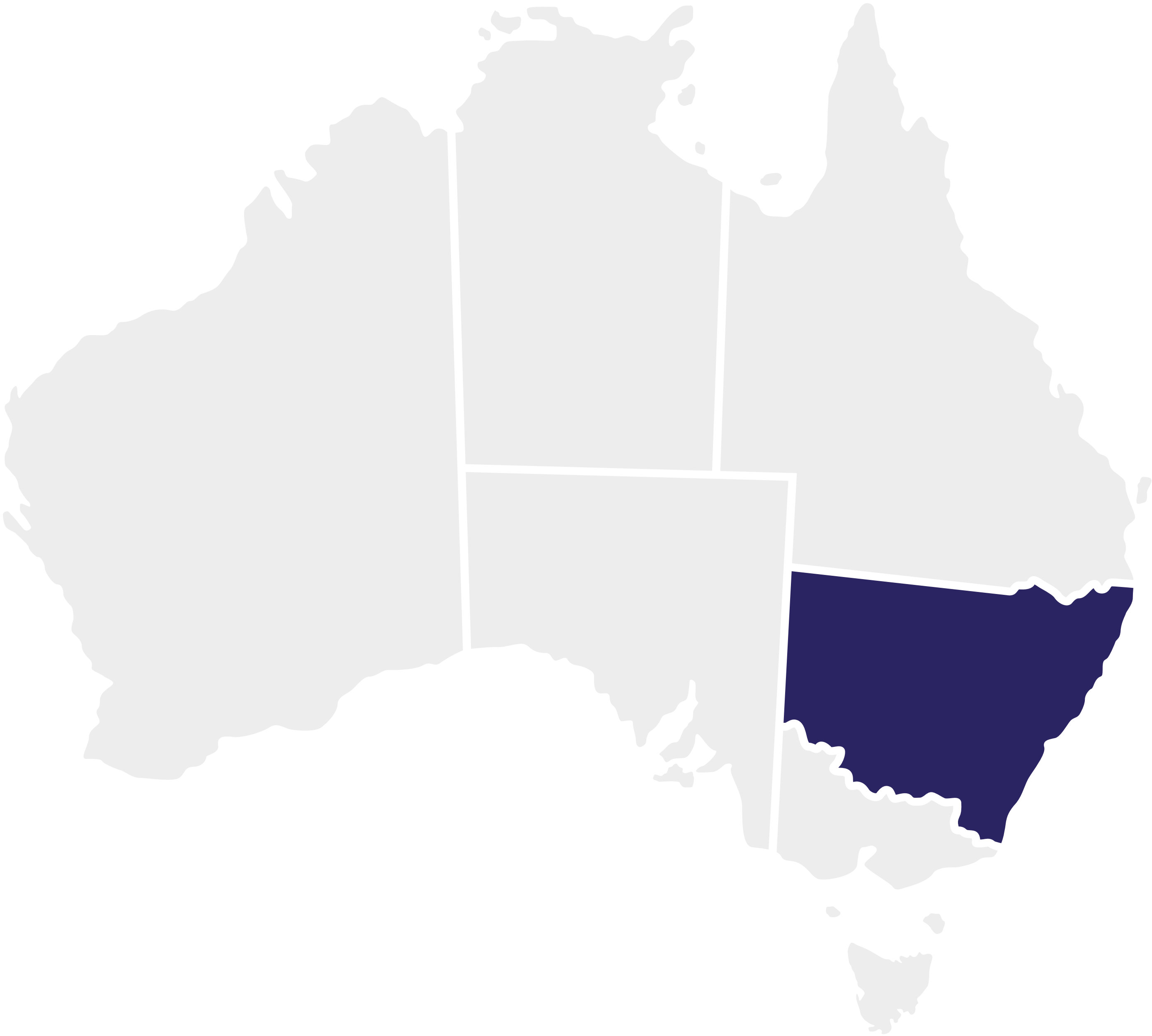

NSW Power to X (P2X) Industry Pre-Feasibility Study

A Roadmap for a P2X economy in NSW

UNSW Sydney

This work was carried out by the UNSW Sydney with the support from the Office of NSW Chief Scientist & Engineer.

CITATION

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Executive Summary

The State of New South Wales (NSW) has world-leading renewable energy in solar and wind as well as pumped hydro resources. The abundant natural resources, combined with rapidly falling technology prices in renewable energy generation and storage, are placing NSW in a position for a global energy superpower. NSW has undertaken great strides in developing renewable energy, both at large-scale and distributed level. This puts NSW on track on reducing electricity price and decarbonising the state's energy sector. Channelling low-cost renewable energy to other sectors and industries will bring substantial economic and decarbonisation opportunities for the state. For this reason, there is a pressing need to develop integrated solutions that can provide sector-coupling impacts to make the most of the NSW's renewable resources and low-cost electricity.

The Power-to-X (P2X) industry offers such potential solutions. P2X technologies can produce clean fuels and chemicals such as green hydrogen, ammonia and synthetic hydrocarbons using low-cost renewable energy and other abundant or waste resources. P2X begins with the conversion of water into green hydrogen for direct use as a clean fuel or as a feedstock for a secondary process to produce other powerfuels, chemicals and green commodities. The P2X pathways **(Figure A)** can close the carbon loop and generate clean and sustainable counterparts to replace fossil fuels across industries. For some high emitting and hard-to-abate industries such as aviation and maritime shipping, P2X offers the most viable decarbonisation solution where there are limited alternatives. P2X products are excellent energy carriers to commoditise Australia's renewable resources and export to overseas markets in a stable, safe and economic way.

All states and territories in Australia have joined the hydrogen race to develop local capacity and capability. The future hydrogen industry is promising for Australia to become a major global producer enabled by low-cost electricity and technology advancement in hydrogen value chains. By looking beyond hydrogen and building on the forthcoming hydrogen economy, converting renewable electricity, green hydrogen and waste streams to make a variety of clean powerfuels, chemicals and products is what P2X industries could offer to NSW. The development of P2X industries can complement and further accelerate the hydrogen economy through knowledge sharing, translatable technology, aggregated demand and economies of scale.

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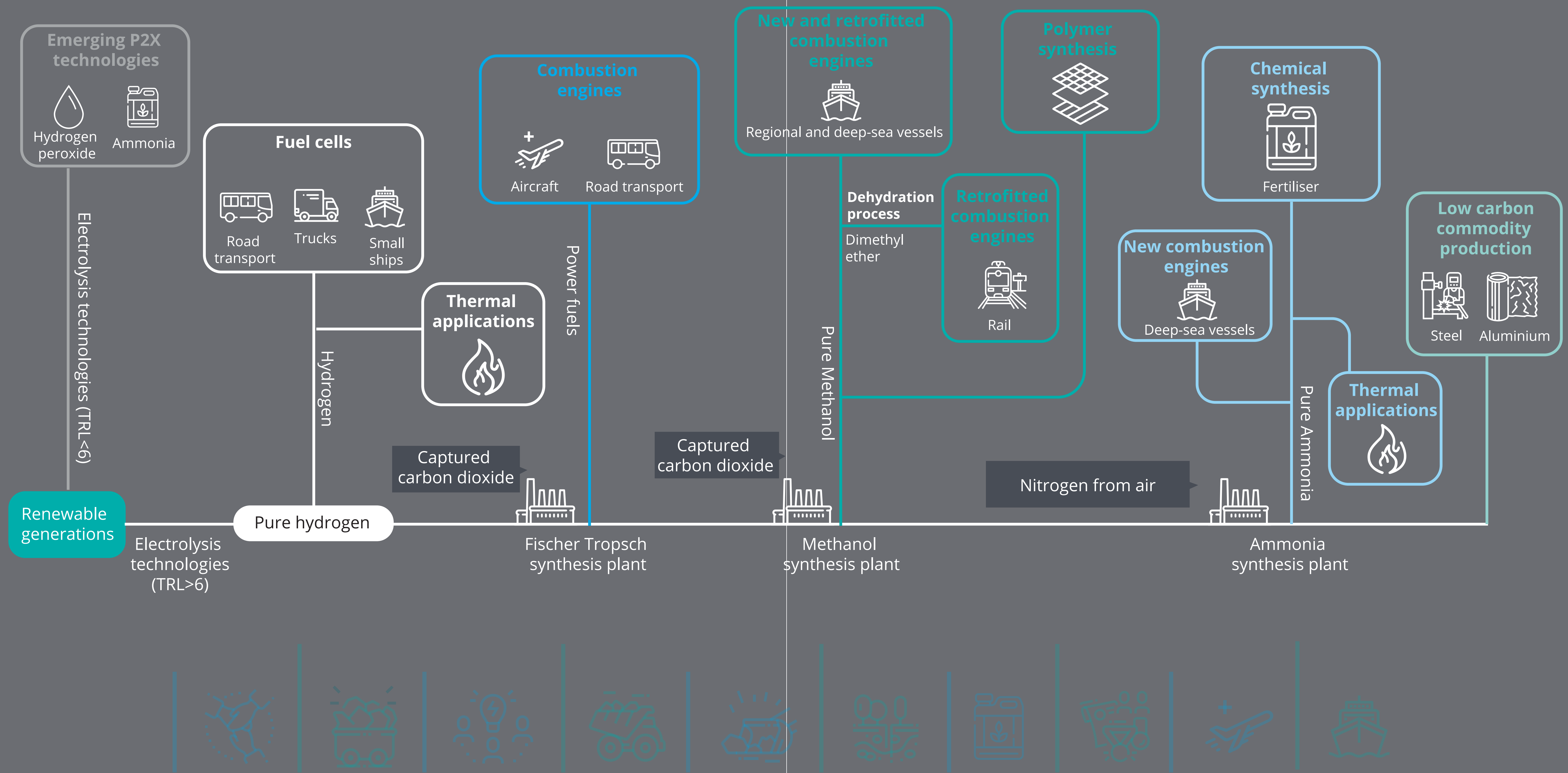
Figure A. P2X pathways to unlock sector coupling and allowing deep-rooted decarbonisation. Note that downstream application of powerfuels may produce emissions which can be closed using P2X technologies.



Recognising P2X's potential, UNSW Sydney led this pre-feasibility study on behalf of the Office of NSW Chief Scientist & Engineer (NSW OCSE). The purpose of this work was to provide an independent, evidence-based and industry-focused perspective on NSW's opportunities of building a future P2X economy. This study's objective is to assess the technological pathway of different P2X industries and to identify prospective locations for large scale P2X production in NSW with preliminary techno-economic analysis.

NSW has a strong business case to invest in P2X where the state has all the successful ingredients for a prosperous new economy. These include existing and growing demand of P2X products, low-cost electricity with the rolling out of the Renewable Energy Zones (REZs) and large electricity infrastructure, coordinated planning and fast-tracking deployment of the Special Activation Precincts (SAPs) and Hydrogen Hubs, world-leading research and development capabilities of P2X technologies as well as supporting decarbonisation policy and financial packages by the NSW Government.

As a technology-enabled new industry, the deployment of P2X in NSW and Australia will be decided by their technological pathways. The study conducted a systematic review of different P2X technologies and their development status and cost, key drivers towards price-parity with their fossil fuel counterparts, applications and end-users within NSW context as well as the local market size and global demand of these P2X products. These P2X pathways considered in this study are Power to Hydrogen, Power to Ammonia, Power to Methane, Power to Methanol, Power to Syngas including others. Power to Hydrogen is the foundational step for all P2X technology pathways and a key factor for their technical and economic viability. There are disruptive P2X technologies invented in NSW and Australia where some of those technologies have been successfully commercialised and at early stage of their industrial translation and mass production.

An assessment framework of P2X Hub has been developed to assist the identification of prospective locations in NSW for large P2X production.* The assessment criteria are based on the requirement of transportation infrastructure, access to renewable energy and feedstock (i.e. water), existing heavy industries and new industrial precinct planning, and export potentials to international markets. Six initial NSW P2X Hubs have been identified, which are Illawarra, Hunter, Parkes, Wagga Wagga, Dubbo and Badgerys Creek, through qualitative assessments conducted according to the framework (**Figure B**).

Three-tiered industry development opportunities have been proposed for NSW P2X Hubs. Tier 1 targets green products and commodities by heavy manufacturing industries such as steel and chemical production; Tier 2 focuses on powerfuels for transport, mining and process industries; and Tier 3 aims to meet local demand with decentralised P2X micro-hubs. Detailed pre-feasibility assessment has been conducted for selected NSW P2X Hubs and industries under Tier 1 and Tier 2. This presents four NSW P2X Hub Business Cases, including Power to Hydrogen in Illawarra for local green steel production, Power to Ammonia in Hunter for exporting to Japan, Power to Fuel for inland rail and Power to Methanol for chemical manufacturing in Parkes.† Each P2X Hub Business Case is supported by quantitative analysis and modelling of feedstock requirements, P2X projects and infrastructure costs, forecasting prices of electricity and P2X products.

In delivering this study, over 50 individuals and organisations have been consulted to understand their perspectives of NSW's P2X opportunities. These stakeholders represent key players and future participants of P2X value chains from NSW and Commonwealth Governments, local industries including startups and SMEs, NSW research and technology inventors, global P2X supply chains, multinationals, and NGOs. It is in general agreement that NSW has the competitive advantages to place the state as a global P2X leader and this requires collaborative efforts and resources pooling from all parties. Stakeholders have pressed strong interest for collaboration and partnership in the technology development and industry capability building for a P2X economy in NSW. To seize the momentum, a NSW P2X consortium was established with more than 40 members across industry, research and government and the network is growing.

Guided by the stakeholders' insights and pre-feasibility findings, a roadmap has been proposed with steps to build capability and capacity for a NSW P2X economy:

1. Formalising a P2X Innovation Network that acts as the central coordinator for collaborative efforts from industry, research and government in technology advancement and industry development.
2. Establishing a P2X R&D Commercialisation Hub that provides technology inventor and end-user with research infrastructure, expertise and resources to support commercialisation-driven R&D projects.
3. Deploying early stage P2X projects such as demonstration projects and feasibility studies to pave the wave of technology adoption at commercial scale.
4. Identifying the export opportunities of P2X products to build investment confidence and seek off-take agreements for large scale production in the longer term.
5. Targeting investment in locally invented disruptive technologies to replicate the successful example of solar PV's industrial translation and deployment.
6. Building vertically integrated P2X value chains and local manufacturing capability from production to utilisation.
7. Developing P2X eco-industrial precincts for large scale production and centralised deployment to lay the foundation for NSW P2X economy.

Like any other technology-led industrial transformation, the technology innovation and commercialisation are the cornerstones for building a prosperous P2X economy in NSW. Therefore, the focus of this study is on the P2X technology pathway and techno-economic feasibilities down to regional and industry levels. This pre-feasibility study is the first step to investigate the opportunity and potential of P2X in NSW to realise the enormous economic and decarbonisation benefits through for the state. This report is the starting point for NSW P2X, not the end.

* Location analysis within this pre-feasibility study is not exhaustive and there are other prospective regions in NSW that can support a P2X economy.

† It must be noted that a wide range of business cases can be developed for the locations proposed, requiring further stakeholder engagement.

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Figure B: A prefeasibility summary of the suitability of the chosen locations for development of potential P2X opportunities.

	Feedstock Assessment		Existing Industry Assessment	Tier 1 & 2 Opportunity Assessment	Tier 1 & 2 Opportunity Assessment	Tier 3 Opportunity Assessment
Location	**Existing Heavy/ Light Industry**	**Access to Renewable Power Generation**	**Access to Pure Water Feedstock**	**Opportunity to P2X to Decarbonise Heavy/ Light Industries**	**Access to port infrastructure**	**Opportunity to Develop a Micro–P2X Economy**
Illawarra – Shoalhaven	●	●	●	●	●	●
Hunter	●	●	●	●	●	●
Parkes	●	◑ Parkes has 2 major water reservoirs (Burrendong and Wyangala) but the region is prone to droughts	◑ Parkes has a mining sector and will be the intermodal point for the 'Inland Rail'	◕ The 'Inland Rail' and mining operations present an opportunity for power fuel application	◕ The 'Inland Rail' can be used for potential power fuel export	●
Wagga Wagga	◑	●	◑ Wagga Wagga has a large agricultural and food processing sector	◑ Power fuels can be utilised for thermal and transportation applications	◑ Freight and logistics pathways can be created	●
Dubbo	●	◑	◑ Dubbo has a mining sector	◕ Mining operations present an opportunity for P2X application	◑ Freight and logistics pathways can be created	◑
Badgerys Creek	◑	●	◑ The aviation industry and Aerotropolis	◑ The aviation industry and Aerotropolis present an opportunity for power fuels adoption	◑ Freight and logistics pathways can be created	●

Key:

● This represents a definitive opportunity to fulfill the criterion

◕ This represents a potential opportunity to fulfill the criterion, however assistance from stakeholders are required to execute

◑ This represents a higher degree of uncertainty to fulfill the criterion, however with greater stakeholder contribution it is possible to execute

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1. Introduction to Power-to-X

Attaining net zero emissions through clean technologies is critical to decarbonise NSW's economy. Undeniably, the increased adoption of renewable energy, notably of solar and wind, is driving down cost of generating electricity, thereby facilitating NSW's (and Australia's) domestic and international competitiveness and at the same time catalysing decarbonisations of downstream consumers of electricity.[1] At present, 21% of electricity supply in the state is from renewable resources with an average wholesale price of ~$70 MWh^{-1} in FY2020-21 (the highest wholesale price amongst other states and territories in Australia).[2] This market share is expected to increase with the deployment of the five announced Renewable Energy Zones (REZs), which is proposed to deliver an intended network capacity of 12 GW within the next decade.

