UNSW SYDNEY

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Working paper for consultation

September 2021

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

In September 2020, Australia and Germany signed a landmark agreement to initiate a joint feasibility study into the potential for closer collaboration and the future development of a hydrogen supply chain between the two countries. The Departments of Foreign Affairs and Trade (DFAT) and Industry, Science, Energy and Resources (DISER) of Australia and the Federal Ministry of Education and Research of the Federal Republic of Germany have jointly agreed to fund, 'HySupply' (project name), a feasibility study to investigate the Australian-German supply chain involving the production, storage, transport and use of hydrogen (including hydrogen-based energy carriers), produced from renewables.[i]

Australia takes a technology neutral approach to developing a clean hydrogen industry which includes production of hydrogen from renewable sources in addition to hydrogen produced from coal and natural gas with carbon capture and storage. The scope of the agreement signed covered the supply chain of renewable hydrogen. Consequently, the scope of HySupply is focused on renewable hydrogen.

This work and modelling was carried out by the UNSW Sydney ('UNSW') with inputs from the UNSW led HySupply Australia consortia members. Deloitte Financial Advisory Pty Ltd ('Deloitte') supported UNSW in the development of the 'State of Play – Working paper for initial consultation'.

The State of Play (SoP) draft paper is released as a consultation paper to the HySupply Consortia, industry stakeholders and government bodies, to facilitate discussion regarding the development of an Australia-Germany green hydrogen supply chain. The SoP preliminary paper has been developed through a deep-dive literature investigation, and supporting modelling and UNSW led stakeholder consultations. The report is designed to foster dialogue with industry and other stakeholders regarding key challenges and opportunities for progressing HySupply, and Australia's green hydrogen exports more broadly. Given the rapid progress in hydrogen technologies, projects, and wider initiatives it is envisaged that this analysis will continue to be updated over the life of the HySupply project.

We welcome and seek stakeholder feedback on this report, the developed open-source models for the value chain analysis, and key priorities for the next stages of the work. Please feel free to contact either Dr Rahman Daiyan (r.daiyan@unsw.edu.au) or Associate Professor Iain MacGill (I.macgill@unsw.edu.au) to discuss further.

Citation

R. Daiyan, I. MacGill, R. Amal, S. Kara, K.F. Aguey-Zinsou, M.H. Khan, K. Polepalle, W. Rayward-Smith. (2021). The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0. UNSW Sydney, Australia. DOI: http://doi.org/10.26190/35zd-8p21

Disclaimer

Clients

Australian Government
Department of Foreign Affairs and Trade

Australian Government
Department of Industry, Science, Energy and Resources

[i] https://www.dfat.gov.au/international-relations/themes/climate-change/joint-declaration-intent-australian-german-supply-chain-feasibility-study-hydrogen-produced-renewables

Consortium Members

Note: We seek and welcome new consortium members across Australia's emerging green hydrogen value chain. Please feel free to contact either Dr Rahman Daiyan (r.daiyan@unsw.edu.au) or Associate Professor Iain MacGill (i.macgill@unsw.edu.au) to explore this further.

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Acknowledgement

The following stakeholders have provided particular guidance, feedback and insights in developing this first version of the HySupply State of Play document. Of course, this report is by no means representative of their individual views and positions on the range of issues covered. We also wish to acknowledge the UNSW data and modelling team for their major contributions to this work - Phoebe Heywood, Charles Johnston, Aaron Kuswara, and Thomas Wood. We further thank DISER and DFAT for their guidance in developing this SoP.

Ambassador Philip Green
Department of Foreign Affairs and Trade (DFAT)

John O'Brien
Deloitte Australia

Dr. Bart Kolodziejczyk
Fortescue Metals Group

Dr. Fiona Simon
Australian Hydrogen Council

Rupert Maloney
Clean Energy Finance Corporation

Patrick Hartley
CSIRO

Professor Frank Jotzo
ANU

Alex Trajkov
H2U™

Dr. Amy Philbrook
Australia Renewable Energy Agency (ARENA)

Peter Benyon
GHD

Matt Walden
Australia Renewable Energy Agency (ARENA)

Florence Lindhaus
AHK

Michael van Baarle
ABEL Energy

Leigh Kennedy
NERA

Martin Hablutzel
Siemens Energy

Alix Ziebell
ATSE

Andy Pickford
Origin Energy

Andrew Dickson
Asian Renewable Energy Hub

David Sheipouri
MAN Energy Solutions Australia Pty Ltd

Daniel Krosch
GPA Engineering

Timothy Meyers
MAN Energy Solutions Australia Pty Ltd

Dr. Emma Aisbett
ANU

Dr. Thomas Longden
ANU

Dr. Alan Rai
Baringa Partners

Dr. Jon Pemberton
Scimita Ventures

Dr. Mobin Nomvar
Scimita Ventures

Dr. Michael Zettinig
AHK

Christoph Freiherr von Spesshardt
AHK

Alan Yu
LAVO

Sara Edmonson
Fortescue Metals Group

Chris Dolman
BOC

Walter Hocker
Linde

Hirofumi Kawazoe
Hydrogen Engineering Australia

Yasushi Yoshino
Kawasaki Heavy Industry

Bretton Cooper
Southern Green Gas

Sussan S. Johnson
Woodside Energy Ltd

Executive Summary

Global efforts are accelerating towards net-zero emissions with jurisdictions that represent 68% of the global GDP, now committed to reaching a net-zero future. Our HySupply project forms part of this wider challenge and opportunity of moving towards a decarbonised global energy supply chain, with a transformation in energy trade from present fossil fuel-based energy resources to renewable energy. Both energy importers and exporters are looking to pivot towards lower carbon energy alternatives.

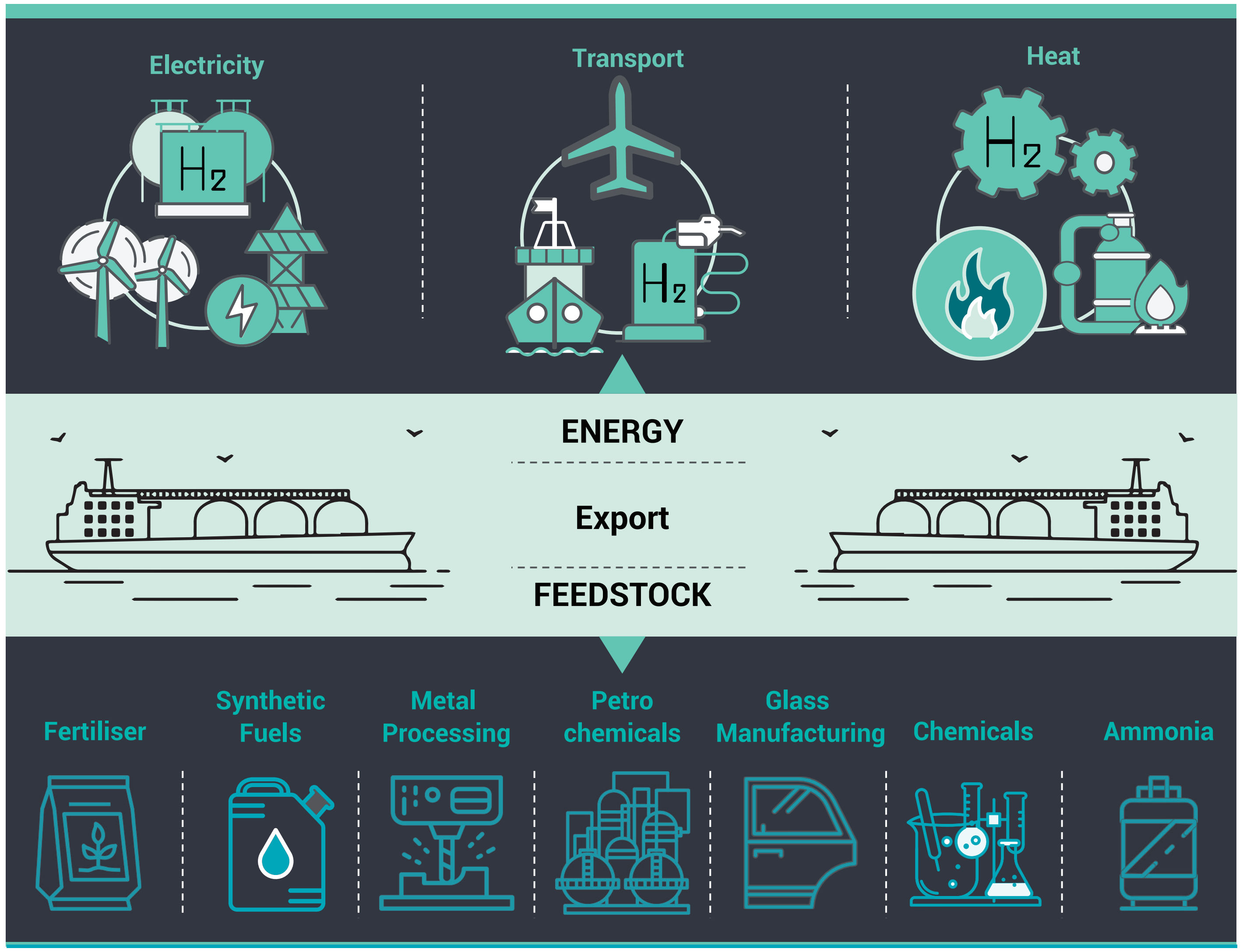
HySupply is a collaboration between key stakeholders in Germany and Australia to investigate the feasibility of exporting renewable energy in the form of hydrogen and hydrogen derivatives, from Australia to Germany, and how this partnership can be facilitated. For Australia, the consortium is led by UNSW Sydney and is funded by the Department of Foreign Affairs and Trade (DFAT) and the Department of Industry, Science, Energy and Resources (DISER). For Germany, the project is led by the German National Academy of Science and Engineering (acatech) and the Federation of German Industries (BDI).

Hydrogen can be the basis for a new wave of 'green commodities'. The promise of hydrogen as an energy carrier lies in its versatility. Hydrogen has the potential to be used as a thermal fuel (similar to natural gas) and for electricity generation using modified gas plants or hydrogen fuel cells (**Figure A**). However, it can do far more, including through its conversion to a range of derivative fuels and feedstocks. Hydrogen already plays a key role industrial role in the global economy. Currently, almost all of the hydrogen produced worldwide is from two key processes: coal gasification and steam methane reforming, making it responsible for over 2% of global carbon emissions, given the present absence of carbon capture and storage from this production. However, hydrogen can also be produced through electrolysis, where renewable electricity is used to split water into hydrogen and oxygen. The product of electrolysis using renewable electricity is referred to as 'green hydrogen' and is the focus of this Australia-Germany hydrogen value chain analysis.

Hydrogen's allure extends beyond energy, as hydrogen is a vital industrial feedstock for various industries. Green hydrogen has the potential to be utilised as a decarbonisation enabler for hard-to-abate industrial processes, and such applications have also underpinned interest in hydrogen as an export commodity. Sectors that can benefit from the embedding of green hydrogen include chemical supply chains, such as those involving methane, ammonia, and methanol. The steel industry is also increasingly being viewed as a potential off-taker for green hydrogen, as hydrogen can be used as a reductant to produce high purity iron (direct reduced iron). The combined use of hydrogen as a reductant and heat source (in blast furnaces) could enable widespread decarbonisation of the steel industry. In summary, green hydrogen can facilitate a potentially wide range of 'green' commodities.

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Figure A: The wide range of opportunities for hydrogen adoption.



German industries currently consume 55 TWh per annum of hydrogen. Approximately 93% of that hydrogen is sourced from fossil fuels, whilst the rest of the ~7% is sourced from chloroalkali based electrolysis processes.[1] Germany's current hydrogen consumption is tied to three main industries, namely ammonia, methanol, and petroleum refining. Germany aims to transition these industries alongside their steel and select transportation sectors towards green hydrogen, as highlighted in 'Germany's Hydrogen Strategy'. This Strategy highlights Germany's appetite for hydrogen adoption, with a planned cumulative public sector investment target of up to ~A$20 billion by 2026, to advance hydrogen technologies and deployment in Germany.[2] One of the focal points for this investment is the identification of potential hydrogen import partners, as the Strategy concludes that most of Germany's hydrogen will need to be imported, given the limited availability of local renewable energy resources, and competing demands for clean electricity. As such, the establishment of a green hydrogen import supply chain to Germany has been identified as a national focus for 'Germany's Hydrogen Strategy'. The development of international hydrogen markets can provide greater assurance and flexibility for both hydrogen importers and exporters, while facilitating wider energy transition.

This 'State of Play' report (SoP) assesses Australia's potential for major green hydrogen production and export capabilities. This is done to provide both German and Australian stakeholders with an overview of how Australia's well established and globally leading role in conventional energy exports, and world-class renewables resources, can be leveraged for the development of a new export energy value chain assisting other countries such as Germany to achieve their clean energy objectives. The report is also intended to enhance the shared understanding of industry, government and private sectors across Australia and Germany around the challenges as well as opportunities of such trade.

The hydrogen sector's State of Play continues to progress, and it is expected that this report will be updated as the HySupply feasibility study progresses. This first preliminary SoP iteration has been developed through literature investigation, supported by modelling and stakeholder consultations. The ambition is for this document to be updated and extended through collaboration with stakeholders in both Australia and Germany over the coming year, and as other workstreams in the HySupply study are progressed.

A summary of our approach and preliminary open-source tools for the development of this SoP is provided below. The approach and learnings from the first iteration of the SoP will form the basis for future Roadmapping and value chain model development exercises that will be built as part of the HySupply feasibility study over the coming year.

The backbone of this green hydrogen export value-chain is the sourcing of low-cost renewable electricity. Preliminary modelling was completed to map out the wind and solar renewable energy potential for several locations in each state and territory within Australia (refer to **section 6.2**).

Our preliminary open-source electricity generation model was used to calculate an estimated levelised cost of hydrogen for selected locations in each state and territory. This modelling provides a high-level overview of how locational factors underpin the economics of green hydrogen production in Australia. Key parameters affecting these production costs were also explored (refer to **section 6.3**).

A preliminary investigation was performed into the different options for hydrogen storage and transportation. The hydrogen carriers that were investigated in this analysis include ammonia, methanol, methane, liquid hydrogen and liquid organic hydrogen carriers (LOHCs). These carriers offer different possible pathways to store, transport and then utilise hydrogen. These vary across technology readiness, energy conversion efficiency, potential applications and infrastructure requirements. Several stakeholders have identified particular challenges in terms of providing assured low emission hydrogen derived energy. We consider their respective opportunities and challenges. Also, a multi-criteria analysis (MCA) tool was developed to provide a means for comparing these hydrogen carriers across a broad range of techno-economic criteria. The MCA will be released as a dynamic tool, to provide users with the ability to prioritise these criteria according to their particular requirements and priorities (refer to **section 6.6**).

An indicative 'example case' MCA output that has the key techno-economic parameters equally weighted was developed. The base case outputs were used to develop three potential example implementation scenarios for the export value chain from Australia to Germany. The scenarios expand on the key learnings and provide a current status of costs across the value chain (refer to **section 6.6**).

Preliminary literature modelling was performed to provide an indicative guide for the shipping costs for each implementation scenario. The foundational analysis from this chapter will form the basis for a more detailed value-chain model as a next step (refer to **section 6.5**).

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Key insights and next steps

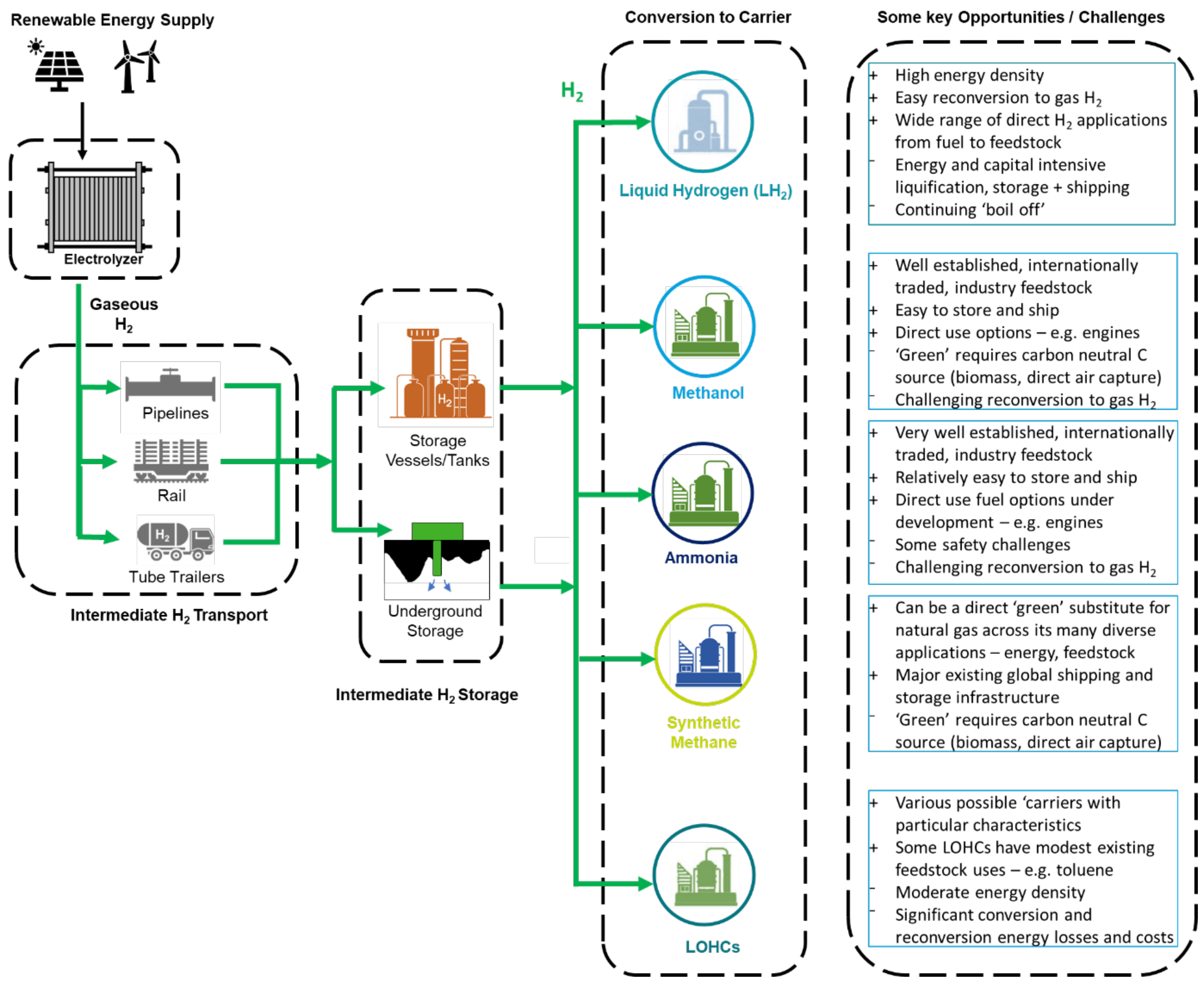
The first iteration of the HySupply Costing tool is being developed to provide users with an interactive platform to map the current levelised cost of hydrogen (LC_{H2}) across various regions in Australia. The tool currently features 41 locations across Australian states and territories, including 35 potential renewable energy zones identified by the Australian Energy Market Operator (AEMO) across the National Electricity Market (NEM) regions of Queensland, New South Wales, Victoria, South Australia and Tasmania. It also covers selected locations with high renewable potential across the Northern Territory and Western Australia. This open-source tool will be released as one of the HySupply project outputs to provide stakeholders with the opportunity to run their own project scenarios and also contribute to improving the tool's functionalities and database, to better provide holistic pre-feasibility assessments for future and downstream hydrogen projects.

Preliminary analysis from the HySupply tool estimates green hydrogen production levelised costs, LC_{H2}, to be in the range of A$3/kg to A$9/kg across Australia, as detailed in Section 6. These cost estimations are indicative (and may not necessarily be project costs experienced by stakeholders owing to a wide range of factors), given limited experience to date with larger scale production, and rapidly changing technology costs. This cost range is a result of variability in renewable resources across Australian locations, reported electrolyser capital costs (in the public domain and input from stakeholders) and renewable project-specific cost parameters. These preliminary estimates are broadly in line with other published efforts to date, as detailed later in this report. **The open-source HySupply costing tool will allow stakeholders to input their own project specific details and technology cost assumptions to make their own cost estimations.** Ongoing refinements will be made to the model as costs, and cost uncertainties evolve, which can support the development of Government and other stakeholder efforts to drive hydrogen production costs towards the Australian Government's 'stretch' target of hydrogen at A$2/kg. Mapping possible pathways to achieve these cost reductions will be drawn out in the HySupply Roadmapping phase that follows the SoP.

Multiple pathways for storing and transporting hydrogen, including a range of hydrogen derivatives are available, all presenting particular opportunities yet also challenges as outlined in Figure B. These pathways differ in terms of conversion processes (at different levels of technology readiness), ease of storage and shipping, other infrastructure requirements and application, from direct feedstock applications to strictly hydrogen carrier roles with reconversion to gaseous hydrogen at point of use.

An indicative hydrogen value chain cost profile for Australia – Germany trade was developed for the hydrogen carriers investigated in this study (Figures C-E). The target LC_{H2} of A$2/kg at the 'farm gate' was used for the development of the value chain cost profiles as this represents the Australian, and some key international, target for green hydrogen production costs over the coming decade. The indicative Australian target LC_{H2} cost was then overlayed with literature-based costs for hydrogen derivative production/liquification, localised storage and vehicular transportation to the local port, providing an indicative cost profile for the hydrogen value chain to point of export. An additional layer was overlayed onto the point-of-export hydrogen value chain to consider preliminary shipping costs (including return journey) associated with exporting the carriers from Australia to Germany, including reconversion costs.

Figure B: Opportunities and challenges for different hydrogen carriers considered.



It must be noted that these cost profiles are indicative. While based on a detailed literature review and preliminary stakeholder consultations, there are still many and varied uncertainties around the respective advantages and disadvantages of these different possible pathways for exporting renewable hydrogen. Beyond technology and commercial considerations, there are remaining questions around certification, project scaling, safety, social license, shipping emissions and feedstock availability for each option (including acceptability of CO_2 feedstock for low-carbon hydrogen carrier pathway), as identified by preliminary stakeholder consultations. Considerable further work is required to better model key process steps and opportunities for cost reductions through scale and learning.

Note – Further refinement of the HySupply costing tools will be carried out with stakeholder engagement in the Roadmapping phase of the project.

Figure C: Indicative A$/kg$_{H2}$ costs for shipping different hydrogen carriers from Australia to Germany considering renewable hydrogen generation all the way to reconversion costs at port of destination (considered here to be Port of Rotterdam).† These costs provide a qualitative comparison of the various economic considerations underlying different Australian-German hydrogen value chains for delivering hydrogen. **Note:** that we assume a (gaseous) hydrogen production cost of A$2/kg. Bilateral stakeholder engagement through the Roadmapping Phase of the Study will further refine project assumptions and refine the value chain costs. A high error bar is estimated for renewable methanol owing to challenges associated with source of CO_2, capture costs and transport to carrier conversion site. For this analysis, a CO_2 capture cost range from A$78-445/ton of CO_2 is considered. Note also that there are a range of possible LOHCs under consideration, and that their technology status is less mature than these other pathways.

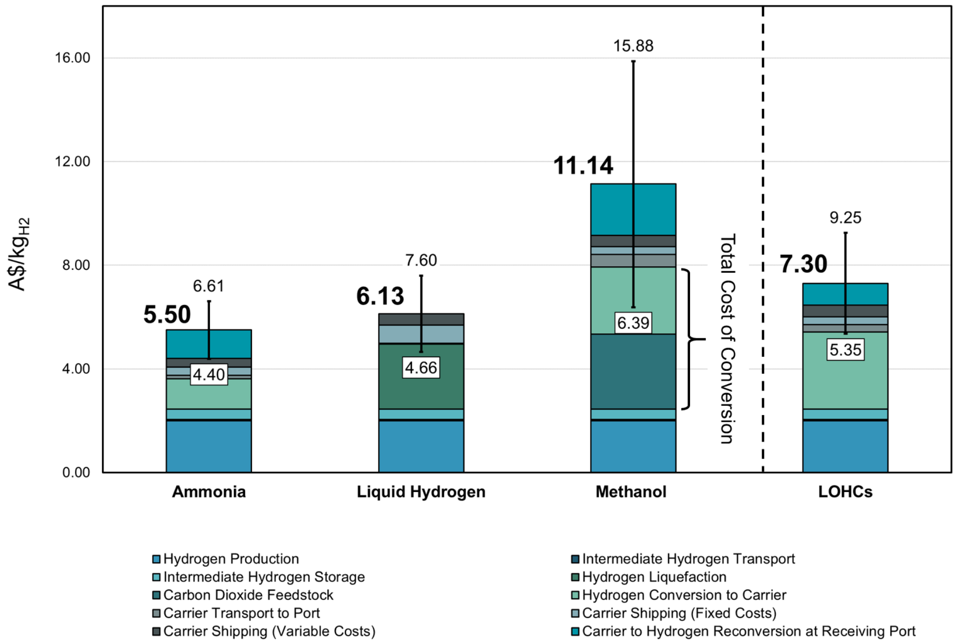


Figure D: Indicative cost estimates for shipping different hydrogen carriers from Australia to Germany in terms of A$/kg$_{Carrier}$. We do not include reconversion costs as the following hydrogen carriers can be directly used for decarbonising German chemical industries, where direct substitution of fossil fuel derived counterparts are possible. **Note:** that these costs are also indicative and assume a hydrogen production cost of A$2/kg. Bilateral stakeholder engagement through the Roadmapping Phase of the Study will further refine these value chain costs.

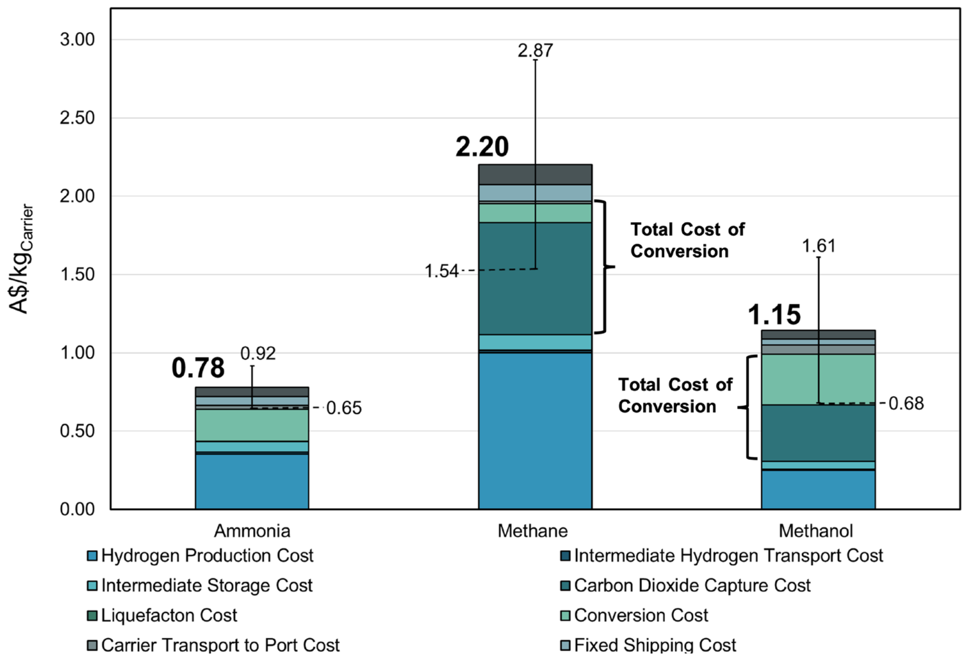
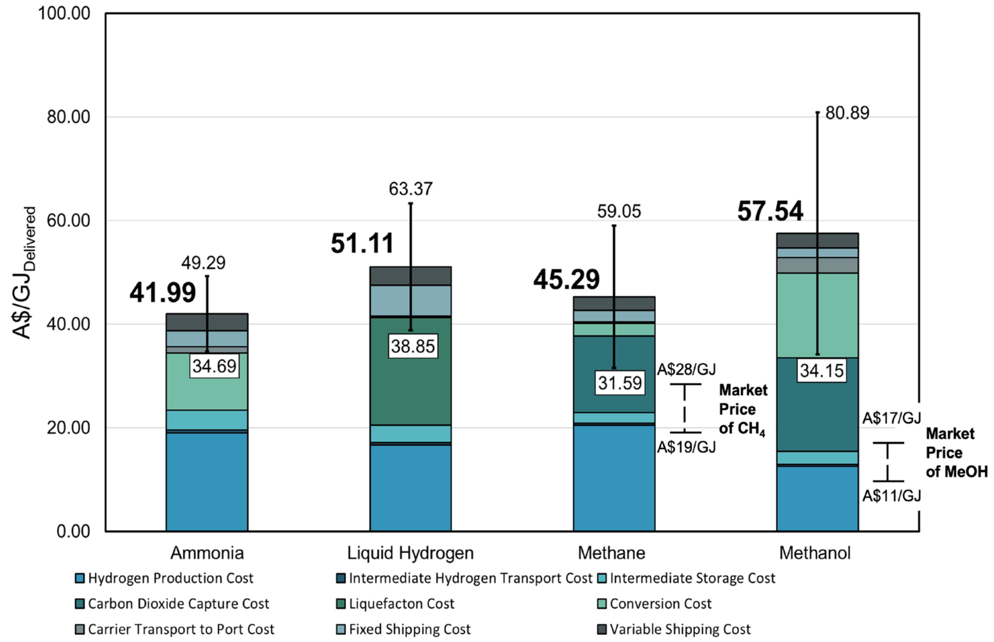


Figure E: Indicative costs for shipping different hydrogen carriers from Australia to Germany in terms of A$/GJ of energy delivered, again assuming a hydrogen production cost of A$2/kg.† All of these hydrogen forms can be used directly as fuels, although ammonia combustion technologies are less developed than the others. Bilateral stakeholder engagement through the Roadmapping Phase of the Study will further refine these value chain costs. The current retail market price range in A$/GJ (based on global export markets) of the established carriers i.e., ammonia, methane (LNG) and methanol are provided for reference (the range was based on average spot price with a + 20% assumed to represent the maximum and minimum costs).[3–5]



While these initial costings are only indicative, they do offer a basis for evaluating the possible cost profiles of different hydrogen export carriers shipped from Australia to Germany according to their envisaged use. These costs are broken down across production, intermediate storage and transport, conversion (including CO_2 capture for input into methanol and methane production), international transport (broken down into fixed and distance dependent costs including return journey) and potential reconversion. Preliminary reconversion costs to gaseous hydrogen are considered in **Figure C** to represent the cost of hydrogen carrier normalised against the weight of hydrogen delivered, providing an indicative benchmark to compare the carriers, in terms of delivered hydrogen. The Roadmapping phase will be used to better assess the likely German market demand for different hydrogen carriers over the coming decade. Based on the outcomes of that exercise, the analysis surrounding re-conversion will be investigated in greater detail. **Figure D** provides a cost comparison for the hydrogen carriers as a unit of carrier exported given the potential direct use of ammonia, methane and methanol, allowing immediate decarbonisation benefits for German off-takers. **Figure E** represents the cost profile for exporting energy in the form of each carrier from Australia to Germany given

† **Note** – In **Figures C–E**, the value chain boundary includes generation of hydrogen (assumed to be A$2/kg), intermediate storage/transport costs for conversion to hydrogen carrier, conversion of renewable hydrogen to different carriers (L_{H2}, methanol, methane, ammonia and LOHCs), transport of different carriers to port for export (assuming a distance of 100 km where methanol and LOHC is transported via road, liquified hydrogen via rail and ammonia and methane using pipeline), shipping costs (fixed and variable including return of carriers back to port at a distance of ~20,550 km, which is the median distance for Australian ports to Port of Rotterdam) and potential reconversion back to hydrogen at port of destination (considered to be Port of Rotterdam). At this stage we do not include onloading, offloading or any intermediate storage costs prior to shipping. We use current shipping fuel costs – the additional costs of clean fuels (quite possibly using the hydrogen carrier itself to power the ships, will be explored further in later work. The dashed black line is used to separate LOHCs as the hydrogen carrier is an intermediate, for which an existing market in Germany is yet to be developed. The total cost of conversion to methanol and methane potentially includes the cost of carbon dioxide feedstock (which is based on CO_2 capture from various point sources as indicated in **Table 9** ranging from A$78-445/ton). The market price of each carrier/product is based on current wholesale export prices and have been provided for context. The individual assumptions to evaluate the costs for each stage of the value chain are elaborated in Section 6 and summarised in **Figure 14** and **Table 16**. Note that each individual components of the value chain have upper and lower bounds and for representation, average values are considered. **These costs and our costing models will be further refined through the Roadmapping Phase of the HySupply Project.**

opportunities for direct energy delivery from the different carriers - a key metric when evaluating the import of low-carbon energy. **A key finding from these value chain costing estimates is that variable shipping costs between Australia and Germany are a modest component of the total cost.**

While these potential hydrogen value chain cost estimations are a key consideration, there are of course numerous other factors that need to be considered when evaluating the most suitable pathway for exporting a hydrogen carrier from Australia to Germany. Given present uncertainties, including the forms of hydrogen preferred by German industrial users, an open-source Multi-Criteria Analysis (MCA) tool has been developed to better illustrate the different technology, infrastructure and commercial status and attractiveness of these different pathways for transporting renewable hydrogen from Australia to Germany.

The key comparative metrics used for this assessment include technology readiness, financial metrics (capital expenditure required for the infrastructure and operational expenditure), transportation metrics (cost to transport, yield loss etc.) and potential decarbonisation benefit. The analysis suggests ammonia have particular strengths for early implementation given i) the technology readiness of key process steps, ii) the ability to utilise existing infrastructure for storage and shipping and iii) existing markets. Methanol represents another export pathway utilising mostly mature technologies for storage and transport, albeit subject to specific off-taker demands and, particularly, questions around sourcing of low carbon, ideally carbon neutral, CO_2 feedstocks for 'green' methanol production that can scale, and are acceptable to German industrial purchasers. Liquid hydrogen, LOHCs and, potentially, solid-state metal hydrides are promising albeit still emerging pathways. These pathways are widely expected to play a key role in a future of emission-free H_2 transport value chain and consequent international hydrogen market. These will be explored in far greater detail during the Roadmapping phase of the project.

The preliminary analysis and findings from this State of Play report are a key input to the Roadmapping phase of the HySupply project, which will further assess the hydrogen value chain with a specific emphasis on technological, commercial, infrastructure, regulatory, policy and workforce drivers and capabilities across Australia. The key barriers and gaps in the hydrogen value chain, identified through initial consultations in preparing this report (**Section 7**) will be investigated further with a wide range of both Australian and German stakeholders, to identify possible next steps for progressing a hydrogen value chain between the two countries. The next steps will target present technical, regulatory, safety and logistical barriers across the value chain, while identifying key opportunities for early staged development of the Australia-Germany hydrogen export value chain.

In summary, this State of Play report presents Australia's rapidly growing credentials as a potential global hydrogen exporter, setting the scene for further work to progress this opportunity for Australia and Germany to partner in developing global clean hydrogen/hydrogen-derivative trade. While there is much to be optimistic about, there is much more still to be done.

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Contents

List of Figures

List of Tables

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

List of Abbreviations

ACT	Australian Capital Territories
AE	Alkaline Electrolyser
AEMO	Australian Energy Market Operator
AHC	Australian Hydrogen Council
AHK	German – Australian Chamber of Industry and Commerce
ANU	Australian National University
ARENA	Australian Renewable Energy Agency
ASU	Air Separation Unit
BDI	Federation of German Industries
CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CEFC	Clean Energy Finance Corporation
CertifHy	EU Hydrogen Guarantee of Origin Certification Scheme
COAG	Council of Australian Governments
CH_4	Methane
CH_3OH	Methanol
CO_2	Carbon Dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAC	Direct Air Capture of Carbon Dioxide
DBT	Dibenzyl Toluene
DFAT	Department of Foreign Affairs and Trade
DISER	Department of Industry, Science, Energy and Resources
DME	Dimethyl Ether
EU	European Union
FEED	Front-End Engineering Design
FID	Final Investment Decision
FDI	Foreign Direct Investment
GDP	Gross Domestic Product
GH_2/CGH_2	Compressed Gaseous Hydrogen
H_2	Hydrogen
HySupply	German-Australian Supply Chain Feasibility Study of Hydrogen produced from Renewables
HyResource	CSIRO led collaborative knowledge sharing resource platform supporting the development of Australia's hydrogen industry
HEFT	Hydrogen Economic Fairways Tool
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPCEI	Important Project of Common European Interest
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy

IRENA	International Renewable Energy Agency
ISP	AEMO's Integrated System Plan
LC_{H2}	Levelised Cost of Hydrogen
LCOE	Levelised Cost of Electricity
LH_2/LH2	Liquified Hydrogen
LOHCs	Liquid Organic Hydrogen Carriers
LNG	Liquified Natural Gas
MCA	Multi-Criteria Analysis
MoU	Memorandum of Understanding
NAP	Naphthalene
NEM	National Electricity Market
NERA	National Energy Resource Australia
NHR	National Hydrogen Roadmap
NH_3	Ammonia
NPV	Net Present Value
NSW	New South Wales
NT	Northern Territory
OECD	Organisation for Economic Co-operation and Development
O&M	Operation and Maintenance Expenses
OPEX	Operating Expenditures
PEM	Polymer Exchange Membrane Electrolyser
PtX	Power to X Technologies
R&D	Research and Development
Solar PV	Solar Photovoltaics
TOL	Toluene
TRL	Technology Readiness Level
QLD/Qld	Queensland
REZs	Renewable Energy Zones
SA	South Australia
SoP	State of Play Report
TAS/Tas	Tasmania
UNSW	The University of New South Wales
VIC/Vic	Victoria
WA	Western Australia
WACC	Weighted Average Capital Cost
WP	Work Plan

List of Units

Power

kW	kilo Watt
MW	Mega Watt (1,000 kW)
GW	Giga Watt (1,000 MW)
TW	Tera Watt (1,000 GW)
kJ	kilo Joules
MJ	Mega Joules (1,000 KJ)
GJ	Giga Joules (1,000 MJ)

Energy

kWh	kilowatt hour
MWh	Megawatt hour (1,000 kWh)
GWh	Gigawatt hour (1,000 MWh)
TWh	Terawatt hour (1,000 GWh)
PWh	Petawatt hour (1,000 TWh)

Mass

kg	kilograms
t	tonnes (1,000 kg)
kt	kilo tonnes (1,000 t)
Mt	Mega tonnes (1,000 kt)
ktpa	kilo tonnes per annum
Mtpa	Mega tonnes per annum

Volume

L	Litres

Currency

A$	Australian Dollar
US$	United States Dollar
€	Euro

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

1. Why Hydrogen

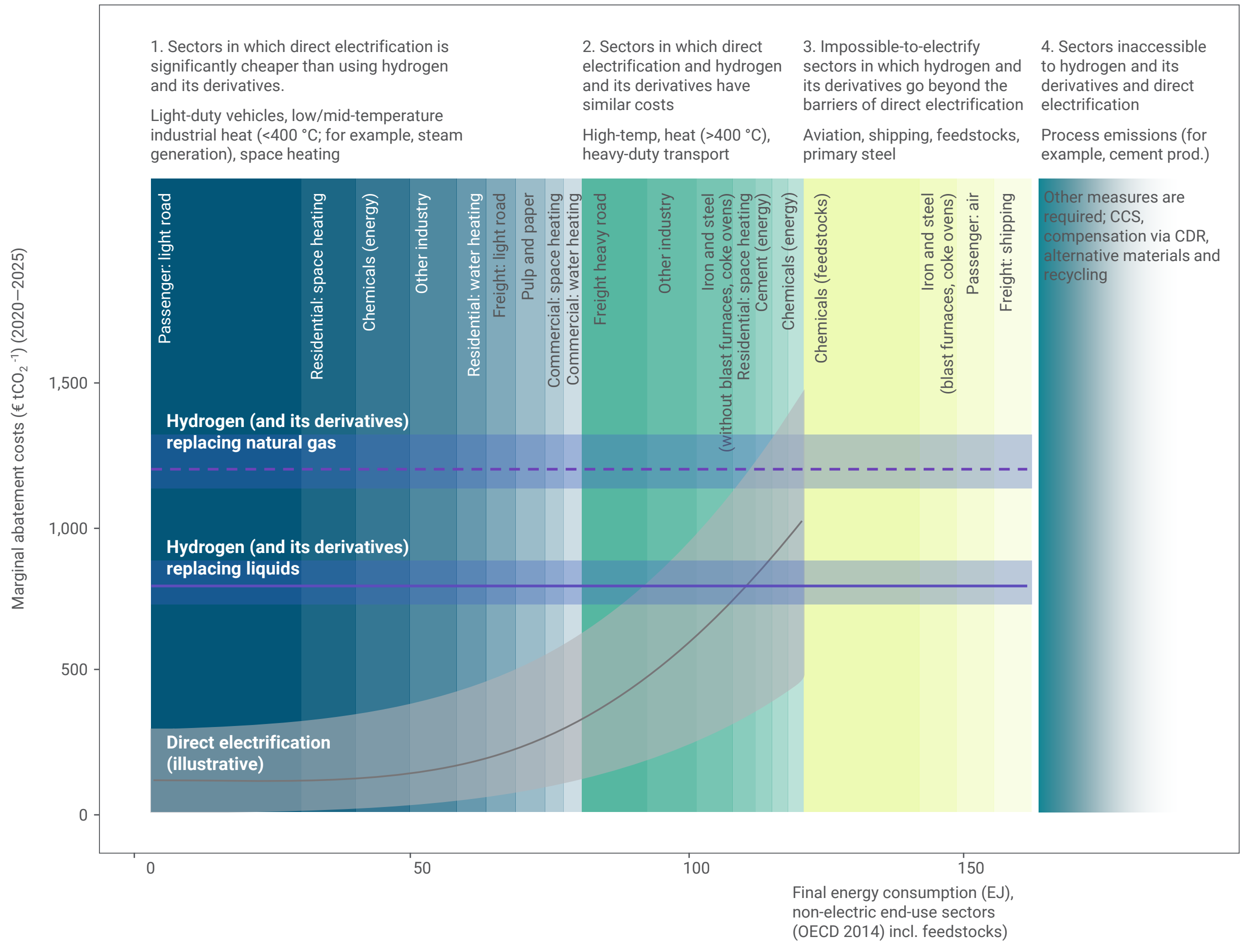
Introducing the role hydrogen can play in the global transition to a net-zero future

1.1. A key contributor to global energy transition to attain net zero emissions.

The Intergovernmental Panel on Climate Change (IPCC) has found that keeping the global temperature rise below 1.5°C, a pledged goal of the Paris agreement, likely requires reaching net zero carbon emission globally by 2050, with deep reductions of other greenhouse gases.[6] There are growing global efforts to enact net zero targets, with 61% of global emissions, 68% of global GDP and 56% of the world's population now covered by national net zero pledges, across some 124 countries and 73 states and regions. Furthermore, 417 of the top 2,000 largest publicly traded companies have also made some form of net zero commitment.[7]
The European Union (EU) has a 2050 net zero target, and Germany has recently announced a 2045 target, five years earlier than its previous goals.[8]

The first and key step for decarbonisation is a massive shift to clean electricity (**Figure 1**), provided primarily from renewable generation, to supply not only current uses but also key, presently non-electrified, sectors including road transport and building heating.* This could see electricity go from providing its present 20% of global final energy demand towards 70%, while also offering greatly improved energy efficiency for most applications.[9] However, direct electrification seems likely to be impossible or uneconomic for some sectors. Hydrogen can play a key role in some of these, including green steel and long-distance transportation, either through direct use or via conversion into derived powerfuels including ammonia and synfuels.[9]

Figure 1: Opportunities for hydrogen and hydrogen derivatives to decarbonise the global economy.*



*** Source:** Potential and risks of hydrogen-based e-fuels in climate change mitigation. Nature Climate Change (2021), Volume 11, Page 384-393.

