ASSIGNMENT COVERSHEET

UTS
UNIVERSITY OF TECHNOLOGY, SYDNEY

UTS: ENGINEERING & INFORMATION TECHNOLOGY

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ASSESSMENT ITEM NUMBER/ TITLE

ASSIGNMENT 4 RESEARCH PROJECT PROPOSAL

X I confirm that I have read, understood and followed the guidelines for assignment submission and presentation on page 2 of this cover sheet.

X I confirm that I have read, understood and followed the advice in my Subject Outline about assessment requirements.

X I understand that 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.

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Statement of Collaboration:

Signature of Student(s) Robert Makepeace Date 22/05/2022

ASSIGNMENT RECEIPT

To be completed by the student if a receipt is required

SUBJECT NAME/NUMBER	NAME OF TUTOR

SIGNATURE OF TUTOR	RECEIVED DATE

UTS: Engineering & Information Technology (2014) Assignment Cover Sheet

A Techno-Economic Analysis of the Export of Green Hydrogen Research Project Proposal

42908 Engineering Project Preparation
By Robert Makepeace (13886357)

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1 Introduction

This research project proposal is for a techno-economic analysis of the export of Green Hydrogen in order to determine the most cost-effective method of transport for different case studies around the world.

1.1 Definitions

Green Hydrogen is hydrogen produced from renewable energy powered electrolysis with close to zero carbon emissions.
Grey Hydrogen is hydrogen produced from fossil fuels with no capturing of carbon emissions.
Blue Hydrogen is hydrogen produced from fossil fuels with carbon capture and storage (CCS).
Techno-economic analysis is a method of evaluating the economic performance of industrial applications through considering the process, equipment sizing, and financial costs.
Export The use of green hydrogen as bulk energy carrier to move energy long distances between countries.

1.2 Report Structure

Section 2 provides background and context to motivation for the export of green hydrogen as part of the hydrogen economy. Section 3 defines the specific research question for this research project. Section 4 details the proposed methodology in terms of data collection, analysis, and validation. Section 5 describes the project management methods for the research project to ensure it achieves the objectives. Section 6 provides an overview of the research progress in what has been achieved so far. The appendices list the different hydrogen transportation methods, a list of proposed green hydrogen export projects and evidence of progress of the research project so far.

2 Background

2.1 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 in 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 hydrogen economy consists of all elements required for the production, storage, transport, and usage of hydrogen. Currently 70 MT of pure hydrogen are produced each year typically through thermochemical processes from the conversion of fossil fuels such as natural gas and coal or as a by-product from chemical processes (NSW Government, 2021). The primary method of green hydrogen production is electro-chemical through electrolysis of water using renewable electricity (wind or solar photovoltaics). Hydrogen has numerous potential future applications across industries currently powered by hard-to-abate fossil fuel sourced energy. 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 (IEA, 2021). It expected that hydrogen will be used to power the transportation sector, electricity generation, direction combustion for heating, green steel production and other chemical manufacturing. Figure 1 shows where transportation fits amongst the hydrogen economy between production and end use applications.

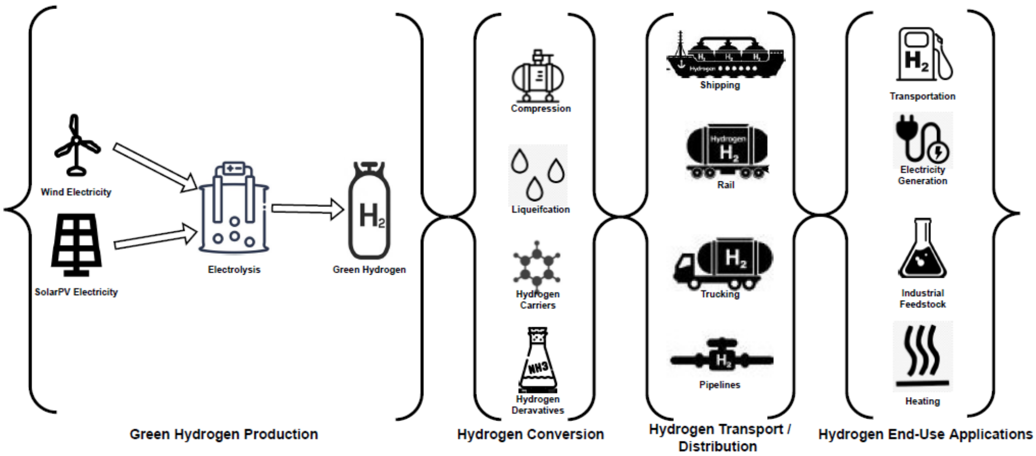

Figure 1: Green Hydrogen Economy Diagram (Hydrogen Transportation consists of the Hydrogen Conversion, Hydrogen Transportation and Reconversion (if required) phases)

There several different mediums being considered for the transportation of hydrogen. Appendix 1: Hydrogen Transport Technologies summarises the different mediums for hydrogen transportation and lists technological readiness, advantages, and disadvantages.

There are numerous large-scale projects being proposed in Australia for the production of green hydrogen with potential to export internationally. Appendix 2: Proposed Australian Green Hydrogen Export Projects provides a summary of some of the key new projects and conversions of existing ammonia production and export facilities.

2.2 Literature Review

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). As the parameter values can influence the outcome of the analysis, it is good practice to quantify the uncertainty of the estimates and understand the sensitivities of each parameter. Batan et al. (2016) incorporates uncertainties into the techno-economic model by using the Monte Carlo, a stochastic simulation method to produce a probabilistic profile of the expected costs. This is an exemplary technique to handle the uncertainties of these types of analysis.

