THE UNIVERSITY OF TECHNOLOGY SYDNEY
Faculty of Engineering and IT

A techno-economic analysis of the export of Green Hydrogen

by

Robert William Makepeace

Final Project Report submitted as a requirement for the degree

Masters of Engineering Management

Submitted: November 6, 2022

Subject: 42003 Engineering Graduate Project

Student ID: 13886357

Supervisor: A/Prof Jahangir Hossain

Internal

SUBMISSION DECLARATION

UTS : FACULTY OF ENGINEERING & INFORMATION TECHNOLOGY

STUDENT NAME:	13886357	DATE(DD/MM/YR): 07/11/2022
SUBJECT NUMBER:	42003 Engineering Graduate Project	
ASSIGNMENT :	Final Report	
PROJECT :	A Techno-Economic Analysis Of The Export Of Green Hydrogen	

I, (Student full name) confirm that:

1. I have read, understood and followed the advice in the Subject Outline about the assessment requirements.
2. If this assignment is submitted after the due date it may incur a penalty for lateness unless I have previously had an extension of time approved and have attached the written confirmation of this extension.
3. I declare that the work contained in this assignment, other than that specifically attributed to another source, is that of the author(s) and has not been previously submitted for assessment.
4. I understand that, should this declaration be found to be false, disciplinary action could be taken and penalties imposed in accordance with University policy and rules.
5. In the statement below, I have indicated the extent to which I have collaborated with others, whom I have named.

Statement of collaboration (if any):

Signature of student Robert Makepeace Digitally signed by Robert Makepeace Date: 2022.11.06 21:12:28 +11'00' **Date** ________________________

STYLE GUIDE for ASSIGNMENT SUBMISSION

Before submitting an assignment, you should refer to the policies and guidelines set out in the following:

- FEIT Study and assessment resources
- UTS Library - referencing
- HELPS - English and academic literacy support
- UTS GSU - coursework assessment policy and procedures

Abstract

Green hydrogen, produced from renewable electricity, has the potential for being a significant new energy carrier for international trade enabling the de-carbonisation of many hard to abate industries. Green hydrogen can be transported long distances in multiple mediums including pure hydrogen in different physical states, converted compounds or with a carrier form. Physically this transportation occurs in pipelines, on ships, trains or trucks. There are numerous salient factors in selecting transportation mediums options in distance, volume, safety, application use and cost. Techno-economic methods are a process of understanding and analysing the viability of processes, such as export of hydrogen across several different case studies. Topical issues in the literature include attributing the source of the hydrogen with embedded carbon emissions, technology safety issues and public perceptions of the technology. Green hydrogen is a significant potential economic opportunity for Australia with its large renewable energy resources, with export into predominately South-East Asia.

This research project's model show the economic viability of green transport along major routes such as Australia to Japan and Saudi Arabia to Europe. Generally shipping is the cheapest transportation vehicle for the long distances and large volumes involved in international trade. Depending on the specific route, green hydrogen is best transported in the ammonia or Liquid Organic Hydrogen Carrier (LOHC) or liquefied hydrogen form. A linear programming analysis has been presented showing that of the projected 300Mt of green hydrogen demand in 2050, 85% will need be transported between countries in order to achieve the most economically optimal distribution.

Acknowledgements

I first developed an interest in the potential for hydrogen during my year working at Davis Station in Antarctica. While employed as a Engineering Officer with the Bureau of Meteorology, I was responsible for the maintenance of an electrolyser and storage system for the production of hydrogen gas for the purpose of meteorological weather balloons. This work taught me about the safety precautions of working with hydrogen and its versatility as a molecule.

I would like to acknowledge the contribution of my employer, Provecta, who have supported my studies and provided financial contribution towards my degree. Green hydrogen is a emerging industry that the business would like to get involved in the future. This research project has allowed me to understand the potential of the technology and where the business can find opportunities in the local hydrogen industry as a control system integrator.

I sincerely thank my supervisor, Associate Professor Jahangir Hossain, who has provided great guidance and advice throughout the process. I have appreciated his technical input and encouragement throughout the year of this research project.

I would like to express my appreciation for everyone who has helped me throughout this research project. It has been a enjoyable journey and I have learnt a large amount along the way. Finally, thanks to the support of my family and friends, in their assistance and support in the project and in my university studies more broadly.

Terminology

Abbreviations

AE	Alkaline Electrolysis
AEM	Anion Exchange Membrane Electrolysis
ARNEA	Australian Renewable Energy Agency
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CEFC	Clean Energy Finance Corporation
$\boldsymbol{CH_2}$	Compressed Hydrogen Gas
$\boldsymbol{CH_3OH}$	Methanol
$\boldsymbol{CO_2}$	Carbon Dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DISER	Department of Industry, Science, Energy and Resources
$\boldsymbol{H_2}$	Hydrogen Molecule
HESC	Hydrogen Energy Supply Chain
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCOE	Levelised Cost of Electricity
LCOH	Levelised Cost of Hydrogen
$\boldsymbol{LH_2}$	Liquefied Hydrogen Gas
LNG	Liquefied Natural Gas

LOHC	Liquid Organic Hydrogen Carriers
MCH	MethylCycloHexane
MH_2	Metal Hydride
NH_3	Ammonia
OPEX	Operating Expenditure
PEM	Proton Exchange Membrane Electrolysis
PV	Photovoltaic
R&D	Research and Development
REDII	Renewable Energy Directive II
SNG	Synthetic Natural Gas
SOE	Solid Oxide Electrolysis
STP	Standard Temperature and Pressure
TOL	Toluene
USA	United States of America

Units of Measure

Unit Symbol	Unit Description	Measurement Category
$	Australian Dollar	Currency
BTU	British Thermal Unit	Heat/Energy
kJ	kiloJoule	Energy
MJ	megaJoule	Energy
kWhr	kiloWattHour	Energy
MWhr	MegaWattHour	Energy
kW	kiloWatt	Power
kWe	kiloWatt Electrical	Electrical Power
kg	kilogram	Mass
Mt	MegaTonne	Mass
Pa	Pascals	Pressure

kPa	kilopascals	Pressure
bar	bar	Pressure
L	litre	Volume
$\boldsymbol{m^3}$	cubic metre	Volume
mm	millimetre	Distance
km	kilometre	Distance
km/hr	kilometres per hour	Speed
m/s	metres per second	Speed
$\boldsymbol{kg/m^3}$	kilogram per cubic metre	Weight Density
kJ/kg	kilojoule per kilogram	Weight Energy Density
$\boldsymbol{kJ/m^3}$	kilojoule per cubic metre	Volumetric Energy Density

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Context

Green Hydrogen is hydrogen produced from renewable energy without the emissions of greenhouse gases. Whilst hydrogen is currently produced mostly using methods with significant carbon emissions, the role of renewably powered electrolysis is predicted to reduce cost and take a much larger role in the future (Alvera, 2021). Hydrogen is seen as a versatile and powerful energy carrier in the decarbonisation of the world economy to replace fossil fuel usage with renewable and sustainable technologies (Judkins and O'Brien, 2019). The transport of hydrogen long distances and export internationally is seen as a significant mechanism for reducing greenhouse emissions and a large economic opportunity for Australia with its extensive renewable energy resources (Walsh et al., 2021). The green hydrogen export concept as part of the hydrogen economy was first suggested by (Bockris, 1975); "Once we have got the energy into the form of hydrogen by electrolysing brackish water, it would be possible to pipe it over very long distances for quite cheap prices" (Bevan, 2022). Bockris' foundational research in the field is exemplary in its foresight, but some of his predictions were inaccurate with liquefied hydrogen being generally cheaper than pipelines for long distance transport. Figure 1.1 provides an overview of the Green Hydrogen economy from production from electrolysis, conversion, transport and end use.

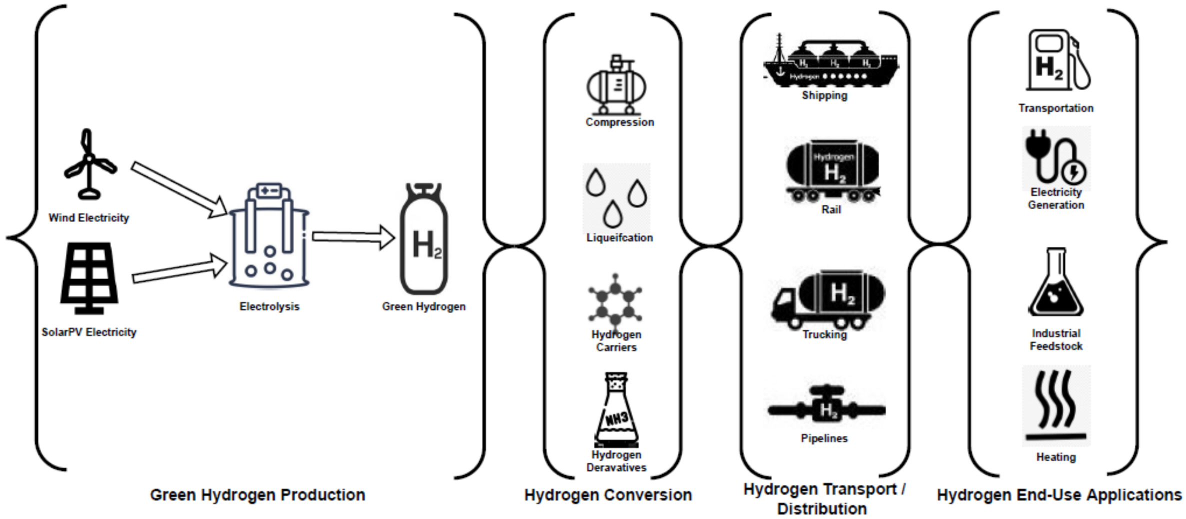

Figure 1.1: Green Hydrogen Economy Diagram (Hydrogen Transportation consists of the Hydrogen Conversion, Hydrogen Transportation and Reconversion (if required) phases)

1.2 Motivation

The motivation for this research project into understanding the technology and economics of the bulk transportation of green hydrogen is to assess the viability and scale of this international green hydrogen trade. Given the pressing challenges of climate change and the rapid transformations of modern economies away from fossil fuel based energy sources, finding alternatives technologies and energy carriers is important. Green hydrogen potentially provides part of the solution with a cheap, low carbon emissions and versatile energy carrier.

1.3 Potential Applications

Green Hydrogen has a large range of potential applications in replacing hard-to-abate fossil fuel based energy. Many renewable sourced energy is generated in the form of electricity which while is flexible and versatile. However, electricity generally instantaneous transfer (no inherent storage) and requires expensive electricity transmission infrastructure between the generators and end users. Therefore electricity is generally not suited for long distance transport of an energy carrier. Green Hydrogen can be used as a fuel, for heating and a feed-stock. As a fuel hydrogen can power transport, provide energy storage and for remote / emergency electricity generation. The heating can be used for residential, commercials and in industrial processes. As a feed-stock, hydrogen is for chemicals such as fertilisers, fuel refining, plastics and products such as glass and green steel.

Figure 1.2 visualising a range of large scale proposed and existing hydrogen projects within Australia. By 2030, there is expected for many of this projects to be operational, supplying local Australian demand for hydrogen and exporting hydrogen to many countries around the world. Refer to Table 1.1 for the full details of these projects.

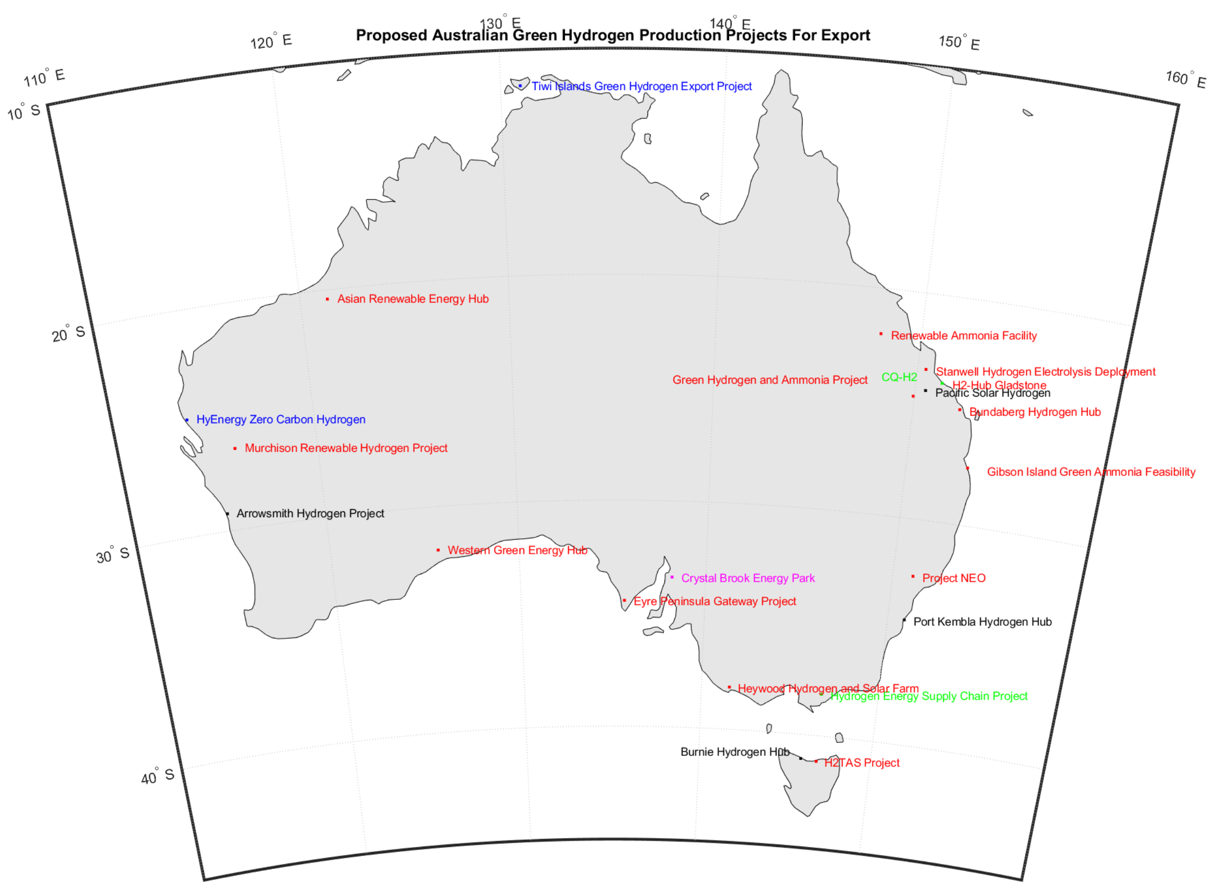

Figure 1.2: Map of Australian Large Proposed Green Hydrogen Production Projects For Export (Colour is Proposed Transportation Medium: Red = Ammonia, Blue = Compressed Hydrogen, Green = Liquefied Hydrogen, Magenta = MCH, Black = To Be Decided)

Table 1.1: Proposed Australian Green Hydrogen Export Projects

Name	**Location**	**Company**	**Renewable Generation**	**Hydrogen Transport**	**Hydrogen Volume**	**Export Market**	**Status**
Asian Renewable Energy Hub	Pilbara	CWP Global	26GW (Wind + Solar)	Ammonia via shipping	10Mt/yr	Singapore via ships	Proposed
Western Green Energy Hub	South-East Western Australia	CWP Global	50GW (Wind + Solar)	Ammonia via shipping	20Mt/yr	South East Asia via shipping	Proposed
HyEnergy Zero Carbon Hydrogen	Carnarvon, Western Australia	Total Eren, Province Resources Ltd	8GW (Wind + Solar)	Compressed hydrogen via shipping	1kt/yr	South East Asia via shipping	Proposed
Murchison Renewable Hydrogen Project	Murchison, Western Australia	Hydrogen Renewables Australia	5GW(Solar / Batteries)	Ammonia via shipping	136kt/yr	South East Asia via shipping	Proposed
Pacific Solar Hydrogen	Callide, Queensland	Austrom Hydrogen	3.6GW (Solar / Batteries)	TBC	200kt/yr	Japan via shipping	Proposed
H2-Hub Gladstone	Gladstone	H2U	3GW (electrolyser)	Ammonia via shipping	5Mt/yr	South East Asia via shipping	Convert existing ammonia export facility
Burnie Hydrogen Hub	Burnie, Tasmania	TBC	1GW	TBC	TBC	TBC	Proposed
H2TAS Project	Bell Bay, Tasmania	Woodside	1.7GW (Electrolyser)	Ammonia via shipping	200kt/yr	Japan via shipping	Proposed
Hydrogen Energy Supply Chain Project	LaTrobe Valley, Victoria	Kawasaki	Blue Hydrogen (Brown Coal Gasification with CCS)	Liquefied H2	90t/yr (Pilot) TBC (Full project)	Japan via shipping	Pilot completed
Heywood Hydrogen and Solar Farm	Heywood, Victoria	Countrywide Renewable Energy	80MW (Solar)	Ammonia via shipping	10kt/yr	South East Asia via shipping	Proposed
Eyre Peninsula Gateway Project	Eyre Peninsula, South Australia	H2U	15MW (Electrolyser)	Ammonia via shipping	10kt/yr	South East Asia via shipping	Proposed
Crystal Brook Energy Park	Crystal Brook, South Australia	Neoen	125 MW (Wind) / 150MW (Solar) and 400MWh (batteries)	methylcyclohexane (MCH) via shipping	9kt/yr	Japan via shipping	Proposed
Project NEO	Hunter Valley, New South Wales	Infinite Blue Energy	5GW (Solar / Wind)	Hydrogen fuel cells for electricity generation	TBC	N/A	Proposed
Bundaberg Hydrogen Hub	Bundaberg, Queensland	Elvin Group Renewables, Denzo Pty Ltd, H2X	80MW (Electrolyser)	Hydrogen fuel cells for transportation	6kt/yr	N/A	Proposed
Stanwell Hydrogen Electrolysis Deployment	Rockhampton, Queensland	Stanwell	10MW (Electrolyser)	Ammonia via shipping	10kt/yr	South East Asia via shipping	Proposed
Renewable Ammonia Facility	Moranbah, Queensland	(Dyno Nobel Moranbah) Incites Pivot Limited	210MW (Solar)	Ammonia via shipping	10kt/yr	South East Asia via shipping	Proposed
Central Queensland Hydrogen Project (CQ-H2)	Gladstone, Queensland	Stanwell	3MW (Electrolyser)	Liquefied H2	292kt/yr	Japan via shipping	Proposed
Gibson Island Green Ammonia Feasibility	Gibson Island, Queensland	Fortescue Future Industries	TBC	Ammonia via shipping	50kt/yr	South East Asia via shipping	Convert existing ammonia export facility
Green Hydrogen and Ammonia Project	Mour, Queensland	Queensland Nitrates Pty Ltd	30MW (Electrolyser)	Ammonia via shipping	1Mt/yr	South East Asia via shipping	Proposed
Arrowsmith Hydrogen Project	Dongara, Western Australia	Infinite Blue Energy	85MW (Solar) / 75MW (Wind)	TBC	9kt/yr	South East Asia via shipping	Proposed
Tiwi Islands Green Hydrogen Export Project	Tiwi Islands, Northern Territory	GEV	2.8 GW (Solar)	Compressed hydrogen via shipping	100kt/yr	Singapore via ships	Proposed
Port Kembla Hydrogen Hub Port	Kembla, New South Wales	Shell	10MW	Ammonia via shipping	10kt/yr	South East Asia via shipping	Convert existing ammonia export facility

1.4 Problem Definition

Green hydrogen production typically requires large, cheap and renewable electricity production for the electrolysis method, which splits purified water into hydrogen and oxygen gas. The production is limited to locations with proximity to significant renewable energy facilities (such as solar photovoltaics or wind energy), water resources, transportation infrastructure and skilled employees (Walsh et al., 2021). The main consumers of green hydrogen are expected to be close to population centres and near industrial applications. There is usually a significant distance between these supply and demand locations leading to a need for transportation.

Areas such as Australia, Chile, USA, Spain, Middle East and North Africa have large and cheap renewable energy resources and are expected to have low levelized production costs for green hydrogen (International Renewable Energy Agency (IRENA), 2021). Areas with high population densities and less potential for local green hydrogen production such as Japan, South Korea and Europe are expected to have higher levelized production costs of green hydrogen (Australian Government, 2017a). When there is a significant differential in green hydrogen production prices there is a potential for arbitrage through international trade of hydrogen. In this way imported hydrogen could be provided cheaper than locally production even when the costs of transportation and hydrogen conversion are factored in.

The defined problem is the limited understanding of the economics related to the long-distance transportation aspects of the green hydrogen economy. Currently there is a gap in the literature in understanding the scale and economics of the potential flows of green hydrogen in international trade. This topic is significant in influencing industry investment in production and infrastructure, broader decarbonisation policies and further technology research and development.

1.5 Objectives

The key objectives of this research project:

- Perform a technical and economic analysis of the different methods of green hydrogen transportation mediums
- Determine the most cost-effective methods of transporting green hydrogen long distances through a techno-economic analysis in terms of hydrogen medium and physical transport
- Estimate the potential volumes of hydrogen exports around the world over the next thirty years through detailed modelling and identify key trade routes
- Compare green hydrogen against fossil fuel-based alternative (such as coal, natural gas, crude oil, grey hydrogen, etc)
- Analyse the impact of carbon pricing on the economics of hydrogen trading

1.6 Report Structure

The report is structured into the following chapters:

Chapter 2 details the literature review of the green hydrogen transportation technologies and discusses topical issues.

Chapter 3 outlines the techno-economic methodology, model design and analysis results. This sections describes the model design, the process for collecting parameters, and outlines the limitations of the analysis.

Chapter 4 presents the results of the techno-economic analysis. It outlines the parameters used, describes the software implementation and presents the various results.

Chapter 5 discusses the broader context and significant of the results. Validity of the results, comparisons to other results and system limitations are explored as well.

Chapter 6 summarises the outputs of the research project. Discussion of the research contribution and recommendations for future work.

Chapter 2

Literature Review

2.1 Overview

This chapter outlines the Literature Review for the thesis. The review covered the context of energy carriers, the lifecycle of the hydrogen economy, techno-economic analysis and related topical issues in the literature.

2.2 Definitions

Green Hydrogen - Hydrogen produced from renewable electricity with electrolysis.
Blue Hydrogen - Hydrogen produced from fossil fuels where any carbon emissions are captured and stored.

2.3 Existing Forms of Energy Exports

Traditionally fossil fuels such as coal, natural gas and oil, and nuclear fuels such as uranium have dominated the long-distance energy carrier trade. This is due to high energy density, cheap prices, wide range of application usages and the geographically localised source of these fuels (Balat, 2008).

Gulagi et al. (2017) discusses the opportunity of exporting energy from Australia to

Asia using excess renewable solar and wind electricity through long distance efficient high voltage direct current (HVDC) connections. Garnaut (2019) agrees with Gulagi on the opportunities of large and cheap renewable electricity generation in Australia providing cheaper prices than internationally made electricity. However, Garnaut argues that due to the transmission losses and capital costs, the electricity would be better utilised by moving energy intensive processes to Australia such as aluminium smelting.

The Hydrogen Energy Supply Chain (HESC) pilot project involves the production of hydrogen gas from brown coal in Australia's Latrobe Valley and export to Japan using a liquefied hydrogen carrier ship (Australian Government, 2019). While the first stage of the project has been successful, the challenge will be modifying the hydrogen production to incorporate a carbon capture and storage (CCS) scheme using sequestration technology. These CCS schemes for hydrogen produced from fossil fuels are currently very costly and have mixed effectiveness (Howarth and Jacobson, 2021).

An effective energy transportation medium in a decarbonised world needs to be cheap, versatile and have low emissions to become widely used (International Energy Agency (IEA), 2021).

2.4 Hydrogen Generation

Currently 70 MT of pure hydrogen are produced each year typically through thermo-chemical processes from the conversion of fossil fuels such as natural gas and coal or as a by-product from chemical processes (Boretti, 2020). These non-renewable sources also coproduce carbon dioxide which is a primary cause of the greenhouse gas effect. The primary method of green hydrogen production is electro-chemical through electrolysis of water using renewable electricity (wind or solar photovoltaics) (Longden et al., 2020). There are some other methods for renewably produced hydrogen such as biomass, fermentation and biological production but these methods currently have low levels of technological readiness and are significantly more expensive. Feitz et al. (2019) discusses potential locations for hydrogen generation on an Australian wide scale with access to raw material resources, water, transport infrastructure and population centres being the key factors. Site selection is impacted by the intended usage of the hydrogen; for local Australian applications or for international export (ARUP, 2019).

Hydrogen is one of the pathways considered in the Power-To-X concept (Daiyan et al., 2020). Power-to-X is a concept of handling fluctuating renewable electricity generation by redirecting the excess power into batteries, transportation or heating. In this was the electricity sector is coupled with the other energy consuming sectors to better match demand with the supply for the intermittent electricity generation. Hydrogen is seen as a viable pathway for the Power-to-X with its potential usage in mobility (transport) and heating.

It is noted that this literature review focuses on the export of hydrogen rather than hydrogen production methods, as other students under the same supervisor will study the hydrogen production in more detail.

2.5 Green Hydrogen End Use Applications

Hydrogen has numerous potential future applications across industries currently powered by hard-to-abate fossil fuel sourced energy (NSW Government, 2021). It is expected that the levelised cost of hydrogen is expected to drop in the next few decades making it competitive or cheaper than the alterative fossil fuel (Owen and Cockroft, 2006).

The most economically viable application will be in the transportation sector powering vehicles with hydrogen fuel cells (Bureau of Infrastructure, 2019). This includes cars, bikes, trucks, buses and potentially ships and planes at a later stage (Sharma and Ghoshal, 2015). The widespread use of hydrogen in vehicles has three challenges; in competition with electric vehicles, the rollout of refuelling infrastructure and safety concerns (Floyd et al., 2019).

Hydrogen can be used to produce electricity through hydrogen fuel cells (Australian Government, 2017b). This can be done on a small scale for backup electricity generators to large scale energy storage and electricity generation for the electricity grid (Bones and O'Brien, 2020). Hydrogen can also be used for direct combustion for heating and for chemical production as an industrial feedstock for oil refineries, ammonia, methanol and other synthetic fuels and chemicals (International Renewable Energy Agency (IRENA), 2021). Green steel is an application of replacing coke with green hydrogen as the reducing agent to minimise the carbon emission of that industry (Bhaskar et al., 2020).

2.6 Hydrogen Transportation Scale

Hydrogen can be used for a variety of uses industry across electricity generation, chemical production, powering vehicle transport and direct combustion for building heating, manufacturing and mining. Other renewable energy sources do not currently effectively replace carbon emitting energy sources for hard-to-abate sectors such as transport, industry processes and direct combustion. Hydrogen sources in the hydrogen economy can be thought of on three scales for the hydrogen distribution chains (Australian-Government, 2017):

- **On Site**: Hydrogen is produced and consumed on the same premise. There may be a need for onsite storage to store the energy embedded in the hydrogen temporally (i.e., time). This includes using hydrogen as an energy storage system for the electricity grid, charge during periods of low energy prices due to excess renewable generation and discharge during periods of high prices due to low renewable generation (Victorian-Government, 2021).
- **Regional**: This hydrogen distribution is for the local distribution is typically for powering transportation vehicles, building heating or small-scale industrial processes. Typically the transport is conducted using pipelines of pure hydrogen or blended hydrogen and natural gas to shift the gas from the source to the end users.

Otherwise, it is often transported on trucks using compressed gas. This transport/local distribution typically occurs with of the hydrogen in the form that it will be used by its end user without a need for additional transformation. This regional distribution can occur after reconversion of hydrogen after international import using a different medium such as liquification or ammonia (Bruce et al., 2018) (ARUP, 2019).

- **International export:** The long distance and bulk export of hydrogen often between countries is the movement of the energy source from the producing region to the consuming region. Typically this occurs where the imported hydrogen will be cheaper than locally produced hydrogen despite the transportation costs. To make the transportation economically, conversions of the hydrogen are required often to increase the density of energy as hydrogen is very low density in its gaseous form (Australian-Government, 2021b). This conversion requires reconversion at the destination to allow the hydrogen to be used by the end user. However, it can be possible to align the transportation medium with the end user medium (such as ammonia) to remove the cost of reconversion. In that way, to fully assess the export transportation costs, the end usage needs to be considered in a holistic manner, and different transportation methods may be more economic for different applications (NSW-Government, 2021).

2.7 Hydrogen Mediums for Transportation

The generation and consumption of hydrogen do not necessarily occur at the same location leading to a need for transportation (Victorian Government, 2021). Long distance transport opens the world for international hydrogen trade, being able to deliver from the cheapest generation to the biggest consumers. Hydrogen in the gaseous form has a very low weight density, making it expensive to transport compared to other common energy carriers. To make the transportation economically viable, hydrogen is converted to different forms to increase its weight and energy density (Australian Government, 2021a). These transportation mediums overlap with hydrogen storage mechanisms (Hirscher et al., 2020). The properties of a good transportation method include high energy density, safety, efficiency in conversions (if required) and cost effectiveness. The major viable options for hydrogen transportation are listed in Table 2.1.

To increase its density for transport, pure hydrogen is either compressed, liquefied, both compressed and liquefied (called cryo-compressed), or stored at the triple point (called Slush hydrogen) (Faye et al., 2022). Compressed hydrogen is more practical for short distance transport and storage as the conversion energy and costs are minor. Liquefied hydrogen is currently the common method for bulk transport internationally due to its higher density. Liquefication is very energy intensive as it requires extremely low temperatures and has issues of boil-off during transport and reconversion prior to local distribution (Aziz, 2021).

Green Hydrogen can be converted to existing transportable fuels prior to transportation instead of using the fossil fuel pathway for these fuels. Ammonia (Chehade and Dincer, 2021), methanol (Li and Tsang, 2018) and synthetic natural gas (SNG) (Becker et al., 2019) are three potential candidates. The concept is for the hydrogen to be converted to the end use chemical closer to the production as the chemical has better transportation properties. Chehade's paper discusses a higher technological readiness of ammonia and versatility as a fuel, whereas Li's and Becker's papers focus on early-stage research and development for methanol and SNG.

Carrier mediums for storing the hydrogen in other forms include liquid organic hydrogen carriers (LOHCs) (He et al., 2015), metal hydrides (Sakintuna et al., 2007) and porous carbon materials (Andrews et al., 2021). These methods aim to have a reversible process for effectively and efficiently storing hydrogen within a carrier medium. He and Andrews discuss novel technical details of their methods, but do not discuss the practicalities of large scale. Conversely, Sakintuna includes critical assessment on the viability of the current materials against the requirements for transport.