At present, around 6% of natural gas and 2% of coal production is converted to around 115 Mt of hydrogen each year (70 Mt as pure H_2 and the remaining 45 Mt as a mixture with other gases e.g. syngas), primarily for use in oil refining and fertiliser production.[10] Fertiliser production remains essential, while hydrogen is a leading contender for supplying some other key sectors, and a possible option in others. Despite these uncertainties regarding the shape of clean energy transition and the role of hydrogen, it is notable that more recent global energy scenarios generally foresee a greater role for hydrogen, perhaps contributing to around 15-24% of final energy demand in 2050.[11–13]

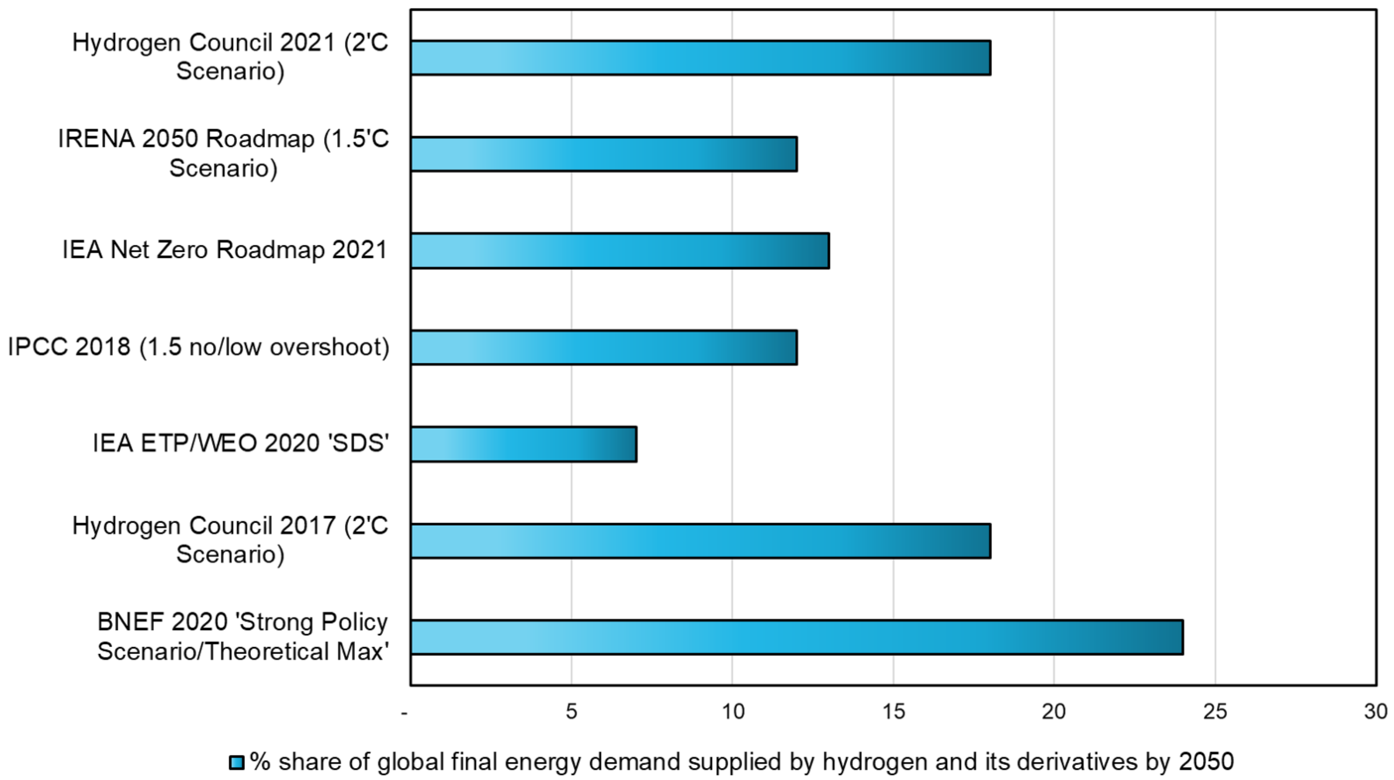
It is increasingly recognised that hydrogen has a key role to play in global clean energy transition (**Figure 2**). However, this hydrogen can and must be generated via a low, and eventually zero, carbon pathway.[14] Current hydrogen production is responsible for around ~2% of global greenhouse emissions, accounting for ~800 Mt of CO_2 emissions.[10,15] In the longer term, zero emission green hydrogen from electrolysers driven by renewable derived electricity will play an increasing role in energy supply as the cost of production becomes competitive with present higher emission alternatives. Fortunately, the present higher costs of green hydrogen are falling, and promise to fall further, with the falling costs of renewable electricity from wind and solar generation and improved and lower cost electrolysers, amongst other factors.

As the International Energy Agency (IEA) notes, "…for projects with low cost financing that tap high quality resources, solar PV is now the cheapest source of electricity in history".[16] However, they also note that flexibility and reliability needs for the electricity sector, and hence increasingly other energy sectors, will also grow as variable renewable penetrations continue to grow.

Challenges for Renewable H_2

For green hydrogen, taking highly variable and somewhat unpredictable wind and solar generation and converting ephemeral electrons into a stable chemical energy form, offers considerable advantages. However, there are inherent inefficiencies and losses associated with hydrogen production that mean it will always be more expensive than the underlying energy source used to produce it. Many existing fossil-fuels based energy conversions are also highly inefficient, so this is not a fundamental barrier, but it does necessitate expanded primary energy supply, along with the associated infrastructure and costs this entails.

Figure 2: Estimated % Share of Energy Supplied Globally by Hydrogen in 2050.



The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Certainly, hydrogen will have to compete against existing energy systems and particularly, given the need for low-carbon transition, other clean energy options. This is a particular issue for applications that can directly use electricity and only require modest energy storage, including short-distance mobility and low temperature heat. Hydrogen's future may be more focussed on sectors where electrification is impossible or non-economic. Alternatively, its flexibility may see it eventually become a near all-encompassing energy vector that fills a wide range of applications. Indeed, as a globally traded and widely used commodity, hydrogen could reshape the map of geopolitics, ending reliance on fossil fuel exporting nations and improving energy security for importers.

The flexibility of hydrogen does actually create challenges in determining its most appropriate role in energy transition.[10] A clear early opportunity is cleaning up what are presently 'grey' hydrogen roles that are aligned with long-term decarbonisation including ammonia and methanol production. There are a range of possible transitional roles with gas blending and co-firing for power generation. In the longer term, decarbonising the steel, shipping, aviation, chemical and power sectors seem certain to involve large quantities of hydrogen, although further technological and market progress will be required. Other possible roles in heating and land transport will depend on success with electrification and short-term battery energy storage.[11]

1.2. How much of a role might hydrogen play?

The International Renewable Energy Agency (IRENA) emphasises that renewables, electrification, and energy efficiency are the main pillars of the energy transition.[17] In particular, renewable electricity generation and electrification of sectors that are currently dependent on fossil fuels, including transport and low-temperature heat, can deliver both greater energy efficiency and carbon-free energy provision. Such electrification might see electricity generation expand threefold by 2050, of which 90% is provided by renewables from its present 25%. IRENA also foresee that 30% of electricity in 2050 might be dedicated to the production of green hydrogen and its derivatives including ammonia and methanol, delivering around 12% of final energy use.[18]

Other recent scenarios also see a greater role for hydrogen in 2050 including Bloomberg's central scenario which suggest hydrogen will provide 24% of final global energy demand, and the Hydrogen Council which suggest a 18% share of global final energy demand.[13,14]

The International Energy Agency (IEA) in their roadmap to achieve Net Zero by 2050, projected a hydrogen and powerfuel demand of ~528 Mt, of which 62% is to be supplied using green hydrogen.[19] This would see hydrogen based fuels providing 13% of final energy demand, specifically in the form of ammonia (providing 45% of global shipping demand), synthetic fuels (providing 33% of aviation fuel) and by substituting natural gas for chemical and iron/steel production (with 10% of natural gas demand being replaced by hydrogen/synthetic methane).

Generally, hydrogen's role in clean energy transition scenarios for 2050 has been growing in more recent studies. Reasons particularly include the falling costs of wind and solar generation, as well as perhaps a growing appreciation of the challenges of high variable renewable generation integration into the electricity sector.[20]

1.3. Progress to date with clean energy transition and hydrogen

Over US$500 billion was invested globally in low-carbon energy transition in 2020, primarily across renewable energy (US$300 billion), electrification of heat (US$50 billion) and transport (US$140 billion), an increase of 9% from 2019. Of this, total investment in hydrogen projects were a mere US$1.5 billion, highlighting both the challenge and opportunity of scaling up hydrogen. European investments represented around a third of this volume, with Germany having the third highest investment after China and the US.[20] These figures do not take into account project commitments.

In Australia, the Australian Government has now committed more than A$1 billion for the development of the hydrogen sector, with the goal of achieving 'H2 under 2'. Australia was one of the first countries to publish a strategy with the release of the 2019 National Hydrogen Strategy outlining the actions needed, including regulatory reform, to support hydrogen industry growth.

The Hydrogen Council notes that there are now more than 200 hydrogen projects across the value chain, with EU leading globally in the number of announced projects with Australia, Japan, South Korea, China and the US following.[14] It is estimated that US$38 billion worth of projects has passed through either final investment decision (FID), is under construction or now operational. An additional US$45 billion is at the feasibility study or front-end engineering design (FEED) stage, while total announced investments to 2030, in order to reach national targets, and government funding pledges exceed US$260 billion.

A key question is of course what green hydrogen will cost. It is notable that cost projections and targets have been generally falling with technological progress, and particularly declining renewable generation and electrolyser costs. IRENA notes that these cost reductions will require lower-cost renewable generation, but also electrolyser cost reductions through both upscaling electrolyser design and construction, and manufacturing economies of scale.[22] Work by the HySupply team has also emphasised the role of these factors, as well as capacity factor optimisation and low risk, hence low weighted average cost of capital (WACC), finance on cost reductions.[23] These cost projections are detailed in depth in **Section 6**.

2. Why international trade in hydrogen?

The export of renewable energy using hydrogen has the potential to become the next generation of major tradable commodities.

2.1. Trade in hydrogen

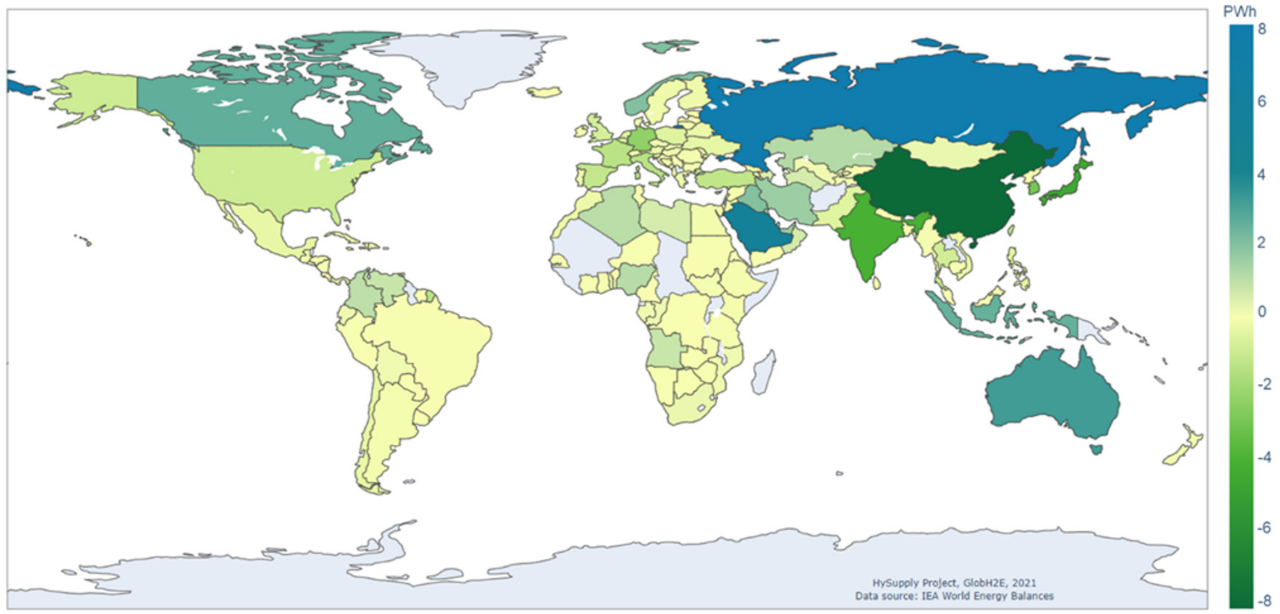
Our present fossil fuel dominated energy systems see very large imbalances between energy importers and energy exporters, an outcome of the very uneven global distribution of low-cost fossil fuel reserves **(Figure 3)**.[24,25] The world's five largest energy importers are China, India, Japan, South Korea and Germany. By comparison, the world's five largest energy exporters are Russia, Saudi Arabia, Australia, Indonesia and Canada.

Fossil fuel-based energy is the global economy's most traded group of commodities, with oil being number one and natural gas number five. A key reason for this trade is the present concentration in fossil fuel production - over 40% of global oil production, over 45% of global gas production and well over 50% of LNG exports come from three countries. As a result, we see considerable dependence on energy imports in many countries.[26]

Clean energy transition has the potential to radically transform energy trade, and energy geopolitics more generally, as 'renewable energy' is far more widely dispersed than fossil fuels. It therefore seems likely that most countries will be able to achieve greater energy independence with consequent higher energy security and wider energy choices by leveraging renewable energy resources.[27]

Some countries, however, will still likely depend on renewable energy trade to meet their energy needs. Estimating the scale of renewable energy resources available to different jurisdictions is challenging, with the need to distinguish between theoretical, technical, economic, and politically feasible potential. While the technical potential is enormous with almost all countries having sufficient resources to meet present demand, the economic and politically feasible potential is considerably lower. The potential scale of deployment is important given that clean energy transition will see a greatly expanded role for the electricity sector in all countries. Economic feasibility in an interconnected world is also linked to the relative costs of renewables between potential trading partners.

Figure 3: Net Primary Energy Exports by Country.
Note: The volume of exports is represented in Petawatt Hours (PWh), with positive value representing net exports and negative value representing net imports. **Source:** HySupply Analysis based on data provided by BP[24] and IEA.[25]



The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Recent work has highlighted a number of countries with relatively limited renewable energy potential relative to their current demand, and hence the greatest likelihood of continuing to require energy imports in a global clean energy future.[28] These include Singapore, Belgium, Germany, The Netherlands, South Korea, Taiwan, Switzerland, Japan, Poland and Italy. Notably, these reports identify Germany as a particular special case, with one estimate, the third lowest solar and wind technical potential in the world relative to its energy demand.

In terms of very high quality and major renewable energy resources, a range of studies have identified key countries for potential hydrogen exports, as outlined in **Table 1**. Possible trade patterns will depend on a range of factors beyond the quantity and costs of renewables amongst different possible exporters, including trading distances to potential importers, existing trade relationships, existing infrastructure, ease of doing business and potential wider geopolitical energy security considerations. We consider these factors for Australia further in the following **Section 4**.

HySupply has mapped out potential high-quality wind and solar resources world-wide. These findings support earlier work in highlighting that Australia is strongly positioned for high-quality wind and solar electricity production, as shown in **Figure 4**.[29]

It is possible that energy trading patterns and relationships might change only modestly given the high renewables potential of the Middle East which provides much of the world's oil and gas – existing petrostates transitioning to 'electrostates' as was recently suggested in *Foreign Policy*.[30] However, the geopolitics of energy security may well see energy importers keen to facilitate greater diversity in suppliers.

Figure 4: Theoretical wind and solar PV resource potential by country.
Note: The analysis is based on energy generation capacity in terawatt hours/year (TWh/y) of high-quality locations with potential wind and solar PV (tracking) farm capacity factors of >38% and >25% respectively). **Source:** HySupply Analysis based on data provided by Chu et al.,2020[29]

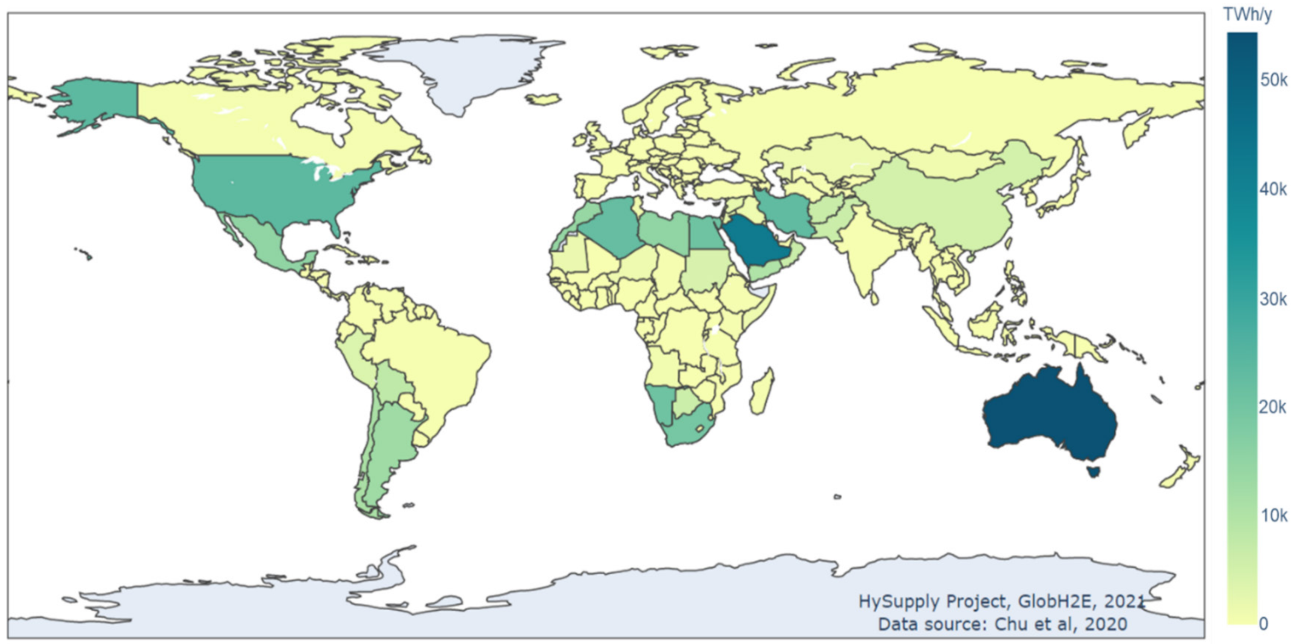


Table 1: Outlook on renewable energy producers and importers as identified in previous studies.

Study	Renewable Exporter	Renewable Importer
Harvard Belfer Centre (2020)[31]	**Australia**, Morocco, Western Sahara, Norway, United States, Canada, Mexico	North Western Europe, Korea, Japan, Southeast Asian Countries
Hydrogen Council (2021)[14]	**Australia**, China, India, Saudi Arabia, South Africa, Iran, Turkey, Norway, Spain, Portugal, US, Chile	All Southeast Asian Countries, Russia, North-western and central European States.
Wood Mackenzie (2019)[32]	**Australia**	Japan and Germany
ACIL Allen (2018)[33]	**Australia**, Middle East, North African countries, and United States.	China, Japan, Korea, Singapore
ERIA (2018)[34]	United States, North African Countries, Middle East	China, Singapore, Korea, and Japan
IEA (2018)[10]	United States, **Australia**, Africa, Middle East, Chile	Japan, Europe
IRENA (2021)[27]	Brazil, Norway, **Australia**, Chile, Sub Sahara, Middle East	Europe, China, Southeast Asia
Carbon Tracker (2021)[35]	Namibia, Botswana, Ethiopia and most of South America, Northern Africa, Middle East, **Australia**	Singapore, Belgium, Germany, Netherlands, South Korea, Taiwan, Switzerland, Japan, Poland, Italy
HySupply analysis	**Australia**, Middle East, Northern Africa, Western South America, United States	Europe.

2.2. Hydrogen: The export vector

The conversion of renewable electricity and water to hydrogen (and hydrogen carriers) presents new opportunities for a range of countries. Success will likely depend on a range of factors that includes renewable resource potentials, water availability, feedstock availability for hydrogen carriers, infrastructure, project financing, proximity to buyers, safety protocols, environmental considerations, sourcing of low-cost electrolysers and so on. We discuss these parameters and provide a state-of-play for the current hydrogen value chain from an Australian perspective in **Section 6**.

How to transport hydrogen?

Transport capabilities and costs will of course be a major determinant in the extent and regional patterns of global hydrogen trade. Transporting hydrogen by pipeline is a relatively well understood and technically mature option. Costs generally vary in a fairly linear manner with distance. The IEA (2019) estimated that pipeline is likely to be the least cost option for distances up to around 1,500 km. The Hydrogen Council (2021) suggests that pipelines might be the preferred option for distances of up to 5,000 km. While there may be some options for repurposing existing oil and natural gas pipelines, one challenge for new pipelines for transporting hydrogen, will be the large, lumpy investments and approvals associated in laying such pipelines.

Role of shipping in hydrogen trade

Shipping carries around 80% of global trade with more than 11 billion tons of cargo carried in 2019 (around 1.5 tons per person), with a total value of US$19 trillion.[36,37] Even for the EU, shipping accounts for 80% of total exports and imports by volume, and some 50% by value.[38] In 2019, just under 30% of trade was via tankers (oil, refined petroleum products and chemicals), and around 30% via bulk carriers (iron ore, grain and coal). Overall, the shipping sector transported roughly 1,800 Mt of oil, 1,500 Mt of coal, 1,500 Mt of iron ore and 370 Mt of LNG in 2019.

Shipping is the only option for some trade routes, but is potentially attractive even when competing with road and rail given its low-cost structure and flexibility. For example, there is extensive shipping-based trade in commodities with prices well under US$1,000/ton, as shown in **Figure 5**. It also typically has lower greenhouse emissions per ton km transported than road and rail, even with the generally high polluting fuels used in large shipping at present.[39-41] Several analyses have estimated that global hydrogen demand in 2050 might be in the order of 350 to 1,370 Mtpa.[11,13,15,42] International shipping trade of even 50% of this production would fall within the tonnage ranges seen already for some key commodities, although there is the question of the effective mass of hydrogen in its various derivatives to consider.

There are some uncertainties around the best form of hydrogen to transport, given not only ease of transport but also the energy losses and costs associated with conversions to hydrogen carriers, and then potentially, reconversion for end-use. For instance, compressed hydrogen has low energy density (energy content/volume) making it unsuitable for longer shipping distances. There is considerable interest and technical progress in converting hydrogen gas to liquid form for shipping. Other possible hydrogen derivatives, such as ammonia and methanol, are valuable inputs into a range of products and already see major international trade. Conversion into and then potentially out of these forms back to hydrogen also involves a range of energy losses and costs.‡ A range of potential Liquid Organic Hydrogen Carriers (LOHCs) specifically intended for transport might also be used, while other technologies may also well emerge.

Status of Hydrogen Derivatives Trade

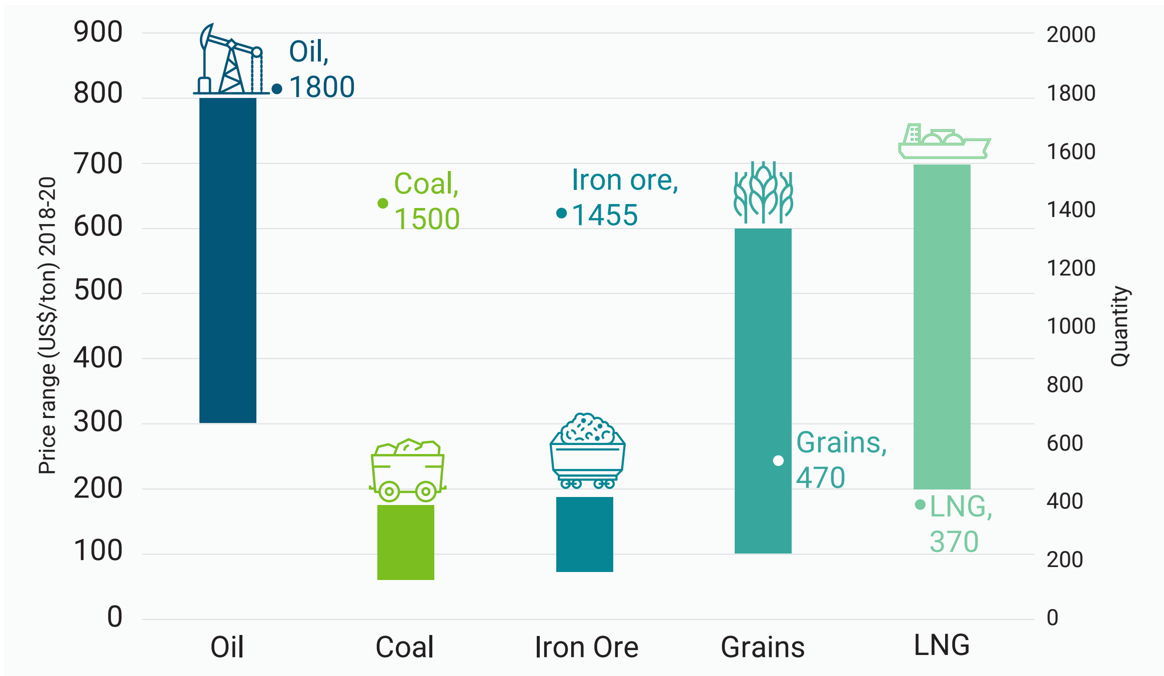
The global ammonia market has annual production of around 175 Mt/year with a US$70 billion turnover.[43] Global ammonia trade is expected to reach 19.3 million tonnes by the end of 2021, this would translate to US$6.7 billion (considering current ammonia price of ~US$350/ton).[44,45]

The global methanol market is estimated to be worth around US$32 billion annually, with a trade market of US$9.1 billion (28 million tonnes), which almost doubled in the past decade.[46] The major importers are China (8 Mtpa) and India (2.3 Mtpa) making up for 50% of the market, while Japan (1.7 Mtpa), Germany (1.4 Mtpa), Taiwan (1.3 Mtpa) and South Korea (1.8 Mtpa) make up around 30% of the global market.[46]

LOHCs include a range of potential candidates. One of the most commercial LOHC at present is toluene, which has an estimated market size between US$18.5 – 23.4 billion (2021).[47,48] The global toluene trade in 2019 was recorded to be US$2.5 billion.[49] The global market for dimethyl ether (DME), another potential LOHC, was estimated to be US$4 billion in 2020, and is expected to roughly double by 2028.[50]

Finally, there are potentially valuable synergies between hydrogen transport and the need to decarbonise global shipping which currently contributes around 2 – 3% of global carbon emissions, which if the sector was considered as a country would make it the world's sixth biggest emitter.[51,52] Estimates show that if urgent action is not taken, these emissions could increase between 50 – 250% by 2050.[53] Renewable ammonia looks particularly attractive as an alternative clean fuel for shipping. The IEA suggests that in 2050 the major use of hydrogen might be in the form of ammonia for shipping, with other hydrogen-derived powerfuels, mostly for aviation, the second major use, 44% of total end-use.[15] This creates potentially highly valuable synergies between ammonia for shipping, and transport via shipping. **Section 6** explores these carriers in more depth.

Figure 5: Shipped tonnage and average price ranges for some key traded commodities.
Note that the price indications are spot price ranges over 2018-2020 and shipped tonnages from 2019. For hydrogen trade, prices of around US$1.50 – 2.50/kg would translate to ~US$1,500-2,500/ton, representing a relatively high value commodity while traded volumes in various 2050 scenarios would likely be well below the shipped tonnage of some existing commodities.



‡ This reconversion may be avoided if the end-user of hydrogen utilises the hydrogen carrier directly for application.

3. A role for early partnerships

The establishment of renewable-sourced hydrogen supply chain is a priority for Germany in transitioning to a net-zero future.

3.1. Why is Germany a key player?

Germany is, and expects to remain, highly dependent on energy imports. However, these imports must become carbon neutral in order for the country to achieve its ambitious net-zero targets. Germany is already a major hydrogen producer and user with around 55 TWh of production in 2019, mainly for the production of ammonia and methanol.[1] Less than 10% (~7% or 3.85 TWh) of that production is currently from electrolysis.

Germany's Hydrogen Strategy (2020) includes the following goals and ambitions:

- A global role for Germany in reducing global greenhouse gas emissions by promoting hydrogen's potential contribution to decarbonisation and developing the international hydrogen market.
- Making hydrogen a competitive option by driving technological progress and economies of scale.
- Developing a strong domestic market in Germany supporting local progress but also paving the way for imports to help meet demand.
- Establishing hydrogen as an alternative for other energy sources: fuelling air and maritime transport, and industries with processes that will be difficult to electrify.
- Making green hydrogen a sustainable base material for the German industrial sector including replacing present fossil-fuel based hydrogen production.

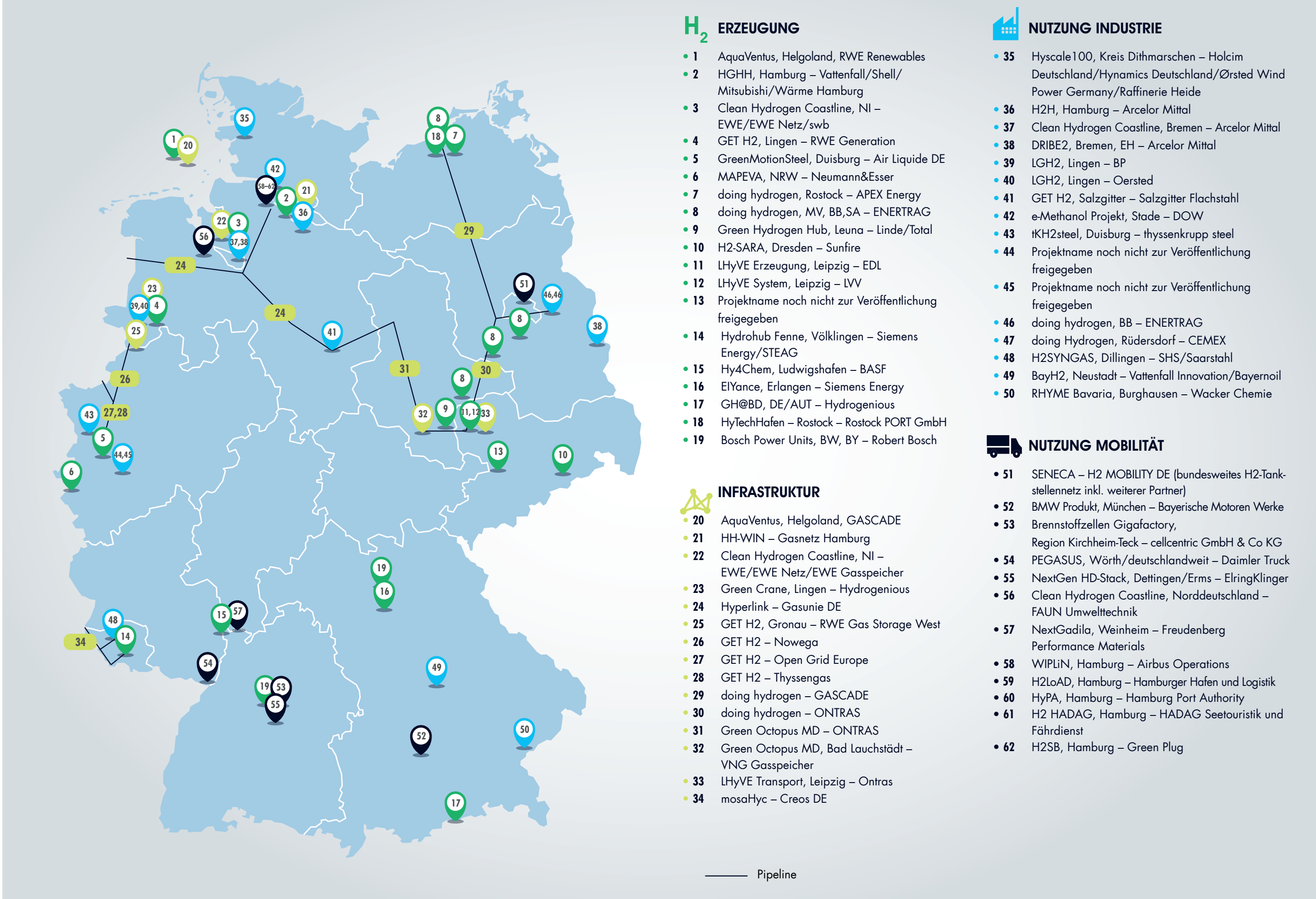
Germany envisages a near doubling in demand in 2030 to 90–110 TWh/year, with electrolyser capacity growing to 5 GW and 14 TWh/year of green hydrogen production. Given the strong interest of the German government in transitioning to net zero emissions target, it is suggested that Germany will need to import hydrogen somewhere in the range of 75–95 TWh/year by 2030 for its economy (data adapted from *HySupply Germany metastudy*).

Germany's goals of international hydrogen cooperation include establishing bilateral hydrogen partnerships and large-scale production in countries where:

- green hydrogen can be produced efficiently and sustainably at scale,
- its import to Germany is both technically feasible and economically viable, and supports diversification of Germany's energy supply,
- a stable and supportive political and business environment supports the long-term investments required,
- there are the skilled workforce and key infrastructure capabilities required to deliver these projects are present,
- the country is also undertaking clean energy transition through renewables.

More generally, Germany has an interest in the fastest possible establishment of a global hydrogen market which will not only support swift technological progress and create new trade relations, but also facilitate a further diversification of energy sources and transport routes.

Figure 6: The 62 large-scale hydrogen projects shortlisted in Germany for potential state investment. Note that these projects are state-funded as part of a joint European hydrogen project entitled IPCEI (Important Project of Common European Interest).[54]



3.2. Why Australia and Germany?

Australia and Germany are natural partners in an energy-export value chain. Australia's renewable energy resources, energy export credentials (outlined in **Section 4**) and ability to deliver mega-scale energy projects makes it a well-placed contender to export renewable hydrogen to buyers such as Germany. Germany's strong net zero commitments and expertise in clean energy technology make an ideal fit to import renewable hydrogen and co-develop Australia's hydrogen infrastructure and manufacturing capability. The governments of both countries were early movers in the development of hydrogen strategies with Australia being the 4th country to release its national hydrogen strategy (in 2019), and Germany the 7th (in 2020).

Germany's hydrogen import demand

In 2030, Germany's projected hydrogen demand is expected to be below 80 TWh. This is forecasted to rise to 400–800 TWh by 2050. Current analysis predicts that Germany's future hydrogen demand (i.e. renewable hydrogen) will be partially met by domestic hydrogen production, with local capacity estimated to be 5 GW in 2030 and increasing to 63 GW by 2050. This shortfall, i.e., 53–80% of hydrogen demand and 79–100% of PtX demand is expected to be imported as highlighted in the German HySupply metastudy report. More details on Germany's projected hydrogen demand and supporting projects (**Figure 6**) are detailed in depth in the German HySupply metastudy report.

Australia and Germany's current trade relationship

Australia and Germany are closely linked with almost 1 million Australian residents of German descent. Germany is Australia's eleventh largest trading partner with two-way trade totalling over A$17.7 billion in 2019-20.[55] Germany is Australia's fourth largest source of imports, notably vehicles and pharmaceutical products whereas the major exports to Germany are precious metals. The two countries are engaged in major services trade and investment amounting to A$150 billion, with German foreign direct investment (FDI) investment to Australia being A$49 billion in 2019 and Australian investment into Germany being A$97.1 billion.[55]

There are around 400 German companies operating in Australia employing more than 56,000 people, in areas including advanced manufacturing, logistics and transport, banking, materials and clean energy. Meanwhile, ~150 Australian companies have a presence in Germany employing around 17,000 people, including in the areas of infrastructure, finance, and energy. Moreover, there are more than 500 partnerships and cooperation agreements between Australian and German research institutions.

Australia and Germany also enjoy significant co-operation in the hydrogen space. In addition to HySupply, the two countries are working together through the Australian Hydrogen Council (AHC), German-Australian Chamber of Industry & Commerce (AHK) as well as through the German-Australian Hydrogen Alliance. HySupply members RWE and The Hydrogen Utility Pty Ltd (H2U™) signed a Memorandum of Understanding (MoU) to explore viability of a hydrogen supply chain from South Australia to Brunsbüttel in Germany. German electrolyser and equipment providers are also very active in Australian demonstration projects. Very recently, Australia and Germany have signed The Australia-Germany Hydrogen Accord, emphasising strategic and close partnership and determination to work together through enhanced bilateral and multilateral cooperation.[56]

4. An Australian Leadership Opportunity

Australia is blessed with extensive energy resources.

Australia is well placed to be the world's 12th largest economy in 2021, while being home to just 0.3% of the global population. At present, Australia's key economic competency comes from its vast energy and mineral resources. The production of these resources greatly exceed local demand, making Australia a major exporter of uranium, iron ore, natural gas and coal.[57] Australia's energy exports amount to ~2.4% of global energy supply with coal and LNG being the largest contributors to this export value chain.[58]

Australia is also blessed with vast renewable energy generation potential, estimated to be ~400 times higher than the country's current energy demand (elaborated in **Section 4.3**).[28] Over the last year, Australia's renewable energy production increased by 7 GW (by 23.2%), marking the highest growth rate of renewable capacity in the world‡,[59,60] The growth has been propelled by solar PV deployment, positioning the country as one of the world's market leader in solar adoption (ranked 7th in terms of installed capacity – 17 GW) in the world.[61]

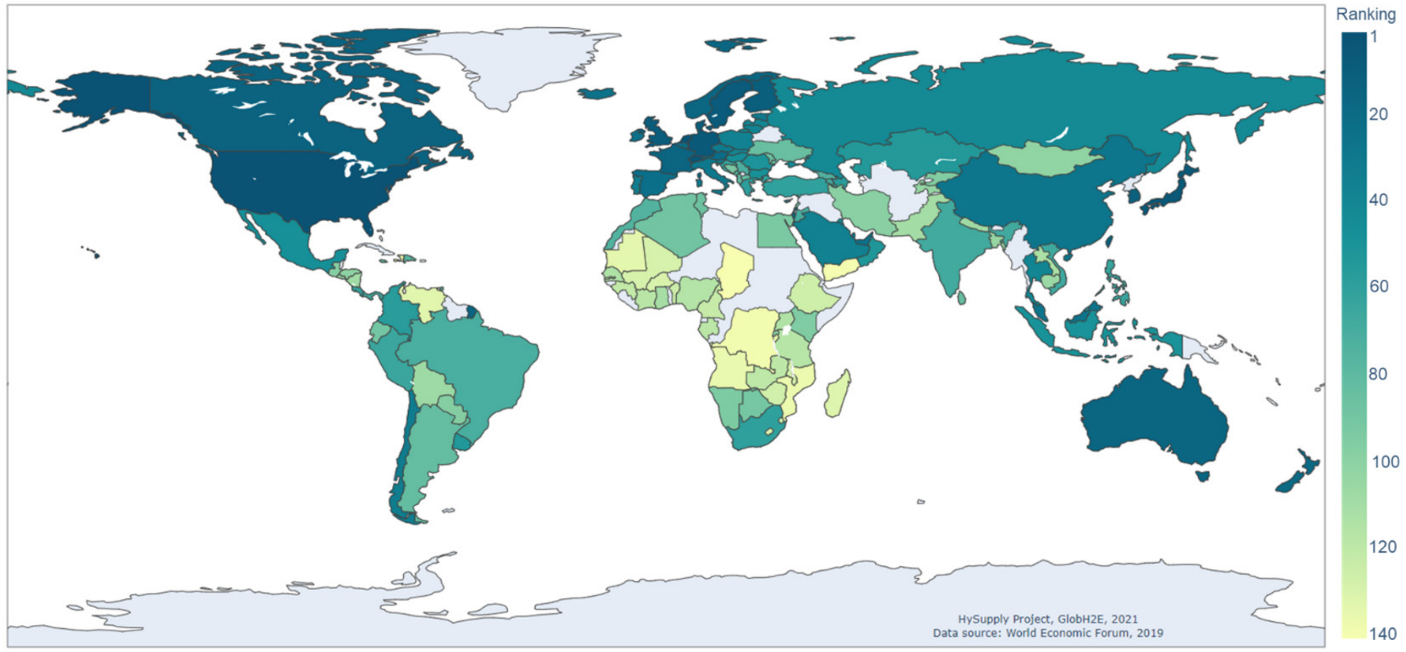
Renewable energy penetration, as a proportion of total generation in 2020, averaged as 27.7% with Tasmania leading at 99.2%, followed by South Australia (59.7%), Victoria (27.7%), Western Australia (24.2%), New South Wales (21%) and Queensland (16.65).[62] Australia is a world leader in the uptake of solar, with one in four Australian homes having a solar PV system.[63] Australia was ranked 6th amongst 40 of the world's largest economies on the EY Renewable Energy Country Attractiveness Index.[64] All together these factors have resulted in global recognition of Australia as both a present but also potential future global energy super hub. This growth in renewables along with the rapidly decreasing costs of renewable energy generation are opening avenues for Australia to emerge as a potential exporter for renewable energy, more specifically hydrogen.[65]

The country also enjoys a high level of political and economic stability, creating a conducive environment for business. Australia is ranked 14th in the World Bank Ease of Doing Business in 2020 (5th in terms of ease of doing business when compared to economies with a population more than 20 million).[66] Favourable Federal and State government policies allow the country to enjoy high levels of foreign investments, attracting A$4 trillion in total investment up to 2020.[67] Particularly, direct foreign investments (FDI) have grown at a rate of 5.6% per year (over the last 5 years) reaching A$1 trillion in 2020, of which a third (~35.1%) went to the energy and mineral industry.[68] This has enabled the development of strong energy trade collaborations, with energy export (coal, natural gas and crude oil) accounting for a combined 20% of the A$436 billion worth exports of Australian goods and services in 2020.[69]

Key to these export collaborations has been Australia's geo-political position, which makes it a key stakeholder in regional socio-economic activities and politics. Overall, Australia ranks 16th in the World Economic Forum's global competitiveness rankings, as shown in **Figure 7**.[70]

‡ The statistics are based on IRENA's "Renewable Capacity Statistics 2021" report.[59] Herein, the renewable energy capacity is represented as a cumulative of solar (PV and CST), wind (onshore and offshore), hydro (hydro power, pumped hydro and marine – wave energy), bioenergy (biomass and biofuels) and geothermal energy capacity.

Figure 7: Australia's global competitiveness.
Source: HySupply Analysis based on ranking established by World Economic Forum.[70]



4.1. Export Credentials

Australia is a globalised economy that is deeply integrated in the international trade in minerals, fossil fuels, agriculture, manufactured products, with a two-way trade amounting to A$873 billion in 2019-2020.[71] Of this, almost two-third of the trade is carried out with Australia's Asia-Pacific partners, followed by EU and US accounting for 14% and 9%, respectively.

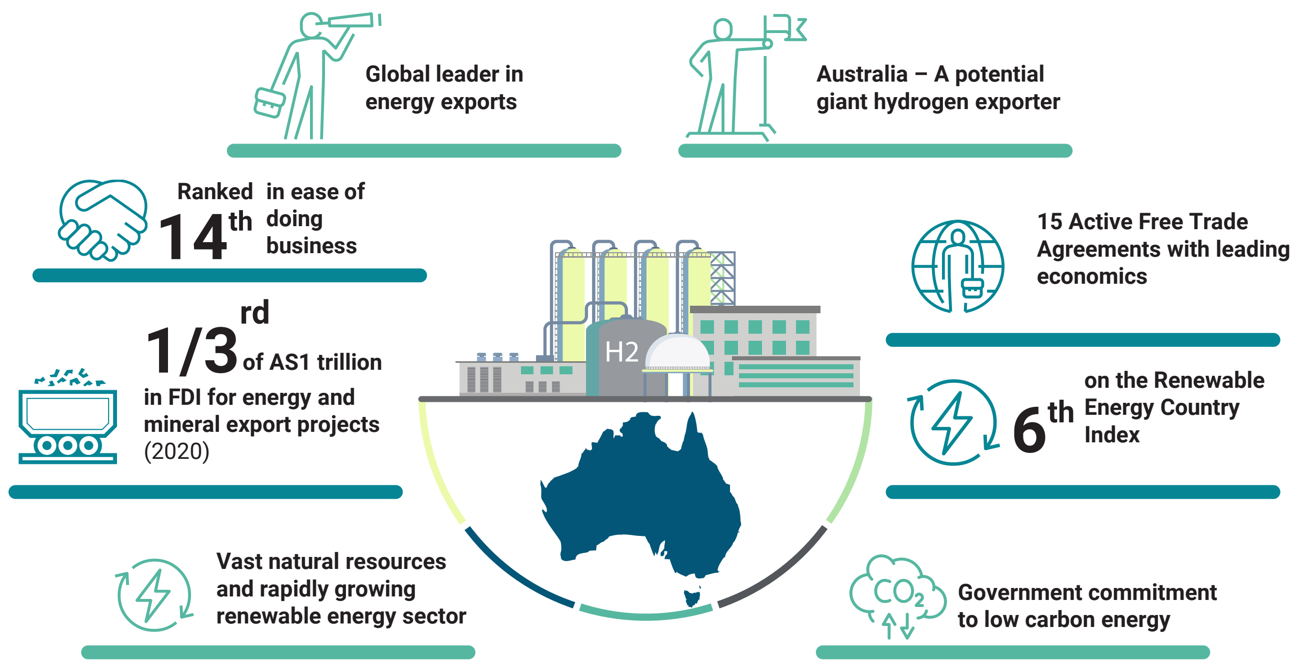
Australia leads international exports in LNG, iron ore and coal. Australia ranks first in both global iron ore reserves and their export, in 2019-2020, Australia exported iron ore worth A$102 billion (21.6% of total exports).[71] Similarly, Australia is amongst the top 5 global exporters of coal with exports amounting to A$54 billion between 2019-2020 (11.5% of total exports).[71] In 2019, Australia became the world's largest LNG exporter, overtaking Qatar by shipping 77.9 million tonnes of LNG per year, worth A$49 billion (~10% of total exports).[72]

The country's well-established supply chain and experience in energy export is linked to the country's infrastructure, ability to ramp up and up-scale projects, adapt to new technology and low costs of doing business. The country is considered to be one of the easiest places in the world to do business, ranking 14th overall and 6th for enforcing contracts and is ranked 1st for technological readiness.[73,74]

Moreover, the country enjoys ease of access to the greater Asia-Pacific Region, an emerging economic zone and energy-hungry region that already relies on Australia's energy and mineral exports. Globally, Australia has 15 Free Trade Agreements (with most agreements with Asia-Pacific countries plus the United States and China) with a further 5 agreements being negotiated (including the United Kingdom, India and the EU).[75] Altogether these credentials, (**Figure 8**) can, if effectively leveraged, strengthen Australia's potential role as a global pioneer in exporting hydrogen.

