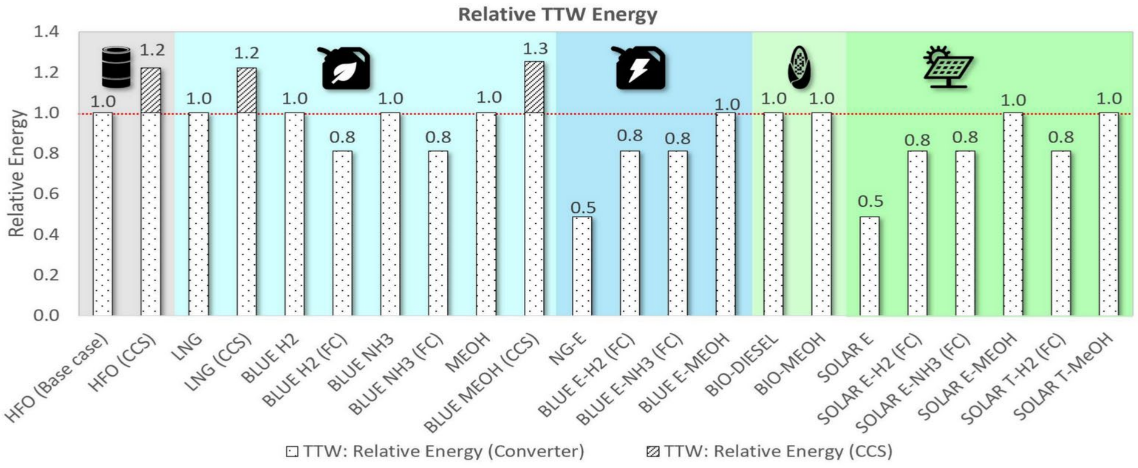


Figure 3: Potential marine fuel pathways. Relative tank-to-wake energy for alternative fuels (Law, Foscoli, Mastorakos, & Evans, 2021, p. 9)

Despite the interesting alternatives named above, this thesis will not consider any other alternatives than the selected hydrogenous options named: LH_2, NH_3, and LOHC.

2.2 The hydrogen

Hydrogen (H), known as the basic chemical element with atomic number 1, is a colourless, odourless, tasteless, flammable gaseous substance in the periodical system; it is the simplest member of the known chemical elements. Under ordinary conditions hydrogen gas is a very loose aggregation of pure molecules. It forms a diatomic molecule named H_2. There is different capability and behaviour of the product, depending on how it is maintained (Jensen et al., 2007). The hydrogen represents a very stable and potent product that can react with many elements and compounds, but at room temperature, the reaction rate is usually so low as to be negligible. Hydrogen's apparent inertness is related to the very high dissociation energy of the molecule. However, at elevated temperatures, the reaction rate is very high and potent.

The product is well suited as an energy carrier, despite a very low boiling point, and not a very solid gap from the triple point (Pedersen, 2021). The boiling point is 19,3K (kelvin) at atmospheric pressure and the liquefied product has a gravity energy concentration of 140 MJ/Kg, and a volumetric energy density of 8,4MJ/l. Pressurised hydrogen at 700 bars has about the same volumetric energy density as the gravimetric energy density of 70Mj/kg, the pressurised state has more than twice the energy density as for the liquefied state of the product (Lindstad et al., 2021). The hydrogen gas can be liquefied by both lowering the temperature and pressure under the critical point. However, there is a pressure limit where the gas cannot be liquefied anymore, hydrogen critical pressure is as illustrated 13.303 bara. Below overview, figure 4 indicates the phase characteristic of hydrogens in different states.

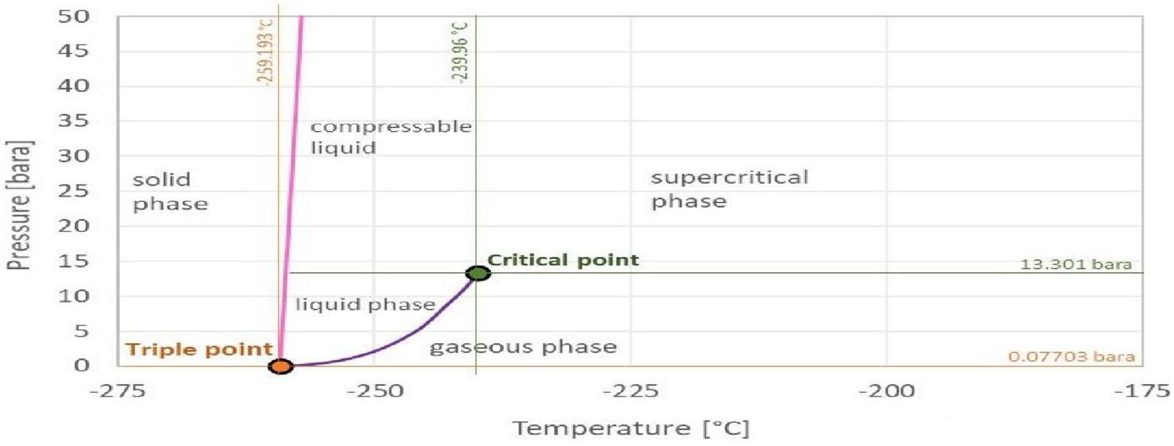


Figure 4: Phase diagram hydrogen (Hydrogen - Thermophysical Properties, n.d.2022, p.1)

The tank and vessel storage onboard of liquefied hydrogen (LH_2) needs to have the possibilities of continuous consumption, as estimated evaporation losses of 1-5% per day are common figures (Jensen et al., 2007). Ships do not normally have any re-liquefaction possibilities and therefore need to flare or consume the hydrogen boil off produced during still stand and port stay.

2.3 Hydrogen, general products, and production

It is possible to produce pure hydrogen in different ways and by several chemical separation methods. The preferred and most sustainable method for large scale production is electrolysis (Kofstad & Pedersen, 2021). Hydrogen is chargeable through an electrolysis process; this method has proven to be efficient and sustainable when done by green or blue energy sources. The hydrogen product can emerge into different forms. Any of those forms are promising and have already proven to be a preferred fuel over fossil fuels in terms of CO_2 emission. When we consider the practical aspects of implementing hydrogen as a fuel, the preferred hydrogenous form varies depending on the purpose onboard (Farias et al., 2022).

The most potent and beneficial advantage of utilizing hydrogen in any known form as a fuel for a marine application, is found in the fact that no harmful emission or pollution is formed or produced during combustion or energy extraction from the product. The only rest element, in any case, is pure water. Today there are two main different pure hydrogen forms that represent the alternatives available as fuel for the maritime industry onboard vessels. Pure hydrogen can be loaded and adapted as a very cryogenic product at atmospheric pressure and a temperature of -259°C, with a gravimetric energy density of 140 MJ/Kg and a volumetric energy density of 8,4MJ/l known as LH_2. It could also be compressed and loaded up to gas state, normally at 350 or 700 bar in ambient temperature conditions, known as CH_2. The later pressurised alternatives with a great degeneration of energy density, together with challenges in conjunction with handling, storage and bunkering of those products, makes it so that pure pressurised hydrogen in the above states is actual only for a very small part of the total world fleet of vessels, due to the limited available technology and infrastructures. Hydrogen for the segments outside coastal trade is therefore loaded into other preferred solutions, typically as either ammonia (NH_3) or a Liquefied Organic Hydrogen Carrier (LOHC). Hydrogen in a synthetic bound, defined as LOHC, has a gravimetric energy density of 7,5MJ/Kg and a volumetric energy density of 5,19MJ/l (*Hydrogen-Feasibility-Study-MariGreen.Pdf*, n.d.).

The synthetic oil product used to load up the hydrogen produced known as LOHC is found as a combination of N-ethylcarbazole and talent, this form creates a product that is easy to handle and easily transferred into storage tanks at atmospheric pressure and temperatures

(Rosen et. al, 2016). On the other hand, the separation procedure and logistics needed when returning sub-products after hydrogen extraction from LOHC is demanding, costly and time-consuming. Ammonia (NH_3) has several upsides and benefits compared to both the above-named hydrogenous alternatives (Kobayashi et al., 2019). NH_3 presents some challenges outside of the focus of this study yet are important to mention. NH_3 is poisonous and its odour is panic inducing. It is an aggressive molecule due to its acidity, to its low dew-point corrosion and to its chemical reaction with a lot of materials, except pure steel. This means everything it is in contact with should be made of pure steel. Lastly, NH_3 has some, but limited fire and explosion risks. Despite those challenges, the advantages of NH_3 are promising, and the product is feasible as a large-scale fuel both for internal combustion engines (ICE) and fuel cell (FC) configurations.

The logistics and product management of NH3 can evidently be built upon existing gas infrastructure, already established and available in all large ports at a worldwide scale. Ammonia has a boiling point of 240K (kelvin) and at 18 bars it will liquefy at room temperature of 20°C. Gravimetric energy density is 22,5 MJ/Kg and a volumetric energy density of 12,7MJ/l. Those characteristics give ammonia superb advantages, despite the degeneration of energy density pr. volume compared to diesel oil (Pedersen, 2021). The great advantages are the possibility of further utilization made possible by existing shore gas tanks and infrastructure, as well as the existing fleet of gas carriers, capable of distributing and bunking the upcoming fleet of ammonia-fuelled vessels.

Those factors appear to be strong drivers for the further evolution of NH_3 as a fuel for the worldwide fleet of vessels. To become the ultimate and realistic alternative for a prompt and instant game change, ammonia needs to be produced in an environmentally friendly way to remain sustainable. Production by electrolysis is very energy demanding and can only be justified by green, blue, such as sun, wind, water, or nuclear energy sources (*Alternative-Marine-Fuels-Study_final_report_25.09.19. Pdf*, n.d.).

The carbon neutral and most common sustainable method for ammonia production is today found in the Haber Bosch synthesis process. This blends air, which has nitrogen and oxygen in it, as well as the water, which has hydrogen and oxygen in it. When these components are warmed up, the components separate and rearrange. Nitrogen from the air and hydrogen from the water bind together to make NH_3, the ammonia product. The ammonia is then used as a host and energy carrier when transporting and handling the hydrogen product. This production method needs a green or blue energy source to be environmentally sustainable. Other methods of ammonia production, such as methane pyrolysis or any other petroleum gases as feedstock will not be further elaborated in this study.

Schematic view figure 5 of a typical Haber Bosch synthesis (HB) production line for NH3, the process is also used when NH3 is produced as a fertiliser or energy carrier for fuel.

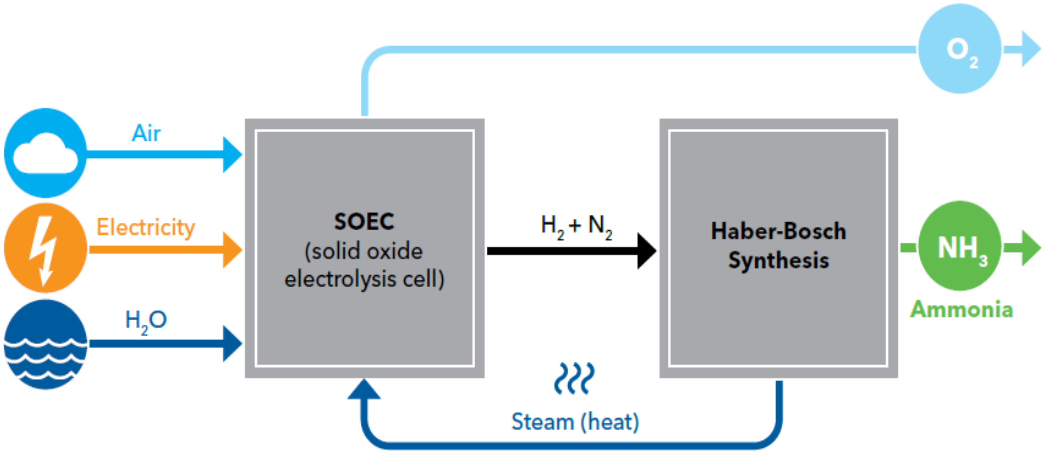


Figure 5: The concept for NH3 production by a HB production line (Ammonia as a Marine Fuel DNV, n.d.2020, p. 8)

A typical water and air train transition is illustrated in figure 5, viewing the pathways of formation during phase transition, where hydrogen is produced and loaded.

The study work will exclude the 700 and 350 bars hydrogen states (CH_2). Those states will only be available for supplying fuel cells adapted into the short sea segment of the business. Hence pros and cons of the following hydrogen states will be carried forward in this section; LH_2 (Liquefied hydrogen storage into cryogenic tanks), LOHC (Liquefied organic hydrogen carrier), and NH_3 (Ammonia state of ambient temperature).

Below the illustrative overview figure 6, indicates different formations and train transitions of actual hydrogen products (informative purposes). Both renewable and fossil fuel with carbon capture and storage technology from production are illustrated. The illustration is meant to give a superficial picture of the three selected energy carrier states: LH_2, NH_3 and LOHC (organic hydrides).

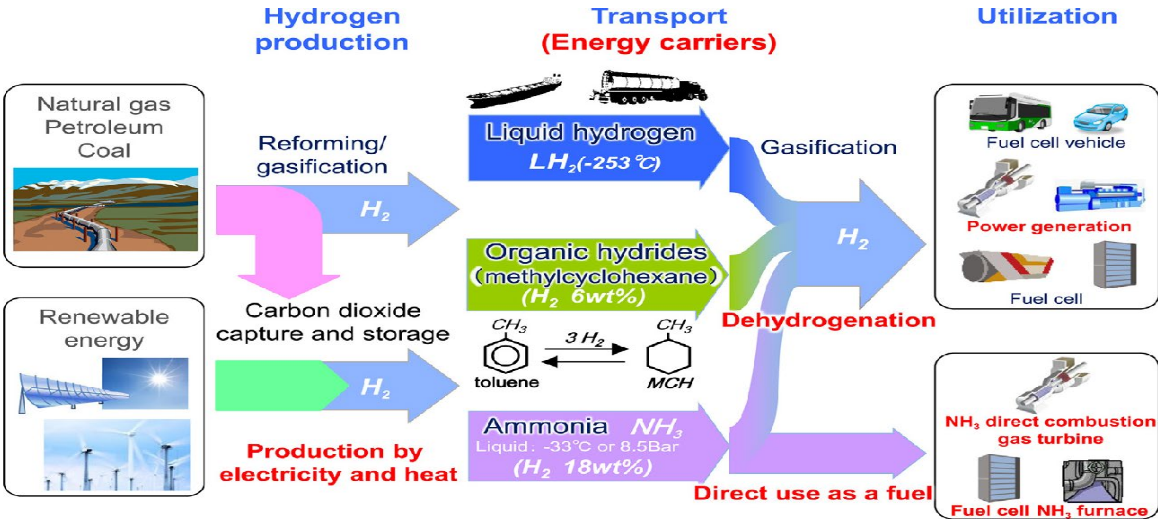


Figure 6: Scheme showing hydrogen production, transport, and various uses. Courtesy of Japan Science and Technology Agency (JST) (Kobayashi et al., 2019, p. 112)

2.4 The elaborated hydrogen alternatives

An informative, consistent, and clear view of the retained practical and operational experiences is needed. The already gained experiences with hydrogenous solutions, the further needs, and the necessary practical constructional and contractual solutions will be to an extent clarified in this chapter. The utilization of the products into different applications onboard and their foreseen challenges was selected as the crucial subject to elaborate on in this study. This will include a more specific general product information and explanation of characteristics, product storage, management, and consumption, with focus exclusively on on-board ships.