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 and resource factors. Walsh identifies geographical regions with potential for development and identifies additional infrastructure required.

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 internationally. 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. 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).

3 Research Question

3.1 Problem Definition

Green hydrogen production typically requires large, cheap and renewable electricity production for the electrolysis method. 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 (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, 2017). 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.

3.2 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.

3.3 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.

3.4 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

4 Methodology

Extending the literature review of techno-economic analysis discussed in Section 2.2, this section outlines the proposed methodology for this research project. Figure 2 provides an overview of the model implementation process.

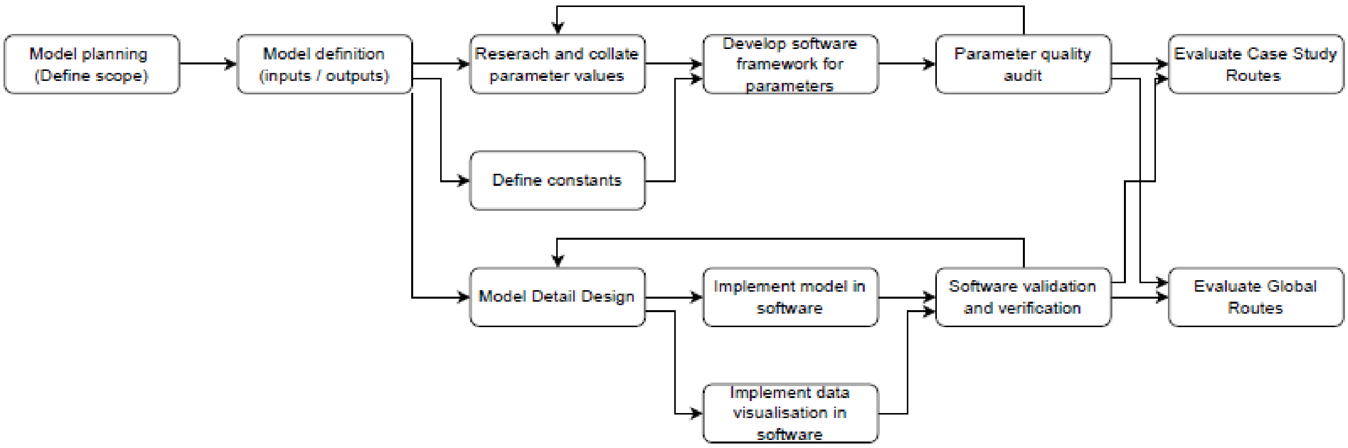

Figure 2: Methodology Implementation Process Diagram

4.1 Data Collection

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.

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 will be collated from a variety of sources including academic research, industry groups, governments, and proposed projects. The parameter values will be averaged from multiple sources where possible and include projections until 2050 and an uncertainty range of the parameter value. Generally, the model will be framed in terms of common parameters that have available estimated cost projections, for example the cost of electricity. Some of the models will require region specific parameter values to allow for analysis of trade between regions which may have differences in cost. Refer to Appendix 3: Data Collection Progress for some examples of the data collected so far.

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

4.2 Data Analysis

An overview of the data analysis is shown in Figure 3 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 will determine 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 for simplicity of the analysis. Refer to Appendix 4: Model Design Progress for an example of a transportation model for hydrogen pipelines.

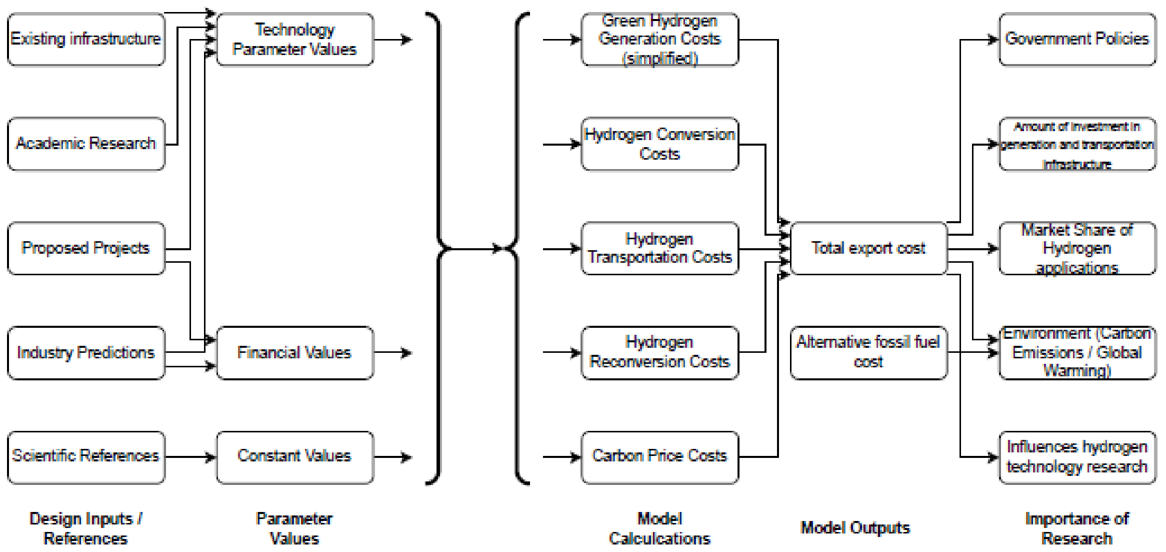

Figure 3: System Functional Block Diagram Overview

The techno-economic model will be implemented in the Matlab software. Matlab has been chosen for its powerful engine with built-in functionality for data visualisation and graphing. The model will be implemented in various scripts and combined together to calculate and present the result findings. It will be 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 will output transport costs for a specified distance and volume for each of the transportation methods.

