TECHNO-COMMERCIAL ANALYSIS OF HYDROGEN SHIPPING

Abstract

The main objective of the research of this thesis was to establish a techno-commercial analytic framework to determine the cost of green hydrogen for an international supply chain. The scope of the study involves firstly exploring the current available hydrogen shipping carriers and technologies. Next, a multi-criteria decision analysis was done to determine the three most feasible hydrogen carriers for an international supply chain. Lastly, a cost evaluation was done between the three selected hydrogen carriers using a basic case study within Asia-Pacific.

Rong Xuan Vincent Chua

TECHNO-COMMERCIAL ANALYSIS OF HYDROGEN SUPPLY CHAIN IN ASIA

By

Vincent Chua Rong Xuan

Thesis submitted to European International University in
fulfilment of the requirements for the degree of
D.B.A (Sustainability)

August 2022

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Abstract

Studies conducted by the Intergovernmental Panel on Climate Change (IPCC) has determined that human activity has resulted in an unusually fast global warming (IPCC, 2013) and the resulting climate change has had significant impacts on both human and natural systems (IPCC, 2014). To mitigate the rate of climate change, there is a drive to decarbonise the fuel source (CRS, 2020) and one alternative is to go towards a clean fuel source such as a Hydrogen economy (Shell, 2017). The ability for efficient transportation of hydrogen thus become crucial for the viability of the hydrogen value chain.

The main objective of the research of this thesis was to establish a techno-commercial analytic framework to determine the cost of green hydrogen for an international supply chain. The scope of the study involves firstly exploring the current available hydrogen shipping carriers and technologies. Next, a multi-criteria decision analysis was done to determine the three most feasible hydrogen carriers for an international supply chain. Lastly, a cost evaluation was done between the three selected hydrogen carriers using a basic case study within Asia-Pacific.

The outcome of the MCDA shows that existing hydrogen carriers such as compressed and liquefied hydrogen and ammonia does have an edge over the innovative hydrogen carriers due to the maturity in technology. In the case study comparison where the end use is hydrogen, it was shown that for regional transportation of hydrogen, compressed hydrogen will provide a cost competitive case against liquefied hydrogen and ammonia. However, if there is no requirement for reconversion of the hydrogen carrier to pure hydrogen for use, ammonia may be the better option.

Acknowledgements

The completion of this dissertation, amidst this ever-changing pandemic situation around the world, was only made possible with the support of others.

I would also like to thank my colleagues and partners from the maritime industry who have provided valuable inputs and expert advice in the scoping of the methodology and analytical framework.

Lastly, I would like to thank my family for their support while my time off-work has been spent towards the completion of the dissertation.

Vincent Chua Rong Xuan

July, 2022

Nomenclature

AEC	Alkaline Electrolysis Cell
AHP	Analytic Hierarchy Process
CA	Conjoint Analysis
CAPEX	Capital Expenditure
CH_2	Compressed Hydrogen
CH_4	Methane
CO_2	Carbon Dioxide
DBT	Dibenzyltoluene
DME	Dimethylether
EC	European Commission
EU	European Union
GHG	Greenhouse Gases
H_2	Hydrogen
IACS	International Association of Classification Societies
IEA	International Energy Agency
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelised Cost of Electricity
LCOH	Levelised Cost of Hydrogen
LH_2	Liquefied Hydrogen
LPG	Liquefied Petroleum Gas
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
MARPOL	Maritime Pollution
MCDA	Multi-criteria decision analysis
MCH	Methylcyclohexane (Toluene)
MJ/L	Mega-Joules per litre
$NaBH_4$	Sodium Borohydride
NH_3	Ammonia

NM	Nautical Mile
OPEX	Operational Expenditure
PEM	Polymer Electrolyte Membrane
PV	Photovoltaic
SMART	Simple Multi Rating
SOLAS	Safety of Life at Sea
SOFC	Solid Oxide Fuel Cell
TRL	Technology Readiness Level
UNFCC	United Nations Framework Convention on Climate
WT%	Percentage Weight of Hydrogen

List of Figures

Figure 1 - Correlation of GHG concentration and the resultant impacts.....1

Figure 2 - Context of Temperature Overshoot 2

Figure 3 - Comparison of specific energy (energy per mass or gravimetric density) and energy density (energy per volume or volumetric density) for several fuels based on lower heating values.....5

Figure 4 - Hydrogen uses as a universal fuel.....6

Figure 5 - Summary of Main Hydrogen Colours and Paths.....7

Figure 6 – Pictorial Illustration of different Electrolysers. 7

Figure 7 - Different Types of Hydrogen Carrying Vessels (LH2, NH3, CH2).....9

Figure 8 - Schematic Representation of LOHC hydrogenation and dehydrohenation process 13

Figure 9 - Research Methodology.....16

Figure 10 – Stakeholders Representation for Public and Private Partnership.....18

Figure 11 - Illustration of Case Study Shipping Cases 25

Figure 12 - Gravimetric and Volumetric comparisons of Fuels.....27

Figure 13 - Illustration of Standardised Scores of Hydrogen Carriers Based on Criteria 35

Figure 14 - Illustration of Weighted Scores of Hydrogen Carriers Based on Criteria 35

Figure 15 - Hydrogen Carrier Supply Pathway Processes 36

Figure 16 - LCOH of Green Hydrogen Based on Electrolyser CAPEX and LCOE 37

Figure 17 - LCOH of Green Hydrogen Based on Different Priced Renewable Source (Wind and Solar).....38

Figure 18 - Cost for Maritime Transportation of Hydrogen Carriers 40

Figure 19 - Cost Breakdown of Shipped Hydrogen (including Reconversion) 41

Figure 20 - Final LCOH (Low and High) of CH_2, LH_2 and NH_3.....42

Figure 21 - Technological Readiness Level Representation.....iii

Figure 22 - Safety Data Sheet Sample.....iv

Figure 23 - LH2 Safety Data Sheet.....v

Figure 24 - CH2 Safety Data Sheet.....vi

Figure 25 - NH3 Safety Data Sheet.....vii

Figure 26 - NaBH4 Safety Data Sheet.....viii

Figure 27 - LOHC Safety Data Sheet.....ix

Figure 28 – Online Survey Template.....x

Figure 29 – Stakeholder Participation in Online Survey Mechanism xi
Figure 30 – Top Technical Criteria Mentioned for Survey xii
Figure 31 – Top Commercial Criteria Mentioned for Survey xii
Figure 32 – Top Environmental Criteria Mentioned for Survey xiii
Figure 33 – Top Social-Political Criteria Mentioned for Survey xiii
Figure 34 – Weightage Based on Stakeholder Survey xiv

List of Tables

Table 1 - Pressure vessel materials according to their type 10
Table 2 - Assessment Criteria and Sub-criteria 19
Table 3 – Criteria Average weighting 19
Table 4 - Assessment of Gravimetric Density 20
Table 5 - Assessment of Volumetric Density 20
Table 6 - Assessment of Hydrogen Carrier Technology Level 21
Table 7 - Assessment of hydrogen Shipping Vessels 21
Table 8 - Assessments of Conversion/Packing Costs 22
Table 9 - Assessment of Re-Conversion/Un-packing Costs 22
Table 10 - Assessment of Hydrogen Carrier Management Cost 22
Table 11 - Assessment of By-Products and Associated Cost 23
Table 12 - Assessment of Carrier Flammability 23
Table 13 - Assessment of Carrier Toxicity 23
Table 14 - Assessment of Regulations 24
Table 15 - Techno-Commercial Specification of Commonly Used Electrolysers 25
Table 16 - Energy Densities and Scoring of Different Hydrogen Carriers 28
Table 17 - Scoring based on TRL Levels of Hydrogen Technology and Shipping Vessels 29
Table 18 - Scoring of Conversion/Packing Costs 30
Table 19 - Scoring of Re-Conversion/Un-packing Costs 30
Table 20 - Scoring of Storage Management 31
Table 21 - Scoring of By-Products and Associated Costs 32
Table 22 - Scoring of Hydrogen Carrier Based on GHS Rating on Flammability and Toxicity 33
Table 23 - Scoring on Regulations 34
Table 24 - Techno-Commercial Specification of Commonly Used Electrolysers 37
Table 25 - Chemical Equations ii
Table 26 – Respondents Breakdown and Representation xi
Table 27 - Tabulated Criteria Scoring xv
Table 28 - Tabulated Criteria Weightage xv
Table 29 - Tabulated Standardised Criteria Scoring xvi

Table 30 - Tabulated Weighted Criteria Scoring xvi

Table 31 - Tabulated Levelised Cost of Hydrogen (LCOH) xvii

Contents

Abstract III

Acknowledgements IV

Nomenclature V

List of Figures VIII

List of Tables X

1 **Introduction** 1
- 1.1 Problem Background 1
- 1.2 Research Gap 3
- 1.3 Research Questions 3

2 **Literature Review** 5
- 2.1 Background 5
- 2.2 Production of Hydrogen 6
  - 2.2.1 Green Hydrogen 7
- 2.3 Transportation of Hydrogen 8
- 2.4 System Description – Hydrogen Storage and Transportation 9
  - 2.4.1 Compressed Hydrogen 10
  - 2.4.2 Liquefied Hydrogen 10
  - 2.4.3 Chemical Hydrogen 11
  - 2.4.4 Metal Hydrides 12
  - 2.4.5 LOHC 13

3 **Methodology** 15
- 3.1 Multi-Criteria Decision Analysis for Selection of Hydrogen Medium 16
  - 3.1.1 Selection of Criteria 17
  - 3.1.2 Selected Criteria and Weighting 19
  - 3.1.3 Technical Criteria Evaluation 20
  - 3.1.4 Economic Criteria Evaluation 21
  - 3.1.5 Social and Environmental Criteria Evaluation 22
  - 3.1.6 Political and Regulatory Criteria 23
- 3.2 Case Study 24
  - 3.2.1 Selection of Green Hydrogen Production Path 25
  - 3.2.2 Comparison of Levelised Cost of Hydrogen 25

4 **Results** 27
- 4.1 Selection of Hydrogen Carriers 27
  - 4.1.1 Criteria Scoring - Energy Density 27
  - 4.1.2 Criteria Scoring – Supporting Infrastructure Maturity 28
  - 4.1.3 Criteria Scoring – Energy Efficiency 29
  - 4.1.4 Criteria Scoring – By-Products 31
  - 4.1.5 Criteria Scoring - Safety 32
  - 4.1.6 Criteria Scoring – Regulatory (Maritime) 33
  - 4.1.7 Final Scoring and Selection 34

4.2 Case Study Comparison 35
4.2.1 Hydrogen Carrier Routes 35
4.2.2 Levelised Cost of Hydrogen 36
5 **Discussion** 43
5.1 Case Selection 43
5.2 Selection Criteria Results 43
5.3 Case Study Results 45
6 **Conclusion and Recommendations** 48
6.1 Conclusion 48
6.2 Recommendations 50
7 **References** 52
8 **Appendices** i
Appendices A – Chemical Processes ii
Appendices B – Technology Readiness Level iii
Appendices C – Safety Data Sheets iv
Appendices D – Survey Results x
Appendices E – Tabulated Results xv

1 Introduction

1.1 Problem Background

Since the 19th century, there has been an increase concentration of key greenhouse gases (GHG) due to human activities (figure 1) with an increasing trend of emission since the 20th century. Given the impact of global warming and thermal expansion as a resultant climate change, this could be irreversible if there are no actions taken to reduce GHG emissions (Solomon et al, 2008).

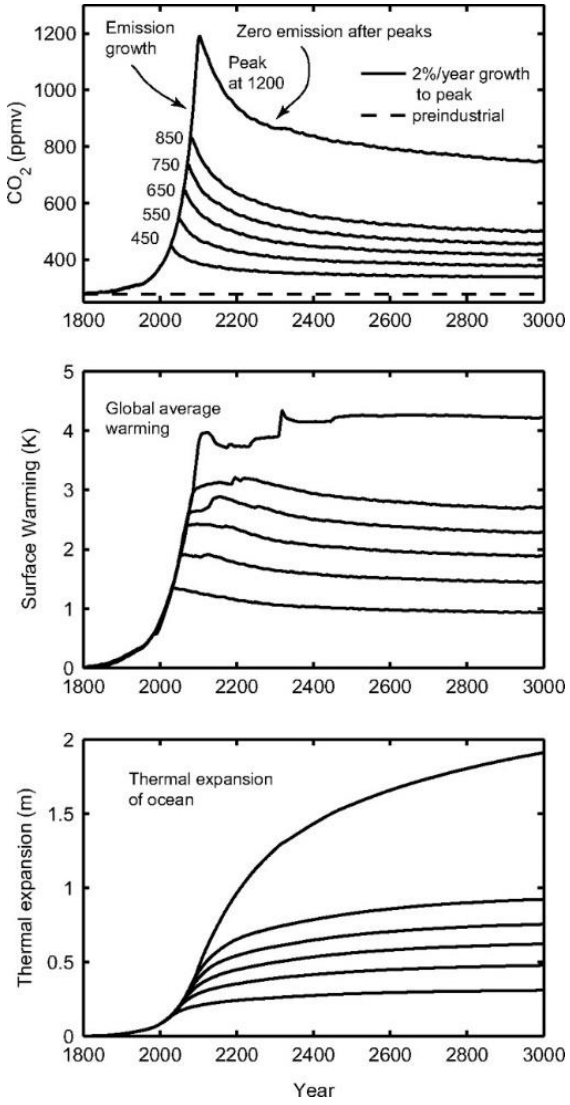


Figure 1 - Correlation of GHG concentration and the resultant impacts.

Source: Solomon et al, 2008

As per Article 2[1] of the UNFCCC, there is a need for reduction of GHG emission to ensure a sustainable economic development. To achieve the limit to global warming to below 1.5 degrees Celsius (°C), global CO2 emissions will have to be reduced by 45% by 2030 and be net-zero by 2050 (IPCC, 2018); and the EU has set-up the 2030 Climate Target Plan[2] to reduce GHG emission by at least 55% by 2030. With energy-related activities accounting for two-thirds of GHG emissions globally (IRENA, 2019), there is a need for an energy transition to meet the climate change targets. By acting now, we can have an acceptable amount of temperature overshot before returning to the targeted temperature level by 2100. However, the longer the delay, the larger and longer will be the temperature overshoot and the harder it will be for the world to return to the temperature target (IPCC, 2018).

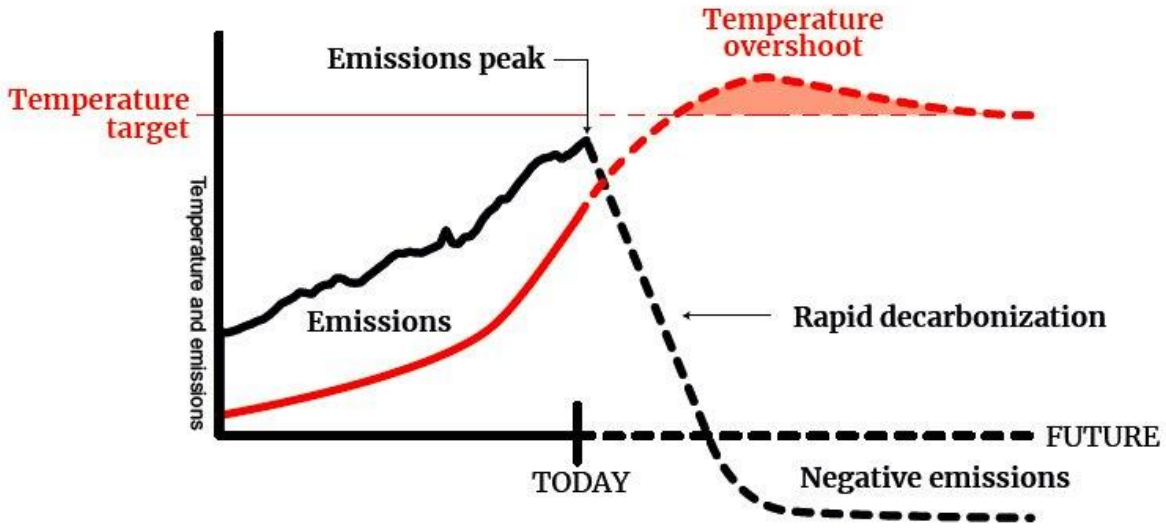


Figure 2 - Context of Temperature Overshoot

Sources: World Meteorological Organization (WMO) and United Nations Environment Programme (UNEP)

[1] **Article 2 of the UNFCC** - *The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.*

[2] *The Commission's proposal to cut greenhouse gas emissions by at least 55% by 2030 sets Europe on a responsible path to becoming climate neutral by 2050. Source: https://ec.europa.eu/clima/policies/eu-climate-action/2030_ctp_en*

1.2 Research Gap

To aid in the reduction of GHG emission, a clean source of alternative energy is needed, and the use of hydrogen could thus play a significant role given that a carbon-neutral value chain can be achieved when restricting to the use of green hydrogen.

However, there remain issues regarding hydrogen transportation. Hydrogen can be transported through many different forms of energy carriers such as pure hydrogen in compressed or liquefied state, chemical hydrogen in the form of ammonia, methanol or methane and even chemically bounded hydrogen in carriers such as metal hydrides and liquid organic hydrogen carbons (Terwel et al, 2018). Different hydrogen carrier will require different processing, storage, shipping and receiving technology before hydrogen can be used by the final consumer (Terwel et al, 2018).

The objective of this research is to

1) explore the different current available hydrogen shipping carrier and the related logistical processes
2) assess and compare the different hydrogen shipping carrier to determine the top three applicable carrier choice
3) using a case study based on a fixed hydrogen production pathway (green hydrogen), to determine the cost competitiveness of the top three applicable carrier to deliver green hydrogen

1.3 Research Questions

Main Question

To determine the extent on how each stage of the hydrogen supply value chain will impact the selection of hydrogen shipping carrier to supply the most cost-efficient green hydrogen to the end user.

Sub-Questions

1. What are the different types of hydrogen shipping carrier and the applicability of the carrier for utilization?
2. What is the comparison in terms of cost for producing and transporting the applicable hydrogen shipping carriers?

    a. Can current gas infrastructure and gas carriers be converted for use for transportation of hydrogen and hydrogen derived fuel?
3. What are the different types of hydrogen transportation vessels that are/will be available for shipping and the associated cost of the hydrogen carrier through the different supply chain?
4. What are the applicable regulations governing the shipping of hydrogen and hydrogen derived carrier and the implication on the cost of hydrogen?
5. To what extent will future developments in renewable technologies influence the choice of transportation?

2 Literature Review

2.1 Background

Hydrogen is the smallest and lightest of all gas molecules and abundant in the universe. Hydrogen can be considered a non-polluting and renewable (DNV-GL, 2014) energy source as it does not contain carbon. As per Figure 3, hydrogen also offers the best energy-to-weight storage ratio of all clean fuels, having an energy content of 120MJ/Kg which more than two times higher than natural gas and biomass fuels. With these advantages, hydrogen can be easily used as an energy carrier due to its flexibility and can be considered as an universal fuel in a zero-carbon emission society (Hordeski, 2008) and can be utilised in a huge number of applications as shown in Figure 4.

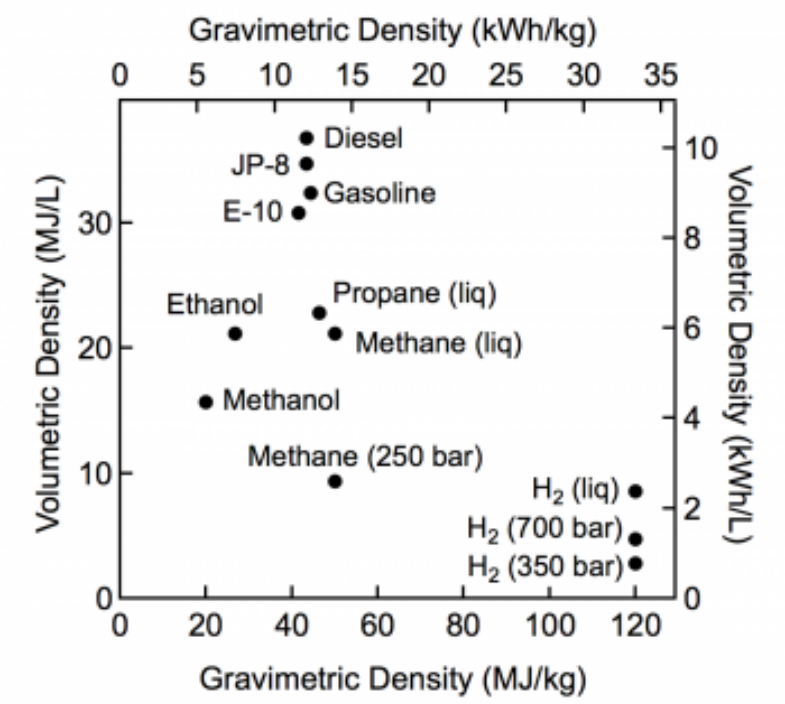


Figure 3 - Comparison of specific energy (energy per mass or gravimetric density) and energy density (energy per volume or volumetric density) for several fuels based on lower heating values.