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Figure 8: Australia's credentials for becoming a hydrogen leader and exporter.



4.2. Infrastructure Capability

Australia enjoys a relatively strong infrastructure network, built on the foundation of planning, financing and delivery of major projects over the past few decades.[76] On average, Australia's infrastructure investment has grown at 30% per annum from 2016 and ranks 2nd for transport infrastructure spending on a per-capita basis amongst OECD countries.[77] As a result, Australia benefits from a strong freight and road transportation connectivity and port infrastructure. Australia has more than 823,000 km of road infrastructure in place (of which 356,000 km is paved), which makes it the world's ninth largest road network.[78,79] Similarly, the Australian rail network, that is used for heavy freight operations, is spread across ~33,000 km, connecting all major cities, industrial hubs and ports across the country.[81] Australia also has several high capacity ports (12 trading regions) spread across the country, as well as access to well-established trade routes that are resulting in a steady growth of exports.[81] Many of these ports are already equipped with infrastructure to support energy export in the form of LNG and coal. From 2016 till 2026, Australia's freight task by tonnage is expected to grow by 26%, focusing on the movement of bulk commodities for export, such as LNG, coal, and iron ore.[76] The Australia Government has committed to invest A$110 billion over the next decade to grow Australia's transport infrastructure.[82]

4.3. Renewables Potential

Australia's renewable energy resources is widely recognised, with several studies suggesting that the potential far exceeds Australia's current and future needs (**Table 2**). Overall, renewable energy has reached a market share of ~28% of current electricity production over the last fiscal year (FY2020-21) (**Table 3**).[62] This share has been growing at a rate of 10% over the last decade (2000 – 2019) and with a record 16.5% in growth recorded in 2020.[83,84]

In 2020, 7 GW of renewable generation capacity was commissioned,[85] and at the end of 2020, 76 additional large-scale solar and wind farms with a combined capacity of 8 GW were under construction across Australia.[62] Globally, Australia already is in the top 10 of countries with respect to per-capita wind energy generation, and the top 3 countries for per-capita PV generation, as shown in **Figure 9**.

Recently, the Australian Energy Market Operator (AEMO) has announced a 2025 target of having the capability of 100% instantaneous renewable power penetration in the Australian grid. It has laid out an action plan, as part of the Renewable Integration Study, intended to foster market and regulatory reform to unlock the full potential of current capabilities. These developments could see Australia becoming a world leader in renewable energy generation, with 27 GW of wind and solar capacity by 2025.[86]

The Australian Government has a formal target under the Paris Agreement to reduce its emissions by 26 to 28% below 2005 levels by 2030 (Australia's 2030 Emissions Reduction Target). The Government expects to invest around A$20 billion in low emissions technologies in the decade to 2030, to leverage more than A$80 billion from the private sector. The Australian Government has committed over A$1 billion invested into the hydrogen sector to date, and more investment is expected to come. Recent commitments include A$314 million support for up to 5 hydrogen hubs.[87]

Figure 9: Per capita solar and wind energy production for different countries
Source: HySupply analysis based on data provided by IEA.[25]

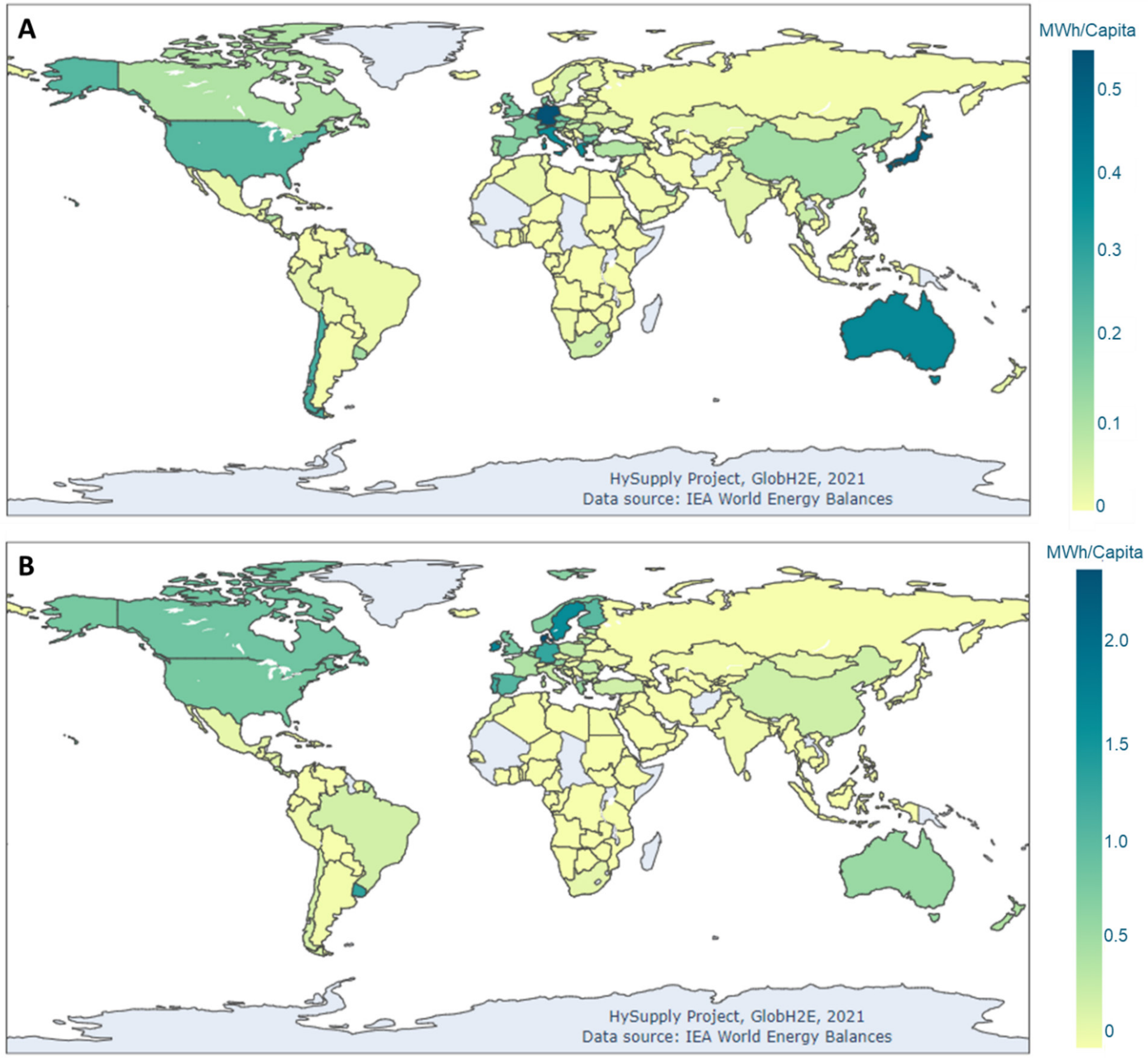


Table 2: Possible high wind and solar scenarios for Australia and total resource potential based on published studies.

Resource	Potential Installation Capacity (GW)					Potential Recoverable Energy (TWh/year)		
Source	**UTS: ISF[a]** (2016)[88]	**Blakers et al.** (2017)[89]	**Teske et al.[a]** (2017)[90]	**Boretti** (2020)[91]	**Chu et al.** (2020)[29]	**Geoscience Australia[c]** (2014)[92]	**UTS: ISF** (2016)[88]	**Blakers et al.** (2017)[89]
Scenario	100% Renewable Powered Grid	100% Renewable Powered NEM	Capturable solar and wind potential	Wind and Solar only NEM	Global VRE Potential mapping		100% Renewable Powered Grid	100% Renewable Powered NEM
Wind Onshore	80	45	23,990	53	8,300		180	136
Wind Offshore					–			
Solar PV	166	23	112,348	90	51,000	58 million PJ[b]	266	36
CST	16	–			–		78	–
Geothermal	10	–			–	120 TWh (total)	51	–
Biomass	20	0.6			–		74	1
Hydro	8	23.4 (Including pumped hydro)			–	60 TWh	19	33 (including pumped hydro)
Wave	13	–			–		50	–
Storage	–	–		>50 GW	–			3

Note: (a) Analysis by UTS: ISF (University of Technology Sydney – Institute of Sustainable Futures) is for a 100% renewable NEM. (b) Analysis by Teske et al. provides the installation capacity based on the capturable solar and wind potential for Australia based on the available area that can be converted to solar and wind farms[90], (c) The solar-PV/thermal capacity value provided by Geoscience Australia represents the total solar energy radiation received by Australia in a year.

Individual states and Territories are also playing a role in Australia's renewable energy future[62]:

- NSW has set a target of delivering 12 GW of renewable energy by 2030 (60% of the state's electricity supply capacity).
- NT and Queensland have set a target to achieve 50% of electricity supply through renewables by 2030. There is also A$2 billion in funding by Queensland government to establish the Queensland Renewable Energy and Hydrogen Jobs Fund.
- Tasmania has a target of achieving 200% of current electricity demand by renewable energy by 2040.
- Western Australia has a target that >70% of the state's electricity generation capacity will be from renewables by 2040
- South Australia has a target to convert its grid to 500% renewables over the long-term. A key driver of which would be a 2.6 GW renewable electrolysis hub.
- The Victorian Government is auctioning 600 MW worth of solar and wind energy projects and has committed A$540 million in investment to develop 6 renewable energy zones.

Table 3: Current Australian energy generation by resource.
Values adopted from the Clean Energy Council's 'Clean Energy Australia Report 2021'.[62]

Resource	Current Generation (GWh) For: FY2020-21	Share of total generation (%) For: FY2020-21
Fossil Fuel	164,469	72.3%
Renewables	55,481	27.7%
Total	**227,386**	
Individual Renewables		
Hydro	14,638	23.3% (6.4%)
Wind	22,605	35.9% (9.9%)
Bioenergy	3,164	5.0% (1.4%)
Solar PV small scale	14,807	23.5% (6.5%)
Solar PV large scale	7,703	2.3% (3.4%)
Total	**62,917**	**100%** (27.7%)

Note: *Values in bracket represent share of renewables of the total 227,386 GWh generated in FY2020-21.

4.4. Political Alignment to Develop a Renewable Export Supply Chain

Under the Paris Agreement, the Australian Government has committed to reducing emissions by 26 to 28 per cent below 2005 levels by 2030. Australia has a comprehensive suite of policies to meet its emissions reduction commitments, encourage innovation, and to back new and emerging technologies, including clean hydrogen.

Australia, through both the Federal, State and Territory governments have rolled out a series of policies and funding to support the development of renewable energy, decarbonisation initiatives and recently on developing a renewable export supply chain. Most notably, opportunities to progress clean hydrogen are seeing an increased policy push from Australian governments and industry as the next catalyst to Australia's continued economic progress and growth.

4.5. Australia's Hydrogen Competitiveness

Australia has a long and rich history of energy export that is supported firmly by the Commonwealth Government to create a conducive ecosystem for international trade. Australia is also currently a major hydrogen producer through the production of ammonia (one of the top 20 producers globally), with seven major producers across Queensland, New South Wales and Western Australia. Australia is well placed to leverage these attributes to become a major player in the emerging hydrogen value chain. The key pillars that Australia can mobilise to build the foundation for an emerging hydrogen value chain are detailed in **Table 4**.

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Table 4: Australia's Hydrogen Competitiveness Matrix.

Pillar	Drivers	Description
Economic	**Existing Trade Relationships**	Australia has an open trade market, with minimal trade restrictions. This has enabled Australia to foster strong trade relationships globally.
	Investment Pathways	Australia encourages foreign investment and has established policies in place to facilitate this process. Australian governments have a particular focus on economic development and job creation, hence facilitating the development of such a promising new export capability.
Infrastructure	**Ports and Shipping Supply Chain**	Australia has an expansive maritime supply chain, that delivers high volumes of energy commodities globally.
	Renewable Generation	Geoscience Australia estimates 11% of Australia's land mass is highly suitable for renewable energy generation. Australia is also fast becoming a global powerhouse in renewable electricity generation with a current national electricity grid uptake of ~28%.
	Feedstock Availability	Preliminary scoping exercises performed by Geoscience Australia have identified numerous sites within Australia that can support major renewable electricity generation in close proximity to freshwater. (Southern WA, Central NT, Northern SA, Western Queensland, and Tasmania are some of the key locations that was identified in the study for high volume hydrogen production). To ensure sustained hydrogen production, Australia can also leverage existing desalination and water recovery infrastructure, to complement the hydrogen generation hubs, therefore de-risking any water supply constraints.
	Gas Pipelines	Australia is home to one of the largest interconnected gas pipeline infrastructure with 38,000 km of transmission lines. The Australian Government is undertaking a review of the National Gas Law and other gas legislation to identify any regulatory reforms needed to remove the barriers for hydrogen blending. Feasibility studies are currently being performed on the suitability of these existing gas pipelines for hydrogen transport and domestic use.
Policies	**Government 'Buy-in'**	The Council of Australian Governments (COAG) and Energy Council formed the National Hydrogen Strategy Taskforce (the Taskforce) in December 2018. The taskforce released the National Hydrogen Strategy in November 2019 which sets out a path to '*a clean, innovative and competitive hydrogen industry that benefits all Australians and for Australia to be a major global player by 2030*.' The strategy includes 57 nationally coordinated government actions that are the first steps Australia needs to make to capture the hydrogen opportunity. Australian, State and Territory governments are working together to implement the National Hydrogen Strategy.
	Regulatory Frameworks	The Australian Government and State and Territory governments are working in collaboration to develop clear, fit for purpose regulation that will enable a future export economy. This regulatory framework is currently under review.
Experience	**Gas Export Supply Chain**	Australia is a LNG export giant with ~78 Mt of LNG exported in 2020, the world's largest exporter. The expansive LNG export supply chain is a testament to Australia's rich capabilities in gas export markets, which can be leveraged to facilitate a future hydrogen export economy.
Research & Development	**Research Ecosystem**	Australia's academic and industrial R&D ecosystems have been at the forefront of hydrogen research and innovation in some key areas. Research outcomes are now being translated into commercialisation.
	Launchpad for Clean Technology	Australia's venture capital and angel ecosystem have a key interest in hydrogen technology and are rapidly growing capabilities for clean technology investment. The support of entrepreneurial investment alongside government and private funding can facilitate a rapid transition of Australia into a global hydrogen superpower.

5. Australia's Emerging Hydrogen Economy

Australia's current pipeline of investment in hydrogen production.

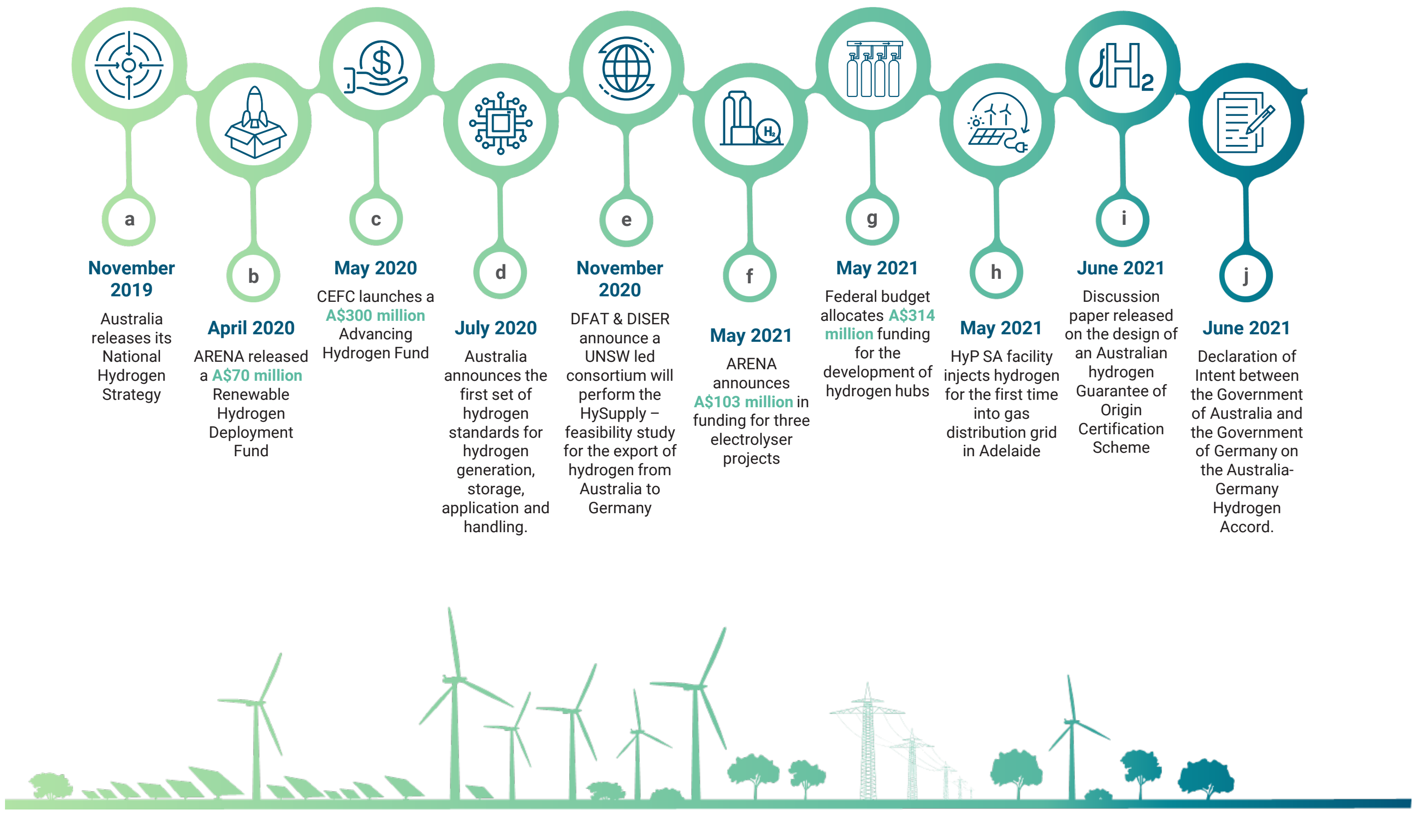
In 2019, Australia developed its National Hydrogen Strategy that outlined pathways and steps required to unlock the country's potential to become a leading hydrogen producer. The Strategy finds that a transition towards hydrogen is inevitable considering the availability of technology and growing market demand, and Australia is well placed to be a leading hydrogen producer. However, to achieve this, Australia must enable supporting infrastructure, production capacity and supporting demand, which would require "*strategic investment along the value chain from both public and private sector*".

The Strategy identified Australia's comparative advantage as a 'giant' exporter of hydrogen to facilitate decarbonisation across Asia-Pacific and beyond.[93] Australia has already negotiated hydrogen export partnerships with Japan,[94] Korea,[94] Singapore and recently with Germany,[96] to enable the exchange of technology to scale production capability and to establish trade routes. These countries are themselves key stakeholders in a future hydrogen economy, and their recognition of Australia's potential reaffirms the country's ability to become a global leader.

A number of studies suggest that Australia might supply up to ~10% of global hydrogen demand by 2050, a majority of which is expected to cater for demand in the Asia-Pacific, where Australia is highly competitive due to established trade networks.[33,34,42] Nevertheless, to get to this stage hydrogen would have to be generated at low cost with a low environmental footprint as the export partners (especially Germany) are increasingly looking to import "green" emission free hydrogen from Australia.

The key to unlocking Australia's hydrogen potential lies in the ability to bring down the cost of generating and providing hydrogen. **Figure 10** provides the country's timeline (till July 2021) to establish hydrogen capacity building within existing energy systems in Australia and to meet export expectations. This potential of hydrogen as a 'decarbonisation catalyst' has been well recognised by the Australian federal and state governments, industry partners, universities, and the public. In a report commissioned by the Australian Renewable Energy Authority (ARENA), it was revealed that the "*Australian public is supportive of the opportunities that are emerging from a potential hydrogen industry.*"[97] This support has translated into numerous government initiatives, research funding, government co-investment, large-scale feasibility studies and on-going projects.

Figure 10: A timeline of Australia's journey in hydrogen.



Federal Support

Hydrogen is one of five priority low emission technologies identified under the Australian Government's Technology Investment Roadmap, released in 2020.[98] Under the Roadmap, the Australian Government is looking to invest A$20 billion into advancing low emissions technologies over the next decade. These technologies will help to reduce emissions, create jobs, and achieve growth in the transition to a decarbonised global economy. The Australian Government's funding is expected to leverage around A$80 billion of total new investment from private sector and other governments in the years to 2030 under the Roadmap.

The Australian Government is prioritising this investment to economic 'stretch goals' for priority technologies set by the first Low Emissions Technology Statement under its Technology Investment Roadmap. For hydrogen, the Australian Government's goal is achieving production at under two Australian dollars a kilogram (or 'H2 under 2'), being the point where hydrogen starts to become competitive with conventional fuels.[87]

To drive production cost reductions, the Australian Government has invested A$314 million to develop up to five clean hydrogen hubs in regional Australia and support further hub design and work studies.[99] Hydrogen hubs can facilitate sector coupling – integration of hydrogen production and end-use sectors to maximise services and benefits that will effectively scale-up industry and drive production cost reductions.

The Australian Government is further working with state and territory governments to review the nation's legal frameworks, to determine what reforms may be needed to support a safe and efficient clean hydrogen industry. This includes accelerating regulations for the blending of hydrogen into domestic gas networks, with trials already underway in parts of Australia (**Appendix A**).

The Government is also progressing a domestic Hydrogen Guarantee of Origin scheme. This complements Australia's efforts to help shape the design of a methodology to guide a future global trade in hydrogen.

Other Australian Government activities to build the industry include:

- investing in building new hydrogen ready gas generation facilities,[98]
- progressing international relationships, including recent major announcements on hydrogen partnership agreements with Germany, Singapore and Japan to build supply chains and advance technology research, such as the Hydrogen Energy Supply Chain (HESC) project in the Latrobe Valley in Victoria,
- establishing a A$300 million Advancing Hydrogen Fund in the Government's Clean Energy Finance Corporation (CEFC),[100]
- over A$100 million invested in three 10MW hydrogen electrolyser projects through the Government's Australian Renewable Energy Agency (ARENA),[101]
- more than A$300 million invested in research, development, and demonstration activities.

The Australian Government has invested more than A$1 billion into the hydrogen sector and is expected to continue to make further investments over time.

The Australian Government is also working in partnership with state and territory governments to implement various National Hydrogen Strategy actions. Collectively the Australian and State and Territory governments have:

- commenced a review of legal and regulatory frameworks,
- commenced a review of arrangements supporting blending of hydrogen into gas networks,
- started a National Hydrogen Infrastructure Assessment,
- commenced work around industry development, including skills and training,
- supported analysis to help understand community attitudes towards hydrogen.

Some of these key policies to support hydrogen generation at federal and state level are presented in **Figure 11**.

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Figure 11: Key Government renewable energy, hydrogen and emission targets, strategies, and investments in Australia. Note: The renewable energy investments up to 2021 are based on ongoing/committed projects between 2017 – June 2021.[62]

Western Australia

- **2020 Renewable Energy Investment: A$2.0 billion** invested last year to grow capacity by 0.4 GW.
- **WA System Plan:** Target established to convert WA's energy supply capacity to 70% renewables by 2040.
- **WA Renewable Hydrogen Strategy and Roadmap:** The state has established long-term goals to develop a hydrogen industry. Key short-term goals (2022) include development of a renewable hydrogen export project and inject H_2 in gas grid.
- **WA Renewable Hydrogen Fund: A$5 million** was provided for hydrogen project feasibility studies. The state government also invested **A$22 million** in 2020 to develop a 1.5 GW renewable energy and hydrogen hub.

Northern Territory

- **2020 Renewable Energy Investment: A$100 million** invested last year to grow capacity by 64 MW.
- **State Renewable Energy Funding:** The state is financing development of large-scale batteries for renewable energy storage, has made grants available for household solar systems and made *'Sun Cable'* project a key priority.
- **Renewable Energy Target:** NT has a target for 50% renewables supply in electricity grid by 2030 and to reach net zero by 2050.
- **NT Renewable Hydrogen Strategy:** The state has developed its hydrogen strategy to become a global hub for hydrogen research, production and technology manufacturing.
- **Renewable Hydrogen Project:** The state government is supporting the "Aqua Aerem" demonstration project to generate hydrogen using water from air and grid supplied renewable electricity.

Queensland

- **2020 Renewable Energy Investment: A$3.4 billion** invested last year to grow capacity by 1.9 GW. (3rd highest amongst other states)
- **Renewable Energy Corridors: A$145 million** committed to develop renewable energy zones in the north, central and south-western part of the state.
- **Renewable Energy Fund: A$500 million** in additional funding committed as part of the Covid-19 Recovery Plan to support commercial energy projects and to develop infrastructure.
- **Queensland Renewable Energy Target:** The state has a target to become 50% renewable powered by 2030 and to attain net zero by 2050.
- **Queensland Hydrogen Industry Strategy:** The state government has committed **A$19 million** to support the emerging hydrogen economy.
- **Queensland Hydrogen Hubs:** QLD government has recently backed the development of a hydrogen hub in Townsville.

South Australia

- **2020 Renewable Energy Investment: A$2.4 billion** invested last year to grow capacity by 1.4 GW.
- **Renewable Energy Target:** Target established to convert SA's grid to 500% renewables to become net energy exporter to the Australia National Energy Market.
- **SA's Hydrogen Action Plan:** Action plan developed to establish SA as a key renewable hydrogen strategy. State has provided **A$17 million** in grants and **A$25 million** in loans to hydrogen projects.
- **South Australia Hydrogen Export Hub:** The state has announced plans to develop 3 renewable hydrogen hubs with a combined capacity of 2.6 GWs.
- **Australia's largest electrolyser:** The state is home to Australia's largest operational electrolyser of 1.25 MW capacity. The SA government provided **A$4.9 Million** in grant funding for the project.

NSW

- **2020 Renewable Energy Investment: A$5.6 billion** invested last year to grow capacity by 3.6 GW. (Highest amongst other states)
- **NSW Electricity Infrastructure Roadmap:** The state expects investment of **A$32 billion** by 2030 to increase its renewable capacity by 12 GW. Hydrogen is expected to be a key growth driver.
- **NSW Net Zero Plan Stage 1:** Stage 1 of NSW Climate Change Policy -**A$2 billion** committed in partnership with the Commonwealth for low emission technology including H_2.
- **NSW Climate Change Policy Framework:** State target of achieving net zero by 2050.
- **NSW Hydrogen Strategy:** Under development.
- **NSW Hydrogen Hubs: A$70 million** committed to Hunter and Illawarra H_2 Hub as part of a greater **A$750 million** Net Zero Industry and Innovation Program.

Tasmania

- **2020 Renewable Energy Status:** The state has the highest share of renewable electricity in power generation (~99%).
- **Tasmanian Renewable Energy Target:** Achieving 200% of current energy demand with renewable electricity supply by 2040 and become a net exporter.
- **Tasmanian Renewable Hydrogen Action Plan: A$50 million** package committed to develop a green hydrogen economy, start H_2 export by 2025 and become a global export hub by 2030.

Victoria

- **2020 Renewable Energy Investment: A$5.0 billion** invested last year to grow capacity by 2.9 GW. (2nd highest amongst other states)
- **Victorian Renewable Hydrogen Industry Development Plan: A$6.2 million** committed to accelerate pilot projects, **A$10 million** committed for Victorian H_2 hub and **A$1 million** available in grants.
- **Victorian 2020 Budget Commitments: A$1.6 billion** committed for development of renewable energy hubs and auction 600 MWs of new solar and wind capacity.
- **Victoria Emissions target:** The state has a target to become net zero by 2050.
- **Hydrogen Energy Supply Chain Project:** The state is host to the world's first H_2 supply pilot. The project was provided with **A$50 million** in funding by the state government.

Federal

- **National Hydrogen Roadmap** (2018) **& National Hydrogen Strategy** (2019).
- **CEFC Advancing Hydrogen Fund: A$300 million.**
- **Low Emission Technology Roadmap (2010): A$1.9 billion** committed **for five priority low emissions technologies**, including hydrogen.
- **ARENA: A$103 million** committed to develop electrolyser projects.
- **National Energy Resource Australia:** seed funding provided to develop 13 Hydrogen clusters.
- **Environmental Pledge:** reduce Australia's emissions by 26% to 28% below 2005 level by 2030.
- **Federal Funding for H_2 Hubs: A$314 million** in funding for developing regional H_2 Hubs and carrying out 10 feasibility studies.
- **German-Australia Hydrogen Innovation and Technology Incubator: A$50 million** commitment.
- **Hydrogen Ready Power Generators: A$24.9 million** in funding to enable hydrogen capable gas power generators.

Snapshot of State and Territory Government Initiatives in Developing an Australian Hydrogen Economy

The various state and territory governments in the Commonwealth of Australia have recognised the deployment of hydrogen as a critical vector for meeting decarbonisation targets and economic growth. A snapshot of state-by-state initiatives are as follows:

- The Queensland government has established a A$25 million hydrogen industry development fund to support projects in the state. In an Australia first, the state government has established a ministry for hydrogen, recognising the powerfuel as an important new industry in the state's economic recovery. The state has also allocated A$2 billion in funding to establish the Queensland Renewable Energy and Hydrogen Jobs Fund.
- New South Wales government has included hydrogen in their plan to achieve net zero emissions across its economy by 2050. The state has recently unveiled its renewable energy zones (REZs) through the Energy Infrastructure Roadmap and has plans to bring 12 GW of new renewable energy into its grid by 2030. Building on this, the state government is supporting a clean industrial revolution including hydrogen as part of its Net Zero Industry and Innovation Program. The A$750 million plan is the largest in Australia aimed at reducing emissions and to position NSW as a global leader in low-carbon innovation. The NSW government has also announced A$70 million in funding for the Hunter and the Illawarra Hydrogen Hubs.
- The Tasmanian Renewable Hydrogen Action Plan, commissioned by the Tasmanian government, outlines the state's vision in becoming a renewable hydrogen exporter. The state government has set up a A$50 million support package for the state's hydrogen economy, of which, A$2.6 million is being invested on carrying out a feasibility study for a renewable ammonia and methanol export project in the Bell Bay Advanced Manufacturing Zone.
- The South Australian government is amongst the first movers in hydrogen in Australia, commissioning the state's hydrogen roadmap in 2017 and following up with an industry co-developed Hydrogen Action Plan. The state has also developed an Australia-first Hydrogen Export Modelling tool to inform the establishment of renewable hydrogen export supply chains. The government has co-invested A$17 million in grants and A$25 million in loans to four hydrogen projects in the state.
- The Western Australia government, through the Western Australian Renewable Hydrogen Strategy has set an ambitious goal of approving an export renewable hydrogen project by 2022 and by 2040, matching WA's market share in hydrogen to today's share in LNG. To date, the state government has committed more than A$35 million towards the renewable hydrogen industry in WA. The WA government is also actively engaged in developing hydrogen based standalone power systems, e.g., 1,000 of such systems have been committed as part of a new A$249 million policy package.
- The Victorian government (in partnership with the Australian and Japanese Governments and Australian and Japanese industry) is supporting the world's first Hydrogen Energy Supply Chain (HSEC) project in the state, aimed at exporting blue hydrogen produced from Victorian coal to Japan. The government has also unveiled a Renewable Hydrogen Industry Development Plan. To further promote R&D in this space, the government has backed a A$10 million hydrogen research facility to be based at the CSIRO Clayton campus. The state's Renewable Hydrogen Business Ready Fund recently provided A$1.0 million to assist businesses to transition to renewable hydrogen and the Victorian Government has committed A$6.2 million of grant funding for capital works projects that support the building of hydrogen pilots, trials, and demonstrations under the Renewable Hydrogen Commercialisation Pathways Fund.
- The ACT Government has introduced the 'ACT's Transition to Zero Emissions Vehicle Action Plan 2018 – 21', which supports fuel cell vehicles usage in ACT. The ACT government has also supported the development of Australia's first public hydrogen refueling station in Canberra. The territory government is working on a natural gas transition plan (as part of the ACT Climate Change Adaptation Strategy) to support zero emission technologies and green alternatives to natural gas including hydrogen and has established a A$12 million Renewable Energy Innovation Fund.

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Current Status of Hydrogen Standards and Regulation

The generation, transport, storage and utilisation of hydrogen presents both environmental and safety hazards which will therefore trigger future regulatory changes as the industry develops. As a part of the development of the 'National Hydrogen Strategy', the law firm Clayton Utz reviewed "*legislation, regulation and standards (Law) potentially relevant to the development of a hydrogen industry within Australia*".[102] It found approximately 730 pieces of legislation and 119 standards met this requirement (A full list can be found in Schedule 2 of the '*Hydrogen Industry Legislation*' report).[102,103] At present, the Australian Government is working with State and Territory governments on a review of legal frameworks and standards relevant to hydrogen industry development and safety.

Furthermore, Australian exporters will be exposed to regulations and standards developed by importing nations and international organisations. Currently, stakeholders across standards agencies (including Standards Australia), government and industry, both domestically and internationally, are working together on the development of a consistent regulatory framework. For example, Australia is participating in forums such as the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE).[102]

More recently, in May 2020, Standards Australia committee ME-093 Hydrogen Technologies, has established five working groups, which are targeted to oversee the development of the emerging hydrogen industry.[104] These groups are concerned with production, handling and storage; pipeline and gas distribution networks; end-use utilisation; fuel cell applications and; mobility applications.[104] The committee also adopted 8 hydrogen international standards in 2020 concerned with production, use, storage and mobility.[105] A range of standards for Hydrogen production, carbon capture, safety, transport and heating are provided in the Standards Australia "Hydrogen Technologies Standards Discussion Paper", which also highlights which international standards have been adopted in Australia thus far.[106]

Certification

Certification of generated hydrogen is necessary to establish trust and confidence for consumers that the product meets their expectations and claimed specifications. This is to ensure that the end-product can be adequately traced from its origins such that transparency exists in the meeting of environmental guarantees, including emissions and water consumption.[103] The development of a certification scheme is a priority under Australia's "National Hydrogen Strategy".[103]

In June 2021, the Department of Industry, Science, Energy and Resources (DISER) released a discussion paper for consultation on the development of "A Hydrogen Guarantee of Origin scheme for Australia".[107] It outlines 'guarantee' methodologies for the production pathways of *"electrolysis, coal gasification with carbon capture and storage (CCS), and steam methane reforming with CCS"* as well as the certification of the energy sources for these production methods.[107] The scheme aims to ensure consumers can make an informed choice and acknowledges that over time this will need to be adapted to incorporate other pathways such as hydrogen carriers, and that issues still arise pertaining to the accounting methods, which must be adopted to track emissions. Further, Australia is a leading participant in the IPHE taskforce to develop an international methodology for calculating the carbon emissions associated with hydrogen production. The approach presented in the DISER discussion paper aligns with the work through IPHE.

An industry-led scheme is also being developed within Australia, driven by Hydrogen Australia, a division of the Smart Energy Council. The Zero Carbon Certification Scheme will be limited to green hydrogen, green ammonia and green metals, specifying that all the products and derivatives must be made from renewable energy sources.[108] Notably, blue hydrogen will not be covered by this certification and the scheme will be based on the CertifHy scheme in Europe.[108]

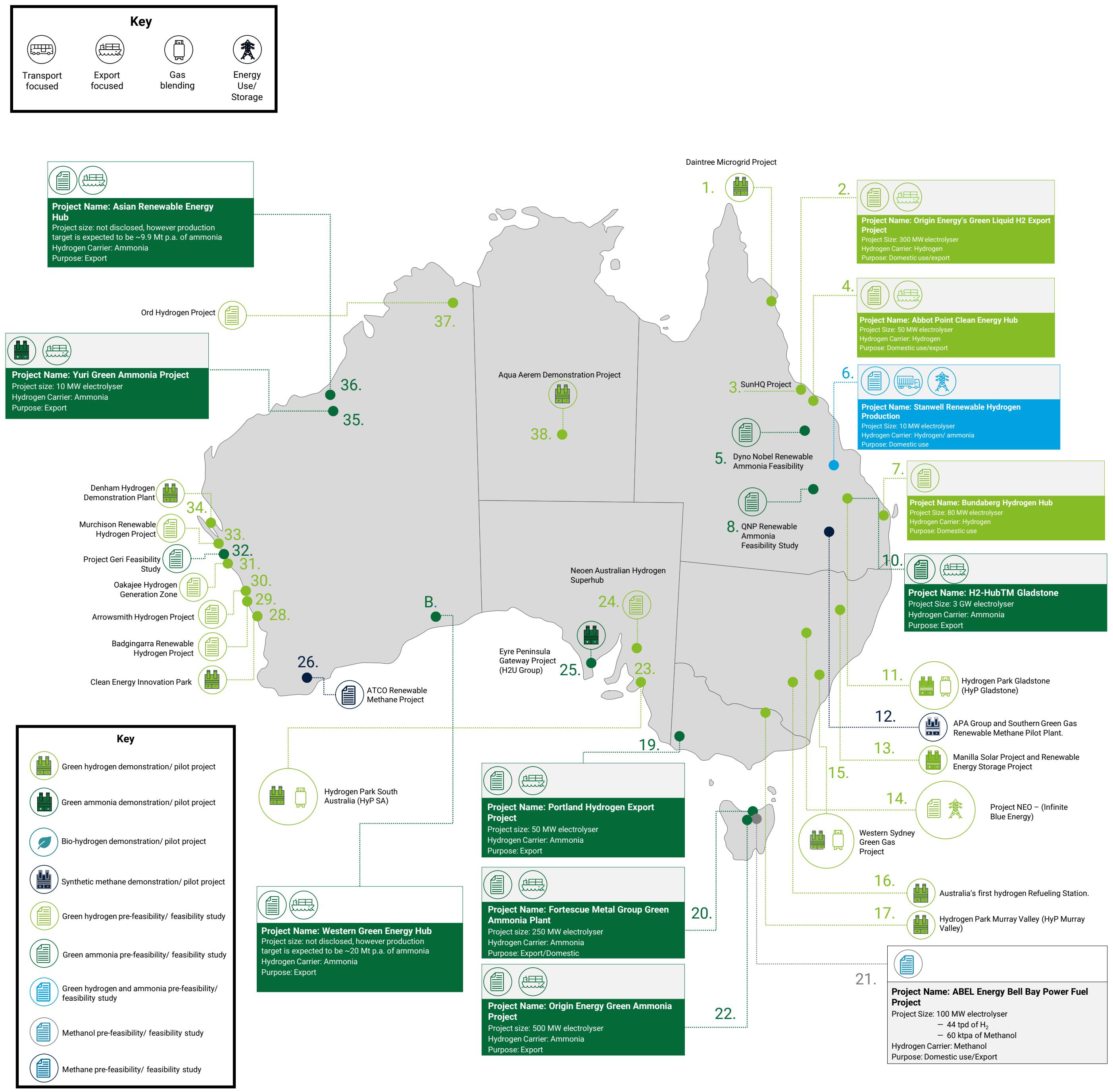
Current Renewable Hydrogen Production Capability in Australia

At present, the major demand for hydrogen in Australia is for ammonia generation, which requires 350,000 tonnes of H_2 per annum. This hydrogen is generated from natural gas using steam methane reforming. However, there is significant global momentum towards clean hydrogen, which includes renewable hydrogen as well as hydrogen production from coal or natural gas with associated carbon capture and storage. This use of clean hydrogen will lower emissions in the energy sector and industrial value chains. Australia aims to be a larger exporter of hydrogen and ammonia on a global scale.

At present, the country has a number of active hydrogen projects, including demonstrator plants, commercial projects and feasibility studies exploring the value chain of renewable hydrogen for both domestic and export market opportunities. To map out these projects and to track Australian research in the hydrogen space, a consortium comprising of CSIRO, Future Fuels CRC, Australian Hydrogen Council (AHC) and National Energy Resource Australia (NERA) have developed a collaborative knowledge sharing platform called HyResource (https://research.csiro.au/hyresource/).

Some key renewable hydrogen projects in Australia that demonstrate that the country is ready, willing and able to export hydrogen to Germany are presented in **Figure 12** and elaborated in **Appendix A.**

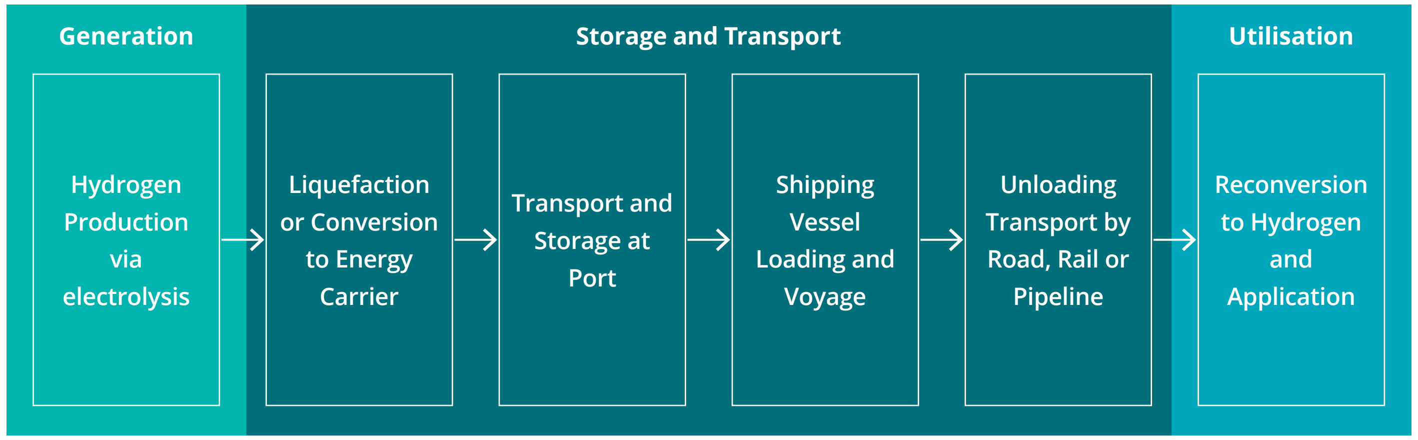
Figure 12: Map of Key Green Hydrogen generation projects in Australia.
These include projects that are currently active, have been committed and/or are under development. A few projects that feature an electrolyser that is greater than 10 MW in size or are export focused have been highlighted, given the nature of this investigation to demonstrate Australia's capability, however all the projects are valuable in Australia's acceleration towards becoming a hydrogen economy. Note: This list is non exhaustive, further details of these projects and hubs are provided in **Appendix A.**



6. Preliminary Investigation for the Development of a Hydrogen Export Value Chain in Australia

6.1. Key analysis to determine the Feasibility of Green Hydrogen

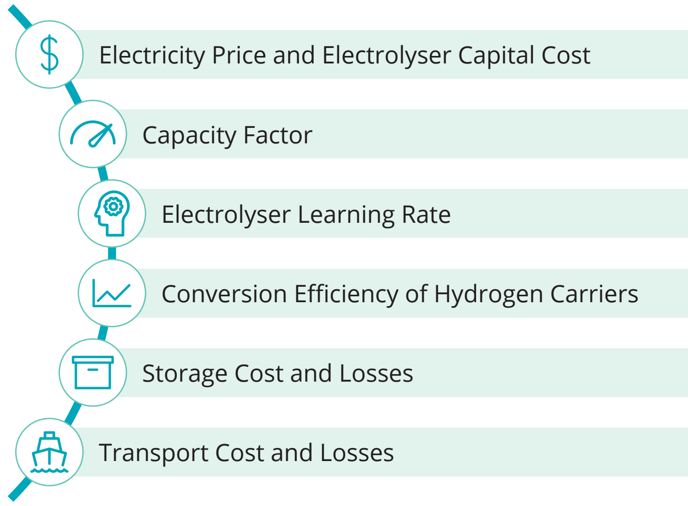
Figure 13: Breakdown of hydrogen value chain into generation, storage and transportation, and utilisation.