The base transportation model will be 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 4. This will apply the different green hydrogen transportation costs to specific trade routes as listed in Table 1. These trade routes will 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 will be a ranking of each technology in terms of cost effectiveness for each case study. This methodology will provide insight on which technologies work best for specific trade routes depending on the characteristics of the specific trade routes.

Table 1: Green Hydrogen Case Study Routes

#	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

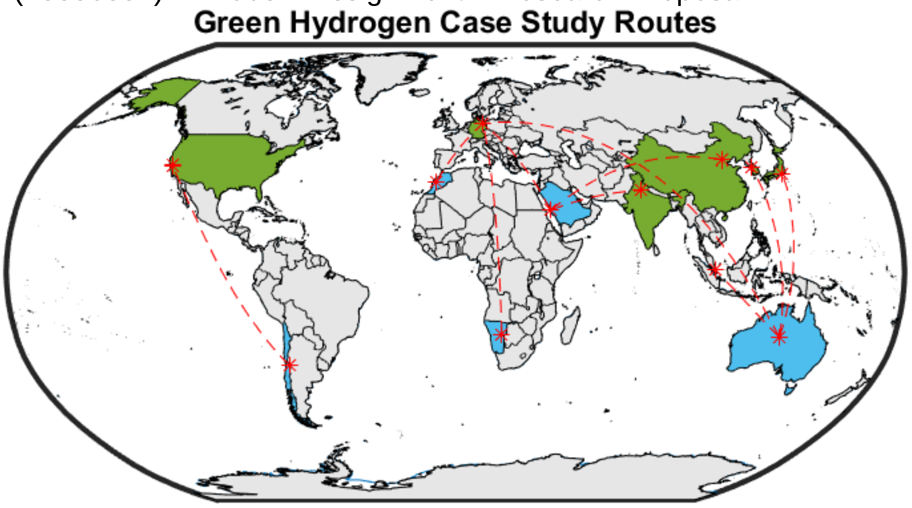

Figure 4: Green Hydrogen Case Study Routes (Blue Exporters, Green Importers, Red Routes See Table 1)

The second analysis approach is a green hydrogen world regional trade optimisation with routes as shown in Figure 5. 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 three mediums will be applied to the simplified fifteen routes shown in

Table 2. The model will have specific parameter values for the local production of green hydrogen in each region. Local production and transportation costs will be 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 will determine if green hydrogen produced locally or imported from the other regions if cheaper. The outputs will provide an estimate of the feasibility of exporting hydrogen for international trade. This analysis will provide insight into the volume of potential green hydrogen trade and identify which routes may be the key trade routes.

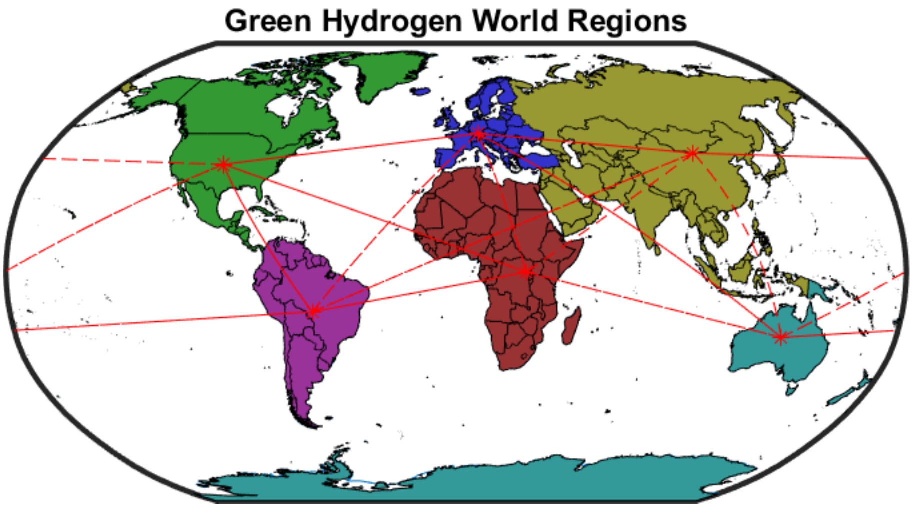

Figure 5: Green Hydrogen World Regions (Europe - Blue, Africa - Brown, Asia - Olive, Oceania - Aqua, North America - Green, South America - Purple, Routes - Red See Table 2)

Table 2: World Region Trade Route Distances in kilometres (Noting each region is simplified to a single location)

		Importer					
		Europe	Africa	Asia	Oceania	North America	South America
Importer	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

The results will be disseminated in the final research project report. It is proposed to display the results in tables, graphs and diagrams highlighting different aspects of the results. There will primarily be the results for each transportation method, the key case study trade routes, and the world region trade. The results will converted to the cost per delivered unit of energy to allow for comparisons with different transportation medium. It is intended to also breakdown the results 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 will be 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 will compare 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, this will be 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 will inform the viability of green hydrogen against other technologies against a range of potential carbon pricing scenarios in the future.

4.3 Validity of Potential Results or Findings

A number of different methods are proposed to evaluate the validity of the results and findings.

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

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

The software implementation will be 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 will be tested against similar research studies on the economics of hydrogen transportation using the same starting data to verify similar output results. The outcomes will be 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, there will be sensitivity and uncertainty analysis of the key parameters 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

4.4 Limitations

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

- There will be 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 will be some variations of parameter values within the local regions and differences in distances, but the results will be 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.