Source from https://www.energy.gov/eere/fuelcells/hydrogen-storage

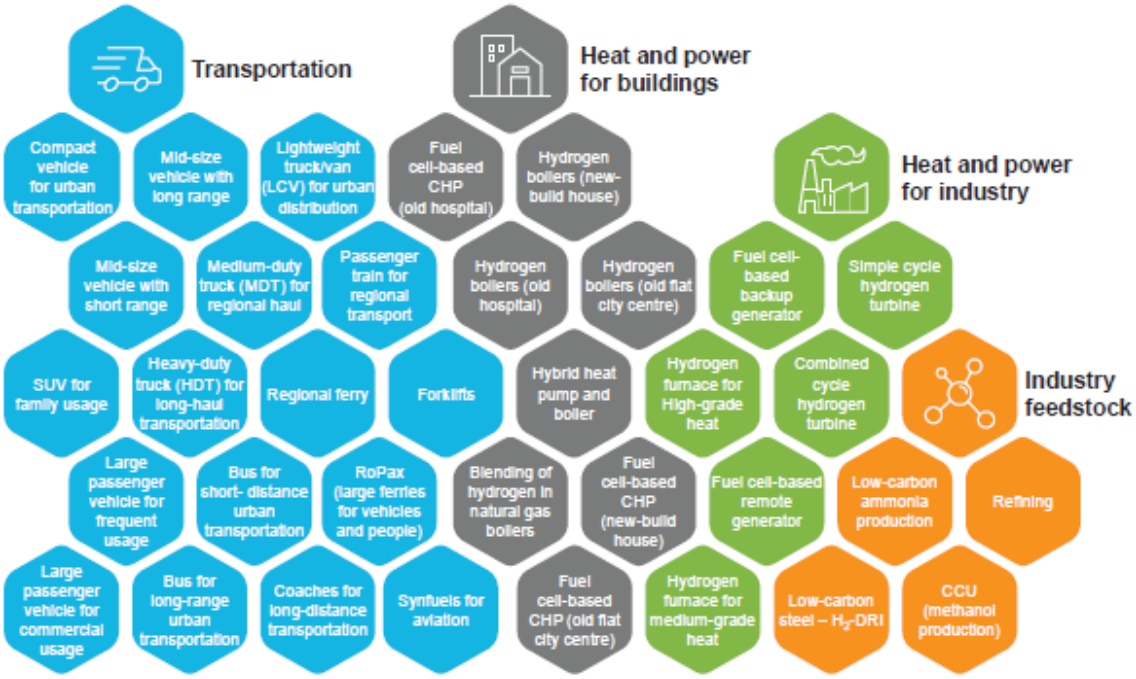


Figure 4 - Hydrogen uses as a universal fuel

Source: Hydrogen Council, 2020

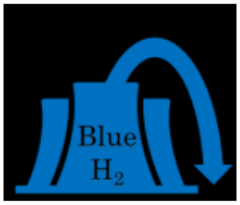
2.2 Production of Hydrogen

Hydrogen can be mainly classified to Blue, Grey and Green hydrogen; with the segregation based on how the hydrogen is extracted and the source of energy used to extract it (Noussan et al, 2021). Grey hydrogen, which is the most common type of hydrogen, is produced industrially using the method of reforming natural gas such as methane or the gasification of coal or biomass (IEA, 2019). Blue hydrogen has the same production method but has the addition of carbon capture systems to lower the GHG emissions. Green hydrogen is defined by the production of hydrogen using renewable sources of energy. The cost of hydrogen production[3] ranges from cheap grey hydrogen at 1.00 USD kg H_2 to 6.70 USD kg H_2 for green hydrogen (IRENA, 2019). For this thesis, the source of carbon-free hydrogen will be fixed on green hydrogen.

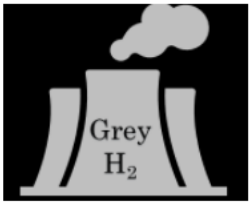
[3] *Green hydrogen costs more than five times that of grey hydrogen as per studies by SGH. Source: https://www.sgh2energy.com/economics*



Green hydrogen is produced by electrolysis of water, using only electricity from renewable energies. The electrolysis process can split water into hydrogen and oxygen molecules using electric energy. Since production is based on renewable energy, hydrogen is produced without any CO2 emissions.



Blue hydrogen is produced from sources and processes that release CO2 into the environment, but which is then captured and stored (and in some cases reused in other processes).



Grey hydrogen is extracted from fossil sources such as methane or coal, resulting in the massive production of CO2 which is then released into the environment without any other use. This is the most widely used method

Figure 5 - Summary of Main Hydrogen Colours and Paths

Source: (Washington State University and RINA, 2021)

2.2.1 Green Hydrogen

The production of green hydrogen is done through the process of electrolysis of water using a renewable source of electricity. The process of electrolysis is where the electricity is pass through an electrolyser which will split the water molecule into hydrogen and oxygen and is shown in the following equation.

$$2H_2O + \text{Electricity} \leftrightharpoons 2H_2 + O_2$$

There are several types of electrolysers that are commonly used for green hydrogen production such as Proton Exchange Membrane, Solid Oxide electrolysers and Alkaline electrolysers (Tijdgat, 2020).

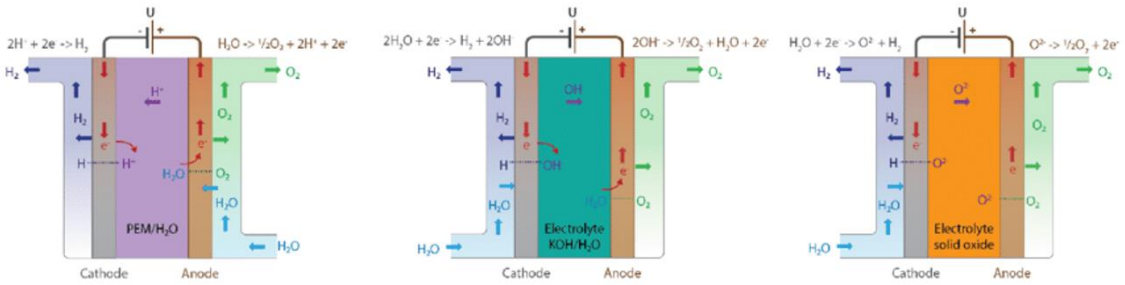


Figure 6 – Pictorial Illustration of different Electrolysers.

Source: Gallandat et al, 2017

This process can also be reversed to produce energy; by alternating the direction of the current, cells based on PEM and solid-oxide technologies are able to work both as a fuel cell or as an electrolyser (NREL, 2010). As electricity or energy is needed to split the water molecule during the electrolysis process, it would be more effective to use an electrolyser that has a higher conversion efficiency.

The current-day CAPEX of electrolysers is one of the key factors for the higher LCOH of green hydrogen (Bristowe et al, 2021). It is expected that with the improvement of technology in the near future, we will be expecting a significant reduction in the CAPEX and an increase in the technical efficiency of electrolysers; reducing the LCOH and making the use of green hydrogen comparable (Bristowe et al, 2021).

2.3 Transportation of Hydrogen

Transportation of the hydrogen carrier is a crucial part of the whole value chain. The method of distribution will depend on the volume and range. For small quantities and short distances, IRENA (2019) has been suggested that transportation via the gaseous form is deemed more suitable while transportation via the liquid form will be the most feasible for longer routes. It is also stated that it could be more efficient for ship transportation of hydrogen carriers such as Ammonia and reconverting it back to hydrogen past the 1500km range (IRENA, 2019).

The cost of hydrogen at the offtake site will depend mainly on the following costs assuming that the source of green hydrogen is constant. Firstly, the cost of production of the green hydrogen. Secondly, the cost of conversion or packing of hydrogen into the carrier form either via changing of state or changing of form. Thirdly, the transportation cost based on the type of vessels and lastly, the cost of reversion or unpacking of the cargo to hydrogen in the gaseous form.

Hydrogen can be liquefied to increase its density for transportation; however, due to the low liquefaction point of -253°C, the energy needed would be up to 35% of the initial hydrogen energy content (Ohlig and Decker, 2014). Although this is similar to the energy needed to convert hydrogen to ammonia and back to hydrogen at the offtake point (Hansen, 2018; Brown 2017); it is to be noted that ammonia liquefies at a higher temperature of -33°C and is 1.7 times denser in terms of hydrogen content as compared than liquefied hydrogen. In addition, ammonia has an existing distribution

network and thus makes it cheaper to transport than pure hydrogen (IRENA, 2019). In comparison, the energy losses for compressed hydrogen are similar at around 65% efficiency (Park et al, 2014) but the hydrogen gas is ready for use directly at the destination with no additional processes needed. The adoption of shipping compressed hydrogen is limited by its capacity and the lack of an existing shipping network. However, with improvement in storage technology, compressed hydrogen shipping may be as cost competitive as compared to liquefied hydrogen and Ammonia (GEV, 2021).



Figure 7 - Different Types of Hydrogen Carrying Vessels (LH2, NH3, CH2)

Source: ClassNK and Kawasaki, MOL, GEV

2.4 System Description – Hydrogen Storage and Transportation

As shown in Figure 3, hydrogen has the highest gravimetric density of 120MJ/kg among transportable fuels such as diesel and methane; however, it has a very low atmospheric volumetric density of around 3.06Wh/L which is around 3000 times lesser as compared to diesel (Hoecke et al, 2021). The low volumetric density poses an issue for effective storage and transportation and several technologies such as compression, liquefaction, physical and chemical storage has been used to make store and transport hydrogen more efficiently (Zhang et al, 2016). Compression and liquefaction of hydrogen are the conventional ways of handling hydrogen for storage and transportation while there are other innovative methods of storing and transporting hydrogen; namely via chemical-bounded carriers such as metal borohydrides, liquid organic hydrogen carriers and chemical hydrogen e.g., methane or ammonia (Rivard et al, 2019). The different types of carriers will be further illustrated in the following sub-sections.

2.4.1 Compressed Hydrogen

In a small-scale setting, compressed gas (hydrogen) can be considered the most well-established hydrogen storage and transportation method. There are four different types of storage (Type I to Type IV) using different structural materials that have been developed for pressured storage of hydrogen of ranging from 200 to 700 bar; see Table 1. Given the high structural strength that is needed to keep accommodate the high-pressure storage of hydrogen, the storage is typically restricted to cylindrical shapes (Rivard et al, 2019). In addition, energy wastage of up to 10% of the hydrogen energy content is needed to cool and compress the hydrogen gas so that it can be stored and transported at 700 bar and yet the volumetric density is still limited to around 0.81KWh/L making it generally more suitable for storage and transportation in smaller range and volume (Hoecke et al, 2021).

Type	Material	Typical Pressure (bar)	Cost (USD/kg)	Gravimetric Density (wt%)
I	All-Metal Construction	300	83	1.7
II	Mostly Metal, Composite Overwrap in hoop direction	200	86	2.1
III	Metal Liner, full composite overwrap	700	700	4.2
IV	All-composite Construction	700	633	5.7

Table 1 - Pressure vessel materials according to their type

Source: (M.Legualt, 2012)

Compressed hydrogen shipping is akin to compressed gas shipping in the natural gas industry. While compressed gas storage technology is matured in the small scale, industrial norm for economical shipping of natural gas is via its liquid form. However, research via gas shipping companies such as GEV and Anthony Veder shows that compressed gas shipment is more economical at shorter ranges (Tijdgat, 2020). The supply chain of liquefied hydrogen, with an even lower boiling point than methane, may present an economical case for shipping via compressed hydrogen for extended distance (GEV, 2021).

2.4.2 Liquefied Hydrogen

Liquefied hydrogen is another method to store and transport pure hydrogen. Hydrogen, cooled to the temperature of -253^{o}C, can be stored and transport like liquefied natural gas (LNG) and shipped like a global commodity (IRENA, 2019). Liquefied hydrogen is stored and transported in cryogenic tanks which are very well-insulated to minimise heat-transfer. Heat transfer from the environment to the liquid

through the insulation will result in the boil-off of the liquefied hydrogen in which the heated liquid hydrogen turns to hydrogen gas. The hydrogen boil-off can either be collected in a buffer tank or re-liquefied and sent back to the cryogenic storage.

The volumetric density of liquefied hydrogen is significantly higher than that of compressed hydrogen. However, liquefaction has a major downside which is the significant amount of energy needed and the additional energy losses incurred due to boil-off. Although there are similarities between both LNG and liquefied H_2, the usage of LNG infrastructure and vessels for LH_2 storage and transportation is not too feasible due to the significant difference in liquefaction temperature and impact of hydrogen on materials such as embrittlement of metals which will require different storage materials (Nerhiem, 2021).

2.4.3 Chemical Hydrogen

Chemical hydrogen describes the process whereby hydrogen is combined with other molecules to become a hydrogen by-product. The main examples of chemical hydrogen are methane (CH_4) which is the combination of carbon and hydrogen by the synthetization process of methanation (Tijdgat, 2020) and ammonia (NH_3) which is a non-carbon combination of hydrogen and nitrogen from the air through the Haber-Bosch process[4].

For the selection and comparison of green hydrogen carriers, we will not take into consideration methane which is carbon-based, and which is already being stored and transported as LNG. Methanol, another potential commonly used hydrogen carrier will also not be considered. Instead, non-carbon carrier such as Ammonia which has been handled and used for ages (IRENA, 2019) will be considered as the representation for chemical hydrogen.

[4] *Haber-Bosch is an exothermic chemical reaction when nitrogen is combined with hydrogen to produce ammonia and is represented by the following equation. $N_2 + 3H_2 \leftrightharpoons 2NH_3$, $\Delta H = -91.8$ kJ/mol. Although exothermic, the reaction requires huge amount of pressure of up to 250 atmospheric pressure which traditionally requires huge amount of energy (generated by fossil fuels). Haber-Bosch is a fairly efficient process with around 60% efficiency rate* https://www.science.org/content/article/ammonia-renewable-fuel-made-sun-air-and-water-could-power-globe-without-carbon

Ammonia has been used as a main component of agriculture fertilizer and is produced chemically via the Haber-Bosch process between nitrogen and hydrogen. Ammonia can be stored and transported via various methods; namely in pressure tanks, in semi-pressured/semi-refrigerated (SP/SR) and fully refrigerated tanks. Ammonia turns to gas at -33^{o}C and the storage tanks are designed to minimize boil-off of ammonia through proper insulation and for tank types that do not accept pressure build-up due to boil-off, the ammonia gas can also be re-liquefied and returned to the tank. Given the similarities in boil-off temperature, ammonia can be shipped using Liquefied Petroleum Gas (LPG) carriers (Tijdgat, 2020). Ammonia can be converted back to hydrogen and nitrogen through a cracking process. However, it is to note that large scale cracking process is still currently under development but can be a game changer once the economically challenges are successfully solved (IRENA, 2019).

2.4.4 Metal Hydrides

Metal hydrides are considered good and innovative carriers for hydrogen transportation and storage (Rivard et al, 2019). Metal hydrides are compounds that consist of chemically bonded metal and hydrogen molecules (Meng, 2006) and have a good energy density e.g. Magnesium Hydride which has a gravimetric energy density of 7.6 wt% and volumetric density of 13.22MJ/L. Hydrogen is stored through the hydrogenation process where hydrogen atoms occupy the interstital sites of the metal lattice structure and heat is generated; the same amount of heat is needed to displace the hydrogen atoms during the dehydrogentation process (Meng, 2006).

Metal hydrides are concluded to be not an efficient hydrogen carrier; however, it has been noted the complex hydrides such as metal borohydrides provide significantly positive energy efficiencies (Rivard et al, 2019) and is a better option for hydrogen carrier selection. Metal borohydrides such as sodium borohydrides ($NaBH_4$)[5] is also a commonly used industrial reducing agent and can be used to store and displace hydrogen via hydrolysis (Ying et al. 2004). The usage of $NaBH_4$ as a hydrogen carrier requires several steps and the full chemical process of how sodium borohydride is synthesized, hydrated and recycled can be found in Appendix A.

[5] *Industrial production of $NaBH_4$ can be achieved using the Brown-Schlesinger process or by alternatively the Bayer process. Abdelhamid, 2021)*

2.4.5 LOHC

Hydrogen can also be stored and transported via liquid organic hydrogen carriers (LOHC) which are organic compounds that can absorb and desorb hydrogen. The liquid compound acts as a reusable hydrogen medium through a series of catalytic hydrogenation and dehydrogenation processes. Hydrogenation typically takes place at 50-150ºC while dehydrogenation takes place at around 300-350ºC. (Figure 8). The volume energy density is like that of liquid hydrogen but LOHC can be easier stored and transported at room temperature and atmospheric pressure. (RINA, 2021). Two of the most promising LOHCs are Toulene and Dibenzyltoluene (H0-DBT) which can be reused for around 1000 cycles (Tijdgat, 2020).

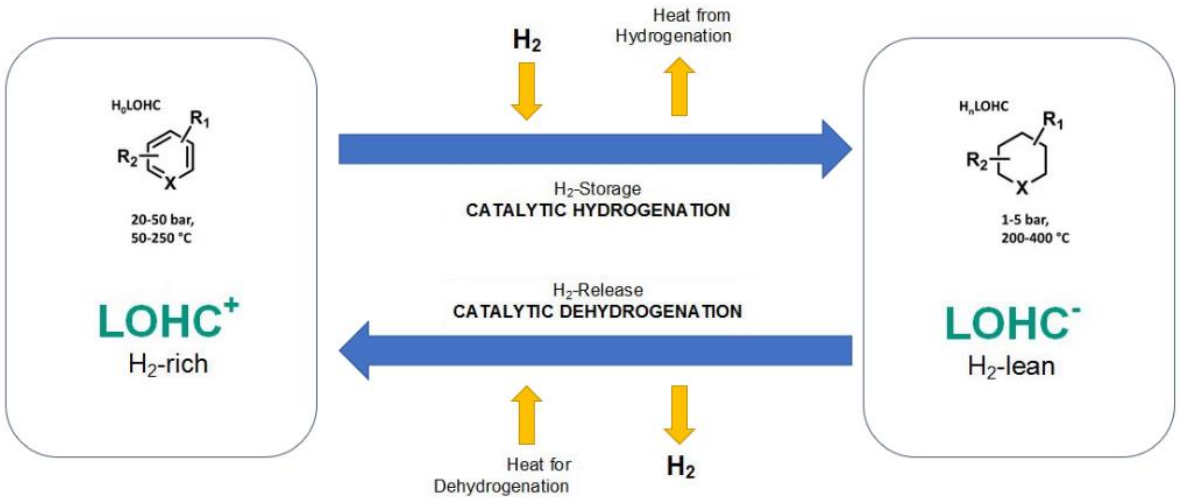


Figure 8 - Schematic Representation of LOHC hydrogenation and dehydrohenation process

During the hydrogenation process of H0-DBT, H0-DBT reacts with pure hydrogen to become H18-DBT with losses in hydrogen and heat energy[6]. Toulene, which is the dehydrogenated version of Methyl-Cyclohexane (MCH)[7], undergoes similar chemical processes but with are less losses of hydrogen (Tijdgat, 2020).