The previous sections explored the geo-political and strategic alignment between Australia and Germany, identifying them as highly complementary trading partners for renewable hydrogen export. Despite these considerations, ultimately, the feasibility of this green hydrogen export value chain will be dictated by the economics of the various steps within the supply chain.

A green hydrogen production supply chain in Australia may involve conversion of renewable electricity to hydrogen using electrolysers, followed by various possible storage and transportation stages before subsequent conversion to energy carriers for export, with again possible storage and transportation stages, prior to delivery to a port for shipping (as illustrated in **Figure 13**). This value chain will bring together technologies across various stages of maturity, efficiency, capital costs, and operating costs (**Figure 14**), requiring interdependence modelling and integration.[Δ]

A particular challenge of modelling a hydrogen value chain is the highly dynamic nature of key market factors, with falling electrolyser capital costs, declining renewable electricity pricing, fluctuating global exchange rates and, critically, likely improvements in storage and transportation efficiency, greatly affecting the overall economic viability. Briefly, the key drivers for a renewable hydrogen supply chain may include:

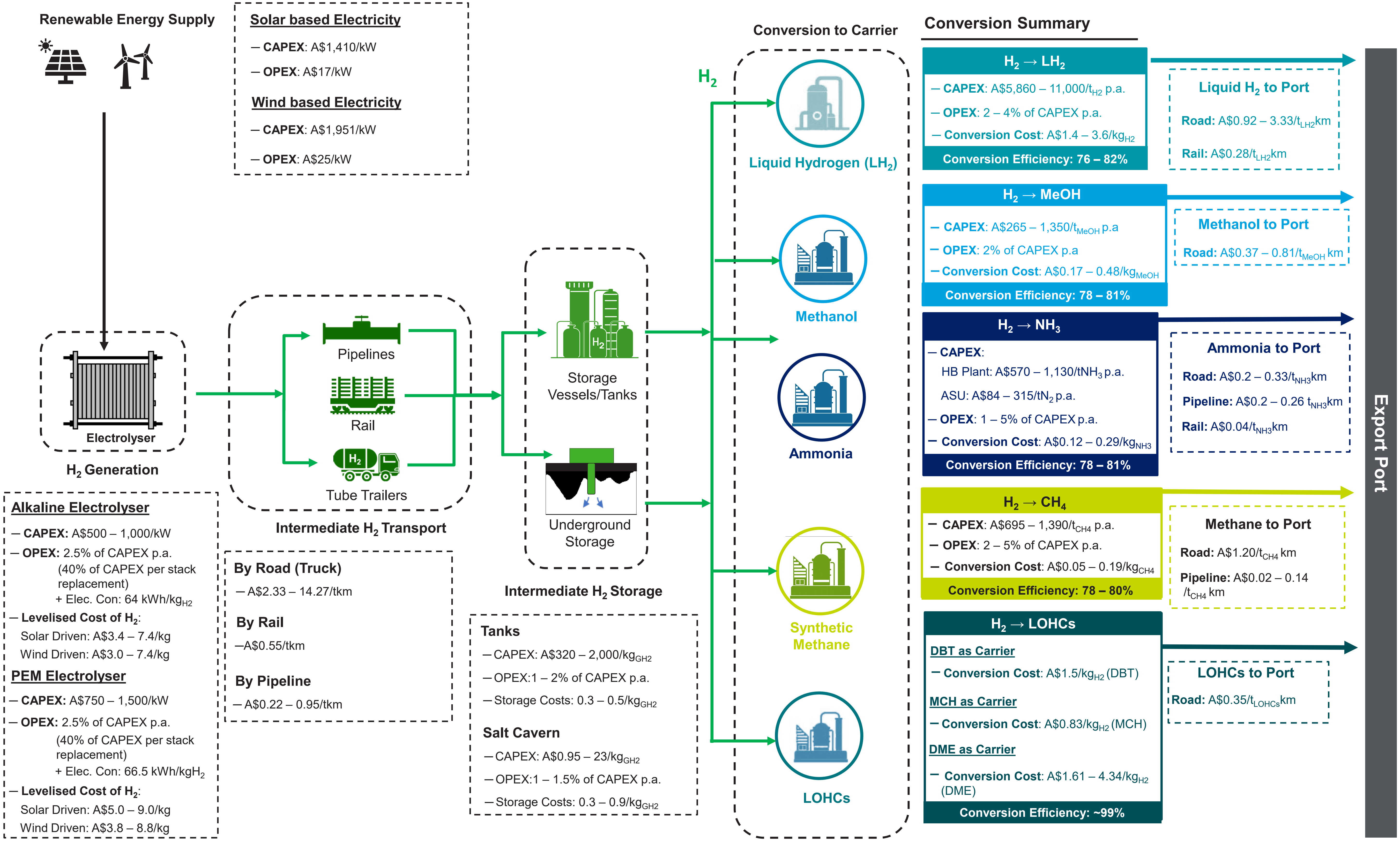


In the following sections, we explore these key drivers in greater depth and present our current analysis of Australia's hydrogen supply chain potential.

Δ Note: A hydrogen value chain may entail adoption of other disruptive technologies in addition to current considerations, which will be expanded in detail within the Roadmapping phase of the feasibility study.

Figure 14: Preliminary overview of current economics of considered hydrogen conversion pathways into carriers.

The costs are represented in Australian Dollars. Note: The capital and operating costs represent the total conversion chain costs of each conversion pathways, these costs were adopted from literature and were normalised over the volume of product generated in each year. The individual values were adopted from literature and are provided/detailed in **Table 16**. The LOHC cost pathway is based on using Dibenzyltoulene (DBT), Methylcylohexane (MCH) and dimethyl ether (DME) as the primary carrier. Plant scaling factors are not considered herein owing to requirement of further stakeholder consultation. It must be noted that the technologies presented above have different technology readiness level (TRL) for different scales and in the Roadmapping phase of the HySupply project, interdependence modelling will be carried out with stakeholder input



HySupply Costing Tools

To allow for flexibility with the changing cost drivers, **HySupply Australia has developed a renewable hydrogen costing tool and export transportation model.** These open-source tools will be released as an asset of the HySupply project with the intent to iteratively improve existing functionalities and data sets to provide holistic, high-level, pre-feasibility assessments for possible hydrogen projects, as we build towards a complete value chain assessment tool.

While there are other valuable tools in the public domain, such as the Geoscience Australia's Hydrogen Economic Fairways Tool (HEFT) and the South Australian Government's Hydrogen Export tool, the HySupply tools seek to extend some aspects of their capabilities, and are designed to allow stakeholders complete open-source access to define (i) a wide range of operational scenarios (solar, wind, hybrid where user defines renewables split, battery storage, oversizing/undersizing compared to electrolyser), (ii) fixed and variable operating costs (renewables, electrolysers, balance of plant), (iii) performance parameters (electrolyser efficiency variation vs load, battery storage efficiencies etc.) and project financing considerations (WACC and to be expanded to include tax regimes, equity, interest, depreciation, etc.), enabling a more detailed project outlook.

Note: that the tool allows stakeholders to evaluate a hydrogen production system as both stand-alone and grid-connected configuration, providing the flexibility to incorporate grid transmission and connection charges. While the capacity factor modelling for standalone systems is based on pre-loaded solar and wind traces for specified locations, the tool allows flexibility for users to amend and input their own traces if required. Moreover, the tool allows hourly simulation of the electrolyser and the powerplant output, providing the user a detailed outlook of hydrogen generation over the year and its daily and seasonal variation. This will be a key consideration for project stakeholders when designing downstream storage and conversion of hydrogen and derivatives through to end-use.

Note: The costing tools will be released in stages, with stage 1 of the tool focusing on analysing farm-gate hydrogen generation costs across Australia. This stage of the tool has already been developed for the preliminary analysis in this report and will be released shortly for public use.* The tool allows for a detailed user defined cost analysis for hydrogen generation using electrolysis across 41 predefined locations across Australia, with additional option for users to define their own location.

6.2. Renewables (temporal and spatial characterisation)

Australia's renewable energy industry has seen continued record-breaking growth, despite the impacts from the COVID-19 pandemic, and other challenges. According to a Clean Energy Council report, renewable energy generation increased by 3.7% in 2020 (compared to 2019), and a further A$1.9 billion worth of projects was commissioned in 2021 to date.[62,109] The country enjoys one of the highest solar radiations in the world alongside strong wind resources, positioning the country in a very favourable situation to use and export renewable energy to Asia-Pacific and beyond.

Declining renewable generation capital and operating costs, supported by favourable government policies and incentives, are already pushing wider deployment of low-cost renewables within the country's Wholesale Electricity Market (WEM). Record levels of renewable energy generation were recorded during 2020, yet only a fraction of Australia's total renewable energy potential is currently being utilised (as discussed in **Section 4.3**). Therefore, significant room exists for deploying hydrogen electrolysers as a highly flexible and potentially valuable load for currently 'underutilised' renewable energy in the country.

It is important to note that the intermittent nature of solar and wind resources will consequently lead to variable operation of electrolysers. Project proponents can boost the capacity factor of this operation through a mix of renewables, storage and grid integration. However, the use of grid power does introduce challenges in certifying that produced hydrogen is derived from renewable energy, however these may be overcome as discussed below.

Australia's renewable resources are of course spatially diverse, with some regions showing higher solar generation potential than wind and vice versa. Combined with other factors such as existing land use and available infrastructure, these spatial and temporal characteristics will dictate where and at what scale electrolyser systems can most economically be installed.

For our modelling, insights on potential locations for deploying electrolysers were taken from studies undertaken by the Australian Energy Market Operator (AEMO). As part of the 2020 Integrated Systems Plan (ISP), AEMO has identified around 35 high renewable energy resource zones (REZs) across the National Electricity Market (NEM).[110] These sites are spread out between Queensland, New South Wales, Victoria, South Australia, and Tasmania, with most locations already aligning with potential hydrogen hubs and hydrogen projects currently in development or being envisioned.

* Note that further refinement of the HySupply costing tools will be carried out with stakeholder engagement in the Roadmapping phase of the project.

The ISP does not include Western Australia (WA) and the Northern Territory (NT), as they are not integrated with the NEM. They do both have some relatively smaller grids, such as the North West Interconnected System (NWIS) and the South West Interconnected System (SWIS) in WA, and the Darwin-Katherine Interconnected System (DKIS) in the NT, which could potentially support major projects. There are other locations of course, such as Geraldton and Ashburton (WA) or Baines and McArthur (NT), that offer great promise as hydrogen hubs but might best be developed as entirely stand-alone projects.[111]

There is considerable discussion on the potential advantage of renewable export projects connecting to the NEM or one of these other grids or being developed as major off-grid projects in unserved regions. Costs associated with participation in the NEM, and other grids can be significant. However, grid-connectivity offers advantages in the provision of firm power sourced from a range of generation options, including potentially widely dispersed renewables.[112]

A key issue for green hydrogen production from facilities connected to major grids such as the NEM will be the degree of certainty that the hydrogen was produced from renewable generation.[107] A range of derivative contracts are used by major energy consumers to facilitate renewable project development, and these can offer some level of matching between average generation and average consumption. However, at present, these do not generally recognise the timing and variability of the underlying renewable resources and the actual match with the timing and variability of consumption.

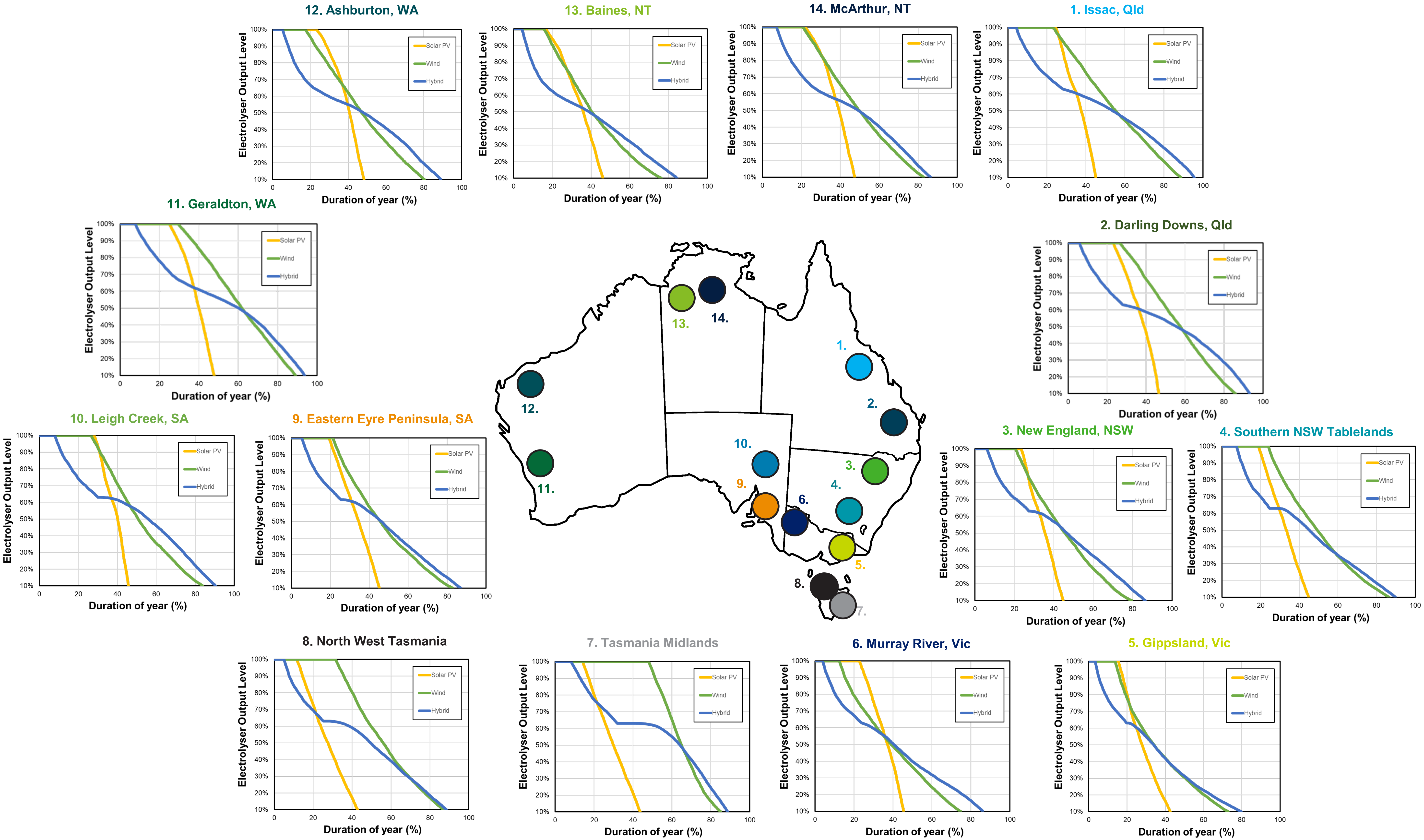
Electrolysers are highly flexible loads that could actually follow renewable generation over time, avoiding concerns about actual emissions associated with consumption. For simplicity, our initial modelling considers electrolyser operation matched to one or more specific renewables projects either directly as seen in off-grid projects, or through time varying power purchase agreements (PPAs) in grid applications. However, we do include potential oversizing as well as mixing both wind and PV PPAs to increase the capacity utilisation of the electrolysers – an interesting trade-off between renewables curtailment and improved electrolyser economics.

AEMO provides the wind and solar traces for the REZs as part of the ISP database, while the profiles for WA and NT locations were sourced using Renewables Ninja, an open-source tool providing wind and solar profiles based on global satellite and numerical weather prediction models.[113] These profiles provide an hourly outlook of electricity generated from these renewable power plants, over a year of operation, which can be arranged to provide yearly generation duration curves.[23] These duration curves provide insight on how much (% of its capacity) and for how long (% of the duration of the year) the solar and wind generator will provide energy. Example profiles utilised by the HySupply tool are presented in **Appendix B**. Note that we would be continuously updating solar and wind traces within the tool.

Moreover, the solar and wind profiles can be integrated as a hybrid energy supply (combination of solar and wind), given both sources are often complementary and can support electrolyser operation for longer durations at a certain capacity as compared to the solar and wind systems alone.

While the HySupply costing tool takes into account all these potential locations (including options for users to add/define their own locations), for the purpose of this report we provide the renewable potential for 14 locations across Australia, selecting 10 locations from those identified by the AEMO ISP, along with Ashburton (WA), Geraldton (WA), Baines (NT) and McArthur (NT), locations which are identified by state governments to be promising for renewable energy export projects. The duration curves for solar, wind and hybrid systems for the selected locations as part of the preliminary analysis are provided in **Figure 15**. Note that the optimal split of solar and wind power supply for hybrid configuration is dependent on technology costs and their combined location-specific generation duration curves, a functionality that the HySupply costing tool provides. However, for simplicity here, we display the duration curves for a 50/50 solar and wind split as an example.

Figure 15: Duration curves of electrolyser operating with a solar PV, wind and hybrid (solar plus wind) electricity supply in selected locations across Australia.
The example is shown for a 10 MW electrolyser system (minimum 10% load) operating with a solar PV farm (10 MW), a wind farm (10 MW) and a hybrid solar + wind supply (10 MW) with a 50/50 split of solar and wind. Source: HySupply tool. Note: The tool allows for the user to choose location beyond what is presented above, including functionality to input 30 minute or hourly generation profiles. Further, the tool allows the user to choose different renewables splits, renewable plant oversizing and incorporate local storage configurations to boost electrolyser capacity factors. Site-specific average capacity factors are summarised in **Figure 18-19**.



6.3. Renewable Hydrogen Production Costs

6.3.1. Current Costs

It is essential, for any hydrogen value chain to be viable, to drive down both the capital costs of electrolysers, increase their capacity factor and improve their overall system efficiency. These are two key performance indicators (KPIs) which currently limit the widespread and large-scale use of hydrogen electrolysers, albeit alongside a myriad of other barriers including market, regulatory and public acceptance, that HySupply is also exploring.[114] Still, in combination with reducing electricity costs from renewable sources, improvements in these KPIs will see the increasing viability of hydrogen value chains within the next decade and beyond.

At present, alkaline and PEM electrolysers are considered as the most mature and prospective technologies for green hydrogen production. While there is considerable R&D underway into solid oxide electrolysers, they require further development and scale-up to increase their technological readiness level. Notably, alkaline electrolyser component parts have been produced at scale for decades as they are similar to those used in the Chloro-alkali process.[115] Modelling based upon a 2018 case within the National Hydrogen Roadmap (NHR) found the levelised cost of hydrogen (LC_{H2}) using alkaline electrolysers to lie between A$4.78 – 5.84/kg at 44 MW/day capacity.[115] In contrast, the NHR estimates that using PEM electrolysis, H_2 can be generated today at A$6.08 – 7.43/kg with 1 MW/day capacity, producing 444 kg_{H2}/day.

It is anticipated that with time, the electrolyser CAPEX is expected to decrease substantially (**Figure 16**) and this is expected to lead to declining LC_{H2} for both AE and PEM systems. The NHR projected that over time, LC_{H2} will be reduced to A$2.54 – 3.10/kg (for PEM) and A$2.29 – 2.79/kg (for AE), arising primarily from declining capital costs, economies of scale, improved efficiency, increased capacity factor and electricity price reductions.[115]

Australia's potential to produce cheap renewable hydrogen is also recognized globally. The International Energy Agency (IEA) as part of their global outlook on renewable hydrogen costs predicted that Australia has the potential to generate hydrogen at A$2.6 – 3.4/kg gate price with a hybrid solar and wind energy supply, assuming electrolyser capital costs of A$600/kW, solar PV capital costs between A$530 – 1,313/kW and wind system costs of A$1,200 – 3,300/kW.[10] Similarly, the International Renewable Energy Agency (IRENA) evaluated hydrogen generation costs using solar energy in Australia, estimating a production cost in the range between A$4.9 – 5.6/kg (electrolyser CAPEX of A$1,080/kW) if solar electricity can be sourced at a cost of A$40 – 53/MWh at 30% capacity factor.[116] Another cost competitive outlook was also provided by the Hydrogen Council, predicting that Australia can generate hydrogen below A$2.6/kg by 2030. This estimate however is based on the assumption that electrolyser CAPEX will decline to A$330/kW and renewable electricity will cost A$17 – 48/MWh.[14]

Modelling by The Australian National University (ANU) provided another outlook of renewable electrolysis using grid provided solar and wind electricity in Australia.[117] Their analysis assumes electrolyser costs of A$500 – 1,000/kW to evaluate hydrogen costs (using a simple empirical methodology), suggesting that the levelised costs can be reduced below A$3/kg for electrolyser CAPEX of A$1,000/kW for A$32/MWh (capacity factor of 30%) and A$46/MWh (capacity factor of 45%). UNSW modelling based on a Monte-Carlo based uncertainty framework projected an optimistic levelised cost of A$4.45 – 5.18/kg for standalone PV-electrolyser system in Australia.[118]

Taken together, these studies all reaffirm that electrolyser capital costs, renewable electricity costs and electrolyser capacity factors will play a key role in dictating the feasibility of Australian renewable hydrogen.

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

CSIRO Electrolyser Cost Projections

Projections of future electrolyser CAPEX costs have been undertaken by CSIRO from 2020 through to 2050 using a technology learning rate analysis (**Figure 16**). Three future scenarios were considered; **(i) the central scenario** assumes current global climate mitigation policies which lead to a constrained increase in technology adoption, **(ii) the high variable renewable energy (VRE)** considers a strong drive towards reaching net zero emissions by 2050, and **(iii) the diverse technology case**, which reflects a mixed global effort towards emissions reduction. Moreover, under each scenario, CAPEX is estimated to fall quickly over the next 5 years, but afterwards more moderate reductions in CAPEX are observed. The current (2021) alkaline electrolyser and PEM electrolyser cost were established as A$2,516/kW and A$3,510/kW, respectively. By 2050, the CAPEX of PEM is predicted to be between ~A$250 – 500/kW and for AE it is predicted to be between ~A$500 – 750/kW.

Figure 16: CSIRO Projections for Future Alkaline and PEM Electrolyser CAPEX from 2020 through to 2050.[217]
Note: Consultation with industry stakeholders is reporting a much faster decline in capital costs than that is projected here.

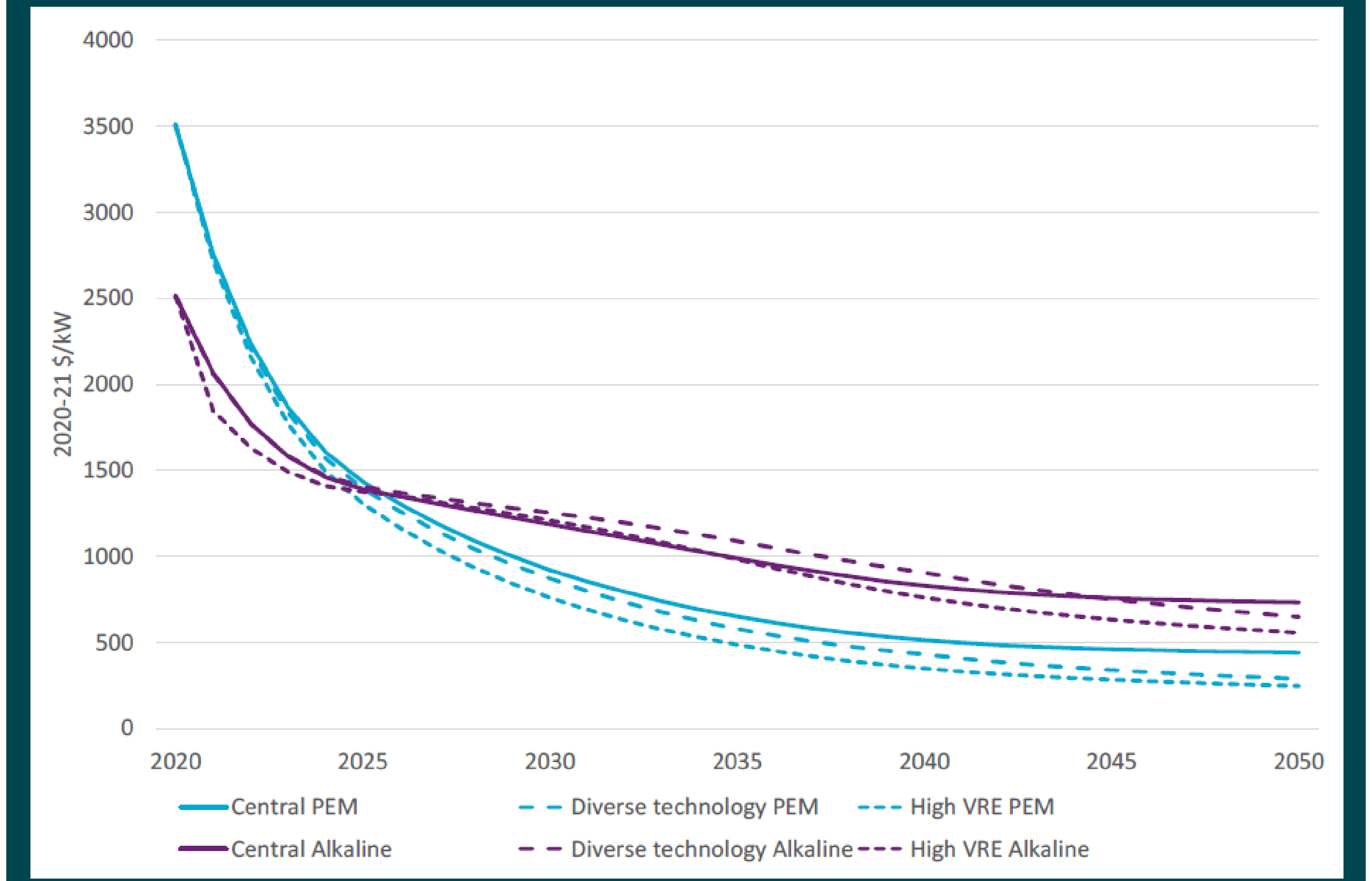


Table 5: International targets for green hydrogen price.
Note: The exchange rates of 1A$ = US$0.74 and 1A$ = €0.62 were used for the currency conversion (RBA Exchange Rates as of 27-07-2021[119]).

Proponent	Target/projection /Scenario	Price range/kg$_{H2}$	Adjusted to A$/kg$_{H2}$	Price year	References
Australian Government	Stretch target		A$2	Not indicated	Low Emissions Technology Roadmap,2020[87]
Hydrogen Council	Projection	US $1.40 – 2.30 (U$1.40 in optimal locations)	A$1.89 – 3.11	2030	Hydrogen insights, 2021[12]
EU	Target	Euro 1.1 – 2.4	A$1.77 – 3.87	2030	Hydrogen strategy, 2020[120]
IEA	Net Zero Emissions scenario	US $1.50 – 3.50	A$2.03 – 4.73	2030	Net Zero by 2050, 2021[19]
IRENA	Scenarios	US $1.40 – 2	A$1.89 – 2.70	2030	Low RE cost scenarios in Green Hydrogen cost reduction, 2020[22]
IEA	Renewables connected scenario	US $2 – 4	A$2.70 – 5.40	2030	Future of Hydrogen, 2019[10]
IRENA	Projection	US $1.80 – 3.30	A$2.60 – 4.78	2030	Hydrogen: A Renewable Energy Perspective, 2019[116]
Bloomberg	Projections	US $1.20 – 2.7	A$1.62 – 3.65	2030	BNEF: Hydrogen Economy Outlook, 2020[13]

6.3.2. Key to H_2 below A$2/kg

The Australian government has set a target of A$2/kg, being the point where clean hydrogen becomes competitive with conventional fuels.[87] While current renewable hydrogen production costs are at least two to three times higher than this target, declining capital costs, increasing electrolyser efficiency and declining cost of renewable projects (influenced by a combination of policies such as government subsidies or financing support) could make this possible in the relatively near-term. It is important to note that the Australian government hydrogen production cost target is similar to a range of international price projections and scenarios as shown in **Table 5**. It is also notable that more recent studies suggest lower prices in 2030. In comparison, hydrogen production costs from fossil fuels with CCS in Australia are estimated to remain stable from 2025 at around A$2.30/kg in suitable locations, although there are some uncertainties with CCS deployment that require further work.

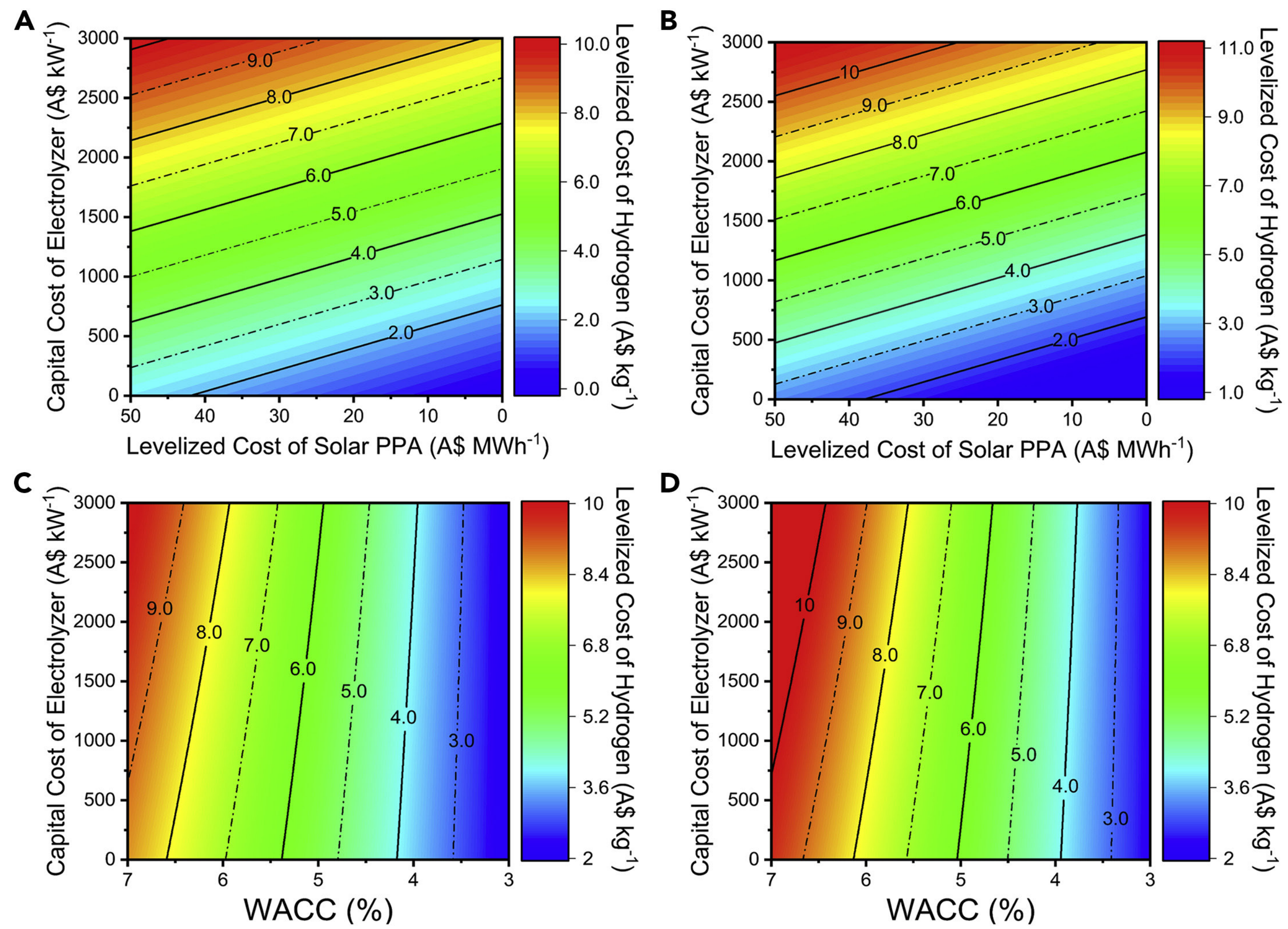
HySupply members recently carried out an optimisation study to identify parameters that can lead to low-cost hydrogen production. The study reveals that a number of possible configurations can lead to the attainment of A$2/kg 'gate' production costs. For instance, solar PV powered electrolysers (capacity factor of 30%) that are financed at a WACC of 6.25% will require an electricity price < A$20/MWh and electrolyser CAPEX below A$500/kW for LC$_{H2}$ to reach A$2/kg. Similarly, if the project WACC can be reduced to 3.5%, then an electrolyser cost of <A$500/kW and current solar PPA costs of A$47/MWh can lead to LC$_{H2}$ reaching A$2/kg.

While electrolyser CAPEX costs are expected to reach these required levels by 2030 (or before as per industry consultation), it must be noted that the required solar PPA costs can only be achieved post - 2050 if solar projects are financed at current WACC levels (the average WACC of renewable projects is 6.25%, based on analysis by AEMO).[23] Nevertheless, it is plausible to achieve these costs by 2030 if WACC can be lowered <4%.

Similarly, a wind turbine run electrolyser (capacity factor >41%) that is financed at a WACC of 6.25% will require an electricity pricing of A$30/MWh at an electrolyser CAPEX of <A$500/kW to attain a LC$_{H2}$ of A$2/kg. For this to happen at current wind PPA costs of A$51/MWh and electrolyser CAPEX of <A$500/kW, a WACC <3% is required. The required wind PPA pricing is projected to be achieved by 2050 under current WACC breakdown (6.25%). Given these projections, near - term wind farm projects would have to be financed below 4% WACC to achieve the A$2/kg LC$_{H2}$ target.

These possible configurations with solar PPA powered AE and PEM electrolysers are presented in **Figure 17**. These results highlight that a number of different project parameters can lead to reducing LC$_{H2}$. Further, through our HySupply tool, we flag capacity factor improvement through mixed renewables PPAs and/or energy storage as strategies to further reduce hydrogen production costs. Note that in the next phase of HySupply, we will be working with industry stakeholders to further refine these potential configurations.

Figure 17: Contour map of LC$_{H2}$ using a range of market conditions for solar PPA-powered electrolysers. LC$_{H2}$ of (a) different solar PPA - AE powered system, (b) different solar PPA - PEM powered system, (c) solar PPA powered AE electrolyser at different WACCs and (d) the solar PPA powered PEM electrolyser at different WACCs.



Note: The impact of the electrolyser capital cost (direct + indirect costs), solar PPA pricing (capacity factor of 30%) and WACC (for capacity factor of 30% and Solar PPA of A$47/MWh) on the electrolyser LC$_{H2}$ is correlated. The initial WACC for Figure A and B was assumed as 6.25%.[23]

6.3.3. Preliminary Modelling Results

As highlighted above, hydrogen production cost estimates are highly subjective to modelling assumptions, renewable feedstock pricing and electrolyser capital costs. In light of this and the highly dynamic market environment for electrolysers and renewable projects, HySupply Australia is developing open-source costing tools allowing stakeholders to input their parameters to calculate location specific levelised costs of hydrogen. This modelling framework will be extended to incorporate buffer storage, hydrogen carrier conversion and port loading during the Roadmapping phase of the project. An example of these preliminary results on location-specific hydrogen costs (in the near term) in Australia is presented in the following pages using costing data from literature (**Figure 18 – Figure 19**) and preliminary stakeholder consultation (**Figure 20 – Figure 21**). Notably, modelling using cost assumptions derived from stakeholder consultation, often based on project feasibility studies, suggest generally lower costs. Note of course that preferred sites for projects will depend not only on production cost estimates but numerous other factors including access to infrastructure, site availability, etc., parameters that will be further explored in the Roadmapping phase of the study.

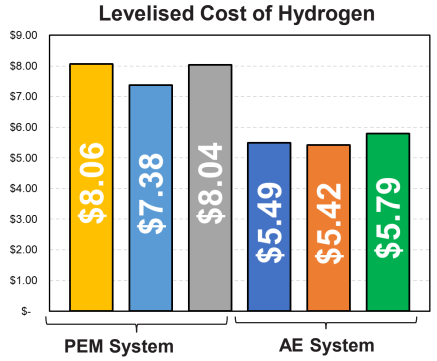
The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Figure 18: Preliminary modelling results for selected locations in New South Wales, Western Australia and the Northern Territory using costing data from a range of published studies.
Assumptions: 10 MW AE or PEM electrolyser operating with a solar PV farm (50 MW), a wind farm (50 MW) and a hybrid solar + wind supply (50 MW) with a 50/50 combination of solar and wind. AE electrolyser is assumed to have an overall system (stack + BoP) energy requirement of 64 kWh/kg, and the PEM system is assumed to energy requirement of 66.5 kWh/kg, based on the average of the energy consumption ranges provided by IRENA.[22] A stack lifetime of 80,000 hrs was used for both AE and PEM electrolyser. The AE electrolyser is assumed to cost A$1,000/kW while the PEM electrolyser costs A$1,500/kW (based on literature costs).[22] Additionally, Electrolyser O&M of 2.5% of CAPEX cost p.a., stack replacement of 40% of CAPEX cost per replacement, solar CAPEX of A$1,410/kW and wind CAPEX of A$1,951/kW was considered. A discount rate of 4% was used over a project life of 20 years. **Source:** HySupply modelling tool. **Note:** all values are in A$.

McArthur, NT

Electrolyser Capacity Factors

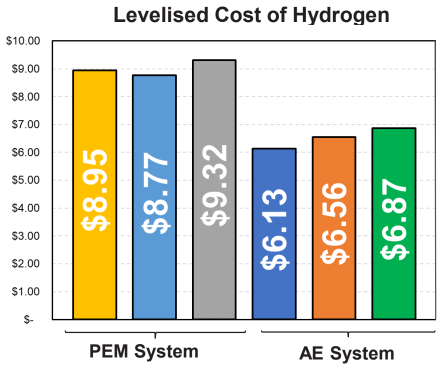
Configuration	AE	PEM
Solar PV	28.30%	28.74%
Wind	37.14%	39.01%
Hybrid	31.88%	33.66%



Baines, NT

Electrolyser Capacity Factors

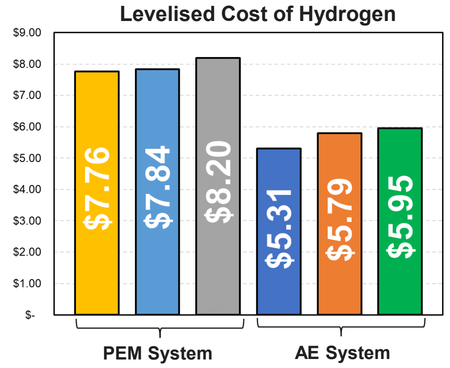
Configuration	AE	PEM
Solar PV	25.31%	28.30%
Wind	30.47%	32.55%
Hybrid	26.73%	28.96%



New England, NSW

Electrolyser Capacity Factors

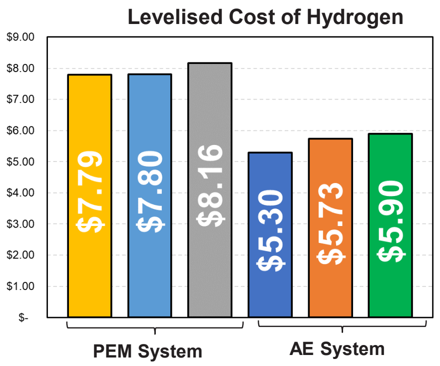
Configuration	AE	PEM
Solar PV	29.28%	29.77%
Wind	34.60%	36.52%
Hybrid	30.96%	33.00%

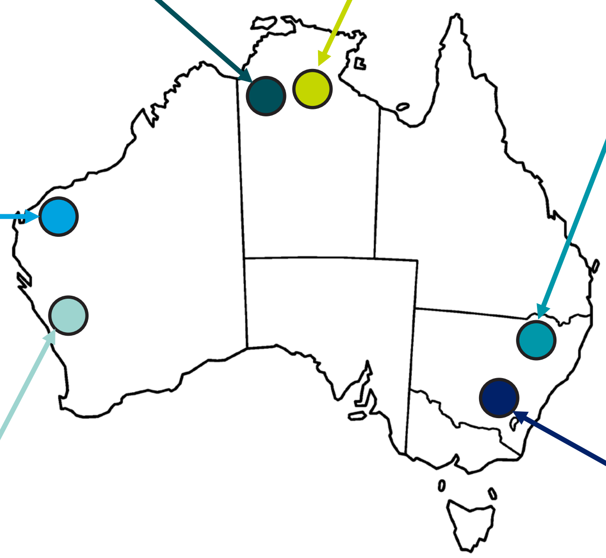


Ashburton, WA

Electrolyser Capacity Factors

Configuration	AE	PEM
Solar PV	29.33%	29.74%
Wind	35.02%	36.88%
Hybrid	31.32%	33.15%

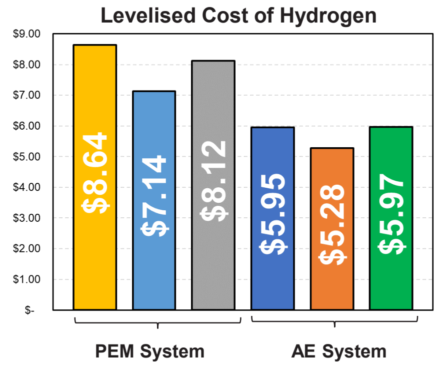




Southern NSW Tablelands

Electrolyser Capacity Factors

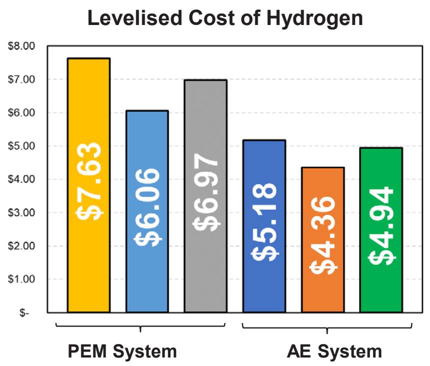
Configuration	AE	PEM
Solar PV	26.07%	26.73%
Wind	38.14%	40.43%
Hybrid	30.86%	33.33%



Geraldton, WA

Electrolyser Capacity Factors

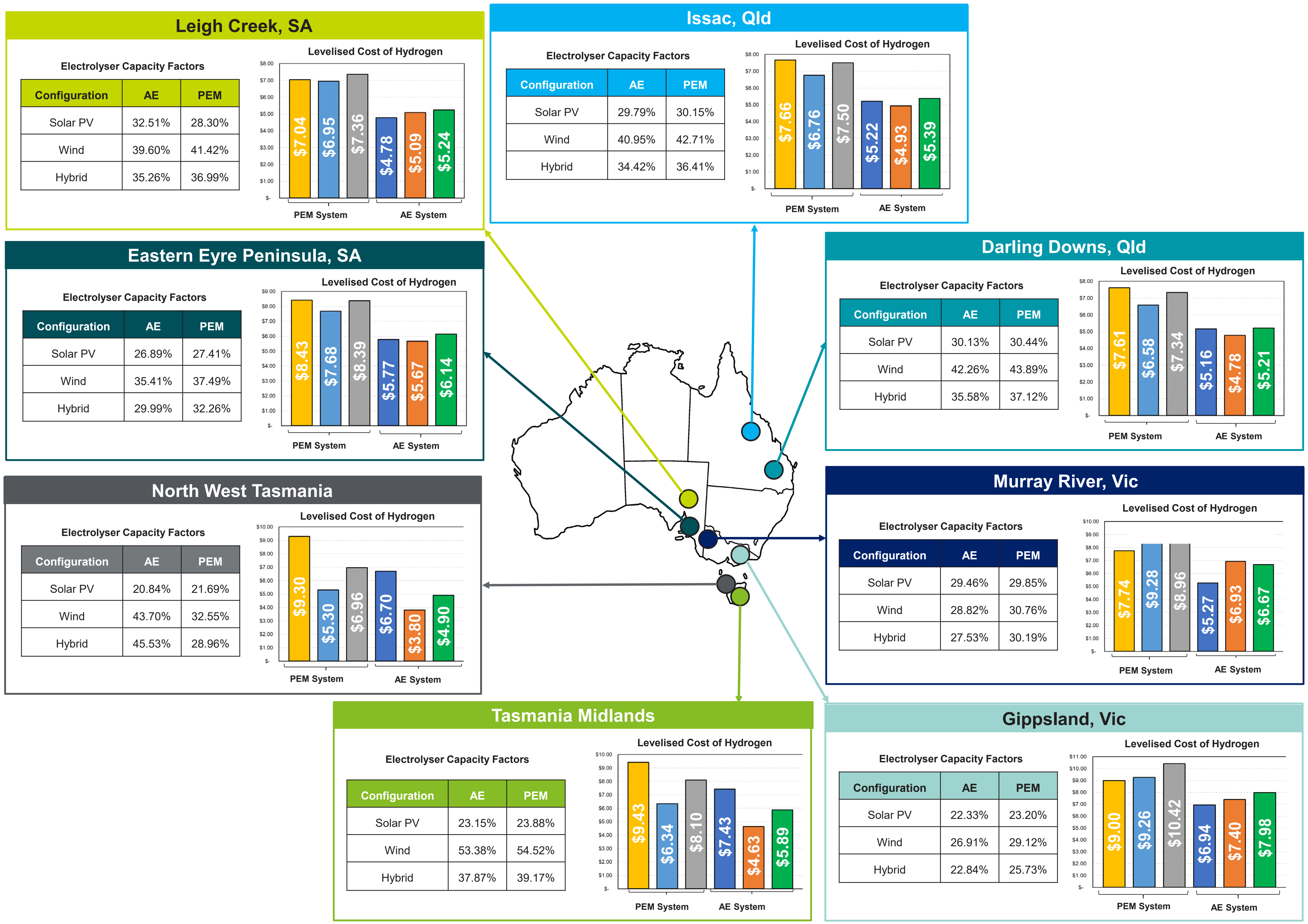
Configuration	AE	PEM
Solar PV	30.00%	30.39%
Wind	46.47%	47.92%
Hybrid	37.54%	39.08%



Key

- Electrolyser Facility
- Solar PV - AE LCH_2
- Wind - AE LCH_2
- Hybrid - AE LCH_2
- Solar PV - PEM LCH_2
- Wind - PEM LCH_2
- Hybrid - PEM LCH_2

Figure 19: Preliminary Modelling Results for selected locations in Queensland, South Australia, Victoria, and Tasmania using costing data from a range of published studies.
Assumptions: 10 MW AE or PEM electrolyser operating with a solar PV farm (10 MW), a wind farm (10 MW) and a hybrid solar + wind supply (10 MW) with a 50/50 combination of solar and wind. The AE electrolyser is assumed to have an overall system (stack + BoP) energy requirement of 64 kWh/kg, and the PEM system is assumed to energy requirement of 66.5 kWh/kg, based on the average of the energy consumption ranges provided by IRENA.[22] A stack lifetime of 80,000 hrs was used for both AE and PEM electrolyser. The AE electrolyser is assumed to cost A$1,000/kW while the PEM electrolyser costs A$1,500/kW (based on literature costs).[22] Additionally, Electrolyser O&M of 2.5% of CAPEX cost p.a., stack replacement of 40% of CAPEX cost per replacement, solar CAPEX of A$1,410/kW and wind CAPEX of A$1,951/kW was considered.. A discount rate of 4% was used over a project life of 20 years. **Source:** HySupply modelling tool. **Note:** all values are in A$.