Three hydrogenous solutions will be considered in this work. Their general consistency, capacities, limitations, and forms will be extended on. As mentioned, all the three hydrogenous solutions have the potential to become the most popular solutions for several parts of the different shipping segments, apparently not for all. Among other barricades, Capital Expenditure (CaPex) is of concern. At this present time, it is considered financially excessive for some of the segments to switch to hydrogen alternatives as a fuel. However, hydrogen is still highly relevant for the shipping industry. The below Figure 7 gives a picture of storage and different technologies divided into subgroups. Along this process, both the physical and material-based products are only shown as very general terms.

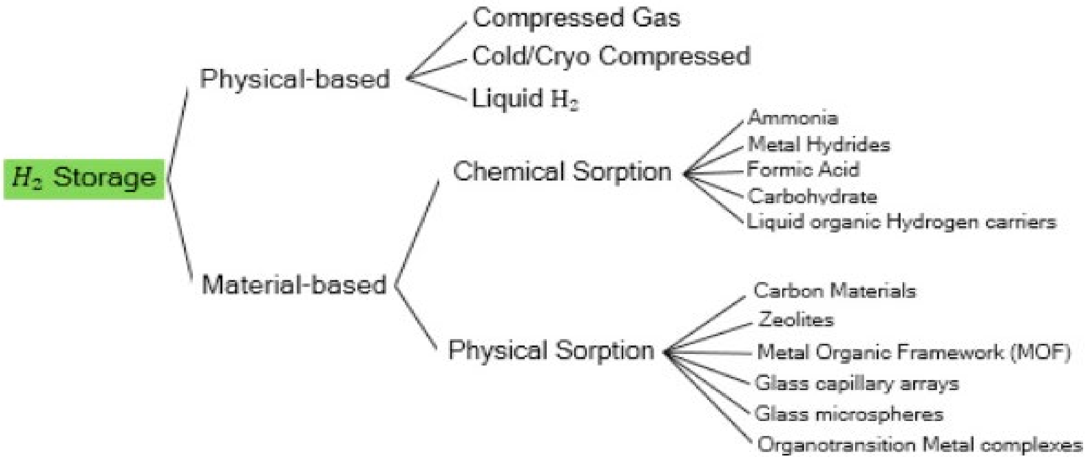


Figure 7: Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis. International Journal of Hydrogen Energy (Moradi, R., & Groth, K. M. 2019, p. 257)

However, attention to the existing and sustainable technology is fast-growing, and a great investment in solutions throughout the range of foreseen related value chains is ongoing. That needs to be in place already before the oncoming predicted expansion. Things that must be in place are typically, but not limited to, logistic, transportation lines, and bunker facilities.

When the comparison between today's fossil fuels alternatives, and the available hydrogenous solutions evoked is done, none of the traditional parameters counted for are reachable. However, nor are the other fossil options giving emission to air realistic, as we need to meet the industry and the decision makers imposed ambitious global targets laid down for 2030 and 2050 levels and further, to do that, it will require a total decarbonization of the entire shipping industry.

The below diagram in Figure 8 indicates properties and energy density compared to weight and volumetric energy density, for comparison of modern fuel including hydrogenous solutions. As one of the challenges, all the traditional fuels and gas options have a higher energy density, meaning that all hydrogenous solutions are more space demanding per energy unit.

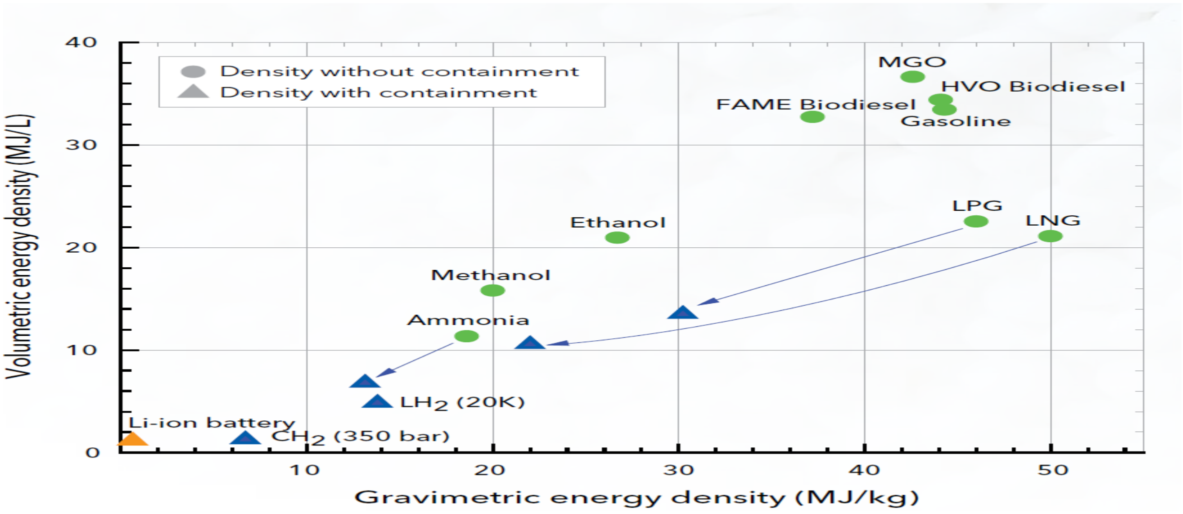
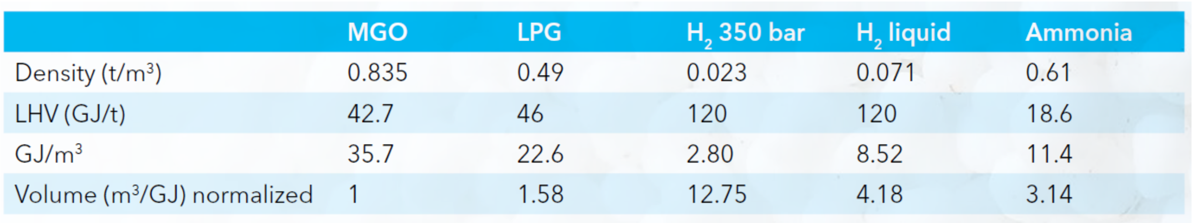


Figure 8: Indicates a diagram of comparison of actual fuel and energy carriers (Ammonia as a Marine Fuel DNV, n.d.2020, p. 4)

Table 1 below weighs actual new fuels and energy carriers, against MGO (marine gas oil). The comparison of volumes, lower heat value, energy unit, and density reviewed shows that the alternatives are demanding and less suitable, seen from a practical point of view, decarbonization gives rise to challenges.

Table 1: Indicates a table of comparison of actual fuel and energy carriers (Ammonia as a Marine Fuel DNV, n.d.2020, p. 4)



	MGO	LPG	H_2 350 bar	H_2 liquid	Ammonia
Density (t/m³)	0.835	0.49	0.023	0.071	0.61
LHV (GJ/t)	42.7	46	120	120	18.6
GJ/m³	35.7	22.6	2.80	8.52	11.4
Volume (m³/GJ) normalized	1	1.58	12.75	4.18	3.14

2.4.1 LH_2, liquefied hydrogen in a cryogenic state

In the context of this study, LH_2 cooled and stored in cryogenic tanks up to 12 bar of pressure is considered. Hydrogen can be challenging in this state due to its nature. Onboard a ship, pure hydrogen will be stored as a liquefied gas at very low temperature (below -253 °C) and allow slightly over-pressured up to 12 bar. The trans critical pressure of liquefied hydrogen is 13,3 bara, the storage tanks shall be kept at pressure with margin (Ratnakar et al. 2021).

Pure hydrogen gas has the smallest of all known molecules, hydrogen gas is more complicated to contain and store than other gases. Besides diffusion, and a wide flammability range, it ignites easily and may to an extent have a self-ignition capability. This combination of properties leads to an overall increased safety risk unless equivalent safety systems and practices concerning hydrogen are correctly and truly implemented accordingly. Cryogenic, low-temperature hydrogen (LH_2) in a liquid state makes it complex and challenging compared to all other fuels for marine applications (Lindstad et al., 2021). Despite this, and at present stage of the evolution, implantation onboard coastal trade smaller vessels are adapting LH_2 feeding of standard fuel cell (FC) for electrical power production. This is presently a promising and evolved consumer of LH_2 onboard this type and size of vessels. This consumption gives neither local nor global emission of pollution to air, the only rest product is depleted oxygen and water.

The typical fuel cell (FC) standard hydrogen consumption configuration is shown in figure 9, the fuel cell consumes LH_2 for electrical power production.

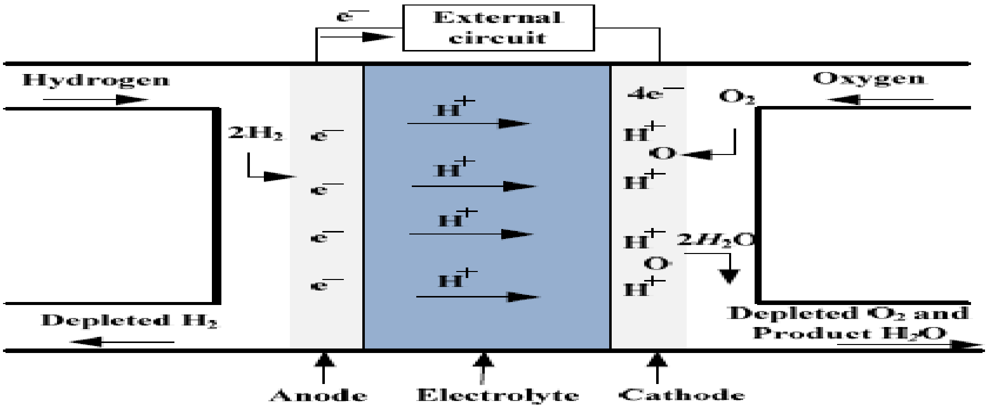


Figure 9: Fuel cell illustration (Han, Charpentier, and Tang 2014, p.2802)

Below is the genetic block diagram figure 10, which shows a typical LH_2 system working with a pressure regulating system and a small conditioning tank onboard.

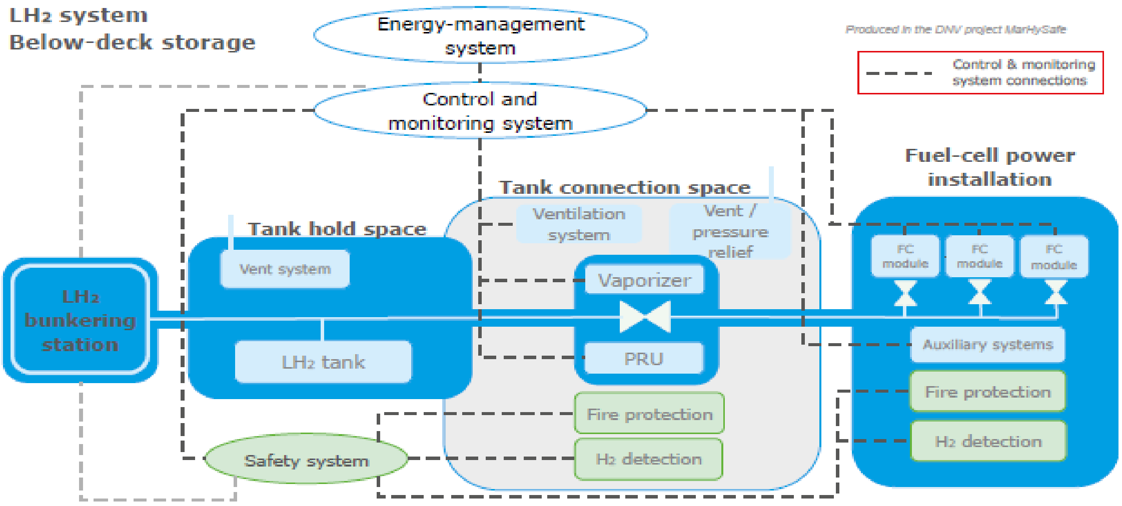


Figure 10: Block diagram of a schematic LH2 system onboard, Handbook_for_hydrogen-fuelled_vessels.pdf (n.d. 2021, p. 26)

Evolution is going fast in terms of making applications ready for hydrogenous solutions. This new technology can use pure hydrogen (LH_2) to be fed directly into an internal combustion engine (ICE). This can also work in a very marginal mixture with LNG. This new technology is in contradiction with methods presently implemented but is very promising and needs consideration (Wahl & Kallo, 2020).

LH_2 is considered a high energy-consuming fuel when kept in storage tanks at low temperature, this due to energy leakage. In addition to those challenges, it has an unstable liquid phase due to the narrow differential of 20 K(Kelvin) temperature range needed for its liquid - phase. For these two reasons, storage tanks built as C-tank need to be insulated in an extremely efficient manner to reduce boil-off and energy degradation when consumption or limited during the period of stillstand or port operation (Ye et al., 2022).

The literature available on this above subject also emphasises pitfalls when approaching the implementation challenges experienced onboard. The cryogenic effect of an LH_2 release or leak must be considered and appropriate measures and precautions need to be implemented. In recent site experiments and tests where LH_2 is released into the air, it was observed that liquid and solid oxygen was formed at the ground, and temperatures as low as 85 K were observed during this formation (Wang et al., 2020). It is believed that a pre-cooled ground from the previous test contributed to the happening in this specific case and that the liquefaction and solidification of oxygen contributed to as possible self-ignition and serious explosion events. This kind of similarities may also emerge onboard (Wang et al., 2020). Liquid hydrogen storage tank design, management and regulation are implemented in The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers 1978 as amended (STCW), and The International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF) adopted by the IMO for utilisation onboard ships. The commonly known C-tank configuration, and applied rules will in principle cover cooled hydrogen in a cryogenically state. However, consideration in addition to initial rules is needed due to the super special conditions and properties of hydrogen. Bunkering operation for low-flashpoint fuels including liquefied hydrogen has been established, However, it includes interactions above traditional bunkering procedures for fossil fuels (Ratnakar et al. 2021).