The storage and transportation of LOHCs are comparatively more convenient as it can be done at atmospheric temperature and normal temperature. Dibenzyltoluene can be stored and transported like oil products and can easily adopt existing oil tankers for

[6] *DBT hydrogenation equation $C_{21}H_{20} + 9H2 \leftrightharpoons C_{21}H_{32}$ + Heat ΔH = -72 kJ/mol*
[7] *Toulene hydrogenation equation $C_7H_8 + 3H_2 \leftrightharpoons C_7H_{14}$ + Heat ΔH = -205 kJ/mol*

shipping given similar properties to oil while Toulene has properties similar to methanol and can only be stored and transported in stainless steel tanks or coated carbon steel tanks to cater for its corrosive properties (Tijdgat, 2020).

3 Methodology

For the initial stage of the research, in-depth literature review and industry research is performed to identify the different hydrogen carriers and their applicability for effective utilisation in a carbon-neutral hydrogen value chain. Given the complexity of sustainable energy projects due to the multi-dimensional and contradicting politico-socio-economical goals, a multi-criteria decision analysis (MCDA) method[8] has been deemed most suitable for this research (Wang et al, 2009).

Under the PEST[9] evaluation criteria format, which will take into consideration the Political, Economical, Social and Technological aspect for the usage of hydrogen and its shipping carrier, a MCDA will be conducted on the list of hydrogen shipping carriers to shortlist the top three hydrogen carriers.

Multi-criteria decision analysis (MCDA) is a formal method that assist in decision-making by considering multiple criteria in a direct way which helps reduce the complexity of the question which leads to better understanding and thus makes the decision-making process easier (Bertalan N et al, 2019).

As part of the MCDA process, stakeholders have been involved to provide their industry inputs for criteria selection as well as weighting of the criteria. This was to ensure that biasness can be minimised with additional inputs during the shortlisting process.

Following the shortlist, an economic analysis on the cost of the full value chain will be done on the three selected hydrogen shipping carrier using a case study[10] within Asia and Australia. Lastly, recommendation will be made to determine the most feasible hydrogen transportation carrier to be adopted within Asia taking into consideration the various techno-commercial factors and future technological advancement.

[8] *The multi-criteria decision analysis (MCDA) process will consist of establishing and selection of criteria, criteria weighting, evaluation of factors, and final aggregation. The criteria will be defined through in-depth literature review of industry research.*
[9] *PEST criteria refers to Political, Economical, Social and Technological evaluation criteria.*
[10] *The case study will look at the three different hydrogen value chain from 1) voyage from Australia to Singapore and 2) voyage from Australia to Japan. Evaluation will be made based on the Levelised cost of hydrogen (LCOH).*

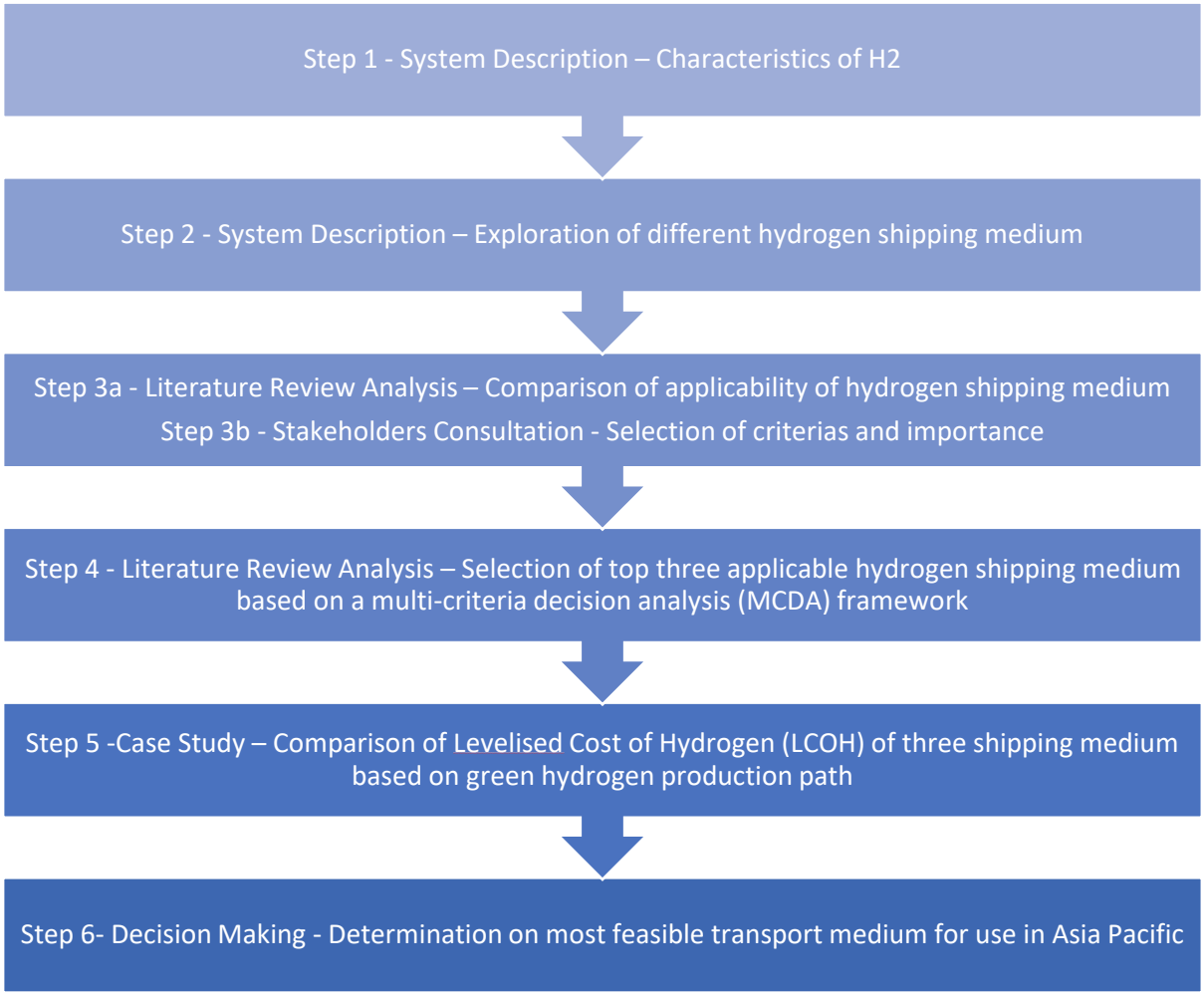


Figure 9 - Research Methodology

3.1 Multi-Criteria Decision Analysis for Selection of Hydrogen Medium

Hydrogen can be transported in many different state and forms such as compressed and liquefied hydrogen or chemical hydrogen as well through other chemically bounded carriers such as metal hydrides and LOHC. Each hydrogen carriers will have different cost associated with the conversion and reversion of hydrogen. There is no universal fit for all hydrogen delivery solution across all scenarios given the different requirements in volume and transportation distance (European Commission, 2021). Transportation via hydrogen could be via trucking, pipeline or via ships and this thesis will be looking specifically at sea-borne transportation. Through a multi-criteria decision analysis (MCDA) framework, we will be shortlisting three top hydrogen carriers across the following different criteria such as energy densities, maturity of hydrogen carrier technology, conversion and reversion cost, existing storage and shipping infrastructure and safety of the hydrogen carrier.

3.1.1 Selection of Criteria

The selection of the criteria was based on a combination of literature review of prior maritime studies and also through stakeholder engagements. Literature review of similar maritime fuel MCDA studies (Ren & Lützen, 2017 and Hansson et al., 2019) has shown alignment in the incorporation of the PEST evaluation criteria framework in relation to the maritime industry. The main criteria were further verified to be capable of meeting the main research objective (Dodgson et al., 2009) which is to analyse the techno-commercial conditions of hydrogen shipping. Lastly, the proposed criteria and sub-criteria were compared against the surveyed results from stakeholders and further refined for the final study comparisons.

3.1.1.1 Selection of Stakeholders

Stakeholders are defined as *"Any Group or Individual who can affect or is affected by the achievement of the organisation's objective"* (Mitchell et al, 1997). Relevant stakeholders are identified by the shipping private-public partnership model which consist of the following: Port Authorities (Public), Regulatory Bodies (Public), Academics (Public), End Users (Private), Traders (Private) and Shippers (Private). Regulatory bodies may include classification bodies such as IACS, international maritime bodies like IMO and also national flag agencies while end users could include power generation companies or gas distribution companies. The good mix of stakeholders among the groups increases the reliability of the criteria selection as the in-depth knowledge of each stake-holders in their own field of expertise reduces bias and help define the weighting factors in the multi-criteria decision analysis process. For this study, twenty-three (23) stakeholders representing the six public and private segments participated in the survey.

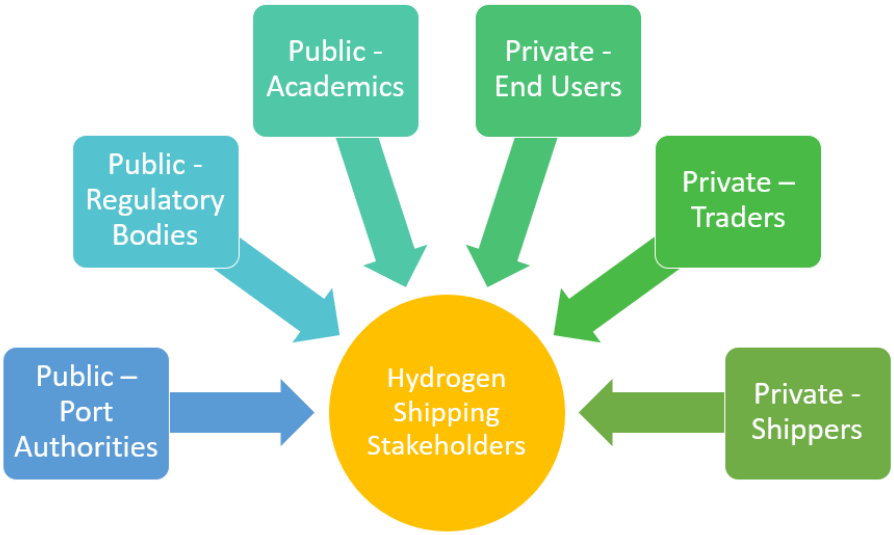


Figure 10 – Stakeholders Representation for Public and Private Partnership

3.1.1.2 Selection of Sub-Criteria (Hybrid)

Relevant sub-criteria under the PEST framework for this research are identified from literature review and through the conduct of research surveys from a stakeholder group identified in the above section (3.1.1.1). Under the four main criteria of political (regulatory), economic, social (environmental) and technical, stakeholders were asked to provide the sub-criteria that they find important and relevant to hydrogen shipping. The sub-criteria are then shortlisted and compared to evaluation criteria identified from literature review. Criteria that were not featured in the surveys were deemed to be not so relevant from the stakeholders' point of view and were omitted in the final sub-criteria list.

3.1.1.3 Selection of Weightage

The selected criteria are not all equally important in the decision-making process and are assigned to a specific weighing factor that correspond to their relative importance, with the relative importance being obtained from the inputs of stakeholders and decision makers from the industry.

There are many criteria weighting methods, ranging from non-comparable methods such as direct rating, swing weighting and simple multi-attribute rating (SMART) to comparison methods such as analytic hierarchy process (AHP) and conjoint analysis

(Bertalan et al, 2019). The method of Direct rating, which has been chosen to augment literature research of the study, can be considered the simplest method for estimating criteria weighting; this is done by asking stakeholders to assign number values out of a fixed scale to the different criteria without any trade-offs (Bertalan et al, 2019).

3.1.2 Selected Criteria and Weighting

The final selected criteria based on the combination of literature review and stakeholder surveys are as per table 2. The inputs for criteria weightage (through a direct rating method) were received from the stakeholders and were tabulated from a scale of one to five based the importance of the criteria to the stakeholders; with one being least important and five being most important. The average weightage scoring of each main indicator was then tabulated in table 3.

Main Indicator	Sub-Indicator	Criteria
Technical	Carrier Properties – Energy Density	Gravimetric Density
		Volumetric Density
	Supporting Infrastructure Maturity	Carrier Technology Maturity
		Vessel Maturity
Economical	Energy Efficiency/Energy Cost	Conversion Losses
		Re-conversion Losses
		Shipping Cost
Social and Environmental	By-Products	Cost of Carriers
		Safety of Carriers
Political	Regulatory	Regulations and Classifications

Table 2 - Assessment Criteria and Sub-criteria

Main Indicator	Average Weighting
Technical	3.69
Economical	3.56
Social and Environmental	3.69
Political	3.47

Table 3 – Criteria Average weighting

The different hydrogen carriers will be assessed and scored according to their pros and cons; either quantitively or qualitatively among the several main and sub criteria in Table 2 and modelled based on the direct rating function from derived from the stakeholder surveys. Given the different scales in each criterion, the scores will have

standard intervals to ensure uniformity of scaling for multi-criteria analysis (Dodgson et al., 2009). The linear conversion to an interval scale from 0 to 10 will be as follows:

*Standard Score = Score / Maximum * 100%*

*Weighted Score = Standard Score * weight factor*

3.1.3 Technical Criteria Evaluation

3.1.3.1 Carrier Properties - Energy Density

The physical properties of the hydrogen carrier are technical factors that needs to be considered when assessing the carrier. One key property will be the energy density which consist of both the volumetric and gravimetric density. Volumetric energy density is defined by the amount of energy that can be packed in a fixed volume and normally measure in Mega-Joules per Litre (MJ/L). The higher the volumetric energy density means that more fuel can be shipped with the same sized vessel. Gravimetric energy density can be defined as how much energy the carrier hold in relation to its weight and is normally measured in weight percentage (wt%).

Hydrogen Carrier has a good gravimetric density (>10 wt%)	3
Hydrogen Carrier has a decent gravimetric density (5-10 wt%)	2
Hydrogen Carrier has a low gravimetric density (<5 wt%)	1

Table 4 - Assessment of Gravimetric Density

Hydrogen Carrier has a good volumetric density (>10MJ/L)	3
Hydrogen Carrier has a good volumetric density (5-10MJ/L)	2
Hydrogen Carrier has a good volumetric density (<5 MJ/L)	1

Table 5 - Assessment of Volumetric Density

3.1.3.2 Supporting Infrastructure Maturity

Storage and transportation require supporting infrastructure and technology. Supporting infrastructure will include the conversion, re-conversion, cargo storage, cargo management and transportation technologies. Hydrogen carriers that are using existing and matured infrastructure and technology will be more desired as such technologies are already proven operationally. The maturity of the infrastructure and

technology will be measured by the established method of Technology readiness levels (TRLs)[11]

Hydrogen Technology are proven by successful implementation in the maritime sector (TRL9)	5
Hydrogen Technology are starting to be implemented in the maritime sector (TRL7-8)	4
Hydrogen Technology are demonstrated by prototypes in the maritime sector (TRL6)	3
Hydrogen Technology are partially demonstrated by prototypes in the maritime sector (TRL 4-5)	2
Hydrogen Technology are designs/concepts (TRL1-3)	1

Table 6 - Assessment of Hydrogen Carrier Technology Level

Besides the technological maturity of the carrier, the current technology maturity of the shipping vessel that would be used to transport the hydrogen carrier internationally would be compared. Vessels that are in the conceptual and prototype stages (TRL 1-5) will require long lead time to obtain regulatory approvals and additional time for ship building before the adoption of the hydrogen carriers. As such, hydrogen carriers that uses existing or available shipping vessels will be more desired as compared to hydrogen carriers that are depending on new conceptual vessels.

Transportation vessel are proven by successful implementation in the maritime sector	**5**
Transportation vessel are starting to be implemented in the maritime sector	4
Transportation vessel are demonstrated by prototypes in the maritime sector	3
Transportation vessel are partially demonstrated by prototypes in the maritime sector	2
Transportation vessel are designs/concepts	1

Table 7 - Assessment of hydrogen Shipping Vessels

3.1.4 Economic Criteria Evaluation

3.1.4.1 Energy Efficiency / Energy Cost

Energy efficiency of the hydrogen carrier considers the full mid-stream supply chain. This includes the energy losses at the conversion, storage, transportation and re-conversion stages. The energy losses will be estimated as a percentage of the total energy content shipped. The smaller the energy losses at each different stage, the more favourable the hydrogen carrier.

[11] *Technology readiness levels has been developed by NASA in the 1970s and is determined by an assessment that examines program concepts, technology requirements, and demonstrated technology capabilities. It goes from TRL1 to TRL9, with TRL9 being a fully matured technology. See Appendix B.*

Hydrogen energy losses and cost high (>40% losses)	**1**
Hydrogen energy losses and cost medium (20%< losses<40%)	2
Hydrogen energy losses and cost low (<20% losses)	3

Table 8 - Assessments of Conversion/Packing Costs

Hydrogen energy losses and cost high (>10% losses)	1
Hydrogen energy losses and cost medium (5%<losses<10%)	2
Hydrogen energy losses and cost low (<5% losses)	3

Table 9 - Assessment of Re-Conversion/Un-packing Costs

In additional to energy losses in the conversion and re-conversion of the hydrogen carrier, storage and transportation at low temperatures or high pressure will require temperature and/or pressure management systems. The operation of such systems will thus incur additional cost across the supply chain.

Hydrogen carrier management cost high	**1**
Hydrogen carrier management cost low	2
Hydrogen carrier management cost insignificant	3

Table 10 - Assessment of Hydrogen Carrier Management Cost

3.1.5 Social and Environmental Criteria Evaluation

3.1.5.1 By-products

The conversion and re-conversion of the hydrogen carrier for storage and transportation may result in by-products, e.g. Ammonia will be broken down to nitrogen and hydrogen during the re-conversion phase and the resultant by-product would be nitrogen gas. Other forms of by-products could be the compounds such as metal hydrides and LOHC that absorbs and desorb hydrogen and will have to be dispose of after their usable cycles are completed.

No By-Product	**3**
Cost-Efficient By-Product	2
Costly By-Products	1

Table 11 - Assessment of By-Products and Associated Cost

3.1.5.2 Safety

Safety is an important factor when it comes to storage and transportation of the hydrogen carrier. The hydrogen carrier behaves like a fuel with its significant energy content and the key identified safety hazards would be the flammability and toxicity of the fuel (Tofalos et al, 2020). The hazards are assessed on their severity and likelihood and defines the safety consideration required when storing, transporting and using the hydrogen carrier. Assessment of the safety criteria will be based on the grading of each hydrogen carrier based on Globally Harmonised System of Classification and Labelling of Chemicals (GHS)[12] standards (UN, 2011).

Flammability – No Hazard – Not Flammable	5
Flammability – Cat 4 – Combustible	4
Flammability – Cat 3 – Flammable	3
Flammability – Cat 2 – Highly Flammable	2
Flammability – Cat 1 – Extremely Flammable	1

Table 12 - Assessment of Carrier Flammability

Toxicity – No Hazard	5
Toxicity – Cat 4 – Practically non-Toxic	4
Toxicity – Cat 3 – Low Acute Toxic	3
Toxicity – Cat 2 – Moderately Acute Toxic	2
Toxicity – Cat 1 - Highly Acute Toxic	1

Table 13 - Assessment of Carrier Toxicity

3.1.6 Political and Regulatory Criteria

3.1.6.1 Regulatory

The successful adoption of a green hydrogen economy will depend on the delivery of hydrogen from the supply to the demand and the key cross-continental transportation method would be via maritime. However, maritime operations will have to meet international safety and environmental standards set by the International Maritime

[12] *Globally Harmonized System of Classification and Labelling of Chemicals (GHS) is a non-binding classification framework developed by the United Nations and used to classifies the hazards of chemical products.*

Organisation (IMO[13]) such as Safety of life at Sea (SOLAS) and maritime pollution (MARPOL) requirements. In addition, vessels used to ship the hydrogen carrier will also need to adhere to classification rules set by members of International Association of Shipping (IACS[14]) before they are able to purchase insurance for the vessel and their cargo (Mass, 2020). The lack of established regulatory framework and classification schemes will hinder the adoption of the carrier.