However, the adoption of renewable energy poses challenges, given its intermittency and availability during specific duration of a day, culminating into issues relating to grid connectivity and subsequent usage. While REZs alongside other elements of the state's energy transition framework are being designed to address these issues with storage (such as battery pumped hydro), these solutions are highly site, scale and duration specific. These issues are restricting further adoption of renewable energy in Australia.

Renewable Power-to-X (P2X) provides a potential solution, as it encompasses processes and technologies that enable conversions of renewable energy into various forms of chemical energy carriers (referred to as 'X') that are readily used as industrial feedstocks and fuel.[3,4] Moreover, as a key environmental advantage, P2X pathways utilise '*abundant*' and at times '*waste*' molecules such as water and emissions especially carbon dioxide (CO_2) and NO_x as feedstocks.

In this manner, P2X offers the opportunity to store intermittent renewable energies and at the same time generate fuels and chemicals that are currently produced from fossil-fuel resources. P2X can promote further uptake of renewable projects, which at times suffer from connectivity issues and lack of demand.

Adoption of P2X will facilitate the integration of renewable energy into hard-to-abate industries. Renewable energy currently plays a minimal role in the industrial sector, which is critical given industrial emissions account for ~40% of global CO_2 emissions.[5] Thus, there is a pressing need for developing integrated solutions that can enable utilisation of renewables in the industrial sector without the need for excessive retrofitting.

It is clear that a renewable P2X economy in NSW can provide this platform to store renewable electricity (electrons) in the form of chemicals, truly providing the opportunity to unlock Australia's renewable potential in the immediate to near-term.

In addition to meeting decarbonisation targets, P2X can provide substantial economic benefits to the state. Through P2X, NSW (and Australia) can reduce its reliance on imports by locally manufacturing chemicals and fuels demanded by its industry. Subsequent scale-up may see the potential for the state to export these powerfuels overseas to its established trading partners in the Asia-Pacific and EU.

A key benefit of a P2X economy is that it will draw investment into high renewable potential regions, which are typically remote, leading to regional development and job growth. Additionally, if the supporting infrastructure and technologies required for P2X industries can be developed and manufactured locally, it will inevitably lead to wider economic benefit for the state and country.

The NSW Government recognises the importance of economical rejuvenation and sustainable job creation through investments in the renewable industry. This early-stage investment in renewables will be a cornerstone transition for NSW to pivot into a low-carbon economy.

One key P2X technology is generating hydrogen (H_2) through water electrolysis, which can be subsequently converted into ammonia and carbon-based products via secondary conversion technologies (such as Haber-Bosch, methanation, methanol synthesis).

Hydrogen (H_2) from electrolysis is already well established (TRL 9), with several large-scale electrolysis projects (> 1 GW) being announced recently.[6-9] Similarly, projects to combine (i) H_2 with CO_2 and (ii) H_2 with Nitrogen (N_2) separated from air to generate renewable methane (CH_4, Technology Readiness Level (TRL) 8-9), methanol (CH_3OH, TRL 5-7) and ammonia (NH_3, TRL 5-7) are being explored worldwide.

Moreover, emerging P2X pathways are also being developed such as direct ammonia synthesis, hydrogen peroxide and oxyhydrocarbon production using electrolysis (TRL: 3 - 5).

1.1. Why Power-to-X?

Currently almost all industrial feedstocks and fuels are sourced from fossil fuels. This presents issues as the use of fossil fuels is leading to an ever-increasing environmental footprint that is undermining the stability of our climate. These realities present an ideal opportunity for a Power-to-X economy, that would enable the following:

Sustainable Value Chains

P2X will enable leveraging of naturally abundant molecules such as water, nitrogen from air (78% of ambient air is N_2) and CO_2 from emissions (currently ~30 GtCO2 yr^{-1} are emitted globally[10]) or direct air capture into valuable commodities.

Integration within existing infrastructure

Most P2X products have the same composition as those generated by their fossil fuel counterparts and thereby can be readily utilised. Hence, emerging P2X industries can take advantage of matured supply chains for storage, transportation, and utilisation.

Job Creation

A P2X economy will enable both direct and indirect job creation for Australia. A recent analysis by Ernst and Young has revealed that every $1 investment in renewables generates three times more jobs than every $1 investment in fossil fuel projects.[11] Moreover, by shifting to green steel generation and ammonia production through P2X based hydrogen, Australia (and NSW) can generate thousands of job opportunities, including opportunities that can leverage existing fossil fuel-based workforce resulting in a smooth transition towards clean energy without significant job loss.[12] A future Australian hydrogen export industry alone can potentially generate up to 16,900 new full-time jobs by 2050, according to a recent Deloitte report.[13]

1.2. Drivers to P2X feasibility

The key driver to P2X viability is low-cost electricity and electrolyser capital costs. The growth in the renewable energy sector is certainly making this possible by not only bringing down the costs of generation, but also the availability of this low-cost energy for longer durations in a day (i.e., higher capacity factor). Specifically, the costs of solar PV and wind-based electricity generation has seen an 82% and 32% decline in costs since 2010, respectively and capacity factors have increased >30% for both solar and wind.[14]

Additionally, electrolyser costs are also reducing significantly, with electrolyser manufacturers projecting a decline in capital costs as much as 40% (in the near term by 2030) to 80% (in the long term by 2050).[15] Norwegian based electrolyser manufacturer, Nel have recently revealed that they expect to reduce their cost of electrolyser by 75%, once the company shifts to their mega automated manufacturing facility.[16]

In tandem, these developments are opening avenues for cost competitive P2X, specifically H_2 generation, which is expected to display a considerable price decrease to $2-4 kg^{-1} in countries like Australia, Chile and Saudi Arabia in the near-term, at par with fossil fuel-based hydrogen costs as early as 2030[17]. Such low cost H_2 will open the avenues for cost competitive subsequent conversion to powerfuels and other chemicals.

In this manner, green renewable fuels and chemicals have significant opportunities to replace their fossil counterparts across the economy. They represent a low-cost strategy (contingent on low renewable hydrogen price) to decarbonise hard-to-abate industries such as gas networks, aviation, steel manufacturing and fertilizer production, without the need for major modification to existing supply chains.

NSW's investment into P2X technologies will result in the development of an export economy. The technology can then be distributed in different Tiers (**Figure 1**). **Tier 1** can potentially involve deployment of large-scale hydrogen electrolysers with the hydrogen then exported or utilized in existing heavy industries such as ammonia generation (Haber-Bosch), steel making, cement manufacturing or injection into the natural gas grid. **Tier 2** would involve development of additional P2X process and infrastructure where H2 can then be converted to green vectors like methanol, methane, or syngas for local use. **Tier 3**, could involve decentralized applications of Power-to-X.

This is the opportune period for NSW to build the required infrastructure building blocks to facilitate the mass adoption of P2X fuels as the world pivots to a low-carbon economy by 2050.

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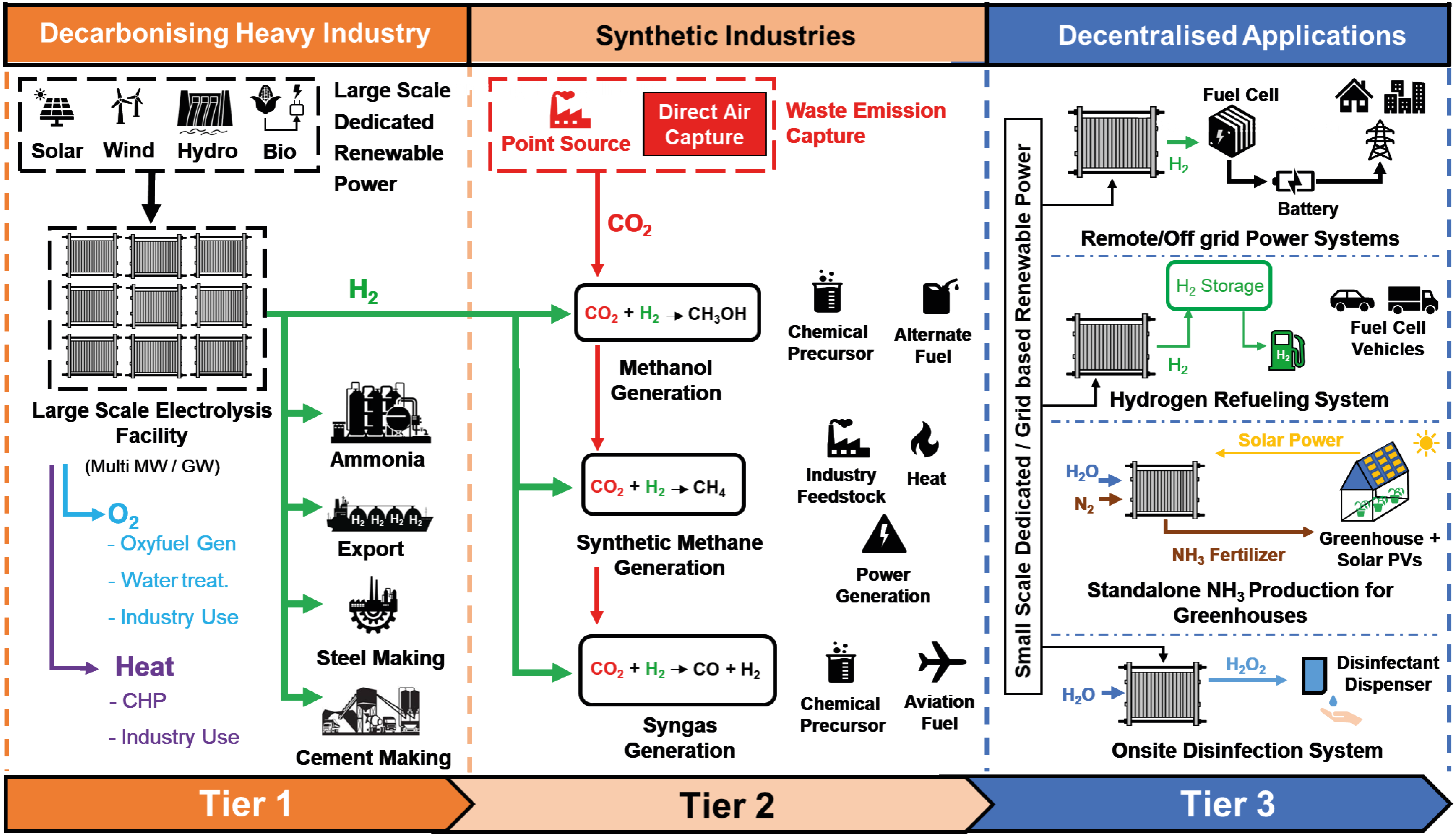
Figure 1: P2X technologies categorized under different end use groups.



2. Why NSW Power-to-X?

2. The Case for NSW Power-to-X

Building a future P2X industry needs immediate targeted and coordinated investments in this technology space. NSW has all the successful ingredients for a future hydrogen economy and an opportunity to lead the P2X development.

2.1. Prioritised Decarbonisation and Economic Opportunities by NSW

P2X technologies and their enabled industries have been identified as priorities for NSW's economic growth, creation of new jobs and industry transformation towards a more sustainable and emissions-constrained economy. In particular, hydrogen has been prioritised by the NSW Net Zero Plan and the NSW 2040 Economic Blueprint, which are the state's climate change action plan and economic strategy by the NSW Government.

The NSW Decarbonisation Innovation Study 2020 is the state's inaugural review into the challenges and opportunities of the state's decarbonisation journey towards net zero for every two years. The study highlighted the economic and emissions reduction opportunities of P2X in NSW across various sectors. Many of the 65 economic opportunities proposed by the study are related to P2X technologies and industries. As versatile energy carriers and feedstocks for many industries, P2X products have applications across electricity, transport, built environment, agriculture and heavy industry of NSW's economy. P2X technologies were recognised by the study as critical technologies that NSW needs to be proactive in developing and adopting, to release their economic and decarbonisation potential.

The Report titled *NSW: A Clean Energy Superpower (Industry Opportunities)* is a key component of the NSW Electricity Infrastructure Roadmap outlining the state's energy plan. The report provided recommendations to The NSW Government in pursuing new industry development opportunities to leverage clean and low-cost energy. Of the various future industries identified by the report, most are associated with P2X including green hydrogen, steel, aluminium, ammonia, sustainable chemicals and synthetic fuels and low-emissions transport. These prioritised P2X industries have substantial sizes of economic development in growing new market and creating new jobs for NSW. For example, every percentage point increase in NSW's green steel industry output will deliver up to $27 million annual revenues and wages.

2.2. A Growing Market for Clean Powerfuels

At this time, the global hydrogen demand is 70 million tonnes with a large majority being used for refining petrochemicals and making fertiliser. The global hydrogen demand is projected for a significant growth when hydrogen is widely adopted as a low carbon powerfuel for energy, transport, built environment, agriculture, and industry sector. The view of forecasted growth is supported by many international energy organisations, industries and investors.[13,15,17–20] In some scenario, modelling predicted a global hydrogen demand of 696 million tonnes, contributing to 24 percent of total energy consumption by 2050.[20] This demand could be as high as 1,370 million if all unlikely-to-electrify sectors use hydrogen as energy source.

Australia has the potential to become a major hydrogen producer in meeting the growing global demand. Australia is expected to have a hydrogen production capacity at least of 100 million tonnes of oil equivalent per year, suggested by the National Hydrogen Strategy.[21]

Locally, NSW is also expected to have a substantial hydrogen demand. The NSW Government has set an aspirational target of up to 10 per cent hydrogen in the gas network by 2030 and this presents a significant demand from local market. The Western Sydney Green Gas Project, Australia's first and largest commercial scale pilot, is underway in NSW to trial hydrogen injection and blending in local gas distribution network for residential use.[22]

In additional to hydrogen, NSW and Australia will have a significant demand for other P2X powerfuels in the medium to long term as the country transitions towards a low-carbon economy. Decarbonising the hard-to-abate transportation industries such as aviation and marine will require close to ~3,000 kilo tons (kt) p.a. of P2X fuels.[23,24] This demand is forecast to grow with initiatives such as gas blending requiring a further 400 ktpa of hydrogen in 2030. The future P2X demand in NSW is driven by the state's strong manufacturing base and significant economic benefits of exporting P2X products to markets overseas. Moreover, a NSW P2X economy will reduce the reliance on overseas imports of fuels and chemical, improving balance of trade as well as energy security.

2.3. Existing Demand from Local Chemical Industries

The chemical industry creates the essential inputs for many industries of competitive strength and strategic priority for Australia, such as food and agriculture, advanced manufacturing, medical and pharmaceuticals, renewable energy and mining.[25] As Australia's third largest manufacturing sector, the chemical industry contributed between $28 billion and $38 billion to the country's economy with more than 5,500 businesses and over 211,821 full time employees (2017-2018).[26] In NSW, the chemical manufacturing industry generated up to $11.3 billion revenue for the state and employed over one third of Australia's chemical industry workforce (2017-2018).[26] The chemical sector is a key enabler of almost every manufacturing value chain and supply inputs for 109 of the 111 industries in Australia.[27] Australia and NSW's chemical manufacturing industries are heavily reliant on fossil fuels feedstock and approximately 75 per cent of petroleum and crude oil feedstock are imported (2017-2018).[28] This has been a significant challenge for the sector to flourish under the impact of the volatile oil price and moving towards global decarbonisation.

Australia and NSW chemical industries are actively exploring option to replace fossil fuels driven by financial and environmental reasons. This represents an existing demand of P2X from the chemical industries in NSW and Australia. For example, the NSW fossil-based ammonia manufacturing industry (i.e. the Orica Kooragang Island Facility) currently has a production capacity of 360,000 tonnes p.a., which is currently used to generate ammonium nitrate.[29] Developing P2X in NSW presents opportunity to revitalise our chemical industries to be more self-resilient and more competitive in terms of production cost and embodied carbon in the global trade market. This could build the foundation for the next generation of clean chemical industries that are more environmentally and economically sustainable. Further, the demand of P2X for chemical industries, both primary chemicals and high-value chemical products, has grown strongly in recent years in Australia and globally and is forecasted to continually increase over the next decades.[30] This presents opportunities for NSW P2X export to other regions and countries to decarbonise their chemical and manufacturing industries.