2.8 Physical Transport Modes

The choice of the physical method of hydrogen transportation depends on distance, volume, timing, safety, and costs factors. Regional transport typically occurs with trucks, rail or pipelines from the generation or port facility to a centralised processing facility for reconversion to the end use application. Export transport occurs for bulk transfers of hydrogen typically using shipping or pipelines. International Energy Agency (IEA) (2019) provides some levelised costs for different transportation methods in terms of fixed and variable costs on distance components (Hydrogen Council, 2017).

For hydrogen gas, pipelines can be used to transport hydrogen gas for both local distribution and long-distance distribution. These are advantageous for not requiring additional reconversion between transportation and end use. There are some early stage pilot projects with 20% blending green hydrogen into existing natural gas pipelines (Ríos-Mercado and Borraz-Sánchez, 2015). The advantage of this approach is building up hydrogen infrastructure prior to a full transition, but is limited by the low energy throughput of Hydrogen Gas at 20% proportion (GPA Engineering, 2019b). (GPA Engineering, 2019a) discusses using the existing natural gas pipeline for pure hydrogen gas transport with some retrofitting, discussing some challenges with the leaking of hydrogen due to its low density and hydrogen embrittlement. Bruce et al. (2018) argues for hydrogen transportation - new tailored pipelines are required which can cost up to twice as much as retrofitting (Hydrogen Council, 2021). Table 2.1 summarises these pipeline options for transporting hydrogen gas.

2.9 Techno-Economic Analysis Method

Techno-economic analysis is a method of evaluating the economic performance of industrial applications through considering the process, equipment sizing, and financial costs (Mezher et al., 2011). Batan et al. (2016) incorporates uncertainties into the techno-

Table 2.1: Comparison of Hydrogen Transportation Technology Methods

Category	**Hydrogen Medium**	**Physical Transport Method**	**Current Usage**	**Technological Readiness**	**Cost**	**Advantages**	**Disadvantages**	**References**
Pure Hydrogen	Compressed	Truck / Rail	Local storage / short distance	High	Cost Effective for short distance	Proven technology, Low conversion cost	Low density, High Pressure	(Hydrogen Council, 2020)
Pure Hydrogen	Liquefied	Shipping / Truck	Long distance	High	Cost Effective for long distance	Proven technology, High density	Conversion energy, Safety issues	(Balat, 2008)
Pure Hydrogen	Cryo-compressed	Shipping / Truck	R&D	Low	Expensive	High density	Technology not proven	(Faye et al., 2022)
Pure Hydrogen	Slush (at triple point)	Shipping / Truck	R&D	Low	Expensive	High density	Technology not proven	(Lee et al., 2021)
Converted Compounds	Green Ammonia	Shipping / Truck	Wide usage (non-green ammonia)	High	Cheap (non-green forms)	High density storage. Ready for application	Toxic, energy intensive conversion	(Chehade and Dincer, 2021)
Converted Compounds	Green Methanol	Shipping / Truck	R&D	Low	Expensive	High density storage	Technology not proven	(Li and Tsang, 2018)
Converted Compounds	Synthetic Natural Gas (SNG)	Shipping / Truck	R&D	Low	Expensive	Existing Infrastructure	Technology not proven	(Becker et al., 2019)
Carrier Substance	Metal Hydrides	Shipping / Truck	R&D	Medium	Expensive	Reversible, High density	Temperature issues	(Sakintuna et al., 2007)
Carrier Substance	Liquid Organic Hydrogen Carrier (LOHC)	Shipping / Truck	Future Long distance	Medium	Potential to be cheaper in future	Safe and cheap, High density	Conversion energy	(He et al., 2015) (Makepeace et al., 2019)
Carrier Substance	Porous Carbon Materials	Shipping / Truck	R&D	Low	Expensive	High conversion efficiency	Technology not proven	(Andrews et al., 2022)
Pipeline	Blending into Natural Gas	Pipeline	Local distribution	Medium	Cheap	Uses existing infrastructure	Low energy throughput. Fixture compatability	(Frontier Economics, 2020)
Pipeline	Existing / New Hydrogen Pipeline	Pipeline	Local distribution / export	Medium	Moderate	Better throughput	More expensive	(Frontier Economics, 2020)

economic model by using the Monte Carlo method, a stochastic simulation method to produce a probabilistic profile of the expected costs in an exemplary paper.

Kannah et al. (2021) provides an extensive techno-economic analysis of the different hydrogen generation techniques and associated financial costs of these projects. Kannah's paper focuses on the specific economics of each hydrogen production technology, whereas, Walsh et al. (2021) analyses the economics for hydrogen production in terms of broader geographical, infrastructure and resource factors to identify the best regions in Australia.

Walsh and Kannah focus the techno-economic analysis on the hydrogen production stage of the hydrogen economy. However, there is a gap in the literature in detailed techno-economic analysis for hydrogen transportation. Currently, Hydrogen Council (2021) provides some simplistic analysis of a few hydrogen transportation case studies with different mediums but does not incorporate the whole generation to application chain. International Energy Agency (IEA) (2019) provides more granular economic analysis on the different methods of transportation compared to the Hydrogen Council and de Vos (2021), but focuses on local distribution and regional transport, and does not consider the carbon emissions of the transportation infrastructure nor local government policies and grants (Utz, 2019).

2.10 Comparisons to Relevant Literature Studies

There are some reference literature studies that provide comparison results for parts of this research project.

Amos has a broad analysis of different hydrogen mediums and different transportation modes, which provides a useful reference for this research project (Amos, 1999). It is noted the paper was published in 1999, so the data may be somewhat out of date, not including technological developments in the last twenty years. However, it has been included as it has the broadest scope of different calculations available.

Anastasopoulou et al presents technoeconomic analysis of metal hydride hydrogen carrier technology for hydrogen transportation. The paper compares metal organic framework against compressed hydrogen gas and liquified hydrogen across a range of distribution and transmission distances. The paper suggests the metal hydride are current five times more expensive than compressed and liquefied hydrogen (Anastasopoulou et al., 2021).

Raab et al investigated the economics of bulk hydrogen transport across LOHC media against liquified hydrogen. It calculated the total delivered cost of hydrogen for a number of different LOHC technologies using a fixed distance of 5000km (Raab et al., 2021).

Lee et al focused on the metal hydride technology for hydrogen transportation Lee2022 (Lee et al., 2022). The paper estimates the costs of toluene-methylcyclohexane (TOL-MCH) and dibenzyltoluene-perhydro-dibenzyltoluene (H0DBT-H18DBT) as shipping mediums. The paper also includes analysis of Liquified Hydrogen, Ammonia and Methanol as reference mediums.

Table 2.2 compares these four papers in terms of the different scope and assumed parameters included in this analysis.

Table 2.2: Comparisons to Relevant Literature Studies - Key Parameters

Paper	Mediums	Transport	Distance	Year Published
(Amos, 1999)	Compressed, Liquified, Metal Hydride	Truck, Rail and Ship	1600km	2021
(Anastasopoulou et al., 2021)	Compressed, Liquified, Metal Hydride	Trucks	100km	1999
(Raab et al., 2021)	Liquified and LOHC	Ship	9260km	2021
(Lee et al., 2022)	Liquified, Ammonia, Methanol and Metal Hydride	Ship	5700km	2022

Some comparisons of the results of this research project and these relevant literature studies are presented in Section 5.4.

2.11 Hydrogen Guarantee of Origin Schemes

Australia currently exports ammonia to Japan which is used to co-combust with the coal in existing coal power stations (Stocks et al., 2022). Whilst this project reduces carbon emissions in Japan as ammonia offsets coal and burns cleanly, the ammonia produced from steam methane reforming and the Haber-Bosch process has significant carbon emissions in Australia. Stocks argues the emissions offset in replacing the coal in ammonia is replaced by the emissions in the ammonia production albeit in a different country. Understanding the source of the hydrogen and any embedded carbon emissions in its production is becoming a topical issue in the literature and an important issue for governments tracking emissions.

An emerging issue in the international trade of hydrogen is a guarantee of origin scheme for the purchaser to understand the source of the hydrogen and any carbon emissions made in its production (Australian Government, 2021b). Transparency of the source of hydrogen allows for the competitiveness of "clean hydrogen" in trade against hydrogen produced from fossil fuels and hydrogen produced with CCS. Understanding the full history of products will be important in application industries in assessing their total carbon emissions and meeting local regulations around carbon pricing schemes such as carbon taxes, etc. Dawood et al. (2020) goes further than the Australian government in considering the cradle to grave carbon emissions.

2.12 Hydrogen Safety and Public Perceptions

A significant factor affecting the export of hydrogen is the safety of the technology and the public perceptions of the safety. The physical and chemical properties of hydrogen make it dangerous, with the key properties of a wide flammability range, low ignition energy, colourless flame and propensity to leak (Najjar, 2013). There needs to be significant care in the design and operation of hydrogen systems to minimise the risk of an accident and to ensure public confidence in the technology (Lambert and Ashworth, 2018). Hydrogen transport infrastructure may need additional equipment for monitoring and safety devices. While Najjar's analysis is rigorous for storage and applications, it does not consider alternate transportation methods beyond pipelines. Furthermore, (Ashworth et al., 2019) discusses improving public perceptions through delivering pilot projects, developing realistic expectations, communicating timeframes and engaging with the community.

2.13 Summary

The production of hydrogen from renewably produced electricity has the potential to play a critical role in the decarbonisation of many industries. The ability to export energy in the form of green hydrogen internationally is a significant opportunity economically and environmentally. There are multiple methods for transporting hydrogen that may be viable across different case-study scenarios. There are some challenges to these technologies, in the properties of hydrogen, the required conversions/reconversions, safety concerns and economic viability. The economic viability of different technology mediums can be assessed using techno-economic analysis methods. This research project is relevant to the emerging hydrogen economy in Australia and globally as part of the decarbonisation of the economy. A broad based and high level comparative analysis of the different transportation methods for green hydrogen provides insight into the potential viability and growth of international hydrogen trade and scale of the export industry. Moreover, it informs the research and industry priorities for enabling technologies and materials.

Chapter 3

Methodology

This chapter outlines the methodology used in designing, implementing, and analysing the results of the techno economic model. The overall system structure, and experiment design are explained.

3.1 Research Question

The research question is what is the most cost-effective method (or combination of methods) for the long-distance transportation of Green Hydrogen? This question will be answered through a techno-economic analysis of the different green hydrogen transportation methods to understand the trade volumes and suitability of transportation methods for different trade routes and end use applications.

3.2 Rationale

This research question has been chosen as it is an interesting and salient topic in the emerging green hydrogen industry. Green hydrogen, as a flexible energy carrier, has the potential to reduce carbon emissions in hard-to-abate sectors and also in countries with limited renewable energy resources. Understanding the economics of green hydrogen export is critical in the development of the hydrogen industry in understanding holistically the future hydrogen economy and international trade of green hydrogen. Through the detailed analysis this project aims to determine the economic viability of long-distance hydrogen transport against the alternative fossil fuel energy carrier. Understanding the projected volumes of exports will determine the scale of production and infrastructure projects needed within a country in conjunction with domestic demand. This research project attempts to address the gap in the literature and potentially contribute to informing future academic research, governments, and industry.

3.3 Data Collection

Figure 3.1 provides an overview of the model implementation process.

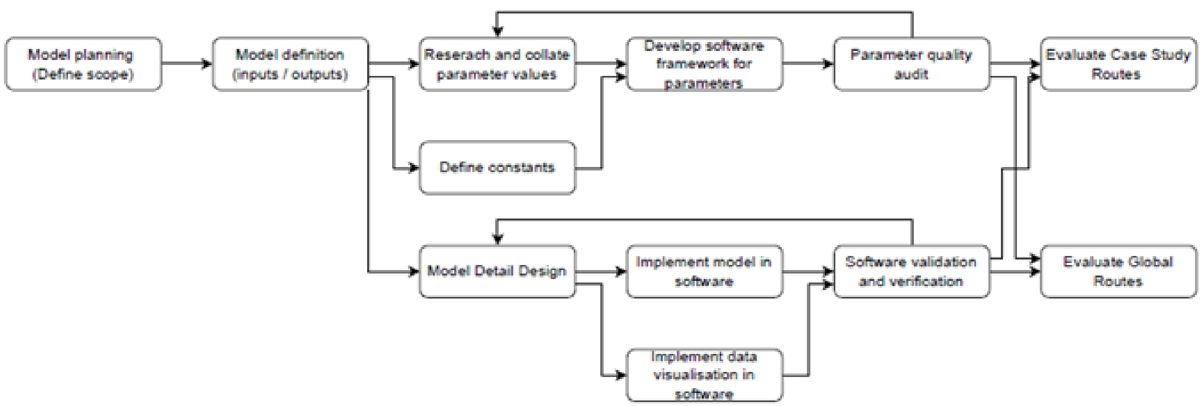

Figure 3.1: Methodology Implementation Process Diagram

Constructing a green hydrogen transportation techno-economic model requires data collection for the inputs of the model. These parameters are shown generally on the left-hand side of the system functional block diagram in Figure 3.2. The model requires parameter values for the technologies, financials, and physical constants. The technology parameters include values such as shipping vessel capacity, hydrogen conversion energy efficiency, etc. Financial parameters include parameters such as capital expenditure costs and the cost of electricity. Finally, some constant values include physical properties of materials and conversions between units.

These values have been be collated from a variety of sources including academic research, industry groups, governments, and proposed projects. The parameter values have been aggregated from multiple sources where possible and include projections until 2050 and an uncertainty range of the parameter value. Generally, the model has be framed in terms of common parameters that have available estimated cost projections, for example the cost of electricity. Some of the models have require region specific parameter values to allow for analysis of trade between regions which may have differences in cost.

The model also involves some data collection in determining the relationships between parameters in determining the dynamics of the different technologies. For example, the pipeline transportation model needs data collection to understand the chemical calculations for hydrogen gas throughout depending on the pipeline and gas characteristics.

The key parameters values and reference information for the source of the parameter values have been included in Section 4.

3.4 Data Analysis

3.4.1 Levelised Cost of Hydrogen (LCOH)

An overview of the data analysis is shown in Figure 3.2 below. The system functional block diagram shows the techno-economic model calculating the different components of costs including generation, conversion, transportation, and reconversion from the raw parameter values. This determines the total export cost of green hydrogen, which in turn can be used for further analysis and contextualisation. The model includes calculations for the different physical transportation (shipping, trucks, pipeline, etc) and different mediums (compressed, liquefied, ammonia, etc). The scope of the model starts from a production hub (typically a shipping port) and includes any conversions required for transport such as liquefaction or conversion to ammonia. It is noted that the majority of green hydrogen production is expected to occur near a transportation hub. The scope of the model ends at an importing hub (typically a shipping port) and includes any reconversion prior the local distribution. The local distribution to end user applications itself has been excluded

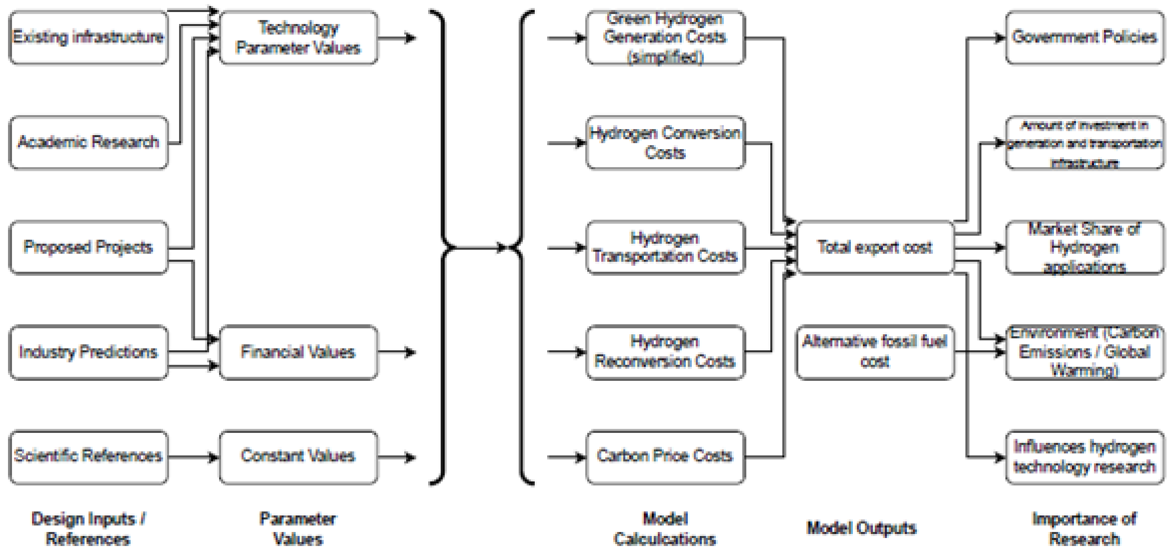

Figure 3.2: System Functional Block Diagram Overview

for simplicity of the analysis.

The techno-economic model is implemented in the Matlab software. Matlab has been chosen for its powerful engine with built-in functionality for data visualisation and graphing. The model is implemented in various scripts and combined together to calculate and present the result findings. The model is implemented in a modular fashion to allow modules for the definition of parameters, base physical transportation calculations, base hydrogen medium calculations, (re)conversion calculations and then different analysis methods. The base techno-economic model outputs transport costs for a specified distance and volume for each of the transportation methods.

Overall Costs

The overall levelised cost of hydrogen (LCOH) is calculated as per Equation 3.1 below. The levelised cost of hydrogen is calculated by dividing the total cost of delivering hydrogen (including production) by the quantity of delivered hydrogen for a fixed time period. The units are expressed in terms of Australian Dollars per kilogram of delivered hydrogen. The five components are described in more detail in the following sections.

Overall Levelised Cost of Hydrogen (LCOH) including up to the regional distribution centre:

$$LCOH_{deliver} = LCOH_{prod} + LCOH_{conv} + LCOH_{transport} + LCOH_{reconv} + LCOH_{CO2} \quad (3.1)$$

Production Costs

The production cost methodology for this research project are simplistic as the focus of the research project was not on this area of the hydrogen supply chain. There is some modelling of the production costing to allow for regional variations of the economic production costs which is required for some of the analysis methodologies presented below. The production costs assume hydrogen generation from electrolysis using renewable electricity. One of the main components of the OPEX is the electricity costs for the electrolysis.

Levelised Cost of Hydrogen (LCOH) - Electrolysis Production Component:

$$LCOH_{Prod} = \frac{CAPEX_{prod} + OPEX_{prod} + ElectricityCost}{DeliveredHydrogenQuantity} \quad (3.2)$$

The detailed parameters are described in Section 4.1.1.

Conversion Costs

The conversion costs covers the transformations of the hydrogen required to convert it from hydrogen gas produced by the electrolysis to a different medium for transport (if required). This conversion equipment can be very capital intensive and some processes require large amounts of energy. The costs are totalised over the lifespan of the equipment.

Levelised Cost of Hydrogen (LCOH) - Conversion Component:

$$LCOH_{conv} = \frac{CAPEX_{conv} + OPEX_{conv} + EnergyCosts_{Conv}}{DeliveredHydrogenQuantity} \quad (3.3)$$

The detailed parameters are described in Section 4.1.2.

Transport Costs

Transport costs includes the transport vehicle, transportation fuel, loading terminal, and unloading terminal. Table 3.1 lists the hydrogen transport mediums that are used in the analysis. These costs are also be presented on the fixed (terminal) and per distance unit basis components for use in the analysis methods below.

Table 3.1: Green Hydrogen Transport Mediums

Medium Index (t)	**Hydrogen Medium**
1	Hydrogen Compressed CH_2
2	Hydrogen Liquified LH_2
3	Hydrogen Cryo-Compressed
4	Hydrogen Slush
5	Ammonia NH_3
6	Methanol CH_3OH
7	Synthetic Natural Gas
8	Methylcyclohexane (LOHC)
9	Porous Carbon
10	Metal Hydride
11	Diesel
12	Natural Gas
13	Liquified Natural Gas
14	Coal

Levelised Cost of Hydrogen (LCOH) - Transport Component:

$$LCOH_{transport} = \frac{CAPEX_{terminals} + OPEX_{terminals} + CAPEX_{transport} + OPEX_{transport} + FuelCosts}{DeliveredHydrogenQuantity} \tag{3.4}$$

The detailed parameters are described in Sections 4.1.3 and 4.1.4.

Reconversion Costs

The reconversion costs include the reconversion at the destination to convert from the transportation medium to the local distribution medium. The costs are totalised over the lifespan of the equipment.

Levelised Cost of Hydrogen (LCOH) - Reconversion Component:

$$LCOH_{reconv} = \frac{CAPEX_{Conv} + OPEX_{Conv} + EnergyCosts_{Conv}}{DeliveredHydrogenQuantity} \tag{3.5}$$

The detailed parameters are described in Section 4.1.2.

Carbon Costs

The carbon costs calculates the carbon costs of the total carbon emissions from the carbon cycle. This allows for assessment of the impact of government policies such as an emissions trading scheme or carbon tax which put apply a cost on carbon emissions.

Levelised Cost of Hydrogen (LCOH) - Carbon Component:

$$LCOH_{carbon} = \frac{TotalSupplyChainCarbonEmissions \times CarbonEmissionPrice}{DeliveredHydrogenQuantity} \tag{3.6}$$

The detailed parameters are described in Section 4.1.6.

3.4.2 Case Study Routes

Case Study Routes Methodology

The base transportation model are applied to two different methodologies to generate relevant results for analysis and discussion. The first analysis approach is the green hydrogen case study trade routes as shown in Figure 3.3. This applies the different green hydrogen transportation costs to specific trade routes as listed in Table 3.2. These trade routes have specific distances, limitations on physical transport (i.e., shipping only for some routes due to the geography) and estimated volumes based on local demand. The output of this methodology is a ranking of each technology in terms of cost effectiveness for each case study. This methodology provides insight on which technologies work best for specific trade routes depending on the characteristics of the specific trade routes.

Calculations

Equation

$$TotalCost_{xt} = x_x \times (p + fc_t + vc_t \times d_x) \tag{3.7}$$

Some routes x, are restricted for some transportation mediums t depending on the nature of the routes (such as no trucking when there is only a ocean connection).

Variables

x Case Study Route Index (Refer to Table 3.2)

t Green Hydrogen Medium Index (Refer to Table 3.1)

x_x Green Hydrogen Transported Volume along route x (includes conversion / transport losses) Units: (kg)

p_s Green Hydrogen Production Costs in region s Units: ($AUD/kg)

fc_t Green Hydrogen Unit Transportation Fixed Cost for Medium t Units: ($AUD/kg)

vc_t Green Hydrogen Unit Transportation Variable Cost for Medium t Units: ($AUD/kg $\times$ km)

d_x Distance for case study route Units: km

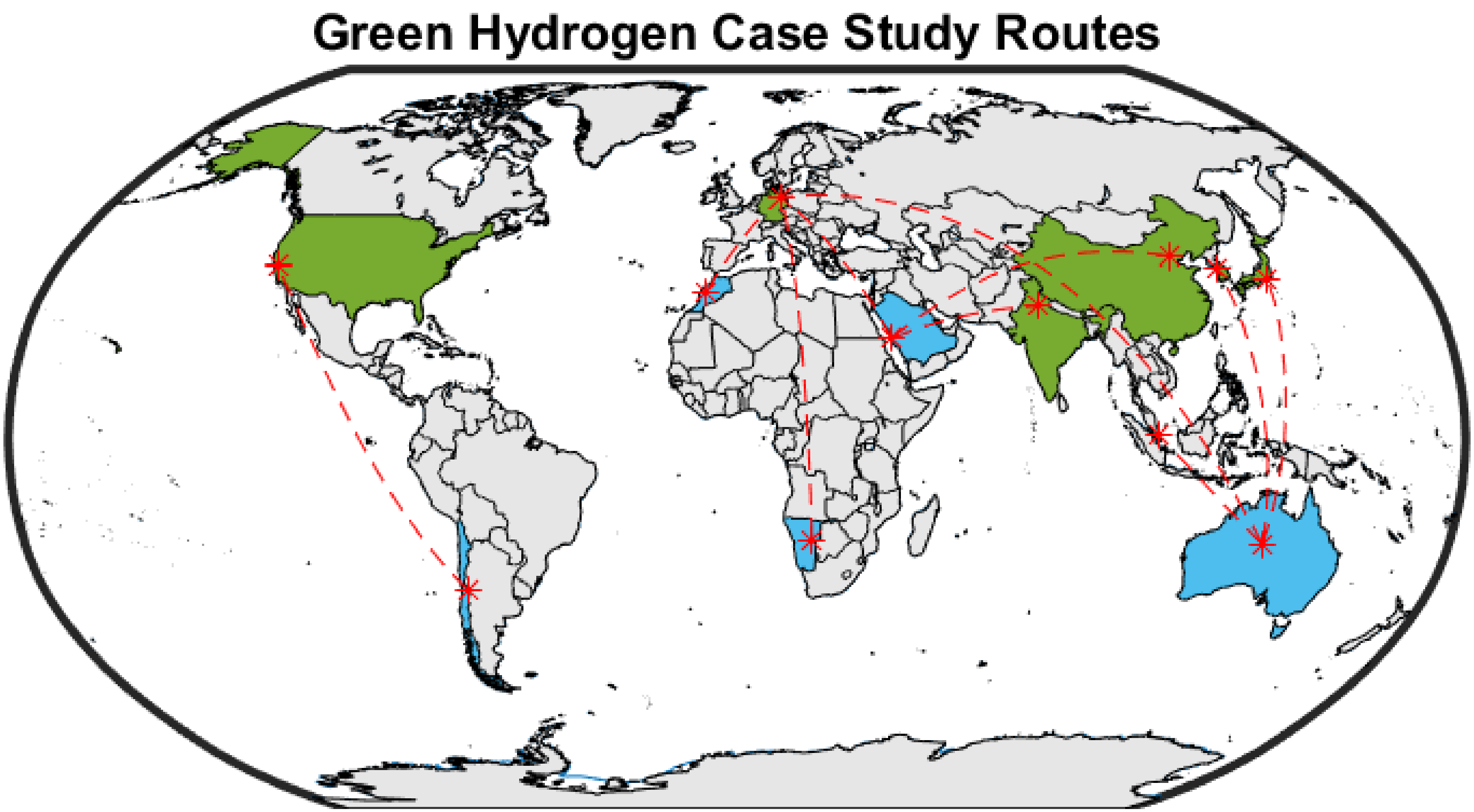

Figure 3.3: Green Hydrogen Case Study Routes (Blue Exporters, Green Importers, Red Routes See Table 3.2)

Table 3.2: Green Hydrogen Case Study Routes

Case Study Index (x)	**Case Study**	**Distance**	**Terrain**	**Significance**
1	Australia – Japan	6,800km	Sea	Japan large import demand
2	Australia – South Korea	6,800km	Sea	South Korea large import demand
3	Australia - Singapore	3,000km	Sea	Maritime Bunker Fuel (shorter distance)
4	Australia - Germany	25,200km	Sea	Very long distance
5	Middle East - India	2,600km	Land or Sea	Mixed terrain options (medium distance)
6	Middle East - China	13,900km	Land or Sea	Mixed terrain options (long distance)
7	Middle East - Europe	3,550km	Land or Sea	Mixed terrain options (medium distance)
8	North Africa - Europe	4,800km	Sea	Comparison of exporters
9	South Africa - Europe	12,200km	Sea	Comparison of exporters
10	Chile - USA	8,500km	Sea	Long distance

3.4.3 Regions Linear Programming

Regions Methodology

The second analysis approach is a green hydrogen world regional trade optimisation with routes as shown in Figure 3.4. For simplicity, the world has been simplified into six regions with fifteen simplified trade routes between these regions. The base transportation costs for the cheapest medium is applied to the simplified fifteen routes shown in Table 3.3. The model has specific parameter values for the local production of green hydrogen in each region. Local production and transportation costs are combined to define a linear programming problem to determine the most cost-efficient means of satisfying demand in each region by supplying green hydrogen from production to application. That is, this determines if green hydrogen produced locally or imported from the other regions if cheaper. The outputs provide an estimate of the feasibility of exporting hydrogen for international trade. This analysis provides insight into the volume of potential green hydrogen trade and identify which routes may be the key trade routes.