Maritime Regulatory Framework and Classification Schemes exist	**3**
Maritime Regulatory Framework and Classification Schemes under development	2
Maritime Regulatory Framework and Classification Schemes do not exist	1

Table 14 - Assessment of Regulations

3.2 Case Study

The selection of case study would be based on current industry developments of the Asia-Pacific green hydrogen energy market. Australia has been selected as the key hydrogen supply source due to the strategic support of the Australian government[15] and its already well-established renewable energy market and the future development of significant renewable energy projects. Singapore and Japan have been selected as the demand centres due to their infrastructure and natural resources constraints for self-production of green hydrogen.



[13] *https://www.imo.org/*
[14] *https://www.iacs.org.uk/*
[15] *https://www.industry.gov.au/policies-and-initiatives/growing-australias-hydrogen-industry*

Figure 11 - Illustration of Case Study Shipping Cases

3.2.1 Selection of Green Hydrogen Production Path

The first step of the case study would be to define the green hydrogen production pathway. Green hydrogen is produced by electrolysis of water only from electricity from renewable energy sources such as solar, wind and hydro and thus will not incur any CO2 emissions. To best select the most cost-efficient green hydrogen production path, the study will compare the different options of green energy in Australia and also take into consideration the electrolyser's techno-commercial parameter from Table 14 such as CAPEX and operating efficiency to determine the best-case production path and the associated levelised cost of hydrogen from the selected path.

	Alkaline Electrolyser		PEM		SOEC	
	Today	Long Term	Today	Long Term	Today	Long Term
Electrolysis Efficiency (% LHV)	64	77	60	72	80	85
Operating Pressure (Bar)	1-30		30-80		1	
Stack Lifetime (thousand hours)	60-90	100-150	30-90	100-150	10-30	75-100
Load Range (%)	10-110		0-160		20-100	
CAPEX (USD/KWe)	500-1400	200-700	1100-1800	200-900	2800-5600	500-1000

Table 15 - Techno-Commercial Specification of Commonly Used Electrolysers

Source: (IRENA, 2019)

3.2.2 Comparison of Levelised Cost of Hydrogen

The second step of the case study would be to compare the levelized cost of hydrogen (LCOH between the top three shipping carrier that has been shortlisted by the MCDA process. The comparison will be based on a fixed production path (green hydrogen) and based on the following shipping scenario in the Asia Pacific; a maximum hydrogen volume of up to 500,000 tonnes per annum[16] and transporting distance of up to 4000 nautical miles (nm) is set as the basis of the case study. The maximum voyage of 4000nm is based he approximate range from Australia to Singapore (2000nm) and Australia to Japan (4000nm).

The case study will be concluded with the presentation of the low and high LCOH estimate of the three selected hydrogen carrier supply chain. The LCOH range will be

[16] *Case study is based on Australia's capacity for hydrogen production is 500,000 tonnes per annum based on reports by the Australian government Source: https://www.aemc.gov.au/hydrogen-new-australian-manufacturing-export-industry-and-implications-national-electricity-market.*

computed by comparing costing estimates from different literature review as well as the voyage cost differences between the two demand centres.

4 Results

4.1 Selection of Hydrogen Carriers

4.1.1 Criteria Scoring - Energy Density

For the transportation of hydrogen, a good energy storage medium would theoretically have both high volumetric and gravimetric densities (Rivard et al, 2019). Data collection was done on material studies such as (Rivard et al, 2019) and presented in the following Table 15. Other studies done by Moller et al (2017) and Saito (2018) also shown that chemical hydrogen carriers such as NH_3, $NaBH_4$ and LOHC would have better energy densities than hydrogen in its original state.

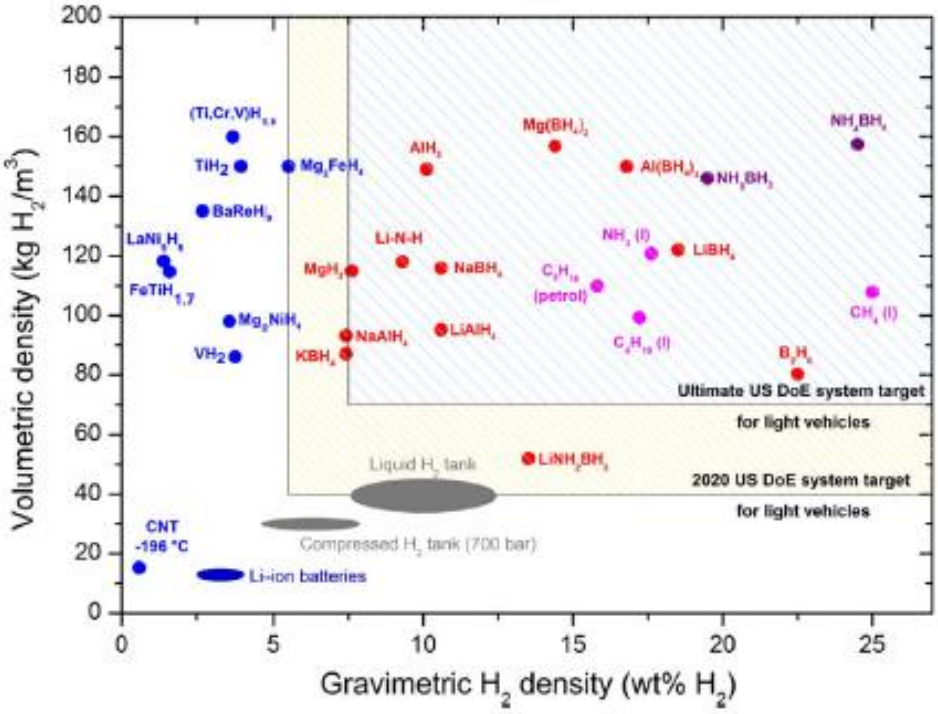


Figure 12 - Gravimetric and Volumetric comparisons of Fuels

Source: (K.T Moller et al, 2017) Hydrogen - A sustainable energy carrier

	Gravimetric (wt%)	Scoring	Volumentric (MJ/L)	Scoring
Liquid Hydrogen	7.5	2	6.4	2
Compressed Hydrogen (700bar)	3.6	1	4.5	1
Chemical Hydrogen (NH3)	17.6	3	11.5	3
Metal Hydride (NaBH4)	7.6	2	13.22	3
LOHC (MCH)	8.5	2	7	2

Table 16 - Energy Densities and Scoring of Different Hydrogen Carriers

4.1.2 Criteria Scoring – Supporting Infrastructure Maturity

In assessing carrier technology maturity, it is observed that both compressed and liquid hydrogen carriers already have existing small scale applications and large-scale application is already under development (IRENA, 2019). In a comparison study by Wijayanta et al (2019) between hydrogen carriers, it was found that the hydrogenation technology for LOHC is still under development while cracking of ammonia has just progressed to large-scale prototype stage. In a study done by the US Department of Energy, metal hydrides as a hydrogen carrier have been successfully tested in a relevant maritime environment (Ronnebro, 2012).

The assessment of the transportation technology is based on the current technology maturity of the shipping vessel that would be used to transport the hydrogen carrier internationally. Liquid hydrogen vessel has started operations within the maritime industry with the first Liquid Hydrogen ship Susio Frontier[17] being delivered in Japan in 2019. Compressed hydrogen gas vessel has also started gaining traction with initial approvals by classification society (GEV, 2021). Ammonia has been shipped using existing LPG carriers and has a matured supporting shipping infrastructure. LOHC such as Toulene and DBT can theoretically be shipped by existing vessel type like methanol carriers and oil tankers (Tijdgat, 2020) but this had yet to be adopted widely in the maritime domain. For $NaBH_4$, it is assessed that it could be transported by a sealed dry bulk carrier which requires extensive retrofitting and not currently available in the market (Tijdgat, 2020).

[17] *https://asia.nikkei.com/Business/Energy/World-s-first-liquid-hydrogen-carrier-ship-launches-in-Japan*

	Hydrogen Carrier Technology (TRL)	Scoring	Vessel Technology (TRL)	Scoring
Liquid Hydrogen	8	4	8	4
Compressed Hydrogen (700bar)	8	4	6	3
Chemical Hydrogen (NH3)	5	2	9	5
Metal Hydride (NaBH4)	6	3	4	2
LOHC (MCH)	5	2	7	4

Table 17 - Scoring based on TRL Levels of Hydrogen Technology and Shipping Vessels

4.1.3 Criteria Scoring – Energy Efficiency

During assessment of the energy efficiencies of the hydrogen carrier, the study considers the full mid-stream supply chain. This includes the energy losses at the conversion, storage, transportation and re-conversion stages. The energy losses will be estimated as a percentage of the total energy content shipped. The smaller the energy losses at each different stage, the more favourable the hydrogen carrier.

Conversion

For the conversion or packing of hydrogen carrier to hydrogen usage, different hydrogen carriers require different processes which incurs energy losses. Compressed hydrogen requires approximately 19% of energy losses when compressing the gas at up to pressure of 200 bars (IRENA, 2019). Due to the cryogenic requirements, immense energy content is required to liquefied hydrogen to -253^{o}C with energy losses of up to 45% (IRENA, 2019). For the packing of chemical hydrogen such as ammonia, the endothermic synthesis process will incur losses of 7-16% of energy content (Bartels, 2018). Synthesizing of $NaBH_4$ is highly efficient with only around 6% energy loss if preparation works are done before the process (Wu et al, 2004).

Studies from Wulf & Zapp (2018) and IRENA (2019) shows that during the hydrogenation process of LOHC, there is energy content loss of 15-35%. This is supported by similar loss data of 30% energy content losses during hydrogenation of Toulene or MCH (Popov, 2019).

	Energy Conversion (Packing) Losses	Scoring	Reference
Liquid Hydrogen	Liquefaction losses approximately 20-45% energy content	2	IRENA, 2019 Bersted, 2013
Compressed Hydrogen (700bar)	Compression losses approximately 19%	3	IRENA, 2019
Chemical Hydrogen (NH3)	Synthesis losses 7-16%	3	Bartels, 2018
Metal Hydride (NaBH4)	Synthesis losses 6%	3	Wu Et al, 2004
LOHC (MCH)	Hydrogenation losses 15% - 35%	1	IRENA, 2019 Wulf & Zapp, 2018

Table 18 - Scoring of Conversion/Packing Costs

Re-Conversion

Like the conversion phases, there are varying degrees of energy losses associated with the different reconversion or unpacking processes. There are two hydrogen carriers that have insignificant losses during the reconversion process, namely compressed hydrogen and $NABH_4$. Decompression of compressed hydrogen doesn't require any energy input (IRENA, 2019) while $NaBH_4$ has a self-sustaining self-hydrolysis process during reconversion (Abdelhamid, 2021). However, there are other losses sustained during reconversion of $NaBH_4$ when considering the regeneration losses after each cycle of hydrolysis (Ouyang et al, 2018).

Other hydrogen carriers require more energy during reconversion. Re-gasification of liquefied hydrogen will require approximately 9% of energy content losses (Popov, 2019). For ammonia reconversion, the cracking process will incur losses of up to 16% energy content (Rassi, 2002). Research have also shown that the dehydrogenation process of LOHC such as Toluene or MCH will be in the range of 12-30% (Popov, 2019).

	Energy Re-Conversion (Un-Packing) Losses	Scoring	Reference
Liquid Hydrogen	Re-gasification at 9%	2	Popov, 2019
Compressed Hydrogen (700bar)	insignificant losses	3	IRENA, 2019
Chemical Hydrogen (NH3)	Cracking losses at 16%	1	Rassi, 2002 BEIS, 2020
Metal Hydride (NaBH4)	Self – Hydrolysis at 5% + NaBH4 regeneration losses of 24%	1	Abdelhamid, 2021 Ouyang et al, 2018
LOHC (MCH)	De-hydrogenation at 12%	1	IRENA ,2019 S.P Popov, 2019

Table 19 - Scoring of Re-Conversion/Un-packing Costs

Storage Management

Qualitative assessment was made on the hydrogen carrier management cost when transporting the hydrogen via shipping. Stable hydrogen carrier such as LOHC can be safely stored and shipped at ambient temperature and pressure which is stable and requires minimum storage management (Ritvard et al, 2019).

Although there is a high CAPEX required for the storage tanks and high associated energy losses for the packing of compressed hydrogen for shipping such as pre-cooling, there is no thermal management needed for the management of the compressed hydrogen during shipping (Ritvard et al, 2019). Similarly, ammonia has similar properties as LPG (BEIS, 2020) and can be easily transported at ambient temperature and minimal pressure management of 10 bars (Ritvard et al, 2019).

Boil-off losses due to storage is a critical issue for extreme low temperature hydrogen carriers during the transportation voyage. Liquefied hydrogen will have to be shipped at -253^{o}C (Rivard et al, 2019) and huge amount of thermal management systems will be required to restrict the daily boil off to be less than 0.03% per day (Popov, 2019).

$NaBH_4$ is shipped in powder form and is relatively stable in the solid state given its decomposition temperature is more than 500^{o}C at sea level (Mao et al, 2014). However, water-tight and dry cargo management is needed due to the hydrolysis process in which hydrogen is released (Popov, 2019).

	Carrier Management Requirements	Scoring	Reference
Liquid Hydrogen	High	1	Ritvard et al, 2019 Popov, 2019
Compressed Hydrogen (700bar)	Low	2	Ritvard et al, 2019
Chemical Hydrogen (NH3)	Low	2	Ritvard et al, 2019 BEIS, 2020
Metal Hydride (NaBH4)	Low	2	Mao et al, 2014 Popov, 2019
LOHC (MCH)	Insignificant	3	Ritvard et al, 2019

Table 20 - Scoring of Storage Management

4.1.4 Criteria Scoring – By-Products

There are no by-products when switching hydrogen to the compressed or liquid form. Ammonia which is formed by combining hydrogen and nitrogen can be broken down to nitrogen and hydrogen through cracking; with the resultant by-product nitrogen

(BEIS, 2020). Metal hydrides such as $NaBH_4$ needs to be regenerated after each use and costly thermo-chemical, mechano-chemical and electrochemical processes will be needed. The cost of storing hydrogen in the cheapest metal hydride is approximately USD 700/kg after taking into consideration raw material and processing cost (Bevan et al, 2011). It has been reported that efficient regeneration methods are already present but will need more improvements in terms of cost per usage (Nunes et al, 2021). LOHC degrades at 0.1% per cycle (Hurskainen et al, 2020) and will have to be disposed after their usable cycles (approximately 1000 cycles) are completed.

	By-Products for Hydrogen Carrier	Scoring
Liquid Hydrogen	No by-products.	3
Compressed Hydrogen (700bar)	No by-products.	3
Chemical Hydrogen (NH3)	Cost efficient by-product Nitrogen	2
Metal Hydride (NaBH4)	Requires $NaBH_4$ medium which needs regeneration	1
LOHC (MCH)	0.1% degradation per cycle	1

Table 21 - Scoring of By-Products and Associated Costs

4.1.5 Criteria Scoring - Safety

Safety of the hydrogen carrier is important especially when being moved through the supply chain. Given that hydrogen carrier will be transported as an energy fuel, the safety criteria of toxicity and flammability are assessed and graded based on the Globally Harmonised System of Classification and Labelling of Chemicals standards (UN, 2011). Datasheets of the different hydrogen carriers were collected, recorded and compared to the scoring criteria; refer to Appendix B for the datasheets. The hydrogen carriers are all generally flammable as they have high energy content and are generally non-toxic except for LOHC.

	Flammability	Scoring	Toxicity	Scoring
Liquid Hydrogen	Cat 1	1	Cat 5	5
Compressed Hydrogen (700bar)	Cat 1	1	Cat 5	5
Chemical Hydrogen (NH3)	Cat 2	2	Cat 4	4
Metal Hydride (NaBH4)	Cat 2	1	Cat 3	3
LOHC (MCH)	Cat 2	2	Cat 2	2

Table 22 - Scoring of Hydrogen Carrier Based on GHS Rating on Flammability and Toxicity

4.1.6 Criteria Scoring – Regulatory (Maritime)

The successful adoption of a hydrogen carrier is dependent on the ability for cross-continental maritime transportation. Vessels used for shipping the hydrogen carriers in bulk will need to follow international regulations set by the IMO as well as IACS classification rules. Ammonia shipping in bulk has been around since 100 years ago (Llyods Register, 2021) and currently also uses existing approved LPG carriers while Liquid hydrogen shipping in bulk was given interim approval by IMO in 2016 through resolution MSC.420(97)[18] and compressed hydrogen has only recently obtained in-principle classification approvals[19] for the development of compressed hydrogen vessels (GEV, 2021). Shipping of solid powder $NaBH_4$ can be done via existing bulk carriers (Mao et al, 2014) while LOHC such as Toluene/MCH is also able to use existing oil tankers for transportation in huge amount but such dedicated vessels have yet to be fully approved by all regulatory bodies (Tijdgat, 2020).

[18] *Resolution MSC.420(97) (adopted on 25 November 2016) is for Interim Recommendations for Carriage of Liquefied Hydrogen in Bulk Source: https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MSCResolutions/MSC.420(97).pdf*

[19] *Some of vessel designs that were awarded approval in-principle are from GEV (https://gev.com/wp-content/uploads/2021/03/gev-receives-approval-in-principle-for-c-h2-ship.pdf) and Wartsila (https://www.wartsila.com/media/news/04-11-2021-wartsila-s-decarbonisation-focus-emphasised-with-approval-in-principle-for-gevs-pilot-hydrogen-vessel-3001446)*

	Regulatory Framework and Classification Schemes	Scoring
Liquid Hydrogen	Pilot vessel in operation, awaiting IMO IGC code approval	2
Compressed Hydrogen (700bar)	Approval in Principle by Classification, Awaiting IMO IGC code approval	2
Chemical Hydrogen (NH_3)	Approved; existing vessels	3
Metal Hydride ($NaBH_4$)	Possibility of shipping via bulk carrier but not yet approved.	1
LOHC (MCH)	Possibility of shipping via existing oil tankers but not yet approved	1

Table 23 - Scoring on Regulations

4.1.7 Final Scoring and Selection

Figure 11 contains the tabulated results of the criteria performance of each hydrogen carrier option. Based on the selection criteria results (presented in Appendix B), the three most desirable hydrogen carrier at present day would be compressed hydrogen, liquefied hydrogen and ammonia.