2.4. Electricity Infrastructure and Renewable Energy Zones

P2X manufacturing is energy-intensive and electricity price is a key deciding factor the cost-competitiveness (*other parameters affecting P2X economics are detailed below*) of P2X products when compared to fossil fuels. NSW has extensive solar and wind energy resources (**Figure 2**) and a significant pipeline of renewable projects of 12 gigawatts of new capacity coming online by 2030. The state's renewable generation profile is relatively balanced with both solar and wind project as well as hydroelectric power as deep energy storage. NSW has the strongest transmission and distribution network in the national energy market (NEM), with the fewest declared system strength shortages. The state's electricity network will be further strengthened by a pipeline of transmission expansion and interconnection projects. NSW's advanced planning and significant investment in large electricity infrastructure will convert these renewable resources to reliable and low-cost electricity that could power the future P2X industries.

The NSW Government's Electricity Infrastructure Roadmap sets out the state's plans to develop renewable energy resources, modernise the electricity system and supply both industrial and residential consumers with low-cost and reliable electricity in the long term. As an important component of the roadmap, the Electricity Infrastructure Investment Safeguard will underwrite investment in variable renewable energy, long duration energy storage and firming capacity in NSW and provide investor long term offtake agreement for their renewable projects. This sends a strong investment signals and will attract P2X investors to the state, capitalising the opportunities of low-cost electricity.

As the first mover in Renewable Energy Zone (REZ) initiatives, NSW has the most advanced REZ projects and Australia's very first REZ is anticipated to be deployed in NSW by the end 2022. The NSW Electricity Infrastructure Roadmap reaffirmed the state's position on REZ development and prioritised five REZs which are Central-West Orana REZ (CWO REZ), New England REZ, South-West REZ, Hunter-Central Coast and Illawarra regions of NSW. These REZ locations benefit from exceptional energy resources, proximity to existing grid infrastructure and have existing investment from the private-sector. Importantly, these REZs do not preclude the development of renewable energy projects in other parts of NSW which may already have sufficient grid capacity to connect new projects. The state's two most advanced REZs, CWO REZ and New England REZ, is proposed to bring 11 gigawatts of new capacity to the NSW grid.

These two REZs have completed their market engagement and has received strong interest from industry and will soon enter detailed planning and design phase. The NSW Government has allocated $120 million funding to fast-track the development of CWO and New England REZs and has recently established the Energy Corporation of NSW to lead the delivery of the NSW REZs.

2.5. Hydrogen Hubs and Special Activation Precincts

The NSW Government has identified two regions to host the first two Hydrogen Hubs for large scale green hydrogen production with commitment of at least $70 million funding for their development. Both Hydrogen Hubs will have access to planned REZs, industrial precincts and existing hydrogen supply chains, deep seaports and logistic infrastructure for developing P2X industries.

- **Port Newcastle-Hunter Hydrogen Hub.** The Hunter and Newcastle region is a heavy industry base that has strategic importance for mining and manufacturing industries. The region is ideally-located for the growth of green hydrogen production, with a number of projects progressing through development stage, including the $2 billion Hunter Hydrogen Network project involving Energy Estate, AGL, APA and ITM Power. The Port of Newcastle handles over 4,400 ship movements and 164 million tonnes of cargo per year.
- **Port Kembla-Illawarra Hydrogen Hub.** The Port Kembla industrial precinct has a demonstrated track record in hydrogen production, transportation and utilisation and over a century of heavy industry. The precinct is home to a range of hydrogen supply chain participants and customers, including Coregas, BlueScope Steel, the Wollongong Wastewater Plant, EnergyAustralia's Tallawarra Hydrogen/Gas Power Station, Squadron Energy's planned hydrogen/gas power station and the proposed Oceanex Energy's offshore windfarm. Port Kembla is a major industrial seaport for Australia's east coast and commodity exportation to international markets.

In addition to NSW Hydrogen Hubs, several Special Activation Precincts (SAP) are promising locations for hydrogen and P2X industries. SAPs are the new approach adopted by NSW for precinct planning and new industry development. So far, six SAPs have been announced by the NSW Government and expanded to four new regions as the Regional Job Growth Precincts. These precincts are provided with coordinated planning and investment services by The NSW Government.

Supported through the $4.2 billion Snowy Hydro Legacy Fund, these SAPs will benefit from de-risked investment from public funded studies, fast tracked planning approvals, government led development and investment in shared infrastructure. Many SAPs are investigating how hydrogen and P2X projects will be integrated into the development of their new industrial precincts through their strengths and opportunities.

For example, Wagga Wagga SAP has an existing industrial precinct that operates as an intermodal freight and logistics hub with access to onsite large solar energy. Parkes SAP is home to the National Logistics Hub, which is strategically located at the only junction of Australia's two rail spines, the Inland Rail and the Trans-Australia Railway, could be a refuelling station for hydrogen-powered rail transportation. Moree SAP has the most productive grain region for agribusiness with a significant demand for green ammonia as fertiliser. These SAPs are attractive to institutional investors and industries to establish P2X supply chains in meeting local demand. Further, these locations are well-connected through road/rail transportation to other regions in Australia and connections to deep ports.

2.6. R&D and Technology Development Capability

NSW hosts outstanding universities, research and development (R&D) organisations and institutions with excellent technology development and commercialisation capabilities in the P2X areas. Recognised as a global innovation leader in hydrogen, NSW has strong R&D capabilities across the hydrogen value chains. The state is home to the national ARC Training Centre for The Global Hydrogen Economy (GlobH2E), the industry-led Hydrogen Energy Research Centre (HERC) and the Newcastle Institute for Energy and Resources (NIER), to name a few. Working closely with academic and technology inventors, NSW industry R&D are actively trialling P2X technologies with their infrastructure and some early movers are deploying pilot projects in preparing for technology adoption at commercial scale.

The research excellence and universities in NSW have been forming partnerships for coordinated and collaborative efforts in accelerating the R&D and commercialisation of clean technologies. For example, the NUW Alliance has founding members from The University of NSW, the University of Wollongong and the University of Newcastle and represents the largest and most compelling Australian research cohort working on energy technologies. The NSW Government has an Innovation Partnership with CSIRO to drive technology advancement and new industry development in the state including hydrogen as one of the priority areas.

NSW has a strong track record of technology innovation and development. The recently released *Action Plan: Turning Ideas into Jobs - Accelerating research* and development in NSW is the state's action plan to accelerate the translation of research capabilities into new industries, products, services and jobs.[31] The recommended five priority actions and 16 supporting actions could further catalyst the P2X industry development through targeted funding, opening data, precinct-based investment and strategic support to NSW universities.[31]

2.7. Public Policy and Financial Packages for Decarbonisation

As Australia's largest economy and accounting for more than 25% of the country's total emissions,[32] NSW needs to secure continued prosperity while transitioning towards a low-emission future. The NSW Government has committed to reducing carbon emissions by 35% comparing to 2005 level and achieving net-zero emissions by 2050. The NSW Net Zero Plan: Stage 1 2020-2030 (the 'Net Zero Plan') is NSW Government's action plan to achieve the 35% emissions reduction target by 2030 and progressing towards net-zero by 2050. The Net Zero Plan sets out four priority areas for action to tackle climate change and emissions reduction with a focus on the technology-led emissions reduction through investing in proven and the next wave of low emissions technologies.

As part of the suite of programs and polices under the Net Zero Plan, NSW Government has announced a $750 million funding package, the Net Zero Industry and Innovation Program, to support industry to accelerate the development of clean technology and decarbonisation. The Net Zero Industry and Innovation Program comprises three areas of focus and each supported by a funding program:

- **Clean Technology Innovation Program (A$195 million):** Supporting the development and continued innovation of emerging clean technologies.
- **New Low Carbon Industry Foundations Program (A$175 million):** Laying the foundations for low emissions industries by building enabling infrastructure and increasing the capability of supply chains.
- **High Emitting Industries Program (A$380 million):** Deploying low emissions technologies and infrastructure to reduce the emissions associated with existing, high emitting industrial facilities.

All three programs under the Net Zero Industry and Innovation Program have strong remits for the development of P2X technologies and industries. Closely aligned with the technology-led decarbonisation principle, these financial packages can attract research, industry and investment to NSW for coordinated and collaborative efforts in building new P2X industries. In particular, the Clean Technology Innovation Program has one focus area on powerfuels and hydrogen with five streams in coordination, R&D projects, research infrastructure, pilot and commercial scale projects and standards. These five complementary streams could set the foundation for a P2X innovation ecosystem in NSW. This ecosystem can ensure NSW have the P2X technologies commercialised and ready to deploy in building new low emissions industries or decarbonise hard-to-abate industries in NSW.

Further, the NSW Government has committed to low emissions planning and infrastructure development, and many regions have incorporated sustainability development in their regional growth plans to 2036.[33] Following clear signals from the state government, local governments and city councils have set up their decarbonisation strategies and action plans. For example, the City of Sydney has set up environmental actions,[34] and the City of Newcastle sets five-year climate change plans to reduce emissions.[35] NSW's new industry precinct developments, such as the SAPs, are adopting the United Nation's eco-industrial park development framework that values sustainability, green infrastructure and technology-led investment. For example, the Parkes SAP aims to become Australia's first carbon neutral precinct.[36] These local policies and programs could further incentivise industries and investors to establish P2X production and utilisation facilities in NSW.

2.8. Business, Workforce and Infrastructure

NSW is the financial powerhouse to Australia. The state's economy is dynamic, multi-faceted and sophisticated, seeing a consistent 2.3 per cent growth in GDP (pre-COVID). NSW is home to 175 out of the 500 largest private companies in Australia and headquarters for over 600 multinational companies. This economically sustainable and business-friendly environment provides investors and industries with confidence to start their P2X value chains in NSW. Further, NSW Government has recently established Investment NSW that will act as central government agency to coordinate and facilitate business, industry, research and government for trade and investment attractions.

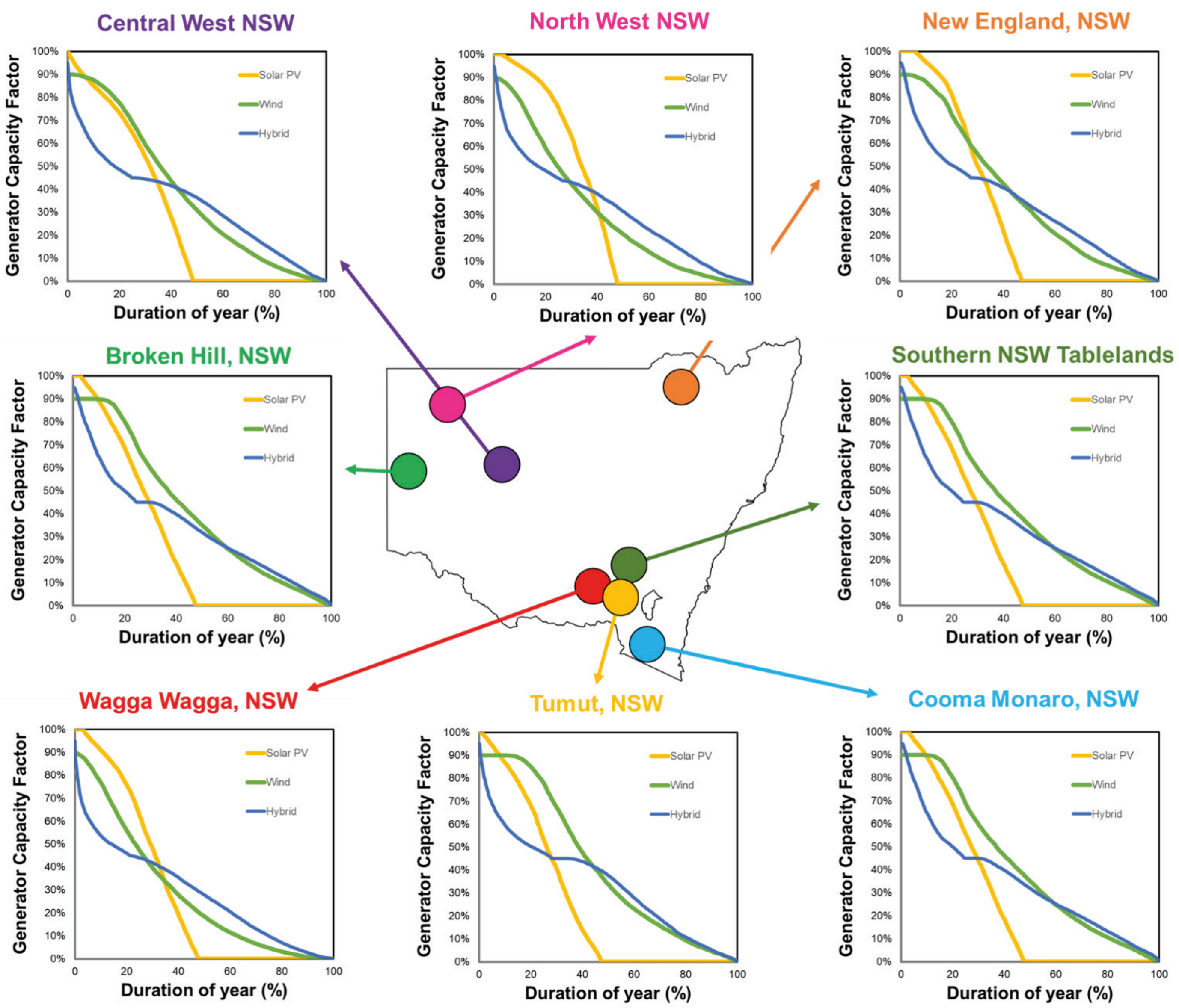
NSW has strong trade relationships with the Asia-Pacific countries given the proximity to these markets. At present, the state exports around A$7.6 billion of products to Japan, South Korea and China.[37] These countries are energy importers and have signalled a high demand for clean powerfuels and chemicals to decarbonise their economies.

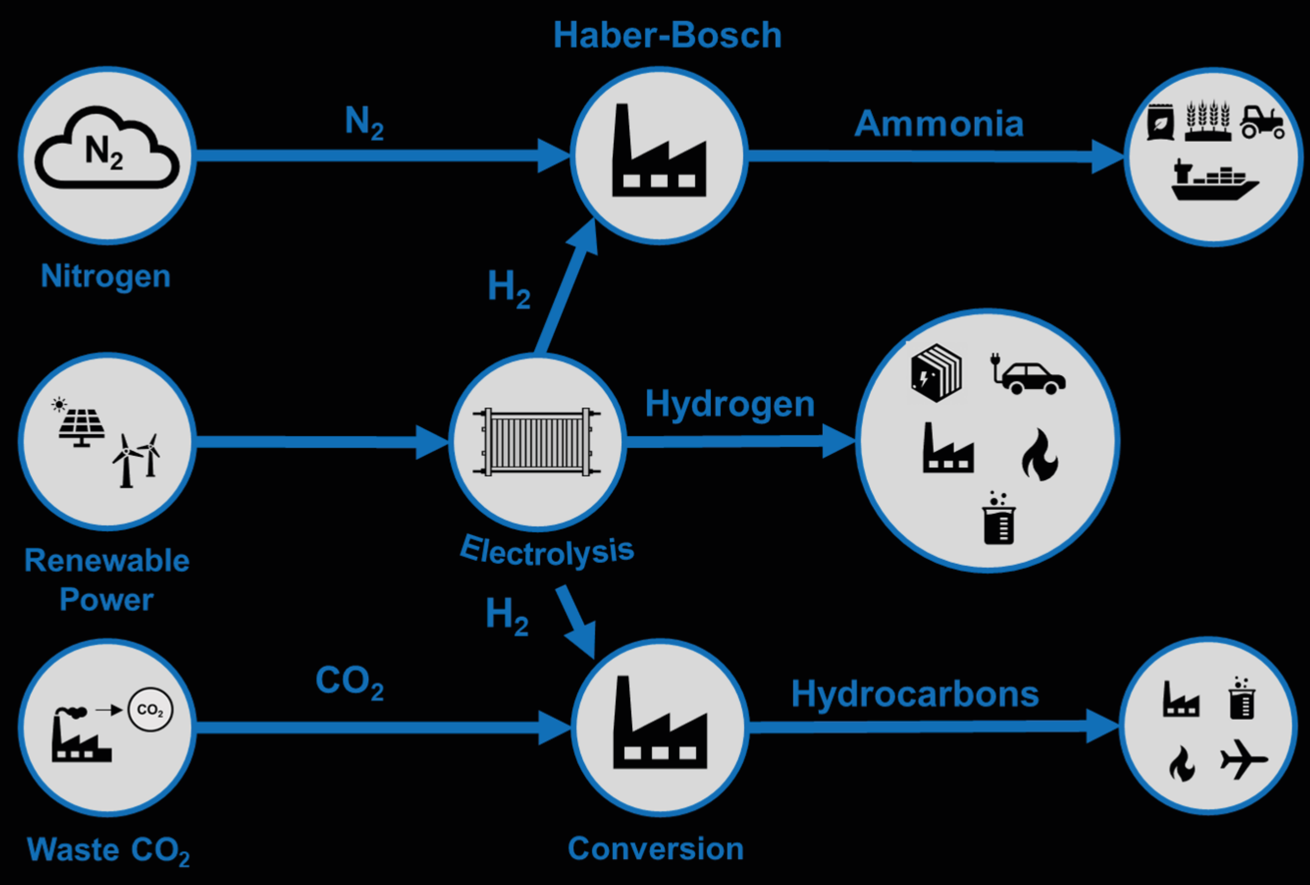
The existing free trade agreements and supply chains can be used to export P2X products manufactured in NSW to Asian markets. NSW is the home of more than 200 Chambers of Commerce, and they could act as the conduit for P2X industry development partnership with other countries.