5 Project Management

5.1 Scope Of the Project

The scope of the project is performing a techno-economic analysis of the different methods of the export of green hydrogen. This the design and implementation of a software model

Inclusions:

- Economic modelling of the different transportation methods for green hydrogen export including conversion, transportation, and reconversion phases
- Basic economic modelling of the baseline current fossil fuel equivalent and equivalent grey hydrogen equivalent technology including the impact of carbon pricing. This allows for a comparison of the green hydrogen methods against alternatives.
- Analysis of the uncertainties and sensitivities in the model of key parameters
- Analysis of the key factors influencing transportation cost

Exclusions:

- No detailed modelling is included for the production and storage of green hydrogen. This work is being conducted by other students with the same supervisor.
- Detailed analysis of the end user application and local distribution costs is excluded. The reconversion and transport to a local hub is included to allow for comparison against local generation
- Generally, the impact of government policy incentives will be excluded from the analysis expect for the impact of carbon pricing. This

5.2 Process and Timeline

The research project is collected into several key phases with the following work breakdown structure:

1. Project Planning
    a. Defining research question
    b. Literature Review
    c. Review of industry projects, trends, and projections
    d. Research Project Proposal
2. Theoretical design of the techno economic model
    a. Collection of Model data
    b. Design of the model
3. Implementation of the Model
    a. Software development of the model
    b. Testing and verification
    c. Data visualisation and output
4. Analysis
    a. Refinement of the model
    b. Sensitivity analysis
    c. Uncertainty analysis
5. Project Report Write-Up

Phase 1 (Project Planning is in progress as part of the 42908 Engineering Project Preparation subject being conducted in the Autumn semester of 2022.

Phases 2-5 are planned to mainly occur as part of the 42003 Engineering Graduate Project subject being conducted in the Spring semester of 2022. The exact timing can be seen in the Gantt chart in Figure 6, with some work scheduled to occur through the winter break.

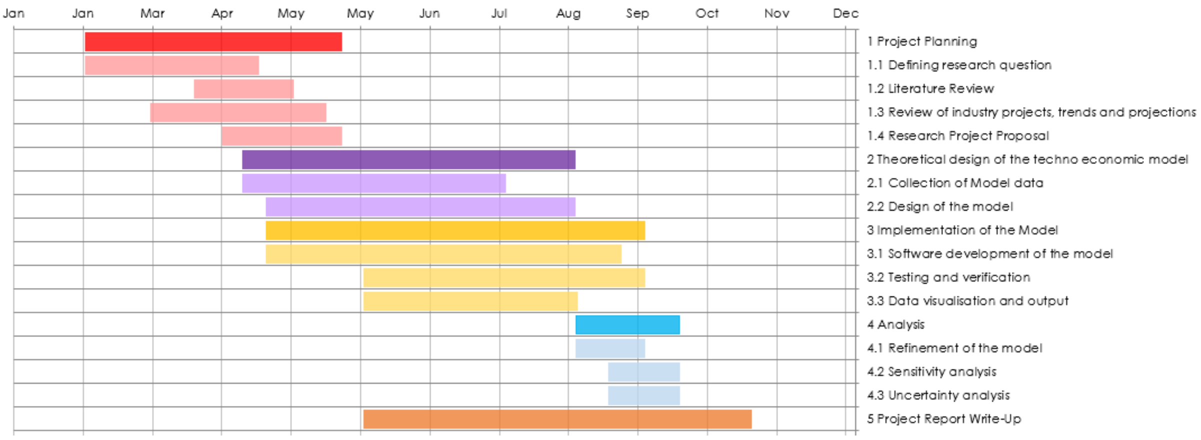

Figure 6: Research Project Gantt Chart

5.3 Milestones and Resources

The project milestones are listed in Table 3. The table lists the formal subject assessment submissions, but also the internal project milestones of the different elements from the work breakdown structure (WBS).

Table 3: Research Project Milestones

Milestone Number	Milestone Description	Milestone Date	Status
1	Assessment – Literature Review Submission	01/05/2022	Complete
2	Assessment – Research Project Proposal Submission	22/05/2022	Complete
3	Assessment – Research Project Report Submission	TBC – Oct/Nov 2022	Planned
4	Phase 1: Project Plan complete	15/05/2022	Complete
5	Phase 2: Model design complete	1/08/2022	In Progress
6	Phase 3: Model implementation complete	1/09/2022	In Progress
7	Phase 4: Analysis complete	30/09/2022	Planned
8	Phase 5: Report write-up complete	15/10/2022	Planned

The project resources are listed below in Table 4. All the project resources have been allocated, are available and setup already as of the time of writing.

Table 4: Research Project Resources

Resource Type	Resource Description	Status
Human Resource	Student – 10-15 hrs/week including winter semester break	Available
Human Resource	Supervisor – fortnightly meetings	Available
Hardware	Computer with sufficient computing power and video conferencing capability	Available and setup
Software	Video conferencing - Zoom	Available and setup
Software	Microsoft office products (Outlook, Word, Excel, PowerPoint, OneNote, Teams)	Available and setup
Software	Referencing - End Note	Available and setup
Software	Software development – Matlab	Available and setup
Software	Version Control - GitHub	Available and setup

5.4 Uncertainties and Risks Control

In terms of health and safety risks, the only risks for the project relate to project ergonomics as the work is all desk and computer based. To mitigate any potential harm, the student will be working in an ergonomic setup and take regular breaks to stretch and move around to avoid any injuries. The office has a regular safety inspection to check for any manual handling, faulty electrical equipment, etc.