Table 3.3: World Region Trade Route Distances in kilometres, rows are importers / columns are exporters (Noting each region is simplified to a single location)

	Europe	**Africa**	**Asia**	**Oceania**	**North America**	**South America**
Europe	N/A	5721	6890	14315	8156	9662
Africa	5721	N/A	8865	11553	13249	9586
Asia	6890	8865	N/A	7827	10805	16470
Oceania	14315	11553	7827	N/A	14762	15747
North America	8156	13249	10805	14762	N/A	7259
South America	9662	9586	16470	15747	7259	N/A

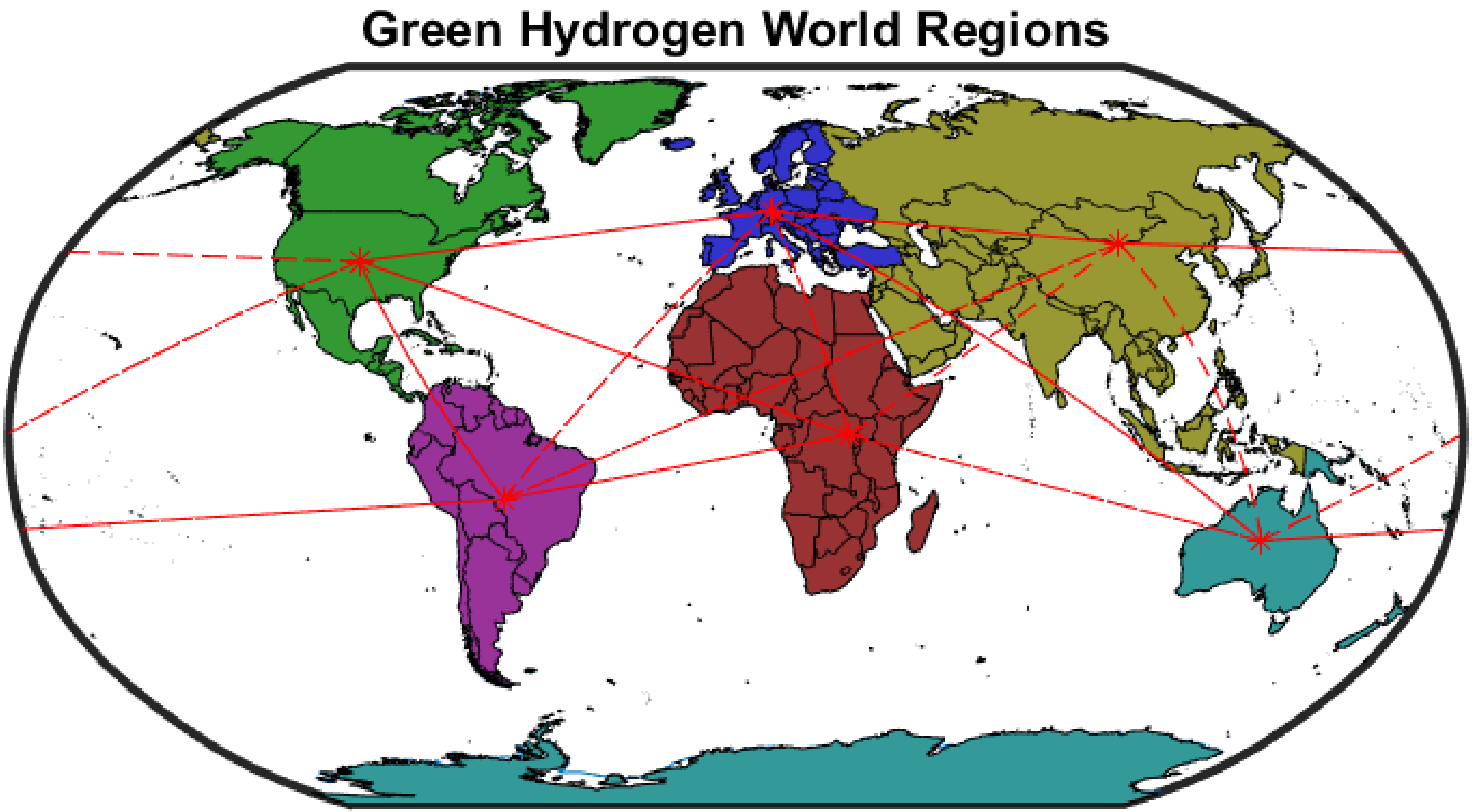

Figure 3.4: Green Hydrogen World Regions (Europe Blue, Africa Brown, Asia Olive, Oceania Aqua, North America Green, South America Purple, Red Routes See Table 3.3)

Linear Programming Definition

Variables

s Source Region Index (1 = Oceania, 2 = Africa, 3 = Europe, 4 = Asia, 5 = North America, 6 = South America)

d Destination Region Index (1 = Oceania, 2 = Africa, 3 = Europe, 4 = Asia, 5 = North America, 6 = South America)

t Green Hydrogen Medium Index (Refer to Table 3.1)

x_{sd} Green Hydrogen Volume transported from Region s to Region d Units: (Mt)

For example:

x_{11} Region 1 (Oceania) local production to Region 1 (Oceania)

x_{32} Region 3 (Europe) local production transported to Region 2 (Africa)

vc_t Green Hydrogen Unit Transportation Variable Cost for Medium t Units: (\$AUD/Mt × km)

fc_t Green Hydrogen Unit Transportation Fixed Cost for Medium t Units: (\$AUD/Mt)

d_{sd} Distance between region s and region d (Refer Table 3.3) Units: km

p_s Green Hydrogen Production Costs Unit for Region ss: (\$AUD/Mt)

c_{sd} Green Hydrogen unit cost to produce Green Hydrogen in Region s and transport to Region d Units: (\$AUD/Mt) (Refer Equations 3.8 and 3.9)

For example:

c_{11} Green Hydrogen unit cost to produce Green Hydrogen in Region 1 (Oceania) and transport to Region 1 (Oceania). Units: (\$AUD/Mt)

c_{32} Green Hydrogen unit cost to produce Green Hydrogen in Region 3 (Europe) and transport to Region 2 (Africa). Units: (\$AUD/Mt)

S_s Total Green Hydrogen supply capacity for each region. Units: (Mt)

D_d Projected Green Hydrogen demand for each region. Units: (Mt)

L_{min} Min Limit for local Green Hydrogen to be used within a region. Units: (Mt)

L_{max} Max Limit for local Green Hydrogen to be used within a region. Units: (Mt)

T Max Limit for Green Hydrogen to be transported between two regions region. Units: (Mt)

The unit transportation cost is calculated the linear programming analysis using Equation

3.8:

$$c_{tsd} = p_s + fc_t + vc_t \times d_{sd} fors = [1, 6], d = [1, 6], t = [1, 14] \quad (3.8)$$

The cheapest unit transportation cost is selected for the linear programming analysis using Equation 3.9:

$$c_{sd} = min(c_{tsd}) fors = [1, 6], d = [1, 6], t = [1, 14] \quad (3.9)$$

Objective function

$$TotalCost = \sum_{s=1}^{6} \sum_{d=1}^{6} c_{sd} \times x_{sd} \quad (3.10)$$

Units: \$AUD

Linear Programming Problem Type: Minimise Objective Function

That is, the linear programming problem attempts to find minimise the total cost of supplying each region's green hydrogen demand with the most economically efficient combination of local production and inter-regional transport from other regions.

Constraints

Region 1 (Oceania) Supply Constraint:

$$x_{11} + x_{12} + x_{13} + x_{14} + x_{15} + x_{16} \leq S_1 \quad (3.11)$$

Region 2 (Africa) Supply Constraint:

$$x_{21} + x_{22} + x_{23} + x_{24} + x_{25} + x_{26} \leq S_2 \quad (3.12)$$

Region 3 (Europe) Supply Constraint:

$$x_{31} + x_{32} + x_{33} + x_{34} + x_{35} + x_{36} \leq S_3 \quad (3.13)$$

Region 4 (Asia) Supply Constraint:

$$x_{41} + x_{42} + x_{43} + x_{44} + x_{45} + x_{46} \leq S_4 \quad (3.14)$$

Region 5 (North America) Supply Constraint:

$$x_{51} + x_{52} + x_{53} + x_{54} + x_{55} + x_{56} \leq S_5 \tag{3.15}$$

Region 6 (South America) Supply Constraint:

$$x_{61} + x_{62} + x_{63} + x_{64} + x_{65} + x_{66} \leq S_6 \tag{3.16}$$

Region 1 (Oceania) Demand Constraint:

$$x_{11} + x_{21} + x_{31} + x_{41} + x_{51} + x_{61} \geq D_1 \tag{3.17}$$

Region 2 (Africa) Demand Constraint:

$$x_{12} + x_{22} + x_{32} + x_{42} + x_{52} + x_{62} \geq D_2 \tag{3.18}$$

Region 3 (Europe) Demand Constraint:

$$x_{13} + x_{23} + x_{33} + x_{43} + x_{53} + x_{63} \geq D_3 \tag{3.19}$$

Region 4 (Asia) Demand Constraint:

$$x_{14} + x_{24} + x_{34} + x_{44} + x_{54} + x_{64} \geq D_4 \tag{3.20}$$

Region 5 (North America) Demand Constraint:

$$x_{15} + x_{25} + x_{35} + x_{45} + x_{55} + x_{65} \geq D_5 \tag{3.21}$$

Region 6 (South America) Demand Constraint:

$$x_{16} + x_{26} + x_{36} + x_{46} + x_{56} + x_{66} \geq D_6 \tag{3.22}$$

Variable Constraints (volumes have to be non negative):

$$x_{sd} \geq 0; fors = [1, 6], d = [1, 6] \tag{3.23}$$

Variable Constraints (Apply limits for maximal transport quantities for each route):

$$x_{sd} \leq T; for s = [1, 6], d = [1, 6] where\ s \neq d \tag{3.24}$$

Variable Constraints (Apply limits for maximal local quantity for each region):

$$L_{min} \leq x_{sd} \leq L_{max}; for s = [1, 6], d = [1, 6] where\ s = d \tag{3.25}$$

Assumptions The linear programming problem is defined with the following assumptions:

- Assume all green hydrogen is used in the same year (assume no long term storage of green hydrogen)
- Each region is simplified to a single location
- No local distribution costs included.
- All transport is assumed to be shipping (for simplicity)
- The cheapest hydrogen medium for long distance is used (for simplicity)

3.5 Results

The results are disseminated in this final research project report. The results are displayed in tables, graphs and diagrams highlighting different aspects of the results. Results are presented for each transportation method, the key case study trade routes, and the world region trade. The results are converted to the cost per delivered unit of energy to allow for comparisons with different transportation medium. The results are broken down by the key parameters such as transportation distance, export volume, end use application to allow insights into the key parameters.

As baselines for the transportation costs for green hydrogen, the results are compared against the alternate fossil fuel-based energy carriers. Currently coal, crude oil and natural gas are the commonly used energy carriers. In the future, blue (with carbon capture) and grey (without carbon capture) hydrogen produced from fossil fuels are expected to potential options in addition to green hydrogen. The analysis compares the transportation costs per delivered unit of energy to compare the costs of green hydrogen against these alternate energy carriers. As shown in Figure 3.2, this is extended by applying the forecasted cost of carbon emissions with a carbon price for the respective energy carriers to determine the overall cost (Longden et al., 2022). This informs the viability of green hydrogen against other technologies against a range of potential carbon pricing scenarios in the future.

3.6 Validity of Potential Results or Findings

A number of different methods have been used to evaluate the validity of the results and findings.

The data collection is verified and checked by using multiple sources of information. Each parameter value that requires projections into the future are quantified with an uncertainty range to identify the likely range of values. These uncertainty ranges are used with the Monte Carlo method to determine probabilistically the output value ranges. In this way, the results have better validity in showing the uncertainty and range of potential outcomes. The model is flexible for changing the parameter values if new information becomes available.

The model design was checked through examples to ensure the calculations are correct and things such as the parameter units match as required. The calculations are compared against reference analysis to compare the results and validate the model. This was done prior to the software implementation to ensure the model is correct for the software to be verified against.

The software implementation has been tested in a modular and holistic fashion through development to ensure the model has been implemented correctly. Each function can be tested individually before the integration of the entire software model can be tested. This testing can be conducted with examples and test cases. The software has be tested against similar research studies on the economics of hydrogen transportation using the same starting data to verify similar output results. The outcomes have been compared to other calculations to determine if the results are similar given the differences in assumptions and parameter values.

To ensure the findings and analysis is valid, sensitivity and uncertainty analysis of the key parameters has been conducted to understand their impacts on the output calculations. One of the proposed ways to contextualise the green hydrogen costs is to compare against the baseline of the fossil fuel-based energy sources and grey hydrogen energy source. These methods allow for the findings to be contextualised and discussed amongst other topical issues related to the technology and implementation such as safety, public perceptions and guarantee of supply standards / certifications.

3.7 Limitations

The research project has several limitations or simplifying assumptions in order to maintain a manageable scope:

- There are several assumptions and simplifications to make the analysis more manageable including ignoring distribution by assuming hydrogen is produced close to transport hub and stopping the analysis at the import hub after reconversion (if required).

- The case studies are limited to a few specific examples of a few regional trade routes. These may skew the analysis to specific technologies that are favourable for the specific conditions of these specific routes.

- The regional trade is limited to six global regions in order to reduce the amount of region-specific parameter values that need to be collected. It is noted there are some variations of parameter values within the local regions and differences in distances, but the results are indicative of the larger trade. It is noted this model ignores any trade within a region for simplicity.

- Projecting future values such as electricity prices and hydrogen demand have significant uncertainty, especially for the emerging industry of green hydrogen. Technology advancements and external developments may influence the projections especially thirty years into the future.

Chapter 4

Analysis

This chapter details the implementation and presents the results of the techno-economic analysis for Green Hydrogen transportation.

4.1 Implementation - Parameter Values

Extending the methodology described in Section 3, this section describes the parameter values used for the model in Matlab.

4.1.1 Production Parameters

Table 4.1 shows the green hydrogen production parameters. These parameter assume large scale production of green hydrogen through electrolysis. It also uses the levelised cost of electricity (LCOE) instead of the wholesale electricity price as most large scale hydrogen production will include a combination of wind farms and solar photovoltaics as part of the production facility. The cost parameters are provided in terms of the electrical rating of the electrolyser. As the production model is simple, only the elements of CAPEX, OPEX and electricity are included in the cost.

Table 4.1: Green Hydrogen Production Parameters

Parameter	Units	Value(2022)	Value(2030)	Value(2050)	Reference
CAPEX	$/kWe	900.0	700.0	450.0	(International Energy Agency (IEA), 2019)
OPEX	$/kWe	13.5	10.5	6.75	(International Energy Agency (IEA), 2019)
LCOE	$/MWhr	40.0	25.0	20.0	(International Energy Agency (IEA), 2020)
Electrolyser Efficiency	%	60.0	70.0	70.0	(Dawood et al., 2020)
Electrolyser Lifespan	yrs	30.0	30.0	30.0	(Adolf et al., 2017)
Electrolyser Utilisation	%	80.0	80.0	80.0	(Adolf et al., 2017)
Electrolyser H_2 Output	$m^3(H_2)/hr/1MW$	200.0	200.0	200.0	(Kannah et al., 2021)

4.1.2 Conversion / Re-conversion Parameters

Table 4.2 shows the green hydrogen conversion / re-conversion parameters. The parameters are listed for the different hydrogen mediums. It includes estimated parameters for the CAPEX and OPEX of the infrastructure required for the conversion from hydrogen gas to the various mediums. There is also a parameter for the energy usage for the conversion. The energy costs are added to the LCOH by assuming the energy is provided in the form of electricity. The capacity and energy are in terms of the input hydrogen weight to allow for comparison between mediums. These parameters cover both the conversion and re-conversion at the other end, and the costs are split between conversion and re-conversion by a proportional factor.

Table 4.2: Green Hydrogen Conversion / Re-Conversion Parameters

Medium	CAPEX($)	OPEX($/year)	Capacity (ktH_2/yr)	Energy ($kWhr/kgH_2$)	Reference
Hydrogen Compressed	25,000	500	100	1.2	(Hydrogen Council, 2020)
Hydrogen Liquified	1,400,000	56,000	260	6.1	(International Energy Agency (IEA), 2021)
Hydrogen Cryo-Compressed	800,000	12,000	100	7.3	(Faye et al., 2022)
Hydrogen Slush	900,000	14,000	100	7.6	(Lee et al., 2021)
Ammonia	116,000	1,740	100	5.5	(International Energy Agency (IEA), 2021)
Methanol	79,000	2,185	100	7.1	(International Energy Agency (IEA), 2021)
Synthetic Natural Gas	900,000	36,000	100	10.0	(Becker et al., 2019)
Methylcyclohexane (LOHC)	130,000,000	1,000,000	4,200	1.5	(International Energy Agency (IEA), 2021)
Porous Carbon	1,150,000	100,000	100	5.0	(Andrews et al., 2022)
Metal Hydride	800,000	70,000	100	5.0	(Sakintuna et al., 2007)

4.1.3 Transportation Parameters

Table 4.3 shows the transportation vehicle parameters for trucking, shipping and for trains.

Table 4.3: Batch Transportation Parameters

Parameter	Units	Truck	Ship	Train	Reference
Weight Limit	kg	24,000	104,000,000	4,400,000	(International Energy Agency (IEA), 2019)
Volume Limit	m3	44	120,000	3,000	(International Energy Agency (IEA), 2019)
Speed	km/hr	60	45	40	(Lee, 2022)
Vehicle CAPEX	$AUD	400,000	10,000,000	10,000,000	(Lee, 2022)
Vehicle OPEX	$AUD/day	500	10,000	10,000	(Lee, 2022)
Terminal CAPEX	$AUD	1,000,000	290,000,000	12,000,000	(International Energy Agency (IEA), 2021)
Terminal OPEX	$AUD/yr	40,000	11,600,000	480,000	(International Energy Agency (IEA), 2021)
Lifespan	years	30	30	30	(International Energy Agency (IEA), 2019)
Utilisation	%	70	90	90	(International Energy Agency (IEA), 2019)
H_2 Pressure	bar	300	250	250	(International Energy Agency (IEA), 2019)
Vehicle Energy Usage	MJ/km	33.5	9464.0	671.0	(Lee, 2022)

Table 4.4 shows the transportation parameters for pipelines.

Table 4.4: Pipeline Transportation Parameters

Parameter	Units	Pipeline	Reference
Pressure	kPa	10,000	(International Energy Agency (IEA), 2019)
Velocity	m/s	10.0	(International Energy Agency (IEA), 2019)
Pipe Diameter	mm	300.0	(International Energy Agency (IEA), 2019)
Utilisation	%	90.0	(International Energy Agency (IEA), 2019)
NG Blend	%	0.0 or 20.0	(International Energy Agency (IEA), 2019)
Lifespan	years	30.0	(International Energy Agency (IEA), 2019)
CAPEX	$/km	5000.0	(International Energy Agency (IEA), 2019)
OPEX	$/km	200.0	(International Energy Agency (IEA), 2019)

Table 4.5 shows the transportation fuel parameters for the different vehicle fuels: diesel, hydrogen and ammonia. When the payload is hydrogen or ammonia, a proportion of the transportation payload is used to power the vehicle to reduce emissions and remove having separate fuels onboard.

Table 4.5: Transportation Fuel Parameters

Parameter	Units	Diesel	Hydrogen	Ammonia	Reference
Cost	$/kg	2.00	3.00	3.68	(International Energy Agency (IEA), 2019)
Energy Density	MJ/kg	45.5	120.0	22.5	(Aylward and Findlay, 2013)
CO2	CO_2/L_{Fuel}	2.00	0.53	0.74	(International Energy Agency (IEA), 2019)
Energy Efficiency	%	50.0	40.0	44.0	(International Energy Agency (IEA), 2019)

4.1.4 Hydrogen Medium Parameters

Table 4.6 shows the different energy carriers physical properties in terms of the gravimetric density, energy density and proportion of hydrogen. Some of the common fossil fuels are included for reference.

Table 4.6: Green Hydrogen Mediums Physical Properties

Description	Weight Density (kg/m^3)	Gravimetric Energy Density (kJ/kg)	Volumetric Energy Density (kJ/m^3))	H_2 Gravimetric Proportion (%)	Reference
Hydrogen Gas (stp)	0.08988	120.0	10.79	100%	(Aylward and Findlay, 2013)
Hydrogen Gas (300 bar)	24.61	120.0	2,953	100%	(Aylward and Findlay, 2013)
Hydrogen Liquified	70.0	120.0	8,400	100%	(Aylward and Findlay, 2013)
Hydrogen Cryo Compressed	81.0	120.0	9,720	100%	(Aylward and Findlay, 2013)
Hydrogen Slush	85.0	120.0	10,200	100%	(Aylward and Findlay, 2013)
Ammonia	730.0	22.5	16,425	17.8%	(Aylward and Findlay, 2013)
Methanol	792.0	22.0	17,424	12.6%	(Aylward and Findlay, 2013)
Synthetic Natural Gas (SNG)	0.7170	50.0	35.85	23.8%	(Aylward and Findlay, 2013)
Methylcyclohexane (LOHC)	770.0	17.24	13,278	14.4%	(Aylward and Findlay, 2013)
Porous Carbon	2270.0	3.6	8,172	5.5%	(Aylward and Findlay, 2013)
Metal Hydride	1240.0	9.0	11,160	7.5%	(Aylward and Findlay, 2013)
Diesel	850.0	45.5	38,675	N/A	(Aylward and Findlay, 2013)
Natural Gas	0.7170	50.0	35.85	N/A	(Aylward and Findlay, 2013)
Liquified Natural Gas	450.0	50.0	22,500	N/A	(Aylward and Findlay, 2013)
Coal	900.0	23.9	21,510	N/A	(Aylward and Findlay, 2013)

Figure 4.1 shows a comparison of the gravimetric density of the various energy carriers. Obviously there is a large range from the gases, where uncompressed hydrogen is one of the lightest molecules to the heavier mediums. Some of the common fossil fuels are included for reference.

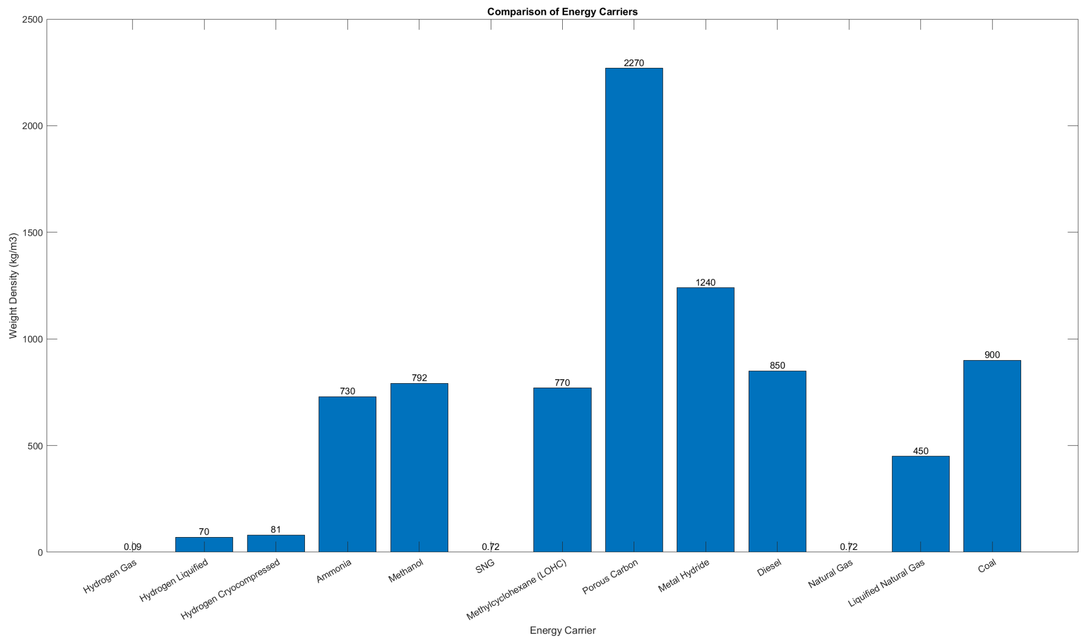

Figure 4.1: Energy Carrier Weight Density

Figure 4.2 shows a comparison of the energy density of the energy carriers both in terms of gravimetric and volumetric energy densities. Transportation vehicles have restrictions on weight and volume, so having a high energy density will allow for less transportation costs. Pure Hydrogen has a very high gravimetric energy density, but a very low volumetric energy density, requiring multiple transportation vehicles to provide the same amount of energy as a much smaller volume of fossil fuels. Some of the alternate energy carrier mediums for hydrogen such as ammonia and methanol have much better volumetric density.

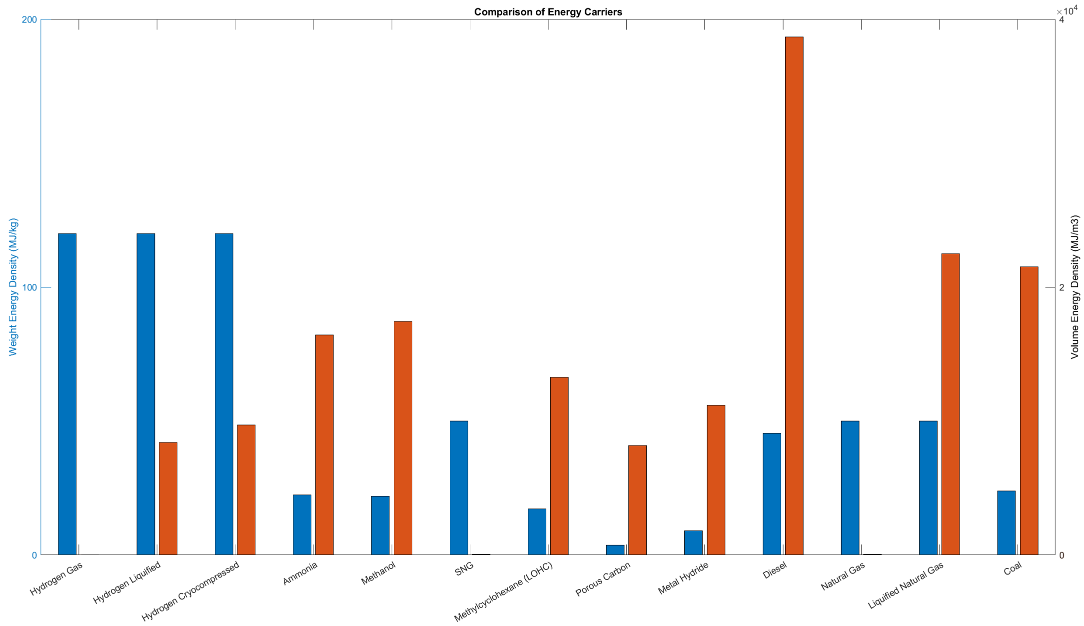

Figure 4.2: Energy Carrier Gravimetric Energy Density (blue) Energy Carrier Volume Energy Density (orange)

4.1.5 Green Hydrogen Supply and Demand Parameters

Table 4.7 shows the projected green hydrogen demand and maximum supply potential parameters for each region. The demand has been calculated by distributing the global projected green hydrogen demand by the region's relative energy usage (using data from (Our World In Data, 2022) and (Hydrogen Council, 2021)). The max supply potential relates to the maximum potential production which is based on the current energy usage and availability of renewable energy resources (i.e Oceania, Africa and South America have a large scope for expansion, Europe, Asia and North America are limited). These parameters will be used in the regions linear programming analysis. This data is also visualised in Figures 4.21 and 4.22

Table 4.7: Green Hydrogen Supply and Demand Parameters

Region	Max Supply Potential (2030)	Max Supply Potential (2050) (Mt)	Demand (2030) (Mt)	Demand (2050)
Europe	39.6	129.0	19.8	64.5
Africa	155.7	507.7	7.8	25.4
Asia	50.5	164.7	25.2	82.3
Oceania	26.7	87.1	1.3	4.4
North America	58.8	191.8	29.4	95.9
South America	88.9	290.0	4.4	14.5
Total	420.2	1370.4	88	287

4.1.6 Carbon Pricing Parameters

Figure 4.3 shows the projected carbon price that is used in this analysis ((International Energy Agency (IEA), 2019)).

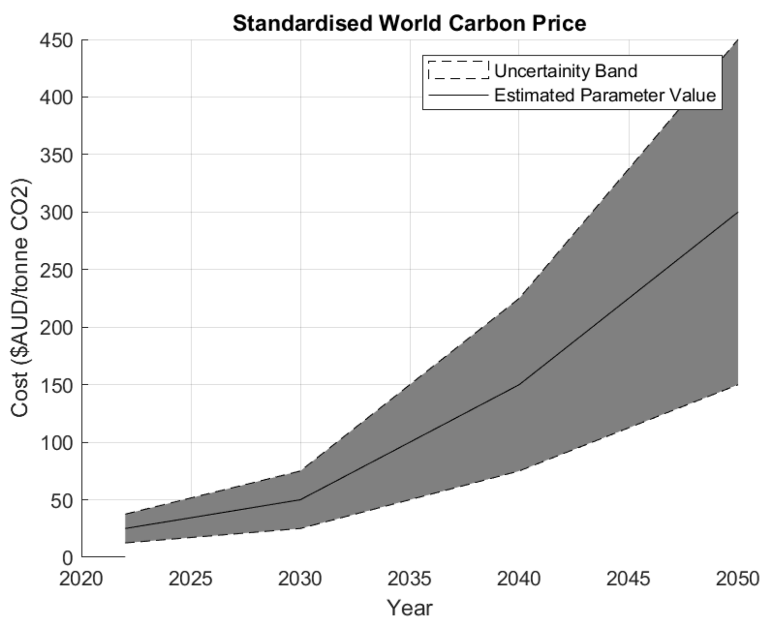

Figure 4.3: Projected Carbon Price (standardised)

Table 4.8 shows the carbon emission parameters of the various fuels when combusted. The carbon emissions will be calculated for when these fuels are the payload or when diesel is used to power the transportation for green hydrogen.

Table 4.8: Carbon Pricing Parameters

Fuel	**$kgCO_2$ Emissions per kg of fuel**	**$kgCO_2$ Emission per MJ**	**Reference**
Coal	3.37	0.104	(The Engineering Toolbox, 2022)
Diesel	3.15	0.069	(The Engineering Toolbox, 2022)
LNG	3.11	0.075	(The Engineering Toolbox, 2022)
NG	2.75	0.050	(The Engineering Toolbox, 2022)

4.1.7 Case Study Analysis Parameters

Table 4.9 shows the parameter values for the case study analysis.

Table 4.9: Case Study Analysis Parameters

Parameter Symbol	Parameter Description	Units	Parameter Value
x_x	Trade volume per route	Mt	10 Mt/year
d_x	Distance between route x	km	Refer Table 3.2
p	Region Production Price	\$/kg	Refer to Table 4.12
fc_t	Fixed Transportation Unit Cost	\$/km	\$0.2 /t (Transportation Results for Ammonia via shipping)
vc_t	Variable Transportation Unit Cost	$\$/(kg \times km)$	$\$0.0046/(t \times km)$ (Transportation Results for Ammonia via shipping)

4.1.8 Regions Analysis Parameters

Table 4.10 shows the parameter values for the regions analysis.

Table 4.10: Regions Analysis Parameters

Parameter Symbol	**Parameter Description**	**Units**	**Parameter Value**
L_{min}	Local Green Hydrogen Min Constraint	Mt	5 Mt
L_{max}	Local Green Hydrogen Max Constraint	Mt	120 Mt
T	Transport Green Hydrogen Constraint	Mt	80 Mt
S_s	Region Supply Capacity	Mt	Refer Table 4.7
D_d	Region Demand	Mt	Refer Table 4.7
x_{sd}	Trade volume	Mt	To be calculated by linear programming solution
d_{sd}	Distance between regions s and d	km	Refer Table 3.3
p_s	Region Production Price	$\$/kg$	Refer to Table 4.12
vc_t	Transportation Unit Cost	$\$/kg \times km$	$\$0.0046/t \times km$ (Transportation Results for Ammonia via shipping)

4.2 Implementation - Software Implementation

This section provides a summary of the model implementation in Matlab. The full software, results and figures are available here:
https://github.com/robmakepeace/GreenHydrogen/tree/main/Software

Generally the software has been implemented in a modular fashion. Where possible, the different sections of the software have been implemented in separate scripts to allow for efficiency in executing the model in parts. The parameters have been defined in common scripts to ensure all parts of the logic are using the same values and these can be easily updated if required. Matlab class definitions have been used to define the parameters to ensure a standard variable structure and standard functions to be used throughout the model.

4.2.1 Production

Table 4.11 shows the cost factors used to modify the green hydrogen costs between different countries and regions. These cost factors were calculated by comparing the large scale renewable (SolarPV/Wind) levelised cost of electricity from (International Energy Agency (IEA), 2020). The availability of large amounts of renewable generated electricity is the largest determining factor in the difference of green hydrogen costs between countries. These cost factors will be multiplied by the Australian green hydrogen cost to determine the green hydrogen costs for each country.