2.4.2 NH3, ammonia in a liquid state

The product pressurised up to 18 bar or cooled down to -33°C, at atmospheric pressure. Representing NH_3, as an alternative for further carbon free fuel (Haram, n.d.). The above earlier explanation of lignified hydrogen LH_2, management and storage onboard at -253°C, requires less space and mass occupation compared to the energy content of the other fuel alternatives in this study, unfortunately, this does not come without operational and management complexities of the product. In addition, cost and required spaces for fuel cells (FC) will be additional concerns at the present state.

Ammonia (NH_3) on the other hand, has superb key benefits of already gaining existing management and transporting experiences, the product is already well established in the industry. The ammonia (NH_3) handling complexity is considered equal to propane (LPG), at the storage temp of -33°C and normal ambient condition, hence this contributes to a significantly easier and more acceptable implementation. The storage cost and product losses are also significantly lower at all states than for the LH_2 product and compared to any of the actual other carbon free fuels today available.

Typical internal combustion engine (ICE) in figure 11 below, illustrating an engine application with configuration consuming and burning NH_3 and H_2. Application with heat recovery and grid is visualised.

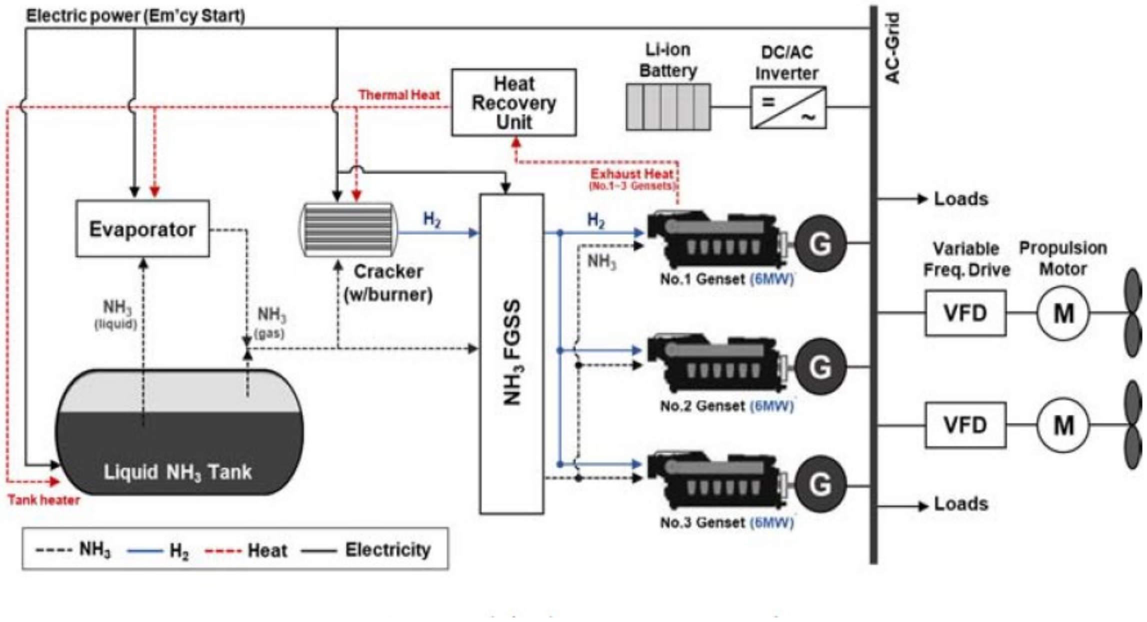


Figure 11: Simplified concept of ICE engine burning NH3 and H2(Kim et al. 2020a, p. 6)

Figure 11 indicates a concept where H_2 becomes formed out of NH_3. Another concept design exists where H_2 is directly formed from LNG with a carbon capture facility onboard. This configuration will form only water and depleted hydrogen and oxygen in addition to thermal NOx, which will be neutralised by Selective Catalytic Reduction (SCR). Furthermore, ammonia (NH_3) is characterised as a carbon free energy carrier and sustainable fuel when it is produced and loaded during refinery processes without the use of a fossil energy source.

The sustainability of the production process for NH_3 drops when natural gas is used as a catalysator and driver. Today, when green and blue energy sources are applied into the production line, NH_3 is more convenient than the other hydrogenous alternatives when it is produced with emission-free technologies. The CO_2 and emission-free ammonia produced from renewable energy are labelled as green ammonia, whereas ammonia produced from sources like natural gas and coal is labelled as brown. The third production line of NH_3 is produced with carbon capture and storage (CCS) which is also labelled blue. There are some notable drawbacks during normal utilisation, this is at present most focused on the toxicity, flame, and explosion. In some ongoing experiments, ammonia has been combusted in an ICE (Internal combustion engine), either as pure product or as a mix into LNG. Those issues need further analysis and to gain operational experiences before a conclusion into which type of hydrogenous fuels will be the preferred (Kim et al. 2020a.).

Typical bunker involvement of stakeholders is shown below in figure 12 where low flash fuels (LFF) such as LH_2, CH_2 or NH_3 is the bunkered product.

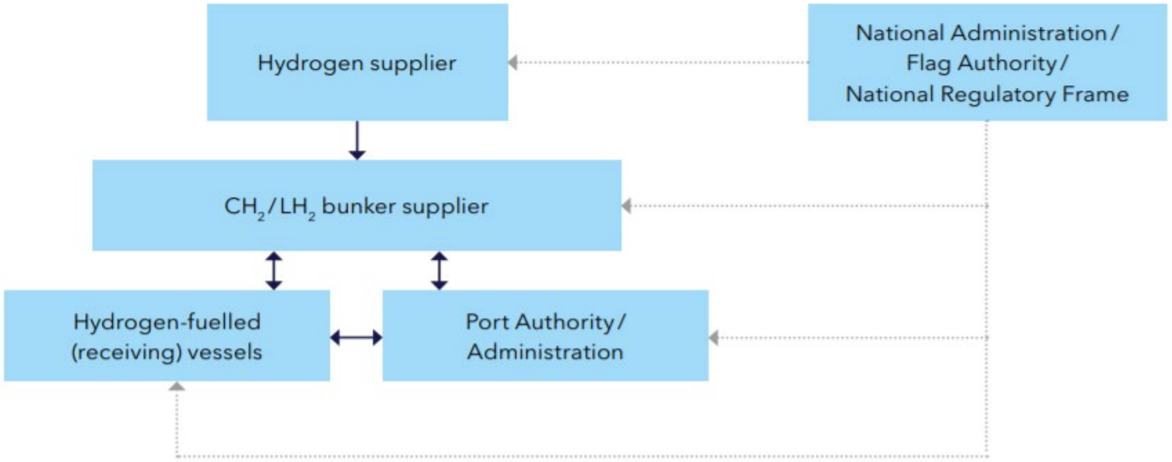


Figure 12: Bunker stakeholder involvement LFF (Handbook_for_hydrogen-Fuelled_vessels.Pdf, n.d, 2021, p 52)

2.4.3 LOHC, Liquefied organic hydrogen carrier

The hydrogen products' numerous storage technologies have been investigated and implemented in recent decades. They all aim to increase the volumetric energy content without compromising on gravimetric energy density capabilities (Moradi & Groth, 2019).

The hydrogenous products are divided into numerous types of chemical composite that may vary depending on the product's intended purpose of consumption. Based on the latest scientific research done, the industry achieves solid and proven process methods in processing chemical bound hydrogen, loaded into liquid organic hydrogen carriers (LOHC). This again supports and emerges possibilities for future prosperity in respect to forthcoming large-scale management and distribution of hydrogen without many elemental hydrogen challenges. Those systems are composed of pairs of hydrogen-lean and hydrogen-rich compounds to store and accumulate hydrogen fractions by repeated catalytic hydrogenation and dehydrogenation cycles (Asif et al. 2021). Hydrogen storage and processing in the form of LOHC's give access to use and extended utilisation of existing bunker systems onboard and shore storage. Already gained public and existing crew knowledge give full confidence in dealing with liquid energy carriers. This contrasts with hydrogen storage by hydrogenation of gasses, such as NOx. Hydrogen is released from the carrier component when first loaded only as pure hydrogen after the separation and condensation of the boiling carrier compounds.

The schematic view of a typical LOHC process is illustrated in figure 13.

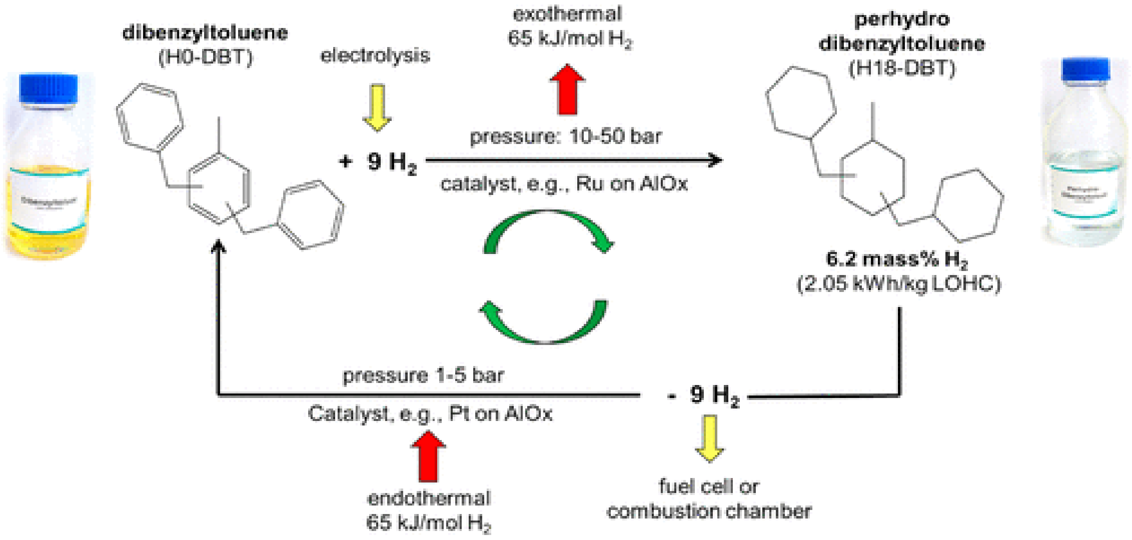


Figure 13: Schematic view of hydrogen storage into Dibenzyltoluene (H0-DBT) and Perhydrodibenzyltoluene (H18-DBT) LOHC System.(Asif et al. 2021, p. 3)

Despite the number of unresolved challenges and lack of knowledge of the LOCH concept for use onboard deep-sea vessels, it is not a stopper for the further exploration and evolutionary work in relation to utilisation of this hydrogenous solution. Keeping in mind the coastal and local ships trade, the concept is technically solved and optional. This shows once again that evidently, there is no straightforward, one size fits all solution available for all segments of the trade.

The challenges are mainly found in relation to the practical management of efficient energy transition onboard. The product separation and re-storage of the synthetic rest product before a final return ashore is among critical issues to be mentioned. (Rosen et. al, 2016). Hydrogen utilized for vessels engines combustion and power generation consumption onboard represents a different source of energy, where hydrogen may be implemented as an organic energy carrier. We shall only elaborate in general form and focus on the onboard known issues, when a straightforward separation and return method is established. This may very well be the large-scale preferred system and method for the further (Abdin et al., 2021).

2.5 Preliminary comparison and product mapping

The following later preliminary table 2 in this chapter gives a review of the three earlier explained different hydrogenous forms, pros and cons accounted for. This concern is only countable in respect to the product after it is received on board. No great concentration or effort is taken into economical, logistic, production, handling, or complexity aspects. The table 2 is based on information gathered by reading and skimming through the preliminary study literature, no specified academic search or research methods are used to form this premature preview, the goal and purpose is to sort out further areas of elaboration again for establishing solid statement and material selection for this thesis research, elaboration, and further study work.

In the table 2, actual advantages, and disadvantages are revealed in a wider term, Which of the three elaborated hydrogenous forms and is consistent is the most promising fuel carrier for internal combustion engines (ICE) and fuel cell (FC) for marine applications. The discovered results of this peripheral work visualised is based on information gathered from white papers, engine producers, studies by technical consultancies and supervisors to the global renewable energy transition, articles, internet, studies, and different books and booklets used in the preliminary unstructured phase of the literature study.

The table 2 below gives a view of advantages and disadvantages discovered during pre-study and elaboration done at an early phase of this thesis, it is therefore only used as an indicator before further study and elaboration that intends to be conducted through a systematic literature study (SLR) methodology.

Table 2: Pre-Study Advantages and Disadvantages, in relation to the different hydrogenous solution

L-H2 (liquefied hydrogen storage into cryogenic tanks).	
Advantages	Disadvantages
- Low volume and high energy density when captured in tanks onboard. - Clean and relatively easy to consume both in FC and ICE configurations onboard. - Available operational experiences gather to some extent from the existing fleet. - Known tank construction and isolating methods - Possible to use enviro-friendly feedstock such as water for production - The product needs no inert when captured in tanks at low temperature onboard	- Complex tank structure and demanding construction. - Complex bunker, handling, inerting, and gas freeing system. - Complex and demanding preheating, boil off and separation system. - Explosive and flammable, need addition and complex safety precautions. - Limited operational experience available - Additional regulations and rules need to be established in addition to IGF code. - Limited infrastructure and great energy loss during handling and transportation.
NH3 (Ammonia state in ambient condition).	
Advantages	Disadvantages
- Existing logistic and bunker facilities in the already existing gas terminal configurations. - High energy density - Existing production lines and distribution - Acceptable tank and system configuration and facilities - Feed for SCR to neutralise NOx production formed in the ICE combustion. - Included and implemented into existing rules and regulation IMO gas appendix and IGF code.	- Poison and explosive, complex safety measures. - Limited operational experiences in ICE and FC utilisation onboard. - Aggressive behaviour, and consistency when in contact with water or any steel alloyed material. - Complex engine safety, control, and operational systems
LOHC (liquefied organic hydrogen carrier).	
Advantages	Disadvantages
- Beneficial tank construction and transfer system. - Volumetric space is beneficial. - No direct safety issues onboard in respect to poison, pressure, or temperatures. - Use of existing fuel tank and transfer system to extend. - No harmful or poisoning effect on crew or facilities. - No fire explosion risk during handling or storage onboard.	- Complex tank and transfer configuration, due to return of organic component and separation system onboard. - Unstable at low ambient temperature - Need special separation and handling equipment and units ashore, excessive logistic return system ashore. - No deep-sea experience in operation - Low energy density compared to other hydrogen alternatives

Advantages and disadvantages above are withdrawal from this thesis pre-study and papers found in section 7.2

The above table of advantages and disadvantages indicators gives only a view of the preliminary practical pros and cons discovered during the surface study and reading performed in this early phase of this work. Further work needs to select and find known academic systematic search methods and systematically find proven bibliographical techniques to conclude, in the forehand of that selection the most beneficial way of streaming and scrolling of information need to be decided. Without a well-organised plan, and a system to extract and build pillars in respect to the remaining scope of work, it will be a challenging task to preside, however, we do again need to retrieve answers and discover areas without hasty conclusions and secured answers, this shall be of concern and given priority in the further work on the thesis.