The project raises no ethical concerns as it all computer-based computer simulations with no human-based data.

Table 5 lists the salient project risks around successful completion of the project including the handling of uncertainties. The table also lists risk mitigations for these risks.

Table 5: Project Risk Register

Risk Index	Risk Description	Risk Mitigation
1	Student works full time and is unable to dedicate enough time to the research project	Work diligently throughout the semester. Have contingency in the project schedule. Breakdown tasks into smaller chunks Plan ahead and schedule regular study
2	Model variable value estimates are inaccurate leading to incorrect conclusions	Specify the parameter values with an uncertainty band to allow for sensitivity and uncertainty analysis. In this way there will be a probability distribution of the output results to better inform conclusions.
3	Technological or economic advancements during the project	Ongoing literature review and ability to update the parameter values or adjust model if required
4	Results are not generalised when tied to specific case study routes	Build the software flexibly that can easily be adjusted to different case study parameters. Conduct the regional analysis to analyse the economics of exporting more generally
5	Model creation and troubleshooting takes longer than expected	Allocate sufficient time for planning, testing, and verification. Develop the software in a modular fashion testing component by component.
6	Loss of data, software, or documentation	Regular automatic backups using OneDrive and GitHub software.

5.5 Communication Management

Communication management is important in managing the successful implementation of this research project. The communication management

Communication between the supervisor and myself will primarily be through fortnightly video calls on the Zoom platform. As there are five students working in the similar topic area of green Hydrogen, we have been doing joint video calls to allow for the collaboration of the different students and sharing of resources. These video calls are an opportunity to provide an update on progress in the past fortnight and get feedback from the supervisor and other students. This format allows for discussion of issues or challenging points in the research.

Outside of these video calls, there will be communication between the student and supervisor via emails on a required email. Emails will be used for any additional contact for things such as the approval of ethics and risk assessment documents or other urgent queries.

All communications will be logged in the student's subject journal. The Microsoft OneNote platform will be used to keep a brief journal of notes cataloguing any communication and any other research conducted on a day. This OneNote software will act as a log of the work completed and have other tools such as a to do list to help organise the various tasks and thoughts around the project.

Other related software tools to be used in supporting the research work is Microsoft OneDrive which automatically back-ups the documents and files and EndNote to manage the referencing in the project. GitHub will be used for version control and back-up of the software.

6 Progress Statement

The project has already made significant progress throughout the first semester of the project. The literature review and research project submission milestones have been accomplished (milestones 1, 2 and 4) (Refer to Gantt Chart Figure 6).

There has been some early work on collecting model data in collating a variety of sources for parameter values includes proposed projects, academic literature, government policies and industry bodies. Refer to Appendix 3: Data Collection Progress for some examples of the data collected so far and data visualisation of the parameter values. There has also been some work progressed in designing the model and preparing the software platform in Matlab (milestone 5, software available at the following website: https://github.com/robmakepeace/GreenHydrogen). Refer to Appendix 4: Model Design Progress for an example of the model design work completed so far.

These efforts have taken roughly as long as expected with the estimate of 10-15 hours per week of study. Now the scope and resources of the project have been clearly defined and setup, the efforts are more productive and relevant. At this current rate of progress, it is expected to complete the research project with some spare time as there is significant buffer in the conservative schedule. Conducting this study whilst also working full-time is challenging, but achievable with effective time management and planning. It is intended to have some additional areas to extend the analysis as discussed in the Methodology section if there is spare time towards the end of the project.

The project work has been mostly smooth, canvassing the wide range of different resources and information sources across academia and industry. There have been some challenges in focusing on the best sources of information and keeping the research directly relevant to the specific research question posed. These difficulties have been overcome by building a library of sources, taking notes and shelving resources if they are not relevant at the time. It was attempted to have some objectives of specific outcomes to determine from reading resources, in order to keep the research activity relevant and productive.

Since the commencement of the subject and selection of the topic, the geopolitical situation in the world has accelerated the hydrogen industries expectations of the timeframes for green hydrogen. The student's attendance at the hydrogen talks of the Smart Energy Expo highlighted that the war in Ukraine has highlighted the dependence of European and other countries on Russia for the supply of energy through natural gas and oil. Numerous countries have accelerated their intentions to produce or import green hydrogen to decrease their energy dependence on Russia. Green hydrogen provides an opportunity for an energy source with less geopolitical complications as many more places have renewable energy resources.

During the research conducted so far, there has been refinement on the research scope as the semester has progressed. Topical issues such as impact of carbon pricing, guarantee of supply, role of standards, safety issues and public perception have been incorporated into the research to ensure a holistic understanding of exporting beyond just the financial aspects. Recent developments in research and industry projects into specific transportation methods and broader hydrogen economy have influenced the scope and methodology of this research.

7 Conclusion

This research project proposal covers the proposed techno-economic analysis for the export of green hydrogen. The long-distance transport of green hydrogen fits amongst the emerging green hydrogen industry of production through to end use applications. The literature review identified a gap in the academic research of a rigorous techno-economic analysis of the different transport mediums for exporting green hydrogen. The research question attempts to address this gap in the research through evaluating the most cost-effective methods for transport. The research methodology in analysing specific case study trade routes and global trade between regions will provide estimates on the costs of transport and estimated volumes projected into the future. The proposed project management strategies have been presented to ensure the successful execution of work. Finally, a statement of progress shows the completion of literature review and initial parameter collection, model design and model programming has already been achieved.