Leigh Creek, SA — Electrolyser Capacity Factors

Configuration	AE	PEM
Solar PV	32.51%	28.30%
Wind	39.60%	41.42%
Hybrid	35.26%	36.99%

Issac, Qld — Electrolyser Capacity Factors

Configuration	AE	PEM
Solar PV	29.79%	30.15%
Wind	40.95%	42.71%
Hybrid	34.42%	36.41%

Eastern Eyre Peninsula, SA — Electrolyser Capacity Factors

Configuration	AE	PEM
Solar PV	26.89%	27.41%
Wind	35.41%	37.49%
Hybrid	29.99%	32.26%

Darling Downs, Qld — Electrolyser Capacity Factors

Configuration	AE	PEM
Solar PV	30.13%	30.44%
Wind	42.26%	43.89%
Hybrid	35.58%	37.12%

North West Tasmania — Electrolyser Capacity Factors

Configuration	AE	PEM
Solar PV	20.84%	21.69%
Wind	43.70%	32.55%
Hybrid	45.53%	28.96%

Murray River, Vic — Electrolyser Capacity Factors

Configuration	AE	PEM
Solar PV	29.46%	29.85%
Wind	28.82%	30.76%
Hybrid	27.53%	30.19%

Tasmania Midlands — Electrolyser Capacity Factors

Configuration	AE	PEM
Solar PV	23.15%	23.88%
Wind	53.38%	54.52%
Hybrid	37.87%	39.17%

Gippsland, Vic — Electrolyser Capacity Factors

Configuration	AE	PEM
Solar PV	22.33%	23.20%
Wind	26.91%	29.12%
Hybrid	22.84%	25.73%

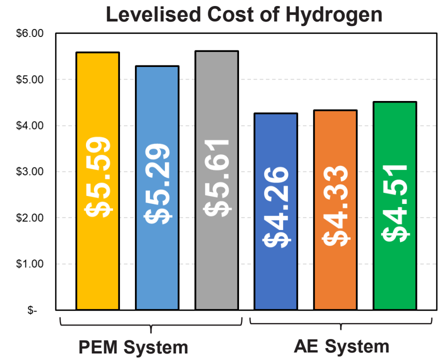
The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Figure 20: Additional Modelling Results for selected locations in New South Wales, Western Australia and the Northern Territory using data provided by stakeholders.
Assumptions: 50MW AE or PEM electrolyser operating with a solar PV farm (50 MW), a wind farm (50 MW) and a hybrid solar + wind supply (50 MW) with a 50/50 combination of solar and wind AE electrolyser is assumed to have an overall system (stack + BoP) energy requirement of 64 kWh/kg, and the PEM system is assumed to energy requirement of 66.5 kWh/kg, based on the average of the energy consumption ranges provided by IRENA.[22] A stack lifetime of 80,000 hrs was used for both AE and PEM electrolyser. The AE electrolyser is assumed to cost A$500/kW while the PEM electrolyser costs A$750/kW (based on Vendor advice Additionally, Electrolyser O&M of 2.5% of CAPEX cost p.a., stack replacement of 40% of CAPEX cost per replacement, solar CAPEX of A$1,410/kW and wind CAPEX of A$1,951/kW was considered. A discount rate of 4% was used over a project life of 20 years. **Source:** HySupply modelling tool. **Note:** all values are in A$.

McArthur, NT

Electrolyser Capacity Factors

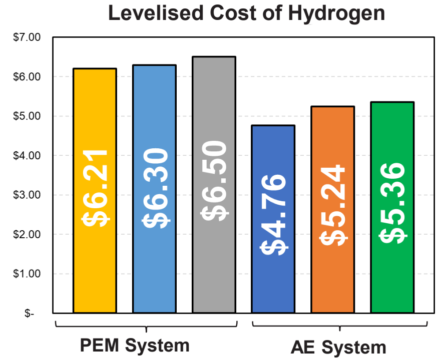
Configuration	AE	PEM
Solar PV	28.30%	28.74%
Wind	37.14%	39.01%
Hybrid	31.88%	33.66%



Baines, NT

Electrolyser Capacity Factors

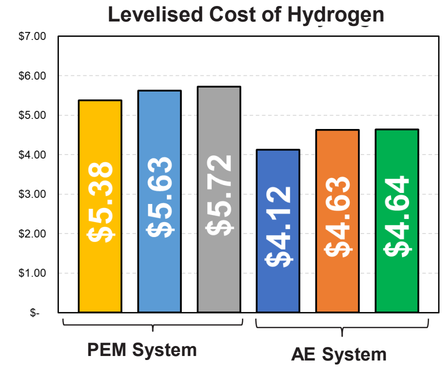
Configuration	AE	PEM
Solar PV	25.31%	28.30%
Wind	30.47%	32.55%
Hybrid	26.73%	28.96%



New England, NSW

Electrolyser Capacity Factors

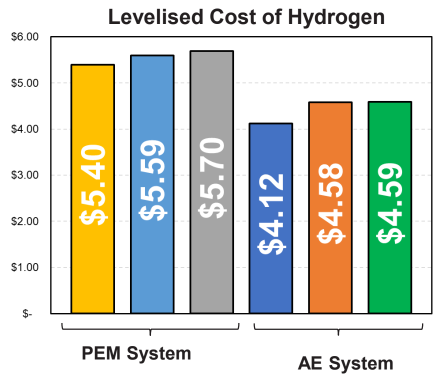
Configuration	AE	PEM
Solar PV	29.28%	29.77%
Wind	34.60%	36.52%
Hybrid	30.96%	33.00%

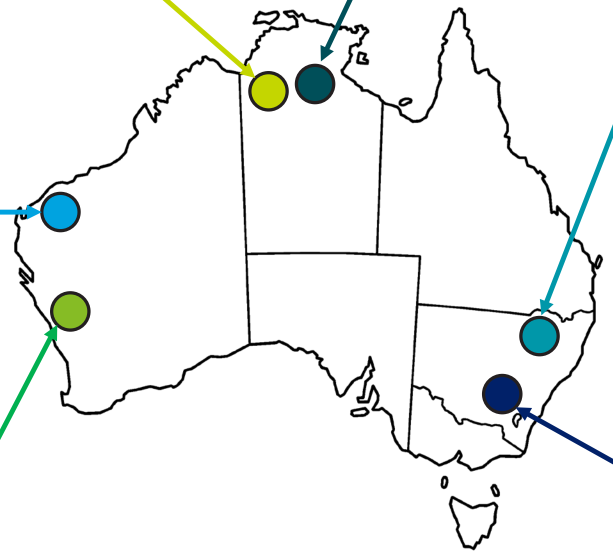


Ashburton, WA

Electrolyser Capacity Factors

Configuration	AE	PEM
Solar PV	29.33%	29.74%
Wind	35.02%	36.88%
Hybrid	31.32%	33.15%

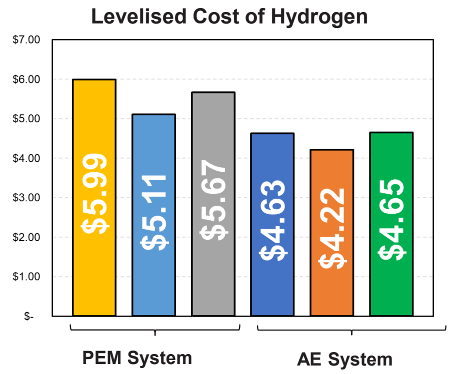




Southern NSW Tablelands

Electrolyser Capacity Factors

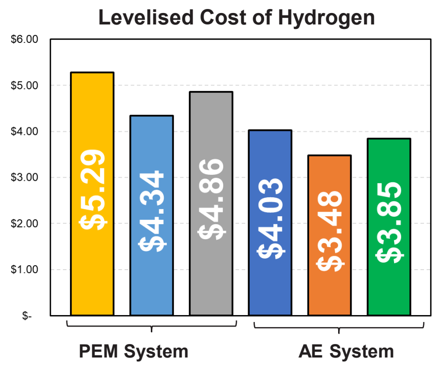
Configuration	AE	PEM
Solar PV	26.07%	26.73%
Wind	38.14%	40.43%
Hybrid	30.86%	33.33%



Geraldton, WA

Electrolyser Capacity Factors

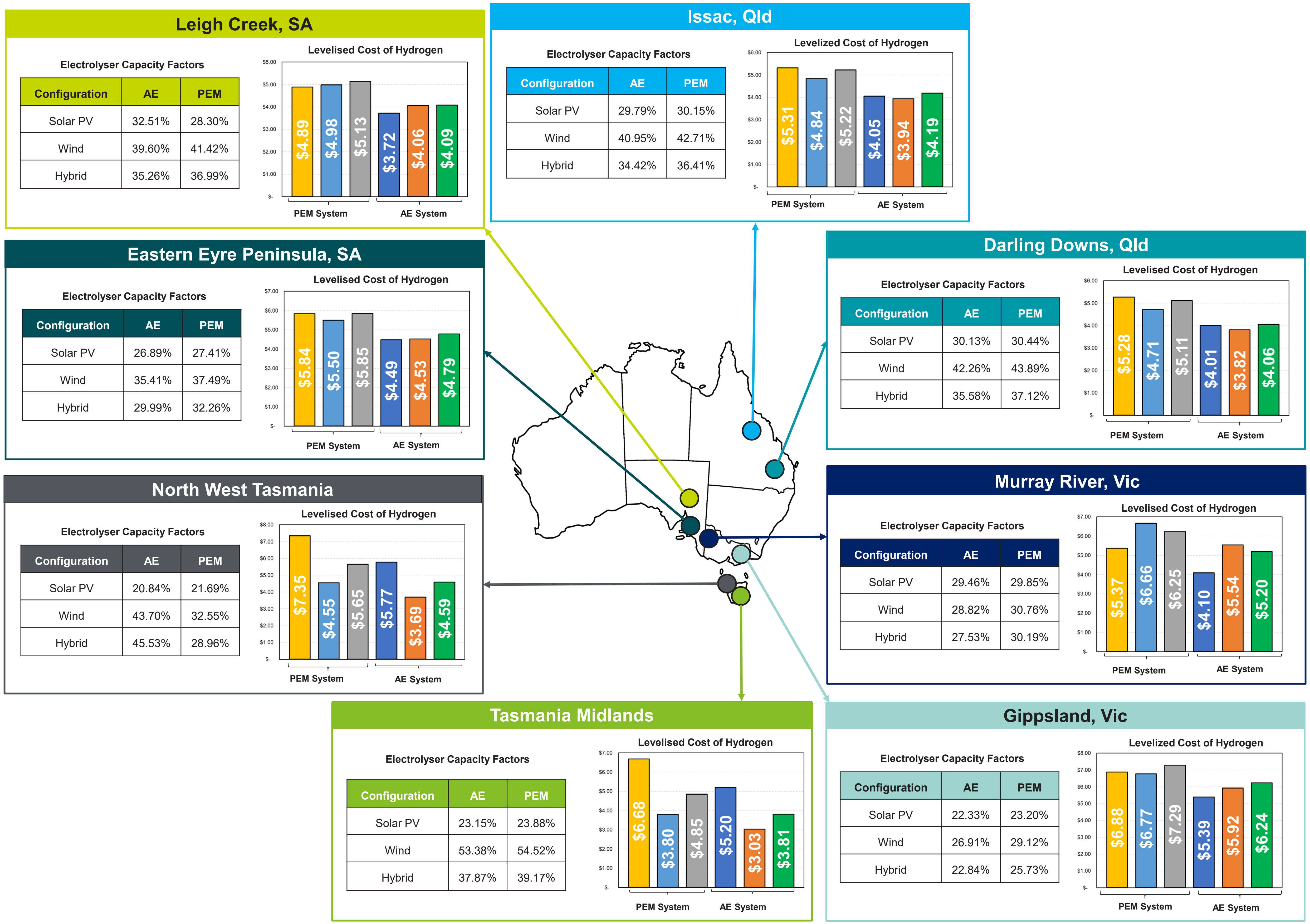
Configuration	AE	PEM
Solar PV	30.00%	30.39%
Wind	46.47%	47.92%
Hybrid	37.54%	39.08%



Key

- Electrolyser Facility
- Solar PV - AE LCH_2
- Wind - AE LCH_2
- Hybrid - AE LCH_2
- Solar PV - PEM LCH_2
- Wind - PEM LCH_2
- Hybrid - PEM LCH_2

Figure 21: Additional Modelling Results for selected locations in Queensland, South Australia, Victoria, Tasmania and South Australia using data provided by stakeholders.
Assumptions: 50 MW AE/PEM electrolyser operating with a solar PV farm (50 MW), a wind farm (50 MW) and a hybrid solar + wind supply (50 MW) with a 50/50 combination of solar and wind. The results were established using the same assumptions listed in **Figure 20** (AE and PEM CAPEX of A$500/kW and A$750/kW respectively, total energy requirement of 64 and 66.5 kWh/kg respectively, Solar and Wind CAPEX of A$1,410 and A$1,951/kW, Electrolyser O&M of 2.5% of CAPEX p.a., Stack lifetime of 80,000 hours at a cost of 40% of CAPEX per replacement, discount rate of 4% and project life of 20 years). **Source:** HySupply modelling tool. **Note:** all values are in A$.



6.4. Storage and Transportation Pathways

A hydrogen export value chain will, of course, require careful consideration of the technical and commercial readiness of different possible storage, conversion, transport and potentially reconversion steps.

Previous R&D investment and investigations have primarily focused on transporting hydrogen in either gaseous or liquid form and relatively small quantities. However, in recent times the conversion of renewable hydrogen to ammonia, low-carbon methane and low-carbon methanol using Power-to-X pathways (PtX) has also received growing interest. PtX enables the use of existing export infrastructure and commercial conversion pathways to transport and store hydrogen in the form of PtX chemicals. Furthermore, liquid organic hydrogen carriers (LOHCs), large-scale liquified hydrogen and metal-hydrides are widely expected to play a key role in a future emission-free H_2 transport value chain. A high-level summary of the various hydrogen carriers including their storage and transportation costs is provide in this section. Section 6.8 overlays carrier conversion costs with storage and transportation costs to provide indicative value chain costs from Australia to Germany.

Current analysis suggests that while the conversion of renewable hydrogen to carriers will incur significant energy losses and costs, the potential additional costs for storage and transportation for these pathways may add a relatively small component to the total value chain cost. In addition, there are some considerable challenges including renewable hydrogen and energy integration for carrier conversion pathways, emissions from shipping and regulatory uncertainty, all also requiring additional investigation. Future transportation pathways may require infrastructure investment and complete retrofitting of maritime shipping and port infrastructure. The Roadmapping phase of HySupply is exploring these challenges in detail.

Given these diverse factors, and the range of potential hydrogen and hydrogen derivative uses in Germany, a number of pathways may succeed side by side. A multi-criteria analysis (MCA) tool has therefore been developed to provide a means for comparing these hydrogen carriers across a broad range of techno-economic criteria (**Sections 6.7**). The MCA has been developed as an interactive tool to enable users to adjust the weighting of individual criterion based on their requirements.

6.4.1. Compressed Hydrogen Gas

Compressed storage provides a commercial pathway for hydrogen storage and transportation over limited distances. Theoretically, hydrogen storage requires 1.05 kWh/kg_{H2} to pressurise hydrogen from 20 bar to 350 bar, however, process inefficiencies increase the energy requirement to 1.7 kWh/kg_{H2}.[121] Compressed gas storage is widely used for stationary storage as well for small-scale vehicular and pipeline transport. However, at present, no current supply chain data exists for exporting compressed hydrogen.[122] **Table 6** presents the current reported costs of compressed hydrogen transport from a range of studies.

A cost-effective alternative for large-scale hydrogen storage is the use of salt-caverns, where large volumes of hydrogen can be stored without the need for additional compression. This was proposed in the NHR for seasonal hydrogen storage.[115] Preliminary analysis by Geoscience Australia have identified salt cavern formations in central Queensland, southern parts of the Northern Territory and northern Western Australia, which might potentially be used for hydrogen storage.[123] From a hydrogen value chain perspective, the co-location of hydrogen generation facility to a port that is in close proximity to a suitable salt cavern, provides an energy efficient and cost effective pathway for hydrogen storage.[124] Further feasibility analysis still needs to be performed to identify salt caverns in Australia that are in close proximity to suitable infrastructure including ports.

Investigations are currently underway for the retrofitting of natural gas storage sites to enable a hydrogen value chain.[125] This could provide another cost-effective solution for large-scale hydrogen storage as Australia's existing natural gas infrastructure can be leveraged. For instance, the Pilbara region in Western Australia provides a potentially highly attractive logistical platform for an Australia-Germany hydrogen value chain due to existing natural gas infrastructure and port access.

Transportation of compressed hydrogen

Compressed hydrogen gas can be transported via trucks, rail, pipelines and ship:

Road Freight: High pressure tube-trailers allow for compressed hydrogen transport up to distances of approximately ~320 km, transporting up to 1,000 kg, depending upon the pressure allowed by regulation.[218,219] The NHR estimates this would cost A$2.33/$t_{H2}$km at 430 bar pressure. Other studies have placed this cost to be between A$2.43/$t_{H2}$km – $3.23/$t_{H2}$km over a 300 km distance, with costs highly dependent upon distance and labor costs.[126]

Railway: Railway systems with tanks (like tube trailers) would allow for a greater quantity of compressed hydrogen transport over longer distances from 800 – 1,100 km at a modelled cost of A$0.55/$t_{H2}$km.[115]

Pipelines: Pipelines for intercity transmission with varied conditions and pipeline materials to overcome hydrogen embrittlement are also an option for distances between 1,000 – 4,000 km. For distances of 1,000 km, the transportation costs are modelled as A$0.22 – 0.42/$t_{H2}$km[128] and for distances of 1,500 km, the costs are estimated to be A$0.95/$t_{H2}$km.[10]

Ship: Currently no commercial data exists for the transportation of compressed hydrogen, however preliminary modelling for compressed hydrogen transport by shipping equates to A$0.52/$t_{H2}$km.[115]

Table 6: Cost analysis for compressed hydrogen transport using road, pipeline, rail and ship.‡

Transportation Method	Distance (km)	Scale Per Trip (t)	Cost Analysis (A$/$t_{H2}$km)	Reference
Road	< 1,000	0.8-1.042	2.33	115
Road	> 300	15	2.43-3.23	126
Road	300-400	-	3.38	127
Road	500	-	5.14	10
Rail	800 -1,100	-	0.55	115
Pipeline	1,000	-	0.22 – 0.42	128
Pipeline	1,500	-	0.95	10
Ship	> 4,000	10,840	0.52	115

Note: The values in the tables are based on preliminary analysis of the values provided in cited literature and is therefore subject to change after more detailed analysis.

6.4.2. Liquefied Hydrogen

Liquefied hydrogen is increasingly viewed as a promising pathway for high volume storage and transportation of hydrogen, as the density of liquefied hydrogen is 71 kg/m^3, providing high volume export benefits. Widely used as rocket fuel, small-scale liquified hydrogen systems have a high technology readiness level. Liquefaction of hydrogen, however, has a significant energy requirement as hydrogen has a freezing point of -253°C, therefore, requiring cryogenic infrastructure. The use of cryogenic infrastructure results in the need for high capital investment, and hence production costs. However, efficiency improvements (from current ~55%) arising from utilisation of complex cooling cycles and technology scale-up is expected to drive down costs.

A hydrogen value chain that features liquefied hydrogen will ideally require the co-location of generation and liquefaction operations near port infrastructure, to minimise energy losses associated with storage and transportation. The co-location of the generation and liquefication processes may also enable the re-circulation of waste heat back into the hydrogen generation process, providing process efficiency benefits.[129] The establishment of such hydrogen value chain may also require specific port facilities allotted solely to hydrogen export, as the feasibility of the process requires hydrogen export at scale.

The key advantage of LH_2 is the avoidance of significant reconversion infrastructure at destination port, making this pathway increasingly attractive for off-takers who seek 'renewable hydrogen'. Further, the ships can be powered by hydrogen itself, enabling a clean hydrogen value chain. Given the similarity in technology and shipping infrastructure with LNG, it is envisaged that lessons and experiences with ramping up LNG trade can be used to guide the development of large-scale LH_2 value chain.

‡ **Note:** HySupply is working with industry partners from Australia and Germany to model accurate storage and transportation costs.

In Australia, the Hydrogen Energy Supply Chain (HESC) project is developing the world-first liquefied hydrogen supply chain (0.25 tpd capacity) from Australia to Japan and the near-term success and findings of the project will enable better understanding of scale-up, costs and financial levers required for implementation.[130] In South Korea, German manufacturer Linde, in partnership with Hyosung, is building the world's largest LH_2 facility (30 tpd), expected to be completed by 2022.[131] Scale-up is also observed with LH_2 carriers, with Kawasaki Heavy Industries announcing plans to build 160,000 m^3 carriers by 2030.[132] The company has launched the first LH_2 carrier, the 8,000 ton Suiso Frontier as well as building the unloading terminal in Kobe, Japan.[133,134]

Table 7 presents the estimated costs of liquefied hydrogen transport from a range of studies. Indicative liquefied hydrogen chain costs are presented in **Section 6.8.**

Table 7: Cost analysis for liquid hydrogen transport using road, rail and ship.

Transportation Method	Distance (km)	Scale Per Trip (t)	Cost Analysis (A$/$t_{H2}$km)	Reference
Road	< 1,000	3.99	0.92	115
Road	500	-	1.14	10
Road	300-400	-	1.35	127
Rail	800-1,100	-	0.28	115
Ship	> 4,000	10,840	0.09	115
Ship	1,850	11,000	0.65	10
Ship	~3,700 (Algiers – Hamburg)	11,370	0.07	135
Ship	9,260 (Tokyo – Melbourne)	11,370	0.05	136
Ship	12,040 (Qatar – Japan)	11,370	0.03	3

Note: The values in the table are based on preliminary analysis of the values provided in cited literature and are therefore subject to change after more detailed analysis.

6.4.3. Renewable Ammonia

Low-carbon ammonia is seen as a promising pathway for hydrogen export as the value chain will leverage existing infrastructure that is currently used for global ammonia trade. The exported ammonia can be used directly as feedstock, or reconverted to hydrogen (with nitrogen as byproduct). Ammonia can also potentially be directly combusted as a fuel although there are some technology issues to be solved. The ammonia export economy represents a A$6.86 billion market, that supports the production of fertiliser and construction/mining explosives globally.[137]

Renewable ammonia is generated by substituting fossil-fuel based hydrogen used in conventional Haber-Bosch process with renewable hydrogen. While ideally renewable electricity should be used to power the Haber-Bosch process to guarantee that the ammonia is free from emissions, renewable intermittency and system integration on large-scale may present challenges.

Currently, ammonia is transported in large volumes, around the world in ships, pipelines and trucks.[138] Ammonia is predominantly exported in liquid form, as it has a high volumetric density of 123 kg/m^3 at -33.6ºC, which makes it well suited for high volume export.[139,140] Ammonia is typically stored either in large quantities (~50kt) ammonia at 1 bar and −33ºC in insulated tanks or for small scale (1.5kt) storage at room temperature under pressure in stainless steel sphere tanks.[138]

The development of a hydrogen value chain that features ammonia as the carrier, can leverage this existing ammonia value chain with the option for ammonia to hydrogen re-conversion by the off-taker. Hydrogen re-conversion from ammonia is still an early-stage technology with a low TRL, current data suggests an additional ~11 – 13 kWh/kg_{H2} of energy is consumed for the process. [7,186] Recently, CSIRO has developed a pilot-scale demonstration system for an ammonia cracking system based on highly efficient vanadium-based membrane that can generate at least 5 kg of high-purity (~100%) H_2 per day from NH3 feed.[141]

At present, a number of projects and feasibility studies relating to renewable ammonia are underway. For instance, the ARENA funded Yara Pilbara 'Yuri Phase 0' feasibility study concluded that the project is feasible as a grant supported commercial project.[142] A similar study by Queensland Nitrates Pty Ltd explored the development of a 20,000 tpa renewable ammonia plant with a 30 MW alkaline electrolyser, concluding that the project is technically feasible and that a commercial pathway existed for a plant producing 1 million tonnes of green ammonia per year without grants, subsidies or concessional loans, with co-located power generation at a required scale of 10,000 GWh pa.[143] A more recent study by GHD for BP Australia also concluded the existence of commercial pathway, provided some key Government support is available including retrofitting of port infrastructure to handle ammonia exports, prioritised approval pathways and transmission upgrades, amongst other factors.[144]

To note, H2U™ has commenced the development of a green ammonia plant in South Australia (40,000 tpa).[145] Furthermore, the Asian Renewable Energy Hub has commenced preparatory works for world's largest renewable ammonia facility in the Pilbara region of Western Australia.[146] In Tasmania, Origin and FMG are carrying out the feasibility of large-scale renewable ammonia projects.[147]

Table 8 presents the current reported costs of ammonia transport from a range of studies. Indicative renewable ammonia supply chain costs are detailed in **Section 6.8.**

Renewable Ammonia Transportation Costs

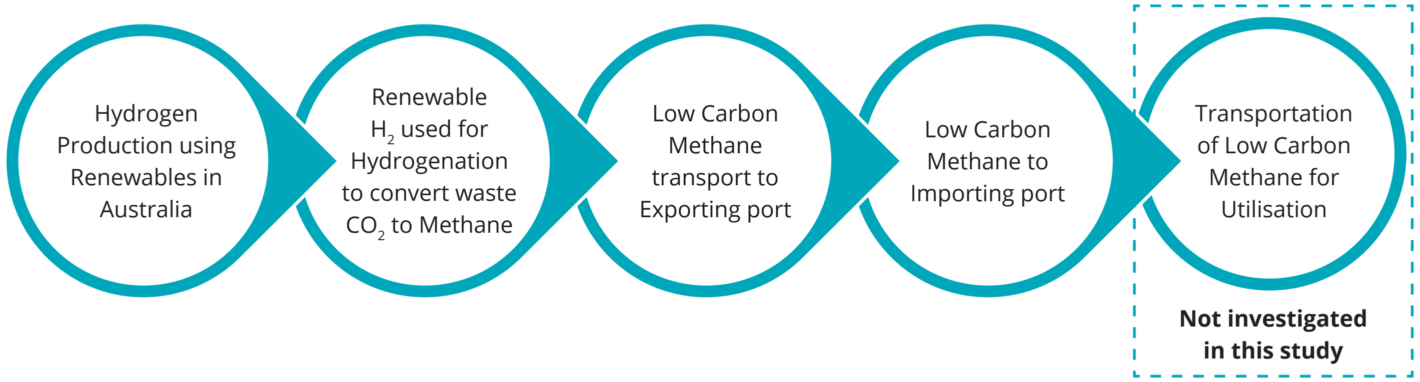
Ammonia can be transported via vehicular, rail and shipping. Road and rail transport for distances more than 1,000 km has a cost profile of A$0.33/$t_{NH3}$km and A$0.04/t_{NH3}km respectively. Intercontinental shipping of ammonia is a mature industry and ammonia's resemblance in liquid characteristics with LPG has enabled the use of LPG infrastructure for ammonia shipping.[205] Current models indicate a cost profile of A$0.03/$t_{NH3}$km.[115]

Table 8: Cost analysis for ammonia transportation using road, pipeline, rail, and ship.

Transportation Method	Distance (km)	Scale Per Trip (t)	Cost Analysis (A$/$t_{NH3}$km)	Reference
Road	< 1000	21.72	0.33	115
Road	500	N/A	0.20	10
Rail	800 -1,100	-	0.04	115
Pipeline	3,000	240,000 tpa	0.26	10
Pipeline	250	-	0.20	148
Ship	3,000	53,000	0.02	10
Ship	> 4,000	-	0.03	115
Ship	12,000 (Qatar to Japan)	109,248	0.01	3

Note: The values in the tables are based on preliminary analysis of the values provided in cited literature and is therefore subject to change after more detailed analysis.

6.4.4. Low-Carbon Methane



Australia is home to one of the world's largest liquid natural gas (LNG) export industries, exporting ~80 million tons of LNG annually. From an infrastructure perspective, the size and scale of the existing LNG industry in Australia means the country is well placed to export low-carbon methane. Currently, all the LNG exported by Australia is sourced from fossil fuel deposits; however, to facilitate a low-carbon methane economy, the LNG will need to be synthetically produced using PtX.

A low-carbon methane pathway will convert CO_2 (from existing point sources such as power plants, biomass or direct air capture) and renewable hydrogen using secondary conversion methanation reactors. This provides Germany with a multi-faceted fuel, as low-carbon methane imported from Australia can be directly integrated into Germany's existing ~95 million-ton LNG import profile, or it can be separated back into hydrogen by the off-taker.[149]

Source of CO_2 for Renewable Methanol and Methane Generation

The sourcing of carbon feedstock for renewable methane and methanol production is subject to much debate. What constitutes as acceptable feedstocks (such as biomass, direct air capture and non-avoidable sources of CO_2) will be further refined through stakeholder consultation with both Australian and German partners. Greater consensus on acceptable sources of CO_2 will markedly influence value chain costs and scalability of these pathways.

In the near-term, Australia may tap into CO_2 emissions from point sources such as natural gas power plants, cement and steel making plants as well as from biomass resources to support synthetic methanol and methane production. While such CO_2 capture technologies enjoy moderately high TRL levels (5 - 9), their costs remain high.[220–225] Literature analysis (**Table 9**), suggests that costs of capture from these sources based on current available technologies can potentially range between A$78 – 150/ton. In the future, DAC may be used, subject to cost reduction and efficiency improvement of the process.

Table 9: Potential carbon capture costs from different point sources based on literature analysis.[226]

Potential Point Source	CO_2 capture cost (A$ per t_{CO2} Captured)
Near Term Options	
Natural Gas Based Power Plants	78 – 150
Steelworks	116 – 122
Cement Kilns	96 – 143
Long Term Options	
Biomass processing facilities	0 – 150
Direct Air Capture (DAC)	370 – 445

Note: The costs were sourced from a review by Dieterich et al.[226], the actual costs were quoted in € (2020 basis) and were converted to U$ basis using the conversion factor of 1€ = 1.18 U$ and then to A$ by using an exchange rate of 1 U$ = 1.37 A$. These costs are subject to change after consultation with stakeholders.

To mobilise this value chain, hydrogen generation will need to be co-located to a suitable waste CO_2 stream, biomass resource or Direct Air Capture (DAC) facility to ensure low-carbon methane production is performed in one centralized location. The low-carbon methane will then be transported and stored using Australia's existing domestic gas pipeline infrastructure, before being subsequently converted into liquid methane and exported using cryogenic storage in ships to Germany.

While renewable Power-to-methane enjoys high conversion technology maturity and a number of such demonstration facilities are operational around the world (including Germany), they present challenges with respect to scalability arising from sourcing of CO_2 stream. As the utilisation of renewable methane will lead to subsequent CO_2 emissions for the end-user, it is likely that the most acceptable CO_2 source for this pathway is from biomass, direct air capture and non-avoidable industrial sources of CO_2. At present, there is limited consensus on what constitute eligible sources of carbon for this pathway. Certainly, the limited availability of biomass, its dispersed distribution and competing demand uses means that the scaling of this pathway may face significant barriers. Direct Air Capture represents the clearest source of carbon neutral CO_2, the associated technologies are still emerging, and have significant energy and cost factors. Existing industrial CO_2. Sources are a lower cost option but pose serious questions for achieved emissions reductions using this methane. Even for non-avoidable point sources that might count as low-carbon, there are challenges of scaling CO_2 capture technologies (including finding the most suitable, efficient technology, and the need to cater for additional impurities and varying concentrations of CO_2 in the flue gas.

While focused on domestic market, Southern Green Gas and APA Group (one of Australia's leading natural gas providers) are exploring the feasibility of renewable methane through their demonstration facility in Queensland which is using direct air capture for its CO_2 source.[150] In Western Australia, ATCO is assessing the feasibility of renewable natural gas that is sourced from a waste facility, with the objective of using this gas for domestic consumers.[151] Findings of these studies will help inform the scalability of a renewable methane pathway.

Table 10 presents the current reported costs of methane transport from a range of studies. Indicative renewable methane supply chain costs are detailed in **Section 6.8.** Note: HySupply is investigating the acceptable carbon sources for methane and methanol pathway through the Roadmapping Phase.

Low-Carbon Methane Transportation Costs

Liquid methane will exhibit the same characteristics as LNG and hence the transportation and storage cost profile will follow the existing LNG value chain cost profile.

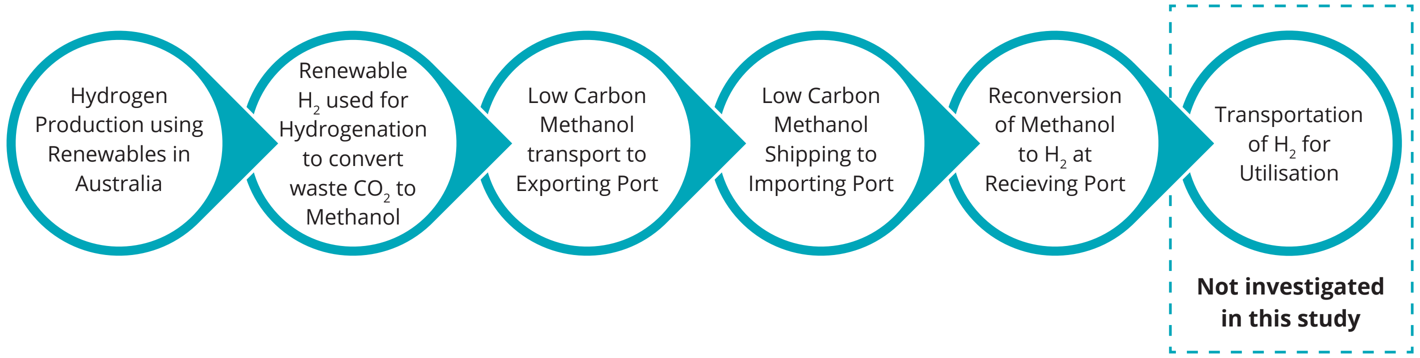
Domestic transportation of methane via steel pipelines costs between A$0.02 – 0.14/$t_{CH4}$km of methane depending upon locations and pipelines.[152] Australia currently, does not export LNG to Germany, however cost profiles for export to Asia are estimated to be between A$0.8 – 1.6 x 10^{-2}/t_{CH4}km of methane.[153,154]

Table 10: Cost analysis for methane transport using road, pipeline and ship.

Transportation Method	Distance (km)	Scale Per Trip (t)	Cost Analysis (A$/$t_{CH4}$km)	Reference
Road	250	-	1.20	148
Pipeline	100 km 174 – 2,081 km	-	0.050 – 0.055 (New Pipeline) * 0.020 – 0.140 (Existing Pipeline) ^	152
Ship	> 4,000 (Australia to Asia)	-	0.8 – 1.6 x 10^{-2}	153,154
Ship	>6,000 km (Qatar to Asia)	-	8 x 10^{-3}	154
Ship	>9,000 km (Canada to Asia)		4 x 10^{-3}	154
Ship	12,000 (Qatar to Japan)	67,696	4.1 x 10^{-3}	3

Note: The values in the tables are based on preliminary analysis of the values provided in the cited literature and is subject to change in the detailed analysis. Here the pipeline gas prices are established based on tariff charges for new * (100 km pipeline) and existing gas pipelines ^ on the eastern and southeastern states of Australia, as suggested by Core Energy Group.[152] The highest existing tariff charge ($A0.154/$t_{CH4}$km) is for the Tasmanian Gas Pipeline which runs offshore for 780 km. While the onshore pipelines range from 174 km (Longford to Melbourne Gas Pipeline) to 2,081 km (Moomba to Sydney Pipeline), with associated tariffs ranging from $A0.020/ton-km to $A0.088/ton-km

6.4.5. Low-carbon Methanol



Globally, over 80 million tons of methanol is traded annually,[155] serving as a key building block for numerous chemical supply chains. The EU itself imported close to 10% of that volume in 2018. At present, methanol is exclusively produced through the conversion of syngas, sourced from steam methane reforming of natural gas, using a hydrogenation reaction. This process involves high temperature (220 - 280°C) and pressure (1-8 MPa),[156] resulting in a high energy input of around 35 GJ and CO_2 emissions of 0.5 ton per ton of methanol generated.[157,158] For the low-carbon methanol pathway, the fossil-fuel derived feedstocks are replaced by renewable hydrogen and waste CO_2 streams (as discussed above in **Section 6.4.4.**).

A key advantage of renewable methanol is that it can be stored under ambient conditions within steel chemical tanks and be transported using existing shipping infrastructure, given that conventional methanol is amongst the most traded chemical commodity around the world, with a wide range of vessels potentially available for charter.

Further, the ships carrying renewable methanol can also be retrofitted to run on the fuel itself. On a small scale, MAN Energy is offering methanol run combustion engines for shipping.[159] Recently, A.P. Moller-Maersk, the world's largest shipping company, has announced plans to produce renewable methanol (from biogenic CO_2) in partnership with REintegrate, to power their first carbon-neutral methanol powered vessel.[160]

In the port of destination, the renewable methanol can then be used directly to support German industries as a feedstock or re-converted into hydrogen. This reconversion, however, presents some challenges as current reconversion technologies entail the requirement of an energy-intensive reforming process at high temperatures (>400°C) followed by purification to remove waste CO_2 and CO streams from hydrogen. Further research into developing low-temperature reforming pathway may assist in alleviating these energy losses and costs.

There are also questions on the acceptability of CO_2 emissions arising from renewable methanol utilisation directly as feedstock in Germany. While there is some discussion that if the methanol is generated using CO_2 feedstocks sourced from biomass and non-avoidable sources, it could be acceptable to off-takers, however at present, there is not yet a clear consensus on this issue. **HySupply will explore the acceptable carbon sources for methane and methanol pathway through the Roadmapping Phase.** Moreover, as discussed above, challenges with large-scale biomass sourcing and scaling of CO_2 capture technologies for non-avoidable sources of CO_2 also present barriers in implementation.

In Australia, ABEL Energy is planning a renewable methanol facility in Bell Bay, Tasmania to generate 60,000 tpa, focused mainly for the export market.[161] The George Olah plant owned and operated by Carbon Recycling International has been operational since 2012, generating 5 million litres of renewable methanol per year.[162] Proman, the world's second largest methanol producer, has announced plans to co-develop a renewable methanol export facility (44,000 tonnes per year) using local CO_2 sources in Scotland, in partnership with Global Energy Group.[163]

Table 11 presents the current reported costs of methanol transport from a range of studies. Indicative renewable methanol supply chain costs are detailed in **Section 6.8.**

Table 11: Cost analysis for methanol transport using road, and ship.

Transportation Method	Distance (km)	Scale Per Trip (t)	Cost Analysis (A$/$t_{MeOH}$km)	Reference
Road	250	-	0.37	135
Ship	3,700 (Algiers to Hamburg)	75,000	0.165	135
Ship	12,000 (Qatar to Japan)	128,800	1.49 x 10^{-3}	3

Note: The values in the table are based on preliminary analysis of the values provided in cited literature and therefore are subject to change after more detailed analysis.

6.4.6. Liquid Organic Hydrogen Carriers (LOHCs)

LOHCs represent a unique opportunity for the hydrogen value chain from Australia to Germany, as the carrier can undergo multiple hydrogenation (adding hydrogen to the $LOHC^-$) and dehydrogenation (removing hydrogen from the $LOHC^+$) cycles, with minimal carrier loss, therefore enabling a potential cyclical value chain to be developed. Common LOHCs include N-ethylcarbazole, Dibenzyltoluene, Naphthalene, dimethyl ether and toluene, each with varying degrees of commercial readiness.[164] For example, toluene is already a commercial manufactured and traded chemical. The advantages of LOHCs include high safety, high storage densities, low cost and ease of handling.[165] Preliminary feasibility studies indicate that LOHC compounds can utilise existing transport and storage infrastructure used for petroleum industry (e.g. pipelines, ships and trucks) reducing the barrier to entry as a hydrogen export pathway.[166]

Key challenges with LOHC use lie in the sourcing of sustainable LOHC compounds, up-scaling of cyclical infrastructure and high costs. Currently, most LOHCs are generated from fossil-fuels, presenting questions on environmental considerations when LOHCs are replaced at the end of their life cycle. While there are proposed pathways of LOHC generation using carbon neutral sources, this requires further R&D. Secondly, given its relatively new application as a hydrogen carrier, existing LOHC hydrogenation and dehydrogenation infrastructure is small-scale (~5 tpd capacity), highlighting the need for considerable scale-up efforts. While LOHC hydrogenation is an exothermic process, releasing heat that can be used in up-stream processes, the downstream LOHC dehydrogenation requires input of thermal energy, and it remains to be seen if such energy input can be provided solely from renewable energy resources in Germany.

The Port of Rotterdam has recently signed a MoU with Mitsubishi Corporation and Chiyoda Corporation, to undertake a feasibility study to develop a commercial scale LOHC infrastructure for hydrogen import at the port, utilising the SPERAHydrogen™ process.[167] Similarly, Hydrogenious LOHC Technologies, a German based company, is developing the world's largest LOHC storage project (1,800 tpa using benzyl toluene) at Dormagen, Germany, as part of a larger plan to develop a green hydrogen supply chain with Rotterdam.[168] The same company is also exploring a LOHC based propulsion systems for ships as a joint venture with the Norwegian company Johannes Østensjø dy AS, with a commercial product expected by 2025.[169]

Table 12 presents the current reported costs of LOHC transport from a range of studies. Indicative LOHC supply chain costs are detailed in **Section 6.8.**

Note- Through consultations with German stakeholders, the appetite for LOHCs will be understood and modelled in the Roadmapping Phase of the study.

Table 12: Cost profile for LOHC transport using road and ship.