NSW has a 7.9 million population (2017/2018), making it home to nearly a third of Australians. The state has a higher proportion of residents aged between 20 to 34 than Australia generally, representing a younger demographic who are at working age, inventive and highly educated. This skilled and diverse talent pool represents a strong future for new P2X businesses and industries in NSW, in terms of potential workforce.

NSW's extensive sea, road, rail and air transport networks and access to sophisticated logistic services make the state perfect industry base for P2X manufacturing and distribution. The full A$87 billion infrastructure pipeline being developed by The NSW Government will provide further logistic and transport support for future P2X supply chains.

Figure 2: Renewable energy generation potential at different energy zones across NSW. Hybrid system represents the aggregate of solar and wind profiles at a 50% - 50% share.





3. Current State Assessment of P2X Technologies

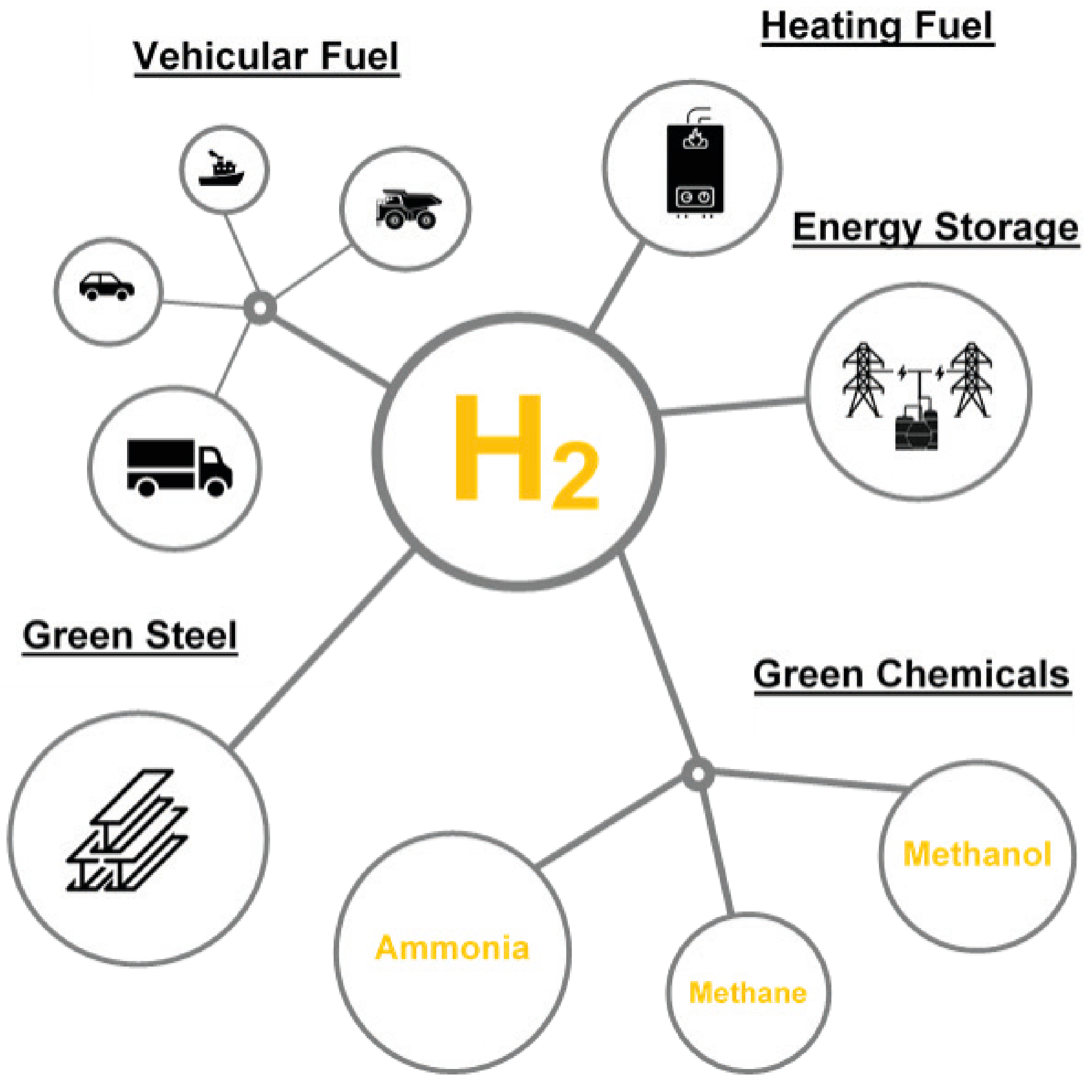
3. P2X Technology Pathways

3.1 Overview of current P2X technologies

P2X offers a unique opportunity for sector coupling as hydrogen is an enabler for deep decarbonisation of hard to abate energy applications and green chemicals (i.e., ammonia, methanol, aviation fuel etc.) as seen in **Figure 3**.

In this section, we present an overview of some key P2X technologies suitable for NSW, outlining their current status and cost, key economic and technological drivers towards feasibility and applicability within NSW context. Overview of current and future commercial scale P2X projects are detailed in **Appendix A**.

Figure 3: The network of opportunities hydrogen unlocks.



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3.2 Power to Hydrogen

In a global context, hydrogen is predominantly used for industrial processes such as ammonia synthesis (55%), crude oil refining (25%) and methanol production (10%).[38] In a smaller scale, hydrogen is also used for iron ore reduction and polymer synthesis.[38]

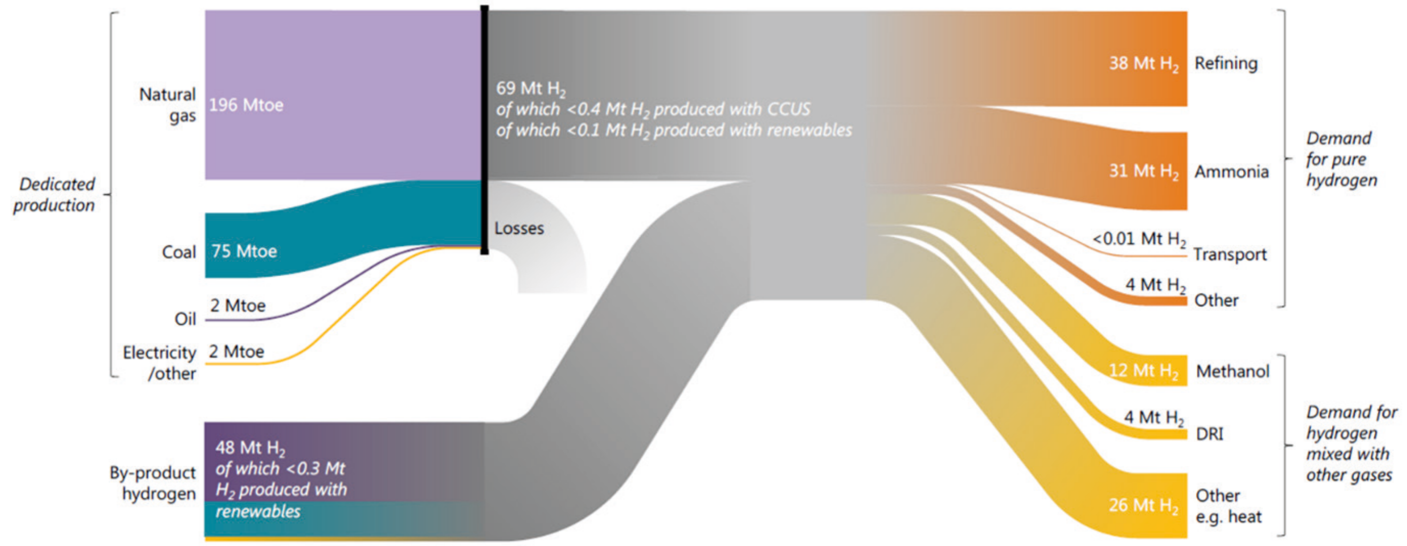
Outlook of Hydrogen Market

Currently almost 115 million tonnes of hydrogen (**Figure 4**) are generated globally every year, with 75 million tonnes utilised directly in pure form for ammonia generation and petroleum refining operations.18 While the rest of the 45 million tonnes is used as a gas mixture such as synthesis gas ($CO + H_2$) that is used to generate chemicals and fuels such as methanol. This demand for hydrogen has been growing steadily since 1975 with a compound annual growth rate (CAGR) of 4%.[18].

Decarbonisation catalyst

The vital advantage of using hydrogen, especially for energy generation, is that combusting hydrogen does not generate any harmful emissions unlike most fossil-based fuels. Therefore, it can be potentially used as a dynamic carrier for both thermal applications (as a replacement of natural gas) and electrical energy generation using fuel cells. The commonality in both applications, is water and heat are the only by-products. Thus, if hydrogen can be generated sustainability, it can be used as a clean energy carrier and a replacement of fossil fuels.

Figure 4: Representation of the current global hydrogen value chain. The demand and supply of hydrogen is shown in million tonnes per year (Mt), while the demand of feedstocks for production are shown in energy terms, million tonnes of oil equivalent (Mtoe). Note: DRI represents direct reduction of iron using hydrogen. H2 produced using CCUS represents hydrogen from fossil fuels with carbon capture for utilisation and storage. The values are shown for estimates in 2018. The image was adopted from IEA, all rights reserved.[18]



The realisation of hydrogen's potential as a catalyst for decarbonisation is widespread that runs across various jurisdictions. Hydrogen is increasingly being referred to as 'a fuel for the 21st century', due to its ability to accelerate decarbonisation in chemical feedstock and energy supply chains[21]. The International Energy Agency (IEA) predicts that to achieve global sustainable development scenario (energy security without compromising climate stability), ~500 Mt of H_2 would be required each year by 2070, fulfilling 13% of total global energy demand. This would require roughly 5 times the increase in global hydrogen generation capacity from 2020.[19]

Pathways to Generate Hydrogen – *Black, Grey, Blue or Green H_2?*

At present almost all of hydrogen generated commercially comes from fossil fuels (~97%) especially natural gas (6% of global natural gas demand) and coal (2% of global coal consumption).[18] Of these, steam methane reforming (SMR) using natural gas is the predominant pathway for producing hydrogen, accounting for ~70% of the global production volume for hydrogen. These techniques are widely adopted due to the high production yield (>500 t per day) and low cost (US$1-3/kg) of production at scale.[18,21]

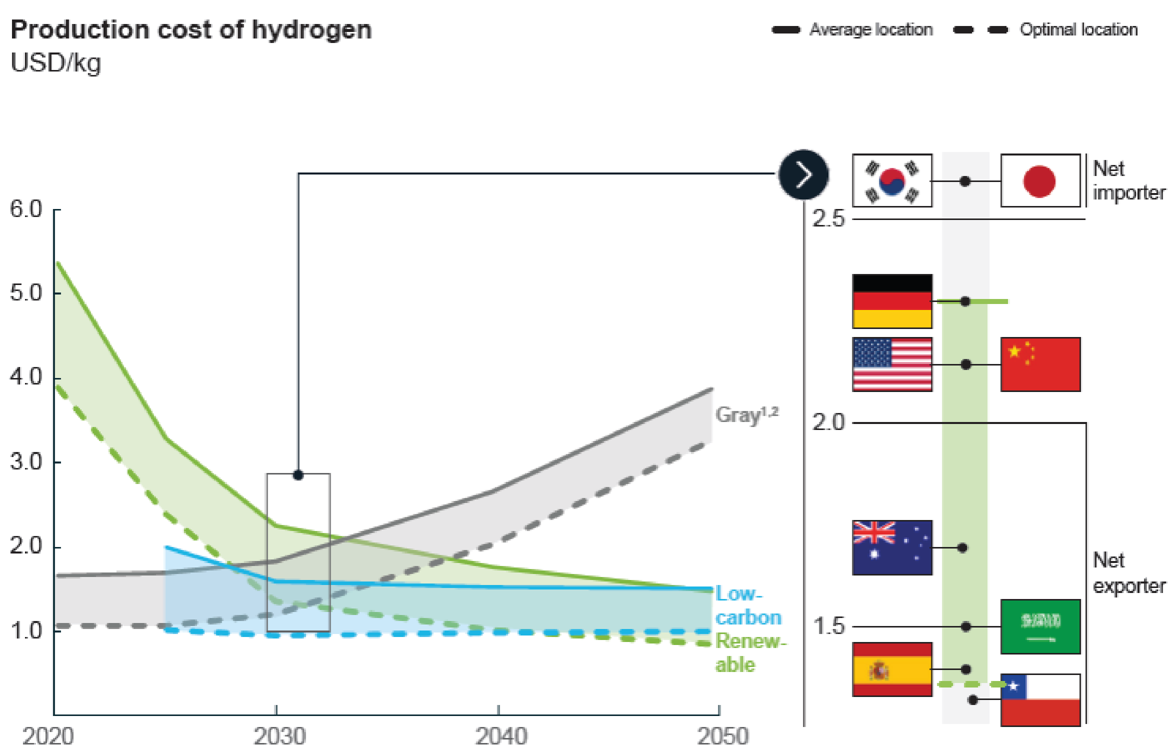
Yet, it is important to consider that these fossil fuel processes have a large environmental footprint of ~830 million tonnes of CO_2 emissions equivalent to ~2% of global emissions in 2018.[18]

Thus, these processes are often categorized as "black or brown" and "grey" ways of generating hydrogen as use of coal, natural gas and other fossil fuel feedstock leads to CO_2 emissions that is added to the atmosphere. There is an expectation that by converting these facilities into "***blue hydrogen***" plants where the emissions generated during production are subsequently captured to be stored underground (CCS) or utilised (CCU) or both (CCUS), will reduce the associated footprint of hydrogen. However, this will inevitably lead to increased cost of generation, due to the additional requirement of carbon capture and storage infrastructure. IEA's analysis shows that a premium of at least USD$50 per ton of CO_2 emission emitted will be required to incentivize investment into integrating fossil fuel based H_2 plants with CCS[18]. There are also practical challenges to adopting CCS in general, as it is very site specific and is prone to environmental and safety concerns.

Alternatively, "Green hydrogen" is produced from the electrolysis that involves electrochemical splitting of pure water into hydrogen and oxygen, by utilizing electricity from renewables. This process currently only supplies ~1% of global hydrogen demand but has a large potential as it can be used to leverage solar and wind energy to develop scalable hydrogen plants for various small scale distributed applications like refuelling stations for fuel cell vehicles as well as large scale applications to provide green hydrogen for generation of ammonia and other synthetic fuels to displace fossil fuels. It is anticipated that by 2070, hydrogen generated from renewable electrolysis would account for ~60% of the supplied hydrogen.[19] However, to achieve that the costs of generating green hydrogen would have to be significantly reduced.