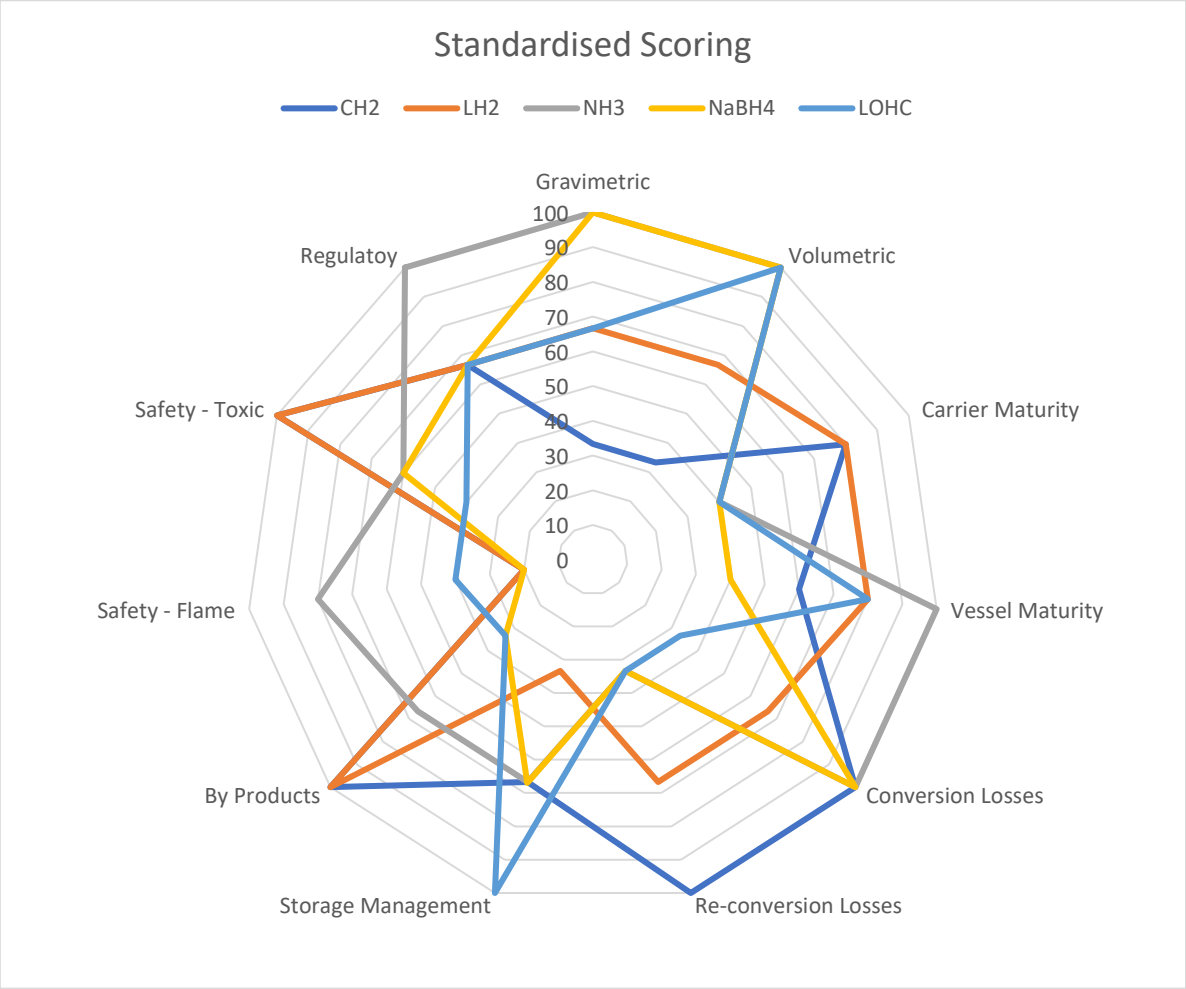


Figure 13 - Illustration of Standardised Scores of Hydrogen Carriers Based on Criteria

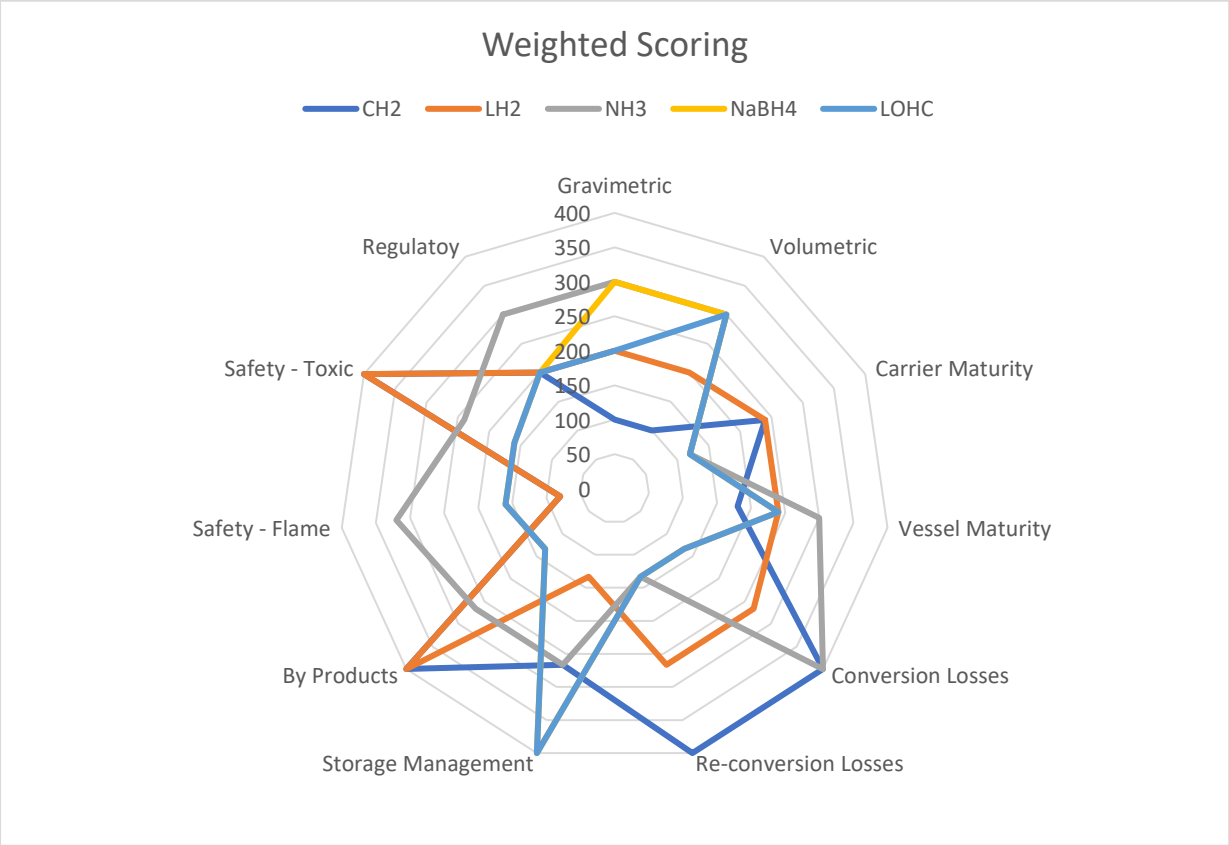


Figure 14 - Illustration of Weighted Scores of Hydrogen Carriers Based on Criteria

4.2 Case Study Comparison

4.2.1 Hydrogen Carrier Routes

The case study compares the levelized cost of hydrogen across the three selected hydrogen carriers[20] supply pathway, starting from the initial production process till delivery at the end destination as pure hydrogen. The supply pathway will consist of the following four stages

1. Green hydrogen production,
2. Hydrogen conversion or packing to hydrogen Carrier
3. Hydrogen carrier storage and transportation,
4. Hydrogen carrier re-conversion or unpacking to hydrogen

[20] *See MCDA results from section 4.1.7*

For this study, we have standardised the green hydrogen production across all different hydrogen carriers. The difference in the levelized cost of hydrogen (LCOH) will be derived from the different processes of each hydrogen carrier at each stage of the supply pathway.

4.2.2 Levelised Cost of Hydrogen

Each hydrogen carrier undergoes different processes in each stage of the supply pathway. The processes are described and compared in the following Figure 12. Compressed hydrogen has the least number of processes throughout the full supply chain as compared to the other hydrogen carriers.

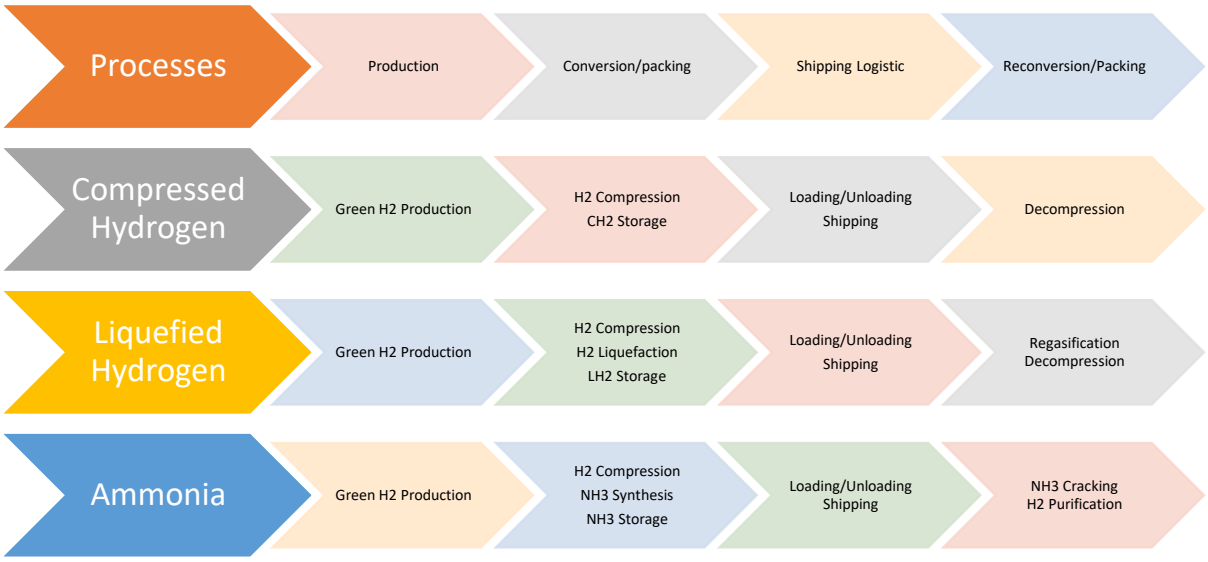


Figure 15 - Hydrogen Carrier Supply Pathway Processes

Source: (GEV, 2021) (IRENA, 2019)

4.2.2.1 Levelised Cost of Hydrogen - Production Component

The main variables that are critical to the LCOH of green hydrogen would be the CAPEX of the electrolyser and the cost of renewable energy used for electrolysis (IRENA, 2019). The technology for Alkaline electroylser is the most matured among the selection and has also the lowest current-day CAPEX cost (see table 23). It has also demonstrated large scale hydrogen production with up to 1000m^3/h already achieved. However, alkaline electroylsers have been disadvantaged by operational maintenance issues such as corrosion and number of components needed (Guo et al, 2019). Promising alternative electrolysers such as PEM and SOEC do not have such issues but are disadvantaged by the existing level of technology maturity and current-

day CAPEX costs (Bai et al, 2009). Alkaline electrolysers, which have the lowest CAPEX, are expected to cost 840 USD/kW and such CAPEX will likely be reduced to 200 USD/kW by 2050 (IRENA, 2019).

	Alkaline Electrolyser		PEM		SOEC	
	Today	Long Term	Today	Long Term	Today	Long Term
Electrolysis Efficiency (% LHV)	64	77	60	72	80	85
Operating Pressure (Bar)	1-30		30-80		1	
Stack Lifetime (thousand hours)	60-90	100-150	30-90	100-150	10-30	75-100
Load Range (%)	10-110		0-160		20-100	
CAPEX (USD/KWe)	500-1400	200-700	1100-1800	200-900	2800-5600	500-1000

Table 24 - Techno-Commercial Specification of Commonly Used Electrolysers

Source: IRENA, 2019 and Tijdat. 2020

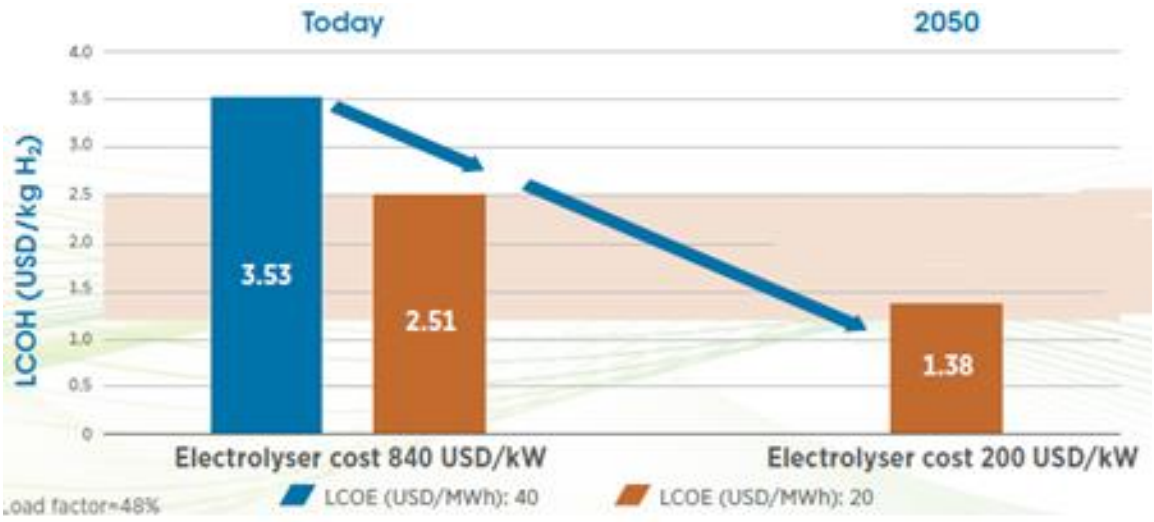


Figure 16 - LCOH of Green Hydrogen Based on Electrolyser CAPEX and LCOE

Source: (IRENA, 2019)

The next important parameter that would affect the levelised cost of green hydrogen produced would be the source of green electricity used. As shown in above figure 13, a reduction on the cost of electricity would reduce the cost of hydrogen produced.

To obtain the LCOH for green hydrogen production, the study considered the two most common and technological matured renewable energy sources e.g. solar PV and

wind. When considering an average energy cost for both solar and wind, the LCOH would be around 6.80 USD/kg H_2 and 4.30 USD/kg H_2 respectively. On the cost-effective low end, renewable energy from solar can provide a cheaper energy cost but has the disadvantage of only having output during sunlight hours which resulted in an overall higher LCOH of 3.20 USD/kg H_2 versus a LCOH of 2.70 USD/kg H_2 (IRENA, 2019). The cost-effective range of LCOH of 2.70-3.20 USD/kg H_2 is within the estimates of 1.50-3.50 Euros/kg H_2[21] as specified in the European Commission hydrogen study (EC, 2021).

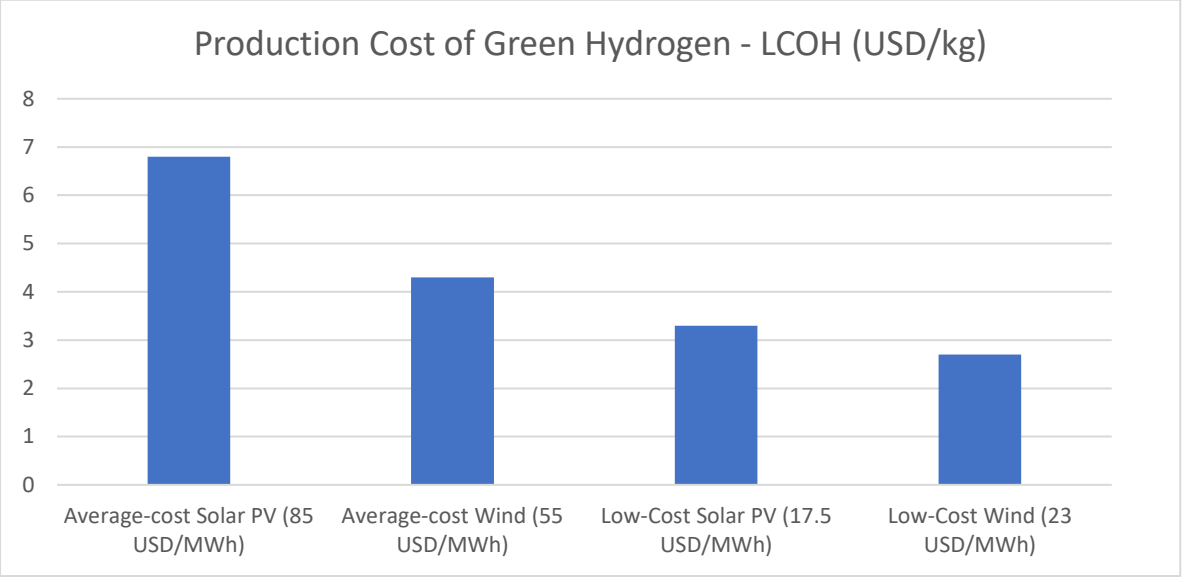


Figure 17 - LCOH of Green Hydrogen Based on Different Priced Renewable Source (Wind and Solar)

Source: (IRENA, 2019)

4.2.2.2 Levelised Cost of Hydrogen - Conversion Component

Hydrogen is typically compressed up to 300 bars for transportation by either using centrifugal or reciprocal compressors; both which can be driven by electric motors or gas turbine (Mokhatab et al, 2006). Costing studies done by NREL (2014) has previously estimated that the cost of compressing H_2 for transportation would be around 1.54 USD/kg H_2. Other more recent study by EC (2021) has provided a range of compression cost of 0.58 USD/kg H_2 to 0.80 USD/kg H_2 (Hydrogen Council, 2020).

For the conversion component for liquid hydrogen, the LCOH would be determined by cost of processes such as hydrogen compression, preparation, liquefaction and load-

[21] *Based on exchange rate of 1 euro to 1.16 USD, the LCOH range for the EC study is 1.74-4.06USD/kg*

out to the vessel (CEFC, 2021). The low range of the conversion would be approximately 0.90 USD/kg H2 to 1.60 USD/kg H2 (Hydrogen Council, 2020). There are several other studies that have obtained packing cost of liquefied hydrogen from 0.80 USD/kg H_2 (EU, 2021) to the high estimates of 1.89 USD/kg H_2 (Gallardo et al, 2021) and 2.00[22] USD/kg H_2 (Connelly et al, 2019).

The main variable in the synthesis process of ammonia would be the energy source. Synthesis LCOH ranges from 0.73 USD/Kg H_2 when using renewable energy that has a constant supply stream such as wind and up to 1.89 USD/kg H_2 when using only solely PV (Gallardo et al, 2021). Other European study (EC, 2021) also put the packing cost of Ammonia to be 0.70-1.16 USD/Kg H_2.

4.2.2.3 Levelised Cost of Hydrogen - Shipping Component

For the shipping component, the focus of the study is on cross-continental transportation from the supply to demand hub where only shipping and related logistical cost was considered.

Given that compressed hydrogen vessel is in the conceptual phase, the shipping cost will have to be compared from similar compressed natural gas vessels. When taking into consideration the shipping distance from Australia to Singapore (2000nm, 3600km) and Japan (4000nm, 7200km), the LCOH for the shipping component is estimated to be from 0.80-1.70 Euro/kg or 0.93-1.97 USD/kg H_2 (Figure 12)[23]. The cost of shipping compressed hydrogen increases by 100% for every additional 5000km transported, decreasing the economic feasibility for shipping outside the Asia-Pacific region.

[22] *Excluding profits, financing and equity cost*
[23] *Studies from the European Union is based on the shipping case of 1 million tons of hydrogen annually by maritime.*

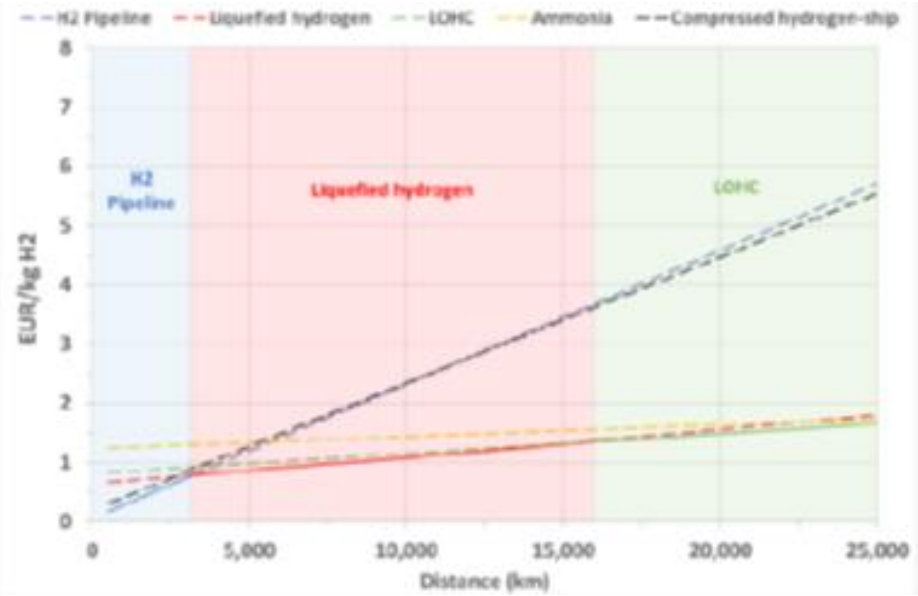


Figure 18 - Cost for Maritime Transportation of Hydrogen Carriers

Source: European Union, 2021

For liquefied hydrogen, shipping cost within Asia-Pacific at present day may cost approximately 15 USD/kg H_2 but it is expected to be reduced to 1.70 USD/kg H_2 by 2030 when more of the liquefied hydrogen vessels gets into service (Hydrogen Council, 2020). When taking into consideration the shipping distance from Australia to Singapore (2000nm, 3600km) and Japan (4000nm, 7200km), the LCOH for the shipping component would be around from 0.93-1.16 USD/kg H_2 (reference from table 15).