2.6 Objective and research question

Before expanding on the title of this thesis, it is necessary to expand on the reason behind its thematic. There were personal interests coming from professional occupation that motivated the search for possessing know-how of the shipping industry's evolution, especially in the general field of maritime technical issues. Those were the strongest motivators for the technical subject selection. Forward-looking and technically oriented knowledge contribution into maritime industry, together with present and instant need for altering existing technology, was chief in the selection of the thesis objectives and research question. The transition to a more sustainable energy source is crucial and gives the ultimate motivation to seek knowledge of new technical solutions now emerging. The industry activities and energy demands will increase, and the fuel consumption will further increase in years to come (Işıklı et al., 2020).

The objectives and research question became formed and formulated, after the preliminary reading of available research work, done in the line of this thesis technical subject. At this stage, gathering a wide spectre and volume of relevant information, learning the rules of the thumbs in question of working and creating a thesis by applying academic methods have been essential. Also, the eventual derivation uncovered by the comparison and finding from pre-study and later SLR research methods and approaches has been evaluated. The focus and area of concern to build knowledge and address present industry knowledge, understanding and sustainability not only concentrate on the environmental aspects, but also vague operational and economical consideration has been of interest and importance to form an objective picture. This also includes possible technical upsides of the hydrogenous solutions and industry introduction, as well as the already accumulated knowledge into maritime clusters and business.

Research objectives

RO1:

Identify advantages and disadvantages of the three selected hydrogenous solutions, as alternative marine fuel.

RO2:

Compare advantages and disadvantages of the three selected hydrogenous solutions, from the comparison and findings after pre-study and SLR study.

RO3:

Explore research trends, sources, and dispersion of academic publications for hydrogenous solutions for the maritime domain.

Research questions

RQ1:

Which of the different hydrogenous solutions and consistency is the most sustainable fuel source and energy carrier for marine applications?

RQ2:

What are the differences discovered between the applied study approaches of the pre-study and the SLR study?

RQ3:

Which factors affect and contribute to research and publications of articles for hydrogenous solutions to the maritime domain?

Chapter 3. Research method

3.1 Elaboration and selection of thematic and study methods

In this section the intention is to review the research and study methods applied and in which way the subjects have been elaborated. How the established knowledge about hydrogen today and in the future will be formed for use in the maritime industry and onboard ships have been of concern. The usage, storage, and utilisation on board is not a clear and easy straightforward solution, and therefore the focus of the thesis will be on the literature giving pictures of the tank to the propeller (TTW). Whether the hydrogen is used to feed the fuel cells (FC) or for the internal combustion engines (ICE), we need to investigate those relationships and possibilities to choose the best possible solution for the different available configurations (Lindstad et al., 2021).

During this preliminary literature study, several different sources of knowledge have been consulted for a deeper elaboration on the present experience gained with hydrogenous product utilisation. Furthermore, results have been integrated and morphed into the objectives and in the work of forming keywords. During this preliminary work and literature review, the intention of the elaboration study is to give a solid basis of knowledge to narrow down the research objectives and the research question.

This pre-study work also included studies and elaboration into academic papers, position papers, and other articles on available searching tools such as Scopus, web of science, science direct, Oria, and google scholar, and the database of CIMAC (International Council on Combustion Engines). When utilising the above tools and search engines, words in this thesis title have been used to do searches. There was no direct hit, nor was found any existing work using the exact spelling chosen as the title for the thesis. Hence, the title is considered as unique, even though there exists other thesis and articles covering part of the thematic, or covering data processed relevant for this topic. This data has been covered throughout the introduction. Among academic papers it is discovered and reviewed work including extensive research on each of the three selected hydrogenous forms. Work covering comparison between the elaborated and selected forms in this thesis is known, however regardless of those discoveries no comprehensive study has included the three selected hydrogenous forms simultaneously, with the same goal as this thesis.

The further study intends to enhance the general knowledge of the new possibilities and the actual onboard operational considerations in relation to hydrogenous solutions. The intention is to include management of the product as well as to reveal available information in respect to engine running parameters, such as thermal efficiency through different operational and load conditions. It will also be necessary to study hydrogen when onboard in practical operational precautions, product preparations and treatment before feeding the engine or eventually fuel cell. Product consumption and combustion pros and cons during daily operation and variable conditions onboard will be rated. Hydrogenous products are available in different diversities around the world, today and soon, this will be the most probable development of modern fuel for ocean going ships. Those parameters require that other angles of concern than todays should be counted, considered, and investigated. The lack of knowledge, experience with hydrogenous solutions and understanding onboard is of utmost importance, therefore the know-how of the crew will be crucial in this paradigm shift. The existing but limited operational experience utilising hydrogen as a feed for prime mover or power production fuel onboard ships in different contexts, forms, and configurations are limited, and this may perhaps be a further focus area. The important linkage through practical handling onboard, typically practical challenges in the TTW handling and the possible links that may be established as a bridge between existing theoretical knowledge and experience that become accumulated and gathered on board is of interest and not to be neglected.

While working through available academic papers and articles, little emphasis is discovered or revealed on practical challenges onboard and explanation of day-to-day operational problems encountered. Also lacking are consideration of the safety risk, technical break-down, running experience, and maintenance routine changes. Besides environmental benefits there is little known about which direction, positive or negative, this energy paradigm shift will affect crew, operators, and engineers onboard.

The work already conducted during the pre-study phase discovered a gap, where no conclusions are drawn considering the objectives forming in this thesis. It is therefore needed to systematically arrange and extract knowledge to build in and fill this gap. It is therefore also needed to do further research into the information available, to build and establish a more solid and pristine visualisation of today’s preferred and practical feasibility among available solutions in respect to the research question later formed.

During this work, the utilisation of the planned systematic research of already existing knowledge will be gathered by a systematic literature review methodology (SLR). This decision has been formed after extensive research and the pre-study performed informal communication with national technical personnel, such as superintendents and technical managers of Norwegian shipping companies. Unfortunately, the knowledge is limited among stakeholders as most of the shipping companies today have not yet started the journey of hydrogen utilisation on board their ships. The general feedback was that this technology and implementation in general is still 5-10 years from today. Hence biofuels, LNG, and battery hybrid solutions were the preferred practically feasible solutions today for the contacted industry and Norwegian shipping companies. By bearing this in mind, the objectives need to be narrowed- down. It is a fact that at this early stage of implementation, very little knowledge of operational experiences is available or systematised. Therefore, the focus will be to answer and elaborate on why one of the selected hydrogenous solutions appears to be the first and preferred alternative for marine applications.

We need to consider and ultimately narrow this further down as we already are discovering huge derivations in between the hydrogenous consistencies and their utilisation issues. It is discovered that different pre answers depend on the type, size, and trade of the ship. The most adaptable hydrogenous alternative for a local ferryboat will not be the same as for an ocean-going vessel crossing the Pacific Ocean. At present, there are different options for several segments, concerning the type of prime movers, trade, vessel size, among other variables. We will strive to study available knowledge and literature to find which of the hydrogenous alternatives will be able to cover more than one segment. In this respect, we shall research and compare available know-how, of infrastructure, bunker facilities, engine, and fuel cell readiness, general knowledge, and experiences already gathered with the different hydrogenous alternatives. Before we select and conclude we need to explain and gather knowledge of the different options before a conclusion or answer to the generalised research question can be explained.

3.2 General introduction to the research methodology

This general introduction addresses and gives a view of the frame and method intended and applied throughout the work. The intention and planned approach explored in this chapter will also address and explain the task and methodology used when conducting and developing this thesis. Among a wide spectrum of options on how to approach and conduct a written research study, a methodology needs to be decided. The chosen method is a systematic literature study (SLR) which gives room for a narrowed and complete approach for retrieving and merging existing knowledge and building solid answers to the research question and objectives.

“It is important that the practical use of research takes in the whole range of findings on a topic, not just the results from one or two studies. For this reason, reviews play a crucial role as a bridge between research and related areas of policy making and practice” (Armitage and Keeble-Ramsay 2009).

We typically divide SLR into two main approaches: Inductive or deductive methods. The deductive method starts with analysing existing theories to try to predict the outcome of a specific situation, or experiment. It seeks to test the theory by confirming or affirming it. Applied to SLR, this means the author will first read the material, and adjust the research objectives along the way. The research question will be formed at the end of the pre-study (Casula et al., 2021).

The inductive method starts practically on the field, where the author collects data and observes patterns, and finally creates a theory from his observations. In the context of an SLR, the inductive method is applied if we equate previously done research work as primary “field” data. This data then needs to be condensed by the author to make a new theory.

Therefore, an SLR uses both the deductive and inductive methods. It uses the deductive methods in its first phase, when defining the research question. It then uses the inductive method to synthesise the existing knowledge into a new recommendation. In the case of this thesis, the goal is to produce a new recommendation as to which hydrogenous solutions are preferred onboard ships.

The SLR research structure has been the chosen approach for the forthcoming study and the required research to build this thesis will depend on both the deductive and inductive methods. It has not been a straightforward procedure, but rather a challenging selection between different available research and working options. Different strategies have been used to answer the preliminary working objectives and question.

Informal interviews of technical business decision-makers have mapped the general knowledge in the industry. The informal interviews were used to answer a few open forms, semi structured preliminary questions. This approach, unfortunately, appeared inadequate for the acquisition of general know-how of the subject among the selected Norwegian shipping companies. The expert’s opinion did not reveal material or new information useful for the thesis, because of limited present knowledge, and therefore limited experience, related to the thesis thematic. However, it did highlight where knowledge was missing.

3.3 Research Strategy

The selection of the thesis research strategy done is based on the ability to review and find possible answers to the addressed research question. The topic has been researched and data for building knowledge was in the early phase collected through a number of academic and non-academic databases. Into the later phase of the work after the pre-study the amount of search engines and non-academic such as with paper was limited, and solid keywords were built, for further elaboration into limited academic searches. The systematic literature review (SLR) has given sufficient valuable study material within the overall topic. So much so that the initial research question established during the pre-study has been further narrowed (Brown, 2008).

3.4 Research design

The design and methods of approach need to be planned and worked out as a template on how to respond and find answers to the research questions and objectives of the thesis. Selection is related partly to unsatisfied in-house knowledge by the Norwegian shipping companies' technical departments know-how of the theme elaborated in this study. It is also worth mentioning that amidst the COVID pandemic, there was limited access to the industry specialists. Interviews as raw material must be handled with care because they are the subjective opinions of selected experts, as opposed to data obtained from literary review, which is objective empirical data. This thesis's research method will include both qualitative and quantitative data to answer the defined research question and objectives (Frankfort-Nachmias et al., 2015). The performed systematic literature review and study is required to be extensive and absorb enough quantitative data. The mixed research method in this context helps us to find the preferred extraction method to find relevant qualitative text. This mixed research and study design often give prime and dependable answers to the research question (Frankfort-Nachmias et al., 2015).

3.5 Data collection method assessment

The SLR method approach is defined as a systematic explicit and reproductive method for identifying, evaluating, and synthesising the existing body of knowledge previously done by researchers, scholars, and any other practitioner (Mengist et al., 2020).

The collecting, assessment and appraisal methods utilised, are done in the phase where the selected articles were chosen and evaluated based on the review's objective and the research question formed. The study selection implied screening of the literature to identify relevant papers for the literary review. It has two basic steps. The first one is to select studies using inclusion criteria and quality assessment. This is done by reading the detected articles, booklets, and literature studies. The second one is to further select the material based on exclusion criteria by forming relevant keywords.

3.6 Method for finding and selecting literature

During the pre-study, an extensive search for knowledge has been done. Numerous databases were combed in the research process and drawn into the main thesis's initial work. These databases are Scopus, Science Direct, Google Scholar, Oria and Web of Science. However, when mapping the core documentation and available present knowledge also, case studies within the thematic were also included. Those studies have been read and elaborated for building and extracting knowledge. In the process of building strong and relevant keywords different approaches were adopted. There was a screening to exclude overlap, and multiple twins of documents were rejected, until the selected material became slimmed down to an acceptable number of articles (Mengist et al., 2020).

3.7 Data collection and analysis method

The data collection, and method applied will be a phase-oriented exercise where the first step will be initially an identification of existing available information into the thematic of the work. The second phase is the appraisal phase, where a screening will be performed to review and select literature based on the review object. The two steps using different sources in each step: database, and supplementary and conclusive search was done prior to final review and analysis. Each step of data collection was embedded in a specific stage of the iterative process of screening publications. To identify recent and quality-checked research into mindfulness and sustainable consumption, the later stage of the SLR focused on peer-reviewed journal articles and dissertations as two publications forms that convey recent state-of-the-art research (Fischer et al. 2017). This will be done by exclusion and inclusion criteria, applied, and used as predefined criteria. Those papers that fulfil the inclusion criteria will be selected for further investigation and content assessment. To do the aftercoming extraction of knowledge proven conclusion we will need to apply categorization steps based on the SLR objective. In the phase where the analysis and extraction will be conducted, we need to specify the targets by applying answers to our research question as criteria, in this work both quantitative and qualitative explanation and pinpointed results give the pathway and direction to proceed with the further research work and creation of the thesis (Mengist et al., 2020).

Figure 14 below indicates illustrative mapping of selected pathways, approach and method for elimination and selection when performing this systematic literature review (SLR) study.