7.1 Research Relevance

This research topic is topical and relevant given the growing local industry for green hydrogen with the list proposed Australian projects shown in Table 7 and Figure 7. 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. It is aimed that this research project will have potentially multiple contributions to research, the hydrogen industry and government as summarised in Figure 3. Better understanding about the economics and scale of opportunity of green hydrogen exports will inform government policies, regulations, and funding grants. In industry, better estimates of the future hydrogen trade will influence investment decisions for the hydrogen sector across production, transportation, and end use applications. Understanding the different potential and costings of transportation methods may influence future academic and industry research and development. Finally, forecasting the growth of the hydrogen industry informs public education about the technology and safety risks towards public acceptable and adoption of the technology.

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Appendix 1: Hydrogen Transport Technologies

Table 6:Comparson of Hydrogen 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)
	Liquefied	Shipping / Truck	Long distance	High	Cost Effective for long distance	Proven technology, High density	Conversion energy, Safety issues	(Balat, 2008)
	Cryo-compressed	Shipping / Truck	R&D	Low	Expensive	High density	Technology not proven	(Faye et al., 2022)
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)
	Green Methanol	Shipping / Truck	R&D	Low	Expensive	High density storage	Technology not proven	(Li and Tsang, 2018)
	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)
	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)
	Porous Carbon Materials	Shipping / Truck	R&D	Low	Expensive	High conversion efficiency	Technology not proven	(Andrews et al., 2022)
	MethylCycloHexane (MCL)	Shipping / Truck	R&D	Medium	Expensive	Efficient hydrogenation	Inefficient hydrogenation	(Obara, 2019)
Pipeline	Blending into Natural Gas	Pipeline	Local distribution	Medium	Cheap	Uses existing infrastructure	Low energy throughput. Fixture compatibility	(Frontier Economics, 2020)
	Existing / New Hydrogen Pipeline	Pipeline	Local distribution / export	Medium	Moderate	Better throughput	More expensive	(Frontier Economics, 2020)

Appendix 2: Proposed Australian Green Hydrogen Export Projects

Table 7 and Figure 7 list the major proposed green hydrogen production and hydrogen transport projects in Australia. This list has been generated from a variety of sources including the presentations at Smart Energy Expo, CSIRO's HyResources (CSIRO, 2022) and vendor websites. Whilst the majority of these projects are at the proposal stage, it provides some indication of the scale of production, the export technologies targeted by industry for export and the initial exports markets that have been identified.

Table 7: 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

Name	Location	Company	Renewable Generation	Hydrogen Transport	Hydrogen Volume	Export Market	Status
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 (Electroylser)	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