Table 4.11: Green Hydrogen Production Country / Region Cost Factor. These cost factors have been calculated from the LCOE of each country sourced from (International Energy Agency (IEA), 2020). Factors have been normalised to Australia.

Parameter	**Units**
USA / North America	0.85
Saudi Arabia	0.92
Chile / Brazil / South America	0.978
Australia / Oceania	1.00
China / India	1.33
Morocco / Namibia / Africa	1.48
Germany / Europe	2.18
South Korea / Asia	2.57
Japan / Singapore	3.82

4.2.2 Conversion / Re-conversion

The conversions and re-conversion calculations have been implemented in Matlab in a modular arrangement. The script uses the parameters presented in Section 4.1.2. These conversions are calculated for a nominal system, some of the parameter data is for different system. The calculations determine the total cost of the system across its lifespan including CAPEX, OPEX and energy costs. The system estimates the predicted throughput of hydrogen. The conversion costs will be presented in terms of the equivalent hydrogen gas weight to allow for comparison between mediums. The unit cost is calculated as the total cost divided by the total hydrogen throughput. The calculations are somewhat simplistic given the broad scope of this research project.

4.2.3 Transportation

The transportation model has been implemented in Matlab. Assuming similar infrastructure required for the transportation of each energy carrier, the amount of each energy carrier that can be carried per transportation vehicle (truck, ship and train) can be calculated. Each vehicle type has a weight limit and volume limit for its payload. The model determines whether each energy carrier will be constrained by weight or volume for each transnational vessel. It then calculates the total cost for a trip uses CAPEX, OPEX, average speed. The unit cost is this the total trip cost divided by the amount of energy carrier in each load. It is noted, that for many of the return journeys the transportation vessel is empty (no back loads), so a lower utilisation factor has been included to incorporate the cost of returning the vehicle to the source. The model also includes the cost of the loading and unloading terminals, but averages it out to a per unit basis. The cost of transportation fuel is also calculated by determining the energy requirements to power the vessel.

4.2.4 Carbon Pricing

The carbon pricing component of the software has been developed using scripts in Matlab. The software uses the parameters of the fuels in Sections 4.1.3 and 4.1.6. The model calculates the energy requirements to power the transportation vehicles. This is converted in to the weight of fuel required and the associated carbon emissions. The carbon price is then applied to these emissions to determine the potential cost of the emissions associated with the transportation fuel. In addition, the total emissions of the delivered alternate fossil fuels (coal, natural gas, diesel, etc) is calculated of the combustion of the fuel itself and its associated transportation.

4.2.5 Monte Carlo Simulations

Monte Carlo simulations have been implemented in Matlab to analyse the impact of the uncertainty in the parameter values. Some parameters have fixed values with no uncertainty, for example the gravimetric density of liquid hydrogen. Some parameters have the same value over time for example the expected lifespan of a truck. Other parameters have values with uncertainty and varies over time such as the capital cost of an electrolyser.

To manage these variations in values, the parameters are defined for each year between 2022 and 2050. Each parameter is also defined with a percentage uncertainty. Monte Carlo simulations generate a random sample of values for each year for each parameter using the defined uncertainty. For simplicity a simplistic normal distribution of the uncertainty in the parameter values is modelled. Figure 4.4 shows an example of these Monte Carlo samples for a parameter value across the 2022 to 2050 timespan.

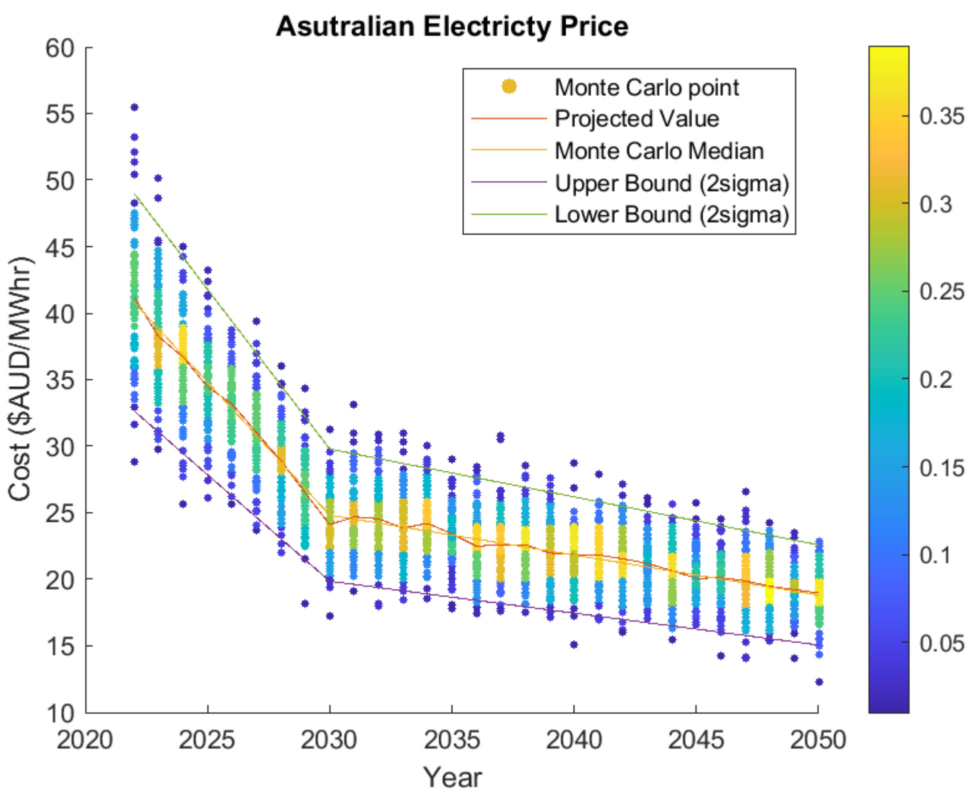

Figure 4.4: Monte Carlo Distribution Example for Australian Levelised Cost Of Electricity: each column is a new year value for the parameter value. Each dot in a column is a Monte Carlo sample, with the colours showing the probability density of the samples at that value. The lines show the average value, lower and upper bounds.

During the analysis calculations, the calculation is repeated multiple times with a different sample of each parameter. In this way, the range of outcomes is calculated with the different parameter values. The output probability distribution from a calculation can then be converted back to a averaged value and a calculated uncertainty value for its distribution. This Monte Carlo approach allows for quantification of doubt of parameter values to allow for a better visualisation of the likely range of outputs. This makes the models more robust by showing the uncertainties in the predicted output values.

4.2.6 Case Study Routes Analysis

The case study analysis has been implemented in Matlab using the scripts and functions. The software implements the equations presented in Section 3.4.2. The equations are modular and can be easily adjusted for new routes or different years of the analysis.

Cost breakdown bar chart diagrams will be used to visualise the outputs of the case study route analysis (Figure 4.11). The diagram shows the cost components of the delivered hydrogen cost due to the different stages of the hydrogen economy; production, conversion, transport, re-conversion and carbon pricing.

4.2.7 Regions Linear Programming Analysis

The linear programming problem is defined in Section 3.4.3 has been implemented in Matlab using the 'linprog' function which is part of the optimisation toolbox.

Alluvial flow diagrams will be used to visualise the outputs of the linear programming problem (Figure 4.24). The diagram shows the quantities of green hydrogen transported from the source regions to the destination regions in the optimised solution. This is implemented in Matlab using the Alluvial Flow diagram add on function in Matlab.

4.3 Results

This section describes the results of the models and various analysis methods.

4.3.1 Green Hydrogen Production

Figure 4.5 shows the components of the simplistic levelised cost of hydrogen production. The main component of the cost of the electricity to power the electrolyser. The electricity price and electrolyser efficiency parameters vary over time. The levelised cost of electricity is expected to reduce with economies of scale and cheap renewable generation. The electrolyser efficiency is projected to improve from 60% to 70% with improved technology. The CAPEX cost is projected to decrease over time with increasing production and optimisation. The OPEX costs will decrease slightly with automation and productivity.

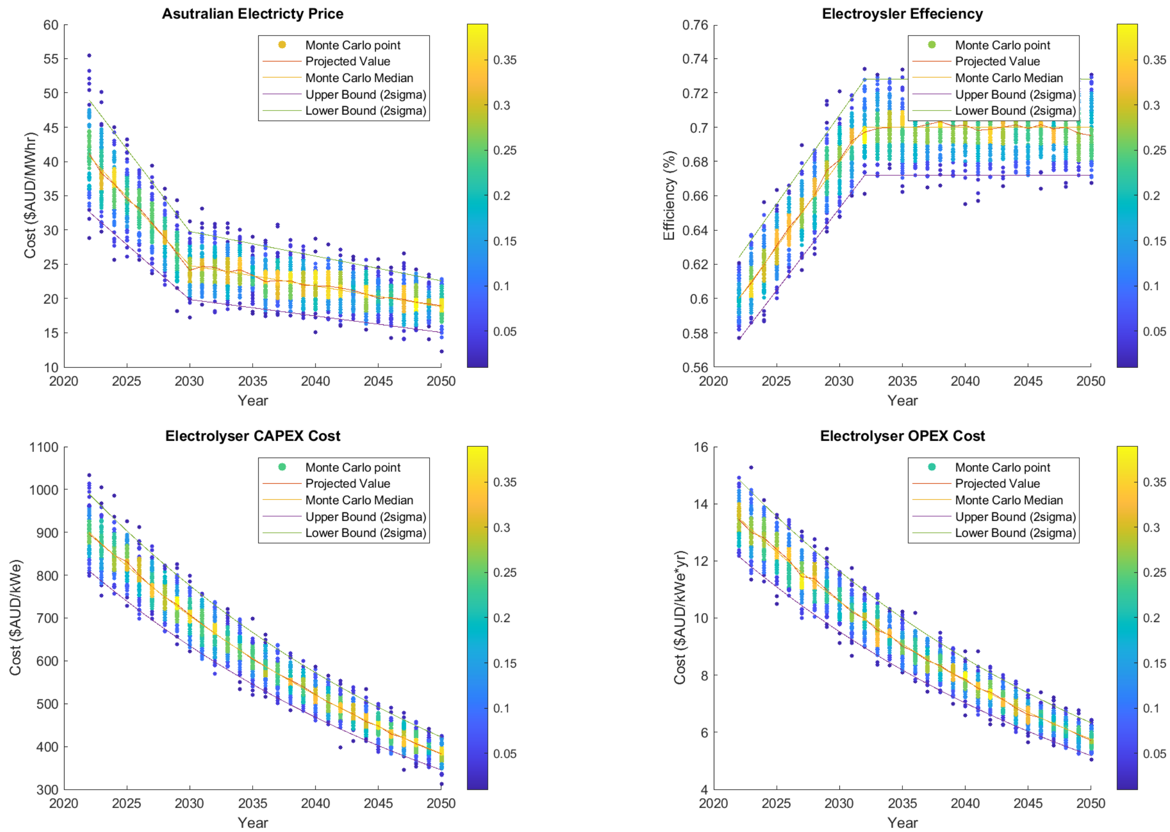

Figure 4.5: Green Hydrogen LCOH Production Components (clockwise from top left: Levelised Cost of Electricity, Electrolyser Efficiency, CAPEX Cost and OPEX Cost.) X Axis is the time (2020 through 2050). Y Axis is the parameter value. Each dot represents one sample of the Monte Carlo, with the colours representing the probabilistic density and distribution of the parameter values.

Figure 4.6 shows the combined calculated levelised cost of hydrogen production for Australia. This has been calculated using Monte Carlo analysis with the samples shown in the distributions for Figure 4.5.

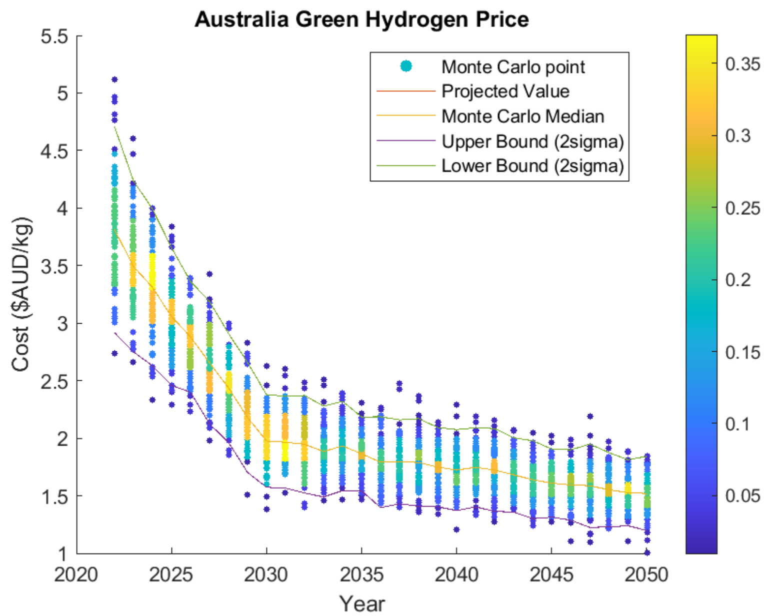

Figure 4.6: Green Hydrogen LCOH Production. X Axis is the time (2020 through 2050). Y Axis is the parameter value. Each dot represents one sample of the Monte Carlo, with the colours representing the probabilistic density and distribution of the parameter values.

Table 4.12 shows the calculated production costs for each country across 2030, 2040 and 2050. A range of the costs is presented as the output of the Monte Carlo simulation showing the two sigma distribution (includes 95% of the potential outcomes)

Table 4.12: Green Hydrogen Production Results

Country	**Region**	**2030 LCOH (\$AUD/kgH_2)**	**2040 LCOH (\$AUD/kgH_2)**	**2050 LCOH (\$AUD/kgH_2)**
Australia	Oceania	1.9 - 2.7	1.6 - 2.3	1.5 - 2.1
Japan	Asia	7.5 - 10.5	6.2 - 9.0	5.5 - 8.0
South Korea	Asia	4.8 - 7.1	4.2 - 6.1	3.7 - 5.4
Singapore	Asia	7.5 - 10.5	6.2 - 9.0	5.5 - 8.0
USA	North America	1.6 - 2.4	1.4 - 2.0	1.2 - 1.8
China	Asia	2.5 - 3.7	2.2 - 3.2	1.9 - 2.8
India	Asia	2.5 - 3.7	2.2 - 3.2	1.9 - 2.8
Chile	South America	1.8 - 2.7	1.6 - 2.3	1.4 - 2.0
Germany	Europe	4.1 - 6.0	3.5 - 5.1	3.2 - 4.6
Saudi Arabia	Asia	1.7 - 2.5	1.5 - 2.1	1.3 - 1.9
Morocco	Africa	2.8 - 4.1	2.4 - 3.5	2.2 - 3.1
Namibia	Africa	2.8 - 4.1	2.4 - 3.5	2.2 - 3.1

4.3.2 Green Hydrogen Conversion / Re-conversion Costs

Table 4.13 shows the green conversion and re-conversion costs. The cheapest medium is compressed hydrogen, following by Ammonia, LOHC and methanol. The other mediums are all more expensive on a per unit basis. The table shows the range of the Monte Carlo outputs.

Table 4.13: Green Hydrogen Conversion Results (2030)

Medium	**Conversion Cost ($AUD/($kgH_2$))**	**Re-conversion Cost ($AUD/($kgH_2$))**
Hydrogen Compressed	0.27 - 0.40	0.03 - 0.04
Hydrogen Liquified	1.25 - 1.87	0.53 - 0.80
Hydrogen Cryo-Compressed	1.44 - 2.16	0.62 - 0.93
Hydrogen Slush	1.52 - 2.28	0.65 - 0.98
Ammonia	0.68 - 1.02	0.68 - 1.02
Methanol	0.87 - 1.31	0.87 - 1.31
Synthetic Natural Gas	1.46 - 2.20	1.46 - 2.20
Methylcyclohexane (LOHC)	0.69 - 1.03	0.69 - 1.03
Porous Carbon	1.15 - 1.73	1.15 - 1.73
Metal Hydride	0.99 - 1.48	0.99 - 1.48

4.3.3 Physical Transportation

Figure 4.7 shows a comparison of the amount of each energy carrier that can be carried per truck. Many of the converted energy carriers such as porous carbon, metal hydrides have the best throughput for trucks given its limitations on weight and volume. Figure 4.8 shows a comparison of the amount of each energy carrier that can be carried per ship. For shipping, volume seems to be a larger constraint than weight when compared to trucks. Figure 4.9 shows a comparison of the amount of each energy carrier that can be carried per train.

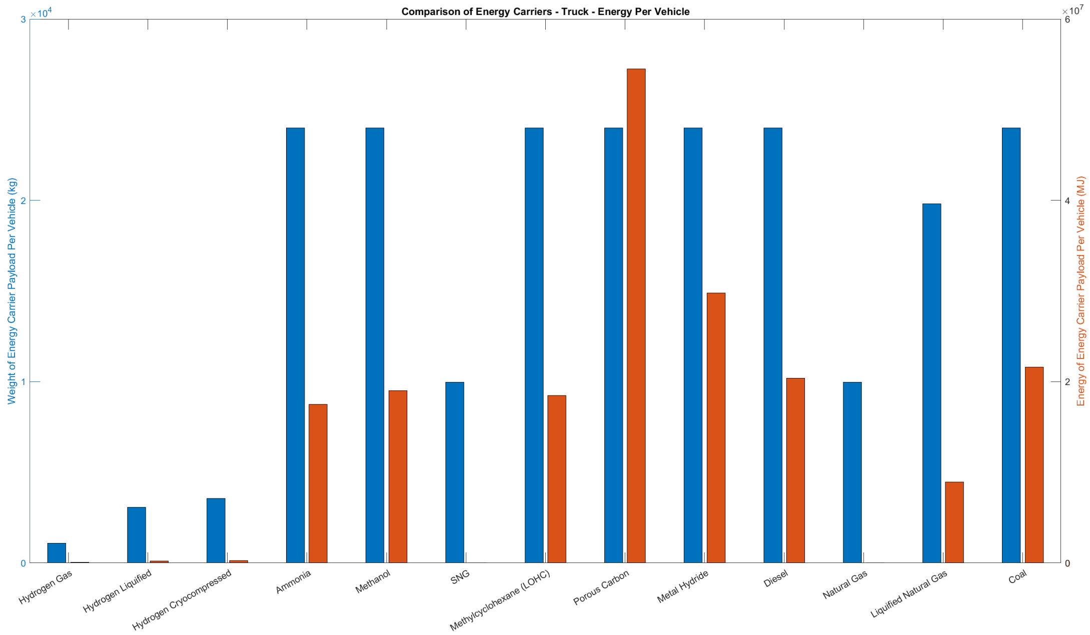

Figure 4.7: Truck - Comparison of Energy Carriers - Energy Per Vehicle. Weight of energy carrier payload per vehicle (blue). Energy of energy carrier payload per vehicle (orange). Note that most carriers are limited by weight

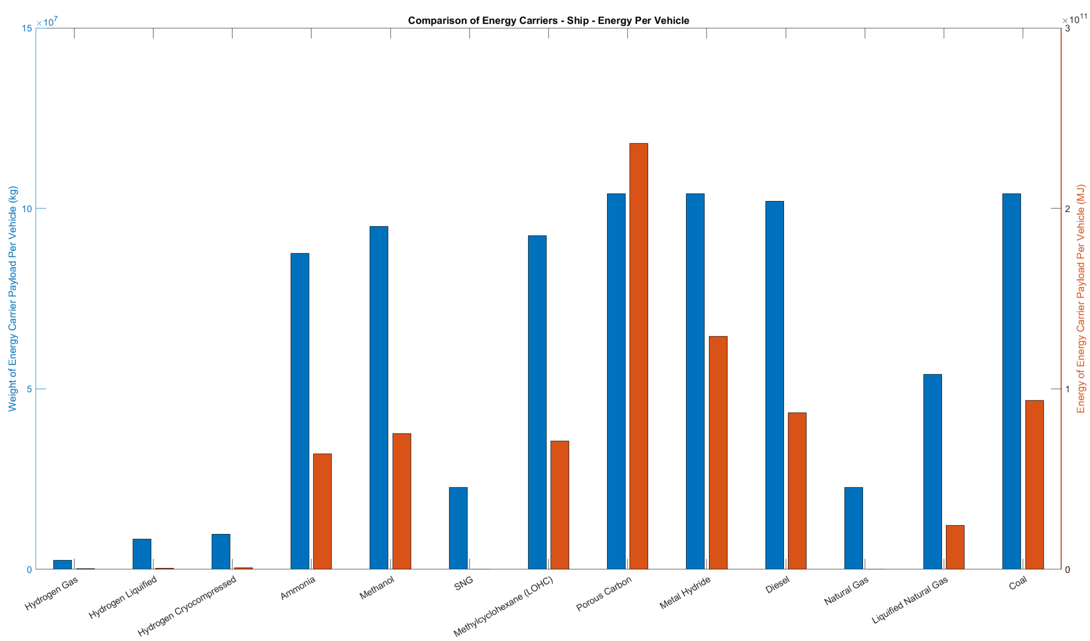

Figure 4.8: Ship - Comparison of Energy Carriers - Energy Per Vehicle. Weight of energy carrier payload per vehicle (blue). Energy of energy carrier payload per vehicle (orange). Note that most carriers are limited by volume not weight

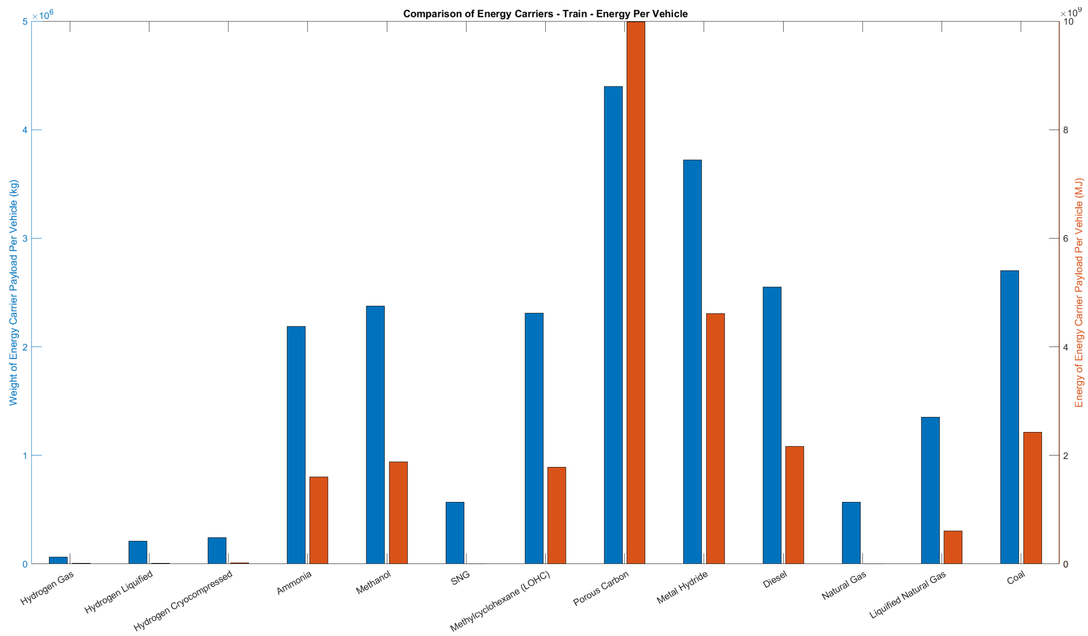

Figure 4.9: Train - Comparison of Energy Carriers - Energy Per Vehicle. Weight of energy carrier payload per vehicle (blue). Energy of energy carrier payload per vehicle (orange)

4.3.4 Green Hydrogen Transportation Mediums

Table 4.14 shows the transportation component of the levelised cost of hydrogen (LCOH) for shipping transportation for a nominal distance of 1000km for each of the mediums in the years 2030, 2040 and 2050. These results are presented in the likely range from the Monte Carlo simulations (two sigma or 95%). The alternate fuels transportation costs are also shown for reference.

Table 4.14: Green Hydrogen Mediums Shipping Transport Results (1000km)

Medium	**2030 LCOH (\$AUD/(tH_2 or tFuel))**	**2040 LCOH (\$AUD/(tH_2 or tFuel))**	**2050 LCOH (\$AUD/(tH_2 or tFuel))**
Hydrogen Compressed	41.5 - 62.3	36.3 - 46.7	31.1 - 41.5
Hydrogen Liquified	12.2 - 18.4	10.7 - 13.8	9.2 - 12.2
Hydrogen Cryo-Compressed	10.6 - 16.0	9.3 - 12.0	8.0 - 10.6
Hydrogen Slush	10.1 - 15.1	8.8 - 11.3	7.6 - 10.1
Ammonia	3.8 - 5.6	3.3 - 4.2	2.8 - 3.8
Methanol	4.6 - 7.0	4.1 - 5.2	3.5 - 4.6
Synthetic Natural Gas	11.5 - 17.3	10.1 - 13.0	8.6 - 11.5
Methylcyclohexane (LOHC)	4.2 - 6.4	3.7 - 4.8	3.2 - 4.2
Porous Carbon	16.2 - 24.2	14.1 - 18.2	12.1 - 16.2
Metal Hydride	6.8 - 10.2	6.0 - 7.7	5.1 - 6.8
Diesel	1.0 - 1.6	0.9 - 1.2	0.8 - 1.0
Natural Gas	4.6 - 6.8	4.0 - 5.1	3.4 - 4.6
Liquified Natural Gas	1.9 - 2.9	1.7 - 2.2	1.4 - 1.9
Coal	1.0 - 1.4	0.8 - 1.1	0.7 - 1.0

Table 4.15 shows the similar results for truck based transportation over a nominal distance of 1000km.

Table 4.15: Green Hydrogen Mediums Truck Transport Results (1000km)

Medium	**2030 LCOH (\$AUD/(tH_2 or tFuel))**	**2040 LCOH (\$AUD/(tH_2 or tFuel))**	**2050 LCOH (\$AUD/(tH_2 or tFuel))**
Hydrogen Compressed	872.8 - 1309.2	763.7 - 981.9	654.6 - 872.8
Hydrogen Liquified	309.4 - 464.0	270.7 - 348.0	232.0 - 309.4
Hydrogen Cryo-Compressed	267.4 - 401.0	233.9 - 300.8	200.5 - 267.4
Hydrogen Slush	254.7 - 382.1	222.9 - 286.6	191.0 - 254.7
Ammonia	186.6 - 279.8	163.2 - 209.9	139.9 - 186.6
Methanol	260.0 - 390.0	227.5 - 292.5	195.0 - 260.0
Synthetic Natural Gas	343.0 - 514.6	300.2 - 385.9	257.3 - 343.0
Methylcyclohexane (LOHC)	228.6 - 343.0	200.1 - 257.2	171.5 - 228.6
Porous Carbon	1065.0 - 1597.4	931.8 - 1198.1	798.7 - 1065.0
Metal Hydride	430.8 - 646.2	377.0 - 484.7	323.1 - 430.8
Diesel	39.7 - 59.5	34.7 - 44.6	29.8 - 39.7
Natural Gas	95.4 - 143.2	83.5 - 107.4	71.6 - 95.4
Liquified Natural Gas	48.2 - 72.2	42.1 - 54.2	36.1 - 48.2
Coal	39.7 - 59.5	34.7 - 44.6	29.8 - 39.7

Table 4.16 shows the similar results for train based transportation over a nominal distance of 1000km.

Table 4.16: Green Hydrogen Mediums Train Transport Results (1000km)

Medium	**2030 LCOH (\$AUD/(tH_2 or tFuel))**	**2040 LCOH (\$AUD/(tH_2 or tFuel))**	**2050 LCOH (\$AUD/(tH_2 or tFuel))**
Hydrogen Compressed	369.4 - 554.2	323.3 - 415.6	277.1 - 369.4
Hydrogen Liquified	109.1 - 163.7	95.5 - 122.8	81.8 - 109.1
Hydrogen Cryo-Compressed	94.3 - 141.5	82.5 - 106.1	70.7 - 94.3
Hydrogen Slush	89.8 - 134.8	78.6 - 101.1	67.4 - 89.8
Ammonia	50.8 - 76.2	44.5 - 57.2	38.1 - 50.8
Methanol	65.4 - 98.2	57.3 - 73.6	49.1 - 65.4
Synthetic Natural Gas	149.6 - 224.4	130.9 - 168.3	112.2 - 149.6
Methylcyclohexane (LOHC)	59.1 - 88.7	51.7 - 66.5	44.3 - 59.1
Porous Carbon	145.4 - 218.0	127.2 - 163.5	109.0 - 145.4
Metal Hydride	69.4 - 104.0	60.7 - 78.0	52.0 - 69.4
Diesel	9.0 - 13.4	7.8 - 10.1	6.7 - 9.0
Natural Gas	40.4 - 60.6	35.4 - 45.5	30.3 - 40.4
Liquified Natural Gas	17.0 - 25.4	14.8 - 19.1	12.7 - 17.0
Coal	8.5 - 12.7	7.4 - 9.5	6.4 - 8.5

Table 4.17 shows the similar results for pipeline based transportation over a nominal distance of 1000km.

Table 4.17: Green Hydrogen Mediums Pipeline Transport Results

Medium	**2030 LCOH (\$AUD/(tH_2))**	**2040 LCOH (\$AUD/(tH_2))**	**2050 LCOH (\$AUD/(tH_2))**
20% Blend Hydrogen	168.0 - 252.0	147.0 - 189.0	126.0 - 168.0
100% Blend Hydrogen	832.0 - 1248.0	728.0 - 936.0	624.0 - 832.0

4.3.5 Case Study Routes Analysis

Figure 4.10 shows the calculated green hydrogen price for each of the countries included in the case study routes for 2030 and 2050 respectively.

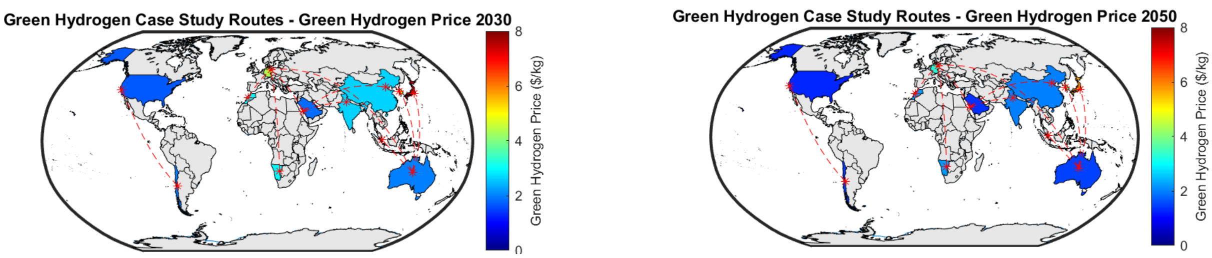

Figure 4.10: Green Hydrogen Case Studies Production Price (left 2030, right 2050)

The case study results are shown in Table 4.18 and the various figures below.