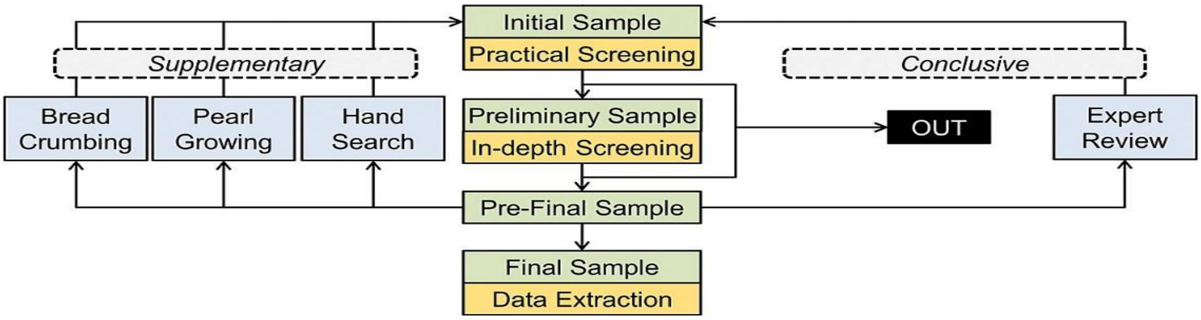


Figure 14: Sampling of information gathered from search to data extraction (Fischer et al. 2017, p. 547)

3.8 Data extraction and bibliography selection

The search for any other thesis or other study work with the same title has been performed through three different academic databases without any direct hit. The database in question is the same that was used to find material for building the research question of this thesis. The following databases are utilised for the preliminary and mapping purpose only, Scopus, Science Direct, and Web of Science. The searches were performed at very early stage, of keywords evolved for later selection and systematisation. The intention is only to pre-review relevant literature. This work was done before the later and final keyword selection process is conducted. The main search process and results will be visualized in figure 15.

The second stage of the specified literature search is intended for clarification and building of solid clues. This will later be adapted into final discussion and conclusion of the work. The literature used to build and form the thesis subject knowledge, and technical know-how, together with the expert’s opinion, the now gathered relevant material will be carefully extracted and adapted into a further systematic study. The prime articles and selected published material are in the later search done by creating combinations and new selections of existing and relevant keywords. The outermost purpose is to narrow and pinpoint the search and exclusively reveal the most relevant available published knowledge.

Further bibliographical academic literature searches will be conducted from the database Scopus, this to compile a manageable amount of data, in this stage ultimately narrowed down. The chosen academic literature in this phase is found by adapting the peer-reviewed journal, result and steps as followed and illustrated in table four below.

Table 3: Final database search after elimination and selection of Scopus database

Step	**Keyword for the search**	**Number of Articles**
1	“Hydrogen*”	1,564,670
2	“Hydrogen*” or “ammonia*” or “LOHC*” and “ship*” or “vessel*”	15,796
3	“Hydrogen*” and “ship*”	1,778
4	“Hydrogen*” or “ammonia*” or “LOHC*” and “ship*” or “vessel*”and “propulsion*”	295
5	“Hydrogen*” or “ammonia*” or “LOHC*” and “ship*” or “vessel*”and “propulsion*”and “emission*”	106
Total	After narrowed and keywords last definition, the total number of academic articles	106

The goal is to keep documents containing relevant technical marine oriented article and papers that represent the academic findings to do a surface meta-analysis. The results from this SLR will be compared to the non-academic pre-study of the advantages and disadvantages for the three chosen hydrogenous forms. This comparison will form a fundamental basis for creation of discussion and conclusion of the systematic literature review results. The above academic study model view is adapted from the Method for conducting systematic literature review and meta-analysis for environmental and technical science research (Mengist et al., 2020).

The below figure 15 illustrates the method used to do systematic selection and evolving keywords as the search’s narrows. It also shows how the selection for scaling off literature is performed, leading down to the dedicated amount of literature documents.

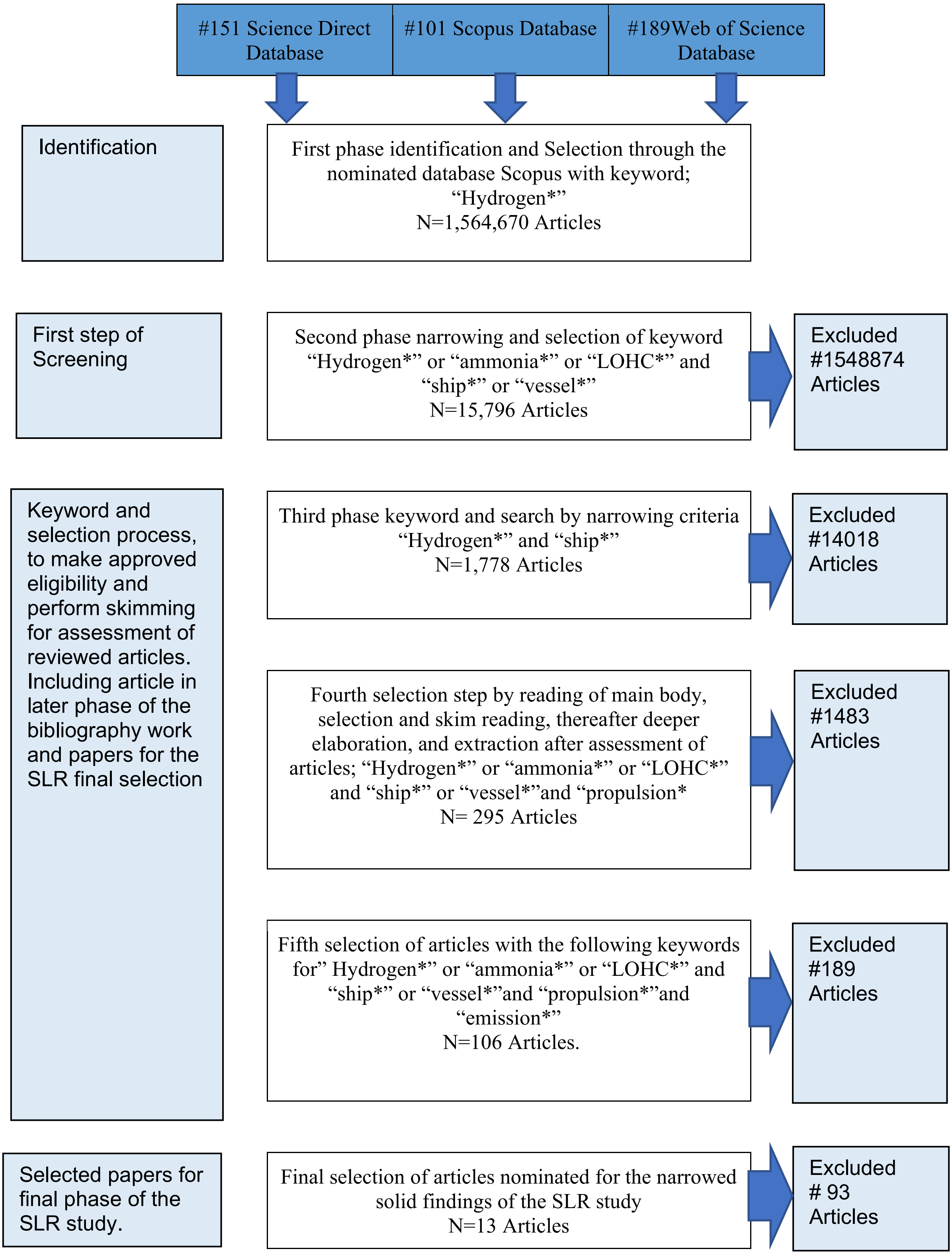


Figure 15: Schematic illustration of the method used when conducting this systematic literature search and selection

3.9 Retrieved comparison documents and papers

The final nomination of articles chosen for the last selection and extraction has been retrieved by skim reading, with concentration and a peripheral vision on evaluating the abstractions and conclusions parts of those 106 articles. It was decided to use this relatively large number of articles to build a solid academic foundation before conclusional extraction and sustainable comparison become initiated. The content and consistency of the material was thereafter processed through an integrated development environmental tool (RStudio) for coding, plotting and extraction of informative data, used to form graphics illustration of articles contents and trends. After the later and final bibliographical selection, based on a simplified manufacturing execution method system on an excel sheet screening and inclusion of relevant content and triggers in close relation to the thesis objectives and research question, a total of 13 articles was thereafter nominated for the narrowed solid finding of the selective literature review. This final nomination of the later accumulated articles is used to build further thematic discussion and conclusion by adding the final theoretical knowledge retained. Hence those observations will also be used for comparisons purposes between the academic SLR methods created by utilisation of keywords and generate searches for building responses to the objectives and research question and the pre-study elaboration through open searches of available databases, forums, and industry participants and withe papers. This performed pre-study work also includes studies and elaboration into academic papers, position papers, and other articles on available searching tools such as Scopus, web of science, science direct, Oria, and google scholar, and database of CIMAC (International Council on Combustion Engines).

3.10 Ethical considerations

During the informal conversation with experts, the open form and semi structural oriented information share of knowledge was performed. Only the opinion as an expert has been used and named in this thesis. Their opinion was extracted, and a firm informal condensation was conducted. No personal or company affiliation or contrary to values was jeopardised. Obtained informed consent varies in format. The in-person participant enrolment in studies includes conversation to bring in general knowledge and benchmarking the level of knowledge contained. “Research surveys can be very informative. Even when surveys seem innocuous, ensuring that the tenets of the ethical conduct of research are maintained is paramount. Maintaining fidelity and scientific rigour is important in all research studies” (Hammer 2017).

Chapter 4. Findings

4.1 Articles and papers findings and document extraction view

The listed extraction below gives a content overview of the elected 13 articles from the SLR study. The intention is to give a visualising of the core takeaways, retained for the final study, after the article retainment. The 13 papers' objectives, content, and conclusions, build the foundation of the SLR part of this thesis. Knowledge is built up from the articles. Together with the information and findings collected and systematised in the pre- study, information from the articles will contribute to answer the thesis' first objective:

Identify advantages and disadvantages of the three selected hydrogenous solutions, as alternative marine fuel.

It will also contribute to answer the first thesis research question:

Which of the different hydrogenous solutions and consistency is the most sustainable fuel source and energy carrier for marine applications?

The content for those inquiries will be extractable and previewed before explanation is given in the discussion chapter five.

The compiled 13 article extractions are listed below:

4.1.1 Study on Applicability of Energy-Saving Devices to Hydrogen Fuel Cell-Powered Ships

The objective of this article is to compare and find existing and emerging energy - saving devices and conclude which solution will be sustainable in the future when hydrogenous solutions may be the preferred fuel and energy carrier.

"*The hydrogen fuel-cell propulsion system will present new challenges when compared to the conventional propulsion system widely used today; a key concern is the fuel cell's sensitivity to fluctuating load demand"* (Stark et al. 2022, p. 27).

Storage of LH_2 between -260 °C and -240 deg °C, requires a significant amount of energy to maintain, this may increase energy demand up to 30 %. When storage as a liquid also boils off, it requires further energy to reliquefy (Stark et al. 2022).

4.1.2 More Environmental Sustainability Routing and Energy Management for All Electric Ships

The objective is to find the ultimate configuration with hydrogenous fuel solutions and propulsions alternatives, to conclude with the best optimization and sailing routes with least GHG emission.

"Hydrogen charging stations will be implemented to further make use of fuel cells for less greenhouse gas emissions" (Pan, Zhu, and Zhao 2022, p. 11).

Space and footprint onboard are of utmost concern, therefore fuel cells and auxiliaries including hydrogen tank and capacities must be restricted to a reasonable level (Pan, Zhu, and Zhao 2022).

4.1.3 Technical reliability of shipboard technologies for the application of alternative fuels

The objective is to evaluate and analyse failure rate of the different new carbon free fuels, the findings indicates that all new hydrogenous fuel alternatives have different advantages and disadvantages, however, most of the new technologies lack experience with long time field-tests in many applications and are still considered to be in an early evolutionary phase.

"On the level of overall failure rate, ammonia is shown to be very promising. Extending the view over a pure failure rate-based evaluation shows that other approaches" (Popp and Müller 2021, p. 1).

On the other hand, hydrogen as liquid LOHC has demonstrated to be a very fortunate solution considering tank, volume and safe handling is a promising option superior to ammonia, that suffer also from high risk of toxicity and corrosion risk (Popp and Müller 2021).

4.1.4 Challenges for Zero-Emissions Ship

The objective of this article is to compare alternative power propulsion systems like hybrid, combined, ICE and fully electric, with hydrogenous fuels utilization. The aim is to find the best solution and to conclude with what will be the most sustainable and preferred one for the different ship types and segments.

"Classification Societies, and the IEA (International Energy Agency) have showed that less than 2% of the total mix of fuels consumed by the shipping industry correspond to

alternative fuels. This low consumption is related to their low availability and demand" (Reusser and Pérez Osses 2021, p. 9).

Fuels such as NH_3 and LH_2 can be utilised as liquid fuels and used by Dual Fuel Engines (DFE). One of the challenges is their storage and energy density, something that is common for any alternative fuel to fossil fuels. Hydrogen properties bonded up into alternatives relevant for the ocean-going fleet of vessels, such as ammonia or LOHC, do not yet measure up to fossil fuels. This is mainly due to energy density on fossil fuels, compared to all other alternatives for Zero Emission Ships (ZES). The drawback of hydrogenous solution is also related to the volume needed for storage (Reusser and Pérez Osses 2021).

4.1.5 System-level comparison of ammonia compressed and liquid hydrogen as fuels for polymer electrolyte fuel cell powered shipping

The objective is to perform analysis of the products pros and cons defined through thermodynamic models to find mass flow rates, enthalpies pressure and temperatures. The article studies the case of two different ship types and configurations.

"The ammonia system and hydrogen system can reach zero GHG emission during operation, however, they might emit significant GHGs during production, distribution, and storage stages. The emissions can be lowest if the hydrogen and ammonia are green hydrogen produced" (Ye et al. 2022, p. 8573).

Ammonia has another important advantage over the other hydrogenous solutions. Ammonia is a known product and has a well-established and mature supply chain and an existing infrastructure owing to the chemical industry and the fertilising business. Ammonia is a hydrogen carrier with high energy and hydrogen content. It means that ammonia has a high volumetric energy density, and it is relatively easy to handle and store, which is of the utmost importance onboard any ship (Ye et al. 2022).

4.1.6 Fuel cells for shipping: To meet on-board auxiliary demand and reduce emissions

The main objective of this study was to analyse whether using hydrogen fuel cells would be a suitable method of decarbonization.

"Therefore, this study has focused on a solution such that the ship could operate for sustained periods without a hydrogen supply to avoid necessitating additional stoppages. Further operations considerations could include reliability and maintenance requirements" (McKinlay, Turnock, and Hudson 2021, p.64).

Today's most energy efficient and sustainable method of storing LH_2 in terms of volume is by liquefaction. However, this requires a temperature between -259°C and -240°C, again requiring a significant amount of energy to retain (McKinlay, Turnock, and Hudson 2021).

4.1.7 Fuel cell power systems for maritime applications: Progress and perspectives

The objective is to analyse and review the different fuel cell configuration with available fuels also including ammonia and hydrogen

"*The results showed that LH_2 and LNG pose similar safety risks, and several countermeasures such as avoiding fuel leaks, providing adequate ventilation, monitoring confined spaces, etc., are required to minimize the risks*" (Xing et al. 2021, p. 2).