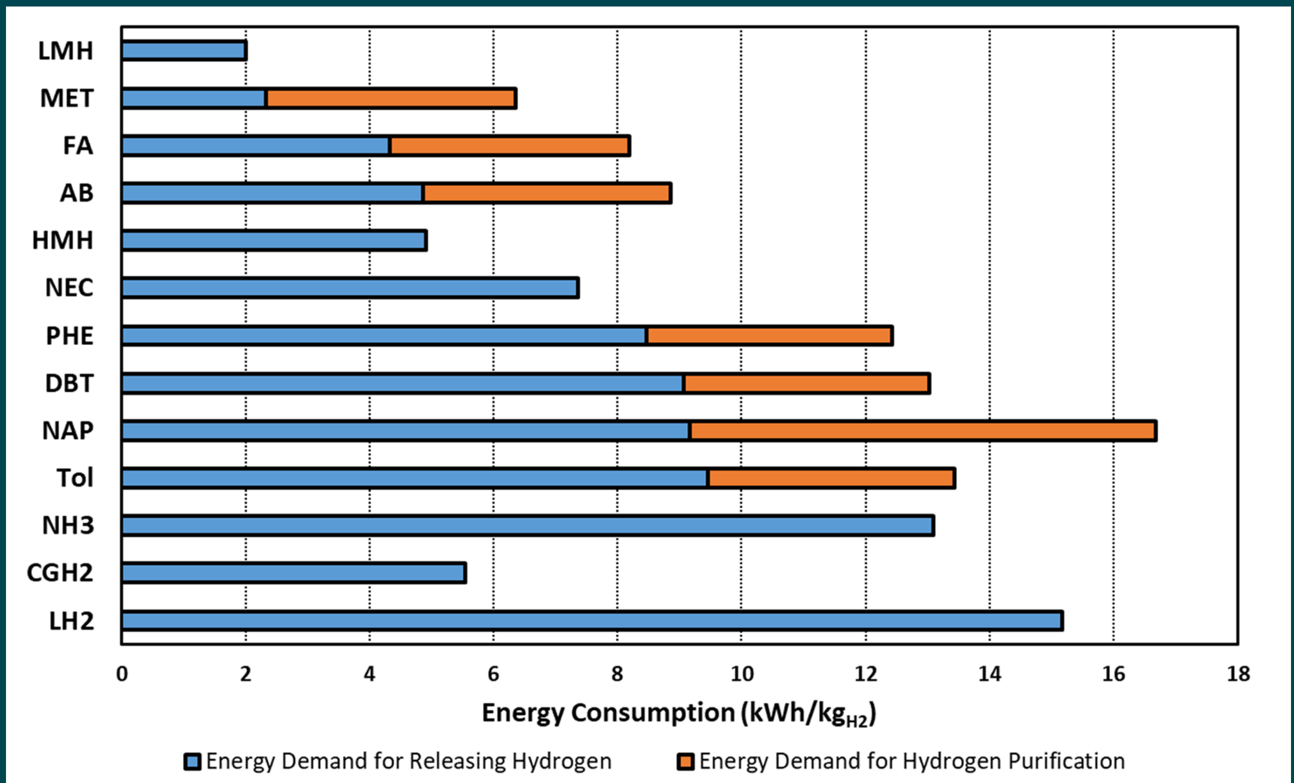
Transportation Method	Distance (km)	Scale Per Trip (t)	Cost Analysis (A$/$t_{LOHC}$km)	Reference
Road	150	-	0.35*	170
Road	300	-	0.34*	171
Ship	1,852	11,000 (tH_2) 110,000 (Toulene)	8×10^{-3}	10
Ship	12,000 (Qatar - Japan)	117,669 (DME)	1.7×10^{-3}	3

Note: The values in the table are based on preliminary analysis of the values provided in cited literature and therefore are subject to change after more detailed analysis. *The costs for road transport are based on methanol.

Carrier Conversion Energy Requirement

In addition to the cost of transport, the total energy requirement for converting hydrogen into the various hydrogen carriers is another key metric. **Figure 22** compares the energy requirement for the different carriers. Overall, the liquid hydrogen has the highest energy requirement, followed by LOHCs, while the compressed hydrogen, methanol and LMH have the lowest energy requirement.

Figure 22: Comparison of energy requirements for different storage technologies.[10,164,204]
Here LH2: liquefied hydrogen, NH_3 is Ammonia, TOL: toluene, NAP: naphthalene, DBT: dibenzyltoluene, PHE: phenazine, NEC: N-ethylcarbazole, HMH: high-temperature metal hydride, AB: 1,2-dihydro-1,2-azaborine, CGH2: compressed hydrogen gas, FA: formic acid, MET: methanol, LMH: low-temperature metal hydride.



Note: There are emerging hydrogen carriers such as solid-state metal-hydrides, which are able to chemically bond hydrogen and then release the molecule with the addition of heat. These carriers will be further explored in the Roadmapping phase of HySupply with stakeholder consultation given limited studies.

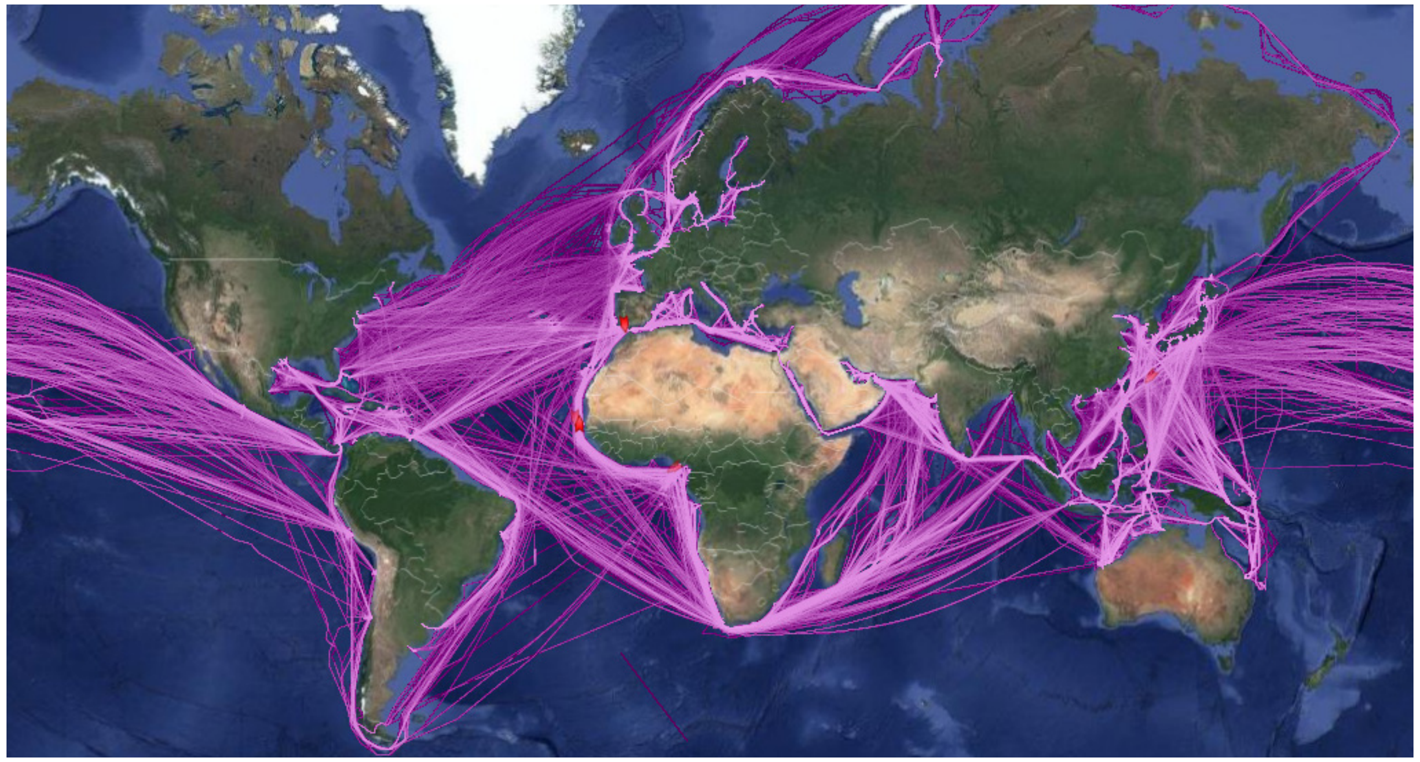
The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

6.5. Preliminary Shipping Modelling

Preliminary transportation modelling was performed using literature-derived data, to provide an indicative basis to compare the 'cost premium' between different locations globally for hydrogen carrier export to Germany. In this analysis various locations in Australia were compared against other emerging hydrogen exporters in North Africa, Middle East, North America, South Africa and Chile. This analysis is also designed to improve our understanding of Australia's hydrogen competitiveness and identify potential next steps that might be required to ensure cost-parity with other key competitors.

It should be noted that the shipping distance between Australia and Germany is one of the longest routes in the world, as shown in **Figure 23**. However, the emergence of low/zero-carbon energy as the primary energy source, may result in the expansion of energy import from larger distances, for markets that are constrained by renewable energy resources.

Figure 23: LNG Shipping Density Map for 2019.[172]



It is widely reported that the cost of hydrogen and its conversion to derivates suitable for transportation is likely to make up the bulk of the transportation costs, and that distances (i.e. days on ship), plays a less significant role. As part of HySupply, we are developing a detailed shipping model on the different carriers identified above to estimated shipment costs from major Australian ports to European ports that can potentially serve German domestic hydrogen demand using established shipping channels. A brief overview of these results is presented in **Table 13**.

Note that these cost estimates are from port of origin to port of destination only and does not take into account port-loading and unloading costs, which is intended to be explored in detail as part of the Roadmapping phase of HySupply. They do include the capital and operating costs of the ships, including potentially different ship fuel costs depending on conventional heavy fuel oil (HFO) or cleaner fuels, including potentially the hydrogen or hydrogen derivative being shipped.

Shipping distances vary from around 7,500 to 11,700 nautical miles depending on the Australian and European port. Nevertheless, estimated shipping costs vary from A$0.85–1.2/kg for liquified hydrogen, A$0.17–0.25/kg for methane, A$0.09–0.12/kg for ammonia, A$0.07–0.105/kg for DME and A$0.07–0.10/kg for methanol. Note that these costs are per kg of carrier itself.

Table 13: Overview of preliminary transportation costs from various Australian ports to Rotterdam and Italy.[††]

Port of Departure	Port of Arrival	Distance Nautical miles (km)	CH_4 (A$/kg)	NH_3 (A$/kg)	CH_3OH (A$/kg)	DME (A$/kg)	LH_2 (A$/kg)
Geraldton (WA)	Italy	7,478 (13,850 km)	0.170	0.087	0.069	0.074	0.847
Geraldton (WA)	Rotterdam	9,441 (17,485 km)	0.205	0.104	0.083	0.088	1.010
Darwin (NT)	Italy	8,053 (14,915 km)	0.180	0.092	0.073	0.078	0.895
Darwin (NT)	Rotterdam	10,016 (18,550 km)	0.215	0.109	0.086	0.092	1.058
Gladstone (Qld)	Italy	9,790 (18,131 km)	0.211	0.107	0.085	0.091	1.039
Gladstone (Qld)	Rotterdam	11,753 (21,767 km)	0.246	0.124	0.098	0.105	1.201
Kembla (NSW)	Italy	9,562 (17,708 km)	0.207	0.105	0.083	0.089	1.020
Kembla (NSW)	Rotterdam	11,525 (21,344 km)	0.242	0.122	0.097	0.103	1.183
Western Port (VIC)	Italy	9,128 (16,905 km)	0.199	0.101	0.080	0.086	0.984
Western Port (VIC)	Rotterdam	11,091 (20,540 km)	0.234	0.118	0.094	0.100	1.147
Port Pirie (SA)	Italy	8,870 (16,427 km)	0.195	0.099	0.079	0.084	0.963
Port Pirie (SA)	Rotterdam	10,883 (20,155 km)	0.229	0.116	0.092	0.098	1.125
Burnie (TAS)	Italy	9,181 (17,003 km)	0.200	0.102	0.081	0.086	0.988
Burnie (TAS)	Rotterdam	11,144 (20,639 km)	0.235	0.118	0.094	0.101	1.151

Note: The values in the table are based on a preliminary analysis conducted internally as part of HySupply and are subject to change in detailed analysis. The values provided are levelised over the amount of carrier and are visualised in **Figure 24.**

We have further estimated the cost of hydrogen shipment in the form of different carriers from other potential hydrogen exporting countries located geographically closer to the EU. These results (**Table 14**) re-affirm that days on ship is not the most critical factor in dictating the feasibility of a hydrogen value chain, given that the transportation costs from Australia are only slightly higher compared to from the Middle East, North and South Americas. It should also be noted that these proposed regions, which are identified to be able to generate hydrogen at low-cost, do not have any existing large-scale hydrogen projects.

[††] **Note:** These costs are representative of just the shipping distance and do not consider pre- and post-conversion costs, which would be elaborated in subsequent modelling exercises.

Table 14: Overview of preliminary transportation costs from various non-Australian ports to Rotterdam and Italy.

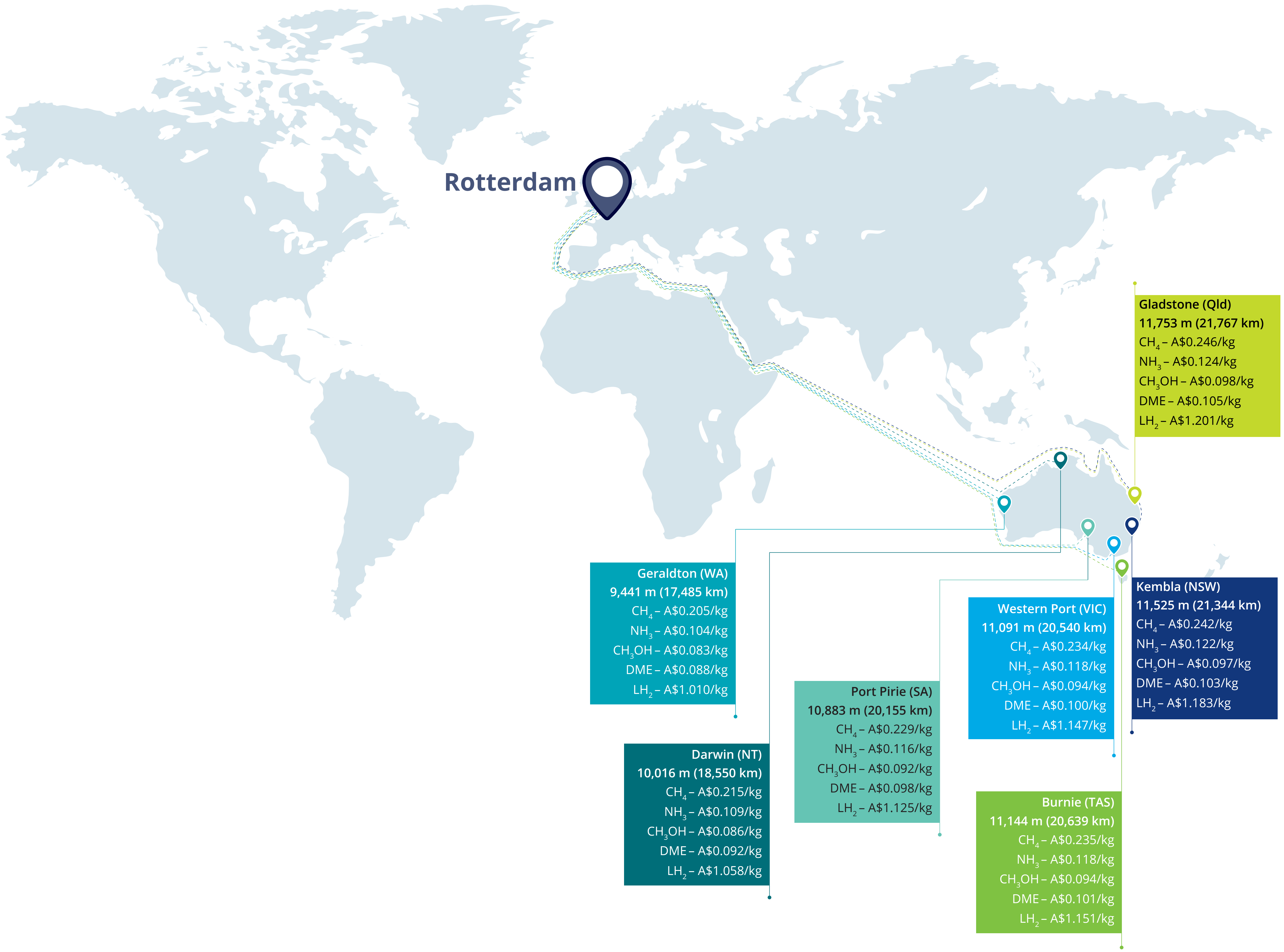
Port of Departure	Port of Arrival	Distance Nautical miles (km)	CH_4 (A$/kg)	NH_3 (A$/kg)	CH_3OH (A$/kg)	DME (A$/kg)	LH_2 (A$/kg)
Doha (Qatar)	Italy	4,380 (8,111 km)	0.115	0.060	0.048	0.052	0.591
Doha (Qatar)	Rotterdam	6,343 (11,747 km)	0.150	0.077	0.062	0.066	0.753
Dubai (UAE)	Italy	4,202 (7,728 km)	0.112	0.059	0.047	0.051	0.576
Dubai (UAE)	Rotterdam	6,165 (11,418 km)	0.147	0.076	0.060	0.065	0.739
Cape Town (South Africa)	Italy	6,657 (12,328 km)	0.139	0.069	0.055	0.058	0.679
Cape Town (South Africa)	Rotterdam	6,163 (11,413 km)	0.130	0.065	0.051	0.055	0.638
Santiago (Chile)	Italy	8,643 (16,006 km)	0.188	0.096	0.076	0.081	0.931
Santiago (Chile)	Rotterdam	7,455 (13,788 km)	0.167	0.085	0.068	0.073	0.833
Jeddah (Saudi Arabia)	Italy	2,034 (3,767 km)	0.074	0.040	0.032	0.035	0.397
Jeddah (Saudi Arabia)	Rotterdam	3,997 (7,402 km)	0.108	0.057	0.046	0.049	0.559
Texas (USA)	Italy	6,392 (11,838 km)	0.134	0.067	0.053	0.057	0.657
Texas (USA)	Rotterdam	5,012 (9,282 km)	0.109	0.055	0.044	0.047	0.543
Algiers (Algeria)	Italy	1,256 (2,326 km)	0.043	0.023	0.018	0.020	0.232
Algiers (Algeria)	Rotterdam	1,773 (3,284 km)	0.052	0.027	0.022	0.023	0.274

Note: The values in the table are based on a preliminary analysis conducted internally as part of HySupply and are subject to change in detailed analysis. The values provided are levelised over the amount of carrier and are visualised in **Figure 25.**

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Figure 24: Estimated transportation costs for different hydrogen carriers for selected Australian ports to Port of Rotterdam.

Note: The levelised cost of shipping is calculated by adding the annual capital and operating costs and dividing by the annual total energy delivered to get a A$/GJ value. This total energy delivered is dependent on the shipping route length, time at port and days per year the ship is available for operation. Annual capital costs were calculated using a capital recovery factor for the ship capital costs, with an interest rate of 10% and economic life of 15 years.[3] Similarly, the operating costs were evaluated based on insurance costs are considered as an additional annual fixed operating cost[227] and the annual variable operating costs which include shipping fuel, labour, canal usage charges, port fees, maintenance, other miscellaneous and BOG costs, the values were adopted from literature and publicly available resources.[3,227–231] Full details on the assumptions and values used are available in https://www.globh2e.org.au/hysupply.



The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Figure 25: Estimated transportation costs for different hydrogen carriers from selected ports around the world to Port of Rotterdam.
Note: The levelised cost of shipping is calculated by adding the annual capital and operating costs and dividing by the annual total energy delivered to get a A$/GJ value. This total energy delivered is dependent on the shipping route length, time at port and days per year the ship is available for operation. Annual capital costs were calculated using a capital recovery factor for the ship capital costs, with an interest rate of 10% and economic life of 15 years.[3] Similarly, the operating costs were evaluated based on insurance costs are considered as an additional annual fixed operating cost[227] and the annual variable operating costs which include shipping fuel, labour, canal usage charges, port fees, maintenance, other miscellaneous and BOG costs, the values were adopted from literature and publicly available resources.[3,227–231] Full details on the assumptions and values used are available in https://www.globh2e.org.au/hysupply.

6.6. Hydrogen Carrier Assessment

A multi-criteria analysis (MCA) tool was developed by HySupply Australia to provide a preliminary analysis mechanism for assessing the most promising form of hydrogen derivative for export between Australia and Germany, subject to different criteria. The MCA tool was developed to assess the hydrogen derivatives against key techno-economic criteria, such as commercial, hydrogen export, energy export, transportation and decarbonisation benefits. The criteria list was developed in collaboration with stakeholders and the justifications are provided in **Appendix C**. It is important to appreciate that the 'scores' for different hydrogen derivative options against each of these criteria and the weighting of different criteria are matters of judgement, and stakeholders will bring their own perspectives to its application.

Note – for the MCA tool, while we provide provision to consider reconversion infrastructure, we do not include it for our analysis as at this stage, it remains unclear if some of the hydrogen carrier options will be used directly or reconverted to extract hydrogen for application in Germany. Further consultation with the German stakeholders will assist in determining preferred forms of hydrogen to meet German requirements.

Preliminary outputs from the MCA tool have been provided in Table 15, to demonstrate how different stakeholder motivations and priorities, can translate into different hydrogen value chain outcomes. Three key outputs are presented, a base case, energy-export focused case, and low-carbon focused case:

- **Base case MCA** - provides a balanced assessment of the hydrogen carriers against key techno-economic considerations such as TRL, CAPEX, OPEX, transportation costs and decarbonisation. The weightings have been spread relatively equally across the key themes required for a robust Australia-Germany value chain.
- **Energy Export Focused MCA** - is designed to promote energy export with a higher focus on energy density, transportation losses and technology readiness. This output represents a case where economic considerations are reduced in weighting, as it presents a scenario where the need for energy outweighs financial considerations for Germany.
- **Decarbonisation Focused MCA** - is designed to particularly promote low-carbon outcomes for Germany through a higher weighting of decarbonisation benefits.

Note – this tool will be updated regularly as the current technology and commercial outlook is focused predominantly on a 2020–2025 time horizon.

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Table 15: Base Case, Energy Export Focused and Decarbonisation Focused Multi-criteria Analysis for the Hydrogen Export Value Chain.
(Here LH_2 is liquefied hydrogen, NH_3 is ammonia, CH_4 is methane, CH_3OH is methanol, LOHCs are liquid organic hydrogen carriers with di-methyl ether, DME, used as the example).

Criterion	Evaluation Band					Base Case MCA						Energy Export Focused MCA						Decarbonisation Focused MCA					
						Weighting	Score					Weighting	Score					Weighting	Score				
	LH_2	NH_3	CH_4	CH_3OH	LOHCs		LH_2	NH_3	CH_4	CH_3OH	LOHCs		LH_2	NH_3	CH_4	CH_3OH	LOHCs		LH_2	NH_3	CH_4	CH_3OH	LOHCs
Commercial Metrics																							
Technology Readiness	3	5	5	4	3	15.00	45	75	75	60	45	15.00	45	75	75	60	45	10.00	30	50	50	40	30
Capital Cost for Carrier Implementation in terms of energy exported p.a. (A$ kWh^{-1} yr^{-1})	2	2	5	2	1	15.00	30	30	75	30	15	5.00	10	10	25	10	5	5.00	10	10	25	10	5
Operating Cost for Carrier Production in terms of energy exported p.a. (A$ kWh^{-1} yr^{-1})	2	4	5	4	1	15.00	30	60	75	60	15	5.00	10	20	25	20	5	5.00	10	20	25	20	5
Hydrogen Export Metrics																							
Hydrogen Storage Density	5	3	4	2	1	5.00	25	15	20	10	5	15.00	75	45	60	30	15	5.00	25	15	20	10	5
Hydrogen Conversion Efficiency	5	3	4	5	4	5.00	25	15	20	25	20	5.00	25	15	20	25	20	5.00	25	15	20	25	20
Energy Export Metrics																							
Gravimetric Energy Density (MJ kg^{-1})	5	2	5	2	4	5.00	25	10	25	10	20	15.00	75	30	75	30	60	5.00	25	10	25	10	20
Volumetric Energy Density (MJ L^{-1})	1	2	5	4	5	5.00	5	10	25	20	25	15.00	15	30	75	60	75	5.00	5	10	25	20	25
Transportation Metrics																							
Transportation Cost (A$ kg^{-1})	5	4	3	5	5	10.00	50	40	30	50	50	5.00	5	20	15	25	25	5.00	5	20	15	25	25
Carrier Yield Loss During Transportation (%)	1	5	4	5	5	10.00	10	50	40	50	50	15.00	15	75	60	75	75	5.00	5	25	20	25	25
Decarbonisation Metrics																							
Decarbonisation Benefit	5	5	1	1	5	15.00	75	75	15	15	75	5.00	25	25	5	5	25	50.00	250	250	50	50	250
						Total	320	380	400	330	320	Total	300	345	435	340	350	Total	390	425	275	235	410

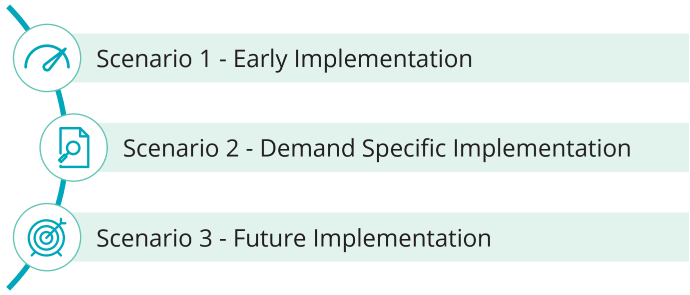
Note: The values in the tables are based on preliminary analysis of the values provided in the cited literature and is subject to change in the detailed analysis. The capital and operating costs represented include the cost of hydrogen generation from electrolysis, its conversion to the carrier, on loading to ship for export, and offloading at receiving port. The costs are then levelised based on the energy content of each hydrogen carrier (in kWh). The analysis is detailed in **Appendix C (Table C1-C2)**.

MCA Summary

Table 15 provides an indicative assessment of the hydrogen carriers against three potential off-taker configurations for hydrogen carrier export from Australia to Germany. Through the base case and energy focused MCA configurations, ammonia and methane have been identified as the highest rated carriers (albeit low-carbon methane may not be the most suitable hydrogen carrier owing to issues discussed below), due to the maturity of the carrier export value chain and the relatively competitive transportation cost profile. In the decarbonisation focused MCA, a greater weighting was provided to the decarbonisation benefits to accommodate for off-takers that prioritise low/zero carbon hydrogen carriers, which resulted in ammonia, LOHCs and liquified hydrogen, being the highest rated carriers respectively. **Note** that the choice of carrier is subjective to off-taker's preference and will be explored in detail within the Roadmapping Phase of HySupply project.

6.7. Hydrogen Export Value Chain Scenarios

The outputs from the 'Base Case MCA' (**Table 15**) have been extrapolated to create three example implementation scenarios for an Australia-Germany hydrogen export value chain. These are indicative and a basis for more detailed discussion and assessment. The selection of the path or paths forward will of course be determined by a potentially wide range of factors including Germany's implementation timeframe, investment appetite, industry involvement and decarbonisation motivation (to be investigated further in the second phase of the HySupply project). These possible implementation scenarios are described below:



Scenario 1: Low-carbon methane seems to provide the most immediate commercially viable hydrogen carrier for an international export value chain, as it mitigates key technology, logistics and infrastructure risks. Furthermore, as described above, Australia has an expansive LNG export supply chain, therefore the infrastructure cost outlay to develop this industry will be relatively modest, as it will overlay on top of Australia's existing operations. Furthermore, Germany is currently a net importer of LNG, hence the port infrastructure on the end-user (Rotterdam) is also equipped to handle low-carbon methane imports (Note Germany is currently developing three LNG terminals). However, concerns on resultant CO_2 emissions arising from low-carbon methane utilisation in Germany, and limitations arising from suitable sourcing of CO_2 and its associated capture costs in Australia, present challenges for early implementation of this hydrogen carrier. Preliminary conversations with German stakeholders suggest that low-carbon methane is not the preferred form of hydrogen carrier for German off-takers (this will be explored further through the Roadmapping phase).

In this regard, zero-emission ammonia is a multi-faceted solution for Germany, as the PtX chemical can be used as both a feedstock for Germany's ammonium nitrate industries, as a thermal fuel for power generation (or co-generation with coal) and marine transport (a potentially key application). Furthermore, ammonia has the highest hydrogen density of all the PtX carriers, therefore in the short to medium term, ammonia can be increasingly considered as a hydrogen carrier as opposed to chemical feedstock. Investment requirements for renewable ammonia are significant, however this carrier provides a flexible solution that appears well placed to adapt with Germany's intention to reach carbon neutrality. There are also challenges with respect to system integration. In the near term, renewable ammonia may be viewed solely as a chemical feedstock for fertiliser and industrial explosives production, but in the long-term pivot to direct use as a fuel, and to hydrogen extraction once the learning rates and commercial viability for ammonia cracking technologies reach industrial scale.

Scenario 2: Low-carbon methanol is a high demand import molecule for Germany, therefore exporting low-carbon methanol as a hydrogen carrier for Germany provides dual functionality, as both a chemical building block for Germany's chemical manufacturing and automotive industries. It is also a proven marine fuel. A methanol export value chain, however, faces a similar challenge to low-carbon methane, as methanol use as a powerfuel results in carbon emissions at point of use, hence reducing the decarbonisation benefits for Germany depending on the source of CO_2. While sourcing of CO_2 from biogenic, direct air capture, and non-avoidable sources may alleviate these concerns, widespread consensus is still lacking. In addition, there are challenges to project scaling with these sources of CO_2, as outlined in **Section 6.4**. Furthermore, the use of methanol exclusively as a hydrogen transport mechanism is still untested at scale, presenting technology uptake risk for the reforming step. This scenario in the near-term is therefore attractive for Germany primarily as a low-carbon feedstock for their chemical and automotive industries, and its use as a hydrogen carrier will require further investigation and industry consultation to determine feasibility and viability. The next steps of HySupply project will investigate this in greater detail.

Scenario 3: LH_2, metal hydrides and LOHCs seem to present longer-term implementation opportunities for hydrogen export from Australia to Germany. Liquified hydrogen enables German hydrogen off-takers to potentially have infrastructure cost savings, as reconversion infrastructure for liquified hydrogen to extract hydrogen is minimal. Although, LH_2 is a high TRL technology at small scales (30 tonnes p.d.), it presents challenges relating to boil-off during transport and requires significant infrastructure investment for cryogenic operation and handling. Therefore, scaling up of LH_2 may require a complete retrofitting of the maritime shipping and port infrastructure. At present, Kawasaki Heavy Industry is building the world's first LH_2 carrier vessel and aims to unlock the key implementation uncertainties surrounding liquified hydrogen export. The near-term success of this project will enable, better understanding of infrastructure requirements, costs and financial levers required for implementation.

The transport of renewable hydrogen in the form of LOHCs enables the use of established supply chain to transport and store the carrier. However, the cyclical value chain associated with LOHCs (chemically binding hydrogen to larger molecules at export port and dehydrogenation at destination port) requires specialised conversion and reconversion infrastructure, requiring significant investment. Furthermore, LOHCs are typically sourced from fossil fuel resources and thereby may not represent the most carbon neutral form of hydrogen carrier. Lastly, after releasing hydrogen at the port of destination, this supply chain will require dehydrogenated LOHC to be shipped back to the port of export for another round of hydrogen delivery, adding in logistical expenditure. It is therefore clear, a LOHC supply chain will require a few more scale-up steps, as well as low/zero-emission shipping, before being considered as a viable hydrogen carrier.

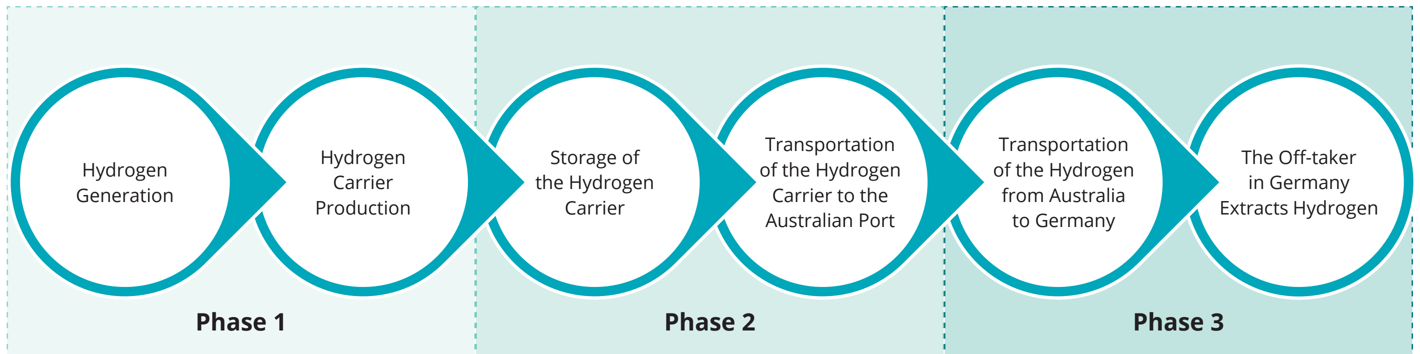
Metal hydrides represent another emerging technology that follows a similar concept to LOHCs, where the carrier can undergo conversion/ reconversion cycles. The class of metal hydrides with the highest TRL, that can undergo conversion/ reconversion cycles in close to ambient temperatures are referred to as 'low temperature hydrides'. These hydrides are capable of performing a conversion/ reconversion cycle with ~90% efficiency.[173] Furthermore, metal hydrides can perform up to ~20,000 conversion/ reconversion cycles, providing a large useful life for the carrier. The limitations with low temperature hydrides, include low storage density (<2% by weight) and insufficient data surrounding the scalability and export of this carrier. Therefore, metal hydrides in a similar manner to LOHCs, require a few more scale-up steps, as well as low/zero-emission shipping, before being considered as a viable hydrogen carrier.‼

6.8. Value Chain Cost Outlook

An export facing hydrogen value chain will involve the conversion of renewable electricity and water to hydrogen using electrolysers, followed by buffer storage/transport before conversion to LH_2 or hydrogen carriers (i.e. ammonia, low-carbon methanol, low-carbon methane, LOHCs). This may occur at the production site, at the port facility or in an intermediate location, requiring localised storage of the hydrogen carrier respectively at these locations. Furthermore, this may require hydrogen transport as a compressed gas, liquefied hydrogen or in metal hydride form to the conversion location, and the transport of these converted products/carriers to port. Alternatively, conversion may occur directly at the hydrogen production site, removing the need for compressed hydrogen or metal hydride storage and transport at this point in the chain. It is clear that a great number of potential configurations for this value chain may exist, which will be further explored during wider consultation with stakeholders in the second phase of the HySupply Project.

As identified by the analysis above, renewable ammonia, and low-carbon methanol, potentially present appropriate early carrier pathways for a short to medium term implementation of an Australia-Germany hydrogen value chain, as the two carriers have existing export supply chains, and the industries are currently operational at scale. Furthermore, in the near-term, these carriers form a critical input to Germany's existing industries, hence can be utilised directly, while they may emerge as a hydrogen source in the medium to long term (provided necessary reconversion infrastructure is developed), as the uptake for hydrogen increases in Germany. Future emission-free hydrogen value chain pathways may well include liquified hydrogen, liquid organic hydrogen carriers and metal hydrides amongst other technologies.

All the implementation scenarios will require an operational skeleton that contains three key phases: carrier generation (farm gate cost), carrier transportation to the local port (free on-board cost) and export to Germany. **Note that the implementation scenarios are subjective to the end-use for the hydrogen carriers, which are to be determined during the Roadmapping phase of the HySupply Project. For qualitative comparison, we also include costs associated with low-carbon methane.** The subset of activities within each phase are described below and highlighted in **Table 16****



‼ Value chain costing for metal hydrides will be carried out in detail in the Roadmapping phase of HySupply project.

** **Note:** The value chain cost projections provided herein are presented as individual components and will be integrated in the next phase of HySupply Project to provide a holistic overview of current and future hydrogen and hydrogen carrier viability to Germany. By bringing together producers, off-takers, freight and government, this exercise is envisioned to bring consensus on first wave of hydrogen supply from Australia to Germany.

Phase 1: Hydrogen and Hydrogen Carrier Generation

At this stage, most hydrogen projects in Australia are decentralised projects/energy hubs. Access to low-cost electricity, increasing renewables capacity factors, declining electrolyser capital costs and favorable financing regimes will govern the commercial viability of hydrogen production. The utilisation of behind-the-meter electricity supply for decentralised hubs can avoid network transmission charges, which account for a significant proportion of the electricity procurement costs in Australia. The preliminary LC_{H2} with renewable solar electricity driven AE and PEM electrolysers is estimated as A$3.4 – 7.4/kg and A$5.0 – 9.0/kg respectively, whereas for renewable wind driven AE and PEM electrolyser, the LC_{H2} is estimated to be A$3.0 – 7.4/kg and A$3.8 – 8.8/kg, respectively (**Section 6.3 – Figure 18** – **21**). However, it is shown that substantial decline in electrolyser CAPEX to A$250 – 500/kW and favorable project financing can lead to the attainment of A$2/kg target.

As the product from water electrolysis, hydrogen will need to be temporarily stored either as a compressed gas, liquefied form or in metal hydride form prior to conversion to hydrogen carriers such as ammonia, methane and methanol at production sites. At present, the most common approach of storing hydrogen for buffering is through compression, which is expected to cost between A$0.3 –0.53/$kg_{H2}$, dependent on the storage pressure. Road transportation of compressed hydrogen is expected to cost A$2.4 – 5.33/$kg_{H2}$ whereas pipeline would add a cost of A$0.22 –0.95/$kg_{H2}$ (based on tables in **Section 6.4**).

The next step in the value chain entails the conversion of hydrogen-to-hydrogen carrier. The cost profiles are provided below:

- **Scenario 1 – Early implementation:** Net-zero ammonia can be produced using the commercial Haber-Bosch (HB) process and renewable hydrogen. The indicative CAPEX for renewable ammonia production is ~A$570 – 1,130 per ton p.a. of ammonia for the HB plant plus an Air Separation Unit (ASU) cost of A$84 – 315 per ton of N_2 p.a. to source the required nitrogen for the HB process. The OPEX of the facility is expected to be around 1 – 5% p.a. of CAPEX. Given the high commercial maturity of the pathway, the conversion process adds a cost of A$0.12 – 0.29/kg of ammonia. In contrast, the indicative CAPEX for low-carbon methane production is ~A$695 – 1390 per ton p.a. (exclusive of carbon capture) with an OPEX of 2 – 5% p.a. of CAPEX. The conversion process is estimated to add a cost of A$0.05/kg – A$0.19/kg of synthetic methane (exclusive of carbon capture costs). As stated in previous sections, challenges relating to suitable source of CO_2 and its associated costs will greatly dictate the economics for renewable methane and methanol production as a hydrogen carrier.
- **Scenario 2 – Demand Specific Implementation:** In this scenario, low-carbon methanol is produced using thermal catalytic conversion of CO_2 and green H_2 from the energy hub. The indicative CAPEX for low-carbon methanol production is A$265 – 1,350 per tonne p.a. (exclusive of carbon capture) with a OPEX of 2% p.a. of CAPEX, resulting in a conversion cost of A$0.17 – 0.48/kg of green methanol (exclusive of carbon capture costs).
- **Scenario 3 – Future Implementation:** In this scenario, cryogenic hydrogen, metal hydrides and LOHCs will be employed as the hydrogen carrier. The indicative CAPEX for LH_2 is A$5,900 – 11,000 per ton p.a. with an OPEX of 2 – 4% p.a. of CAPEX, resulting in a conversion cost of A$1.39 –3.6/kg of liquefied hydrogen. The indicative conversion costs for LOHCs are estimated to be A$1.5/kg of H_2 if stored in form of DBT, A$0.83/kg of H_2 using MCH and A$1.61 – 4.34/kg of H_2 using DME, respectively.

Phase 2: Hydrogen Carrier Transportation to the Port

The best-case scenario for hydrogen export is the development of specialised export hubs, integrating electrolyser hydrogen production, conversion to hydrogen carrier, storage of the hydrogen carrier and port facilities for export. In a situation when grid-connection becomes expensive, developing a new high-voltage line from REZs may be economical. This allows for large-scale production, minimising the cost of renewable electricity transmission and export infrastructure by having it all in a single location and achieving economies of scale at such facilities.[143] Currently such facilities are being considered in Burnie and Bell Bay in Tasmania,[174] in the Pilbara in Western Australia,[146] and in the Eyre Peninsula in South Australia.[175]

However, in the scenario where this is not possible, vehicular (road and rail) and pipeline transportation will be used to transport the carriers to the port facilities. Liquefied hydrogen must be stored at -253˚C, whilst ammonia is stored at -34˚C and methanol at 5˚C.[176] As such, it is more beneficial to transport compressed hydrogen to the port facility and then undertake liquefaction. This is being explored by the Hydrogen Energy Supply Chain (HESC) project where hydrogen from the gasification plant is transported 150 km by land to the Port of Hastings in Victoria.[177,178] Ammonia and methanol are usually transported in carbon-steel or steel tankers with a capacity around 15 – 20 t.[179] Furthermore, transport by rail involves similar storage vessels and conditions as by truck, except railway infrastructure is required. The larger-scale of railway transport tends to allow for larger economies of scale to be achieved than for land transport, allowing for a lower addition to cost overall.[115]

Another transport option is through pipelines. This is particularly useful for methane transport as natural gas infrastructure already exists but can also be used for compressed hydrogen depending upon the pressure and piping material. The transport of pure hydrogen can cause embrittlement in conventional steel pipes, however other piping materials such as fiber reinforced plastic (FBR), carbon steel and stainless steel have been proposed for transmission and distribution. FBR is useful for the transmission of hydrogen at 103 bar at a cost of A$0.61/$t_{H2}$km whilst HDPE is useful for distribution at 20 bar at a cost of A$2.58/$t_{H2}$km. Some of these cost estimates (elaborated in **Section 6.4**) are as follows:

- Liquefied hydrogen is able to be transported by truck and rail. Specialised tube-trailers can transport hydrogen up to 1,000 km with capacities of between 4,000 – 5,000 kg. Modelling shows that liquefied hydrogen transport by road would cost A$0.92 – 3.35/$t_{LH2}$km and A$0.28/t_{LH2}km by rail (**Table 7**), with rail cars capable of carrying 2.3 – 9.1 t of liquefied hydrogen.
- Renewable ammonia is transportable by road, rail and ship. Road and rail transport in excess of 1,000 km is possible at a cost of A$0.33/$t_{NH3}$km and A$0.04/t_{NH3}km respectively (**Table 8**), lower than compressed hydrogen and liquefied hydrogen.
- Low-carbon methane, once created, can be transported using existing natural gas infrastructure. Methane transport generally involves a network of pipelines for domestic supply and as LNG for export upon ships, requiring cryogenic tanks. Within Australia, transmission via steel pipelines costs between A$0.02 – 0.140/$t_{CH4}$km (A$0.85 – 2.05/GJ) depending upon locations and pipelines (**Table 10**).
- Low-carbon methanol can be transported by road transport at a cost of A$0.34 – 0.81/$t_{MeOH}$km (**Table 11**).
- LOHCs can be transported by road transport at a cost of A$0.35/$t_{LOHCs}$km (**Table 12**).

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Phase 3: Hydrogen Carrier Export to Germany

Export industry maturity was a critical consideration in the development of the three implementation scenarios, alongside existing port infrastructure, and transportation cost. The first two implementation scenarios (i.e., NH_3 and CH_4 for immediate implementation and CH_3OH for demand-specific implementation) are compatible with existing maritime infrastructure, ensuring the hydrogen export value chain can overlay with existing export supply chains in Australia.

Export of hydrogen carrier from Australia to Germany will entail utilisation of port facilities incurring both infrastructural and logistical expenses for fueling the carrier ships. Determination of these parameters during the Roadmapping phase of the project with industry and port stakeholders will be crucial in accurately estimating port loading costs.