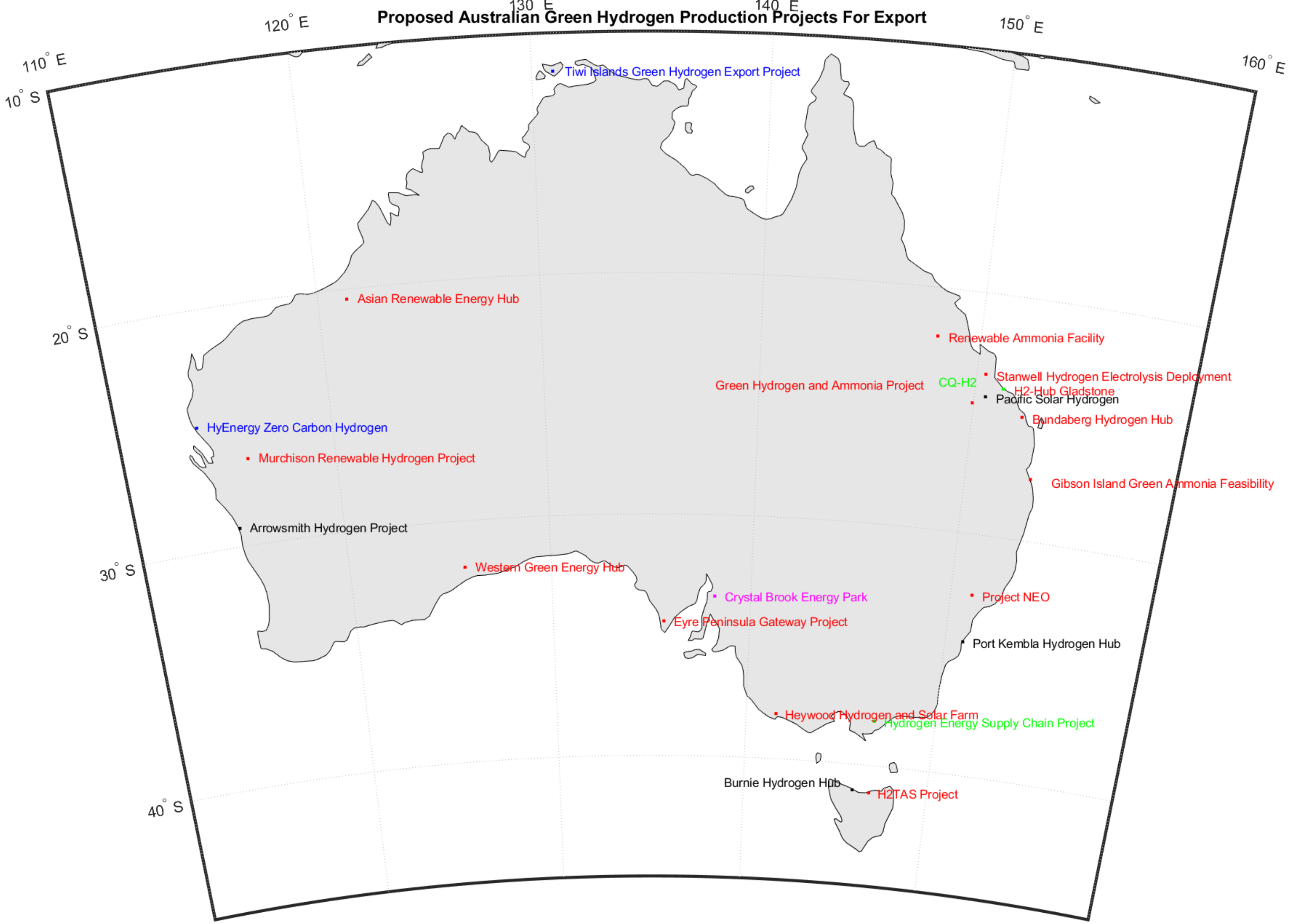

Figure 7: Map of Australian Large Proposed Green Hydrogen Production Projects For Export (Colour is Proposed Transportation Medium: Red = Ammonia, Blue = Compressed Hydrogen, Green = Liquefied Hydrogen, Magenta = MCH, Black = To Be Decided)

Appendix 3: Data Collection Progress

The graphs below demonstrate the progress in the data collection for the research project. These parameter values have been collated from a variety of sources including academic literature, industry bodies and government policies. The parameters include yearly values projected to 2050 and a range of the uncertainty of the parameter value. Some examples of the parameters collected so far are included in the graphs below generated in the Matlab software package.