The current cost of generating green hydrogen is USD$4 – 6/kg, that is 2 to 3 times more expensive than fossil fuel-based hydrogen generation (**Figure 5**).[17] However, these costs are expected to become at par with fossil fuel-based generation by 2030 (<USD $2 kg^{-1}), especially in Australia that can leverage its renewable energy potential to provide favourable electricity pricing for hydrogen generation.[17]

Figure 5: Projected costs of generating Green, Blue and Grey hydrogen generation.[17]



Emerging Hydrogen Economy in Australia

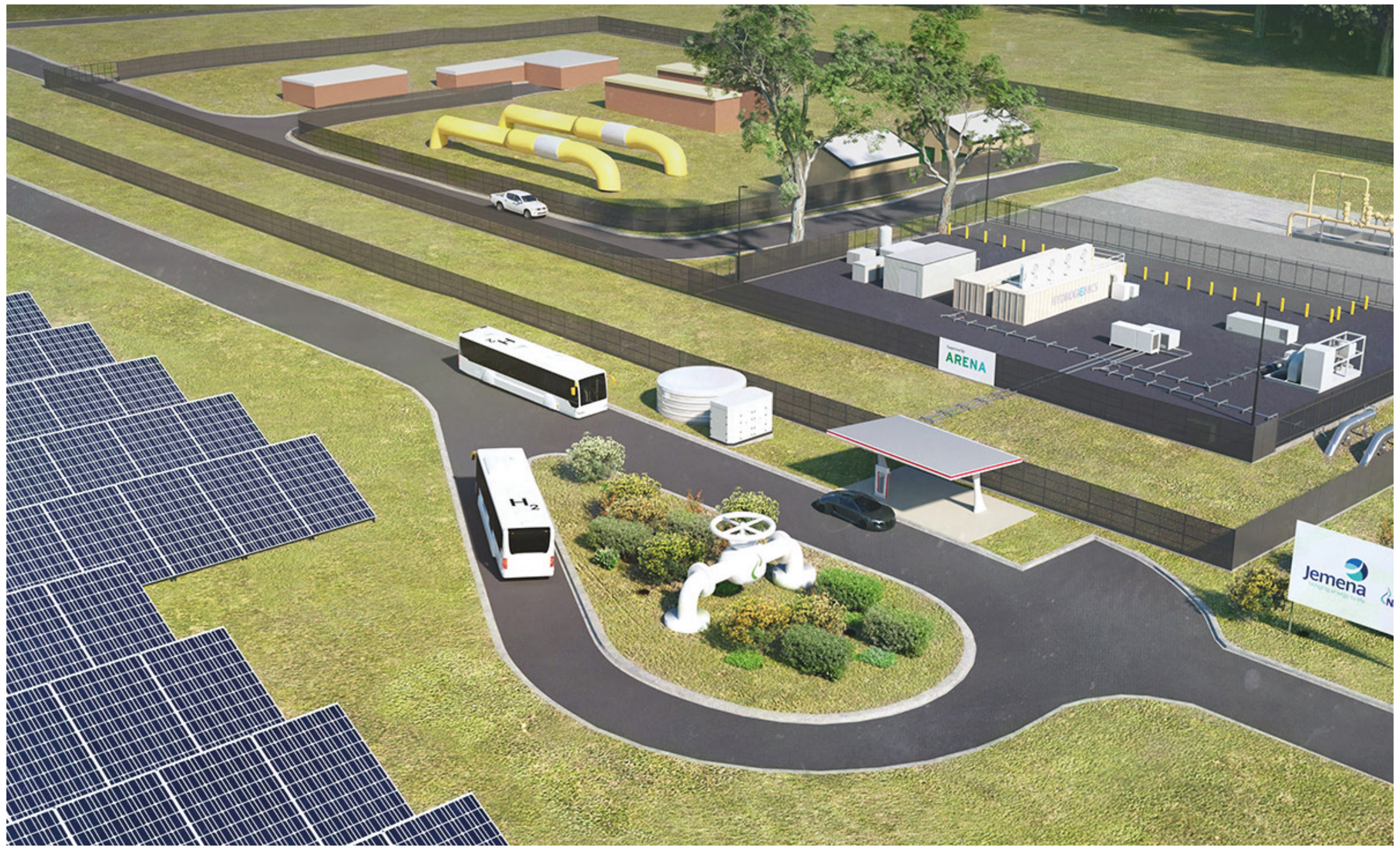
From an Australian context, the current demand for hydrogen is mostly driven by ammonia generation, consuming 350,000 tonnes of H_2 per annum.[13] While this demand for hydrogen is mostly generated from natural gas, it is expected that in the near future, renewable hydrogen will supplement and eventually replace fossil fuel derived hydrogen. The country is already being championed as a potential "giant exporter of hydrogen" as it can essentially generate large amounts of hydrogen to decarbonise its own energy and industrial value chains as well as position itself to be a larger exporter of hydrogen and ammonia to Asia Pacific and beyond.[39,40]

This emerging Australian H_2 economy is expected to generate up to 16,900 direct and tens of thousands of indirect job for the Australian economy, and is expected to generate $26 billion per year revenue by 2050.[13] Specifically, a future H_2 export industry to Asia Pacific alone is expected to contribute $2.2 billion to the Australian economy by 2030 (500,000 t_{H2} yr^{-1}), with a potential to increase to $5.7 billion by 2040.[41] Australia's hydrogen production capability is also recognised by European Union countries, notably Germany and the two respective governments have inked a joint understanding and feasibility study to explore this trade.[42,43]

NSW's Renewable Hydrogen Opportunity

New South Wales can benefit from taking a share of the developing hydrogen market in Australia. The state is also exploring the potential use of renewable based green hydrogen from electrolysis as an energy carrier (**Figure 6**). It is expected that NSW can essentially become a "clean energy superpower" by leveraging its renewable energy potential to generate hydrogen (either as energy source or as feedstock) for production of green steel, aluminium (estimated: A$70 million in revenue combined) and ammonia (A$102 million).[44] NSW is home to several of these manufacturing facilities and is expected to drive decarbonisation initiatives across Australia.

Figure 6: Western Sydney Green Gas Project being developed by Jemena. The project will generate H_2 from solar/wind powered electrolysis for injection into the gas network (~2% by volume – energy for 250 homes). The site will also incorporate a turbine to generate electricity for grid and future H_2 refuelling facility. Image courtesy of Jemena.



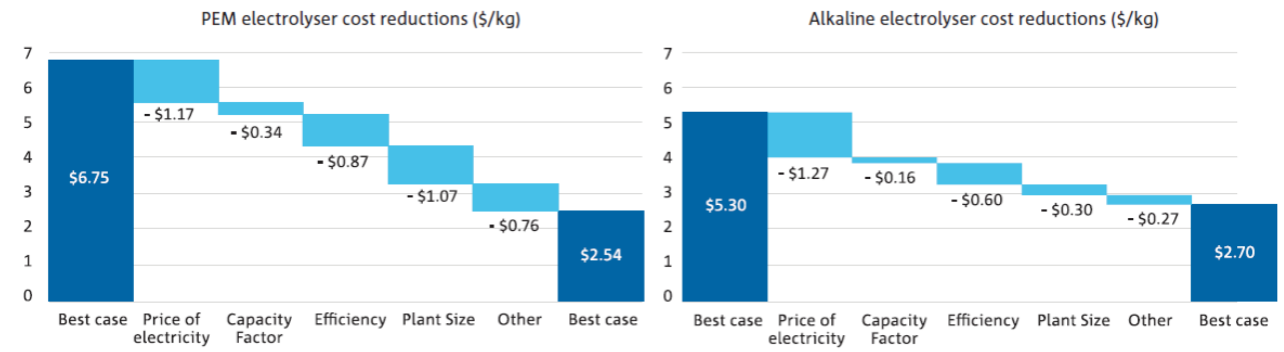
Key Drivers to Reducing Green Hydrogen Costs

The National Hydrogen Roadmap suggests that the current cost of generating hydrogen from electrolysis is between A$5 – 6/kg, in comparison to the blue hydrogen generation costs of A$2 – 3/kg. The current barriers for green hydrogen include:

1. **Price of electricity from renewables:** Current commercial Alkaline (AE) and Polymer Electrolyte Membrane (PEM) electrolysers require between ~50 -60 kWh/kg of electricity to produce hydrogen. Therefore a $0.01/kWh decrease in the price of electricity, will result in an ~6-8% decrease in hydrogen cost per kg, assuming the ceteris paribus.[21] Recent analysis by CSIRO shows that the solar PV and wind farms are currently the cheapest to build, especially cost of new solar PV farms are expected to decrease by up to ~35% by 2030.[45] Thus, as newly built solar and wind farms come online, the costs of generating hydrogen onsite can be significantly reduced.[‡]
2. **Capacity factor:** In addition to the cost of electricity, the availability of low-cost electricity also affects the cost of generating hydrogen. Though solar and wind farms provide low-cost electricity, they are intermittent and generate electricity only when the 'sun shines' or when 'the wind blows'. The Australian Energy Market Operator (AEMO) suggests that the capacity factor of solar and wind farms in Australia to be around 30% and 40% respectively.[46] However, the availability of renewables can be further increased as new solar and wind farms come online, leading to larger amounts of renewables being available via special power purchase agreements with energy suppliers as well as through storage technologies. NSW has already seen a 40% increase in renewable energy generation (solar and wind) since 2018.[47] The state has also developed plans to increase renewable energy capacity by 12 GW, providing further opportunity for P2X implementation within the state.[48]
3. **Scaling of Hydrogen Generation:** The increasing interest and demand for low-cost hydrogen is driving significant research and development into reducing the cost of electrolyser unit as well as improving their efficiency. In particular, as the demand for large scale hydrogen projects is increasing, it has incentivized manufacturers to invest into better supply chain and optimum manufacturing techniques. As highlighted earlier electrolyser manufacturer NEL expects to reduce capital costs of electrolyser by 75% by scaling its production facilities.[16] Expert elucidation studies have also forecasted such decrease in capital costs, thereby facilitating the feasibility of renewable hydrogen.[15,49,50]
4. **Availability of Water:** With current technology, generating 1 kg of hydrogen using electrolysis requires ~9 – 10 L of water.[51] This would be a key concern for generating hydrogen in Australia. Thus, water would have to be sourced through unconventional means like desalination and reclaiming recycled wastewater. Though these water resources are expected to be costlier especially desalination (~A$5/kL[52]), cost of water feedstock is expected to take up only ~2% of eventual cost of generating hydrogen.[21] NSW benefits from supply of low-quality, waste and saline water across the state, with saline aquifers in regional NSW providing opportunity for P2X and alleviating concerns on fresh water usage competition with agriculture.

All together, these developments point towards significant reduction in cost of generating hydrogen (**Figure 7**).

Figure 7: Potential of reducing hydrogen generation costs from electrolysis in Australia. Costs are in Australian Dollars[21].



‡ Modelling on future network transmission fees is required to estimate hydrogen costs using remote renewable electricity supply.

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3.3 Power to Ammonia

Ammonia is the base building block used to produce prominent chemicals such as urea and ammonium nitrate - 90% of the global ammonia production is used to generate fertilizer. Other small-scale applications for ammonia include generating cleaning products and as a refrigeration gas for air conditioning.

Global Demand for Ammonia – *On the Rise*

The global ammonia market (US $50 billion) is undergoing a steady compound annual growth rate (CAGR) of over ~5- 7%, with demand centred on Asia Pacific that is being driven by the growing agricultural markets in South Asia and China as well as Russia, Brazil, and Sub-Saharan Africa.[53] The major production players are in Russia, China, US, and India.

Australia's Ammonia Market

Australia generates around 2 million tonnes per annum (Mtpa) of ammonia, with 7 active production facilities across the country (mostly located in Queensland and Western Australia).

In New South Wales, an ammonia production facility owned by Orica, is operating in Kooragang Island that produces 360 ktpa of ammonia. The facility has three major processing plants: ammonia, nitric acid and ammonia nitrate production plants as shown in **Figure 8.**[54] Recently, a new ammonium nitrate plant is proposed by Perdaman Industries in Narrabri. The plant will use natural gas from the planned Narrabri Gas Project (14.5 PJ yr^{-1}) to generate 300,000 tonnes of fertilisers per year.[55]

Figure 8: Orica's Kooragang Island facility. Image courtesy of Orica

Opportunity to use ammonia beyond fertilisers

Ammonia (NH_3) has the potential to be a valuable energy vector for hydrogen, specifically for transportation across large geographical regions. This is because ammonia is easy to compress and transport as liquified fuel than compared to compressed or liquified H_2. Ammonia can be liquified at a pressure of 10 bar at room temperature or at –33°C under atmospheric pressure. Liquified ammonia has an energy density (15.6 MJ L^{-1}) which is three times more compared to liquified hydrogen (5.6 MJ L^{-1}), thereby storing more H_2 per L. Besides, ammonia is being actively transported globally for well over hundred years, thus ammonia is seen a competitive means of transferring bulk amount of H_2 by taking advantage of existing ammonia supply networks.

For utilisation, ammonia can then be directly consumed. Direct consumption may include use in fertilisers, feedstock in chemical manufacturing or as fuel for power generation and transportation. Recently, Mitsubishi Heavy Industries announced that they are developing the world's first fully ammonia powered (100%) gas turbines, the 40 MW turbine is expected to be commercialized by 2025.[56] In addition, trials are underway for co-firing coal and ammonia mix fuel for power generation in Europe and Japan[57].

Ammonia can also be used in electricity generation with ammonia fuel cells which produce N_2 and water as by-products.[58] MAN Energy Solutions are developing ammonia fuel cells and engines for retrofitting marine vessels by 2025.[59]

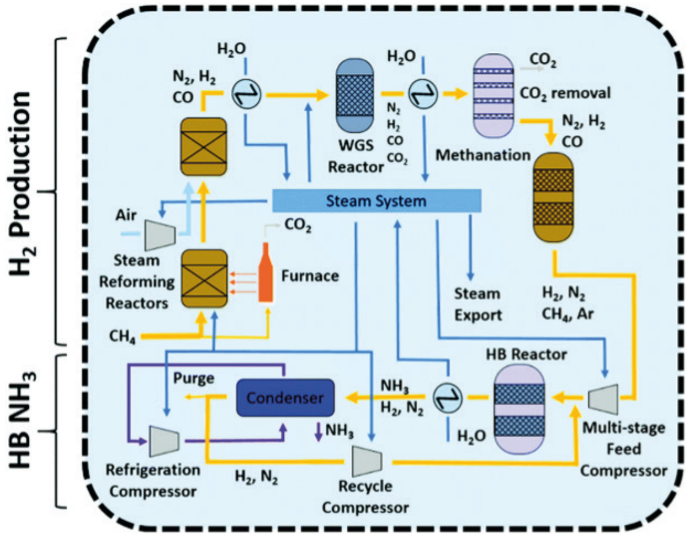
The direct utilisation of ammonia as a fuel for transportation engines, power generation systems, and turbines however generates NO_x emissions, which is an environmental concern and must be addressed. Current technologies can convert NO_x into its inert form or capturing the emissions in special absorbents or adsorbents (**Appendix B**). In addition, these waste NO_x emissions can also be converted into renewable ammonia through electrochemical nitrate/nitrite reduction, providing another P2X technology deployment opportunity (detailed below).

Ammonia can also be split back into H_2 and N_2 that can be subsequently used. Processes for cracking ammonia to H_2 are being developed that includes thermal cracking (300 – 700°C and 1-10 bar) and electrochemical splitting (at 250°C).[58,60] High temperature ammonia cracking (>700°C) has already achieved a TRL Level of 7 – 9, but efforts are being made to develop low temperature cracking (<450°C), currently at TRL of 2 – 4.[61] Whereas electrochemical splitting is also currently in very early stage of development (TRL 2 – 4).

Current process for ammonia production

Almost all commercial NH_3 production worldwide is through the Haber-Bosch (HB) process which was designed in the early 20th century and is still followed to this day. This process (**Figure 9**) involves the synthesis of hydrogen from steam reforming of natural gas, with nitrogen that is extracted from an air separation unit. The conversion to ammonia is carried out over an iron-based catalyst at 500°C and 150 – 200 bar of pressure.[62]

Figure 9: Schematics of Haber Bosch process.[63]



Key issues of Haber-Bosch

The environmental footprint of HB and its energy demand brings into question its sustainability in a future decarbonised economy.

The H_2 required to drive the HB reaction is currently exclusively sourced from steam reforming of natural gas or coal, that have a large environmental footprint as highlighted earlier. In fact, ~2 – 3 tons of CO_2 emissions are produced per ton of ammonia generated, contributing to an environmental footprint of ~1% of global GHG emissions.[64,65] To put this in local perspective, the Orica Kooragang facility (350ktpa) alone generates ~0.7 – 1 Million tonnes of CO_2 per year.