One of the key advantages of ammonia as a hydrogen carrier is its associated shipping cost. With a very matured supporting maritime infrastructure, the present-day shipping cost varies from 0.30 USD/kg H_2 (BEIS, 2020) to 0.50 USD/kg H_2 (CEFC, 2021).

4.2.2.4 Levelised Cost of Hydrogen – Re-Conversion Component

The reconversion stage of the hydrogen carrier is for delivery of pure hydrogen for use at the destination. Unlike chemical hydrogen carriers, compressed and liquefied hydrogen does not need energy intensive chemical processes like dehydrogenation or cracking. For compressed hydrogen, throttling of the pressurized hydrogen will need to be conducted to reduce the pressure to delivery pressure while liquefied hydrogen will have to undergo gasification process through the application of heat (GEV, 2021). The reconversion cost process for compress hydrogen is estimated to be 0.10 US/kg H_2 (EC, 2021) and 0.17 USD/kg H_2 (NREL, 2014) while the gasification process of

liquefied hydrogen is estimated to range from 0.10 USD/kg H_2 (GEV, 2021) to 0.20 USD/kg H_2 from Table 12 (IEA, 2019).

The extraction of pure hydrogen from ammonia will require cracking. Efficiencies of present-day small-scale ammonia crackers ranges from 75-85% (Tijdat, 2020) but there are many intermediate processes such as ammonia reforming, recovery, purification and compression before gaseous hydrogen can be delivered (BEIS, 2020). As the technology for large scale ammonia crackers have not been fully adopted, the reconversion cost estimates of ammonia varies. IEA (2020) estimates that reconverting ammonia to hydrogen to cost around 1.10 USD/kg H_2 while studies with higher end costing put ammonia cost to be around 2.50USD/kg H_2 (IRENA, 2018) to 4.70USD/kg H_2 (BEIS, 2020).

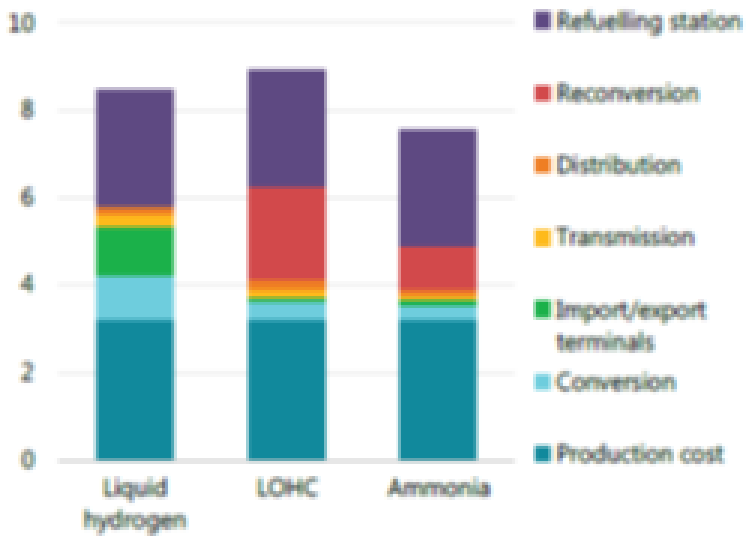


Figure 19 - Cost Breakdown of Shipped Hydrogen (including Reconversion)

Sources: (IEA, 2019)

4.2.2.5 Levelised Cost of Hydrogen – Total

To compare the different hydrogen carrier options, the total levelized cost of hydrogen was tabulated after taking into consideration the four stages of the hydrogen supply chain. The final LCOH is presented in Figure 17 below.

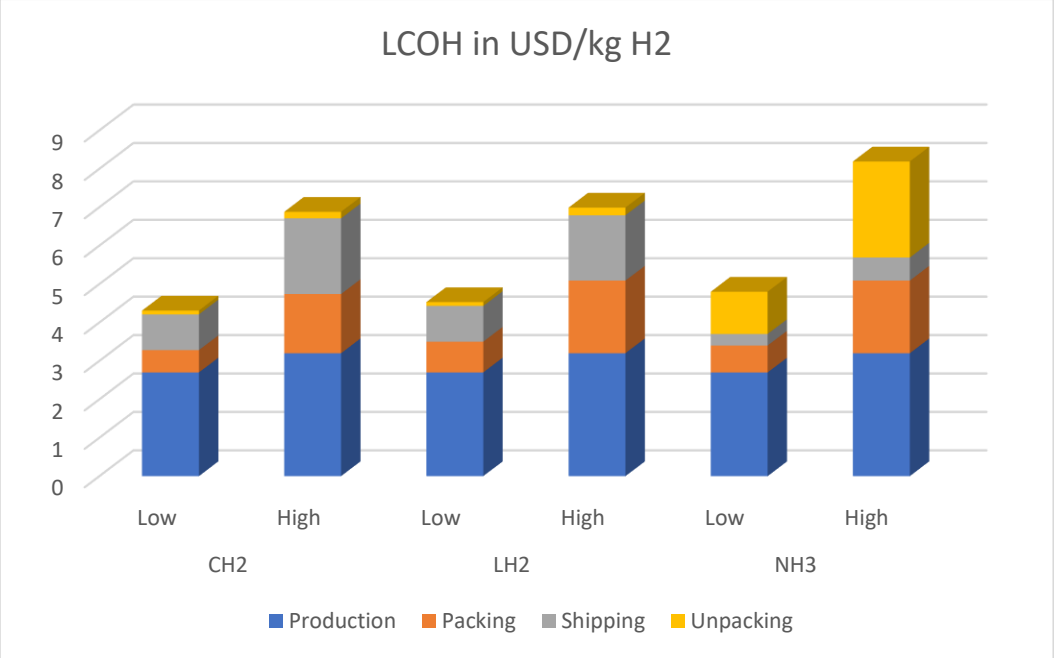


Figure 20 - Final LCOH (Low and High) of CH_2, LH_2 and NH_3

The LCOH of the three hydrogen carriers remains competitive in the low-end costing estimates (including the shorter voyage parameter). In the high-end costing estimates of the supply chain, the competitiveness of compressed hydrogen is reduced against liquefied hydrogen. In both cases, compressed hydrogen supply chain is still determined to be more cost competitive hydrogen carrier for an Asia-Pacific case study.

5 Discussion

The results of the study are discussed in this chapter. The study provides an indication on the selection of suitable hydrogen carriers through the MCDA analytical framework. Indicative LCOH values used for the case study has been based on literature research. Limitations and assumptions of the study are addressed and suggestions for further research are also provided.

5.1 Case Selection

The case selection of hydrogen carriers for evaluation in section 2.4 takes into consideration GHG produced during the packing and/or unpacking processes. As such, carbon-based hydrogen carriers such as synthetic natural gas, methanol, ethanol and dimethylether (DME) were not considered due to the emission of CO2 at the unpacking process. This restricted the study to the more commonly known hydrogen carriers that is compared in this thesis and other studies from IRENA (2019), EC (2020) and Hydrogen Council (2020). Further studies can be done to compare the cost effectiveness of all forms of hydrogen carriers given that the LCOH of carbon-based hydrogen carriers could also be more cost effective due to existing technological maturity.

5.2 Selection Criteria Results

The MCDA framework was set up to measure and evaluate the different hydrogen carrier options which cannot be easily compared directly. The framework used hydrogen-as-a-fuel characteristics as the basis to select the relevant criteria. Selection of the different criteria were done through both literature review as well as stakeholder involvement. Qualitative and quantitative data sets from different literatures and studies were first combined to successfully analyse the hydrogen carrier options; survey results from stakeholders were then taken into consideration to reduce the study bias of the shortlisted criteria. Direct rating weightage of each criteria were also sought from the stakeholders in the engagement. The final MCDA result matrix summed-up the relative strength and weakness of each hydrogen carrier and provided a viable ranking among the carriers. In addition, the selection results of the top three viable hydrogen carriers does tally with other comparison studies done by IRENA (2019) and GEV (2021). However, there could be further refinements on the number

of selected criteria, weighting factors of the criteria and lastly the measurement scale within the MCDA framework which may tweak the top three ranking.

Criteria

Through basic PEST analysis, ten sub-criteria were considered relevant in evaluating the different hydrogen carrier options. The selection of the criteria was completed based on academic research and similarities from the LNG industry. PEST analysis, being a generic macro environment assessment tool, is best suited for the MCDA approach taken in the study as it provided guidelines in identifying key parameters and conceptually evaluating the relative importance of each parameter for decision-making (Iacobidou et al, 2017). However, there are some areas of improvement that can be made in the criteria selection. One key area is the number of criteria considered. The direct survey guidelines scoped the criteria to be within the PEST format but more criteria could be obtained from extended industry surveys and interviews with other industry experts. This would result in a more throughout evaluation of the different hydrogen carriers during the MCDA selection. This could be further expanded in future studies.

Weighting Factors

The weighting of each criteria can significantly influence the outcome of the MCDA process and weighting allocated to each qualitative and quantitative should be criteria (Odu, 2019); the current study took a simplistic approach by using a direct rating weight determination of the main four criteria under the PEST format from the stakeholders. This simplistic approach does not give individual sub-criteria weight which could likely further refine the final scoring of the MCDA. More complex weighing method (which was not used in this study) requires additional relativity comparison determination of each criteria against the other and will require a more complex stakeholder survey with a significantly bigger stakeholder base for inputs (Odu, 2019).

Future studies could include having more complex relative weighting factors based on inputs from different techno-commercial stakeholders such as energy and maritime authorities, shipping companies and end users. When undertaking such inputs, it is to be noted that a balanced selection of technical and commercial stakeholders will be

required to prevent skewed weighting due to specialization of the stakeholder e.g., commercial criteria being weighted more by commercial experts (Maas, 2020).

Measurement Scales

The measurement scales of the criteria in the study were a mix of qualitative and quantitative due to lack of accurate data especially for criteria like shipping management systems as well as by-products. The increased usage of the new hydrogen carriers and associated vessels in the future will provide more data points for comparison and such criteria could then be measured on an ordinal scale. Future research could include measuring these criteria quantitatively which could provide a more precise result for the study.

5.3 Case Study Results

The selection of the case study using an intra-Asia-Pacific scenario was taken due to the perceived global hydrogen supply and demand scenario. Australian hydrogen supply was proposed due to the multiple projects announced for green hydrogen export with expected demand centres in Japan and Singapore (GEV, 2021).

Green Hydrogen Production

The LCOH from green hydrogen production has been significantly researched and published. Current green hydrogen production cost is heavily impacted by the LCOE of production and the existing electroyser's CAPEX and OPEX. LCOE from green energy source such as solar and wind are expected to decrease in the near future with the improvement of renewable technologies and the increased in scale of the renewable farms at cost competitive renewable hubs such as Australia and South Africa (RINA, 2021). It is also expected that technological improvement of next generation electroysers will also significantly aid in the cost decrease of green hydrogen production.

Hydrogen Conversion/Packing

It has been observed that the LCOH of each hydrogen carrier is dependent on the complexity and technological maturity of the conversion/packing process. Gas compression is a very straight forward process in comparison to liquefication and synthesizing which requires additional energy intensive procedures (GEV, 2021).

However, NH_3 conversion was found to be less costly compared to liquefied H_2 conversion due to an existing matured conversion (synthesising) technology while H_2 liquefaction technology, while already available in small scale, is not commercially available on the large scale (Hydrogen Council, 2020).

Hydrogen Transportation

It is to note that although shipping cost between the three hydrogen carriers was derived through literature review, the LCOH price point for the case study is limited to a reasonable estimate due to the current stage of development of the international logistic network for compressed and liquefied hydrogen. The current fleet of compressed and liquefied hydrogen carriers are very limited in both capacity and numbers which resulted in a much higher predicted shipping cost especially when huge volumes is required to be shipped internationally. However, it is expected that large scale shipping cost for compressed and liquefied hydrogen will decrease over time due to the increase in vessel numbers and improvement for the respective storage technology and capacity of the vessels.

Hydrogen Re-conversion

Unlike the significant impact in LCOH for compressed and liquefied hydrogen in both the conversion and transportation phase, the re-conversion or unpacking phase has less of an impact in terms of LCOH due to the study's consideration of pure hydrogen as the end use. Chemical hydrogen on the other hand is severely limited in the technological immaturity of the cracking technology and high energy demand; the resultant highest relative hydrogen unpacking cost the critical factor in making ammonia uncompetitive. This is in-line with studies by (Hydrogen Council, 2020) which stated that future improvement to the reconversion technology and process will be needed to increase the competitiveness of the ammonia hydrogen carrier option.

Hydrogen Carrier Cost-Competitiveness Conclusion

In summary, the key finding of the study is that among the existing hydrogen carrier supply chain, compressed hydrogen is the most feasible and cost-competitive option when shipping from Australia to demand centres within the Asia-Pacific region. The cost competitiveness comes from the reduced amount of required processes throughout the supply chain. However, this cost advantage is limited to shorter voyage

ranges as compressed hydrogen shipping costs escalates proportionally to the increase in voyage distance.

For longer shipping routes, liquefied hydrogen could serve as a better option (GEV, 2021) but significant increase in shipping and production capacity is required for LCOH to be reduced (Hydrogen Council, 2020). Ammonia could be considered as an alternative given the existing global infrastructure but will require technological advancement in the unpacking process.

6 Conclusion and Recommendations

6.1 Conclusion

The aim of this research study was to evaluate the techno-commercial feasibility of a green hydrogen supply chain through the answering of the main research question (presented in Section 1.3); which is *to determine the extent on how each stage of the hydrogen supply value chain will impact the selection of hydrogen shipping medium to supply the most cost-efficient green hydrogen to the end user.* The sub questions were used to guide the research with each respective answer cumulating to a final response to the main question.

1. What are the different types of hydrogen shipping carrier and the applicability of the carrier for utilization?

In Section 2, the thesis went through the different types of hydrogen carriers such as hydrogen shipping mediums in compressed and liquefied states, chemical hydrogen, hydrogen nitrates as well as LOHC.

2. What is the comparison in terms of cost for producing and transporting the applicable hydrogen shipping carriers?
    a. Can current gas infrastructure and gas carriers be converted for use for transportation of hydrogen and hydrogen derived fuel?

In section 4.2, the thesis illustrated the cost of green hydrogen production by conventional electrolysis method as large-scale biomass hydrogen production has not yet reached technological maturity. As the cost of electricity would be the determining factor for the LCOH for production, average electricity values from differing sources were compared. In section 4.3, the LCOH of the top three hydrogen carriers (Compressed H2, Liquefied H2 and Ammonia) of each stage of the supply chain were compared which includes the packing of the hydrogen carrier prior to shipping, the shipping and the unpacking of the hydrogen carrier at destination. It was observed that compressed hydrogen could be a commercially viable alternative as a hydrogen shipping medium within Asia Pacific, with the lowest LCOH.

In Section 2.4, we could see that current LNG gas carriers and gas infrastructure such as storage tanks will not be able to fully accommodate LH_2 shipping and

storage due to the different storage specification as well as the corrosive behaviour of LH_2. However, ammonia shipping has the current advantage of being able to utilise current LPG vessels and the supporting infrastructure. Compressed H2 could utilise existing CNG vessels but such CNG vessels are also very limited in numbers.

3. What are the different types of hydrogen transportation vessels that are/will be available for shipping and the associated cost of the hydrogen carrier through the different supply chain?

There is a diverse selection of hydrogen carriers that are available for shipping but for this study, the focus has been on hydrogen carriers that has no-carbon expendables like methane (CH_4) or methanol (CH_3OH). The study provided a case selection in Section 2.4 of the different hydrogen carriers such as NH_3, CH_2, LH_2, LOHC and $NaBH_4$ and provide the LCOH comparison of NH_3, CH_2 and LH_2 in Section 4.2.2. It was observed in the case study comparison that CH_2 has the lowest LCOH on the low scale while LH_2 has the lowest LCOH on the high scale.

4. What are the applicable regulations governing the shipping of hydrogen and hydrogen derived medium and the implication on the cost of hydrogen?

In section 4.1.6, the study highlighted the key regulations regarding hydrogen carriers shipping. The main international maritime regulations governing the shipping of hydrogen will be IMO and classification society regulations. Both regulations focus on safety during shipping and the implication on the cost of hydrogen will be on the CAPEX and OPEX of the shipping component.

5. To what extent will future developments in technologies influence the LCOH?

In Section 4.2, we could see that future improvement of green hydrogen production technology such as the efficiency and cost of the electrolysers would significantly reduce the LCOH of green hydrogen. Improvement in the technologies along the supply chain will also provide a positive impact to the LCOH especially in non-matured technologies of compressed and liquefied hydrogen shipping and unpacking of chemical hydrogen like ammonia.

6.2 Recommendations

In this section, limitations of the methodology and recommendations for future works are as follows.

- Case Selection: Given the consideration of GHG production, carbon-based hydrogen carriers were not considered in the MCDA framework. Further studies can be done to compare the cost effectiveness of all forms of hydrogen carriers given that the LCOH of carbon-based hydrogen carriers could also be more cost effective due to existing technological maturity.

- Criteria Selection: More criteria could be considered in the PEST analytic framework to provide a more comprehensive evaluation of the different hydrogen carriers during the MCDA selection.

- Criteria Selection: Future studies could include having more complex weighting methods based on relative importance of each criteria against the other. More extensive stakeholder size from the different techno-commercial stakeholders such as energy and maritime authorities, shipping companies and end users will help reduce the bias (if any) from the stakeholder inputs in any given criteria.

- Case Study – H2 Production: The study only considered green hydrogen production which only accounts for less than 6% of hydrogen produced (Shell, 2017). The usage of Grey hydrogen, which accounts for 94% of hydrogen produced in the world (RINA, 2021) could be considered given the significant reduction in LCOH at the hydrogen production stage (Hydrogen Council, 2020).

- Sensitive Analysis: Further sensitive analysis can be done on the voyage ranges and capacities to verify the cross-over point of optimal hydrogen carrier which was presented in the study done by the European Commission (EC, 2020) and presented in Figure 15.

- Delivered type and quality of commodity: The offtake commodity at demand centre is modelled to be pure hydrogen. Given that the final use of the hydrogen could be for power generation or other industrial uses, the purity of hydrogen

delivered by each hydrogen carrier could be further investigated in future studies. In addition, adjustment to the final delivered commodity could have an impact on the evaluation.

- Transportation Fuel Usage and Efficiency: In future studies, the usage of the hydrogen carrier as a fuel and comparison of the transportation efficiency could be considered.

In summary, even though the three most optimal hydrogen carriers were selected through the MCDA framework and the respective LCOH derived based on the supply chain configuration proposed in this study, there are still additional areas that could be further optimised for enhanced evaluation.

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8 Appendices

Appendices A – Chemical Processes

Processes	Chemical Equations
Steam Reforming	**Steam-Methane Reforming Reaction** $CH_4 + H_2O$ (+heat) → $CO + 3H_2$ **Water-Gas Shift Reaction** $CO + H_2O \rightarrow CO_2 + H_2$ (+small amount of heat)
Electrolysis	$2H_2O$ + Electricity ⇋ $2H_2 + O_2$
Methanol Production	$CO_2 + H_2 \leftrightharpoons CO + H_2O$ ΔH = +41.2 kJ/mol $CO + 2H_2 \leftrightharpoons CH_3OH$ (+ Heat) ΔH = -90.7 kJ/mol $CO_2 + 3H_2 \leftrightharpoons CH_3OH + H_2O$ (+ Heat) ΔH = -49.5 kJ/mol
Schlesinger Process and Bayer Process	**NaBH4 synthesising** $4NaH + B(OCH_3)_3 \rightarrow NaBH_4 + 3NaOCH_3$ $Na_2B_40_7 + 7SiO_2 + 16\ Na + 8H_2 \rightarrow 4NaBH_4 + 7Na_2SiO_3$ **NaBH4 hydration** $NaBH_4 + 2H_2O \rightarrow NaBO_2 + 4H_2$ (+ Heat) ΔH = -75 kJ/mol **NaBH4 recycling** NaBO2 + 2MgH2 → NaBH4 + 2 MgO
Ammonia Synthesis	$N_2 + 3H_2 \leftrightharpoons NH_3$+ Heat ΔH = -92 kJ/mol
LOHC Hydrogenation	**DBT hydrogenation** $C_{21}H_{20}$ + 9H2 ⇋ $C_{21}H_{32}$ + Heat ΔH = -72 kJ/mol **Toulene hydrogenation** $C_7H_8 + 3H_2 \leftrightharpoons C_7H_{14}$ + Heat ΔH = -205 kJ/mol

Table 25 - Chemical Equations

Appendices B – Technology Readiness Level

Technology Readiness Levels (TRLs) is a tool which is used to evaluate technology maturity level. It is globally implemented across public and private sectors.