Direct thermal cracking of ammonia for use in a Solid Oxide Fuel Cell (SOFC) is possible. The feedstock and internal reforming of hydrocarbon fuel and LNG or methanol need high temperature and therefore represents a relatively high cost. Also, the rate of Ammonia decomposition is influenced by different catalysts and different operational conditions. For instance, high partial pressure and temperature of ammonia could increase the decomposition of ammonia (Xing et al. 2021).

4.1.8 Sizing and Control of a Hybrid Ship Propulsion System Using Multi-Objective Double-Layer Optimization

The objective of this study is to investigate feasibility of hydrogenous solutions for several different types of ships, as well as the effect of hybridization on the reduction of emission.

"*The emission reduction mainly depends on the amount of the hydrogen and the onshore electricity consumed for the propulsion. This agrees with our expectations but be proved by the optimized results presented in this paper"* (Wang et al. 2021, p. 72599).

Hydrogen storage onboard as another alternative for zero CO2 emission is sustainable. The hydrogen preferentially to be stored in the form of a liquid phase or compressed as another alternative (Wang et al. 2021).

4.1.9 Analysis of the use of electric and hybrid drives on swath ships

The objective is to compare diesel electric system configuration on swath vessels. The comparison is of the total emission when applying hydrogenous fuel to different fuel cell configurations.

"Energy Storage System, which are a combination of systems consisting of batteries, hydrogen fuel cells and diesel generators for the presented configurations of propulsion systems is most sustainable" (Łebkowski and Koznowski 2020, p. 1).

The utilization of hybrid solutions and propulsion systems is attractive, despite explosion and additional protection systems, simultaneously and positively enabling beneficial adaptation to increasingly stringent environmental goals and meeting environmental protection regulation of those vessels for ship owners. The usage of hybrid drives in combination allow for an optimal placement of the elements required onboard (Łebkowski and Koznowski 2020).

4.1.10 Generation of H_2 on Board LNG Vessels for Consumption in the Propulsion System

The objective is to find the optimal mixture of hydrogen into LNG vessel DFE, utilising the Boil of Gas (BOG) as feed to an onboard hydrogen produced from steam reforming plant, this will reduce the overall emission from transportation of LNG.

"The availability of H2 on board thus leads to a need to store it on board, so that it can be subsequently consumed during navigation, thereby reducing CO2 and SOX emissions" (Fernández et al. 2020a, p. 93)".

A mixture of 70% LNG and 30% H_2 requires no modifications to the fuel injection system on engines, each day of operation of the hydrogen reforming plant can generate enough H_2 for an autonomy of almost 3 days, and engine consumption decreases by 11.38%. Hydrogen tanks have been the most utilised method of storage, it can be done at low or high pressure dependable of need and amount to be stored. Low pressure storage is normally used in system that requires a high H_2 flow, in this phase the hydrogen has a relatively high energy density, where also production and consumption are carried out at the same state, this is the preferred solution onboard LNG vessel consuming reformed hydrogen (Fernández et al. 2020a).

4.1.11 A preliminary study on an alternative ship propulsion system fueled by ammonia: Environmental and economic assessments

The objective of this study is to find sustainable power propulsion concept utilizing ammonia as fuel, in combinative configuration with battery, fuel cells and diesel engines.

"The results show that the ammonia-based ship would require more volume (1.6–2.3 times) and weight (1.4–1.6 times) than the conventional HFO-based ship, and it costs 3.5–5.2 times from the total lifecycle perspective." (Kim et al. 2020b, p. 17).

Mixes and dilution of an ammonia -hydrogen composition can be directly combusted in a direct compression ignition (CI) or a spark ignition (SI) of an internal combustion engine. The direct compression and self-ignition are bound to certain controlled mixtures and their corresponding ignition timings based on the principle of design. In CI engine configuration, it is a trade-off between compression ratio to promote complete ammonia combustion and the limited compression ratio required to prevent hydrogen from ringing (Kim et al. 2020b).

4.1.12 Fuel consumption and CO_2 emission reductions of ships powered by a fuel-cell-based hybrid power source

The objective of this article is to find derivation and power demand during different operating modes of different ship types and conclude which type of fuel cell is the preferred one for the different operations and ships.

"In order to apply the hybrid system to ships, it is possible to maximize the CO_2 *emission reduction effect by setting the capacity of the fuel cell + battery to be able to take charge of the base load"* (Roh et al. 2019, p. 21).

Hydrogen powered fuel cells are eco-friendly, high-efficiency power sources that may be a direct alternative to any combustion engine at a certain segment of the shipping industry, and in all cases as a shave or carrying capacity for hybrid battery packages onboard in combinations. There are normally no emissions (for example, NOx, SOx, CO2, or PM); the fuel cells would produce no noise or vibration compared to a diesel engine configuration and would have good power generation efficiency (Roh et al. 2019).

4.1.13 Benzyltoluene/dibenzyltoluene-based mixtures as suitable liquid organic hydrogen carrier systems for low temperature applications

The objective is to compare the different compositions of liquefied organic hydrogen carriers as a marine fuel and energy carrier, to find and map pros and cons.

"Temperatures below ambient may cause application challenges in colder regions. Therefore, we have presented in this paper an approach to design lower viscous" (Jorschick et al. 2020, p. 14904).

LOHC is a very potent alternative as a hydrogenous carrier for the shipping industry, with a low risk and high capabilities and with existing infrastructure. Depending on the configuration, some forms of LOHC may be problematic to utilize with low ambient temperature. However, the product is a promising alternative moving the industry toward a carbon neutral energy economy (Jorschick et al. 2020).

The table 5 below, reviews discovered advantages and disadvantages from the extraction of material from the final SLR. The content is captured and processed from the mentioned 13 articles. The material is not withdrawn consequently from only the abstraction or conclusion chapter of the article. The context also includes material from the paper document itself, after the bibliographical screening and reading. The tables contain extracted content to build knowledge of the three hydrogenous solutions selected for this study, as marine fuels and energy carriers onboard.

Table 4: SLR final view of Advantages and Disadvantages in relation to the different hydrogenous solutions

<table>
<tr><td colspan="2">L-H2 (liquefied hydrogen storage into cryogenic tanks).</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>- The preferred C-tank configuration for storage is known, and insolation technologies established.
- Thermodynamically predictable and the most abundant chemical substance
- The simplest hydrogenous solutions.
- High energy density when production and consumption are carried out at the same state onboard.
- The energy leak can be used to liquefying LNG on carrier whereas mixed fuel is utilized</td><td>- Storage of hydrogen between -260°C and -240 °C, requires a significant amount of energy to maintain,
- The lignified hydrogen may increase energy demand up to 30 %.
- The storage capacity and autonomy are limited
- Need predictable load factor, need complex power management system regulation.
- Needs to take bunker in small and frequent loads to be sustainable
- Hydrogen is explosive with a high flammability range</td></tr>
<tr><td colspan="2">NH3 (Ammonia state in ambient condition).</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>- Ammonia is a relatively easy product to handle, it can be stored at ambient temperature by applying 10 bar or at 1 atm and -34 °C
- Low overall operational and system failure rate.
- Appliable to FC an ICE configuration
- Ammonia fuelled ship could reduce GHG emissions by approximately 83.7–92.1%</td><td>- Toxicity and material corrosion risk.
- Panic spreading in low concentration, needs additional safety precautions.
- Ammonia costs is 3.5–5.2 times from the total lifecycle perspective, compared to HFO based ships
- Need exhaust SCR treatment in ICE</td></tr>
<tr><td colspan="2">LOHC (liquefied organic hydrogen carrier).</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>- Nontoxic and easy handling compared to other hydrogenous solutions
- The hydrogen lean LOHC is industrially used since the 1960
- Energy carrying transfer oil for LOHC product is available in technical quantities at relatively low cost in form of an isomeric mixture</td><td>- Complex and demanding hydrogen release from organic carrier
- Temperature of at least 250°C is necessary to enable for thermodynamic energy release of LOHC-bound hydrogen
- Significantly decrease of viscosity at temperatures below 20°C
- Infrastructure challenges and thermal return system challenges</td></tr>
</table>

4.2 Final comparison between academic SLR approach and pre-study work

Final informative technical extraction for comparison of the remaining 13 academic articles and the non-academic performed pre-study is visualised below. Common features from those study methods when comparing the three chosen hydrogenous options in this study are shown below in table 6,7 and 8. The later tables give a prime overview and comparison picture of the differences and common findings between the pre-study and the academic SLR study techniques. The extracted search results of advantages and disadvantages of the selected three hydrogenous products when comparison was evoked and clarified. The pre-study was done by reading sources of general information in addition to technical and non-academic databases. Gathered and retrieved papers and know-how was added, extracted from engine makers, councils and societies who all are working on the concept for introducing hydrogenous solutions into their portfolios. The academic SLR methods' last phase and findings are in technical matters narrowed and indeed specific. The tables below give a view of final advantages and disadvantages while combining study methods.

Table 5: Advantages and disadvantages of LH2 (liquefied hydrogen) onboard

LH2 (liquefied hydrogen storage into cryogenic tanks).					
Advantages	Pre-study	SLR	Disadvantages	Pre-study	SLR
Low volume and high energy density when captured in tanks onboard.	X	X	Complex tank structure and demanding construction procedures.	X	
Clean and relatively easy to consume both in FC and ICE configurations onboard.	X		Limited operational experience available, complex bunker, handling, inerting, and gas freeing system.	X	
The cold energy is used as liquefier for boil off gas on LNG carrier, to improve energy efficiency of the system.		X	Complex and demanding preheating, boil off and separation system.	X	X
Available operational experiences gather to some extent from existing fleet	X		Explosive and flammable. Need addition and complex safety precautions.	X	X
No chemical treatment of the product onboard before consumption	X		Limited tank size of maximum 1000m^{3,} as maintaining the vacuum isolation may become impossible.		X
The product is chemically neutral and noncorrosive	X	X	Additional regulations and rules need to be established in addition to existing IGF code.	X	
The product will fast evaporate if a leak occurs, and the gas will arise	X		Limited infrastructure and great energy loss during handling and transportation.	X	X

Table 6: Advantages and disadvantages of NH3 (Ammonia) onboard

NH$_3$ (Ammonia liquified state in ambient condition).					
Advantages	Pre-study	SLR	Disadvantages	Pre-study	SLR
Existing logistic and bunker facilities in the already existing gas terminal configurations.	X	X	Poison and explosive, relatively complex safety measures.	X	X
Relatively high energy density, compare to other energy carriers	X	X	Limited operational experiences in ICE and FC utilisation onboard.	X	
Ammonia reduces storage cost significantly compared to liquefied hydrogen.		X	Aggressive behaviour, and consistency when in contact with water or any steel alloyed material.	X	X
Acceptable tank and system configuration and facilities	X		Complex engine safety, control, and operational systems onboard.	X	
Feed for SCR to neutralise NOx production formed in the ICE combustion.	X		Modern ICE fueled with NH$_3$ require SCR system or /and fuel additive to decompose and mitigate NOX emission.		X
Included and implemented into existing rules and regulation IMO gas appendix and IGF code.	X		Tanks need to be gas freed with clean and moisture free inert gas, before atmospheric ventilation can be done.	X	

Table 7: Advantages and disadvantages of LOHC (liquefied organic hydrogen carrier) onboard

LOHC (liquefied organic hydrogen carrier).					
Advantages	Pre-study	SLR	Disadvantages	Pre-study	SLR
Beneficial tank construction bunker and transfer system.	X	X	Energy for hydrogenation onboard is excessive if waste heat is unavailable.		X
Volumetric space is beneficial.	X		Unstable at low ambient temperature.	X	X
The LOHC based propulsion systems are very promising and show a low failure rate.		X	Need special separation and handling equipment and units ashore, excessive logistic return system ashore.	X	
Use of existing fuel tank and transfer system to extend.	X		No deep-sea experience in operation.	X	X
No harmful or poisoning effect on crew or facilities.	X	X	Low energy density compared to other hydrogen alternatives.	X	
No direct safety issues onboard in respect to explosion, fire, poison, pressure, or temperatures.	X	X	Complex tank and transfer configuration, due to return of organic component and separation system onboard.	X	

Advantages and disadvantages in the above tables are withdrawn from the pre-study documents and articles found in section 7.2, and the SLR academic study documents, and articles found in section 7.3. Those retained indicators will be parts of the results and conclusions of this work to answer the thesis' second objective:

Compare advantages and disadvantages of the three selected hydrogenous solutions, from the comparison and findings after pre-study and SLR study.

The comparison gives indication that the early observations in the pre-study are in line with the findings during the SLR. Academic papers tend to have less practical approach content and informative pros and cons in respect to operational handling and challenges from a practical point of view, when elaborating the hydrogenous products. Meanwhile the opposite appears to be true in the makers and stakeholders' organisations, councils, societies, and contributor's informative documents such as white papers. Furter visualisation is done in table 6,7 and 8 focusing on advantages and disadvantages of the three selected hydrogenous solutions. Which of the elaborated hydrogenous forms and consistency in this study is the most promising fuel carrier for internal combustion engines (ICE) and fuel cell (FC) for marine applications onboard, will be answering the second research question of this thesis:

What are the differences discovered between the applied study approaches of the pre-study and the SLR study?

The extracted information that will be drawn into the discussion and conclusion.

4.3 Bibliographic results and trend analysis of the thesis documents

After selection and screening of the106 nominated articles, the information retrieved indicates at first some notable trends that support statements gathered from the experts in respect to the early evolution phase proclaimed. The concept of hydrogenous solutions as an energy carrier and fuel for the shipping industry, onboard vessels is new and still considered as in the early stages of its evolution. The publication trend, both the article production and the amount of situation, proves that the technology still is in a very early exploration phase.

The topic and technology interest are escalated as new possibilities are reviewed and research work is produced. The highest number of published articles within the selected field and keywords is found in 2021 with 47 pieces out of the 106 nominated, and the number of this year indicate a raise, however no notable research activity is found before 2014 on this subject. Most of the work is conducted between 2014 and present day. There has been a significant increase in research work and number of publications and the trend appears to continue. This shall be considered as a positive and required trend for implementation and utilisation into the future. It has not discovered any declining activities in the field of research about hydrogen solutions.

Graphic curve figure 16, illustration distribution and annual production of the 106 academic articles.