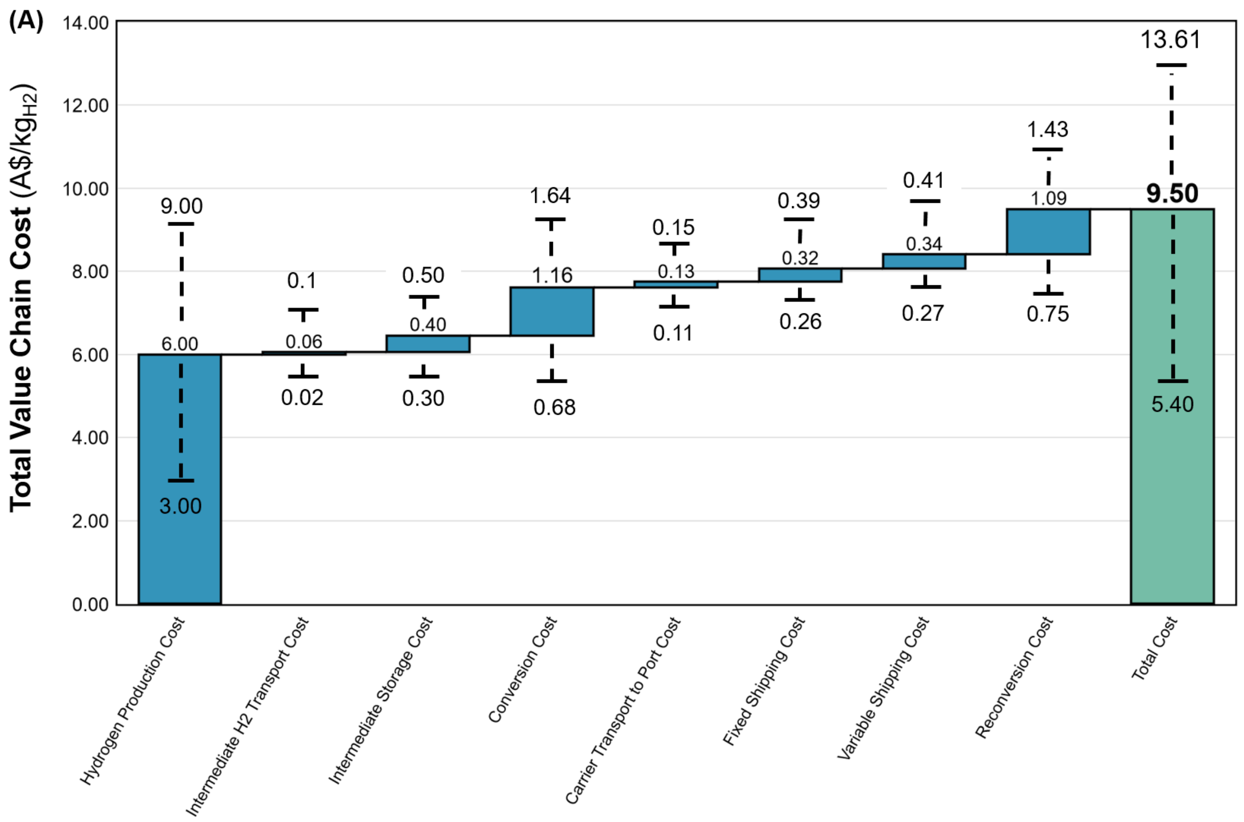
As noted earlier, HySupply Australia is also developing a shipping cost-tool (encompassing loading costs) from Australian ports to destination port. Shipping costs from Australian ports to Port of Rotterdam (**Table 13**) is estimated to vary from A$0.85/kg-A$1.2/kg for liquified hydrogen, A$0.17 – 0.25/kg for methane, A$0.09 – 0.12/kg for ammonia, A$0.07 – 0.105/kg for DME and A$0.07 – 0.10/kg for methanol.

Value Chain Cost Estimates

The estimated current value chain cost profile for the different pathways are provided below using the median farm-gate cost that was modelled using the HySupply tool. The value chain model factors in the estimated costs from hydrogen generation through to export (discussed above), however, does not consider reconversion costs. These value chain models are indicative, and the underlying assumptions will be refined through stakeholder consultation as part of the Roadmapping phase.

Early Implementation Scenario - Hydrogen Value Chain Costs

Figure 26: Indicative Total Export Value Chain Cost Breakdown for Ammonia.
(A) Cost normalised per kg of hydrogen exported and (B) normalised per kg of carrier (A$/$kg_{NH3}$).



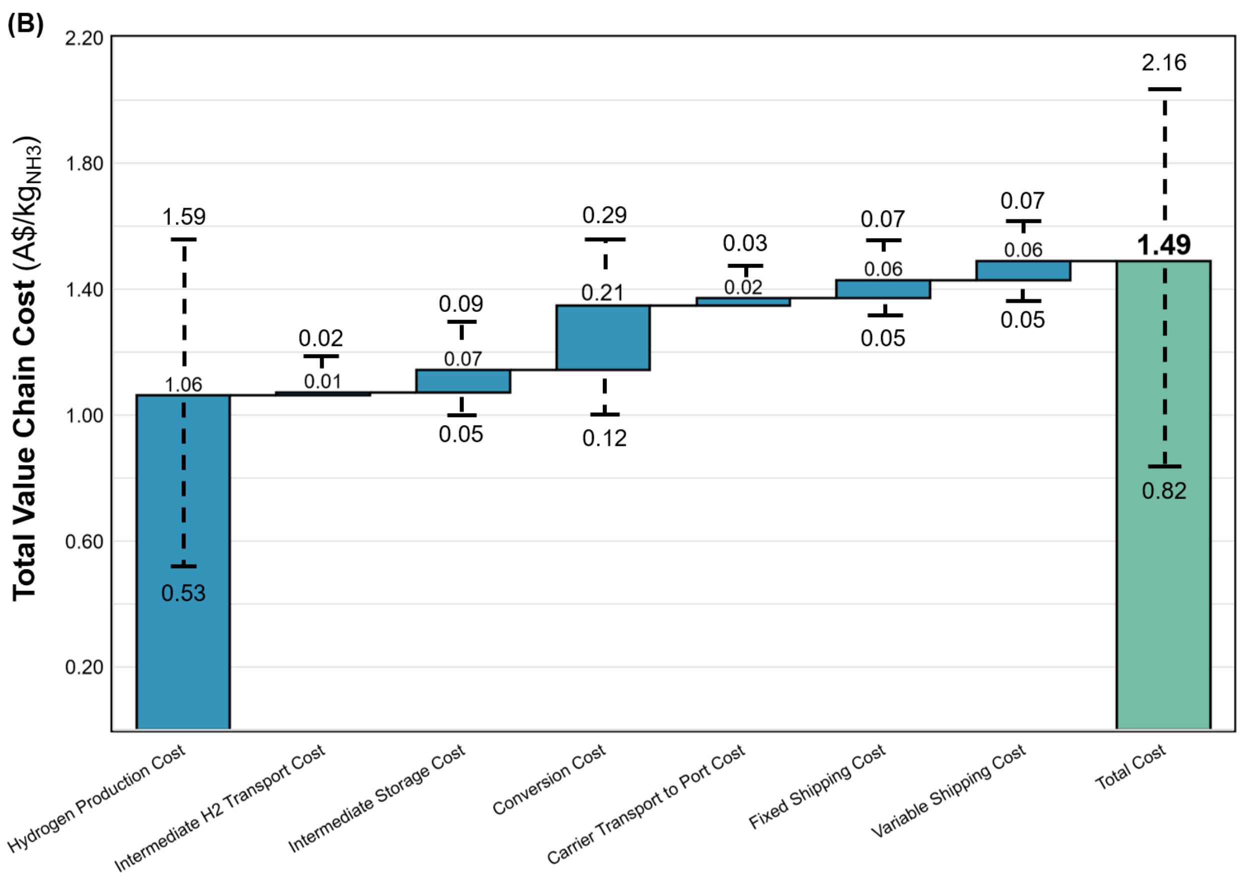
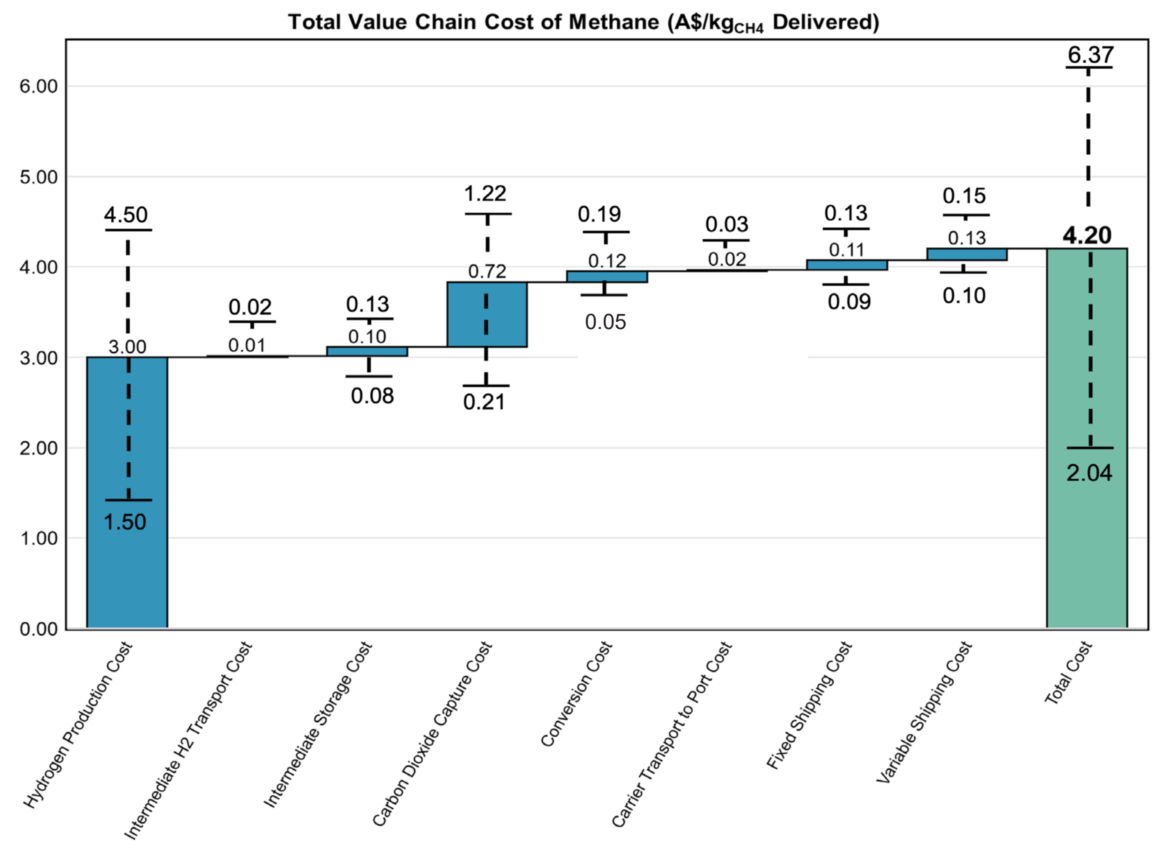
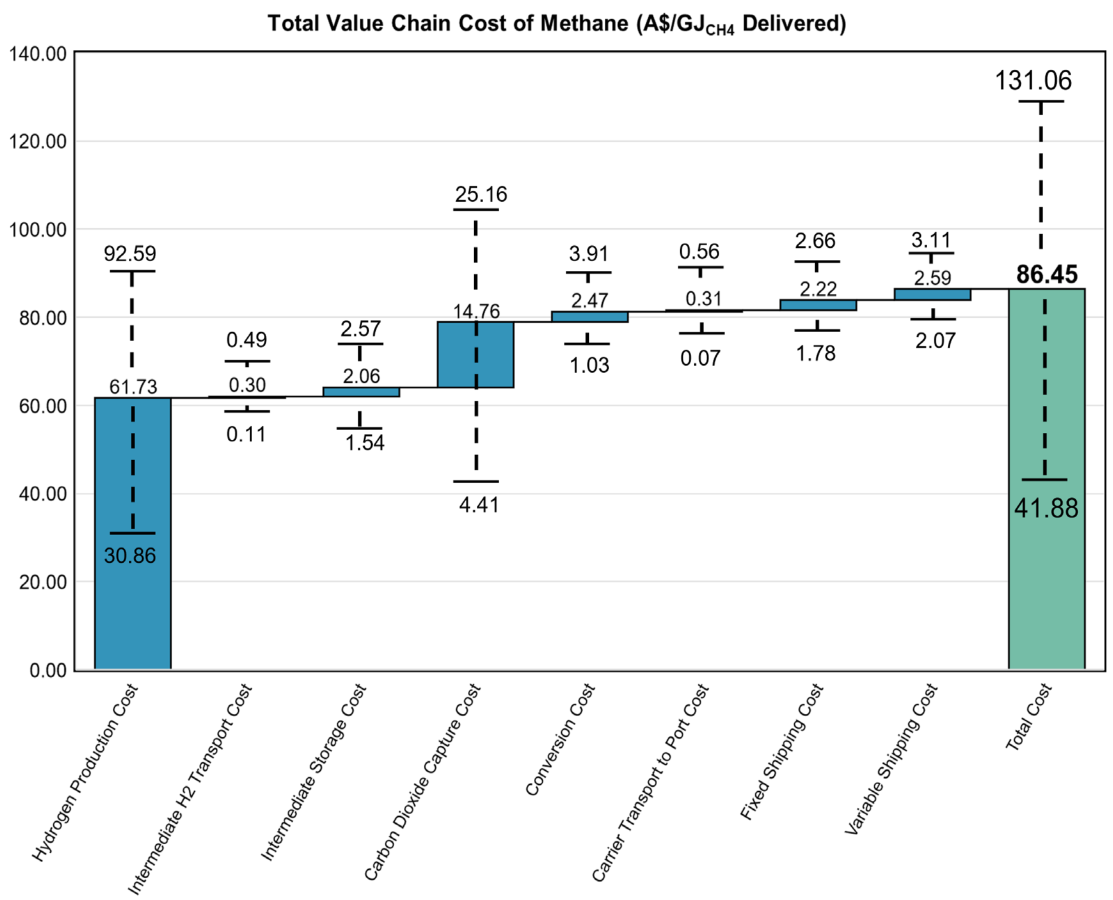


Figure 27: Indicative Total Export Value Chain Cost Breakdown for Low-Carbon Methane.
(A) Cost normalised per kg of hydrogen exported and (B) normalised per kg of carrier (A$/$kg_{CH4}$).



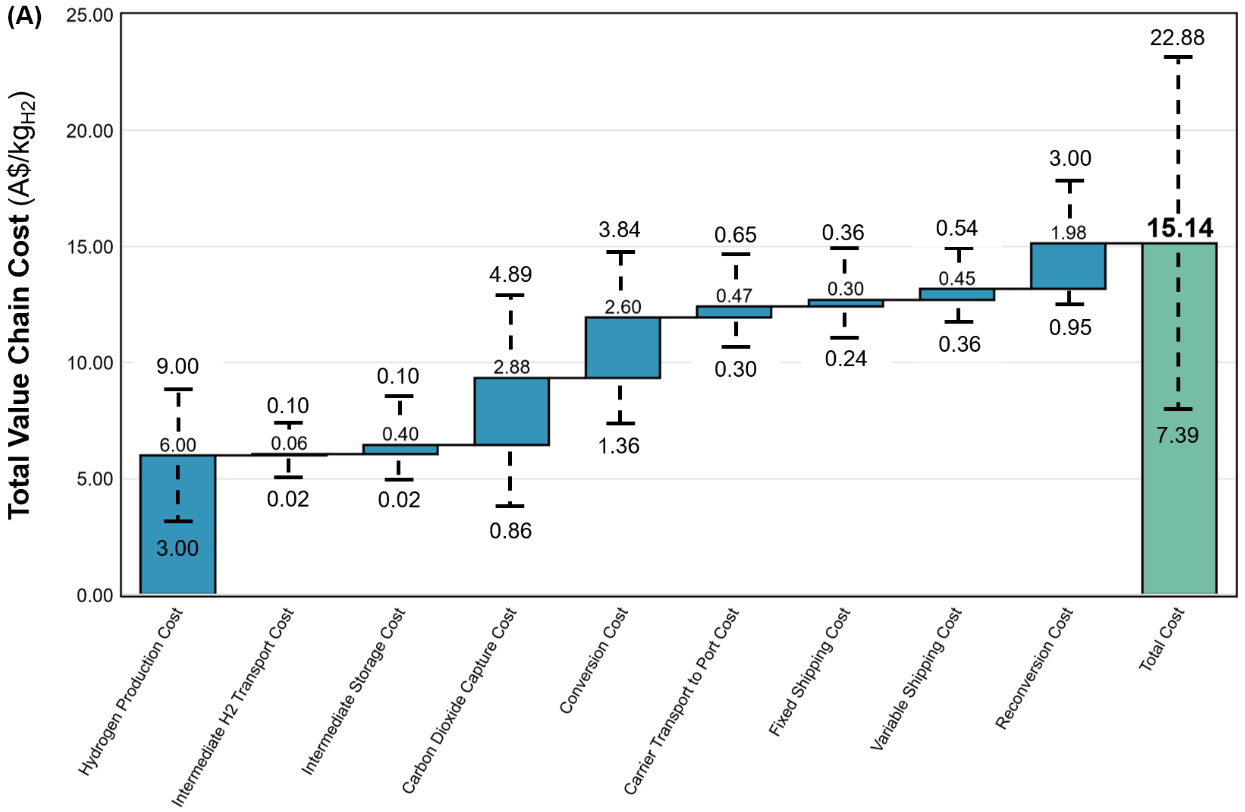


The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

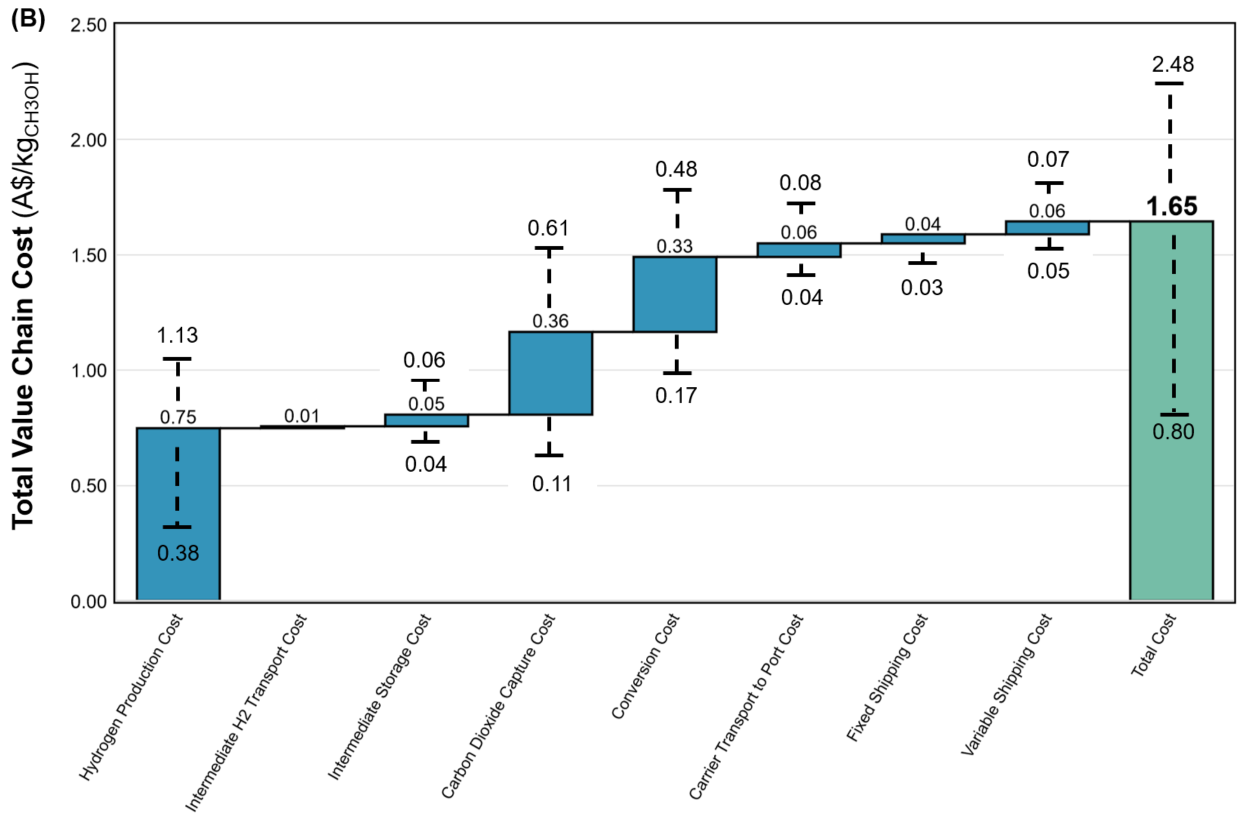
Demand Specific Implementation Scenario - Hydrogen Value Chain Costs

Figure 28: Indicative Total Export Value Chain Cost Breakdown for Low-Carbon Methanol.
(A) Cost normalised per kg of hydrogen exported and (B) normalised per kg of carrier (A$/$kg_{CH3OH}$).

(A)



(B)



The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Future Implementation Scenario - Hydrogen Value Chain Cost

Figure 29: Indicative Total Export Value Chain Cost Breakdown for Liquefied Hydrogen (A$/$kg_{H2}$)

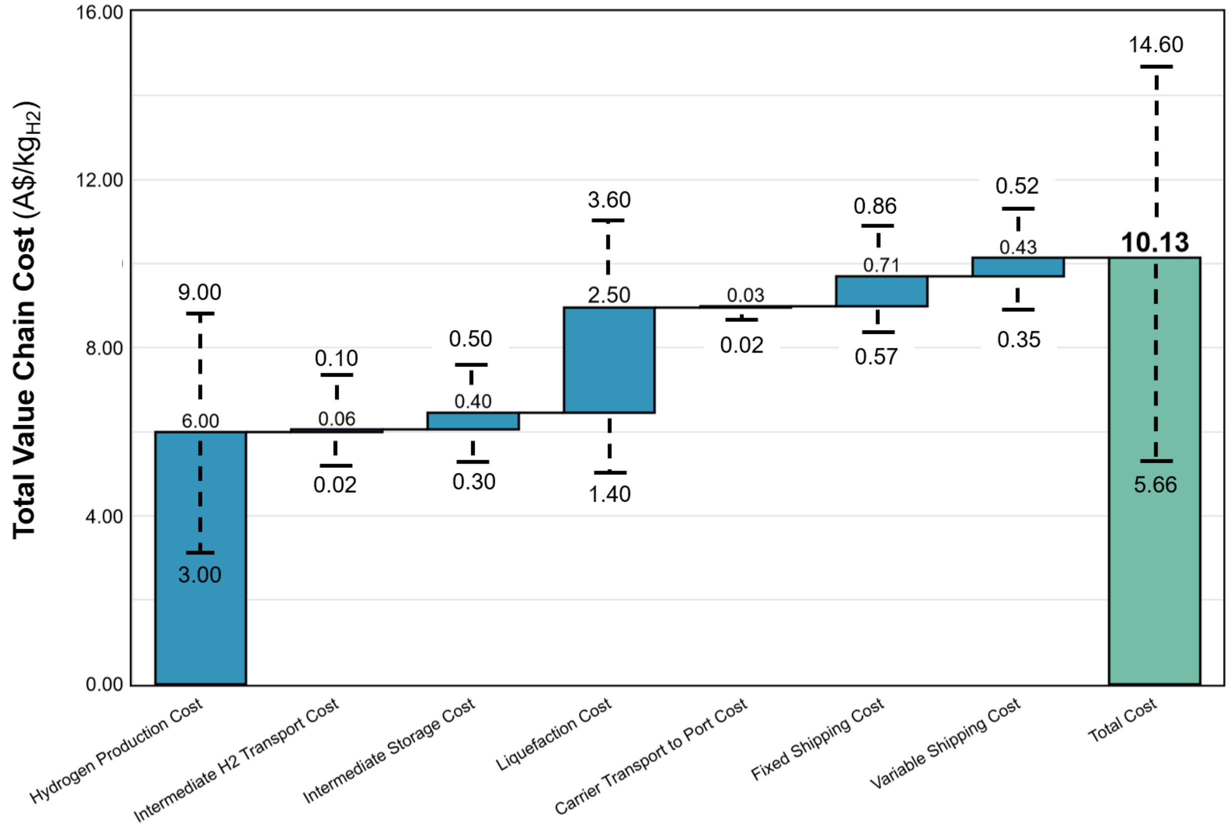
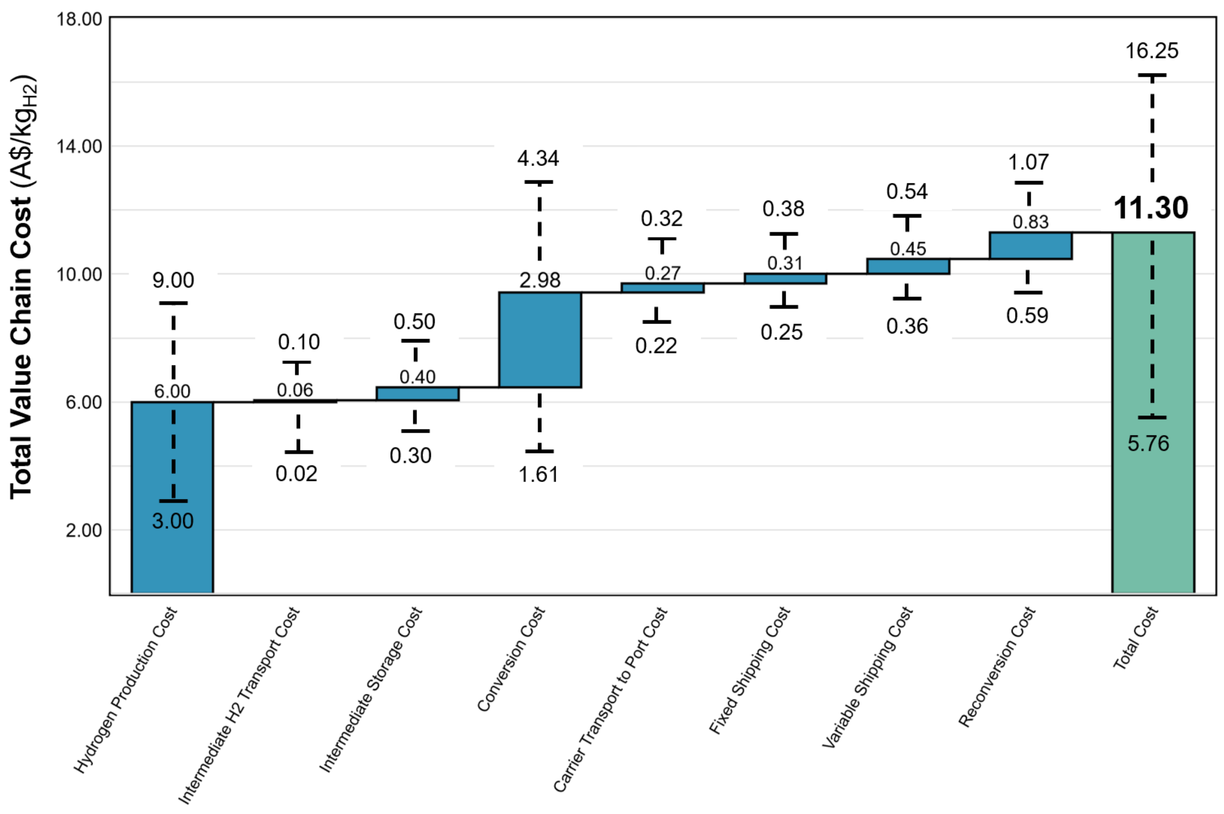


Figure 30: Indicative Export Value Chain Cost Breakdown for LOHC. (A$/kg$_{H2}$)



The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

Table 16: Preliminary cost outlook of hydrogen carrier value chains in Australia.

	Value Chain Costs						
Hydrogen Carrier	**Renewable Electricity**	**Electrolysis**	**H_2 Intermediate Storage**	**H_2 Intermediate Transport Cost**	**H_2 Conversion to Carrier Cost**	**H_2 Carrier transport to Port Cost**	**Carrier Reconversion at receiving Port**
Liquefied Hydrogen (LH_2)	**Solar PV** CAPEX: A$1,410/kW (Gencost, 2021)[180] OPEX: A$17/kW (Aurecon,2020)[181] **Wind** CAPEX: A$1,951/kW (Gencost, 2021)[180] OPEX: A$25/kW (Aurecon,2020)[181]	**Alkaline Electrolyser** CAPEX: A$500 – 1,000/kW OPEX: 2.5% of CAPEX p.a. + stack replacement (40% of electrolyser costs per replacement) Levelised Cost of H_2 For AE System: Solar driven PV A$3.4– 7.4/kg Wind driven: A$3.0 – 7.4/kg **PEM Electrolyser** CAPEX: A$750 – 1,500/kW OPEX: 2.5% of CAPEX p.a. + stack replacement (40% of electrolyser costs per replacement) Levelised Cost of H_2 For PEM System: Solar driven PV A$5.0 – 9.0/kg Wind driven: A$3.8 – 8.8/kg The above costs data is based on literature data and stakeholder consultation (**Section 6.3**). The levelised cost of hydrogen were evaluated using the HySupply Cost Analysis Tool (**Figure 18 – 21**)	**Salt Caverns (if available)** CAPEX: A$0.95 – 23 /$kg_{GH2}$[182-185] OPEX: 1 – 1.5% of the CAPEX p.a.[182-185] Storage Cost per kg of H_2: A$0.3 – 0.9/$kg_{H2}$[10,186] **Tanks** CAPEX: A$320 –2,000/$kg_{GH2}$[185,187–189] OPEX: 1 – 2% of the CAPEX p.a.[185,187–189] Storage Cost per kg of H_2: A$0.4 – 0.5/$kg_{GH2}$ (35 Bar storage)[115] A$0.3 – 0.37/$kg_{GH2}$ (150 Bar storage)[115] A$0.34 – 0.42/ kg_{GH2} (350 Bar storage)[115]	Transported in gaseous hydrogen form **Road:** A$2.33 – 14.27/$t_{GH2}$km[7,11,113,167] **Rail:** A$0.55/$t_{GH2}$km[115] **Pipeline:** A$0.22 – 0.95/t_{GH2}km[10,128,148] **Note:** These costs include the capital and operating costs associated with the transportation infrastructure. The cost is levelised over the amount of product (tonnes) and distance of travel (km). Similarly, the costs for transporting the carriers were also levelised over the amount of product (tonnes) and distance of travel (km).	CAPEX: A$5,860 – 11,000/$t_{LH2}$ p.a.[191–193] OPEX: 2 – 4% of CAPEX p.a.[191–193] Conversion Efficiency: 76 – 82%[10,136,194] Conversion Cost: A$1.4 – 3.6/$kg_{LH2}$	**Road:** A$0.92 – 3.33/$t_{LH2}$km[10,115,127,148] **Rail:** A$0.28/$t_{LH2}$km[115]	
Methanol					CAPEX: A$265 – 1,350/$t_{MeOH}$ p.a.[192,195–197] OPEX: 2% of CAPEX p.a.[195] Conversion Efficiency: 78 – 81%[135,194,198] Conversion Cost: A$0.17 – 0.48/$kg_{MeOH}$	**Road:** A$0.37 – 0.81 /$t_{MeOH}$km[13,148,171]	CAPEX: A$1,050 – A$3,620/t_{H2} p.a.[135,198,199] OPEX: 3 – 4% of CAPEX p.a.[135,198] Reconversion Costs: A$0.95 – 3/$kg_{H2}$[135,198,199]
Ammonia					CAPEX: HB Process: A$570 – 1,130/$t_{NH3}$ p.a.[5,115,200,201] ASU: A$84 – 315/$t_{N2}$ p.a.[192,200,201] OPEX: 1 – 5% of CAPEX p.a.[10,194,200,201] Conversion Efficiency: 78 – 81%[10,136,202] Conversion Cost: A$0.12 – 0.29/$kg_{NH3}$	**Road:** A$0.2 – 0.33/$t_{NH3}$km[10,115] **Pipeline:** A$0.2 – 0.26/$t_{NH3}$km[10,148] **Rail:** A$0.04/t_{NH3}km[115]	CAPEX: A$1,700 – 1,800/$t_{H2}$ p.a.[10,203,204] OPEX: 4% of CAPEX p.a.[10,204] Reconversion Costs: A$0.75 – 1.43/$kg_{H2}$[210,199,203,204]
Methane					CAPEX: A$695 – 1,390/$t_{CH4}$ p.a.[192,205–207] OPEX: 2– 5% of CAPEX p.a.[192,205–207] Conversion Efficiency: 78 – 80%[208-210] Conversion Cost: A$0.05 – 0.19/$kg_{CH4}$	**Road:** A$1.20/$t_{CH4}$km[148] **Pipeline:** A$0.02 – 0.14/t_{CH4}km[152]	
LOHCs					**Using DBT as Carrier** Conversion Cost: A$1.50/$kg_{H2}$ **Using MCH as Carrier** Conversion Cost: A$0.83/$kg_{H2}$[211,212] **Using DME as carrier** Conversion Cost: $1.61 – 4.34/$kg_{H2}$[213,214] Conversion Efficiency: ~99%	**Road:** A$0.35/$t_{LOHCs}$km[170,171]	CAPEX: A$1,025 – 1,985/$t_{H2}$ p.a.[189] OPEX: 3 – 4% of CAPEX p.a.[189] Reconversion Costs: A$0.59 – 1.07/$kg_{H2}$[135,189,199]

Note:

- The values in the tables are based on preliminary analysis of the values provided in cited literature and are subject to change through stakeholder consultation in the Roadmapping phase of HySupply project. It is important to note that these costs are indicative based on literature, and are subjective to change based on system scale, WACC and project lifetime assumptions.
- The capital and operating costs range were levelised over the production scale (ton/year).
- The conversion costs were evaluated based on the capital and operating costs ranges while assuming a WACC of 7% and project life of 30 years. The levelised cost of electricity (LCOE) and hydrogen (LC_{H2}) was calculated based on WACC of 7% and project life of 25 years for the solar/wind farm and 20 years for the electrolyser system, respectively.
- The cost of hydrogen was not included as an operating cost, while evaluating the conversion costs to the carrier.
- For the conversion to ammonia pathway, the additional operating and capital costs of the ASU system were included in the conversion costs.
- For modelling renewable methanol and methanation pathway, capital and operating cost of CO_2 capture were not directly included while assessing the conversion costs. However, a carbon capture cost of A$78 – 445/ton of CO_2 were adopted from literature sources to represent capture opportunities from various point sources (**Table 9**). These costs are included in the bar charts in the executive summary (**Figure C – E**) and the waterfall charts (**Figure 26 – 30**) as part of the value chain outlook. A thorough detailed modelling for the carbon capture integration with the conversion pathways will be conducted during the Roadmapping phase of the project.
- For the LOHC pathway various carriers including DME, MCH, DBT and BT as the carrier. The conversion/reconversion costs represent the indicative range for using these carriers, these costs are represented per unit of H_2 (kg) stored in the LOHC.
- For hydrogen conversion to carrier and the reconversion of carrier to hydrogen pathways, the energy requirement (both thermal and electrical) was assumed to be sourced exclusively through electricity, as an additional expense assuming a renewable PPA of A$50/MWh. Opportunities for integrating heat/excess electricity between different stage of value chains will be considered during the Roadmapping phase of the project.

7. Next Steps

In midst of the Covid-19 recovery and accelerating global action on climate change through net zero targets and policies to meet these, possible pathways towards an Australian export-facing hydrogen sector is taking shape. This state-of-play report presents Australia's rapidly growing credentials as a potential global hydrogen exporter, providing an overview of Australia's current and emerging hydrogen value chain for exporting green hydrogen to Germany, and presenting some of the open-source tools that we have been developing to assist stakeholders in analysing these opportunities. However, given only limited experience in key stages of the hydrogen production, conversion and processing required, here in Australia and globally, and in the absence of tailored regulatory, market and policy frameworks to support international hydrogen trade, considerable further efforts will be needed to realise the opportunity. Initial discussions with a number of HySupply Australia industry partners have identified a range of barriers and questions, which could be addressed in the next HySupply Roadmapping phase, intended for July 2021 to March 2022, in conjunction with our German partners. Note that this is an ongoing conversation and further consultation on these barriers and opportunities will be conducted in the early phase of this Roadmapping exercise.

Identified key barriers	Potential Actions
Misconception of role of hydrogen as only a renewable energy carrier. Use of hydrogen as a pathway to meet emissions reduction goals needs to be prioritised.	Through bilateral consultation, short-run and longer-term hydrogen applications in Germany will be better identified and their potential contributions to emissions reduction targets quantified.
Misapprehension on hydrogen safety requiring co-education and awareness. Some hydrogen carriers are well-established export commodities but are facing renewed criticism of safety and suitability.	Identify and compile existing standards on hydrogen carrier generation, storage, loading, transportation and unloading. Track current developments and consider further key steps. At present, the Australian Government is supporting Australian emergency services to participate in training courses from the US Center for Hydrogen Strategy. Activities such as these will greatly assist in alleviating these safety concerns.
Regulatory and social licensing barriers. Development of hydrogen projects will be subjected to emerging regulation and societal barriers.	Development of a social license framework. The framework will encompass community considerations, water footprint and environmental deliberations. Identification of current regulation relevant to hydrogen export and specify gaps and actions needed from stakeholders, which is currently underway through the Australian Government led legal frameworks review.
Global electrolyser manufacturing capability is currently limited and may present supply shortages in the near-term unless production can be ramped up.	Consultation with equipment providers and project developers to map out current and future scenario of electrolyser supply in the near-term. Findings will be used to inform Australian government on local manufacturing opportunities.
Demand Side Barriers	
Uncertainty on the exact markets and off-takers for renewable hydrogen in Germany.	At present, Australia is playing a leading role in International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) in developing an international standard to guarantee the origin of hydrogen production to facilitate transparency to consumers. The Australian Government has invested A$9.7 million to support the development and implementation trials of a Guarantee of Origin emissions certification scheme[95,214], and has recently released a discussion paper on Australia's approach to a Guarantee of Origin framework. It lays out key issues and options for enabling Australia to export high quality renewable hydrogen.[215] Further, considerations on emissions arising from hydrogen carrier conversion, transport and reconversion need to be explored with German stakeholders, to provide a more detailed outlook on hydrogen certification and acceptable carbon accounting practices noting that different buyers may place different emphasis on these issues.
Questions on renewable hydrogen certification and definition on different colour hydrogen that is acceptable to German buyers. Specifically, to be considered as green, is there a requirement for shipping fuel to be renewably generated as well?	At present, Australia is playing a leading role in International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) in developing an international standard to guarantee the origin of hydrogen production to facilitate transparency to consumers. The Australian Government has invested A$9.7 million to support the development and implementation trials of a Guarantee of Origin emissions certification scheme[98,215], and has recently released a discussion paper on Australia's approach to a Guarantee of Origin framework. It lays out key issues and options for enabling Australia to export high quality renewable hydrogen.[216] Further, considerations on emissions arising from hydrogen carrier conversion, transport and reconversion need to be explored with German stakeholders, to provide a more detailed outlook on hydrogen certification and acceptable carbon accounting practices noting that different buyers may place different emphasis on these issues.
Availability of long-term contracts? It is envisioned that long-term contract, akin to those within the LNG industry in Australia, may reduce cash-flow variability, reduce investor risk, and promote development of hydrogen projects.	Work with HySupply German partners on suitable market and contracting arrangements. Such agreements can include equity participation and upfront payment by the purchaser into the production project (to facilitate covering costs of initial investment), dispute resolution, etc. A draft contractual framework will be developed.
Geographically, the distance between Australia and Germany ensures that transport costs are higher than perhaps other proposed producers located near to the EU market (such as Chile, Middle East, North Africa, North America). Specifically, there is a considerable interest in growing local offshore wind coupled with electrolysers as a potential source in Europe. It remains to be seen if these competitors are serious of their intent and if they can provide improved economics along with the necessary infrastructure, workforce and political stability.	As a benchmark of comparison, HySupply can carry out a risk analysis and model the potential cost of a hydrogen value chain from these prospective suppliers. Dialogue with hydrogen off-takers in Germany can help us better understand their intent on sourcing hydrogen from various partners.
Domestic barriers	
A concerted University, government and industry effort is required to upskill Australia's workforce for the emerging hydrogen industry for both export and domestic applications. Australia needs to train engineers, operators and technicians to be able to design, develop, operate and maintain hydrogen infrastructure.	While beyond the scope of HySupply, the project seeks to identify key skills and training needed by the Australian workforce to transition towards a hydrogen economy. This ties with existing Federal efforts where the South Australian members of Hydrogen Project Team is leading work on skills, training and emergency services for hydrogen industry development and work programs of ARC Training Centre for The Global Hydrogen Economy, hosted at UNSW and other research/university centres around the country. Further Government work in this space that should continue to be leveraged includes the Commonwealth Science and Industrial Research Organisation (CSIRO) hydrogen industry mission. A crucial activity underpinned through this mission is development of the hydrogen knowledge centre.
Australia needs to develop safety protocols and devise a safety permit mechanism for hydrogen export. From a technical point of view, it remains to be seen how such safety protocols and system integration translates as hydrogen production is ramped up in Australia.	Roadmapping exercise with project developers and Standards Australia ME-093 Hydrogen Technologies Technical Committee to explore gaps and next steps in safety, standards and permit mechanism.
Limited project investment for emerging and medium-scale hydrogen export-focused projects given low level of predictable hydrogen offtake. This issue may be circumvented through co-investment in projects through Federal and state-government, akin to support received by the LNG and coal industries, and infrastructure support through centralised port facilities aimed at exporting hydrogen around the country.	The Australian Government has committed A$314 million to the creation of hydrogen hubs to foster domestic hydrogen off-takers and is forming international partnerships to support export linkages. Further actions could include consultation with project developers in Australia to identify financing conditions that may enable quick project uptake and viability. Discussion with state and Federal government agencies to explore further support and incentives.
For Australia to truly benefit from a global hydrogen economy, the country and its manufacturers need to work alongside technology providers to build up a domestic equipment manufacturing base and capability for hydrogen derivative production. This will ensure that the country is not only a net exporter of resources and importer of technology but rather is a co-developer in this hydrogen value chain, leading to greater job creation and other economic outcomes.	Consultation with equipment providers and project developers to identify component of project that can be manufactured locally. Engagement with growth centres, manufacturing associations and government to outline manufacturing support available.

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

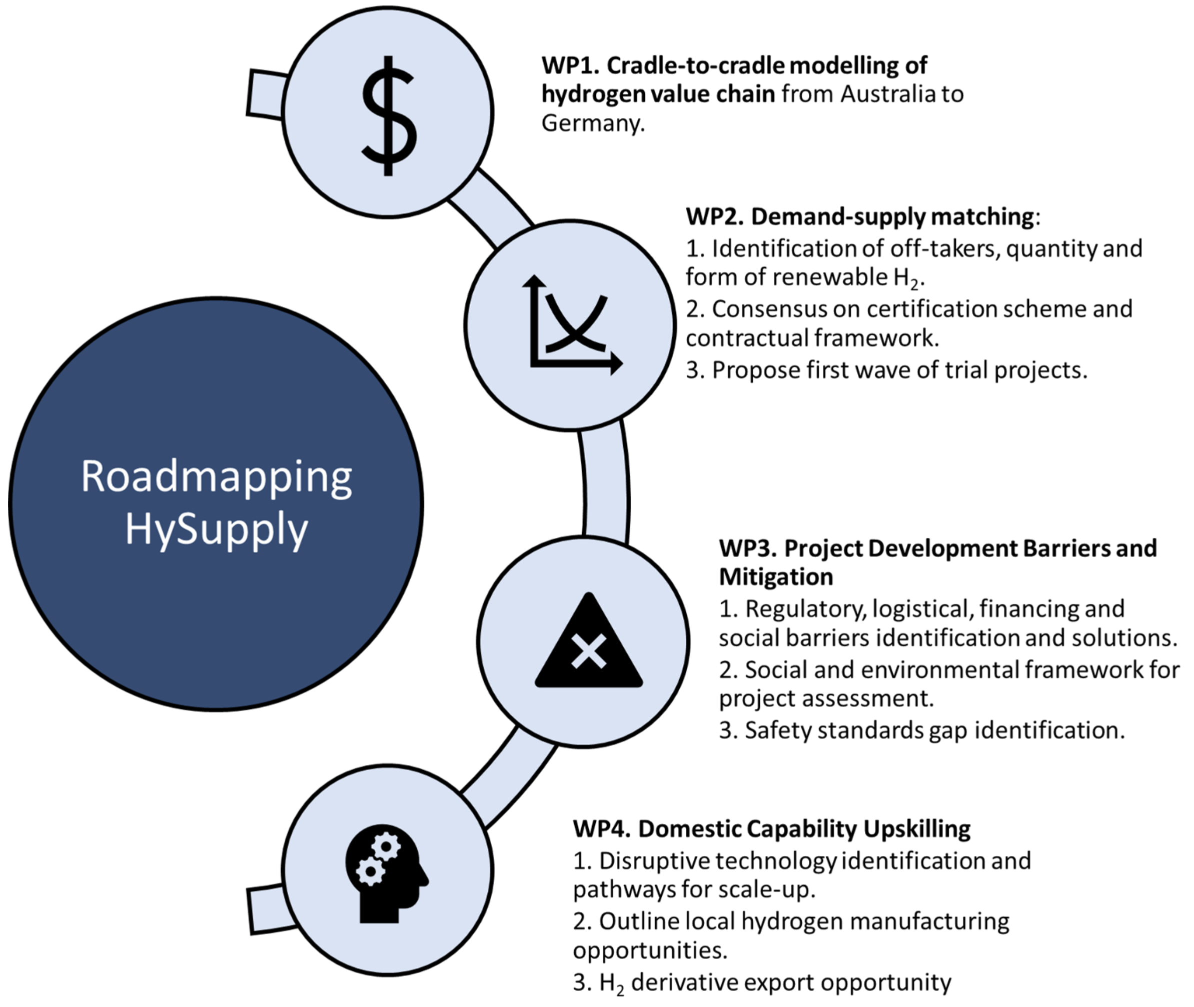
Opportunities for Australia

Australia stands to gain from a hydrogen export industry to Germany. In addition to direct economic benefits arising from exporting this emerging commodity, Australia can avail the following opportunities:

- Australia can position itself to supply hydrogen-based commodities such as green steel, refined/green aluminium and reduced iron ore, embedding hydrogen into current export value chains. This will require close cooperation with technology providers including German partners and provide suitable commercial development opportunities for all parties. This might involve special economic zones and suitable incentives for co-development of projects.
- Given many of the potential project locations are in remote and regional areas, a hydrogen export economy will facilitate working with original title holders, allowing active participation in regional development.
- HySupply also presents the opportunity for Australia and Germany to partner up to build–up a hydrogen manufacturing base and co-develop projects in Australia aimed at supplying the Asian-Pacific market.
- Growth of hydrogen ecosystem involving domestic researchers, engineers, IP and knowhow can be facilitated through HySupply for the dual benefit of domestic decarbonisation efforts and economic growth.