TRL has nine (9) levels and is separated into three (3) main grouping:

TRLs 1-3 indicating research stages,

TRLs 4-6 indicating developmental stages, and

TRLs 7-9 indicating deployment stages of development.

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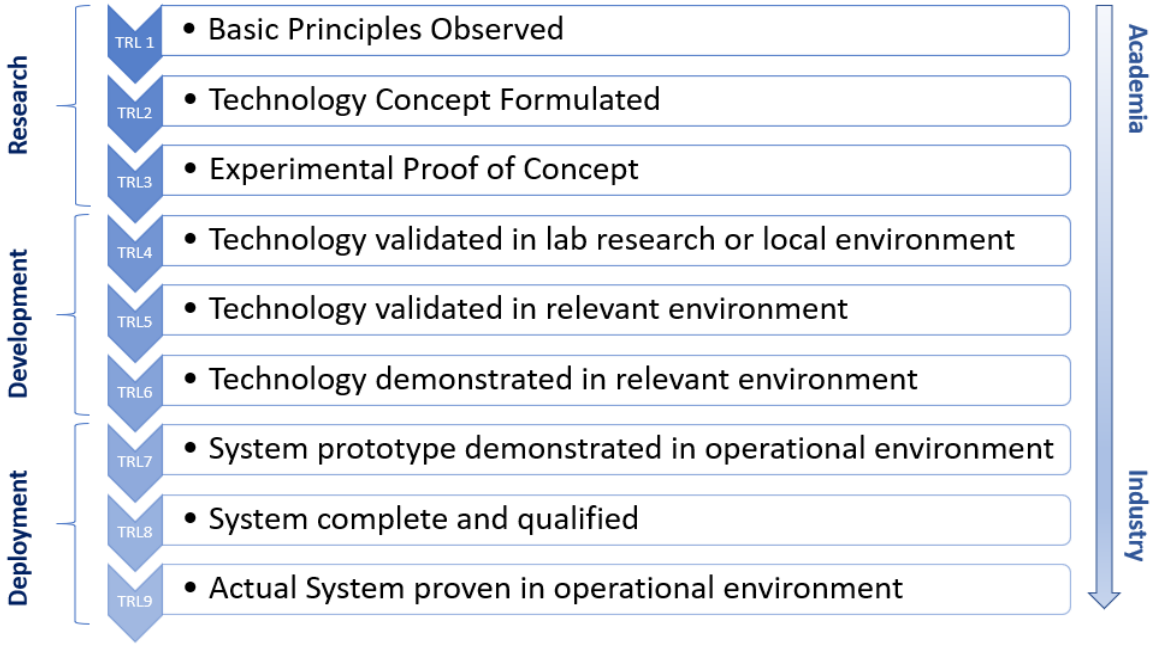


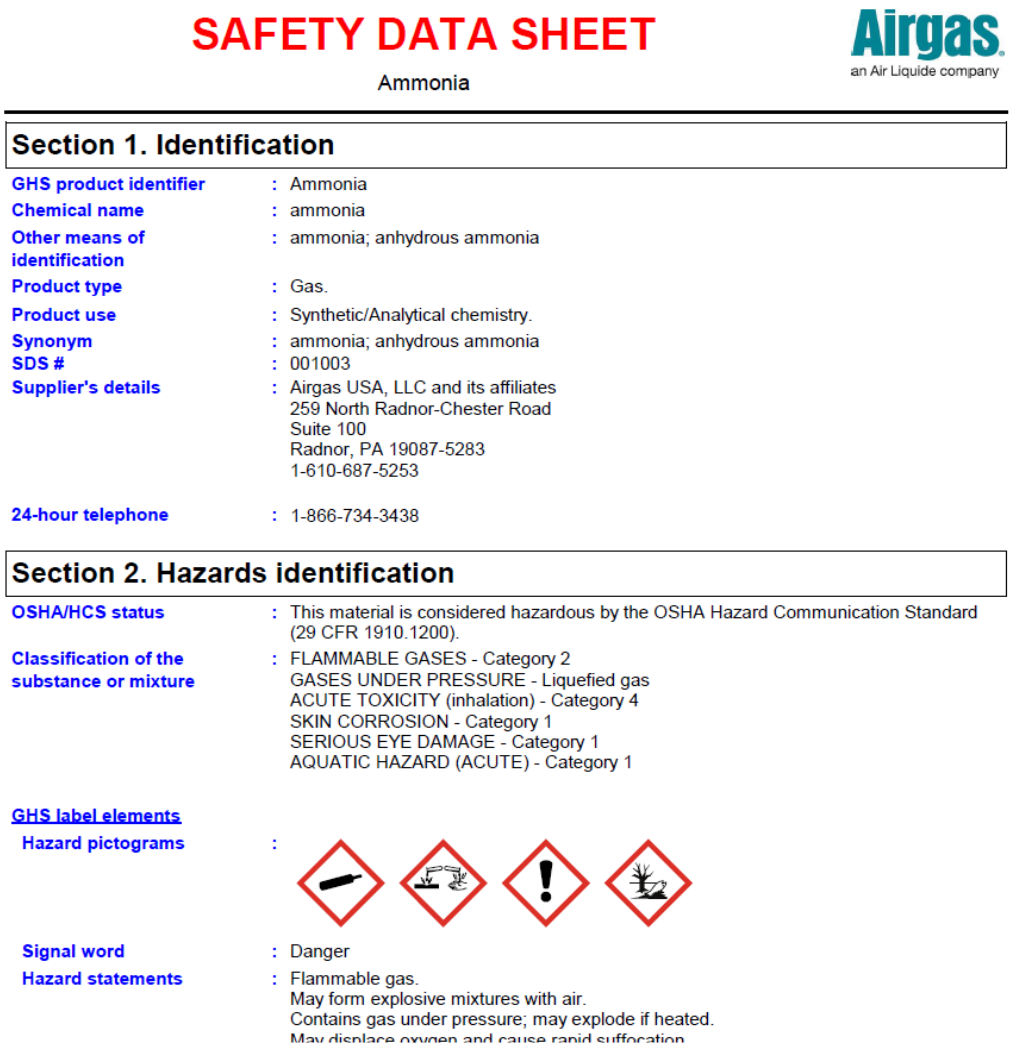
Figure 21 - Technological Readiness Level Representation

Source: Frontier SI https://frontiersi.com.au/trl/

Appendices C – Safety Data Sheets

Assessment of the safety criteria is done by grading each hydrogen carrier based on Globally Harmonised System of Classification and Labelling of Chemicals (GHS) standards (UN, 2011) system. The data has been collected and founded via safety data sheets of each different hydrogen carrier.

Figure X shows a pictorial sample of the safety datasheet for NH3 from Air Liquide



SAFETY DATA SHEET

Ammonia

Airgas
an Air Liquide company

Section 1. Identification

GHS product identifier	:	Ammonia
Chemical name	:	ammonia
Other means of identification	:	ammonia; anhydrous ammonia
Product type	:	Gas.
Product use	:	Synthetic/Analytical chemistry.
Synonym	:	ammonia; anhydrous ammonia
SDS #	:	001003
Supplier's details	:	Airgas USA, LLC and its affiliates 259 North Radnor-Chester Road Suite 100 Radnor, PA 19087-5283 1-610-687-5253
24-hour telephone	:	1-866-734-3438

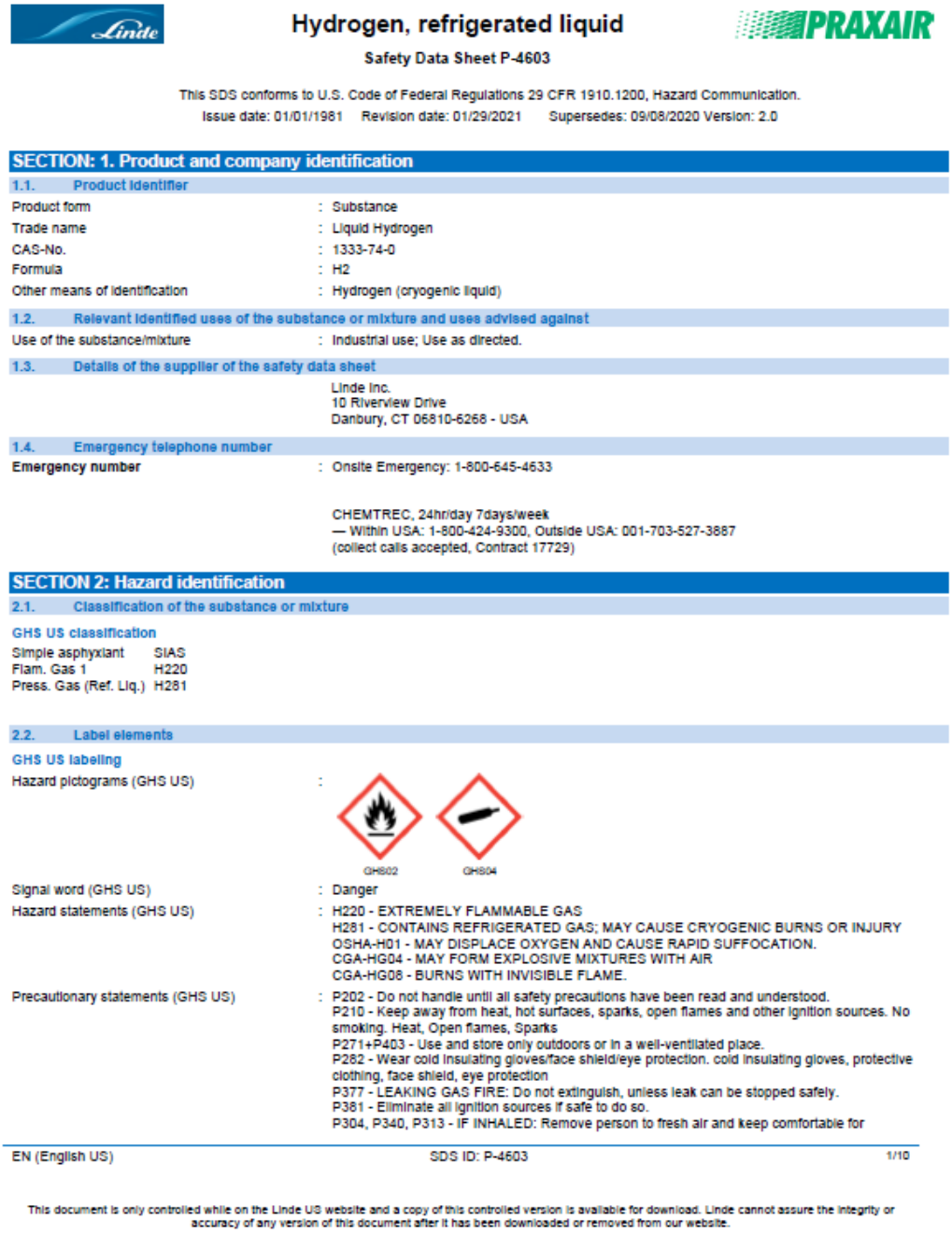
Section 2. Hazards identification

OSHA/HCS status	:	This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).
Classification of the substance or mixture	:	FLAMMABLE GASES - Category 2 GASES UNDER PRESSURE - Liquefied gas ACUTE TOXICITY (inhalation) - Category 4 SKIN CORROSION - Category 1 SERIOUS EYE DAMAGE - Category 1 AQUATIC HAZARD (ACUTE) - Category 1
GHS label elements		
Hazard pictograms	:	
Signal word	:	Danger
Hazard statements	:	Flammable gas. May form explosive mixtures with air. Contains gas under pressure; may explode if heated. May displace oxygen and cause rapid suffocation

Figure 22 - Safety Data Sheet Sample

The different datasheet and scources can be found below

Liquid Hydrogen



Hydrogen, refrigerated liquid

Safety Data Sheet P-4603

This SDS conforms to U.S. Code of Federal Regulations 29 CFR 1910.1200, Hazard Communication.
Issue date: 01/01/1981 Revision date: 01/29/2021 Supersedes: 09/08/2020 Version: 2.0

SECTION: 1. Product and company identification

1.1. Product identifier

Product form	:	Substance
Trade name	:	Liquid Hydrogen
CAS-No.	:	1333-74-0
Formula	:	H2
Other means of identification	:	Hydrogen (cryogenic liquid)

1.2. Relevant identified uses of the substance or mixture and uses advised against

Use of the substance/mixture	:	Industrial use; Use as directed.

1.3. Details of the supplier of the safety data sheet

Linde Inc.
10 Riverview Drive
Danbury, CT 06810-6268 - USA

1.4. Emergency telephone number

Emergency number : Onsite Emergency: 1-800-645-4633

CHEMTREC, 24hr/day 7days/week
— Within USA: 1-800-424-9300, Outside USA: 001-703-527-3887
(collect calls accepted, Contract 17729)

SECTION 2: Hazard identification

2.1. Classification of the substance or mixture

GHS US classification

Simple asphyxiant	SIAS
Flam. Gas 1	H220
Press. Gas (Ref. Liq.)	H281

2.2. Label elements

GHS US labeling

Hazard pictograms (GHS US) :

GHS02 GHS04

Signal word (GHS US) : Danger

Hazard statements (GHS US) : H220 - EXTREMELY FLAMMABLE GAS
H281 - CONTAINS REFRIGERATED GAS; MAY CAUSE CRYOGENIC BURNS OR INJURY
OSHA-H01 - MAY DISPLACE OXYGEN AND CAUSE RAPID SUFFOCATION.
CGA-HG04 - MAY FORM EXPLOSIVE MIXTURES WITH AIR
CGA-HG08 - BURNS WITH INVISIBLE FLAME.

Precautionary statements (GHS US) : P202 - Do not handle until all safety precautions have been read and understood.
P210 - Keep away from heat, hot surfaces, sparks, open flames and other ignition sources. No smoking. Heat, Open flames, Sparks
P271+P403 - Use and store only outdoors or in a well-ventilated place.
P282 - Wear cold insulating gloves/face shield/eye protection. cold insulating gloves, protective clothing, face shield, eye protection
P377 - LEAKING GAS FIRE: Do not extinguish, unless leak can be stopped safely.
P381 - Eliminate all ignition sources if safe to do so.
P304, P340, P313 - IF INHALED: Remove person to fresh air and keep comfortable for

EN (English US) SDS ID: P-4603 1/10

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Figure 23 - LH2 Safety Data Sheet

Source: https://www.lindeus.com/-/media/corporate/praxairus/documents/sds/hydrogen/liquid-hydrogen-gas-h2-safety-data-sheet-sds-p4603.pdf?la=en

Compressed Hydrogen

SAFETY DATA SHEET

Hydrogen

Airgas
an Air Liquide company

Section 1. Identification

GHS product identifier	:	Hydrogen
Chemical name	:	hydrogen
Other means of identification	:	Dihydrogen; o-Hydrogen; p-Hydrogen; Molecular hydrogen; H2; UN 1049
Product type	:	Gas.
Product use	:	Synthetic/Analytical chemistry.
Synonym	:	Dihydrogen; o-Hydrogen; p-Hydrogen; Molecular hydrogen; H2; UN 1049
SDS #	:	001026
Supplier's details	:	Airgas USA, LLC and its affiliates 259 North Radnor-Chester Road Suite 100 Radnor, PA 19087-5283 1-610-687-5253
24-hour telephone	:	1-866-734-3438

Section 2. Hazards identification

OSHA/HCS status	:	This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).
Classification of the substance or mixture	:	FLAMMABLE GASES - Category 1 GASES UNDER PRESSURE - Compressed gas

GHS label elements

Hazard pictograms :



Signal word	:	Danger
Hazard statements	:	Extremely flammable gas. Contains gas under pressure; may explode if heated. May displace oxygen and cause rapid suffocation. Burns with invisible flame. May form explosive mixtures with air.

Precautionary statements

General	:	Read and follow all Safety Data Sheets (SDS'S) before use. Read label before use. Keep out of reach of children. If medical advice is needed, have product container or label at hand. Close valve after each use and when empty. Use equipment rated for cylinder pressure. Do not open valve until connected to equipment prepared for use. Use a back flow preventative device in the piping. Use only equipment of compatible materials of construction. Approach suspected leak area with caution.
Prevention	:	Keep away from heat, hot surfaces, sparks, open flames and other ignition sources. No smoking.
Response	:	Leaking gas fire: Do not extinguish, unless leak can be stopped safely. In case of leakage, eliminate all ignition sources.
Storage	:	Protect from sunlight. Store in a well-ventilated place.
Disposal	:	Not applicable.
Hazards not otherwise classified	:	In addition to any other important health or physical hazards, this product may displace oxygen and cause rapid suffocation.

Figure 24 - CH2 Safety Data Sheet

Source: https://www.airgas.com/msds/001026.pdf

NH3

SAFETY DATA SHEET

Ammonia

Airgas
an Air Liquide company

Section 1. Identification

GHS product identifier	:	Ammonia
Chemical name	:	ammonia
Other means of identification	:	ammonia; anhydrous ammonia
Product type	:	Gas.
Product use	:	Synthetic/Analytical chemistry.
Synonym	:	ammonia; anhydrous ammonia
SDS #	:	001003
Supplier's details	:	Airgas USA, LLC and its affiliates 259 North Radnor-Chester Road Suite 100 Radnor, PA 19087-5283 1-610-687-5253
24-hour telephone	:	1-866-734-3438

Section 2. Hazards identification

OSHA/HCS status	:	This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).
Classification of the substance or mixture	:	FLAMMABLE GASES - Category 2 GASES UNDER PRESSURE - Liquefied gas ACUTE TOXICITY (inhalation) - Category 4 SKIN CORROSION - Category 1 SERIOUS EYE DAMAGE - Category 1 AQUATIC HAZARD (ACUTE) - Category 1

GHS label elements

Hazard pictograms :



Signal word	:	Danger
Hazard statements	:	Flammable gas. May form explosive mixtures with air. Contains gas under pressure; may explode if heated. May displace oxygen and cause rapid suffocation. Harmful if inhaled. Causes severe skin burns and eye damage. Very toxic to aquatic life.

Precautionary statements

General	:	Read and follow all Safety Data Sheets (SDS'S) before use. Close valve after each use and when empty. Use equipment rated for cylinder pressure. Do not open valve until connected to equipment prepared for use. Use a back flow preventative device in the piping. Use only equipment of compatible materials of construction. Always keep container in upright position. Approach suspected leak area with caution.
Prevention	:	Wear protective gloves. Wear eye or face protection. Wear protective clothing. Keep away from heat, hot surfaces, sparks, open flames and other ignition sources. No smoking. Use only outdoors or in a well-ventilated area. Avoid release to the environment. Avoid breathing gas. Wash hands thoroughly after handling.

Figure 25 - NH3 Safety Data Sheet

Source: https://beta-static.fishersci.com/content/dam/fishersci/en_US/documents/programs/education/regulatory-documents/sds/chemicals/chemicals-a/S25164.pdf

NaBH4



Part of Thermo Fisher Scientific

SAFETY DATA SHEET

Creation Date 29-Jan-2010 **Revision Date** 26-Dec-2014 **Revision Number** 1

1. Identification

Product Name Sodium borohydride

Cat No. : S678-10; S678-25

Synonyms SBH; Sodium tetrahydroborate (Powder)

Recommended Use Laboratory chemicals.