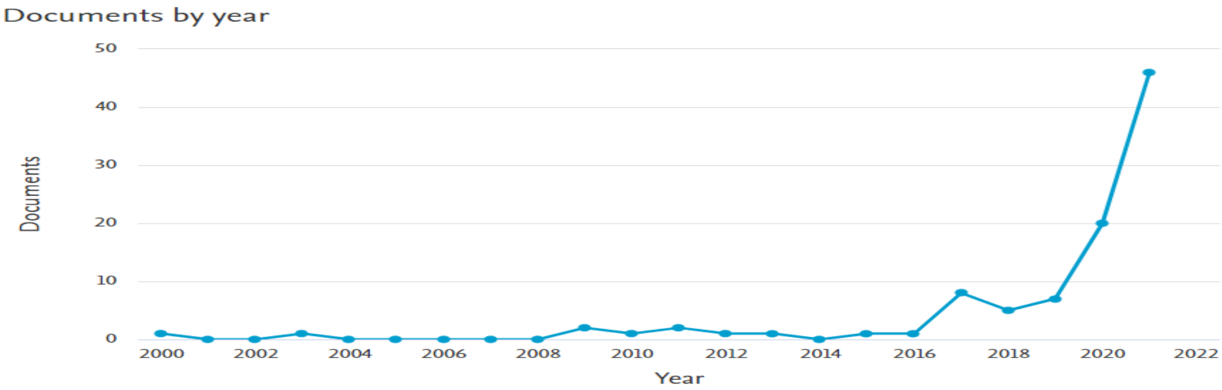


Figure 16: Number of articles published retrieved from Scopus database

Graphic curve below figure 17, illustration of the amount of citation each year of the 106 academic articles between 2014-2022.

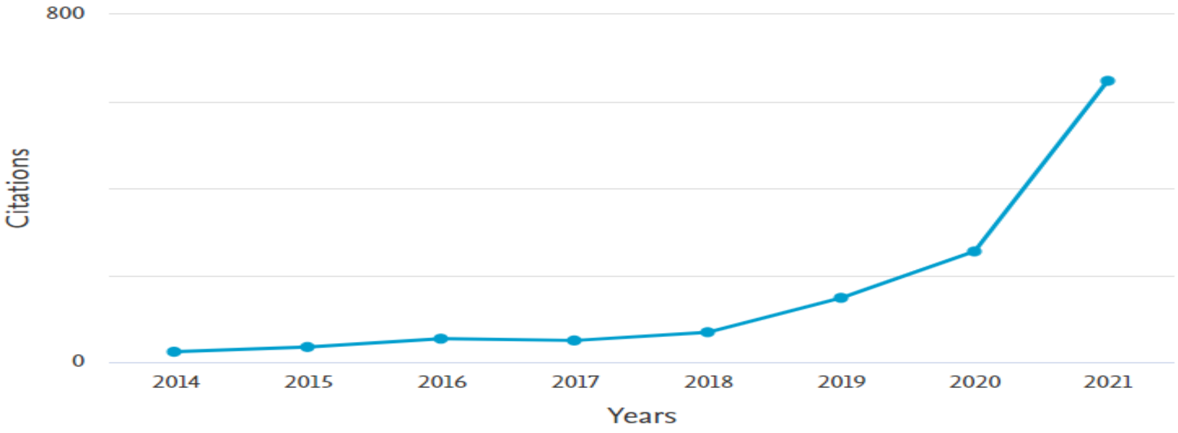


Figure 17: Number of citations from Scopus overview

The graphs and illustrations are retrieved from the software tools that give us a unique insight into the context and research activities within the fields. This, together with data extraction from Scopus, give solid documentation and discovery possibilities. The 106 nominated publications were situated 1704 times. The year of 2021 was a total of 648 citations performed, 38 % of the selected articles were also produced this year.

The total number of publications in relation to the keywords does correlate with the number of citations revealed. As a readable and visual fact, when the number of publications increases, so does the number of citations. There is a significant increase in the number of publications and citations within this field over the last 2-3 years. The above figure 16 And figure 17 visualise the real correlation between the publications and citations. This supports the earlier discovered early age of the thematic.

4.4 Publisher sources and dispersion

During the pre-study, and study prior to the SLR, the sources of general information have been in addition to the academic searched databases gathered, not limited but also retrieved from engine makers from engine makers, councils and societies who all are working on the concept for introducing hydrogenous solutions into their portfolios. Those sources have been used to build a solid general understanding and know-how of the different present and further concepts. During this process, a downscaling of sources for elaboration and research has been performed and piled down by elimination, in the final phase only Scopus as the academic database for deeper collaboration and selection of final journals for the final research was finally nominated. Hence journals and published documents for the final work are distributed and contributed as below figure 18, illustration indicates:

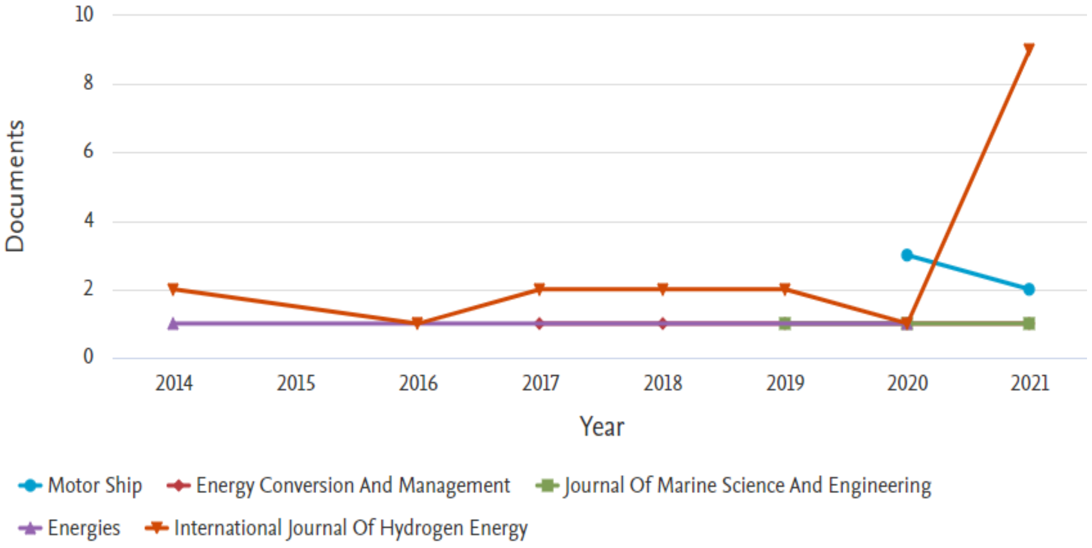


Figure 18: The 5 top publishers of documents over the last years, from Scopus

As indicated a great part of the published documents have only published one or two articles within the field of the selected keywords. The leading journal and top contributors have published 19 documents in total between the years 2014-2022. The leading articles are found by the International Journal of Hydrogen Energy who has a production of 10 documents in 2021. Out of the total, 51% of the article's subject area was related to energy, with pure and clear focus on hydrogenous solution and analyses of the product implementation. It is important to realise that the terms used during this search are directly related to the context and area of the search, i.e. several parameters such as temperature, pressures, gas, and liquid that commonly describe state and situation of the hydrogenous states in different contexts, from gas, liquid and as in a cryogenic form or as a synthetic carrier.

It is also discovered that the origin of the articles is distributed throughout the same country as by the one in the forefront of the evolution, the founding sponsors are also benchmarked and found to be distributed as below figure 19, overview shows.

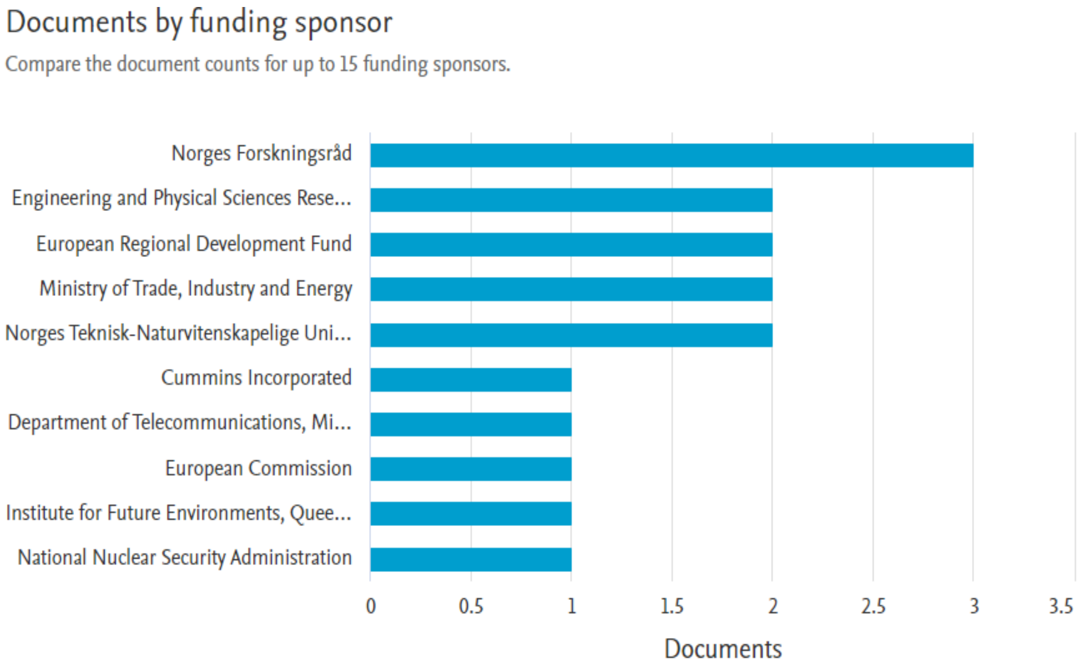


Figure 19: Document by founding sponsors retrieved from Scopus

The bibliographic systematisation and benchmarking form selective reading has been done to understand the mechanisms and finding formed during work.

The retracted parameters from the defined keywords, and title of the 106 articles give the below figure 20, thematically an evolutionary view and an informative understanding of the context withdrawal from the document.

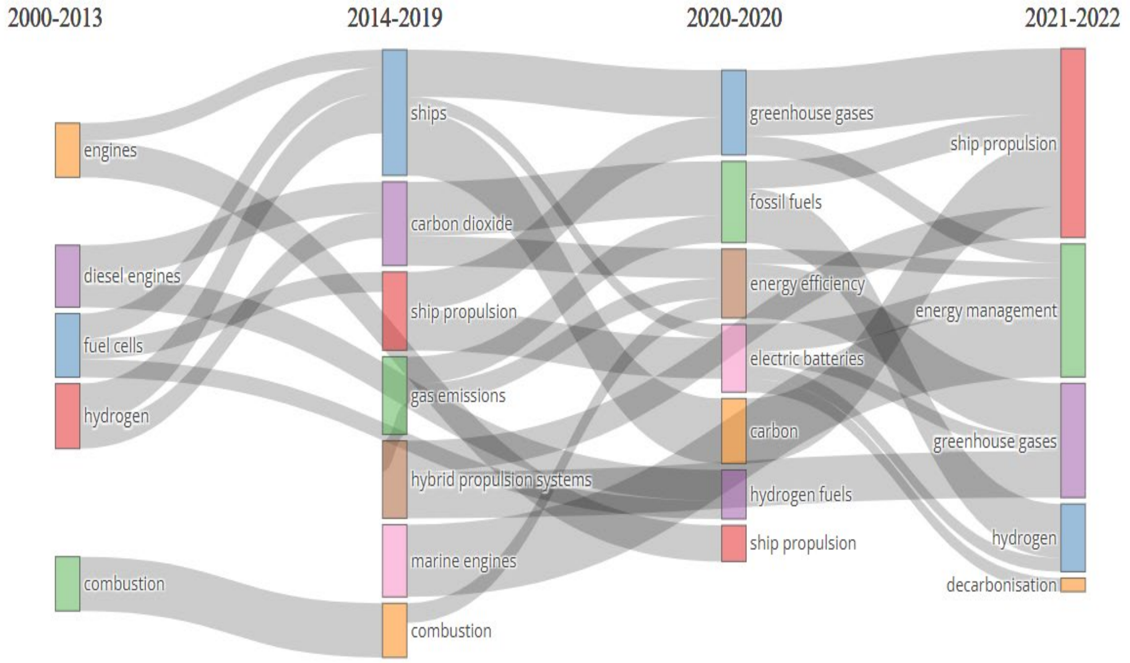


Figure 20: Evolutionary view of the context, keyword, and title used during analyzes of findings retrieved from Scopus

Adapting hydrogenous solutions on a large scale will make it possible to meet the energy demands of the maritime industry and to adapt to the new regulation imposed to the industry over the last year, as well as to make the total paradigm shift a reality. Finding indicates prime and clear synergies, tied-up to the transferable technology and cooperation between industrial countries. There are documented traces of transferable technologies and motivation exchanges of scale. The evolution and urge for hydrogen transition and utilisation is more significant due to these facts, than the other individual factors found. This revived discovery that synergies help to understand why some countries have been significant contributors into this research field, and why other countries have not yet been engaged or participated. It is without discussion noted a lack from less industrialised countries. This may be a negative boundary for adapting those new promising hydrogen technologies into the shipping business. The number of research countries where hydrogenous solutions for shipping are investigated can be vital for further evolution. It will globally be a significant weakness for the implementation and will create delays in reduction of the ongoing participation of the shipping industry to climate changes.

The above findings of trends, Publisher sources and dispersion is used to visualise the thesis’ third objective:

Explore research trends, sources, and dispersion of academic publications for hydrogenous solution for the maritime domain

And to answer the third research question:

Which factors affect and contribute to research and publications of articles for hydrogenous solutions to the maritime domain?

The result of the bibliographic work done on the selected articles, will also be brought into the thesis discussion and conclusion review in chapter five and six.

Chapter 5. Discussion

5.1 Discussion introduction and overview

The discussion will include a review of results and findings discovered during this work. The intention is to provide further insight for the readers and to link the thesis objectives and research questions to the findings. In this chapter a presentation and discussion of the observations and findings accumulated throughout the study will be revealed and presented before the conclusion is explained in chapter 6. Mapping the advantages and disadvantages of the operational and practical approach linked to the three chosen hydrogenous options and technologies was done throughout the pre-study phase, including collecting expert opinions. Later, a systematic review was used, thereafter a bibliographic systematisation to form solid insight into the study objectives and research questions. All lead to general informative and know-how, covering and explaining the title of the thesis “Hydrogen as marine fuel source and energy carrier for ships power production and propulsion.

5.2 Study methods comparisons and validity

During the first phase of the study, it was required to elaborate in a very broad context to achieve the latest knowledge available, building a technical know-how fundamental to understand the different contexts and possibilities hydrogenous solutions represent. The information gathered during this phase of the study was somehow more practical, operational, and specialised. It was acquired in a more informative manner than the later SLR method. When decision makers and ship operators of the present want to search for information in respect to the ongoing paradigm shift and elaborate on further options for their fleet of vessels, typically an informational and understandable character of information is appreciated. To meet and understand the complexity of switching from fossil fuels to any carbone free alternatives, as in this case with hydrogenous solution, it may be recommended to approach and seek know- how directly from the stakeholders of the industry itself, instead of searching and striving to build own insight and knowledge through academic searching tool and databases. The later academical approach is often narrowed and less informative, and therefore seldom gives a total and overall informative practical picture to the nominated questions. However, often the reliability and validity of academic articles are superior compared to the information contributed by fabricators and other stakeholders.