Table 4.18: Green Hydrogen Case Study Routes Results

Number	**Case Study**	**Distance**	**Terrain**	**Transport LCOH (\$AUD/kgH_2)**
1	Australia – Japan	6,800km	Sea	3.2 (Ammonia)
2	Australia – South Korea	6,800km	Sea	3.2 (Ammonia)
3	Australia - Singapore	3,000km	Sea	2.3 (Ammonia)
4	Australia - Germany	25,200km	Sea	3.7 (Ammonia)
5	Middle East - India	2,600km	Land or Sea	1.2 (Compressed H_2 Gas)
6	Middle East - China	13,900km	Land or Sea	2.1 (Ammonia)
7	Middle East - Europe	3,550km	Land or Sea	2.5 (Ammonia)
8	North Africa - Europe	4,800km	Sea	2.3 (Ammonia)
9	South Africa - Europe	12,200km	Sea	3.7 (Ammonia)
10	Chile - USA	8,500km	Sea	3.5 (Ammonia)

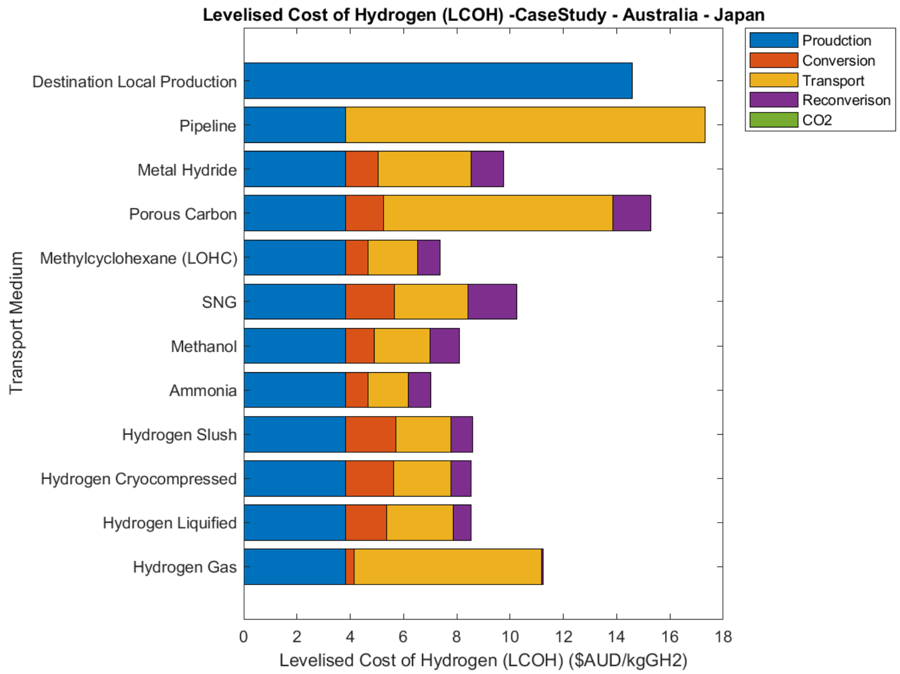

Figure 4.11: Case Study 1 Australia to Japan Cost Breakdown (2030)

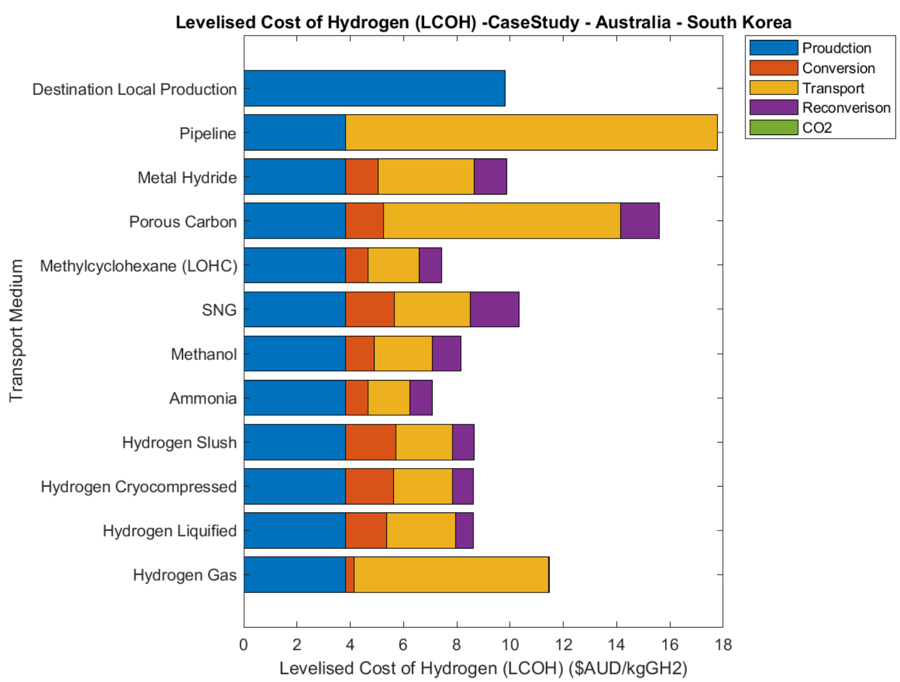

Figure 4.12: Case Study 2 Australia to South Korea Cost Breakdown (2030)

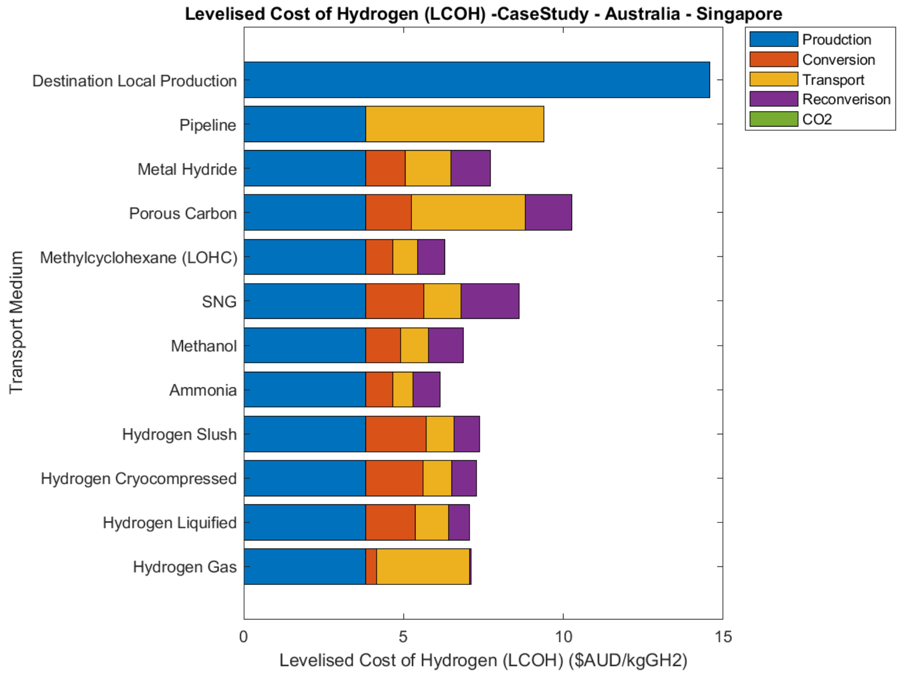

Figure 4.13: Case Study 3 Australia to Singapore Cost Breakdown (2030)

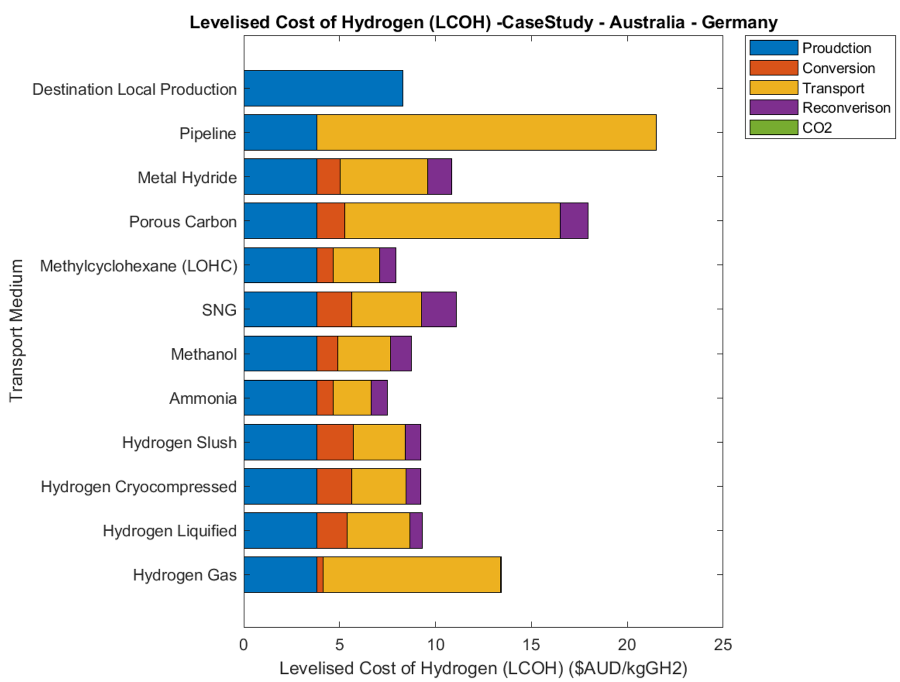

Figure 4.14: Case Study 4 Australia to Germany Cost Breakdown (2030)

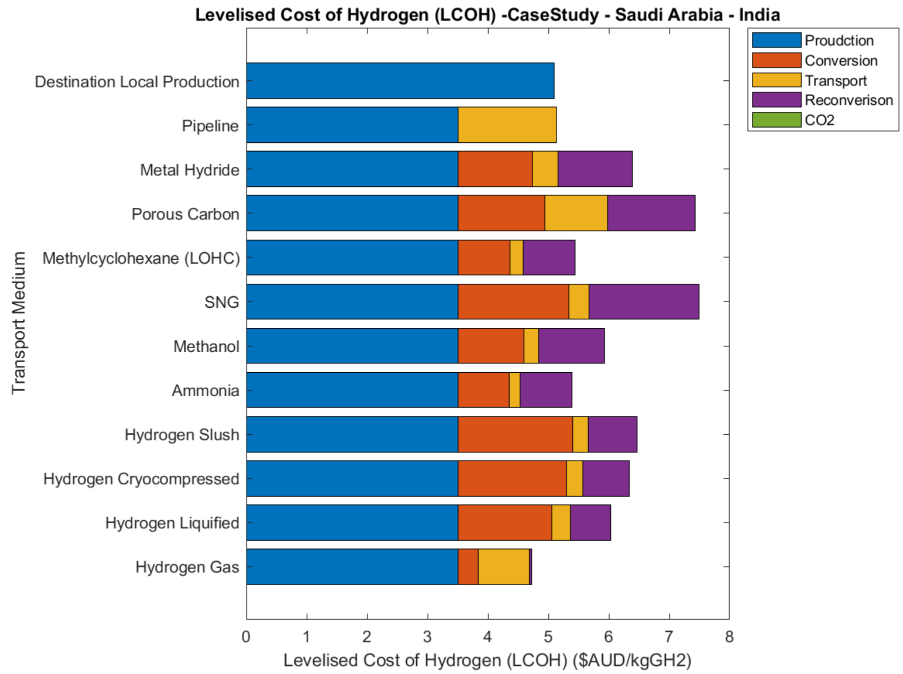

Figure 4.15: Case Study 5 Saudi Arabia to India Cost Breakdown (2030)

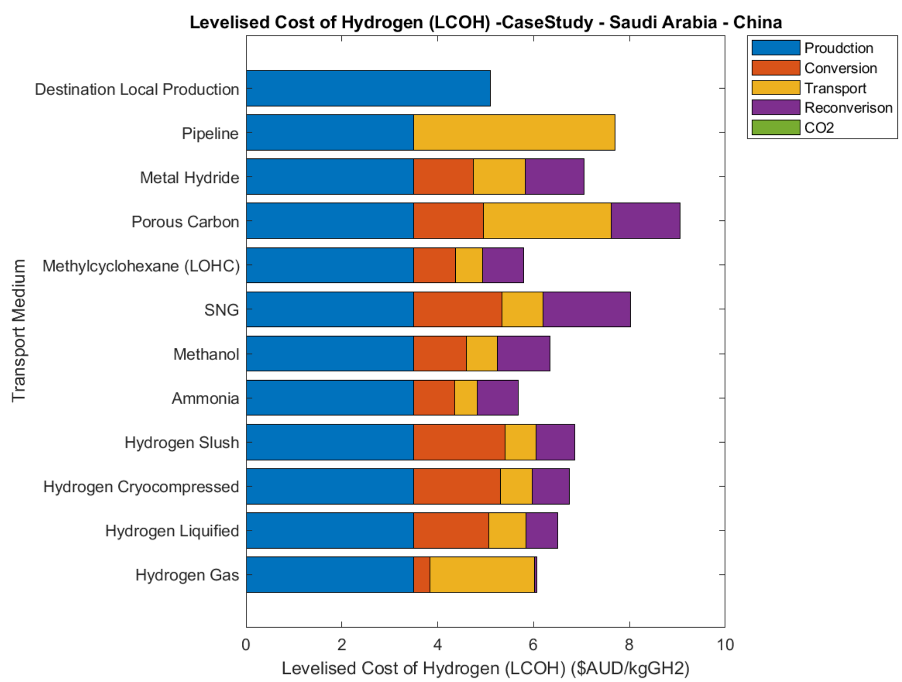

Figure 4.16: Case Study 6 Saudi Arabia to China Cost Breakdown (2030)

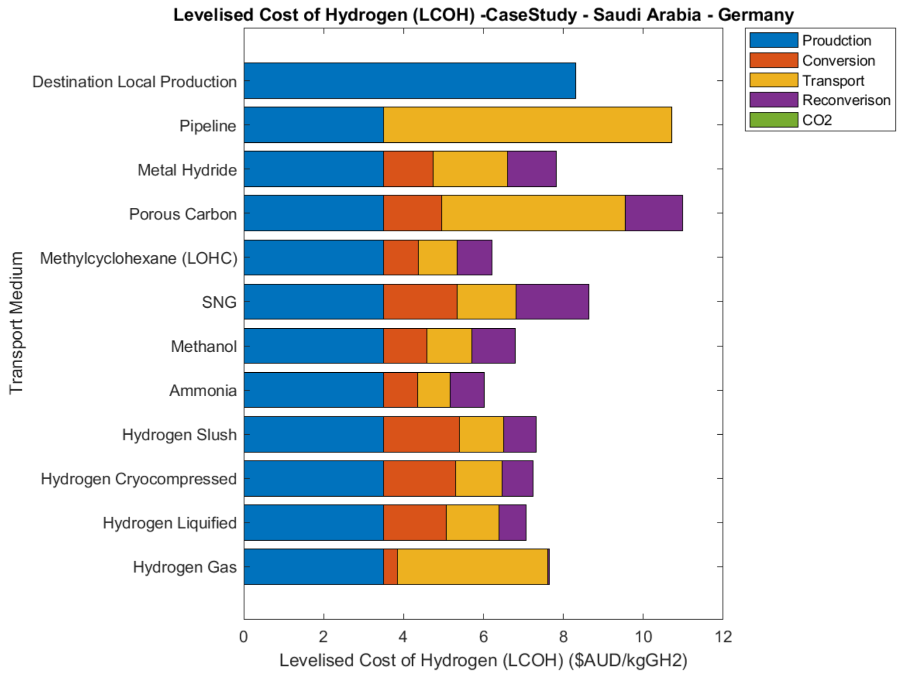

Figure 4.17: Case Study 7 Saudi Arabia to Germany Cost Breakdown (2030)

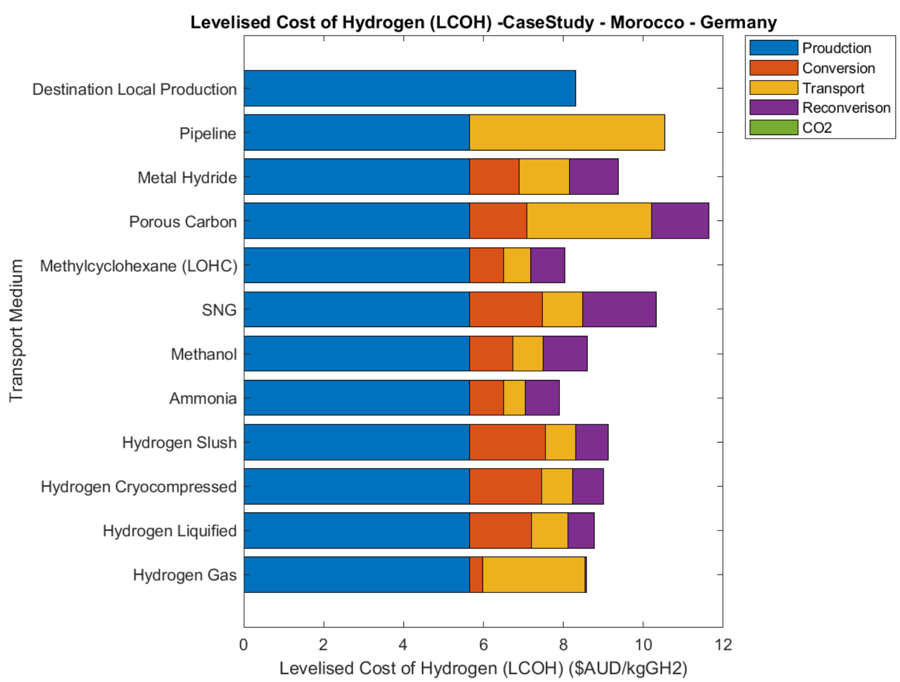

Figure 4.18: Case Study 8 Morocco to Germany Cost Breakdown (2030)

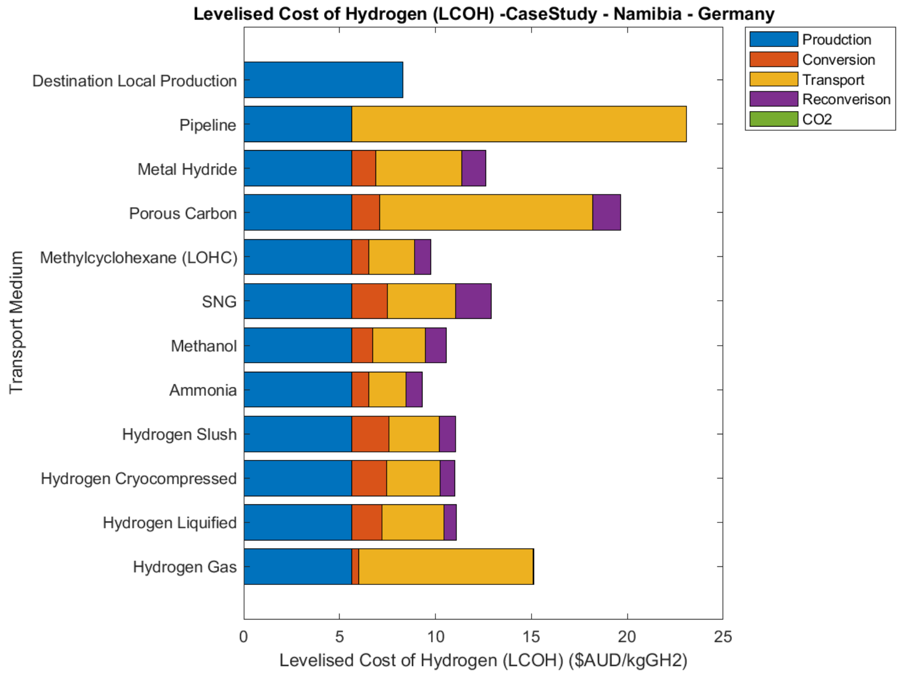

Figure 4.19: Case Study 9 Namibia to Germany Cost Breakdown (2030)

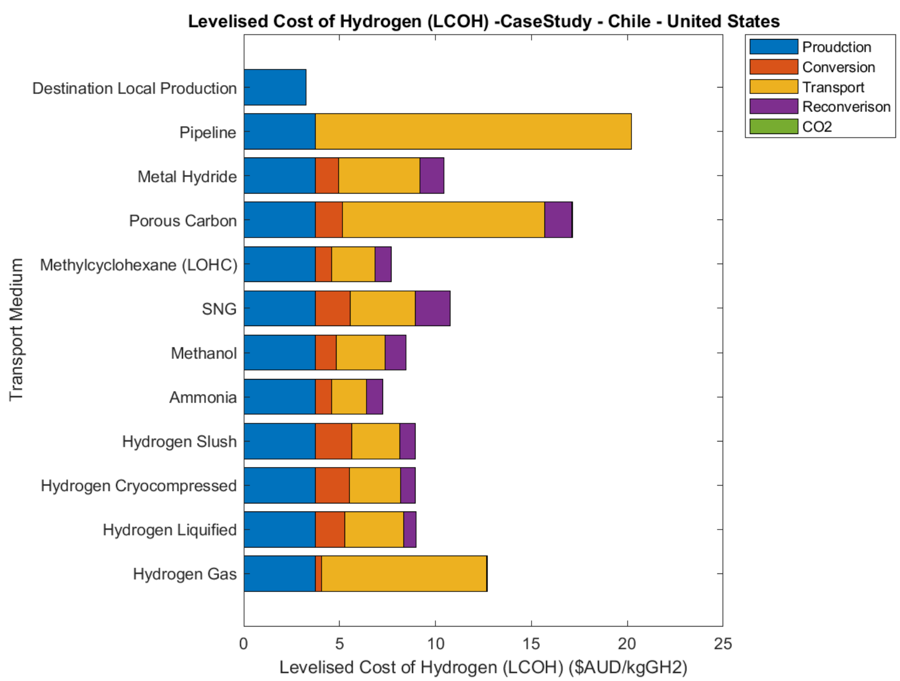

Figure 4.20: Case Study 10 Chile to United States Cost Breakdown (2030)

4.3.6 Regions Linear Programming Analysis

Figure 4.21 shows the projected green hydrogen demand for each region for the years 2030 and 2050 respectively

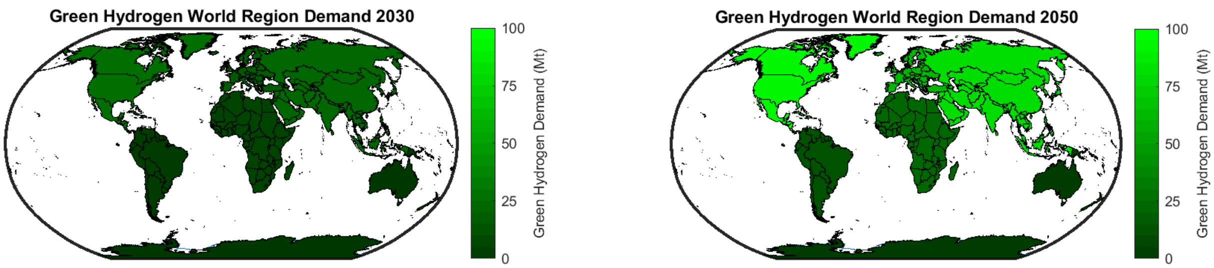

Figure 4.21: Green Hydrogen Regions Demand (left 2030, right 2050)

Figure 4.22 the projected green hydrogen max potential supply for each region for the years 2030 and 2050 respectively.

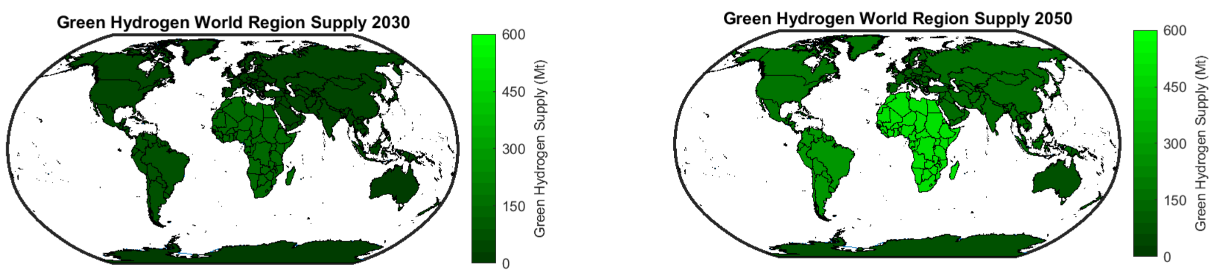

Figure 4.22: Green Hydrogen Regions Max Potential Supply (left 2030, right 2050)

Figure 4.23 shows the calculated green hydrogen price for each of the countries included in the case study routes for 2030 and 2050 respectively.

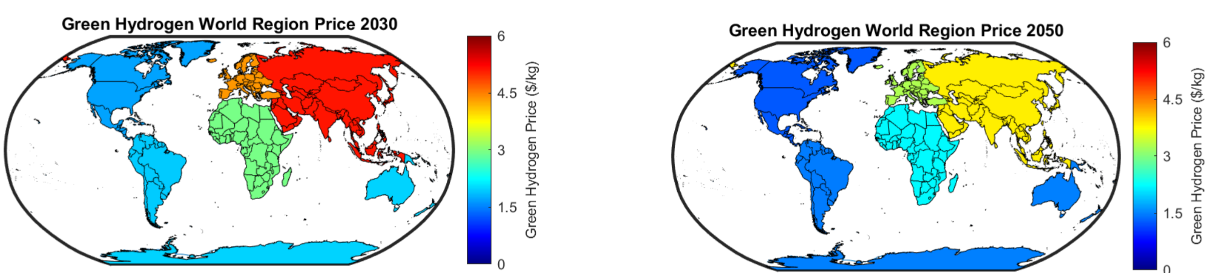

Figure 4.23: Green Hydrogen Regions Production Price (left 2030, right 2050)

Figures 4.24 and 4.25 shows the results for the regions analysis in the form of an alluvial flow diagram. The diagram shows the flow from the source regions on the left to the destination region on the right. The thickness of the lines reflects the volume of hydrogen transported on each route.

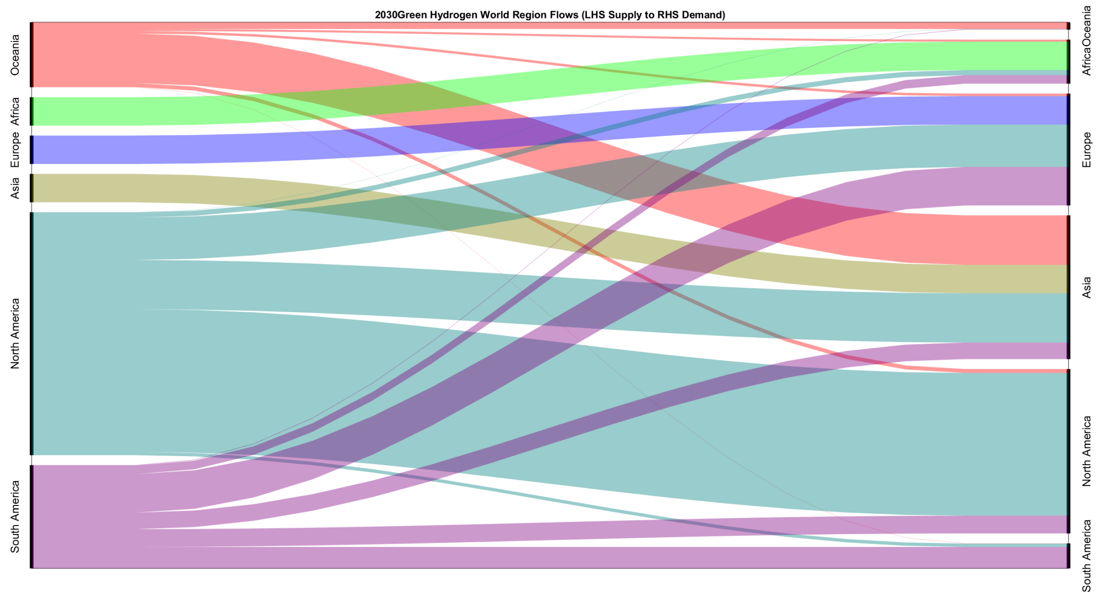

Figure 4.24: Green Hydrogen Regions Alluvial Flow Diagram 2030

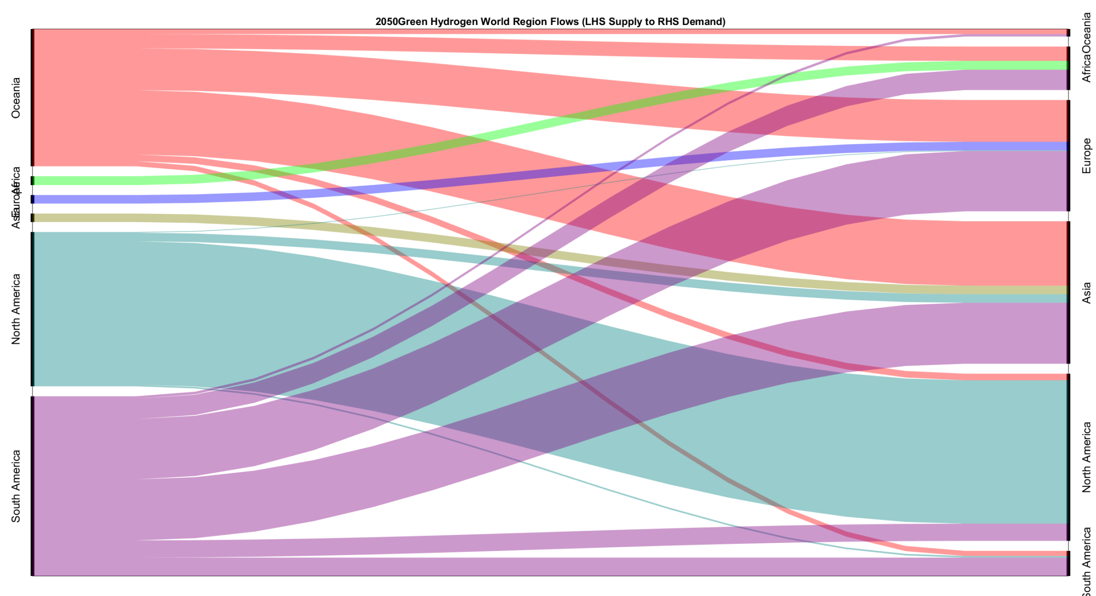

Figure 4.25: Green Hydrogen Regions Alluvial Flow Diagram 2050

Tables 4.19 and 4.20 shows the output of the regions analysis for the years 2030 and 2050 respectively. The table shows the volumes of green hydrogen transported between the regions. This output provides is the optimised lowest cost for this problem. The analysis shows about 52% of the green hydrogen is economically efficient to produce and consume locally, with the remaining 48% requiring long distance transportation to achieve the economically optimised solution in 2030. This reduces to 16% in 2050 for local with 84% requiring long distance transportation.