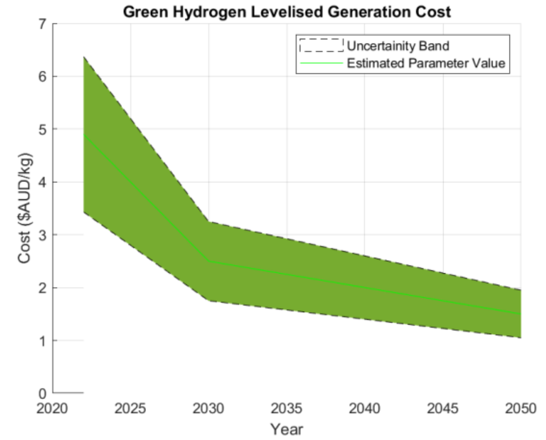

Figure 8: Data Collection: Green Hydrogen Production Levelised Cost

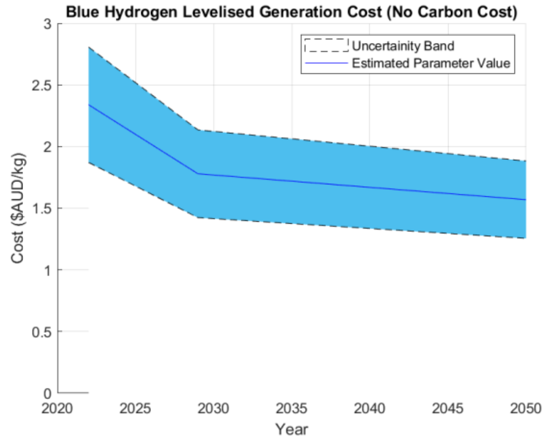

Figure 9: Data Collection: Blue Hydrogen Production Levelised Cost

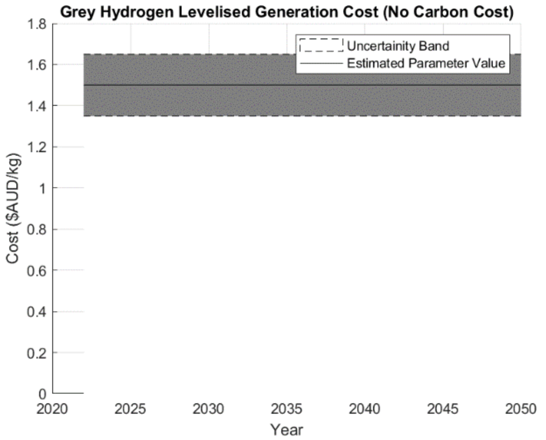

Figure 10: Data Collection: Grey Hydrogen Production Levelised Cost

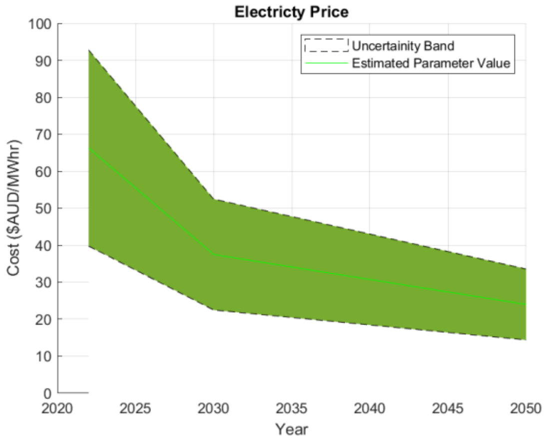

Figure 11: Data Collection: Electricity Price

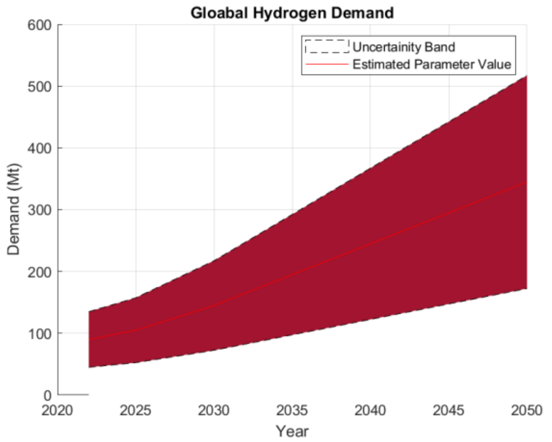

Figure 12: Data Collection: Global Hydrogen Demand

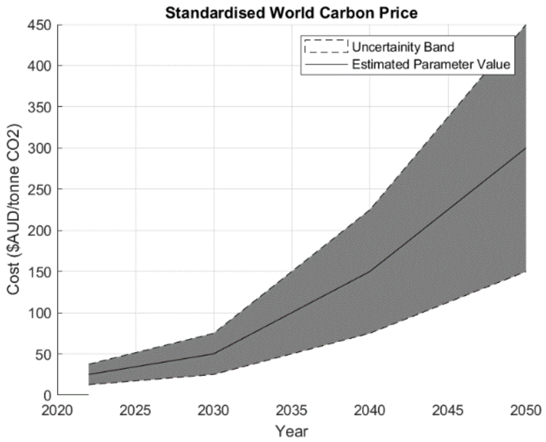

Figure 13: Data Collection Standardised World Carbon Price

Appendix 4: Model Design Progress

Figure 14 below highlights the progress in the early design work of the model creation. The diagram shows the model for the techno-economic analysis of pipelines for hydrogen transport. The diagram shows the relationship between the parameters in converting the raw parameters into the desired output parameters. This model will need additional refinement and verification in the next stage of the project. It is anticipated similar models will be developed for the other transportation mediums and conversion/reconversion phases.

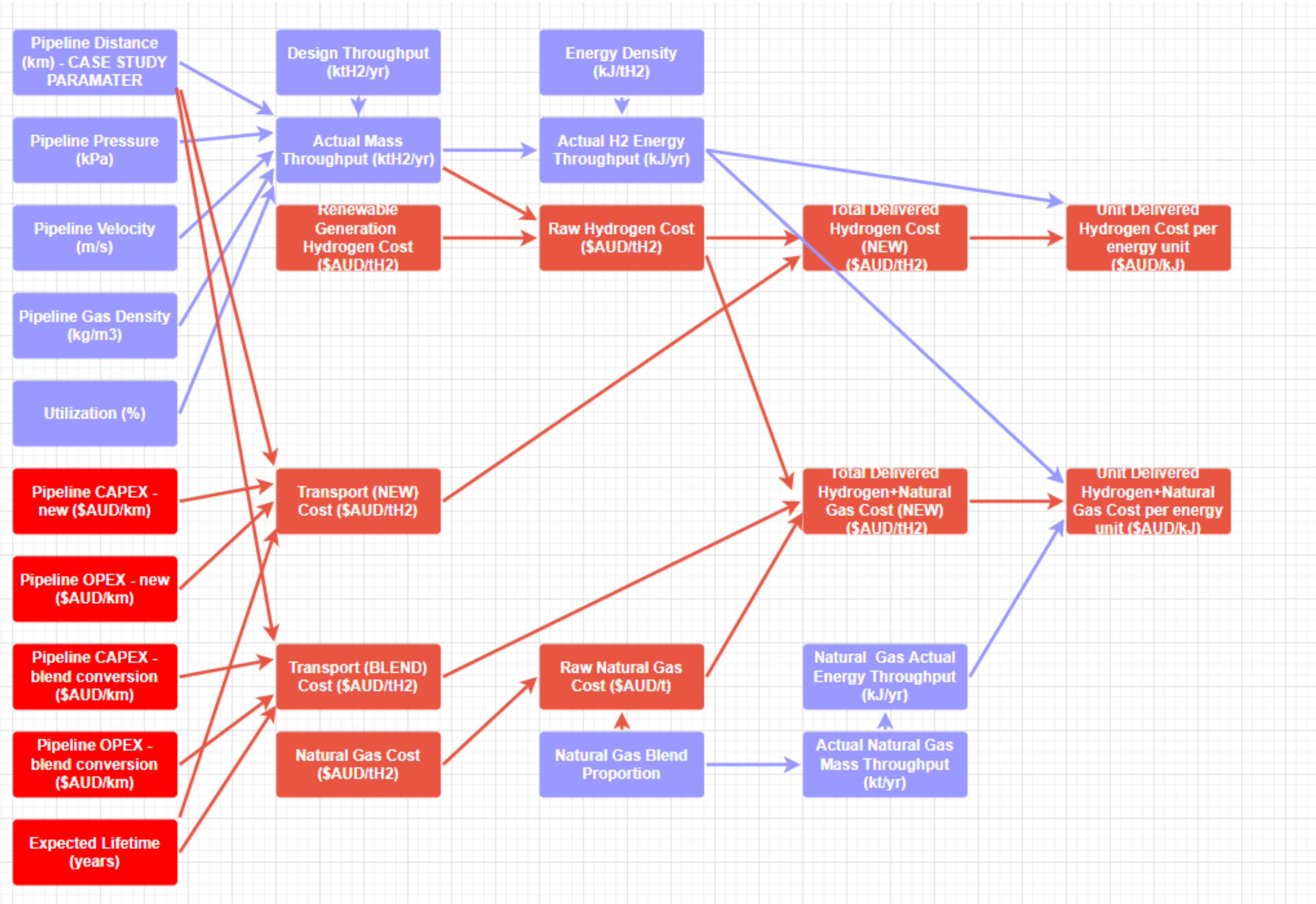

Figure 14: Model Design: Early work on developing the model design. This diagram shows the model for the transport of green hydrogen via pipelines combining physical (purple) and financial (red) parameters.