In addition, ammonia generation from HB is highly energy intensive, accounting for 1% of global energy demand. For instance, up to 30 – 50 GJ of natural gas is required to produce 1 tonne of NH_3.[66] As 72% of global ammonia production is carried out using natural gas, this presents significant pressure on sustainable gas supply.[67]

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The transition to green ammonia

The production of green hydrogen will be the key enabler to produce green ammonia in scale in the immediate near term. Green hydrogen is produced using pure-water electrolysis that is powered by renewable energy (**Figure 10**). The injection of green hydrogen into the existing ammonia production will open opportunity to produce a versatile green commodity. Alternate P2X technologies such as waste NO_x conversion to ammonia, plasma-hybrid electrolyser technologies and direct nitrogen reduction reactions are also being scaled-up for green ammonia generation.[68–71] The global demand for green hydrogen is expected to be USD ~850 million by 2030, at a CAGR of ~55%.[72]

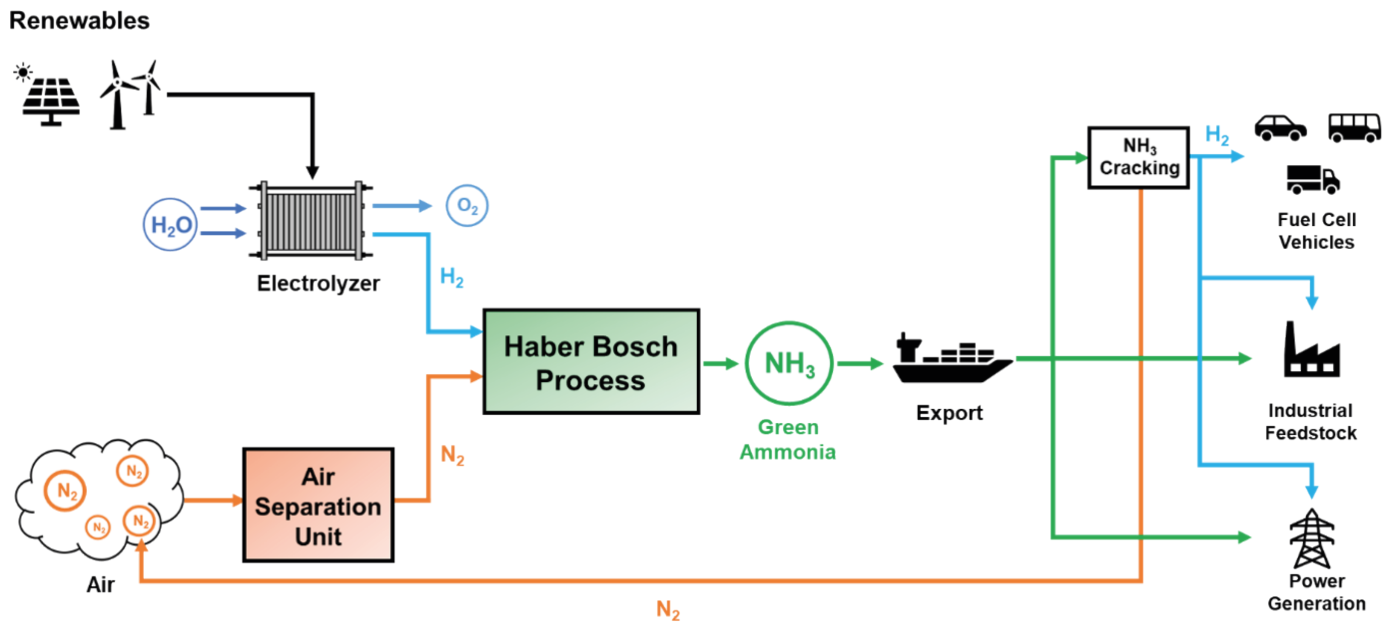
Green Ammonia in Australia

Australia by leveraging its renewable energy can generate green ammonia for domestic fertiliser market as well as for export. The National Hydrogen Roadmap outlines ammonia as a key vector in enabling the storage and transportation of hydrogen generated in Australia for export.[21]
Several activities to explore such opportunities are under way, as elaborated below:

- Yara Australia is already exploring the possibility of converting their ammonia plant in Pilbara, WA into a green ammonia facility (800 ktpa by 2028).
- QNP nitrates are also exploring similar opportunities for converting their ammonia plant to source H_2 from electrolysis (>20 ktpa).
- Other mega green H2 projects like the Asian Renewable Energy Hub (in WA), Murchison Renewable Hydrogen Project (in WA) and Eyre Peninsula Project (in SA) are all expected to generate green ammonia for export.

NSW can also become a part of this drive towards a green ammonia market and can generate A$102 million in revenue for every percentage point that the state can supply to meet the global demand.[44] As an immediate opportunity, retrofitting Orica's Newcastle facility and establishment of modular renewable H_2 driven Haber-Bosch plants in Illawarra-Shoalhaven Precinct or in Newcastle/Hunter Precinct can allow NSW to tap into this market opportunity. NSW can also exploit renewable ammonia for co-firing in coal-based powerplants for immediate decarbonisation steps.

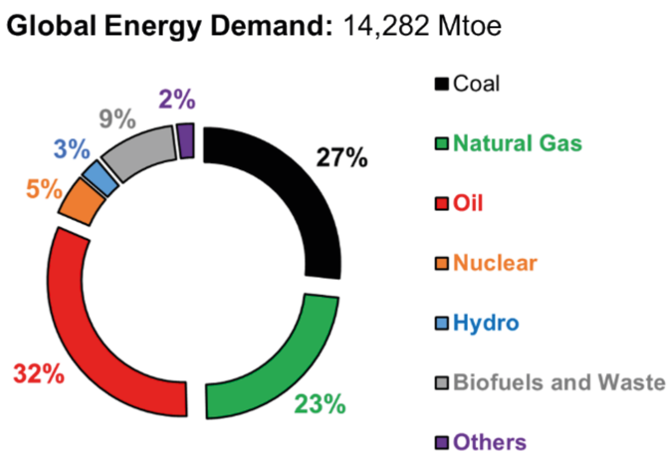
Figure 10: Potential supply chain of green ammonia as an energy vector from NSW.



3.4. Power to Methane

Methane in the form of natural gas is a key energy resource (~95% of natural gas is methane/CH_4) – currently 23% of global energy demand is provided by natural gas (**Figure 11**).

Figure 11: Breakdown of global energy supply by source. Data was adopted from IEA's analysis of global energy supply in 2018.[73]



Growing Demand for Methane

The International Energy Agency (IEA) estimates show that in 2019, the global demand for natural gas reached ~4,000 billion cubic meters, recording a CAGR of 2.7% since 2009.[74] In this manner, the market for natural gas is predicted to be worth U$1,031 billion per year by 2022 (CAGR of 7.7%).[75] Moreover, the market for Liquified Natural Gas (LNG) alone, which is a major energy export commodity, could be worth U$18 Billion with a volume of 530 million tonnes by 2027 (CAGR of ~6%).[76] Though the demand for natural gas is expected to decline in the near term due to the pandemic, IEA expects demand for natural gas to rebound strongly as natural gas is expected to displace coal as a cleaner fossil fuel and with more countries in Asia expected to rely on imported LNG due to diminishing domestic reserves.[77,78]

Synthetic Methane Production

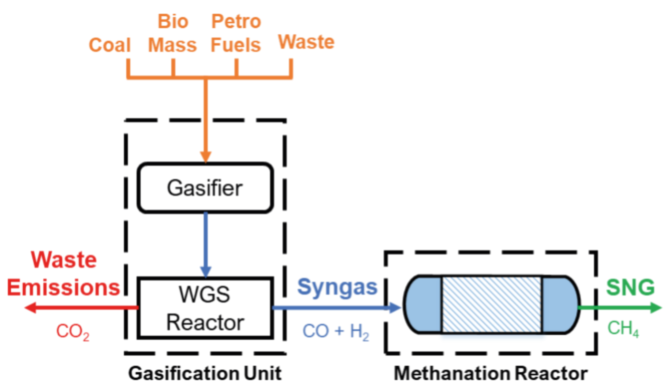
Methane currently is almost exclusively sourced by processing natural gas. However, a synthetic pathway for generating methane was developed as early as 1902, when 'catalytic methanation' was suggested by Sabatier and Senderns.[79]

The Sabatier methanation process involves generation of methane by catalytic conversion of carbon dioxide and hydrogen (at temperatures between 150 – 550°C and pressures of 1 – 3 bar)[79]:

$$CO_2 + 4H_2 \leftrightharpoons CH_4 + 2H_2O$$

The process has a high Technology Readiness Level (TRL) of 8 – 9.[80] At present, companies such as Linde, Haldor Topsoe, Clariant and Foster Wheeler, Linde, Etogas and MAN Energy offering off-the shelf methanation reactors for commercial applications.[79] These applications involve the catalytic conversion of CO_2 generated from coal, Petro fuels, waste, or biomass, into methane – synthetic natural gas (SNG) in the methanation reactor (**Figure 12**).

Figure 12: A high level schematic of conventional methanation process.



Renewable Methanation – *Role of P2M*

The key issue of current methanation technology is the source of hydrogen, requirement of high temperature and pressure as well as source of CO_2 feedstock. Currently almost all commercial hydrogen is generated from fossil fuels, and this has a large environmental footprint equivalent to ~2% of global CO_2 emissions (**Section 3.1**)

Power to Methane (P2M), offers an alternative option given that green hydrogen can be sourced from renewable electrolysis. Moreover, we now also have technology that can capture CO_2 emission from industrial process (TRL 7 – 9, refer to **Appendix B**) or even separated from the atmosphere (e.g., Direct Air Capture). These technologies can enable conversion of waste CO_2 emissions by combining with green hydrogen into methane through commercial methanation process. The methane can then be injected into the gas grid as a synthetic natural gas (SNG) and used downstream as a fuel or industrial feedstock. The subsequent emissions from its combustion can then be recovered and reused in the P2M process, essentially closing the loop (**Figure 14**).

In this manner, P2M not only offers an environmental solution but also provides an avenue for enhancing renewable penetration into the gas supply chain.

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Applications of P2M

Several, P2M facilities are already operating or being developed globally, especially in EU.[81] The first such project was developed by Audi in Germany and has been operational since 2015, generating 1,000 tonnes of renewable methane that is then utilised by Audi's gas-powered vehicles.[81] Recently, a 3.5 million cubic meter per year facility for synthetic methane is being developed in China in an industrial zone in Shaanxi Province.[82] The facility will use the Sabatier reaction pathway to convert CO_2 captured from the local power plant and surplus H_2 generated in the industrial precinct (including electrolysis-based hydrogen). Once operational the facility is expected to be the largest methanation facility in the world.

Southern Green Gas and the APA group, one of Australia's largest natural gas provider are developing a demonstration facility (Southern Green Gas Project) in Queensland, that will generate methane using CO2 sourced from air and renewable electricity (**Figure 13**).[83] Similarly, ATCO Australia is exploring the feasibility of developing renewable methane facility in Western Australia, the findings of the study are expected this year.[84]

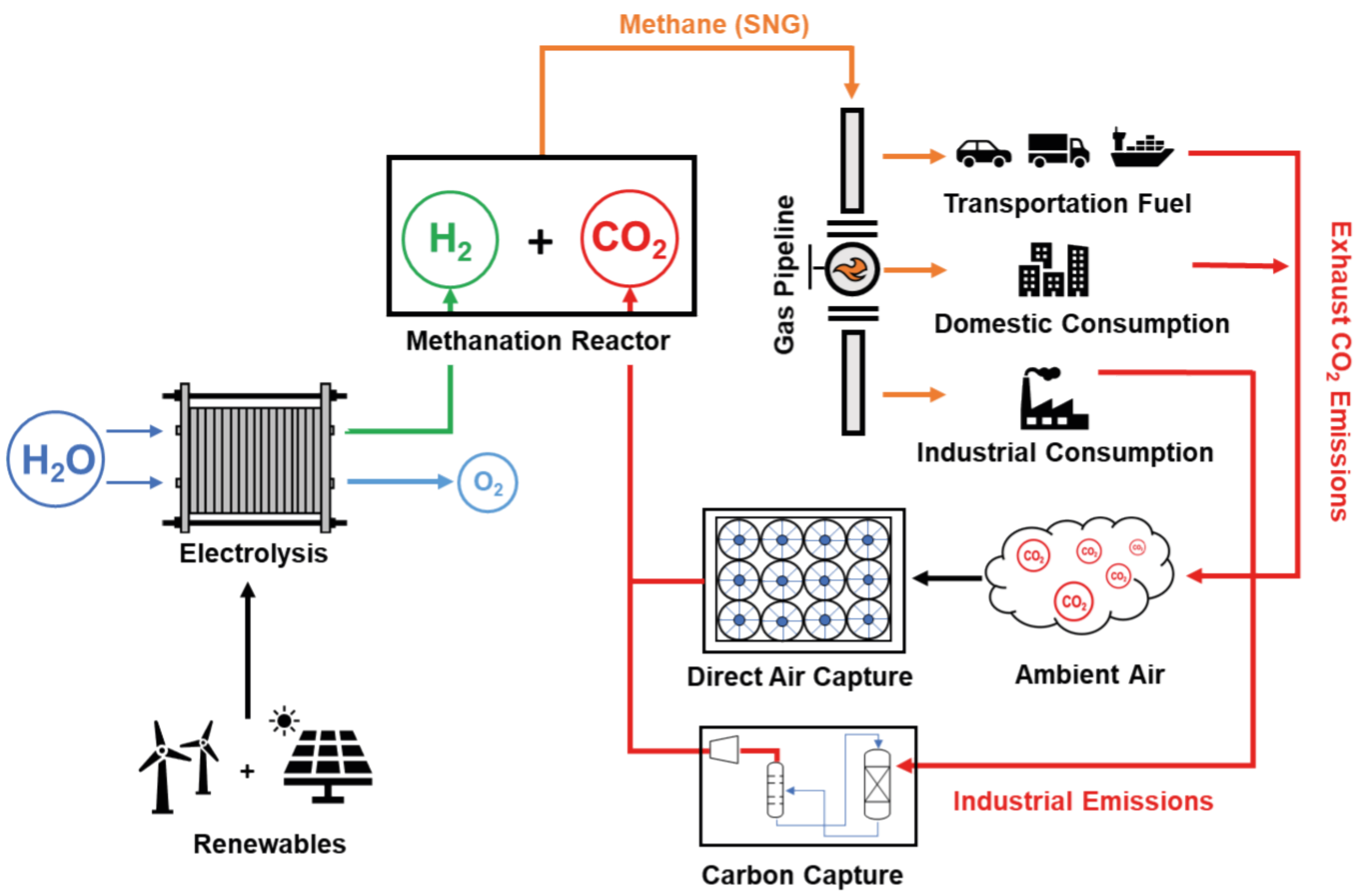
Figure 13: APA Renewable Methanation Project in Queensland. Image provided by APA.[83]

Additionally, Australia's first biomethane project is being developed in Sydney. The Malabar Biomethane project will generate biomethane through anaerobic digestion of organic matter available in Sydney Water's water treatment plant in Malabar, NSW. The project will add 95 TJ yr^{-1} of biomethane into the NSW gas grid, with the capacity expected to increase to 200 TJ yr^{-1} in the future.[85] The A$8 Million facility is expected to be operational by 2022. CSIRO Energy, based at Newcastle, is also exploring the feasibility of generating renewable methane (148 m^3/hour) by using renewable hydrogen (2.7 MW electrolyser) and CO_2 sourced from the atmosphere using a dedicated amine-solution based process (capturing 0.29 tCO2/hour).[86] If scaled up, it is proposed that a synthetic methane cost of $5.3/GJ can be attained with a CO_2 capture volume of 1 million tpa (0.4 million tpa of methane).[86]

NSW Synthetic Natural Gas Opportunity

NSW is expected to face a gas shortage due to rapidly depleting production from existing reservoirs and uncertainty in future supply from untapped resources.[87] The Australian Energy Market Operator (AEMO) projected that NSW could face a natural gas shortfall of 14 PJ by 2024 that could potentially increase to 70 – 128 PJ by 2030.[88] Such a shortfall is considerable given that current NSW demand for natural gas stands around 131 PJ yr-1 (2018-19).[89] Even under the optimistic case where supply is boosted by importing LNG, a shortfall of 70 PJ would still prevail. Hence, the creation of synthetic methane to supplement natural gas through leveraging NSW's growing renewable energy potential to generate synthetic natural gas or green hydrogen for blending into the natural gas (70 PJ = 5 Mt of H2 (LHV: 120 MJ kg^{-1}) would provide significant market opportunities.

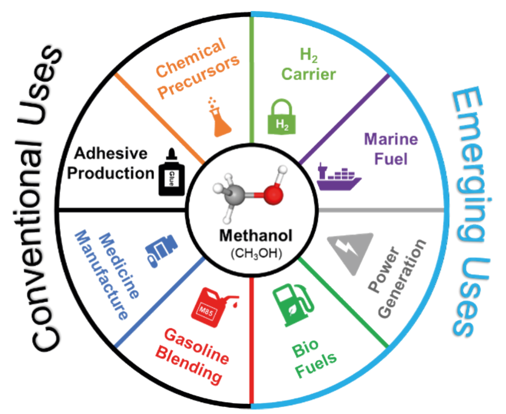
Figure 14: A closed loop Power to Methane (P2M) process using renewable electrolysis and carbon capture.