Table 4.19: Regions Analysis Results 2030 - Green Hydrogen Volumes transferred between source regions (rows) to destination regions (columns). These results have been averaged across multiple Monte Carlo simulation runs.

Quantities (MT)	**Oceania**	**Europe**	**Europe**	**Asia**	**North America**	**South America**
Oceania	1.2	0.4	0.4	8.8	0.7	0
Africa	0	5.0	0	0	0	0
Europe	0	0	5.0	0	0	0
Asia	0	0	0	5.0	0	0
North America	0	0.9	7.5	8.7	25.2	0.6
South America	0.1	1.5	6.8	2.9	3.1	3.8

Table 4.20: Regions Analysis Results 2050 - Green Hydrogen Volumes transferred between source regions (rows) to destination regions (columns). These results have been averaged across multiple Monte Carlo simulation runs.

Quantities (MT)	**Oceania**	**Europe**	**Europe**	**Asia**	**North America**	**South America**
Oceania	2.9	8.4	24.3	37.5	3.8	3.0
Africa	0	5.2	0	0	0	0
Europe	0	0	5.0	0	0	0
Asia	0	0	0	5.0	0	0
North America	0	0	0.4	5.0	83.4	0.9
South America	1.5	11.8	35.1	35.5	10.0	10.7

4.3.7 Carbon Pricing

Figure 4.26 shows a comparison of the different carbon emissions from different energy carriers. This includes the emissions from the combustion of the fuel itself and the transport emissions from diesel powered shipping transport of the fuel over a nominal distance of 5,000km. The graph is scaled by delivered energy units to allow for the different energy densities of the different fuels. The transport emissions mainly follow the difference in the weight / volume densities in the fuels.

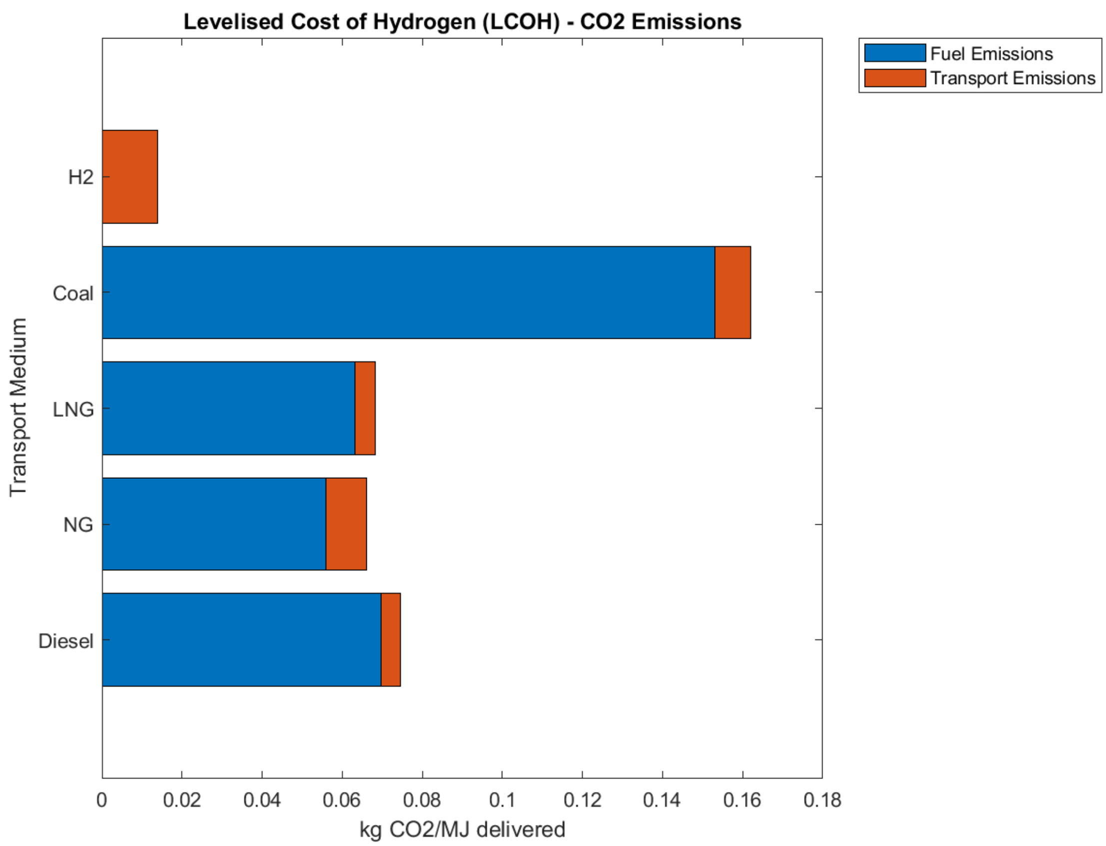

Figure 4.26: Energy Carrier CO_2 Emissions Comparison. Scaled by delivered energy units than weight of fuel for fair comparison.

Figure 4.27 shows a comparison of carbon pricing for the different energy carriers. A carbon price of \$100AUS / $kgCO_2$ has been used for this graph.

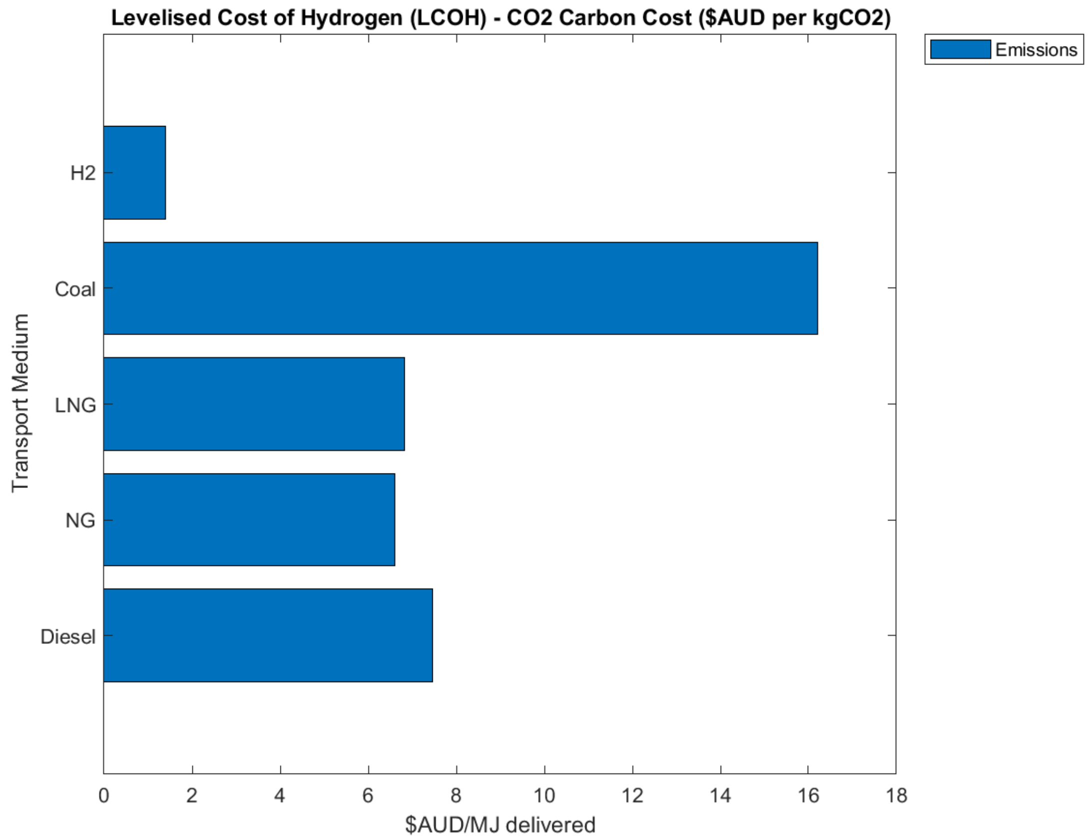

Figure 4.27: Energy Carrier Cost Comparison With Carbon Pricing. Carbon price: $100AUS / kgCO_2$. Scaled by delivered energy units than weight of fuel for fair comparison.

4.3.8 Alternative Energy Carriers

Table 4.21 shows a comparison of costs between the alternate energy carriers and hydrogen. The costs are per delivered energy unit to allow comparison between fuels. For simplicity, this table the prices of the fuels are based on market prices, which don't include any transportation costs.

Table 4.21: Alternate Energy Carriers

Fuel	Volume (L) for 1GJ	Weight (kg) for 1GJ	Cost ($\$/kg$)	Cost ($\$/GJ$)
Green Hydrogen Gas (2025)	338.5	8.3	5.0	41.5
Green Hydrogen Gas (2030)	338.5	8.3	3.0	24.9
Green Hydrogen Gas (2050)	338.5	8.3	2.0	16.6
Coal	46.4	41.8	0.416	17.4
Diesel	26.0	22.0	2.0	44.0
LNG	44.4	20.0	1.5	30.0
NG	27,894.0	20.0	1.0	20.0

Figure 4.28 shows the breakeven carbon price to allow for price equity with Green Hydrogen. Diesel is more expensive than hydrogen in 2025 in terms of raw energy, but is still widely used for its practicality, i.e. high weight density and existing infrastructure. LNG, Coal and Natural Gas are cheaper than hydrogen in 2025 with no carbon price, but break even with hydrogen with carbon prices of $\$154/kgCO_2$, $\$234/kgCO_2$ and $\$432/kgCO_2$ respectively. This break even prices reduce in 2030 and green hydrogen is cheaper than these other fuels without any carbon price in 2050. This analysis assumes constant fuel prices, noting these prices are likely to rise in the next 30 years, potentially reducing the break even carbon prices further.

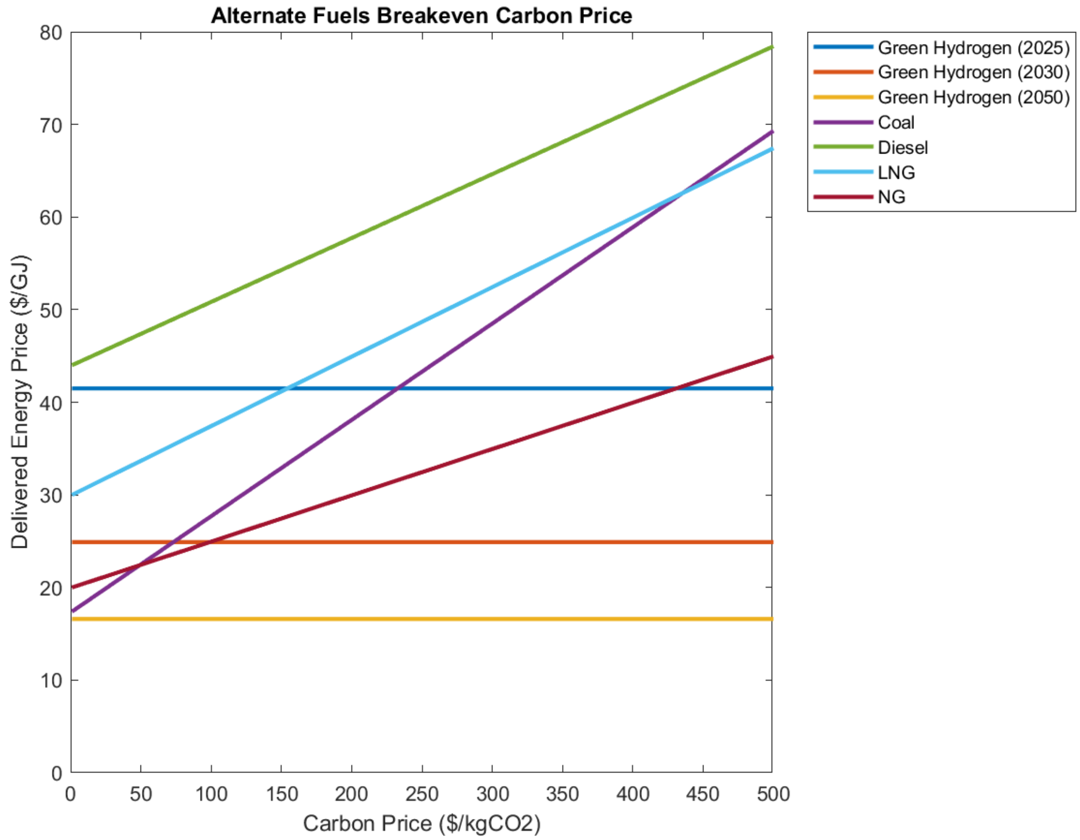

Figure 4.28: Alternate Fuels Breakeven Carbon Price. This graphs shows the impact of different carbon prices (x axis) on the total delivered fuel cost (y axis). The costs are per delivered energy unit to allow comparison between fuels

Figure 4.29 shows the breakdown of costs for the alternate fuels on the Australia to Japan route in 2030. Carbon pricing of $\$100/kgCO_2$ to show the comparison of these energy carriers with the various green hydrogen mediums.

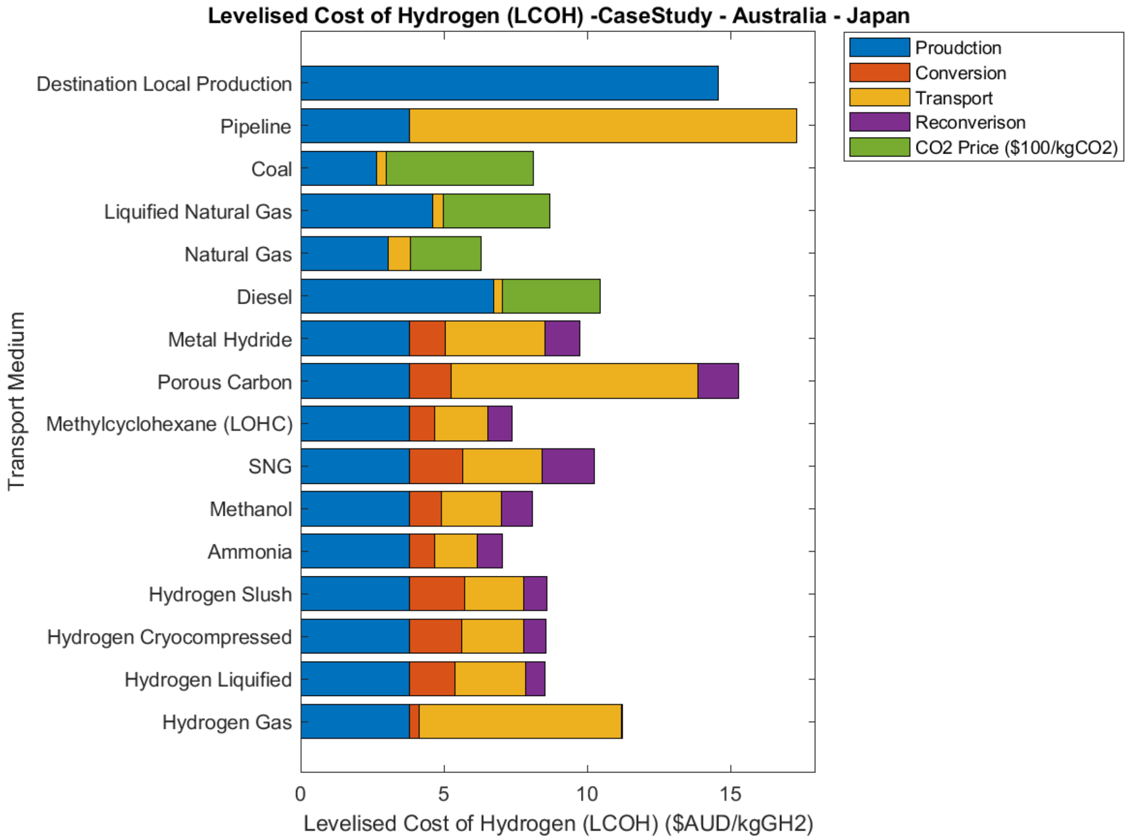

Figure 4.29: Alternate Fuels Breakdown for the Australia to Japan case study route with carbon pricing of $\$100/kgCO_2$

4.3.9 Comparisons to Relevant Literature Studies

This section presents the model outputs to allow comparison with relevant literature studies. Using the studies referenced in Section 2.9, the model outputs of this research paper have been adjusted to allow for a like for like comparison by aligning the parameters used for each study. This includes aligning the same transportation medium, same distance, same volume of payload and similar parameters for the transportation. These parameters are shown in Table 2.2.

Table 4.22 compares the results of this research project against (Amos, 1999), noting the Amos results are from over twenty years ago.

Table 4.22: Comparisons to Relevant Literature Studies - Amos et al (Amos, 1999)

Medium	**LCOH: Amos et al ($ per kg for 1600km)**	**LCOH: This Research Project ($ per kg for 1600km)**
Compressed Gas Delivery by Truck	$9.85	$2.12
Compressed Gas Delivery by Rail	$2.39	$1.11
Liquid Hydrogen Delivery by Truck	$0.49	$2.84
Liquid Hydrogen Delivery by Rail	$0.14	$2.44
Liquid Hydrogen Delivery by Ship	$1.99	$2.25
Metal Hydride Delivery by Truck	$5.59	$3.33
Metal Hydride Delivery by Rail	$3.09	$2.61
Pipeline Delivery	$0.21	$2.04

Table 4.23 compares the results of this research project against (Anastasopoulou et al., 2021). This paper provides more recent results especially focused on metal hydride technology with compressed and liquified hydrogen mediums for reference.

Table 4.23: Comparisons to Relevant Literature Stuides - Anastasopoulou et al (Anastasopoulou et al., 2021)

Medium	**LCOH: Anastasopoulou et al ($ per kg for 100km)**	**LCOH: This Research Project ($ per kg for 100km)**
Compressed H_2 truck (350bar)	$1.80	$0.48
Compressed H_2 truck (500bar)	$1.70	$0.48
Liquid H_2 truck (350bar)	$3.10	$2.26
Metal Hydride truck	$7.30 - $29.00	$2.52

Table 4.24 compares the results of this research project against (Raab et al., 2021). This paper focus on the LOHC medium, and liquified hydrogen reference. The presented costs

for Raab are higher than the other studies as they include the cost of production in their analysis with a relatively high value $\$5/kgH_2$ and use Euro currency. These have been converted into Australian Dollar and the production component removed from the cost. Note the results of the Raab paper have been converted from Euro currency to Australian dollars using the conversion rate of $1.50/1 Euro.

Table 4.24: Comparisons to Relevant Literature Studies - Raab et al (Raab et al., 2021)

Medium	**LCOH: Raab et al ($ per kg for 9260km)**	**LCOH: This Research Project ($ per kg for 9260km)**	**Comment**
Liquified Hydrogen	$3.75	$2.27	Converted from paper value: 7.5 Euro/kg (inc production)
LOHC Ship	$2.85	$1.86	Converted from paper value: 6.9 Euro/kg (inc production)

Table 4.25 compares the results of this research project against (Lee et al., 2022). This paper focus on three metal hydride mediums, with liquified hydrogen and ammonia as reference mediums. Production costs have been removed from the total.

Table 4.25: Comparisons to Relevant Literature Studies - Lee et al (Lee et al., 2022)

Medium	**LCOH: Lee et al ($ per kg for 5700km)**	**LCOH: This Research Project ($ per kg for 5700km)**
Liquified Hydrogen Shipping	$6.36	$1.81
Ammonia Shipping	$4.48	$1.73
Methanol Shipping	$4.30	$2.21
Metal Hydride (TOL-MCH) Shipping	$3.83	$2.52
Metal Hydride (DBT) Shipping	$6.00	$2.52

Chapter 5

Discussion

This chapter discussions the relevance and context of the results of the techno-economic analysis.

5.1 Case Study Routes Analysis

With reference to the results of the green hydrogen case study routes analysis presented in Section 4.3.5, these results provide some insight into the key potential green long distance hydrogen trade routes. They also contextualise the transportation medium results on how the practical implementation would develop.

With reference to Figure 4.11, the Australia to Japan route is a very viable route with the large difference in the countries' green hydrogen production cost. Australia is in a good position to provide Japan green hydrogen, with other exporters a much larger distance away from Japan. Australia already has pilot projects of transporting hydrogen to Japan, with ammonia used to co-combust in Japan's coal generators. Shipping with ammonia or LOHC is the most economic mediums for this route.

With reference to Figure 4.12, the Australia to South Korea route is similarly viable to the Australia - Japan route. This route may develop after Japan as the price difference is smaller for South Korea. Shipping with ammonia or LOHC is the most economic mediums for this route.

With reference to Figure 4.13, the Australia to Singapore route is another well discussed route due to Singapore's role as a key maritime fuel bunker location. Due to the shorter distance, some of the lower density hydrogen medium, such as compressed hydrogen, could be more viable as they have lower conversion costs. It is likely to use the medium for this route to be in the form of the end use maritime fuel. Therefore ammonia or LOHC via shipping could be the most viable.

With reference to Figure 4.14, the Australia to Germany route is a possible but less likely route. It is more likely for Europe's green hydrogen to be provided by Northern Africa, the middle east or North America with the shorter transportation distances. This route is longest distance of all the case studies and shows the most viable mediums for very long distance. In isolation, the Australia to Germany route could be viable with high density mediums such as liquefied hydrogen or metal hydrides in addition to ammonia, methanol and LOHCs.

With reference to Figures 4.15 and 4.16, these routes from Saudi Arabia to India and China were chosen to allow a comparison between shipping and land based transport (train / truck). For these long distances, shipping is more economical. The price difference is fairly small between the countries' green hydrogen prices, therefore the route is less viable than some of the other routes. India and China are forecast to produce more green hydrogen in the local region than require importation. Pipelines were viable for transport to India and LOHC medium for transport to China.

With reference to Figures 4.17, 4.18 and 4.19, there are a number of other viable sources for Europe's green hydrogen. Saudi Arabia, Morocco and Namibia all can produce green hydrogen cheaper than Europe. Saudi Arabia is potentially the most viable due to its lower production costs. Saudi Arabia requires land based transport with trains or pipelines being the most economical. African sources may require mixed transport with both shipping and land based modes. This needs additional ports and terminals to change transportation modes.

With reference to Figure 4.20, this shows that the Chile to USA route is not viable. While Chile has large potential for cheap green hydrogen production, it is a long distance from the importing countries. USA also has inexpensive green hydrogen production, so it will generally be cheaper to use locally produced green hydrogen instead of importing it from Chile.

5.2 Regions Linear Programming Analysis

With reference to the results of the green hydrogen region analysis presented in Section 4.3.6, these region results provide some insight into global scale hydrogen trade and potential volumes of trade.

With reference to Figure 4.24 and Table 4.19, the regions analysis shows potential for global hydrogen trade even as soon as 2030. With the relatively higher green hydrogen prices, Europe and Asia are projected to generally be net importers of green hydrogen. With lower prices, Australia, South America, North America and Africa are projected to be net exporters. Due to the simplified single locations of the regions, many of the inter-regional distances are fairly similar. The similar distances of routes mean that the green hydrogen production prices are the main determining factors of the net trade. The transport costs from each region for similar distances will be equivalent. In 2030, North America is the largest exporter, followed by Oceania and South America. Africa does not export any hydrogen due to its slightly higher production costs.

With reference to Figure 4.25 and Table 4.20, the results for 2050 are similar to 2030, but with a much large net volume of hydrogen demand. Approximately 15% of the optimal solution includes hydrogen being produced and consumed locally within a region. The remaining 85% of hydrogen in the optimal solution is transported between regions. The biggest inter region trade is green hydrogen produced in North America and transported to Europe.

Given the assumptions as part of the analysis, the results show the broad scale of the hydrogen trade and importance of the raw production costs. The actual hydrogen trade will be more complicated with varied demand and supply costs within regions, different models of transportation to match the end use application and the ability to store hydrogen. Moreover, the energy demands will slowly adapt to the new sources of energy, with energy intensive activities moving closer to the energy source.

Shipping will be the most likely medium for long distance transportation due to the geography and costs. The local distribution over shorter distances is expected to be with land based transport of trains, pipelines and trucks. The most likely mediums are ammonia, LOHC or liquefied hydrogen with the best balance of practicality, energy density and low conversion costs.

5.3 Comparison to Other Energy Carriers

Earlier sections of this report have discussed the important role energy carriers play in the world economy. This section discusses green hydrogen as a energy carrier against the other alternative energy carriers in the context of the results presented.

5.3.1 Comparison to Other Renewable Energy Carriers

Ammonia, Methanol and Synthetic Natural Gas can be defined as distinct energy carriers in their own right but have been included in this research project as potential derivatives of green hydrogen. In terms of other renewable energy carriers there are a few other options: electricity transmission lines, electrical batteries, pumped hydro, mechanical storage and thermal.

Renewable energy is already carried long distance by electricity transmission lines. There have been technological developments in high voltage transmission lines with minimise losses. There has been some recent proposed projects for electricity lines between countries including a project link between Australia and Singapore. While the technological readiness is high, the cost of transmission lines is high making it only suitable where there is existing infrastructure or for shorter distances.

Batteries provide energy storage for electricity. While batteries are useful in electric vehicles and in large scale batteries for the grid, they are not suitable for long distance trade of energy carriers due to charge retention and weight. Batteries are best suited for short term storage for a stationary application.

Pumped hydroelectric storage is a well developed energy storage system. Water can be pumped from a low dam to a high dam to "store" energy in gravitational potential energy. The pumped hydro is limited in that is it fixed to the specific location and the limitations of geography for creating new locations.

Thermal storage is another emerging energy storage technology. Molten salts is a leading technological contender for being able to retain heat until it is required at a later stage. Unfortunately, thermal storage is restricted to a specific location and is not suitable for transport due to weight and required infrastructure.

Of these energy carriers, electricity transmission is the only potential alternate energy carrier against hydrogen and its derivatives. Electricity Transmission has been estimated to cost $41.50 per MWhr ($11.53/GJ) of transmitted energy for a distance of 1000km transmission (DeSantis et al., 2021). By comparison, the same study evaluating hydrogen gas via pipeline energy carrier to cost $4.90 per MWhr ($1.36/GJ) of transmitted energy for a distance of 1000km, almost a factor of ten cheaper than electricity transmission (DeSantis et al., 2021). Therefore hydrogen is most more suitable for medium to long distances. Due to the better conversion efficiencies than hydrogen electricity is more cost effective for shorter distances. Green Hydrogen is suited for applications such as long distance transport where the lower conversion efficiencies are compensated by economies of scale with distance.

5.3.2 Comparison to Other Fossil Fuel Energy Carriers

With reference to the results in Section 4.3.8, a number of existing fossil fuel based energy carriers have been analysed against green hydrogen.

Diesel based energy carriers including crude oil are a ubiquitous energy carrier of the 20th and early 21st century. As the fuel is in a liquid form, it has a high energy density and is often transported in ships, trains and trucks. It is a versatile energy carrier allowing it be transported long distances and also power the vessel itself. Projecting crude oil prices is a challenging problem, but generally they are expected to slightly increase in the decades to come, with ongoing short term volatility. Diesel will have lower transport costs than green hydrogen due to the higher volumetric energy density, but green hydrogen is projected to have lower production costs as raw fuel prices rise.

Coal is a common energy export and is used extensively for baseload power generation. Coal as a solid phase fuel, has one of the highest energy densities of the fossil fuel based fuels. Due to the geographic location of coal mines, it often also requires trains to transport the coal from the mines to shipping facilities in places such as Newcastle and Gladstone. The high energy density makes it a economically viable energy carrier with less ships required for transport. It requires no conversion/reconversion for transport reducing the cost of the fuel. It is expected for the coal supply to reduce in the decades to come as existing coal mines cease production, with few new coal mines opening. Depending on the scale of the reduction in demand for coal, the price for coal may rise slightly. There will still be some coal transport for the remaining coal power stations, but there will be increasing pressure for them to use lower emission coal fuel, co-combust with ammonia or utilise carbon capture and storage. Green Hydrogen will have higher transport costs than coal due to the chemical properties of the energy carrier, but is projected to have lower production costs to make the delivered cost similar.

Compressed Natural Gas is currently transported short and medium distances with pipelines. This is often used for regional and local distribution as it is in a gaseous form that can be used in pipelines. Compressed natural gas is transported in a form that can be used by the end use application. Economically, with the current natural gas prices, transporting green hydrogen via pipelines is generally more expensive due to the lower volumetric energy density of hydrogen compared to natural gas. Blending green hydrogen with natural gas may reduce the emissions of natural gas, but it only makes a marginal improvement to carbon emissions. Transporting pure green hydrogen in pipelines requires much more hydrogen gas to be transported to deliver the same amount of energy. Moreover, significant capital expenditure is required to convert natural gas pipelines to be suitable for pure hydrogen, which will be expensive. Synthetic Natural Gas derived from green hydrogen may be an alternate medium for no carbon energy carrier transport by pipeline, but this requires additional research and development to reduce the cost of the chemical conversion process.

Liquified Natural Gas (LNG) has 2.4 times higher volumetric energy density than compressed gaseous natural gas, making it commonly used as a long distance energy carrier. LNG requires extensive terminal for the processing and loading of ships for long distance transport. Specially design ships are used to accommodate the LNG and transport around the world. LNG is economically one of the cheapest energy carriers due to the lower price of the raw fuel compared to diesel or coal. There is some potential for existing LNG infrastructure to be repurposed for green hydrogen shipping with similar cryogenic and safety equipment required.

Blue hydrogen, where hydrogen is produced from the gasification of fossil fuels is an alternate for green hydrogen. Given the low levels of technological readiness for the carbon capture and storage component and increasing costs of raw material (Coal or natural gas), it is not expected to be economically competitive with green hydrogen. Once produced, blue hydrogen would utilise the same transportation methods discussed above for green hydrogen. It is expected that blue hydrogen may be used in a few cases where hydrogen is produced as a by-product from another process or for specific applications, but not widely used to produce bulk hydrogen for export.