Workplan

The next steps to unlocking the Australia-Germany hydrogen value chain will be to bring together concerted stakeholders from industry, academia and government stakeholders from both countries to establish common certification protocols, and greater consensus on key project opportunities, identification of regulatory and logistical barriers, proposed pathways for mitigating these challenges and for developing appropriate contractual frameworks. These would be delivered as per the following proposed work packages:



There is much to be optimistic about, but much more to be done in order to establish an Australia-Germany hydrogen supply chain, and, in the longer term, a global green hydrogen market that assists all countries in meeting their decarbonisation targets while driving economic progress and development. We seek and welcome stakeholder feedback on this State of Play report, the various open-source models are being developed, and key priorities for the work to come.

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

8. References

1. Federal Ministry for Economic Affairs and Energy. *National Hydrogen Strategy*. (Federal Ministry for Economic Affairs and Energy Public Relations Division, 2020).
2. Fuhrmann, M. Germany's National Hydrogen Strategy - Serious efforts to realize a decarbonized society; development of green hydrogen supply infrastructure is the challenge. *Mitsui Co. Glob. Strateg. Stud. Inst. Mon. Rep.* 1–11 (2020).
3. Al-Breiki, M. & Bicer, Y. Comparative cost assessment of sustainable energy carriers produced from natural gas accounting for boil-off gas and social cost of carbon. *Energy Reports* **6**, 1897–1909 (2020).
4. METI. Trend of the price of spot-LNG. https://www.meti.go.jp/english/statistics/sho/slng/result/pdf/202103_e.pdf%0A (2021).
5. Nayak-Luke, R. M. & Bañares-Alcántara, R. Techno-economic viability of islanded green ammonia as a carbon-free energy vector and as a substitute for conventional production. *Energy Environ. Sci.* **13**, 2957–2966 (2020).
6. Masson-Delmotte, V. *et al. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,*. vol. 2 https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf (2018).
7. Black, R. *et al. Taking Stock: A global assessment of net zero targets*. https://ec.europa.eu/clima/policies/strategies/2050_en (2021).
8. Net Zero Tracker . *Energy & Climate Intelligence Unit* https://eciu.net/netzerotracker (2021).
9. Energy Transitions Commission. *Making Clean Electrification Possible: 30 Years to Electrify the Global Economy*. www.linkedin.com/company/energy-transitionscommission (2021).
10. IEA. *The Future of Hydrogen*. *IEA* (2019).
11. Energy Transitions Commission. *Making the Hydrogen Economy Possible: Accelerating clean hydrogen in an electrified economy*. (2021).
12. McKinsey & Company & Hydrogen Council. Hydrogen Insights. (2021).
13. Bloomberg New Energy Finance. *Hydrogen Economy Outlook*. (2020).
14. Hydrogen Council & McKinsey & Company. *Hydrogen Insights: A perspective on hydrogen investment, market development, and cost competitiveness*. www.hydrogencouncil.com. (2021).
15. IEA. *Energy Technology Perspectives 2020*. (IEA, 2020).
16. IEA. *World Energy Outlook 2020*. (IEA, 2020).
17. IRENA. *World Energy Transitions Outlook: 1.5oC Pathway*. (2021).
18. S&P Global. World oil demand may have peaked in 2019 amid energy transition: IRENA . *Petrochemicals* https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/031621-world-oil-demand-may-have-peaked-in-2019-amid-energy-transition-irena (2021).
19. IEA. *Net Zero by 2050 - A Roadmap for the Global Energy Sector*. https://www.iea.org/reports/net-zero-by-2050 (2021).
20. In-depth Q&A: Does the world need hydrogen to solve climate change? | Carbon Brief. https://www.carbonbrief.org/in-depth-qa-does-the-world-need-hydrogen-to-solve-climate-change.
21. BloombergNEF. Energy Transition Investment Trends 2021. https://about.bnef.com/energy-transition-investment/.
22. IRENA. *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5^{0}C Climate Goal*. (2020).
23. Ali Khan, M. H. *et al.* Designing Optimal Integrated Electricity Supply Configurations for Renewable Hydrogen Generation in Australia. *iScience* **24**, 102539 (2021).
24. BP. Statistical Review of World Energy. 66 (2020).
25. IEA Energy Atlas. *IEA* http://energyatlas.iea.org/#!/tellmap/-1002896040/0.
26. IEA. *The Role of Critical Minerals in Clean Energy Transitions*. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions (2021).
27. IRENA. *A New World: The geopolitics of energy transformation*. (IRENA, 2019).
28. Carbon Tracker Initiative. The Sky's the Limit: Solar and wind energy potential. *Energy Transitions* https://carbontracker.org/reports/the-skys-the-limit-solar-wind/ (2021).

29. Chu, C.-T. & Hawkes, A. D. A geographic information system-based global variable renewable potential assessment using spatially resolved simulation. *Energy* **193**, 116630 (2020).
30. Ferrara, G. The New Geopolitics of the Energy Transition . *Internationalaffairshouse.org* https://www.internationalaffairshouse.org/the-new-geopolitics-of-the-energy-transition/ (2021).
31. Pflugmann, F. & De Blasio, N. Geopolitical and Market Implications of Renewable Hydrogen New Dependencies in a Low-Carbon Energy World. 62 (2020).
32. Matich, B. Green hydrogen to reach cost parity by 2030. *pv Magazine* https://www.pv-magazine-australia.com/2019/11/15/green-hydrogen-to-reach-cost-parity-by-2030/ (2019).
33. ACIL Allen Consulting. Opportunities for Australia from Hydrogen Exports. 1–114 (2018).
34. Kimura, S. & Li, Y. *Demand and Supply Potential of Hydrogen Energy in East Asia*. *ERIA Research Project FY2018 No.01* https://www.g20karuizawa.go.jp/assets/pdf/Demand and Supply Potential of Hydrogen Energy in East Asia.pdf (2019).
35. The Sky's the Limit: Solar and wind energy potential is 100 times as much as global energy demand. *Carbon Tracker Initiative* https://carbontracker.org/reports/the-skys-the-limit-solar-wind/ (2021).
36. United Nations. *Review of Maritime Transport 2020*. *United Nations Conference on Trade and Development* (United Nation Publications, 2020).
37. United Nations. *Key Statistics and Trends in International Trade 2020 - Trade Trends Under The COVID-19 Pandemic*. *United Nations Conference on Trade and Development* (United Nation Publications, 2021).
38. International Chamber of Shipping. Shipping and world trade: driving prosperity. *Shipping Facts* https://www.ics-shipping.org/shipping-fact/shipping-and-world-trade-driving-prosperity/.
39. European Environment Agency. Specific CO2 emissions per tonne-km and per mode of transport in Europe . https://www.eea.europa.eu/data-and-maps/daviz/specific-co2-emissions-per-tonne-2#tab-chart_1 (2017).
40. IEA. Tracking Transport 2020. https://www.iea.org/reports/tracking-transport-2020 (2020).
41. Kaack, L. H., Vaishnav, P., Morgan, M. G., Azevedo, I. L. & Rai, S. Decarbonizing intraregional freight systems with a focus on modal shift. *Environ. Res. Lett.* **13**, (2018).
42. Deloitte. Australian and Global Hydrogen Demand Growth Scenario Analysis COAG Energy Council – National Hydrogen Strategy Taskforce. (2019).
43. MacFarlane, D. R. *et al.* A Roadmap to the Ammonia Economy. *Joule* **4**, 1186–1205 (2020).
44. Ewing, R. Global ammonia prices jump as key plants go offline. *ICIS* https://www.icis.com/explore/resources/news/2021/02/12/10606213/global-ammonia-prices-jump-as-key-plants-go-offline (2021).
45. Argus Media. Global ammonia trade to recover in 2021. https://www.argusmedia.com/en/news/2158915-global-ammonia-trade-to-recover-in-2021 (2020).
46. IndexBox. Rising Demand for Alternative Fuels to Spur the Global Methanol Market . *Global Trade Magazine* https://www.globaltrademag.com/rising-demand-for-alternative-fuels-to-spur-the-global-methanol-market/ (2021).
47. MarketandMarkets.com. Toluene Market Global Forecast to 2021. https://www.marketsandmarkets.com/Market-Reports/toluene-market-1095.html.
48. The Business Research Company. Global Toluene Market Data And Industry Growth Analysis. https://www.thebusinessresearchcompany.com/report/toluene-global-market-report.
49. The Observatory of Economic Complexity. Toluene (HS: 290230) Product Trade, Exporters and Importers. https://oec.world/en/profile/hs92/toluene.
50. Fortune Business Insights. Dimethyl Ether (DME) Market Size, Trends | Analysis, 2021-2028. *2021* https://www.fortunebusinessinsights.com/dimethyl-ether-market-104309.
51. Josephs, J. Climate change: Shipping industry calls for new global carbon tax . *BBC News* https://www.bbc.com/news/business-56835352 (2021).
52. Walker, T. R. *et al.* Chapter 27 - Environmental Effects of Marine Transportation. in (ed. Sheppard, C. B. T.-W. S. an E. E. (Second E.) 505–530 (Academic Press, 2019). doi:https://doi.org/10.1016/B978-0-12-805052-1.00030-9.
53. Lee, D. S. *Update of Maritime Greenhous Gas Emission Projections*. https://cedelft.eu/wp-content/uploads/sites/2/2021/03/CE_Delft_7I69_Update_of_Maritime_Greenhouse_Gas_Emission_Projections_DEF.pdf (2017).
54. BMVI - BMVI and BMWi are launching 62 large-scale hydrogen projects. https://www.bmvi.de/SharedDocs/DE/Artikel/K/62-wasserstoff-grossprojekte.html.
55. Department of Foreign Affairs and Trade. Germany country brief . https://www.dfat.gov.au/geo/germany/germany-country-brief.

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

56. Prime Minister & Minister for Energy and Emissions Reducition. Australia and Germany Partner on Hydrogen Initiatives . *Media Releases* https://www.pm.gov.au/media/australia-and-germany-partner-hydrogen-initiatives (2021).
57. Australian Trade and Investment Commission. *Why Australia: Benchmark Report 2021*. (2021).
58. Geoscience Australia. Australia's Energy Production, Consumption and Exports. https://www.ga.gov.au/scientific-topics/energy/overview#heading-1.
59. IRENA. *Renewable Capacity Statistics 2021*. (International Renewable Energy Agency, 2021).
60. Peacock, B. Australia's renewable growth outpaces world, even as new report finds record global expansion in 2020 – pv magazine Australia. *PV Magazine* https://www.pv-magazine-australia.com/2021/04/06/australias-renewable-growth-outpaces-world-even-amid-record-global-expansion-in-2020/ (2021).
61. IRENA. Installed Capacity of Solar Energy. *Country Rankings Dashboard* https://www.irena.org/Statistics/View-Data-by-Topic/Capacity-and-Generation/Country-Rankings.
62. Clean Energy Council. *Clean Energy Australia Report 2021*. http://www.cleanenergycouncil.org.au (2021).
63. CSIRO. Australia installs record-breaking number of rooftop solar panels . *Media Releases and Statements* https://www.csiro.au/en/news/news-releases/2021/australia-installs-record-breaking-number-of-rooftop-solar-panels (2021).
64. Ernest & Young. Renewable Energy Country Attractiveness Index (RECAI). https://www.ey.com/en_au/recai (2020).
65. WWF Australia. *Renewable Superpower Scorecard 2021 - Australia's race to Renewable Future*. (2021).
66. Doing Business. *Doing Business 2020*. (The World Bank, 2019).
67. Australian Bureau of Statistics. ABS Cat No. 5352.0 - International Investment Position, Australia: Supplementary Statistics. https://www.abs.gov.au/statistics/economy/international-trade/international-investment-position-australia-supplementary-statistics.
68. Department of Foreign Affairs and Trade. Australian industries and foreign direct investment. *Trade & investement data, information & publications* https://www.dfat.gov.au/trade/resources/investment-statistics/australian-industries-and-foreign-investment.
69. Australian Government Department of Foreign Affairs and Trade. Australia's trade in goods and services 2020 . *Trade Statistics* https://www.dfat.gov.au/trade/resources/trade-statistics/trade-in-goods-and-services/australias-trade-goods-and-services-2020 (2020).
70. Schwab, K. *The Global Competitiveness Report 2019*. (2019).
71. Department of Foreign Affairs and Trade. *Composition of Trade Australia 2018-19*. (2020).
72. Toscano, N. Australia tops Qatar as world's biggest LNG exporter. *The Sydney Morning Herald* https://www.smh.com.au/business/the-economy/australia-tops-qatar-as-world-s-biggest-lng-exporter-20200106-p53p5h.html (2020).
73. Johnston, M. Singapore scores top marks in new tech readiness ranking . *Channel Asia* https://www.channelasia.tech/article/641966/singapore-scores-top-marks-new-tech-readiness-ranking/ (2018).
74. Australian Trade and Investement Commission. Doing business in Australia is easier. *Economic Analysis* https://www.austrade.gov.au/news/economic-analysis/doing-business-in-australia-is-easier (2019).
75. Department of Foreign Affairs and Trade. Australia's free trade agreements (FTAs) . https://www.dfat.gov.au/trade/agreements/trade-agreements.
76. Infrastructure Australia. *An assessment of Australia's future infrastructure needs*. *The Australian Infrastructure Audit 2019* (2019).
77. Nangia, I. *et al.* Australia's infrastructure innovation imperative. *McKinsey Co.* (2019).
78. Department of Infrastructure and Regional Development. At a Glance Kilometres of Road Length Lane Kilometres of Road Length. 1–44 (2016).
79. The world's biggest road networks. https://www.roadtraffic-technology.com/features/featurethe-worlds-biggest-road-networks-4159235/.
80. Department of Infrastructure and Regional Development. *Trainline 5 Statisitcal Report*. (Commonwealth of Australia, 2017).
81. Bureau of Infrastructure Transport and Regional Economics (BITRE). *Australian Maritime Activity to 2029-2030*. (2010).
82. $110 Billion Plan : About : Department of Infrastructure, Transport, Regional Development and Communications. https://buildingourfuture.gov.au/110-billion-plan#top.
83. Commonwealth of Australia. *Australian Energy Statistics 2020 Energy Update Report*. (Department of Industry, Science, Energy and Resources, 2020).
84. Minister for Energy and Emissions Reduction. Australia sets new renewables records in 2020 . *The Hon Angus Taylor MP Media Releases* https://www.minister.industry.gov.au/ministers/taylor/media-releases/australia-sets-new-renewables-records-2020 (2021).

85. Minister for Energy and Emissions Reduction. Australia sets new renewables records in 2020 . *Media Releases* https://www.minister.industry.gov.au/ministers/taylor/media-releases/australia-sets-new-renewables-records-2020 (2021).

86. ARENA. 75% renewable NEM possible by 2025: AEMO . *ARENAWire* https://arena.gov.au/blog/75-renewable-nem-possible-by-2025-aemo/ (2020).

87. Australian Government. *Technology Investment Roadmaps - First Low Emissions Technology Statement 2020*. https://www.industry.gov.au/data-and-publications/technology-investment-roadmap-first-low-emissions-technology-statement-2020 (2020).

88. Teske, S., Dominish, E., Ison, N. & Maras.K. *100% Renewable Energy for Australia - Decarbonising Australia's Energy Sector within one Generation*. *ISF for GetUp! and Solar Citizens* (2016).

89. Blakers, A., Lu, B. & Stocks, M. 100% renewable electricity in Australia. *Energy* **133**, 471–482 (2017).

90. Teske, S., Nagrath, K., Morris, T. & Dooley, K. Renewable Energy Resource Assessment BT - Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5°C and +2°C. in (ed. Teske, S.) 161–173 (Springer International Publishing, 2019). doi:10.1007/978-3-030-05843-2_7.

91. Boretti, A. Production of hydrogen for export from wind and solar energy, natural gas, and coal in Australia. *Int. J. Hydrogen Energy* **45**, 3899–3904 (2020).

92. Geoscience Australia and BREE. *Australian Energy Resource Assessment 2014*. https://arena.gov.au/assets/2018/08/australian-energy-resource-assessment.pdf (2014) doi:10.1016/B978-0-12-805474-1.00008-7.

93. World Energy Council. New Hydrogen Economy-Hope or Hype. *Innov. Insights Br.* 6 (2019).

94. Nagashima, M. *Japan's Hydrogen Strategy and Its Economic and Geopolitical Implications*. (2018).

95. Ha, J. E. Hydrogen Economy Plan in Korea Current situation in Korea Aiming High. 1–2 (2019).

96. Australian Renewable Energy Agency. Australia and Germany come together to assess hydrogen supply chain. *ArenaWire* https://arena.gov.au/blog/australia-and-germany-come-together-to-assess-hydrogen-supply-chain/ (2020).

97. Lambert, V. & Ashworth, P. *The Australian public's perception of hydrogen for energy*. https://arena.gov.au/assets/2018/12/the-australian-publics-perception-of-hydrogen-for-energy.pdf (2018).

98. Commonwealth of Australia. Budget 2021-22: Building a more secure and resilient Australia . *2021* https://budget.gov.au/2021-22/content/resilient.htm#three.

99. DISER. Major investments for international partnerships and hubs to build demand for Australian hydrogen. *Australian Hydrogen News* https://mailchi.mp/industry.gov.au/australian-hydrogen-news-april-2021?e=67e4c5e738 (2021).

100. Australian Government Department of Industry, Science,Energy and Resources. Government announces $300m Advancing Hydrogen Fund. *Web Release* https://www.energy.gov.au/news-media/news/government-announces-300m-advancing-hydrogen-fund (2020).

101. ARENA. Three hydrogen projects share in $103 million of funding . *ARENAWire* https://arena.gov.au/blog/three-hydrogen-projects-share-in-103-million-of-funding/ (2021).

102. Clayton Utz. *Hydrogen Industry Legislation*. https://energyministers.gov.au/sites/prod.energycouncil/files/publications/documents/nhs-hydrogen-industry-legislation-report-2019_0.pdf (2019).

103. Commonwealth of Australia. *Australia's National Hydrogen Strategy*. (COAG Energy Council Hydrogen Working Group, 2019).

104. Standards Australia. Hydrogen. *Flagship Projects* https://www.standards.org.au/engagement-events/flagship-projects/hydrogen.

105. Standards Australia. Hydrogen Standards Release Summary July 2020. https://www.standards.org.au/getmedia/52741f79-b166-40f7-b998-e0cf5287aec0/Hydrogen-standards-release-summary-July-2020.aspx (2020).

106. Standards Australia. *Hydrogen Technologies Standards Discussion Paper*. (2018).

107. Australian Government Department of Industry, Science,Energy and Resources. *A Hydrogen Guarantee of Origin scheme for Australia - Discussion Paper*. https://consult.industry.gov.au/climate-change/hydrogen-guarantee-of-origin-scheme-discussion/ (2021).

108. Hydrogen Australia. Overview of Zero Carbon Certification Scheme. 1–2 https://www.smartenergy.org.au/sites/default/files/uploaded-content/website-content/overview_of_the_zero_carbon_certification_scheme.pdf (2020).

109. Clean Energy Council. Project Tracker -Clean Energy Projects Australia . *Resources* https://www.cleanenergycouncil.org.au/resources/project-tracker.

110. AEMO. *2020 Integrated System Plan For the National Electricity Market*. https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/ISP/2018/Integrated-System-Plan-2018_final.pdf (2020).

111. Vorrath, S. Call to develop 1.5GW green hydrogen hub gets 'super major' response . *RenewEconomy* https://reneweconomy.com.au/call-to-develop-1-5gw-green-hydrogen-hub-gets-super-major-response/ (2021).

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

112. Pendlebury, R., Meares, T. & Tyrrell, J. Hydrogen: the new Australian manufacturing export industry and the implications for the National Electricity Market (NEM) | AEMC. *AEMC* https://www.aemc.gov.au/hydrogen-new-australian-manufacturing-export-industry-and-implications-national-electricity-market.

113. Pfenninger, S. & Staffell, I. Renewables Ninja. https://www.renewables.ninja/.

114. Schnuelle, C., Wassermann, T., Fuhrlaender, D. & Zondervan, E. Dynamic hydrogen production from PV & wind direct electricity supply – Modeling and techno-economic assessment. *Int. J. Hydrogen Energy* **45**, 29938–29952 (2020).

115. Bruce S *et al. National Hydrogen Roadmap*. https://www.csiro.au/~/media/Do-Business/Files/Futures/18-00314_EN_NationalHydrogenRoadmap_WEB_180823.pdf?la=en&hash=36839EEC2DE1BC38DC738F5AAE7B40895F3E15F4 (2019).

116. IRENA. *Hydrogen: a Renewable Energy Perspective*. (IRENA, 2019).

117. Longden, T., Jotzo, F., Prasad, M. & Andrews, R. Green hydrogen production costs in Australia: implications of renewable energy and electrolyser costs. (2020).

118. Yates, J. *et al.* Techno-economic Analysis of Hydrogen Electrolysis from Off-Grid Stand-Alone Photovoltaics Incorporating Uncertainty Analysis. *Cell Reports Phys. Sci.* **1**, 100209 (2020).

119. Reserve Bank of Australia. Exchange Rates . https://www.rba.gov.au/statistics/frequency/exchange-rates.html.

120. European Commission. *A hydrogen strategy for a climate-neutral Europe*. vol. COM(2020) https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf (2020).

121. *DOE Hydrogen and Fuel Cells Program Record 9013: Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs*. (2009).

122. Barthelemy, H., Weber, M. & Barbier, F. Hydrogen storage: Recent improvements and industrial perspectives. *Int. J. Hydrogen Energy* **42**, 7254–7262 (2017).

123. Feitz, A. J., Tenthorey, E. & Coghlan, R. *Prospective Hydrogen Production Regions of Australia. Record 2019/15*. http://dx.doi.org/10.11636/Record.2019.015%0D (2019).

124. Wolf, E. Large-Scale Hydrogen Energy Storage. in *Electrochemical Energy Storage for Renewable Sources and Grid Balancing* 129–142 (Elsevier Inc., 2015). doi:10.1016/B978-0-444-62616-5.00009-7.

125. Geoscience Australia. Hydrogen | Geoscience Australia. https://www.ga.gov.au/scientific-topics/energy/resources/hydrogen (2020).

126. Lahnaoui, A., Wulf, C., Heinrichs, H. & Dalmazzone, D. Optimizing hydrogen transportation system for mobility via compressed hydrogen trucks. *Int. J. Hydrogen Energy* **44**, 19302–19312 (2019).

127. Hydrogen Council. Path to hydrogen competitiveness: a cost perspective. 88 (2020).

128. Giorgio. *IEA-ETSAP© Technology Brief P12-February 2014-www.etsap.org ENERGY TECHNOLOGY SYSTEM ANALYSIS PROGRAMME Hydrogen Production & Distribution*.

129. Ozcan, H. & Dincer, I. Thermodynamic modeling of a nuclear energy based integrated system for hydrogen production and liquefaction. *Comput. Chem. Eng.* **90**, 234–246 (2016).

130. About HESC | Hydrogen Energy Supply Chain.

131. Linde. Linde and Hyosung Partner to Develop Hydrogen Infrastructure in South Korea. *Press Releases* https://www.linde.com/news-media/press-releases/2021/linde-and-hyosung-partner-to-develop-hydrogen-infrastructure-in-south-korea (2021).

132. Kawasaki Heavy and Shell to partner on technologies for transporting liquefied hydrogen by sea . *Green Car Congress* https://www.greencarcongress.com/2016/03/20160314-khi.html (2016).

133. Harding, R. Japan launches first liquid hydrogen carrier ship. *Financial Times* https://www.ft.com/content/8ae16d5e-1bd4-11ea-97df-cc63de1d73f4 (2019).

134. Kawasaki Heavy Industries Ltd. Kawasaki Completes World's First Liquefied Hydrogen Receiving Terminal Kobe LH2 Terminal (Hy touch Kobe). *Press Release* https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20201203_2378&fbclid=IwAR1SW2jVItPYN7xl8V22FY3HU2omoC1FObuE18H814aV2Vdlef4Vbz_GXcg (2020).

135. Niermann, M., Timmerberg, S., Drünert, S. & Kaltschmitt, M. Liquid Organic Hydrogen Carriers and alternatives for international transport of renewable hydrogen. *Renew. Sustain. Energy Rev.* **135**, 110171 (2021).

136. Raab, M., Maier, S. & Dietrich, R.-U. Comparative techno-economic assessment of a large-scale hydrogen transport via liquid transport media. *Int. J. Hydrogen Energy* (2021) doi:https://doi.org/10.1016/j.ijhydene.2020.12.213.

137. The Observatory of Economic Complexity. Ammonia (HS: 2814) Product Trade, Exporters and Importers . https://oec.world/en/profile/hs92/ammonia?redirect=true.

138. Klerke, A., Christensen, C. H., Nørskov, J. K. & Vegge, T. Ammonia for hydrogen storage: challenges and opportunities. *J. Mater. Chem.* **18**, 2304 (2008).

139. Chiuta, S., Everson, R. C., Neomagus, H. W. J. P., Van Der Gryp, P. & Bessarabov, D. G. Reactor technology options for distributed hydrogen generation via ammonia decomposition: A review. *International Journal of Hydrogen Energy* vol. 38 14968–14991 (2013).
140. Andersson, J. & Grönkvist, S. Large-scale storage of hydrogen. *International Journal of Hydrogen Energy* vol. 44 11901–11919 (2019).
141. Dolan, M. Delivering clean hydrogen fuel from ammonia using metal membranes. in *2017 AIChE Annual Meeting* (AIChE, 2017).
142. Yara & Engie. *ENGIE-YARA Renewable Hydrogen and Ammonia Deployment in Pilbara YURI Phase 0: Feasibility Study Knowledge Sharing Report*. (2020).
143. QNP, ARENA & Neon and Worley. QNP Green Ammonia Project Feasibility Study. (2020).
144. ARENA. Project GERI Feasibility Study. *Projects* https://arena.gov.au/projects/project-geri-feasibility-study/.
145. Brown Trevor. H2U moves forward with 3 GW green ammonia export plant . *Ammonia Energy* https://www.ammoniaenergy.org/articles/h2u-moves-forward-with-3-gw-green-ammonia-export-plant/ (2020).
146. Intercontinental Energy. Asian renewable energy hub . https://intercontinentalenergy.com/asian-renewable-energy-hub.
147. CSIRO. Origin Green Hydrogen and Ammonia Plant. *HyResource* https://research.csiro.au/hyresource/origin-green-hydrogen-and-ammonia-plant/ (2020).
148. Dias, V., Pochet, M., Contino, F. & Jeanmart, H. Energy and Economic Costs of Chemical Storage . *Frontiers in Mechanical Engineering* vol. 6 21 (2020).
149. Liquefied Natural Gas in Germany. https://eurasianventures.com/liquefied-natural-gas-in-germany/.
150. ARENA. APA Renewable Methane Demonstration Project. *Projects* https://arena.gov.au/projects/apa-renewable-methane-demonstration-project/.
151. ATCO. ATCO investigates renewable natural gas in Albany, Western Australia. https://www.atco.com/en-au/about-us/stories/atco-renewable-natural-gas-albany.html (2020).
152. Core Energy Group. *Gas Production and Transmission Costs Eastern and South Eastern Australia*. https://aemo.com.au/-/media/Files/Gas/National_Planning_and_Forecasting/GSOO/2015/Core--Gas-Production-and-Transmission-Costs.ashx (2015).
153. Cassidy, N. & Kosev, M. *Australia and the Global LNG Market*. *Reserve Bank Of Australia* https://www.rba.gov.au/publications/bulletin/2015/mar/pdf/bu-0315-4.pdf (2015).
154. Rogers, H. *The LNG Shipping Forecast : costs rebounding , outlook uncertain*. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2018/02/The-LNG-Shipping-Forecast-costs-rebounding-outlook-uncertain-Insight-27.pdf (2018).
155. Chemistry in Australia - Economics: Volatility in the methanol market (Asia Collection) - Informit.
156. Jadhav, S. G., Vaidya, P. D., Bhanage, B. M. & Joshi, J. B. Catalytic carbon dioxide hydrogenation to methanol: A review of recent studies. *Chemical Engineering Research and Design* vol. 92 2557–2567 (2014).
157. Pérez-Fortes, M., Schöneberger, J. C., Boulamanti, A. & Tzimas, E. Methanol synthesis using captured CO2 as raw material: Techno-economic and environmental assessment. *Appl. Energy* **161**, 718–732 (2016).
158. Alsayegh, S., Johnson, J. R., Ohs, B. & Wessling, M. Methanol production via direct carbon dioxide hydrogenation using hydrogen from photocatalytic water splitting: Process development and techno-economic analysis. *J. Clean. Prod.* **208**, 1446–1458 (2019).
159. MAN Energy Solutions. World-First Order for Methanol Engine within Container Segment. *Press Releases* https://www.man-es.com/company/press-releases/press-details/2021/07/27/world-first-order-for-methanol-engine-within-container-segment (2021).
160. Maersk. Maersk secures green e-methanol for the world's first container vessel operating on carbon neutral fuel . *Press Releases* https://www.maersk.com/news/articles/2021/08/18/maersk-secures-green-e-methanol (2021).
161. ABEL Energy. Bell Bay Power Fuels Project.
162. Carbon Recycling International. Projects: Emissions-to-Liquids Technology — CRI . *Projects* https://www.carbonrecycling.is/projects.
163. Proman. Proman to build world's largest green methanol plant at North Sea renewables hub . *News* https://www.proman.org/news/proman-to-build-worlds-largest-green-methanol-plant-at-north-sea-renewables-hub/ (2020).
164. Niermann, M., Beckendorff, A., Kaltschmitt, M. & Bonhoff, K. Liquid Organic Hydrogen Carrier (LOHC) – Assessment based on chemical and economic properties. *International Journal of Hydrogen Energy* vol. 44 6631–6654 (2019).
165. Gonda, M., Ohshima, M. A., Kurokawa, H. & Miura, H. Toluene hydrogenation over Pd and Pt catalysts as a model hydrogen storage process using low grade hydrogen containing catalyst inhibitors. in *International Journal of Hydrogen Energy* vol. 39 16339–16346 (Elsevier Ltd, 2014).

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

166. Preuster, P., Papp, C. & Wasserscheid, P. Liquid organic hydrogen carriers (LOHCs): Toward a hydrogen-free hydrogen economy. *Acc. Chem. Res.* **50**, 74–85 (2017).
167. Port of Rotterdam. Feasibility study on export of South Australian green hydrogen to Rotterdam . *News and Press Releases* https://www.portofrotterdam.com/en/news-and-press-releases/feasibility-study-export-south-australian-green-hydrogen-rotterdam (2021).
168. Hydrogenious LOHC Technologies. Kick-off for construction and operation of the world's largest plant for storing green hydrogen in Liquid Organic Hydrogen Carrier. *Press Release* https://www.hydrogenious.net/index.php/en/2021/03/03/kick-off-for-construction-and-operation-of-the-worlds-largest-plant-for-storing-green-hydrogen-in-liquid-organic-hydrogen-carrier/ (2021).
169. Hydrogenious LOHC Technologies. Novel path towards safe zero-emission shipping: Hydrogenious LOHC Technologies and Østensjø Group join forces with tailwind from Enova funding. *Press Release* https://www.hydrogenious.net/index.php/en/2021/07/02/lohc_maritime-2/ (2021).
170. Hurskainen, M. & Ihonen, J. Techno-economic feasibility of road transport of hydrogen using liquid organic hydrogen carriers. *Int. J. Hydrogen Energy* **45**, 32098–32112 (2020).
171. HYSTOC & FCHJU. Hyrdogen Supply and Transportation using Liquid Organic Hydrogen Carriers (HySTOC) WP8 Business Development and sustainability – Concept Studies , Economic Analysis , Life Cycle Assessment. 1–24 (2020).
172. MarineTraffic: Global Ship Tracking Intelligence | AIS Marine Traffic. https://www.marinetraffic.com/en/ais/home/centerx:22.1/centery:43.2/zoom:2.
173. CSIRO. Hydrides: metal . *Hydrogen Technology Marketplace* https://www.csiro.au/en/work-with-us/ip-commercialisation/hydrogen-technology-marketplace/hydrides-metal.
174. Tasmanian Government. Tasmanian Renewable Hydrogen Action Plan Growing our Hydrogen Industry from abundant low-cost reliable Tasmanian renewable energy Contents. 40 (2020).
175. Government of South Australia. Hydrogen projects in South Australia. *RenewablesSA* http://www.renewablessa.sa.gov.au/topic/hydrogen/hydrogen-projects-south-australia.
176. Al-Breiki, M. & Bicer, Y. Investigating the technical feasibility of various energy carriers for alternative and sustainable overseas energy transport scenarios. *Energy Convers. Manag.* **209**, (2020).
177. Kamiya, S., Nishimura, M. & Harada, E. Study on introduction of CO2 free energy to Japan with liquid hydrogen. in *Physics Procedia* vol. 67 11–19 (Elsevier B.V., 2015).
178. Okazaki, S. & Cornell, A. Hydrogen - the fuel of the future? *Bluenotes* https://bluenotes.anz.com/posts/2020/05/hydrogen-australia-japan-kawasaki-heavy-industries?adobe_mc=MCMID%3D59447298986312306920467979088521483179%7CMCAID%3D2F2C49458515A13C-40000B4E644DD55D%7CMCORGID%3D67A216D751E567B20A490D4C%2540AdobeOrg%7-CTS%3D1593406 (2020).
179. Allman, A., Daoutidis, P., Tiffany, D. & Kelley, S. A framework for ammonia supply chain optimization incorporating conventional and renewable generation. *AIChE J.* **63**, 4390–4402 (2017).
180. Graham, C., Hayward, P., Foster, J. & Havas, J. GenCost 2020-21 Consultation draft. 2020–2041 (2020).
181. Aurecon & AEMO. 2020 Costs and Technical Parameter Review. (2019).
182. Steward, D., Saur, G., Penev, M. & Ramsden, T. *Lifecycle Cost Analysis of Hydrogen Versus Other Technologies for Electrical Energy Storage Lifecycle Cost Analysis of Hydrogen Versus Other Technologies for Electrical Energy Storage*. (2009).
183. Tarkowski, R. & Czapowski, G. Salt domes in Poland – Potential sites for hydrogen storage in caverns. *Int. J. Hydrogen Energy* **43**, 21414–21427 (2018).
184. Gorre, J., van Leeuwen, C. & Ortloff, F. Innovative large-scale energy storage technologies and Power-to-Gas concepts after optimisation Report on the optimal time profile and operation of the conversion technology during a repre- sentative year, in the perspective of the available storage cap. (2018).
185. Sgobbi, A. *et al.* How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system. *Int. J. Hydrogen Energy* **41**, 19–35 (2016).
186. Ahluwalia, R. K. *et al.* System Level Analysis of Hydrogen Storage Options. in *2019 Annual Merit Review and Peer Evaluation Meeting* (U.S. DOE Hydrogen and Fuel Cells Program 2019, 2019).
187. Ikäheimo, J., Kiviluoma, J., Weiss, R. & Holttinen, H. Power-to-ammonia in future North European 100 % renewable power and heat system. *Int. J. Hydrogen Energy* **43**, 17295–17308 (2018).
188. Parks, G., Boyd, R., Cornish, J. & Remick, R. *Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs: Systems Integration*. https://www.osti.gov/biblio/1130621 (2014) doi:10.2172/1130621.

The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0

189. Reuß, M. *et al.* Seasonal storage and alternative carriers: A flexible hydrogen supply chain model. *Appl. Energy* **200**, 290–302 (2017).

190. Lahnaoui, A., Wulf, C. & Dalmazzone, D. Building an optimal hydrogen transportation system for mobility, focus on minimizing the cost of transportation via truck. *Energy Procedia* **142**, 2072–2079 (2017).

191. Stolzenburg, K. *et al. Efficient Liquefaction of Hydrogen: Results of the IDEALHY Project*. (2013).

192. Hank, C. *et al.* Energy efficiency and economic assessment of imported energy carriers based on renewable electricity. *Sustain. Energy Fuels* **4**, 2256–2273 (2020).

193. Connelly, E., Penev, M., Elgowainy, A. & Hunter, C. *Current Status of Hydrogen Liquefaction Costs*. *DOE Hydrogen and Fuel Cells Program Record* (2019).

194. Hank, C. *et al.* Economics & carbon dioxide avoidance cost of methanol production based on renewable hydrogen and recycled carbon dioxide-power-to-methanol. *Sustain. Energy Fuels* **2**, 1244–1261 (2018).

195. Bos, M. J., Kersten, S. R. A. & Brilman, D. W. F. Wind power to methanol: Renewable methanol production using electricity, electrolysis of water and CO2 air capture. *Appl. Energy* **264**, 114672 (2020).

196. Adnan, M. A. & Kibria, M. G. Comparative techno-economic and life-cycle assessment of power-to-methanol synthesis pathways. *Appl. Energy* **278**, 115614 (2020).

197. Lee, B. *et al.* Renewable methanol synthesis from renewable H2 and captured CO2: How can power-to-liquid technology be economically feasible? *Appl. Energy* **279**, 115827 (2020).

198. Terwel, R. & Kerkhoven, J. *HyChain 2: Cost implications of importing renewable electricity, hydrogen and hydrogen carriers into the Netherlands from a 2050 perspective. Model User Guide, Technical Documentation, First Results and Country Profiles*. (Institute of Sustainable Process Technology, 2019).

199. Papadias, D. D., Peng, J. . & Ahluwalia, R. K. H2@Scale: Outlook of Hydrogen Carriers at Different Scales. in *Department of Energy Hydrogen Carriers Workshop: Novel Pathways for Optimized Hydrogen Transport & Stationary Storage* (2019).

200. Fúnez Guerra, C. *et al.* Technical-economic analysis for a green ammonia production plant in Chile and its subsequent transport to Japan. *Renew. Energy* **157**, 404–414 (2020).

201. Nayak-Luke, R., Bañares-Alcántara, R. & Wilkinson, I. "Green" Ammonia: Impact of Renewable Energy Intermittency on Plant Sizing and Levelised Cost of Ammonia. *Ind. Eng. Chem. Res.* **57**, 14607–14616 (2018).

202. Hank, C. *et al.* Energy efficiency and economic assessment of imported energy carriers based on renewable electricity. *Sustain. Energy Fuels* **4**, 2256–2273 (2020).

203. Cesaro, Z., Ives, M., Nayak-Luke, R., Mason, M. & Bañares-Alcántara, R. Ammonia to power: Forecasting the levelised cost of electricity from green ammonia in large-scale power plants. *Appl. Energy* **282**, 116009 (2021).

204. Ishimoto, Y. *et al.* Large-scale production and transport of hydrogen from Norway to Europe and Japan: Value chain analysis and comparison of liquid hydrogen and ammonia as energy carriers. *Int. J. Hydrogen Energy* **45**, 32865–32883 (2020).

205. Chiuta, S., Engelbrecht, N., Human, G. & Bessarabov, D. G. Techno-economic assessment of power-to-methane and power-to-syngas business models for sustainable carbon dioxide utilization in coal-to-liquid facilities. *J. CO2 Util.* **16**, 399–411 (2016).

206. Böhm, H., Zauner, A., Rosenfeld, D. C. & Tichler, R. Projecting cost development for future large-scale power-to-gas implementations by scaling effects. *Appl. Energy* **264**, 114780 (2020).

207. Gorre, J., Ortloff, F. & van Leeuwen, C. Production costs for synthetic methane in 2030 and 2050 of an optimized Power-to-Gas plant with intermediate hydrogen storage. *Appl. Energy* **253**, 113594 (2019).

208. Uebbing, J., Rihko-Struckmann, L. K. & Sundmacher, K. Exergetic assessment of CO2 methanation processes for the chemical storage of renewable energies. *Appl. Energy* **233–234**, 271–282 (2019).

209. Schaaf, T., Grünig, J., Schuster, M. R., Rothenfluh, T. & Orth, A. Methanation of CO2 - storage of renewable energy in a gas distribution system. *Energy. Sustain. Soc.* **4**, 2 (2014).

210. Götz, M. *et al.* Renewable Power-to-Gas: A technological and economic review. *Renew. Energy* **85**, 1371–1390 (2016).

211. Kimura, S., Kutani, I., Ikeda, O. & Chihiro, R. Review of Hydrogen Transport Cost and its Prespective (Liquid Organic Hydrogen Carrier). in *Demand and Supply Potential of Hydrogen Energy in East Asia – Phase 2* 52–59 (2020).

212. Wijayanta, A. T., Oda, T., Purnomo, C. W., Kashiwagi, T. & Aziz, M. Liquid hydrogen, methylcyclohexane, and ammonia as potential hydrogen storage: Comparison review. *International Journal of Hydrogen Energy* vol. 44 15026–15044 (2019).

213. Skorikova, G. *et al.* The Techno-Economic Benefit of Sorption Enhancement: Evaluation of Sorption-Enhanced Dimethyl Ether Synthesis for CO2 Utilization . *Frontiers in Chemical Engineering* vol. 2 22 (2020).

214. Michailos, S., McCord, S., Sick, V., Stokes, G. & Styring, P. Dimethyl ether synthesis via captured CO2 hydrogenation within the power to liquids concept: A techno-economic assessment. *Energy Convers. Manag.* **184**, 262–276 (2019).

215. CSIRO. Australian Government – Hydrogen Industry Policy Initiatives. *HyResource* https://research.csiro.au/hyresource/policy/australia-and-new-zealand/australia/ (2021).

216. Australian Government Department of Industry, Science, Energy and Resources., Australian Government Department of Industry, Science, Energy and Resources. *A Hydrogen Guarantee of Origin scheme for Australia - Discussion Paper*. (2021).

217. Graham, P., Hayward, J., Foster, J. & Havas, L. *GenCost 2020-21: Final report*. (2021).

218. Barckholtz, T. *et al. Hydrogen Delivery Technical Team Roadmap 2013*. *U.S. Drive, Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability* (2013).

219. U.S. DRIVE Partnership. *Hydrogen Delivery Technical Team Roadmap*. (2017).

220. Bakhtiary-Davijany, H. & Myhrvold, T. On Methods for Maturity Assessment of CO2 Capture Technologies. *Energy Procedia* **37**, 2579–2584 (2013).

221. Bhown, A. S. Status and Analysis of Next Generation Post-combustion CO2 Capture Technologies. *Energy Procedia* **63**, 542–549 (2014).

222. Plaza, M. G., Martínez, S. & Rubiera, F. CO2 Capture, Use, and Storage in the Cement Industry: State of the Art and Expectations. *Energies* vol. 13 (2020).

223. Hills, T., Leeson, D., Florin, N. & Fennell, P. Carbon Capture in the Cement Industry: Technologies, Progress, and Retrofitting. *Environ. Sci. Technol.* **50**, 368–377 (2016).

224. Folger, P. Carbon capture: a technology assessment. in (LIBRARY OF CONGRESS WASHINGTON DC CONGRESSIONAL RESEARCH SERVICE, 2013).

225. Abanades, J. C. *et al.* Emerging CO2 capture systems. *Int. J. Greenh. Gas Control* **40**, 126–166 (2015).

226. Dieterich, V., Buttler, A., Hanel, A., Spliethoff, H. & Fendt, S. Power-to-liquid via synthesis of methanol, DME or Fischer–Tropsch-fuels: a review . *Energy Environ. Sci.* (2020) doi:10.1039/d0ee01187h.

227. Rogers, H. *The LNG Shipping Forecast : costs rebounding , outlook uncertain*. (The Oxford Institute for Energy Studies, 2018).

228. Timera Energy. Deconstructing LNG shipping costs . https://timera-energy.com/deconstructing-lng-shipping-costs/ (2018).

229. Canal de Panama. Tolls Calculation Guide for a LNG Vessel. http://www.pancanal.com/peajes/pdf/examples/LNG-n-LPG.pdf.

230. Ship & Bunker. World Bunker Prices. World Bunker Prices https://shipandbunker.com/prices (2021).

231. Stream. LNG Shipping Overview. *Global LNG Hub* https://globallnghub.com/wp-content/uploads/attach_47.pdf (2013).