3.5. Power to Methanol

Methanol (CH_3OH) is a very versatile chemical and is readily used in the industry (**Figure 15**). A key feature of methanol is the availability of the Methyl Group (CH_3-) that allows it to be used as a precursor to generate structures like formaldehyde (chemical precursors), acetic acids (pharmaceutical applications) and ethers (used in adhesives). Methanol is also blended with gasoline to improve engine performance and most countries around the world have regulations allowing use of different blends of methanol in fuel.[90]

Figure 15: Conventional and emerging uses of methanol.

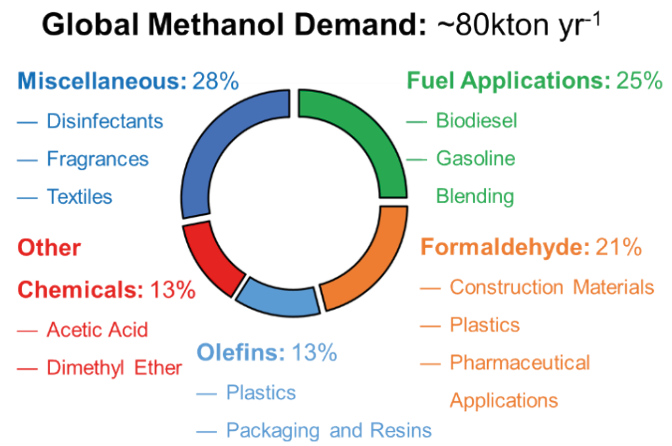


Growing Demand for Methanol

Methanol is amongst the top five most traded chemicals in the world. The global methanol market is expected to double in size by 2027 and is growing at steady CAGR of 5% since 2016.[91] The global demand of 78,900 thousand metric tonnes per year (**Figure 16**) is mostly attributed to production of formaldehyde (21%) and olefin generation (13%), while the biggest share is taken up by use as a fuel (~25%).[92] Overall, the Asia Pacific region is expected to be the major driver of methanol market.[93] Moreover, methanol is expected to be used as renewable energy carrier for hydrogen (as highlighted below), and can play a vital role highlighted below), thus this demand can significantly increase as the world transits towards a hydrogen-based economy.

NSW Power to X (P2X) Industry Pre-Feasibility Study

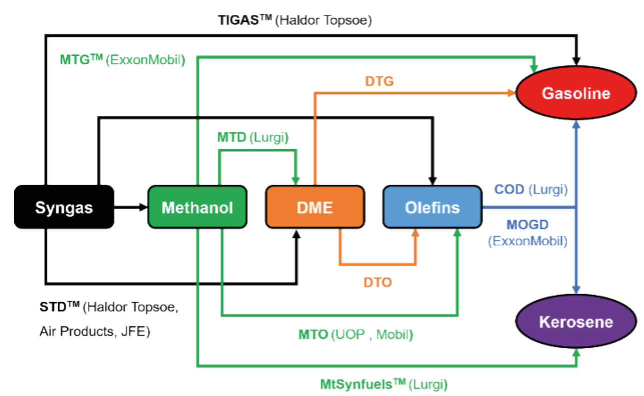
Figure 16: Global Demand of methanol by end use sectors.[92]



Methanol Generation

Conventional methanol generation starts with syngas production, that is then subsequently converted to methanol using thermal catalytic conversion referred to as CO_2/CO hydrogenation. This conversion process is usually conducted in presence of metal-based catalysts CuO, ZnO and Al_2O_3 at a temperature of 200 – 250°C under pressure of 5 – 10 MPa.[94] This process has already been commercialized by various companies (and has a TRL level of 6 –7) (**Figure 17**).[80] Methanol is also generated through Fischer-Tropsch synthesis, that is elaborated in **Section 3.5.**

Figure 17: Commercialized pathways for methanol and methanol-based fuel (DME, Olefins and paraffins) generation.[95]



Renewable Methanol

The Power-to-X pathways for methanol generation are already being actively demonstrated by using H_2 from renewable electrolysis and CO_2 captured from industrial emissions for subsequent conversion to methanol in commercial catalytic reactors.

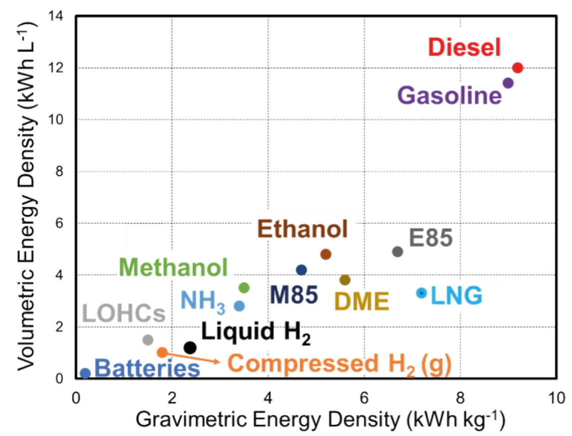
Moreover, recent developments in electrocatalysis is opening avenues for co-electrolysis of H_2 and CO_2 that would allow direct synthesis of syngas (for conversion to methanol) and even methanol using renewable electricity (**Figure 21**).[96] Though these technologies are in their early stage of development (TRL 2), the International Renewable Energy Agency (IRENA) expects them to play a vital role in developing fully sustainable methanol value chains.[97]

Use of Renewable Methanol

Methanol is expected to play a vital role as a hydrogen carrier in a "hydrogen economy". It has a significant advantage over other hydrogen carriers like ammonia due to higher energy densities (**Figure 18**), allowing it to store larger amounts of energy in both unit mass and volume. It can then also be subsequently converted into ethanol and dimethyl ether (DME) that have a higher energy density (energy competitive) through a simple one step conversion.

Given its versatility of usage (both as a fuel and industrial feedstock), increasing demand, and potential for sustainable production, renewable methanol is being championed as a "future proof fuel".[98] This could see, use of methanol as a source of power generation and as a transportation fuel especially in sectors like heavy duty applications, aviation, or marine use where use of batteries is expected to be limited.[97]

Figure 18: Comparison of energy densities of conventional and emerging energy carriers. Here, M85 represents an 85% mix of methanol and 15% gasoline, similarly E85 represents an 85% mix of ethanol and 15% gasoline, DME represents Dimethyl Ether and LOHCs represent Liquid Organic Hydrogen Carriers (considered here as Toulene).



Status of Renewable Methanol Projects

The first renewable methanol plant was developed by the Carbon Recycling International Group – CRI in Iceland (**Figure 19**). The facility is in operation since 2011 and generates methanol (4,000 t yr-1) through CO_2 sourced from a nearby geothermal power plant that also provides the electricity to generate the required H_2 from electrolysis.[97] CRI is also offering their technology as turnkey solutions with plants capacities between 50,000 to 100,000 t yr^{-1} for commercial applications.[99]

Figure 19: CRI's facility in Iceland is the world's first Power to Methanol project.

Analysis by IRENA shows that renewable methanol plants (P2X) with a combined capacity of 700,000 t yr^{-1} have already been committed.97 These include mega projects in Sweden (45,000 t yr^{-1}), ABEL energy's Bell Bay project in Australia (60,000 t yr^{-1}) and CRI's project in Norway (100,000 t yr^{-1}) that are expected to be operational by 2024.

Australia's Methanol Potential

Australia's only methanol facility was installed in 1994 by Coogee Chemicals in Victoria, supplying 70,000 t yr^{-1} of Australia's methanol demand (**Figure 20**).[100] Since 2016, due to unavailability of competitive natural gas pricing (<A$10 GJ-1), the plant has been shut down and is expected to be decommissioned.[101]

Figure 20: Australia's only existing Methanol Plant in Victoria. The facility stopped operating in 2016 due to high gas pricing.[102]

In 2019, Coogee Chemicals announced plans to conduct a feasibility analysis to develop another methanol plant in Northern Territory, where the company says it will be able to secure favourable gas supply costs.[103] The decision is yet to be made on the $500 Million plant that could be operational by 2024.

ABEL Energy Powerfuels Project

ABEL Energy is planning a renewable methanol plant in Bell Bay, Tasmania. The plant will leverage Tasmania's renewable energy potential (especially hydroelectricity) to power a 100 MW renewable hydrogen electrolyser and generate 60,000 t yr-1 of methanol, mainly for export.[104] A future proposed development includes a plant to convert some of the methanol to DME to cater local demand. The proposed project is expected to cost ~$270 million and generate 30 jobs.[105]

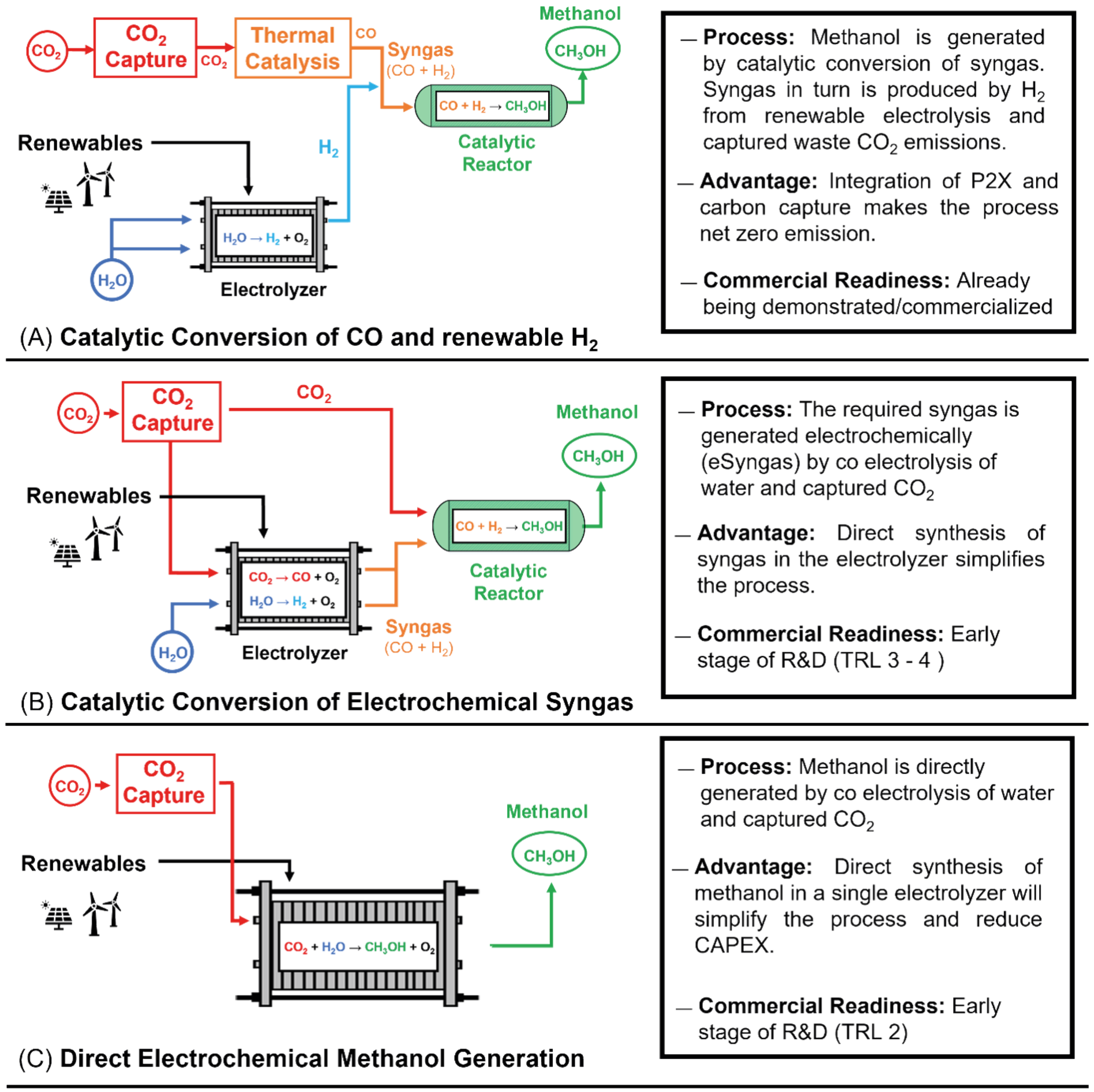
NSW's Renewable Methanol Opportunity

NSW can leverage its existing waste CO_2 sources from powerplants and biomass resources with renewable hydrogen to generate renewable methanol. This may be used for the local market as feedstock and fuel or can serve as an export vector for renewable hydrogen as methanol is reported to have a higher energy density than compressed hydrogen.

In addition, methanol presents a unique opportunity to promote the gradual transition to a low-carbon economy as methanol can be used as a blend fuel. Methanol blending with petroleum is being considered as a decarbonisation pathway in Asia-Pacific as an intermediate step towards zero emission mobility.

NSW Power to X (P2X) Industry Pre-Feasibility Study

Figure 21: Potential P2X pathways for Methanol Generation. **(A)** The first pathway involves conversion of captured CO_2 to CO using thermal catalysis, after which it is combined with H2 from renewable electrolysis and the subsequent syngas mixture (CO+H_2) converted to methanol through secondary conversion reactor. **(B)** The second pathway (TRL 3-4) being explored is the conversion of waste CO_2 and water within CO_2 electrolysers to generate syngas, which can be converted to methanol through secondary conversion reactor. **(C)** Research is being carried out to develop direct electrolysis of CO_2 and water to generate methanol.



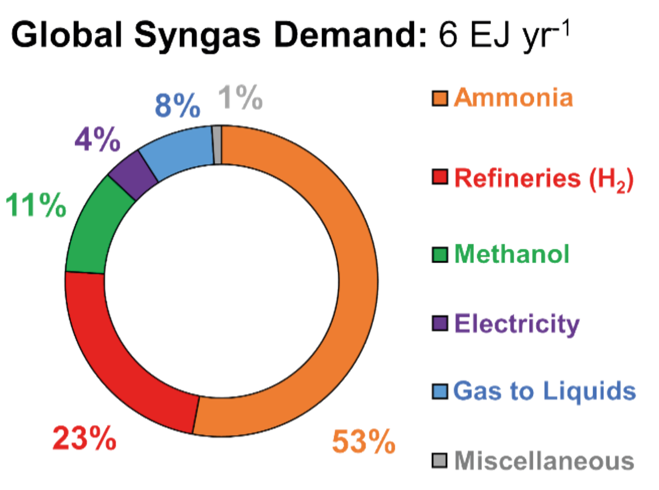
3.6. Power to Syngas (Synthetic Fuels)

3.6. Syngas Production and Conversion using Fischer-Tropsch Process

Synthesis gas (syngas) is an essential fuel gas mixture, consisting primarily of hydrogen and carbon monoxide of different ratios. At present, syngas is used as an intermediate step to generate hydrogen for industrial use in ammonia manufacturing (where the CO is converted to CO_2 and is emitted to the atmosphere), petrochemical industry, and methanol generation (**Figure 22**). It is also indirectly used in electricity generation, especially in coal power stations, as it is a major product of coal gasification. Another emerging application is converting syngas into liquid fuels (notably aviation fuel) and chemicals through Fischer-Tropsch (FT) process.