5.4 Comparisons to Relevant Literature Studies

Table 4.22 compares the research project results of this research project against (Amos, 1999). The results differ between the studies. Amos seems to have higher costs for truck transport due to a higher assumption of labour costs for truck transport. Amos's liquified hydrogen costs are lower as the paper underestimated the practical hosts of liquefying hydrogen which is very energy intensive and requires sophisticated equipment. Otherwise the costs are mostly comparable.

Table 4.23 compares the research project results of this research project against (Anastasopoulou et al., 2021). This paper was focused on much shorter transport chooses 100km as their distance and only including truck based transport in their analysis. The outputs of the costs are similar, noting the large range for the metal hydride medium due to uncertainties about its technological readiness.

Table 4.24 compares the research project results of this research project against (Raab et al., 2021). The results for Raab and this research project are fairly similar, due to the similar calculations and parameter values. The longer distance used in the analysis highlights the potential of LOHC for very long distances.

Table 4.25 compares the research project results of this research project against (Lee et al., 2022). The costs are higher in the paper due to the smaller volume of hydrogen used in their analysis than used in this research paper. There are potential economies of scale for transportation of larger volumes and amortisation of the infrastructure.

5.5 Validity of Results

Economic models for immature technology can be challenging to construct due the large uncertainties involved in the key parameters. Any models with future projections include a number of assumptions to simplify and project parameter values into the future. These assumptions affect the validity of the results by introducing uncertainties. There may be unforeseen technological developments, new government policies or complex interactions which increase the uncertainties and reduce the validity of the results. Some of the parameter values have large uncertainty due to lack of the technology being deployed at scale.

The green hydrogen model has significant uncertainties in the results due to the nature of the technology. In this research project it has been attempted to incorporate uncertainties into the analysis using Monte Carlo analysis to show the range of outcomes not just a single value. This range of outcome values is a means of visualising the uncertainty. For simplicity and clarity, many of the graphs and tables are shown in this report with a single value. However, the underlying model calculates the expected range of outcomes. These Monte Carlo results are shown on a subset of the results. Otherwise the assumptions, parameter values and calculations have been described earlier in this report to make the model transparent. Therefore the model validity can be verified by another party and updated as new parameter values are identified in the future.

The model has been developed to directly address the aims and objectives outlined in Section 1.5. This has been confirmed by reviewing the structure and outputs of the model against the original research question.

The results are valid in the sense of measuring what was intended. The model created by this research measures the overall costs of the green hydrogen transportation that it is intended to measure by breaking into its components. This has been confirmed by the case study analysis to provide practical outputs of the analysis.

In terms of the content, the model representative all aspects of the transportation that it is intended noting the assumptions and simplifications around the green hydrogen production and end use applications. This has been confirmed by comparing the methodology to similar literature studies of the content of the different cost elements.

In terms of accurately measuring the outcomes, the analysis has been constructed to maximise its validity in the way the methodology has been constructed. Any uncertainties in the model and parameter values are quantified and included in the analysis. This has been evaluated using the comparisons to relevant literature studies in Section 5.4.

5.6 Impact on Energy System

The model assumes that green hydrogen is a substitute energy carrier to fossil fuels in terms of energy production and consumption. While this will be generally true, the changes to the energy medium will have some impact on the nature of energy production and consumption. With pricing feedback, there may be changes to human behaviour which will affect the amount of hydrogen production and consumption in each region. This will in turn impact the amount of green hydrogen that may need to transported. The following are some key potential changes in energy system with green hydrogen:

- Green Hydrogen may provide new opportunities for low carbon mobility, supplementing the electric vehicle market, especially for long distances, remote locations or bulk transport.
- Production of the energy carrier will likely be shifted from fossil fuel rich countries to renewable energy rich countries
- Energy intensive loads (for example aluminium production, steel production) may be shifted from countries with cheap labour and cheap electricity closer to the green hydrogen production to reduce costs on the transport of the energy carrier. Cur-

rently, there Asia has many energy intensive loads with access to cheap electricity and labour, but these loads may be shifted to Australia or Africa to be closer to the energy carrier production

- Using hydrogen as a medium term energy storage in the electricity grid would have significant benefits. It would supplement other storage technologies such as pumped storage and batteries in buffering intermittent renewables and providing robustness. This would contribute to the reliable electricity grid operation as the remaining baseload coal power stations are retired.

- Hydrogen can also be used for emergency, remote or backup electricity replacing diesel generators.

- Cheap transportation of hydrogen allows countries with low renewables potential to decarbonise in a efficient and achievable means, especially in hard to abate sectors of the economy.

As the green industry expands there will be opportunities for entrepreneurs and businesses to develop new uses for hydrogen and change the way energy is used in society. These innovations may somewhat affect the flows of energy carriers, but there will still be large volumes of energy carriers transported around the world. Having cheap and low emission energy that can be transported long distances will be a key enabling pillar of the new decarbonised economy.

5.7 Technological Readiness

As listed in Table 2.1, the different hydrogen transportation mediums have varying levels of technological readiness. The model did not account for technological readiness directly, but did include it indirectly in the projects for the capital costs of associated equipment. Mediums with high technological readiness will have lower capital costs. Whereas, mediums with low technological readiness will have high initial capital costs initially and lower capital costs in the longer term.

Hydrogen production in the form of electrolysers has high technological readiness. Alkaline Electrolysis (AE) and Proton Exchange Membrane Electrolysis (PEM) are proven technologies across many small and medium systems (Adolf et al., 2017). There is room for economies of scale in the increased production of electrolysers in order to achieve the production required of all the potential projects. There is also additional research and development occurring into the technology to optimise the efficiency of these electrolysers. There is also significant work in scaling the production of electrolysers to reduce cost in terms of manufacturing facilities and materials. There is work underway in the means of operating electrolysers with intermittent renewable electricity as electrolysers typically do not tolerate interruptions. In sites collocated with solar photovoltaics and wind, the electrolysers may only operate when the assets are generating, potentially with a utilisation of 50-80%. Higher utilisations are unlikely due to the need for purchasing electricity from the grid in periods of high prices.

End use applications of green hydrogen are still generally at a moderate level of technological readiness. Using hydrogen to power vehicles already has some prototypes with fuel cells, but requires more development to be ready for widespread adoption. Lighter vehicles such as passenger cars and motorcycles have higher technical readiness than heavy transport such as trucks, trains and ships (Adolf et al., 2017). Further development of hydrogen/ammonia power trains for heavy transportation would enable the replacement of fossil fuels such as diesel and bunkering fuel. This is a critical step in ensuring the green hydrogen transport is low carbon emissions. There will need to be investment in the associated refuelling infrastructure for widespread adoption. The projected price of fuels and no carbon emissions make substituting diesel fuels with ammonia or hydrogen a cost efficient option for transportation.

Stationary hydrogen applications have a moderate level of technological readiness. There is room for future trials and implementation of green hydrogen in emergency power, heating, co-generation, green steel and other chemical production. The free market will help drive innovation in these sectors once the green hydrogen price is competitive with the current alternate fuels.

5.8 Certifications and Standards

There are a number of international and national standards and certifications applicable for green hydrogen. The standards and certifications are important for ensuring that green hydrogen is produced to a high quality and is consistent. Standards ensure the safety of equipment by providing the minimum design requirements to minimise the risks of harm to people. Standards also ensure the combability of different pieces of equipment and goods between different vendors to allow systems to be integrated together.

Certifications allow for trade by ensuring products from different vendors are equivalent and have be assessed against required certification framework. As an early stage market there is a number of different standards and certification schemes competing for adoption more broadly. These different schemes are similar, but have differences in the definitions of green hydrogen and the boundaries of the system to account for carbon emissions. Eventually it is expected for these schemes to harmonise somewhat as industries stakeholders adopt different schemes. International trade where green hydrogen is potentially sources from many different regions requires consistent certification to allow for the customers to have confidence in the source of the green hydrogen. There may be needs for mutual recognition between different schemes to allow trade to occur efficiently. The specific of Guarantee of Origin Schemes are discussed further in Section 5.9

Other standards cover the safe handling and transport of hydrogen. Hydrogen is currently widey used in stationary applications, with existing standards and management procedures. There are some existing standards for the management of hazardous areas which store or process hydrogen gas. There are existing standards for the transport of dangerous goods such as hydrogen gas or ammonia. As the industry expands, more practical standards will be developed and updated as the technology advances to promote best practice design. Given the dangerous chemical properties of hydrogen and public perceptions of the technology, standards play a big role in enforcing safety standards and allowing continual improvement in the industry. Electrolysers will require detailed standards, especially if they will be produced overseas to ensure the quality and safety of the equipment. Large scale transport of hydrogen is also new, which will require new and updated regulations for technical aspects of the storage vessels.

As electrolysers typically need to be run continuously and renewable energy is usually intermittent, carbon offsets can be used to certify that all the electricity used to produce the hydrogen is sourced from renewable energy. These offsets are an accounting mechanism to allow the source of electricity to be attributed when obtained from the grid where the actual source of the electricity used is unclear. An important emerging concern in the renewable electricity area, is the temporal and geographic use of carbon offsets. In the past decade, carbon offsets generally are applied on an energy unit basis regardless of the difference in time between the renewable energy being produced and electricity being consumed. Given the daily generation profile and transmission constraints in the electricity market, accounting for temporal and geographic usage of electricity is a more detailed and accountable mechanism for offsetting the electricity used as carbon neutral.

Standards Australia are working on a number of hydrogen standards around the industry and specific to the Australia. These Australian Standards cover hydrogen production, carbon capture, storage, transport, safety and applications. Where possible, these Australian standards will attempt to align with international standards such as ISO and IEC, but some local conditions and interfacing with other Australian standards requires unique standards for Australian (Standards Australia, 2022). Some existing standards may need to be updated to accommodate the hydrogen technology or new ones developed to cover gaps in the existing documentation with this new sector.

5.9 Hydrogen Guarantee of Origin Schemes

As discussed in Section 2.11, a guarantee of origin scheme is required to allow for fair and transparent trade of hydrogen on a global stage. Chemically, as the hydrogen produced from electrolysis with renewable electrolysis is indistinguishable from hydrogen produced from the gasification of coal, there is a challenge of accounting for the source of the hydrogen. Customers of hydrogen would generally like to know the origins of the hydrogen in terms of the carbon emissions emitted during its production to ensure they are meeting their environmental commitments. Suppliers want to ensure that the source of hydrogen is transparent to ensure they competing against similarly sourced hydrogen. When trade is direct on one vessel it is easy to track the source of goods, but pipelines and multiple hop transportation make the tracking more complex. A Guarantee of Origin Scheme identifies the source of hydrogen and sets the definitions of each type to ensure fair and transparent trade.

This issue is more prominent for hydrogen than it has been for previous energy carriers. Coal is only sourced for mining and is chemically different depending on the type of coal source it is mined from. There is less of requirement to identify the origin of the coal as all coal comes from the same type of source. Natural gas also has a similar nature of being sourced from a singular process. In the pipeline transmission of natural gas, radioactive markers are often used to identify the transitions between different batches for a continuous pipeline. These markers allow for the quantities and different sources of gases to be accounted for over the long distances of the pipelines.

These certifications allow transparency on the origins of the hydrogen purchased and guarantees about its sustainability. This allows for reporting and verification for the use of corporate or national emission reporting and emission reduction targets. It allows for custody transfer through the supply chain if there are multiple parties through the transport from generation to application. The goal is to minimise potential fraud with the ambiguity of the origins of hydrogen from different production pathways and the associated carbon emissions.

The Hydrogen Guarantee of Origin and Certification scheme attempts to categorise the carbon intensity of the hydrogen produced. The certificates are created with a batch of hydrogen produced and then cancelled when the hydrogen is consumed. The scheme would identify the boundaries of carbon emissions to be included in the analysis. Scope 1 emissions are directly from the processes used to produce and transport hydrogen (e.g. coal gasification emissions, tuck emissions). Scope 2 emissions include the purchased electricity emissions used in the process, for renewable wind and gas these emissions should be minimal. Scope 3 emissions include indirect emissions from purchased materials upstream and downstream (e.g. purified water, embedded emissions of infrastructure, etc). At this stage the Australian scheme is expected to include Scope 1 and Scope 2 emissions, but not Scope 3 emissions.

At this stage there are multiple schemes including but not limited to:

- Australian Government Department of Industry, Science, Energy and Resources (DISER) - Australia's Hydrogen Guarantee of Origin and Certification Scheme (Australian Government Department of Industry, Science, Energy and Resources (DISER), 2022)
- Smart Energy Council - Zero Carbon Certification Scheme (Australia) (Smart Energy Council, 2022)
- Green Hydrogen Organisation - GH2 Standard (Global) (Green Hydrogen Organisation, 2022)
- CERTIFHY (Europe) (CERTIFHY, 2022)
- REDII (Renewable energy directive) (Europe) (European Commission, 2022)
- TUV SUD (Europe) (TUV SUD, 2022)

As the hydrogen economy expands, it is expected the number of certification schemes will be consolidated. It will be more practical to have fewer schemes and mutual recognition between different schemes.

5.10 Hydrogen Safety and Public Perceptions

The public perception of hydrogen is currently quite cautious due to the explosive properties of hydrogen gas. Many people are aware of the risks of hydrogen especially with famous accidents such as the Hindenburg airship accident. As of 2022, there have been no major incidents in Australia with hydrogen gas. In April 2022, in the pilot program of the Hydrogen Energy Supply Chain (HESC) of a shipment of liquified hydrogen from Australia to Japan, there was a fire on the separate part of the vessel. Whilst this fire was extinguished before it spread, it did pose a large risk. Any broader adoption of hydrogen technology requires careful design with appropriate sensors, monitoring and handling procedures to ensure safety. Some of the specific safety risks that need to be managed in relation to transport:

- Management of any ignition sources close to hydrogen. Hydrogen has a low minimum ignition energy, so careful management is required. Hydrogen infrastructure typically is classified as a hazardous area, which entails specific requirements on the instrumentation within that area.

- Hydrogen gas has a large flammable and explosive range when mixed in air, creating high risks. Hydrogen burns clear and is lighter than air, which provide specific challenges for managing fires.

- As some of the mediums require significant cooling, the safety risks created by cryogenics need to managed carefully.

- Hydrogen can be a asphyxiant gas in enclosed spaces. This may cause a hazardous environment for humans with insufficient oxygen quantities for human survival. Any hydrogen facilities need to be designed with ventilation to avoid this risk.

- Hydrogen can damage materials that carry it, which causes many design challenges with issues such as embrittlement and oxidation of materials.

These risks can be managed in transportation with careful design which eliminates, substitutes or mitigates these hazards. Some storage mediums such as LOHCs are advantageous to hydrogen gas in being more stable and safe with the hydrogen in a non flammable form. Specific safety measures include monitoring gas leaks, removing ignition sources and ensuring adequate ventilation can make the technology safer. Hydrogen venting and flaring are methods of alleviating dangerous situations in a controlled manner if they arise. For hydrogen pipelines, the blend proportion of natural gas attempts to minimise the dangers of hydrogen's explosive properties. Pure hydrogen pipelines require additional design features to manage any explosive risks from leaks and to manage any pipeline material degradation.

Regardless of the implemented safety measures, hydrogen production and transportation infrastructure will mostly be separated from heavily populated areas to minimise the impact of unforeseen accidents. For transportation vehicles, there needs to be careful preparation of disaster management scenarios given the potentially remote nature of accidents. Some of the existing management practices of coal and LNG transportation could also be applicable for green hydrogen transportation.

The public perceptions of hydrogen technology need to be carefully managed to facilitate the success of the technology. There needs to be education to improve the awareness and understanding of the technology. Avoiding any major accidents will be key to the ongoing support of the general population in green hydrogen projects. There will need to be close engagement with local populations who live near major production facilities and transportation infrastructure to ensure that any concerns or issues are addressed.

Major projects will provide large employment opportunities for local populations. Many hydrogen hubs in Australia are planned to be in areas that have traditionally been heavily fossil fuel based jobs. In areas such as Gladstone and Newcastle, new employment in green hydrogen industry jobs provides an opportunity for transition and re-skilling for local workers who used to work in the coal industry. In this way the impact on the local community can be managed to build a positive public perception of hydrogen technology.

In terms of the adoption of end use applications, consumers generally focus on price and quality. Therefore any hydrogen products (such as vehicles) need to be able to perform as well as the alternate fossil fuel powered product for a similar price. If the new hydrogen based product is cost equivalent or cheaper, while upholding the quality there should be general acceptance of the product. Any increased costs or poorer functionality may delay the adoption of the technology and affect its public perception.

5.11 Impact of Carbon Pricing

This analysis has included the scope 1 carbon emissions, direct emissions from the production/transportation process, in the analysis. Scope 2 emissions, emissions from the electricity, are generally not applicable for this analysis, as it is assumed all electricity used is sourced from renewable generators especially for the electrolysis. For simplicity scope 3 emissions, indirect emissions from the materials used in the production and transport, have been excluded as they are very complicated to calculate.

The model has included different types of vehicle fuel in the form of diesel, ammonia and hydrogen. Without a carbon price, diesel generally remains the cheapest transportation option given the existing infrastructure for powering vessels and distribution framework. It is expected for ammonia and hydrogen to become more viable as lower emission fuels in the decades to come as alternate fuel engines reach high levels of technological readiness. Applying a carbon price to the emissions of the diesel fuels, makes the ammonia and green hydrogen fuel more competitive sooner. It is noted that due to the international nature of shipping, carbon pricing between international waters may be challenging to implement and enforce.

Figures 4.26 and 4.27, shows the impact of different carbon pricing on the different fossil fuels, which includes the emissions from their combustion and transport over an average distance of 5000km. The figure shows a the impact of a range of different carbon prices against green hydrogen which is not impacted by a carbon price. It shows the higher carbon emitting fossil fuels such as coal and diesel, are most effected by a carbon price. Natural gas is relatively lower emissions, so is expected to have a slightly longer future.

The breakeven point for green hydrogen with other alternate fossil fuels has been calculated in Section 4.3.8 in terms of the carbon price across 2025, 2030 and 2050. Lower or no carbon price, means it will take longer for green hydrogen to be generally cost competitive with these fuels. A higher carbon price would allow for rapid growth in the green hydrogen industry to contribute to the de-carbonisation of the world economy.

5.12 Impact of Government Policies

Aside from the carbon pricing policies discussed in the previous section, there are a number of governmental policies that impact the analysis. Governments often subsidise new projects in the renewable energy space in the form of grants or cheaper finance. Governments also support the education of workers required for these projects.

Australian Renewable Energy Agency (ARNEA) supports the development of green hydrogen projects including transportation with financial grants to projects. These projects span the range from the hydrogen economy from production to transportation to application. ARENA are supporting the Yuri Renewable Hydrogen to Ammonia Project in West Australia to produce green ammonia from electrolysis with onsite wind and solar. This project modifies an existing ammonia production facility using Steam Methane Reforming to use the green hydrogen pathway as a demonstration for future export projects (Australian Renewable Energy Agency (ARENA), 2022b). ARENA are also supporting the Renewable Hydrogen Demonstration for Heavy Transport project which involves using hydrogen fuel cells for large trucks and associated refuelling infrastructure (Australian Renewable Energy Agency (ARENA), 2022a). These projects and many others help demonstrate the technology, accelerate the early adoption of technology and allow for learning for later projects. Providing these grants helps develop the local engineering knowledge and builds the market to allow larger projects to be financially independent in the future.

The Clean Energy Finance Corporation (CEFC) is another government agency that provides discounted financing for renewable energy projects. The discounting funding allows the projects with support in obtaining financing and cheaper rates than the standard market. The CEFC has a specific Advancing Hydrogen Fund which targets projects involving transportation, generation balancing, industry feed stocks, industry fuels or building fuels. The $300 million aims to encourage the growth of a local hydrogen industry and the development of an export market. As these are loans rather than grants, the money will go further and deliver better value for taxpayers (Clean Energy Finance Corporation (CEFC), 2022).

A new hydrogen industry requires a new workforce of skilled workers to design, build and maintain all the new infrastructure required. The government plays a critical role in education policy in ensuring that workers are trained in industry relevant skills to allow these projects to proceed. Skilled migration complements the local workforce to fill gaps in the labour force to provide the skills and expertise to deliver these projects safely. As these projects are generally decentralised out of big cities, they can provide opportunities for well paid jobs for regional communities. As fossil fuel usage declines, there will be a number of workers from the mining and coal industries who may lose employment. Governments have a responsibility to assist these workers transition with reskilling and promoting projects in similar communities. Many of the proposed hydrogen hubs in Australia are proposed in areas that were previously heavily dependent on fossil fuels. This allows for transition to new jobs, with some overlap in the required skills.

Governments can help in the development of new international relationships which facilitate new trade opportunities of green hydrogen. Governments often initiate these connections and then allow businesses to connect to provide opportunities for trade and collaboration. Governments help foster these relationships and develop markets for the export production of hydrogen. This forms a core part of the green hydrogen policies and road maps.

Indirectly, governments can also impact the green hydrogen industry in the way they handle their existing fossil fuel industries. The role of subsidies for existing fossil fuel mining companies impacts the cost of these energy carriers, and therefore impacts the economics of the green hydrogen. The fossil fuel industry has many powerful lobbyists who advocate for grants and tax exemptions. As an emerging industry, green hydrogen has fewer lobbyists, so governments need to consider the impact of their actions holistically on emerging clean energy technology.

5.13 Industry Enablement

The green hydrogen industry in Australia requires a number of resources and developments in order to achieve the projections summarised in this research report. These include:

- Development of regional hubs for the sharing of infrastructure and local knowledge
- Conversion of existing ammonia facilities to green ammonia production
- Reduction in cost for electrolyser production and increase of scale
- Conversion of existing shipping transportation facilities to accommodate green hydrogen shipping vessels
- Investment in green hydrogen transportation vehicles and associated infrastructure
- Ongoing reduction in the capital cost of large scale wind and solar renewable electricity generation
- Development of transportation power trains fuelled by hydrogen derived fuels such as hydrogen gas or ammonia

- Improvements in safety and management of hydrogen
- Improvements and reduced cost of Hydrogen storage, a required component of the transportation lifecycle
- Increased uptake of hydrogen in end usage application (powering transport, green steel, chemical production, backup electricity, etc)

5.14 Summary

This section summarises the discussion and contextualisation of the results presented in the previous section. It provides some further analysis of the results presented and the meaning of these results on topical issues in the literature and industry such as guarantee of origin schemes and safety.

Chapter 6

Conclusion

This section summarises the research project in terms of the relevance, contribution and potential future work.

6.1 Project Results Addressing Research Question

This research project has successfully implemented techno-economic analysis for the export of green hydrogen. The long-distance transport of green hydrogen is emerging as a critical aspect of the emerging green hydrogen industry to transport energy across the world. The literature review identified a gap in the academic research of rigorous techno-economic analysis of the different transport mediums for exporting green hydrogen. The research question attempted to address this gap in the research through evaluating the most cost-effective methods for transport across a range of different mediums. The research methodology in analysing specific case study trade routes and global trade between regions provides estimates on the costs of transport and estimated volumes projected into the future. This research methodology allows practical application of the model results to understand the potential trade routes and scale of hydrogen production in the years to come. The results have been baselined against other comparable studies in the literature and the fuels for which green hydrogen seeks to replace.

6.2 Research Relevance

This research topic is topical and relevant given the growing local Australian industry for green hydrogen with the list proposed Australian projects shown in Table 1.1 and Figure 1.2. The local production and export industry is expected to grow significantly in the next thirty years providing a significant economic and environmental opportunity in the decarbonisation of hard-to-abate sectors of the economy and industry. Being able to export green hydrogen expands the potential scale of the local industry by increasing the amount of customers to include South East Asia and potentially other countries around the world. Green hydrogen provides an opportunity for energy independence replacing fossil fuels which are typically sourced from geopolitically unstable regions of the world. Green hydrogen provides a promising opportunity to decarbonise the world economy especially in hard-to-abate sectors, and export transportation is a core enabling component of this.

6.3 Thesis Contribution

This research project has potentially multiple contributions to research, the hydrogen industry and government as summarised in Figure 3.2. The contributions of this research project include better understanding about the economics and scale of opportunity of green hydrogen exports that will:

- Inform government policies, regulations and funding grants. It also identifies which countries which have the largest demand for imported green hydrogen and which are the best opportunities for Australian exporters.

- Inform business investment decisions relating to green hydrogen production and transportation projects

- Create opportunities for green hydrogen end-usage applications through estimating the delivered cost of hydrogen.

- Inform the viability of replacement energy carrier replacements for fossil fuel energy carriers

- Influence future research and development of green hydrogen storage and transportation materials.

6.4 Recommendations For Future Research Work

The recommendations for future research work include:

- Integrate the green hydrogen transportation modelling with the green hydrogen production models to allow for the optimal location of production facilities in terms of the transportation infrastructure.
- Integrate the green hydrogen transportation modelling with more detailed end-use application modelling to assess the type of reconversions of hydrogen medium required. Minimising the amount of reconversion (i.e. transporting the hydrogen in the form of the end usage application) could reduce the costs significantly
- Calibrate the transportation model as pilot projects come online and have available data in the next five years
- Allow for more customisation to be able to adjust the model to specific transportation vessels or particular production facilities.
- Update of assumptions and parameter values as the green hydrogen grows in the next few years.

6.5 Recommendations For Professional Practice

In the green hydrogen industry, better estimates of the economics of potential future hydrogen trade will influence investment decisions for the hydrogen sector across production, transportation, and end use applications.. The recommendations for professional practice (industry, academia and governments) include:

- Governments are encouraged to financially support pilot projects to allow for the initial stage of the local Green Hydrogen industry. Governments can support the industry through polices that accelerate the growth the industry until it is profitable by itself. Governments can assist in developing foreign relationships for the establishment of trade routes with international customers. This research shows the potential of Australia as a green hydrogen exporter, but it requires early adoption and investment in the local industry.

- Understanding the different potential scale and costings of transportation methods may influence future academic and industry research and development in terms of specific hydrogen medium research and development. This allows for the prioritisation of the development of specific materials and chemical processes to ones which will be useful for the green hydrogen industry. The transport model framework provides a means for evaluating the potential of materials and optimising existing materials.

- Forecasting the growth of the hydrogen industry informs public education about the technology and safety risks towards public acceptance and adoption of the technology. This research provides an indication of the timeline and scale of the technology, which can inform the public education about the technology, its advantages and its potential risks.

- Having fair and competitive global trade of hydrogen requires global standards to be developed and enforce to ensure an even playing field for trade. Given the multiple pathways for producing hydrogen, there needs to be accountability and transparency on the origin of hydrogen to ensure the green hydrogen is identifiable against blue or grey hydrogen competitors which are produced from fossil fuels.

- Given the significant increase in hydrogen being transported and the potential damage to human life in the advent of an accident, there is scope for global collaboration on improving transportation safety. This could be in the form of standards, monitoring equipment or procedures to ensure the safe movement of hydrogen.

Bibliography

Adolf, J., Balzer, C. H., Louis, J., Schabla, U., Fischedick, M., Arnold, K., Pastowski, A., and Schüwer, D. (2017). Shell hydrogen study energy of the future? sustainable mobility through fuel cells and h2. *Shell, Hamburg.*

Alvera, M. (2021). *The Hydrogen Revolution A Blueprint for the Future of Clean Energy.* Basic Books.

Amos, W. A. (1999). Costs of storing and transporting hydrogen.

Anastasopoulou, A., Furukawa, H., Barnett, B. R., Jiang, H. Z., Long, J. R., and Breunig, H. M. (2021). Technoeconomic analysis of metal–organic frameworks for bulk hydrogen transportation. *Energy & Environmental Science*, 14(3):1083–1094.

Andrews, J., Niya, S. R., and Ojha, R. (2022). Electrochemical hydrogen storage in porous carbons with acidic electrolytes: Uncovering the potential. *Current Opinion in Electrochemistry*, 31:100850.

Andrews, J., Ojha, R., Niya, S. M. R., and Seibt, S. (2021). Electrochemical storage reactions of hydrogen in activated carbon from phenolic resin. *Catalysis Today.*

ARUP (2019). Australian hydrogen hubs study technical study.

Ashworth, P., Witt, K., Ferguson, M., and Sehic, S. (2019). Developing community trust in hydrogen.

Australian Government (2017a). Basic hydrogen strategy.

Australian Government (2017b). The strategic road map for hydrogen and fuel cells - industry-academia-government action plan to realize a "hydrogen society".

Australian Government (2019). Australia's national hydrogen strategy.

Australian Government (2021a). A hydrogen guarantee of origin scheme for australia discussion paper.

Australian Government (2021b). State of hydrogen.

Australian Government Department of Industry, Science, Energy and Resources (DISER) (2022). Australian government department of industry, science, energy and resources (diser) - australia's hydrogen guarantee of origin and certification scheme. https://www.cleanenergyregulator.gov.au/Infohub/Markets/guarantee-of-origin#:~:text=The%20scheme%20will%20enable%20Australian,domestically%20and%20to%20the%20world. Accessed: 2022-09-11.

Australian Renewable Energy Agency (ARENA) (2022a). Arena - renewable hydrogen demonstration for heavy transport. https://arena.gov.au/projects/renewable-hydrogen-demonstration-for-heavy-transport/. Accessed: 2022-09-25.

Australian Renewable Energy Agency (ARENA) (2022b). Arena - yuri renewable hydrogen to ammonia project. https://arena.gov.au/projects/yuri-renewable-hydrogen-to-ammonia-project/. Accessed: 2022-09-25.

Aylward, G. and Findlay, T. (2013). *SI Chemical Data 7th edition*.

Aziz, M. (2021). Liquid hydrogen: A review on liquefaction, storage, transportation, and safety. *Energies*, 14(18):5917.

Balat, M. (2008). Potential importance of hydrogen as a future solution to environmental and transportation problems. *International journal of hydrogen energy*, 33(15):4013–4029.

Batan, L. Y., Graff, G. D., and Bradley, T. H. (2016). Techno-economic and monte carlo probabilistic analysis of microalgae biofuel production system. *Bioresource technology*, 219:45–52.

Becker, W. L., Penev, M., and Braun, R. J. (2019). Production of synthetic natural gas from carbon dioxide and renewably generated hydrogen: a techno-economic analysis of a power-to-gas strategy. *Journal of Energy Resources Technology*, 141(2).

Bevan, M. (2022). 50 years ago, john saw the future of australia's climate crisis.

Bhaskar, A., Assadi, M., and Nikpey Somehsaraei, H. (2020). Decarbonization of the iron and steel industry with direct reduction of iron ore with green hydrogen. *Energies*, 13(3):758.