Uses advised against No Information available

Details of the supplier of the safety data sheet

Company
Fisher Scientific
One Reagent Lane
Fair Lawn, NJ 07410
Tel: (201) 796-7100

Emergency Telephone Number
CHEMTREC®, Inside the USA: 800-424-9300
CHEMTREC®, Outside the USA: 001-703-527-3887

2. Hazard(s) identification

Classification
This chemical is considered hazardous by the 2012 OSHA Hazard Communication Standard (29 CFR 1910.1200)

Substances/mixtures which, in contact with water, emit flammable gases	Category 1
Acute oral toxicity	Category 3
Skin Corrosion/irritation	Category 1
Serious Eye Damage/Eye Irritation	Category 1
Reproductive Toxicity	Category 1B
Specific target organ toxicity (single exposure)	Category 3
Target Organs - Respiratory system, Central nervous system (CNS).	

Label Elements

Signal Word
Danger

Hazard Statements
In contact with water releases flammable gases which may ignite spontaneously

Page 1 / 7

Figure 26 - NaBH4 Safety Data Sheet

Source: https://www.eurofinsus.com/media/446935/sodium-borohydride_sb.pdf

LOHC (Toulene)

Safety Data Sheet
according to 29CFR1910/1200 and GHS Rev. 3

Effective date : 01.31.2015 Page 1 of 8

Toluene, Reagent Grade

SECTION 1 : Identification of the substance/mixture and of the supplier

Product name : **Toluene, Reagent Grade**

Manufacturer/Supplier Trade name:

Manufacturer/Supplier Article number: **S25611**

Recommended uses of the product and uses restrictions on use:

Manufacturer Details:

AquaPhoenix Scientific
9 Barnhart Drive, Hanover, PA 17331

Supplier Details:

Fisher Science Education
15 Jet View Drive, Rochester, NY 14624

Emergency telephone number:

Fisher Science Education Emergency Telephone No.: 800-535-5053

SECTION 2 : Hazards identification

Classification of the substance or mixture:



Flammable
Flammable liquids, category 2



Irritant
Skin irritation, category 2
Specific target organ toxicity following single exposure, category 3



Health hazard
Reproductive toxicity, category 2
Specific target organ toxicity following repeated exposure, category 2
Aspiration hazard, category 2

Flam. Liq. 2
Skin Irrit. 2
Repr. 2
STOT SE 3, Central nervous system
STOT RE 2
Asp. Tox. 1
Aquatic Acute 2

Signal word :Danger

Hazard statements:
Highly flammable liquid and vapour
May be harmful if swallowed and enters airways
Causes skin irritation
May cause drowsiness or dizziness
Suspected of damaging fertility or the unborn child
May cause damage to organs through prolonged or repeated exposure
Toxic to aquatic life

Created by Global Safety Management, Inc. -Tel: 1-813-435-5161 - www.gsmsds.com

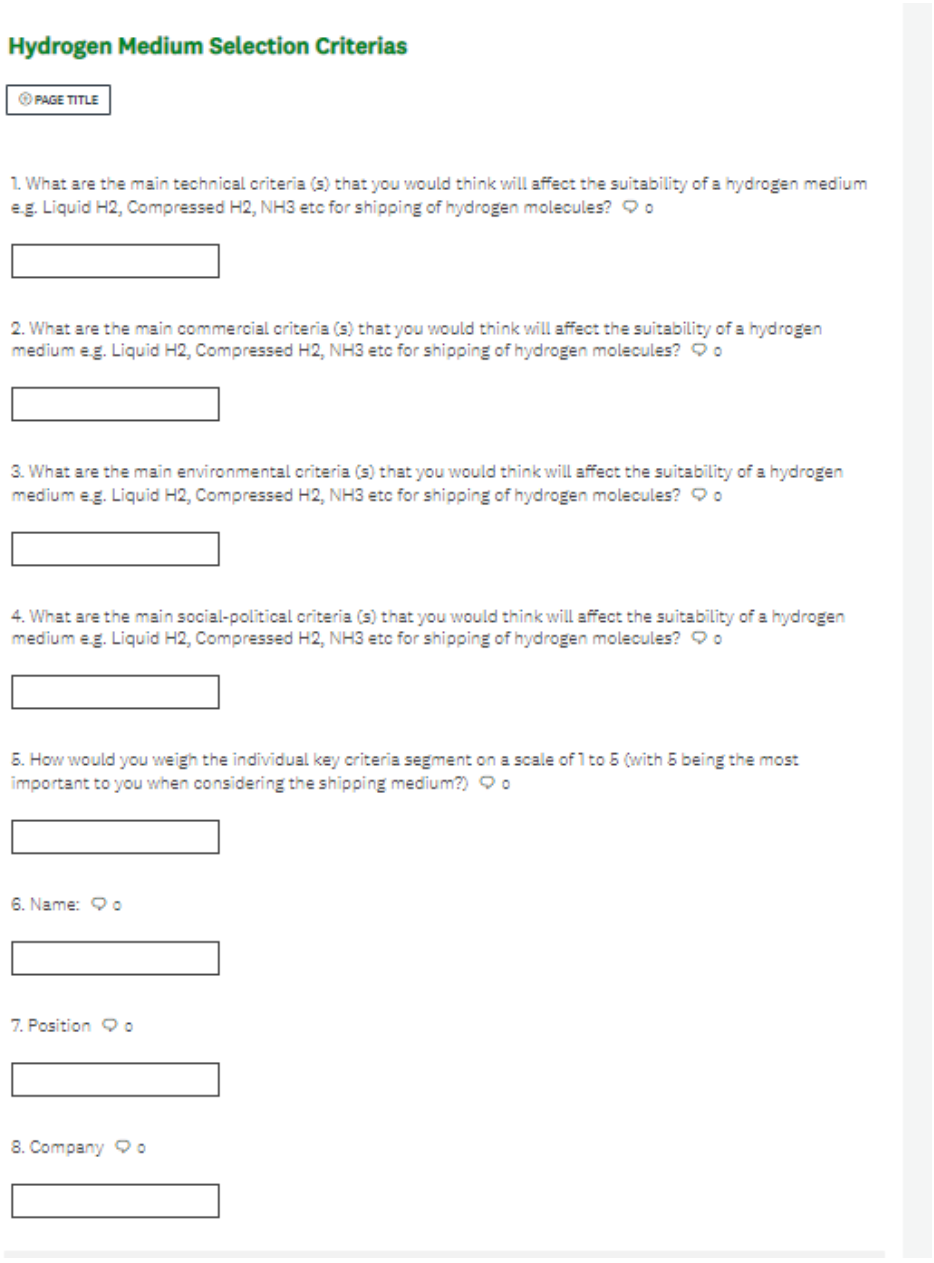
Figure 27 - LOHC Safety Data Sheet

Source: https://beta-static.fishersci.com/content/dam/fishersci/en_US/documents/programs/education/regulatory-documents/sds/chemicals/chemicals-t/S25611.pdf

Appendices D – Survey Results

Survey Template

This appendix contains the external survey questions (which was conducted through online survey platform SurveyMonkey[24]) and the associated responses.



Hydrogen Medium Selection Criterias

PAGE TITLE

1. What are the main technical criteria (s) that you would think will affect the suitability of a hydrogen medium e.g. Liquid H2, Compressed H2, NH3 etc for shipping of hydrogen molecules?

2. What are the main commercial criteria (s) that you would think will affect the suitability of a hydrogen medium e.g. Liquid H2, Compressed H2, NH3 etc for shipping of hydrogen molecules?

3. What are the main environmental criteria (s) that you would think will affect the suitability of a hydrogen medium e.g. Liquid H2, Compressed H2, NH3 etc for shipping of hydrogen molecules?

4. What are the main social-political criteria (s) that you would think will affect the suitability of a hydrogen medium e.g. Liquid H2, Compressed H2, NH3 etc for shipping of hydrogen molecules?

5. How would you weigh the individual key criteria segment on a scale of 1 to 5 (with 5 being the most important to you when considering the shipping medium?)

6. Name:

7. Position

8. Company

Figure 28 – Online Survey Template

[24] www.surveymonkey.com

Survey Respondents

As part of the survey process, references from the energy industry was approached to A total of 23 respondents from the six different stakeholder categories provided their inputs through the online survey; with the following breakdown.

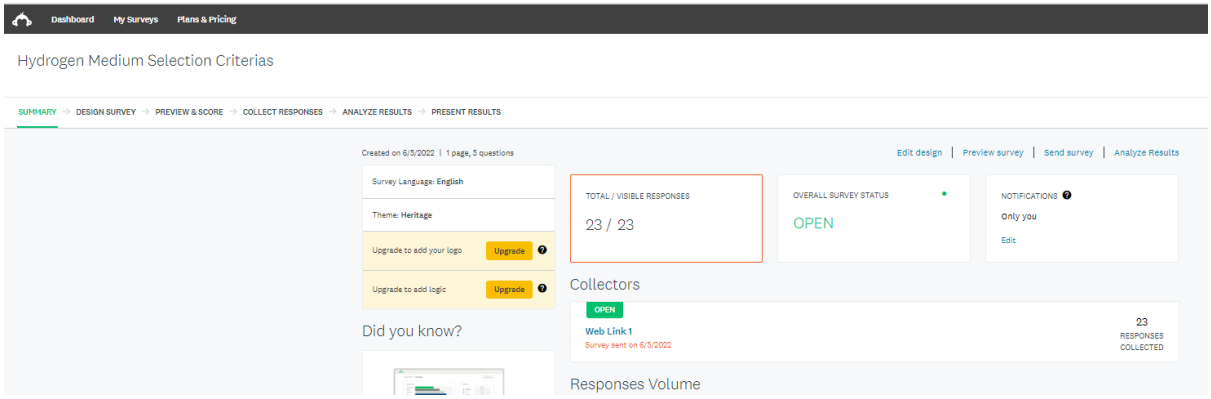


Figure 29 – Stakeholder Participation in Online Survey Mechanism

Categories Breakdown of Respondents	Number of Respondents	Companies Represented
Public – Port Authorities	3	PSA, MPA
Public – Academics	3	NUS, JTC, BRG
Public – Regulatory Bodies	5	RINA, ABS, Bureau Veritas
Private – End Users	6	Angelin Energy, JAPEX, Keppel, Vopak, Iteco, Sembcorp
Private – Shippers	3	MOL, Total
Private - Traders	3	Top International, GRM Resource
Total	23	-

Table 26 – Respondents Breakdown and Representation

Survey Results - Criterias

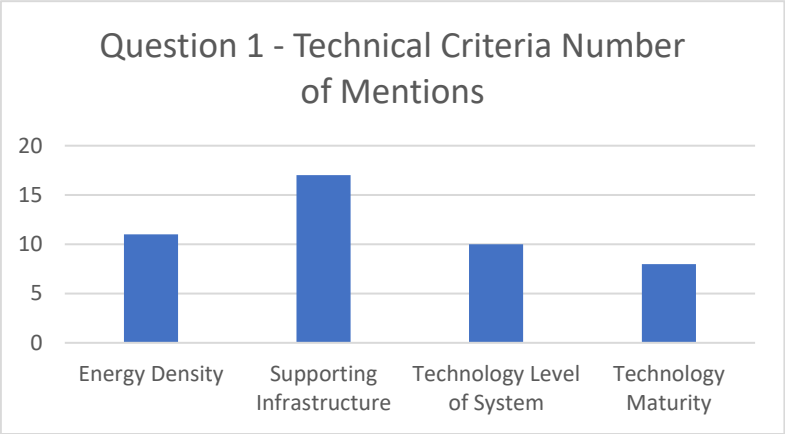


Figure 30 – Top Technical Criteria Mentioned for Survey

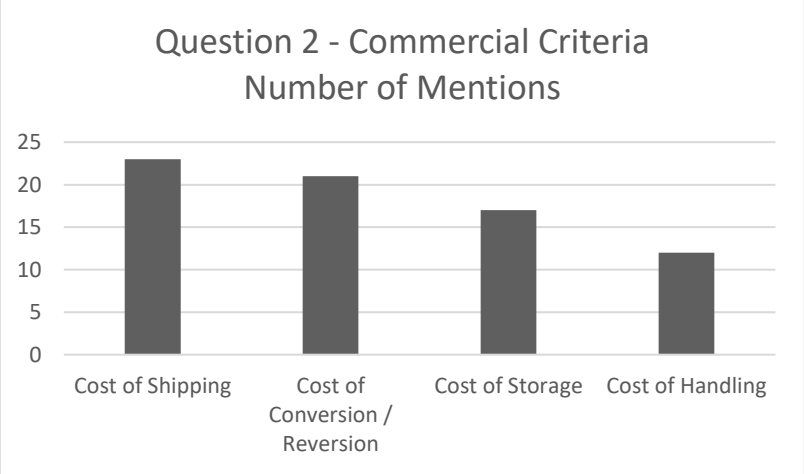


Figure 31 – Top Commercial Criteria Mentioned for Survey

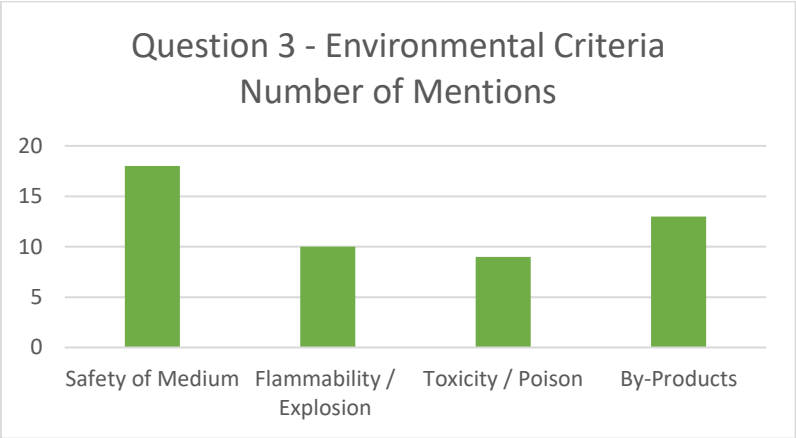


Figure 32 – Top Environmental Criteria Mentioned for Survey

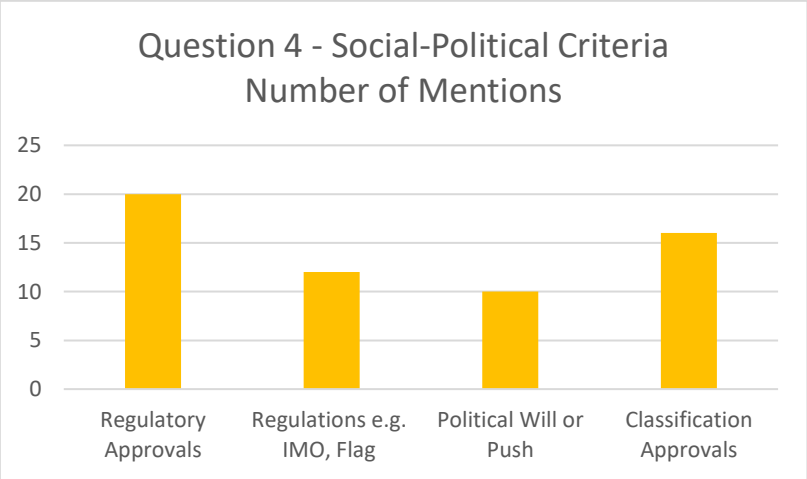


Figure 33 – Top Social-Political Criteria Mentioned for Survey

Survey Results – Weight Factors

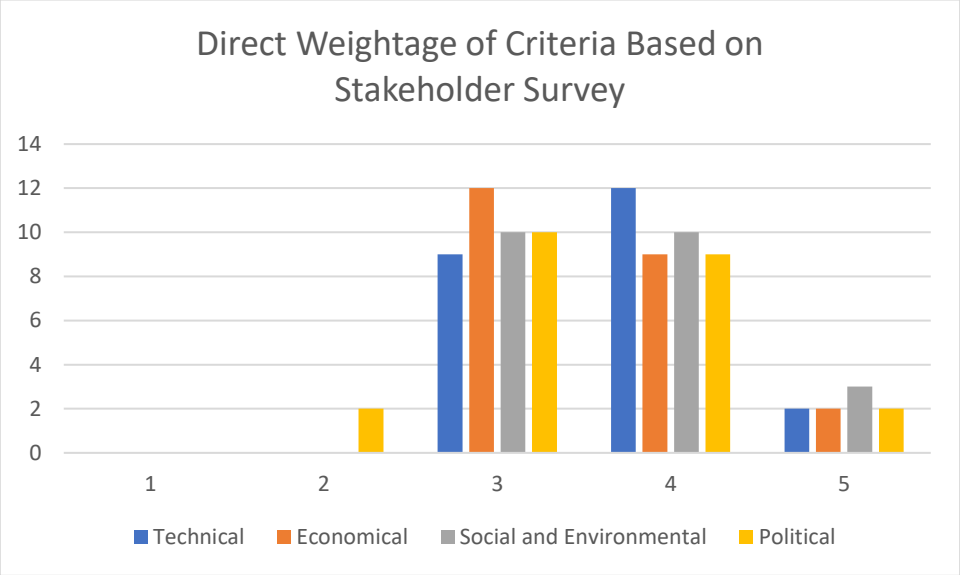


Figure 34 – Weightage Based on Stakeholder Survey

Appendices E – Tabulated Results

Criteria Scoring

	CH2	LH2	NH3	NaBH4	LOHC	Maximum
Gravimetric	1	2	3	3	2	3
Volumetric	1	2	3	3	3	3
Carrier Maturity	4	4	2	2	2	5
Vessel Maturity	3	4	5	2	4	5
Conversion Losses	3	2	3	3	1	3
Re-conversion Losses	3	2	1	1	1	3
Storage Management	2	1	2	2	3	3
By Products	3	3	2	1	1	3
Safety - Flame	1	1	4	1	2	5
Safety - Toxic	5	5	3	3	2	5
Regulatory	2	2	3	2	2	3

Table 27 - Tabulated Criteria Scoring

Criteria Weight

Weightage (Survey)	1	2	3	4	5	Total
Technical	0	0	9	12	2	23
Economical	0	0	12	9	2	23
Social and Environmental	0	0	10	10	3	23
Political	0	2	10	9	2	23

Table 28 - Tabulated Criteria Weightage

Criteria Standardised Scoring and Top three Selection

	CH2	LH2	NH3	NaBH4	LOHC
Gravimetric	33	67	100	100	67
Volumetric	33	67	100	100	100
Carrier Maturity	80	80	40	40	40
Vessel Maturity	60	80	100	40	80
Conversion Losses	100	67	100	100	33
Re-conversion Losses	100	67	33	33	33
Storage Management	67	33	67	67	100
By Products	100	100	67	33	33

Safety - Flame	20	20	80	20	40
Safety - Toxic	100	100	60	60	40
Regulatoy	67	67	100	67	67
Total	**760**	**747**	**847**	660	633

Table 29 - Tabulated Standardised Criteria Scoring

Criteria Weighted Scoring and Top three Selection

	CH2	LH2	NH3	NaBH4	LOHC
Gravimetric	100	200	300	300	200
Volumetric	100	200	300	300	300
Carrier Maturity	240	240	120	120	120
Vessel Maturity	180	240	300	240	240
Conversion Losses	400	267	400	133	133
Re-conversion Losses	400	267	133	133	133
Storage Management	267	133	267	400	400
By Products	400	400	267	133	133
Safety - Flame	80	80	320	160	160
Safety - Toxic	400	400	240	160	160
Regulatoy	200	200	300	200	200
Total	**2767**	**2627**	**2947**	2280	2180

Table 30 - Tabulated Weighted Criteria Scoring

Low and High LCOH Range for CH2, LH2 and NH3 (USD/Kg H_2)

	CH2		LH2		NH3	
Stages	Low	High	Low	High	Low	High
Green Hydrogen Production	2.70	3.20	2.70	3.20	2.70	3.20
Hydrogen Conversion (Packing)	0.58	1.54	0.8	1.89	0.70	1.89
Hydrogen Carrier Shipping	0.93	1.97	0.93	1.70	0.30	0.60
Hydrogen Carrier Reversion (Unpacking)	0.10	0.17	0.10	0.20	1.10	2.50
Total (USD/Kg H_2)	4.31	6.88	4.53	6.99	4.8	8.19

Table 31 - Tabulated Levelised Cost of Hydrogen (LCOH)