5.3 Elaboration of results and achieved objectives

Elaboration written in the later phase and in the discussion part of the thesis, intends to give a narrowed review and digestible insight of the results and findings discovered during this study. The intention is also to provide further insight and linking the objectives and research questions into findings visualised and discussed below.

There were numerous themes that fell outside of the thesis objects that were excluded, and this may affect opinions and contribute to alter choices. This might influence the selection of preferred hydrogenous solution. Among excluded themes worth mentioning, this study has barely taken the economical aspect into consideration. It has been focused on the feasibility of the operations needed to adapt to hydrogenous solutions onboard. It considered only the pros and cons in relation to the three selected hydrogenous forms adapted and elaborated for use onboard oceangoing vessels.

5.4 Hydrogen production and availability as an energy carrier

When the shipping industry first started the journey of reducing its environmental footprint, it focused largely on its emissions to the air. It had no intention of total decarbonization. However, the industry was later imposed ambitious regulations, and is now therefore urged to choose a sustainable alternative to fossil fuel products. Hydrogenous solutions were selected as one of the preferred energy carrier products. To find a sustainable circular pathway for any of the hydrogenous alternatives, we need to understand that the hydrogen product itself needs to be produced and loaded in a sustainable and environmentally friendly manner. There is a risk that today’s available green or blue energy sources such as hydropower, solar or wind, fail to meet the demands of a large-scale production of hydrogenous products. To remain sustainable, the energy would then need to be sourced from, for example, nuclear energy, to prevail as a sustainable solution.

The different pros and cons of the hydrogenous products have been considered in this thesis context only in relation to objectives and generated research questions for this thesis, all of which were of an informative and operational oriented matter. For example, consideration was given to installations and tanks in conjunction with storage and handling onboard, as well as void spaces and required blueprints for auxiliaries all to reflect on the risk of liquified hydrogen that typically needs to be stored on deck, required to reduce risks, and meet regulations.

Items that were typically not considered were for example onboard equipment investment and costs for technical components. These have been excluded as prices are very fluctuating, and in this phase of the transition impossible to acquire. Different ships designs may also have considerable price impact when installing hydrogenous retrofit solutions. Simulations of price for new-built ships are also unpredictable.

5.5 The hydrogenous alternatives, factors considered

Sustainability has among other an ethical and psychosocial dimension, which the shipping industry must comply with. This work also took into consideration some safety aspects of using hydrogenous solutions. Minimising risk of harm for crew, operators, and engineers onboard are crucial and were not neglected. Energy efficiency has also been studied to an extent.

However, a general review of the first objective:

Identify advantages and disadvantages of the three selected hydrogenous solutions, as alternative marine fuel.

and answer to the first research question:

Which of the different hydrogenous solutions and consistency is the most sustainable fuel source and energy carrier for marine applications?

has been a paramount goal. Mapping and evaluating advantages, disadvantages, pros, and cons of the three different hydrogenous solutions discovered in the two different study approaches are discussed and visualised as an answer to the first research question and objective.

5.5.1 LH2, liquefied hydrogen in a cryogenic state

This elaborated alternative holding pure hydrogen at a very low liquefied temperature is defined as LH_2. The product captured in this form turns into gas at a very low temperature before utilisation. It needs a preheating treatment before it is fed into the consumer, and in this phase, it is extremely volatile. The product ignites very easily and requires very little ignition energy. It will burn and transit in a very wide range of air dilutions and mixtures. Furthermore, the gas is colourless and odourless meaning that excessive countermeasures are required onboard to control and manage the product, typically hydrogen detectors and extensive ventilation systems. Any leak of LH_2 will not immediately evaporate but cooling down surroundings and stay at the lowest ground like a dense gas and freezing down super construction. If by accident this is ignited during a collision or a fire onboard, the condensed oxygen mixed with hydrogen may result in a very potent explosion. This form of hydrogen presents immense operational challenges and risk, has high energy losses during transportation and handling, and the global infrastructure is not ready for these extremely demanding precisions.

Conclusion: this form of hydrogen shall presently only be considered as an alternative for a very limited part of the total fleet of vessels, and therefore not found as the preferred one in this study.

5.5.2 NH_3, ammonia in a liquid state

Ammonia (NH_3) also has notable negative issues when considering utilisation onboard in confined spaces such as engine rooms. The product is toxic and carries an odour that will create panic and is deadly poison at a relatively low concentration. The product requires excessive handling and operational consideration such as, tank inerting, ventilation, monitoring, and extensive safety systems. Ammonia is a chemically aggressive regent, and it will cause corrosion and chemically negative reactions to any material alloys except pure carbon steel.

Despite the above disadvantages, the product is already well adapted into the existing shipping industry and has already well-established product experiences in operation, and handling procedures are in place, as the product is widely distributed globally for other uses such as fertiliser reagent and cooling medium for the refrigeration industry. The ammonia has a very potent energy density, and it is considered as a superb energy carrier for hydrogen, the product does not need any special pre-treatment before use. Rather, it can be injected or added relatively easily into both FC and ICE configuration onboard. When the product is applied into an ICE combustion engine, the formation of NOx is abundant, and a small part of the feed needs to be consumed as a catalytic feed for after treatment in SCR as required. The product's strongest pros are found in the fact that a global product distribution and logistics is already established and in place as well as established safety protocols and regulations. The product also has superb energy density and thermodynamic characteristics. The shipping industry has already gained product knowledge, and application flexibility is counted as a crucial factor for large-scale implementation.

Conclusion: Ammonia in ambient condition is found to be the preferred and most sustainable, promising, and feasible hydrogenous solution presently evoked for the global deep sea shipping industry.

5.5.3 LOHC, liquefied organic hydrogen carrier

The product is found to be a potent energy carrier for hydrogen, where the hydrogen molecules are adapted into a thermal synthetic energy carrier. LOHC is a generalised but exists in a variety of different composites available in the market, hence only the product as a general alternative is considered. The available composites all have almost the same characteristics, which make them suitable onboard vessels. Those products are barely flammable, they are non-explosion or represent no extensive fire risks. The product behaves like light fuel or diesel, and is an aromatic compound, giving an easily detectable characteristic odour when leak or spill occurs. Those benzene-based components are carcinogens, and precautions and normal protection gear should be worn. The simplest form of LOHC has a smaller molecule structure which should be considered when in contact with these products.

LOHC sensitivity to low ambient temperature may be challenging in cold climate areas. Nonexclusive research on this theme was discovered during the literature study, and only vaguely mentioned in the SLR selected research papers and webinar contributed. When hydrogen is adapted into the synthetic carrier, it is a demanding and high energy consuming chemical process. The product contains less energy density than the other two hydrogenous alternatives elaborated in this work. Another downside of the product is found in the rather demanding separation and release of hydrogen onboard, and the fact that the thermal carrier after hydrogen disposal onboard, needs to be returned and perform a re-trading for us and return to refineries and chemical plants.

However, the LOHC appears to be very adaptable and has the potential to be a large-scale solution for the future. It is the easiest and safest alternative in the existing transport chain and industry logistics. It is today not a worldwide solution, as challenges in how transport and cost in relation to these mentioned issues need to be solved.

Conclusion: Despite this, for the present, LOHC is in a phase where it is expanding, and appears to be for now the most promising hydrogenous solution for short sea and local trade, therefore not found as the preferred one in this study.

5.6 Comparison of the different study approaches

To find solid and concrete answers to all aspects related to the three selected hydrogenous solutions, a wider approach than a general pre-study and systematic literature study with a bibliographic review of selected publications is necessary. A systematic literature review through academic publications and articles is the preferred method to start with and may also be recommended for further work (Frankfort-Nachmias et al., 2015). However, the applied research method did not exclude objective approach, or any other part of the mixed methods, where the qualitative and quantitative way of evincing answers gave results for the second objective:

Compare advantages and disadvantages of the three selected hydrogenous solutions, from the comparison and findings after pre-study and SLR study.

And give answer to the second research question:

What are the differences discovered between the applied study approaches, of the pre-study and the SLR study?

The comparison between the applied study method approaches gives indication of results in line with earlier observation. Academic papers tend to produce less practical on hand usable and informative pros and cons in respect to handling and operational challenges of the three selected hydrogenous products. The opposite is discovered in the makers and stakeholders. This is a source of more informative oriented documents, such as brochures and white papers. These were considered and elaborated during the pre-study phase.

This methodology is considered a sufficient and well-established academic method when the purpose is to build reliable answers and solid assumptions to the defined research questions and objectives. However, this work and comparison did not reveal any contradiction nor notable deviation, only a thorough documented comparison between the three chosen hydrogenous solutions that was not systematically done before. Hence it will give readers of this thesis recommendation, knowledge and information when considering hydrogenous solutions and alternatives among the three selected and elaborated alternatives.

5.7 Research review limitation, study level and further recommendations

This study holds limitations as only three different alternatives of hydrogenous solution were deployed for deeper elaboration in this study work. There are several other hydrogenous configurations and concepts that may be of interest and relevant for further study. Clear answers are very demanding in this early phase of the energy transition. A broad part of the know-how gathered shall be considered as testing and have only premature industry standards. Lack of operational experience on several of the concepts elaborated during this research work and study is a fact and should not be neglected. The thesis also has limitations due to database limitation in the later phase. The only literature selected was what was found with the selected keywords from the Scopus database.

During the later phase of this thesis, while doing the systematic review work, it is discovered that there is a clear publication bias that affects available academic articles. The assortment is composed of mostly articles from peer -reviewed journals. This automatically gives limitations when other material such as conference papers or industrial white papers which discuss challenges and possibilities are not included in the latest findings. Those sources have been adapted into this work at an earlier stage for informative and explanatory purposes. Therefore, the remaining articles may be of lesser quality when considering the practical point of view. However due to the innovative nature and exploratory nature of this thesis, those limitations are deemed to be of insignificant nature considering the total outcome and information given in this work. Hence a systematic literature review will be affected in addition by the work itself, carried out during the evolution of the thesis, and by limitations inherent in the keyword selection to cover the research questions formed as foundation for the work.

Hydrogen has the potential of being the preferred fuel and energy carrier to cover the energy demands of the shipping business in the future. It also presents as possibly the most sustainable solution for the entire shipping industry. It is today feasible and proven to be an industrially preferred contributor to meet the upcoming emission and pollution reduction goals laid down by IMO, among others.

The later bibliographical part of this study revealed in chapter four gives an insight and analyses of the article’s trend, dispersion, source, and nature. This giving an insight into the thesis third objective:

Explore research trends, sources, and dispersion of academic publications for hydrogenous solutions for the maritime domain.

And answers the third research question:

Which factors affect and contribute to research and publications of articles for hydrogenous solutions to the maritime domain?

It is further recommended to engage a larger scale of the non-industrialized countries’ participation into the fossil fuel elimination and decarbonization process. Both on the implementation and evolution side of the technology, as-well as on the development and research activities. It is a fact that a large part of the world's tonnage and fleet is engaged and registered in those less industrialised countries. The bibliographical part of this study also uncovered a situation where few large established academic contributors dominate a broad part of the publications relevant for this research field of interest. To achieve a positive and increased focus, it should be a priority to articulate the need for more research in an eloquent way to motivate several different actors to take part. This will in the most fortunate way hurry along new successful achievement and sustainable implementation of this new technology. It will be important to establish an even higher research activity rate to meet and succeed with the ambitious goals for decarbonization. Hydrogenous solutions have the potential to replace fossil fuels for the entire global fleet.

Chapter 6. Conclusion

The shipping industry needs to drastically reduce its CO_2 emission footprint and air pollution. IMO is imposing demanding rules and regulations. A technological paradigm shift of which we are at the beginning is needed to implement and achieve this energy transition. This thesis elaborates on three selected hydrogenous solutions, and which is the most sustainable energy carrier and fuel for ships. The three research questions developed, are answered throughout this study.

RQ1: Which of the different hydrogenous solutions and consistency is the most sustainable fuel source and energy carrier for marine applications?

Ammonia (NH_3) in ambient condition is found to be the most sustainable, promising, and feasible hydrogenous solution presently evoked for marine applications onboard the shipping industry's global fleet of ships. It is therefore chosen as the answer to the first research question.

However, it is of note that for short sea and geographically selected local trades, liquefied organic hydrogen carriers (LOHC) is in a phase where it is expanding, and might become the most promising hydrogenous solution for those segments.

The liquified hydrogenous solution in sub-cooled condition as LH_2, was found presently to not be a sustainable alternative for any segment of the shipping industry.

RQ2: What are the differences discovered between the applied study approaches, of the pre-study and the SLR study?

This work did not reveal any contradiction nor notable deviation between the pre-study and the SLR. The two forms of research were complementary. The pre-study was a source for more practice-oriented documents, such as brochures and white papers, while the SLR produced academic articles, which were less practically oriented. The two research methods allowed for a thorough documented comparison between the three chosen hydrogenous solutions giving valuable answers into this study.

RQ3: Which factors affect and contribute to research and publications of articles for hydrogenous solutions to the maritime domain?

Two factors of note affect the publications in this research field. For one, it was discovered that few large established academic contributors dominate a broad part of the publications relevant for this field of interest. On the other hand, there is yet little involvement from non-industrialized countries in the research field on hydrogenous solutions. In both cases, it is deemed crucial for the evolution of this technological field, that there would be larger global interest and involvement in the future.

This thesis presents an overview, a review, and a comparison of three hydrogenous solutions as potential fuel for the shipping industry. It included novel practical information and focused on presenting the results in an accessible manner for pragmatic decisions about which direction to focus further research on hydrogen as a fuel alternative.

Numerous different hydrogenous configurations, including in combination with other fuels, were excluded for this thesis. It can be expected that new, unheard of hydrogenous compositions see the light of day in the future. All of these would be an interesting subject for further research.

Producing and loading hydrogen-based energy carriers as fuel for the shipping industry risks requiring more energy than green and blue energy sources presently can give. This may put back and recess the potential of hydrogen fuel as a sustainable option for the shipping industry. To help hydrogenous solutions achieve the shipping industry's goal of reducing its CO_2 emission footprint and air pollution impact, there will most likely be a need for the introduction of nuclear energy and power. Those plants would probably be able to supply enough non-carbon-based energy to hydrogen production facilities onshore. Nuclear energy is also possible to apply onboard, in the form of minor nuclear fuel reactors as a fuel source. The further development of nuclear energy would also be an interesting subject for future research.

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