Bockris, J. O. (1975). Energy: the solar-hydrogen alternative.

Bones, D. and O'Brien, L. (2020). Ghd.

Boretti, A. (2020). Production of hydrogen for export from wind and solar energy, natural gas, and coal in australia. *International journal of hydrogen energy*, 45(7):3899–3904.

Bruce, S., Temminghoff, M., Hayward, J., Schmidt, E., Munnings, C., Palfreyman, D., and Hartley, P. (2018). Csiro national hydrogen roadmap pathways to an economically sustainable hydrogen industry in australia.

Bureau of Infrastructure (2019). Hydrogen as a transport fuel location options for a freight-based limited initial deployment of hydrogen refuelling stations.

CERTIFHY (2022). Certifhy - guarantee of origin scheme. `https://www.certifhy.eu/`. Accessed: 2022-09-11.

Chehade, G. and Dincer, I. (2021). Progress in green ammonia production as potential carbon-free fuel. *Fuel*, 299:120845.

Clean Energy Finance Corporation (CEFC) (2022). Cefc - advancing hydrogen fund. `https://www.cefc.com.au/where-we-invest/special-investment-programs/advancing-hydrogen-fund/`. Accessed: 2022-09-25.

Commonwealth Scientific and Industrial Research Organisation (CSIRO) (2022). Hyresource: A collaborative knowledge sharing resource supporting the development of australia's hydrogen industry.

Cormos, C.-C. (2009). Assessment of hydrogen and electricity co-production schemes based on gasification process with carbon capture and storage. *International journal of hydrogen energy*, 34(15):6065–6077.

Daiyan, R., MacGill, I., and Amal, R. (2020). Opportunities and challenges for renewable power-to-x.

Dawood, F., Anda, M., and Shafiullah, G. (2020). Hydrogen production for energy: An overview. *International Journal of Hydrogen Energy*, 45(7):3847–3869.

de Vos, R. (2021). Cefc australian hydrogen market study sector analysis summary.

DeSantis, D., James, B. D., Houchins, C., Saur, G., and Lyubovsky, M. (2021). Cost of long-distance energy transmission by different carriers. *Iscience*, 24(12):103495.

European Commission (2022). European commission - renewable energy directive.

Faye, O., Szpunar, J., and Eduok, U. (2022). A critical review on the current technologies for the generation, storage, and transportation of hydrogen. *International Journal of Hydrogen Energy*.

Feitz, A., Tenthorey, E., and Coghlan, R. (2019). Geoscience australia prospective hydrogen production regions of australia.

Floyd, H., Hibbert, A., and Amico, A. (2019). Hydrogen for transport prospective australian use cases.

Frontier Economics (2020). Frontier economics - indicative analysis of blending hydrogen in gas networks – update.

Garnaut, R. (2019). *Superpower: Australia's Low-Carbon Opportunity*. Black Inc.

GPA Engineering (2019a). Hydrogen impacts on downstream installations and appliances.

GPA Engineering (2019b). Hydrogen in the gas distribution networks.

Green Hydrogen Organisation (2022). Green hydrogen organisation (gh2) - green hydrogen standard - guarantee of origin scheme. `https://gh2.org/publication/green-hydrogen-organisation-develop-green-energy-standard`. Accessed: 2022-09-11.

Gulagi, A., Bogdanov, D., Fasihi, M., and Breyer, C. (2017). Can australia power the energy-hungry asia with renewable energy? *Sustainability*, 9(2):233.

He, T., Pei, Q., and Chen, P. (2015). Liquid organic hydrogen carriers. *Journal of energy chemistry*, 24(5):587–594.

Hirscher, M., Yartys, V. A., Baricco, M., von Colbe, J. B., Blanchard, D., Bowman Jr, R. C., Broom, D. P., Buckley, C. E., Chang, F., and Chen, P. (2020). Materials for hydrogen-based energy storage–past, recent progress and future outlook. *Journal of Alloys and Compounds*, 827:153548.

Howarth, R. W. and Jacobson, M. Z. (2021). How green is blue hydrogen? *Energy Science And Engineering*, 9(10):1676–1687.

Hydrogen Council (2017). Hydrogen council - hydrogen scaling up a sustainable pathway for the global energy transition.

Hydrogen Council (2020). Hydrogen council - path to hydrogen competitiveness a cost perspective.

Hydrogen Council (2021). Hydrogen council - hydrogen insights 2021.

International Energy Agency (IEA) (2019). Iea - the future of hydrogen seizing today's opportunities.

International Energy Agency (IEA) (2020). Iea - levelised cost of electricity calculator.

International Energy Agency (IEA) (2021). Iea - global hydrogen review 2021.

International Renewable Energy Agency (IRENA) (2021). Irena - green hydrogen supply a guide to policy making.

Judkins, M. and O'Brien, J. (2019). Deloitte australian and global hydrogen demand growth scenario analysis.

Kannah, R. Y., Kavitha, S., Karthikeyan, O. P., Kumar, G., Dai-Viet, N. V., and Banu, J. R. (2021). Techno-economic assessment of various hydrogen production methods–a review. *Bioresource Technology*, 319:124175.

Lambert, V. and Ashworth, P. (2018). University of queensland the australian public's perception of hydrogen for energy.

Lee, C., Ryu, J., Sohn, G., and Park, S. (2021). Technical review on liquid/solid (slush) hydrogen production unit for long-term and bulk storage. *Transactions of the Korean hydrogen and new energy society*, 32(6):565–572.

Lee, J.-S. (2022). Large-scale overseas transportation of hydrogen: Comparative techno-economic and environmental investigation. *Renewable and Sustainable Energy Reviews*.

Lee, J.-S., Cherif, A., Yoon, H.-J., Seo, S.-K., Bae, J.-E., Shin, H.-J., Lee, C., Kwon, H., and Lee, C.-J. (2022). Large-scale overseas transportation of hydrogen: Comparative techno-economic and environmental investigation. *Renewable and Sustainable Energy Reviews*, 165:112556.

Li, M. M.-J. and Tsang, S. C. E. (2018). Bimetallic catalysts for green methanol production via co 2 and renewable hydrogen: a mini-review and prospects. *Catalysis Science And Technology*, 8(14):3450–3464.

Longden, T., Beck, F. J., Jotzo, F., Andrews, R., and Prasad, M. (2022). 'clean'hydrogen?–comparing the emissions and costs of fossil fuel versus renewable electricity based hydrogen. *Applied Energy*, 306:118145.

Longden, T., Jotzo, F., Prasad, M., and Andrews, R. (2020). Green hydrogen production costs in australia: implications of renewable energy and electrolyser costs. *Centre for Climate And Energy Policy: Canberra, Australia.*

Makepeace, J. W., He, T., Weidenthaler, C., Jensen, T. R., Chang, F., Vegge, T., Ngene, P., Kojima, Y., de Jongh, P. E., and Chen, P. (2019). Reversible ammonia-based and liquid organic hydrogen carriers for high-density hydrogen storage: Recent progress. *international journal of hydrogen energy*, 44(15):7746–7767.

Mezher, T., Fath, H., Abbas, Z., and Khaled, A. (2011). Techno-economic assessment and environmental impacts of desalination technologies. *Desalination*, 266(1-3):263–273.

Najjar, Y. S. (2013). Hydrogen safety: The road toward green technology. *International Journal of Hydrogen Energy*, 38(25):10716–10728.

NSW Government (2021). Nsw hydrogen strategy - making nsw a global hydrogen superpower.

Obara, S. (2019). Energy and exergy flows of a hydrogen supply chain with truck transportation of ammonia or methyl cyclohexane. *Energy*, 174:848–860.

Our World In Data (2022). Our world in data -global energy consumption. https://ourworldindata.org/energy-production-consumption#per-capita-where-do-people-consume-the-most-energy. Accessed: 2022-10-15.

Owen, A. D. and Cockroft, C. (2006). A cost-benefit analysis of perth's hydrogen fuel cell buses.

Raab, M., Maier, S., and Dietrich, R.-U. (2021). Comparative techno-economic assessment of a large-scale hydrogen transport via liquid transport media. *International Journal of Hydrogen Energy*, 46(21):11956–11968.

Ríos-Mercado, R. Z. and Borraz-Sánchez, C. (2015). Optimization problems in natural gas transportation systems: A state-of-the-art review. *Applied Energy*, 147:536–555.

Sakintuna, B., Lamari-Darkrim, F., and Hirscher, M. (2007). Metal hydride materials for solid hydrogen storage: a review. *International journal of hydrogen energy*, 32(9):1121–1140.

Sharma, S. and Ghoshal, S. K. (2015). Hydrogen the future transportation fuel: From production to applications. *Renewable and sustainable energy reviews*, 43:1151–1158.

Smart Energy Council (2022). Smart energy council - zero carbon certification scheme - guarantee of origin scheme. https://smartenergy.org.au/zero-carbon-certification-scheme/#:~:text=In%20December%202020%2C%20the%20Smart,derivatives%20in%20Australia%20and%20overseas. Accessed: 2022-09-11.

Standards Australia (2022). Standards australia - hydrogen technology standards discussion paper. https://www.standards.org.au/engagement-events/strategic-initiatives/hydrogen. Accessed: 2022-09-25.

Stocks, M., Fazeli, R., Hughes, L., and Beck, F. J. (2022). Global emissions implications from co-combusting ammonia in coal fired power stations: An analysis of the japan-australia supply chain. *Journal of Cleaner Production*, 336:130092.

The Engineering Toolbox (2022). The engineering toolbox - combustion of fuels - carbon dioxide emission. https://www.engineeringtoolbox.com/co2-emission-fuels-d_1085.html. Accessed: 2022-10-26.

TUV SUD (2022). Tuv sud - green hydrogen certification. https://www.tuvsud.com/en/themes/hydrogen/green-hydrogen-certification. Accessed: 2022-10-16.

Utz, C. (2019). Hydrogen industry legislation a report scoping out legislation, regulations and standards relevant to the development of a national hydrogen industry in australia.

Victorian Government (2021). Victorian renewable hydrogen industry development plan.

Walsh, S. D., Easton, L., Weng, Z., Wang, C., Moloney, J., and Feitz, A. (2021). Evaluating the economic fairways for hydrogen production in australia. *International Journal of Hydrogen Energy*, 46(73):35985–35996.

Appendix A - Ethics Form

LOW RISK STUDENT RESEARCH APPLICATION FORM

For Undergraduate, honours, and masters by coursework students

Due to the short timeframes available for the completion of these projects, it is recommended that undergraduate, honours, and masters by coursework students undertake projects that are of nil/negligible or low risk. The ethics review process for these projects can then be undertaken at the Faculty level. **Undergraduate, honours, or masters by coursework research projects that are higher than low risk must be reviewed by the UTS HREC.** This application form to be completed AFTER the project method has been discussed and confirmed with project supervisor/s.

Section 1: General Information	
Full Project / Subject Title:	
A techno-economic analysis of the export of green hydrogen	
1.1 Student details	
Name:	Robert Makepeace
Student ID:	13886357
Faculty:	Faculty of Engineering and IT
Degree/Course:	Masters of Engineering Management
UTS student email address:	robert.w.makepeace@student.uts.edu.au
Telephone number:	0408 357 646
1.2 Supervisor / Subject Co-ordinator details	
Name:	Dr Jahangir Hossain
Position:	Associate Professor School of Electrical and Data Engineering
Faculty:	Faculty of Engineering and IT
Email address:	jahangir.hossain@uts.edu.au
Telephone number:	+61 2 95142541

Section 2: Ethics risk assessment

Does your research involve any of the following? ~~Y~~/N

Establishment of a register or databank **of identifiable data** for possible use in future research projects	Reference National Statement Chapter 3.1, Element 4, pages 32-38	☐ Y ■ N
Collection, transfer and/or banking of human biospecimens	E.g. tissue, blood, urine, sputum etc.	☐ Y ■ N
Any significant alteration to routine care or health service provided to participants	E.g. deviation from standard care or usual practice	☐ Y ■ N
Interventions and therapies, including clinical and non-clinical trials, and innovations	Reference National Statement Chapter 3.1.4-3.1.7 and the WHO definition of a Clinical Trial	☐ Y ■ N
Targeted recruitment or analysis of data from any of the vulnerable groups listed in Chapter 4 of the National Statement (or where any of these vulnerable groups are likely to be significantly over-represented in the group being studied)	Women who are pregnant and the human fetus (Chapter 4.1, page 61)	☐ Y ■ N
	Children and young people (under 18 years) (Chapter 4.2, page 65)	☐ Y ■ N
	People in dependent or unequal relationships (e.g. lecturer/student [except T&L], doctor/patient, employer/employee) (Chapter 4.3, page 68)	☐ Y ■ N
	People highly dependent on medical care who may be unable to give consent (Chapter 4.4, page 70)	☐ Y ■ N
	People with a cognitive impairment, an intellectual disability, or a mental illness (may include the disadvantaged/homeless) (Chapter 4.5, page 73)	☐ Y ■ N
	People who may be involved in illegal activities (including those affected e.g. victims of domestic violence) (Chapter 4.6, page 75)	☐ Y ■ N
	Aboriginal and Torres Strait Islander Peoples (Chapter 4.7, page 77)	☐ Y ■ N
Collection, use or disclosure of **personal** information **without** consent of the participant	Name, address and other details about the participant (e.g. date of birth, financial information etc.)	☐ Y ■ N
	Photographs, images, video or audio footage	☐ Y ■ N
	Fingerprints	☐ Y ■ N
Collection, use or disclosure of **health** information	Personal information (as defined above) collected to provide, or in providing, a health service (e.g. admission to hospital, GP visit, pathology, pharmacy etc.)	☐ Y ■ N

	Information or an opinion about: (i) the health or a disability (at any time) of an individual; or (ii) an individual's expressed wishes about the future provision of health services to him or her; or (iii) a health service provided, or to be provided, to an individual	☐ Y ■ N
	Personal information about organ donation	☐ Y ■ N
	Genetic information about an individual or the individual's relatives	☐ Y ■ N
Collection, use or disclosure of **sensitive** information	Racial, ethnic information, political, religious and philosophical beliefs, sexual activity or identity, and trade union membership	☐ Y ■ N
Projects involving covert observation, active concealment, or planned deception of participants	E.g. covert observation of the hand-washing behaviour of hospital employees, undisclosed role-playing by a researcher, etc. Does NOT include observation in a public place WITHOUT the use of photographs, images, video or audio footage (Chapter 2.3, page 19)	☐ Y ■ N
Activity that potentially infringes the privacy or professional reputation of participants, providers or organisations	E.g. observation in the workplace, collection of commercially confidential information, etc. Commercially confidential information - Any information which is not in the public domain or publicly available, and where disclosure may undermine the economic interest or competitive position of the owner of the information (TGA adopted definition from European Medicines Agency (EMA))	☐ Y ■ N
People in / from countries that are	Politically unstable; where human rights are restricted; and/or where the research involves economically disadvantaged, exploited or marginalised participants from such countries	☐ Y ■ N
Potential for participants to experience harm	E.g. physical, psychological, social, economic and/or legal (Chapter 2.1, page 12)	☐ Y ■ N

Answering Y to any of the above questions makes this a high risk application, which must be reviewed by the UTS Human Research Ethics Committee. Please contact your Supervisor or Faculty representative for assistance. You can also contact research.ethics@uts.edu.au for more information.

If you answered N to all of the above, please continue with Section 3 below.

UTS UNIVERSITY OF TECHNOLOGY SYDNEY

Section 3: Project Information	
3.1 Lay Description **Briefly describe the project in plain language** *Include the primary and secondary aims/objectives, key research questions, and/or a clearly defined hypothesis, and potential significance.*	Research into the transportation and export of hydrogen and hydrogen based products produced with low carbon emissions. Research into different methods of transportation and analysis of different case studies. Computer based simulations and modelling of the economic and technical capabilities of different methods and.
3.2 Methodology **Briefly describe the proposed project methodology for work to be undertaken at UTS** *Include your study design/course outline, participants (specifying any inclusion/exclusion criteria), recruitment methods, and/or data collection.*	Literature review of current technology Computer Modeling/Simulations of the economics of different transportation methods. All computer work to be conducted remotely from student's home.
3.3 Consent **Briefly outline the consent process to be used in the study** *If informed consent will not be collected/ is not required please indicate why?*	Not applicable - no humans involved in the research
3.4 Participant information and consent forms attached? *Note: Students MUST use the templates provided on StaffConnect*	☐ Yes ■ No
3.5 Data storage and security **Outline how you will store your data, and how participant privacy and confidentiality will be protected.** *Where required, advice should be sought from UTS eResearch and/or Research.Ethics@uts.edu.au*	Not applicable - no data regarding people collected as part of the project

3.6 Risks identified? **Briefly outline any potential risks to participants, researchers (including yourself), and/or to UTS** *Where required by your Faculty please attached completed risk assessment template.*	Ergonomic risks from computer based work. Computer equipment tag and tested Office space clear and organised to avoid trip hazards.
3.7 External organisation approval attached? *Provide evidence of agreement to participate in this research from all external partners/organisations.*	☐ Yes ■ No ☐ N/A
3.8 Recruitment of UTS staff and/or students (or access to their data)	☐ Yes ■ No Please note: If Yes, approval from the Dean or DVC(ES) may be required.

NOTE:

- **If you have answered 'Yes' to section 3.8, please complete section 4.1 and 4.2 and email it to feitcapstone@uts.edu.au for faculty approval.**
- **If NOT, complete section 4.1 and 4.2 and leave section 4.3 and submit on UTSOnline**

Section 4: Declaration & Sign off	
4.1 Student	I have answered all questions in the risk assessment truly and completely to the best of my knowledge **I declare that I believe this research to be of low risk in accordance with the with the National Statement on Ethical Conduct in Human Research (Chapter 2.1)** I will notify the UTS Human Research Ethics Committee of any variation to this research that may alter the level of risk associated with it This research will be undertaken in compliance with the UTS Research Ethics and Integrity Policy or any replacement or amendment thereof This research will be undertaken in compliance with the Australian Code for the Responsible Conduct of Research and National Statement on Ethical Conduct in Human Research **Name (Please Print):** Robert Makepeace **Signature:** Robert Makepeace Digitally signed by Robert Makepeace Date: 2022.03.14 20:31:36 +11'00' **Sign off date:** 14/03/2022
4.2 Supervisor / Subject Co-ordinator	**I declare that I believe this research to be of low risk in accordance with the with the National Statement on Ethical Conduct in Human Research (Chapter 2.1)** This research will be undertaken in compliance with the UTS Research Ethics and Integrity Policy or any replacement or amendment thereof This research will be undertaken in compliance with the Australian Code for the Responsible Conduct of Research and National Statement on Ethical Conduct in Human Research **Name (Please Print):** Jahangir Hossain **Signature:** Jahangir Hossain Digitally signed by Jahangir Hossain Date: 2022.04.07 05:54:10 +10'00' **Sign off date:** 7/04/2022
4.3 Faculty *Course Director, Head of School, Associate Dean or delegate - as determined by each Faculty.*	**Name (Please Print):** **Signature:** **Position held:** **Sign off date:**

Appendix B - Risk Assessment

STUDENT RESEARCH PROJECT SAFETY PLAN

FEIT CAPSTONE/GRADUATE PROJECT SUBJECTS

Instructions:

- To be completed by Capstone and graduate project students prior to commencement of research project (Refer to subject outline for the submission date)
- This plan should be regularly reviewed, and updated when changes to project affect health, safety or environmental risk.
- Plan to be signed off by UTS Academic advisor (and Industry Advisor, if relevant).
- Refer to UTS Research Safety information pages for more details.

(1) STUDENT & PROJECT DETAILS

Student name	Robert Makepeace	Student number	13886357
Major	Masters In Engineering Management	Subject number	42908 Engineering Project Preparation
Academic advisor name	Dr Jahangir Hossain	Academic advisor email	jahangir.hossain@uts.edu.au
Project title	A techno-economic analysis of the export of green hydrogen		
Project Start Date	21/02/2022		
Estimated Project End Date	31/12/2022		
Brief Description of Project	Research into the transportation and export of hydrogen and hydrogen based products produced with low carbon emissions. Research into different methods of transportation and analysis of different case studies. Computer based simulations and modelling of the economic and technical capabilities of different methods.		
Location(s) of research work if applicable:	UTS Building:	Not applicable – work from student's home	
	UTS Lab name:	Not applicable	
	External location address	Not applicable	
Induction required into specialist laboratory?	Yes ☐ No ☐ Not applicable ☒		

(2) WILL THE PROJECT BE CARRIED OUT AT A WORKPLACE OTHER THAN UTS? YES ☐ NO ☒

If you answer YES, Appendix A (Host Organisation Health & Safety Checklist) **MUST** be completed as well as this form.

(3) IS THE PROJECT ENTIRELY DESK/COMPUTER-BASED? YES ☒ NO☐

If you answer YES please go directly to section 4. If you answer NO please proceed to fill in the rest of the form.

(2) HAZARD IDENTIFICATION

Use the table to identify hazards involved in the project and follow the measures to help manage them.

FIELDWORK

Does this project involve …	Yes	No	If the answer is 'Yes' – then:
Any research conducted at fieldwork locations other than the regular campuses of the University (including outside Australia)?			• Document UTS Fieldwork Risk Assessment prior to fieldwork. • Refer to UTS Fieldwork Guidelines

WORK IN HEALTHCARE SETTINGS

Does this project involve …	Yes	No	If the answer is 'Yes' – then:
Any work in a healthcare setting not controlled by UTS (includes hospital, clinic, allied health service or household)?			• Complete the Work in Healthcare Settings checklist prior to conducting the research. • Refer to UTS Work in Healthcare Settings

OVERSEAS ACTIVITIES

Does this project involve …	Yes	No	If the answer is 'Yes' – then:
Any work in overseas hazardous facility, such as laboratory, workshop or factory?			• Refer to UTS Work in Overseas Research Facilities

PATHOGENS

Does this project involve ...	Yes	No	If the answer is 'Yes' – then:
PC2, PC3 or PC4 pathogens?			• Obtain approval from Biosafety Committee prior to any biosafety dealings. • Refer to UTS Microbiological
Imported biological material?			

GENETICALLY MODIFIED ORGANISMS

Does this project involve ...	Yes	No	If the answer is 'Yes' – then:
Genetically modified organisms?			• Obtain approval from Biosafety Committee prior to any genetic modification dealings. • Refer to UTS Genetically Modified Organisms

IONISING RADIATION SOURCES

Does this project involve ...	Yes	No	If the answer is 'Yes' – then:
Radioactive isotopes?			• Obtain approval from Biosafety Committee prior to any work with radioactive isotopes. • Refer to UTS Radiation
Radiation apparatus?			
Ionising radiation sources?			

LASER SOURCES

Does this project involve ...	Yes	No	If the answer is 'Yes' – then:
A LASER of class 2M or above?			• Contact your local Laser Safety Officer. • Reference Risk Assessment in the Register below.

PLANT AND EQUIPMENT

Does this project involve ...	Yes	No	If the answer is 'Yes' – then:
Machinery, tools, appliances and equipment?			• Perform a UTS Health & Safety Pre-purchase Checklist for new items. • Refer to UTS Plant and Equipment

DRONES (Remote Piloted Aircraft)

Does this project involve ...	Yes	No	If the answer is 'Yes' – then:
Flying Drones?			• Refer to UTS Drones (Remote Piloted Aircraft)

DIVING

Does this project involve …	Yes	No	If the answer is 'Yes' – then:
Diving?			• Engage a Dive Officer • Register dive sites and dive proposals with the Dive Officer prior to diving. • Provide Scientific diver / Rescue diver / Dive Master

PLUG-IN ELECTRICAL EQUIPMENT

Does this project involve ...	Yes	No	If the answer is 'Yes' – then:
Use of any plug-in electrical equipment in a "hostile operating environment"?			• Ensure plug-in electrical equipment is tested and tagged • Refer to UTS Electrical Safety Guidelines

HAZARDOUS CHEMICALS

Does this project involve ...	Yes	No	If the answer is 'Yes' – then:
Hazardous chemicals / dangerous goods / schedule drugs?			• Obtain UTS Biosafety Committee Approval prior to any dealings with category 1 carcinogens, mutagens or reproductive toxicants. • All other chemicals included in risk assessment. • Refer to UTS Chemical Safety Guidelines
Cryogens e.g. liquid nitrogen / argon?			

OTHER SOURCES OF HEATH, SAFETY AND ENVIRONMENT RISK

Are there any hazards NOT covered in risk management strategies noted above?

Does this project involve …	Yes	No	If the answer is 'Yes' – then:
Noisy equipment (sound level monitoring may be required)			• Ensure the hazard is addressed in an appropriate risk assessment
Vibrating equipment			
Dust			
Hazardous gases			
Nanomaterials			
Pressure vessels/boilers (license may be required)			
Electrical wiring (license may be required)			
Working at a height			
Working in a confined space			
Hot Works			
Driving vehicles/4WD/boats			
Work with bodily fluids/parts			
Working with animals/insects			
Sharps/needles			
X-ray equipment			
Microwave radiation			
Working with ionising ultraviolet light			
Hazardous waste (e.g. biological, chemical)			
Emissions to atmosphere			
Discharge to soil and water bodies (including stormwater run-off)			
Nuisance noise or odour			
Extreme temperatures			

Ergonomics: repetitive or awkward movements			
Manual handling: lifting or moving awkward or heavy objects			
Slippery surfaces/trip hazards			
Poor lighting/ventilation/air quality			
Violent or volatile clients/interviewees			
Working in isolation for extended periods			
Cash handling			
Engaging construction contractors			
Any others not already listed:			

(3) RISK ASSESSMENT

Complete this for hazards in your project identified in Section (2). Refer to [Health & Safety Risk Management video] and [UTS Risk Assessment] for help on how to carry out risk assessment.

TASK List and describe hazardous task/activity/process/step/equipment	**ASSOCIATED HAZARD(S)**	**INHERENT HARM** Harm that could occur from these hazards if controls fail or are not in place.	**EXISTING CONTROL MEASURES** Control measures currently in place to minimise risk	**RISK LEVEL** (High/ Medium /Low)	**PROPOSED CONTROL MEASURES** Additional control measures needed to reduce risk further	**TARGET DATE** To implement proposed controls	**RESIDUAL RISK LEVEL** (High/ Medium/ Low)
			• • • •		•		
			• • • •		•		
			• • • •		•		

TASK List and describe hazardous task/activity/proces s/step/equipment	**ASSOCIATED HAZARD(S)**	**INHERENT HARM** Harm that could occur from these hazards if controls fail or are not in place.	**EXISTING CONTROL MEASURES** Control measures currently in place to minimise risk	**RISK LEVEL** (High/ Medium /Low)	**PROPOSED CONTROL MEASURES** Additional control measures needed to reduce risk further	**TARGET DATE** To implement proposed controls	**RESIDUAL RISK LEVEL** (High/ Medium/ Low)
			• • • •		•		

Emergency preparation and response					
EMERGENCY List and describe foreseeable potential emergency situations *(e.g. fire, spill, personal injury)*	**INHERENT HARM** Harm that could occur from these hazards if controls fail or are not in place.	**EXISTING CONTROL MEASURES** Control measures currently in place to minimise risk	**PROPOSED CONTROL MEASURES** Additional control measures needed to reduce risk further	**TARGET DATE** To implement proposed controls	**RESIDUAL RISK LEVEL** (High / Medium / Low)

(4) SIGNATURES

Confirm that:

- In case my project is entirely desk/computer-based, I will inform my academic advisor and arrange for him/her to sign this section. If not, I will fill in all sections of this form.
- Health, safety and environmental hazards arising from this project are identified and their risks assessed.
- Control measures will be implemented to reduce risks to an acceptable level.
- Safe work information and training will be provided, as required.
- As new hazards arise during the life of the project, risks will be re-assessed and control measures implemented.

Student - Name	Signature	Date
Robert Makepeace	Robert Makepeace Digitally signed by Robert Makepeace Date: 2022.04.07 20:07:41 +10'00'	06/04/2022
Academic advisor - Name	Signature	Date
Dr Jahangir Hossain	Jahangir Hossain Digitally signed by Jahangir Hossain Date: 2022.04.08 05:44:02 +10'00'	8/4/22

Appendix – A

HOST ORGANISATION HEALTH AND SAFETY CHECKLIST
FOR ORGANISATION HOSTING UTS STUDENTS

This checklist is to be completed prior to hosting UTS students in host organisations for any course related project work.
It should be returned from the host organisation at least two (2) weeks prior to intended commencement of the project work.
By completing this checklist you assure UTS that our students are in safe hands.
Guidance notes on completing this checklist

SECTION 1
THIS SECTION IS TO BE COMPLETED BY THE UTS ACADEMIC ADVISOR PRIOR TO SENDING THIS FORM TO THE HOST ORGANISATION

Details of University academic advisor

Name	Dr Jahangir Hossain
Faculty/Unit	Faculty of Engineering and IT
Telephone	+61 2 95142541
Email	jahangir.hossain@uts.edu.au

SECTION 2
THIS SECTION IS TO BE COMPLETED BY THE HOST ORGANISATION ACCEPTING UTS STUDENTS

Name of host organisation	
Address	
Telephone	
Email	
Summary of host organisations business	

TO BE COMPLETED BY THE HOST ORGANISATION

The organisation has an accredited H&S Management System (AS/NZS 4801, OHSAS 18001, ISO 45001 or similar) and all workers are covered by insurance **If "Yes", skip direct to Declaration**.	Yes	No

IF "NO", COMPLETE THE FOLLOWING

HOST ORGANISATION HEALTH AND SAFETY COMPLIANCE CHECKLIST		
INDUCTION AND TRAINING		
All new employees and workers (including student interns) are provided with a safety induction and training in safe work practices appropriate to the activities to be undertaken.	Yes	No
EMERGENCY MANAGEMENT		
There is a formal emergency action plan which has been communicated to all workers as part of the induction process.	Yes	No
The organisation will maintain a register of emergency contact details for hosted UTS staff and students.	Yes	No
FIRST AID		
First aid facilities are available and provided to injured workers.	Yes	No
ACCIDENTS/INCIDENTS		
There is an accident/incident and hazard register maintained for the organisation which details remedial action taken.	Yes	No
WORK ENVIRONMENTS AND ACTIVITIES		
Health and safety risks associated with work practices are identified and controlled	Yes	No
Regular inspections of work environments are conducted to identify and control health and safety hazards	Yes	No
INSURANCE		
Workers at this workplace are covered by insurance	Yes	No

HOST ORGANISATION DECLARATION

To the best of my knowledge, the above statements are true and correct.

Signed		Name	
Position Title		Date	