Notably, FT process has reached high levels of commercialisation and is actively being implemented on a global scale (TRL 5 – 9).[80] Commercial systems are already available from market leaders such as General Electric (GE), Lurgi AG, Shell and Siemens. Large scale FT projects include Sasol's plant in South Africa providing >300,000 barrels per day (bpd) of synthetic fuels. In 2005, the plant provided 28% of the country's diesel demand amongst various other products.[106] Shell is operating the USD$19 billion Pearl GtL (Gas to Liquids) Facility in Qatar, with a capacity of 140,000 bpd of products since 2011.[107]

Figure 22: Breakdown of Global Syngas Demand per end use sector.[108]



Global Demand of Syngas

Global demand for syngas is ~6 EJ yr^{-1} (i.e. $6*10^{12}$ MJ), equivalent to 2% of the world's primary energy consumption.[108] The global market for syngas and its derivatives is projected to be worth 6.6 EJ per year by 2022 and is witnessing a CAGR of over 10% since 2016.[109]

Demand in Australia

In Australia, syngas is mostly indirectly generated while providing H_2 for ammonia generation. Alternatively, several projects were explored for generating syngas from coal gasification for subsequent conversion to fuels (FT conversion) in South Australia (SA), Victoria, and Queensland, but none of them were commercialized.[110] However, the Leigh Creek Energy Project in SA, is currently exploring the possibility for syngas generation by utilizing local coal reserves, but for use in ammonia and urea generation. The project will develop an *in-situ* coal gasification facility, resulting in gasification of coal underground into syngas that can then be retrieved for use. The company is aiming to conduct a "bankable" feasibility analysis on the proposed $2.6 billion facility that could become carbon neutral by 2030.[111]

AgBioEn is developing a $2 billion biomass to FT facility in Victoria, that will generate green diesel. The project is expected to save 45 ktpa of emissions and generate up to 1,500 jobs.[112]

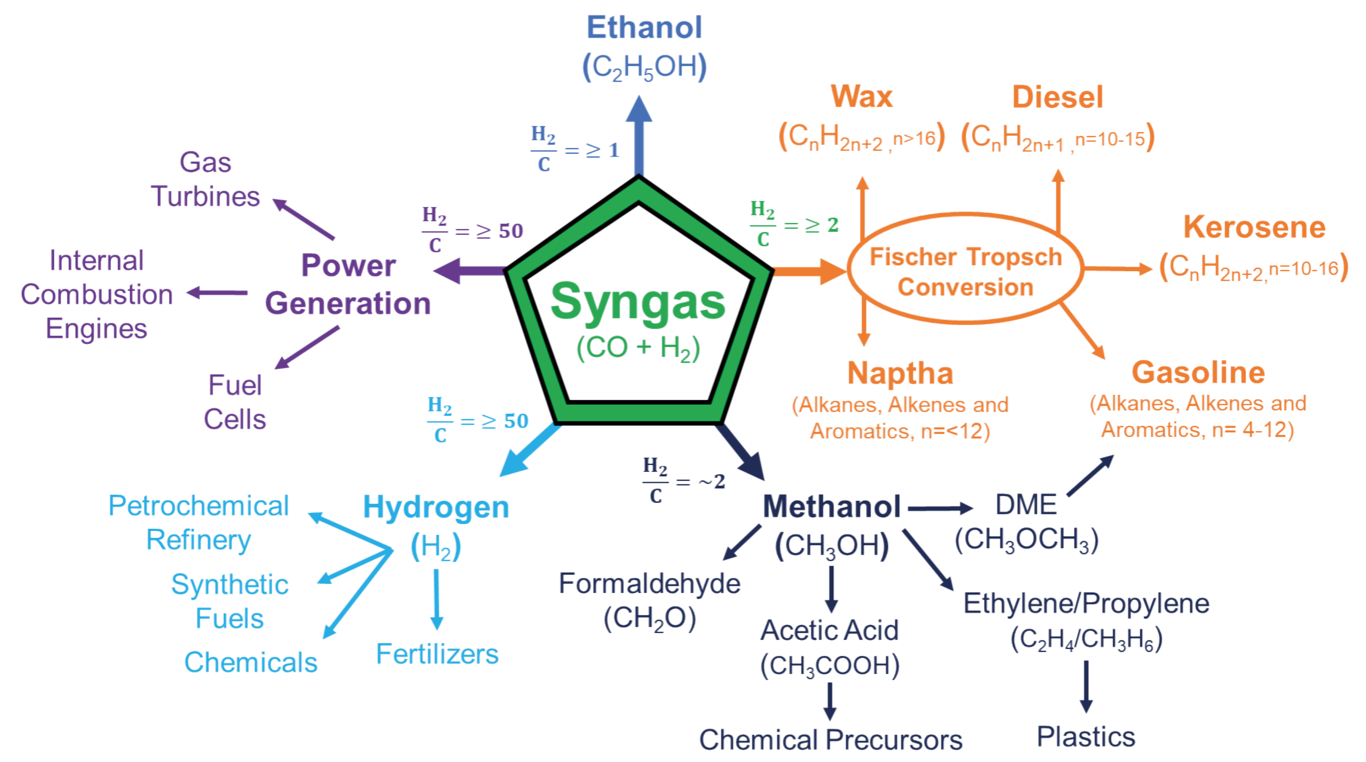
Key Feature of Syngas

Syngas is considered as the chemical equivalent of 'lego blocks', as the basic building blocks of CO and H_2 can be combined together in various configurations to give plethora of products. This functionality is defined by the syngas ratio i.e., is the molar ratio of H_2:CO within the syngas mixture. Various syngas ratios have already been established for using syngas as an intermediary for potential use as an energy source or feedstock for generating a wide variety of chemicals and fuels through either direct use or through FT process (**Figure 23**).[113]

Syngas Generation

Currently, most FT process are categorized as Gas to Liquid (GtL) plants that uses natural gas or petroleum feedstocks. In China and South Africa, Coal to Liquid (CtL) plants are being readily used to generate bulk amounts of syngas.[114] Other emerging pathways involve using biomass and even solid municipal waste to generate syngas.[115] The common industrial techniques for syngas generation are the catalytic steam methane reforming (SMR), autothermal reforming (ATR) and partial oxidation (POX).

Figure 23: Syngas derivatives based on the syngas ratio (H2/CO).[113]



Role of P2X in syngas production

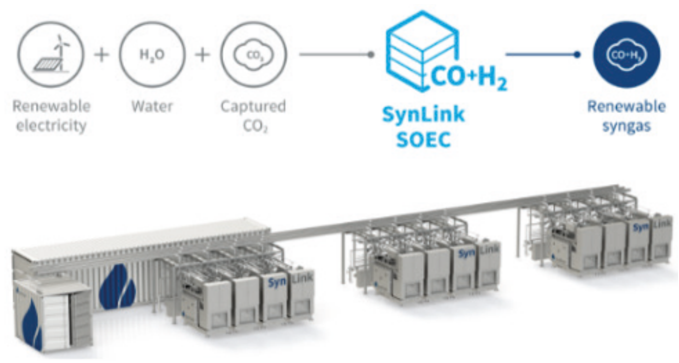
Power-to-X technologies can offer opportunities in decarbonised syngas production via renewable energy.

1. Renewable hydrogen can be mixed with waste CO_2 to generate syngas for use in FT reactor. This approach often referred to as Power to Liquid (PtL), is being championed for generation of renewable methanol and other FT based fuels.[116] Sasol, the South African based chemicals company is investigating the potential of converting their aforementioned coal-based FT facilities in South Africa to a renewable hydrogen based PtL plant.[117] Several other projects are also being developed in the EU, as discussed below.
2. Direct CO_2 and water electrolysis to syngas is also possible using transition-metal based catalysts.[113] Through catalyst tuning, the syngas ratio can be easily altered, that will provide a versatile control on the different synthetic hydrocarbon products that can be generated by subsequent FT conversion. Considerable effort is devoted to developing syngas catalysts (within NSW universities) and for system scaleup overseas.

Sunfire GmbH, a German based company has commercialised electrolysers for direct synthesis of syngas (upto 750 Nm^3 hr^{-1}) (**Figure 24**). The electrolyser will enable generation of syngas with selective syngas ratios from co-electrolysis of water and captured CO_2 emissions.

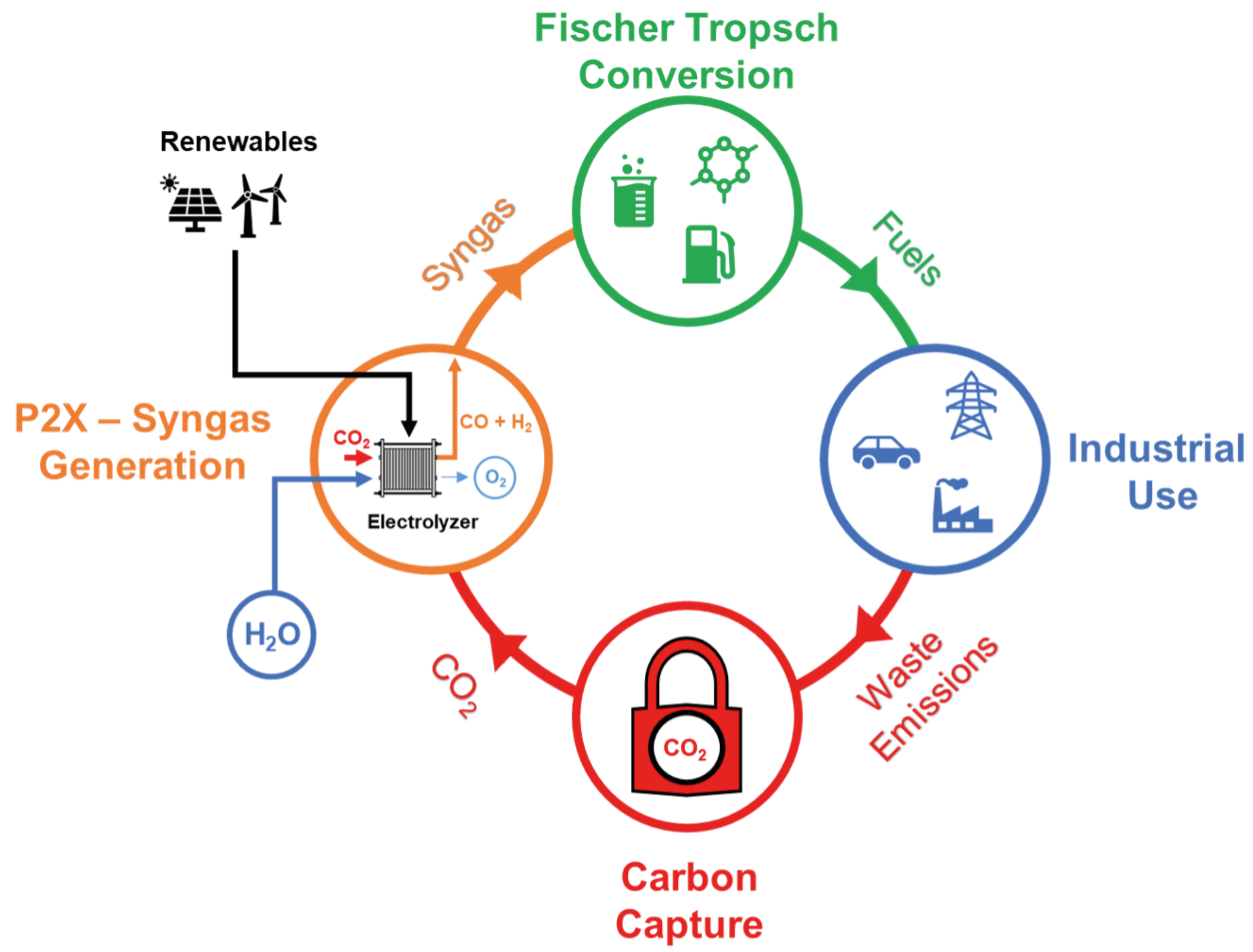
The company is currently partnering with CO_2 capture company ClimeWorks to develop the "Norsk efuel" pilot project in Norway, where their technology will be used to generate 100 million litres of synthetic fuels by 2026.[118]

Figure 24: The Sylink SOEC system for direct synthesis of syngas developed Sunfire GmbH.



These developments open avenues for developing closed looped PtL systems where synthetic fuels can be generated from captured CO_2 emissions (**Figure 25**). IEA expects the demand for such synthetic hydrocarbon, especially that of synthetic kerosene as aviation fuel, to reach 250 Million tons of oil equivalent (Mtoe) per year by 2070.[19] This would translate to ~$134 billion market (current price of Aviation fuel: $68 bbl-1)[119]. Recently, KLM, a leading Dutch based airline, revealed that they operated the world's first commercial flight using synthetic kerosene generated using PtL.[120] The company is also a key stakeholder in projects being developed to establish PtL plants to provide synthetic kerosene for flight operations at Amsterdam and Rotterdam Airports.

Figure 25: Electrochemical syngas generation using P2X to close the loop.



NSW's opportunities for Power-to-Syngas

In addition to methanol production from syngas (discussed in **Section 3.5**), there is a market opportunity to generate a wide range of powerfuels from syngas in NSW.
One immediate prospect is synthetic aviation fuel production in the Western Sydney Aerotropolis. Further, application of renewable syngas to generate olefins and polymers may present economic opportunities for local manufacturing industries.

3.7. Other Power-to-X Technologies

3.7. Other P2X Pathways

In addition to the above pathways, several other P2X technologies are being investigated. These include direct CO_2 electroreduction pathways into formic acid, ethanol/methanol, and other complex hydrocarbon products.[121] In fact, it is reported that there remains possibility in coupling different electrochemical pathways together in a single system to enhance flexibility. A recent report by Na *et al.,* suggested that up to 295 different combination of electrochemical pathways can be generated, giving a wide variety of gaseous and liquid products.[122] Some of these P2X technologies are discussed as follows.

Renewable Power to H_2O_2

Hydrogen Peroxide (H_2O_2) is a valuable chemical that is used as a commercial oxidizing agent; especially in the pulp and paper industry that accounts for 60% of the global H_2O_2 demand. Further, H2O2 is used as a disinfectant for water treatment and sterilization. This property is highly significant considering the current pandemic environment, the US Centres for Disease Control include Hydrogen Peroxide amongst potent disinfectant that are safe to use.123 Currently, hydrogen peroxide is generated using Anthraquinone process, which generates hydrogen peroxide by catalytic redox conversion of anthraquinone. A usual precursor of this process is the generation of hydrogen from steam methane reforming, which is used to hydrogenate the anthraquinone and is later removed in the oxidation phase to generate hydrogen peroxide.[124]

Recent development in electrocatalysis have however, opened an avenue for generating hydrogen peroxide from oxygen from air and hydrogen from water in a single electrolyser unit.[125] This could lead to a simple, inexpensive, portable device that could produce hydrogen peroxide continuously from just air, water, and electricity onsite for utilization at airports, hospitals, sporting events etc.

Biomass to H_2

An alternative to renewable hydrogen generation from electrolysis is hydrogen generation from biomass. Thermochemical hydrogen generation from biomass is already an established approach where biomass is mixed with coal or natural gas or directly used in gasification or pyrolysis processes to generate hydrogen. Alternatively specialized biological processes are being investigated which involve breakdown of biomaterial into hydrogen using specially designed biocatalysts.[126] Though biomass offers a vast renewable resource for hydrogen generation, the conversion to hydrogen is a slow process, would require significant area to cultivate biomass and to develop reactors for large scale hydrogen generation, which currently limits its scalability.[127]

CO_2 mineralisation

CO_2 mineralisation is a promising P2X pathway that that converts waste CO_2 into value added materials such as cement and construction materials. Given the volume of these materials used within the global economy, mineralization of CO_2 is being championed as a potentially large volume CO_2 utilisation and storage pathway.[128] At present, CO_2 mineralisation is currently limited by high energy requirement and slow kinetics.[129] Renewable energy could play a role in scaling mineralization by providing the energy to drive the process and scale up process such as direct air capture.

Mineral Carbonation International (MCi), an Australian based company, is already developing commercial mineralization technology over the last 7 years. They have raised over $20 million in seed funding from government and industry that has been spent to design and build a pilot plant at the University of Newcastle.[130,131]

4. Disruptive P2X technologies from NSW and Australia

4.0. Disruptive P2X technologies from NSW and Australia

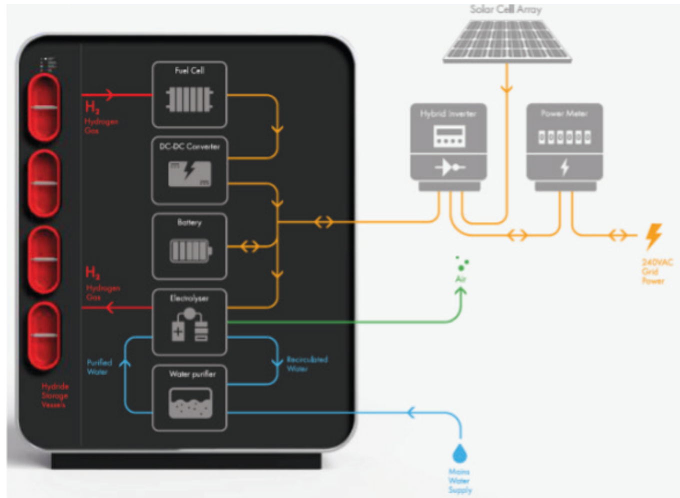
NSW (and Australia) hosts outstanding capability for research and development (R&D) in the P2X domain. This is driven by high-quality work in engineering and applied sciences, especially in key focus areas such as: renewables, energy conversion, nanotechnology, catalysis, process design & engineering, increasing the productivity and efficiency of manufacturing and in mixed energy-chemistry systems.

Some examples of NSW and Australian spinoff technologies in P2X space are presented below.

Hydrogen Storage Systems by LAVO

LAVOTM, a UNSW spinoff, have developed their proprietary hydrogen-based hybrid energy system (40 kW capacity) for application in residential homes and business. The system (**Figure 26**) is equipped with a hydrogen electrolyser that can be operated by supplying water from the mainline and electricity from rooftop solar arrays. The generated hydrogen is then stored in a metal hydride system, and the stored hydrogen can be used for power generation using a fuel cell at times when solar energy is not available. The company is currently taking orders for shipment by July 2021 (Cost per unit: $29,450).

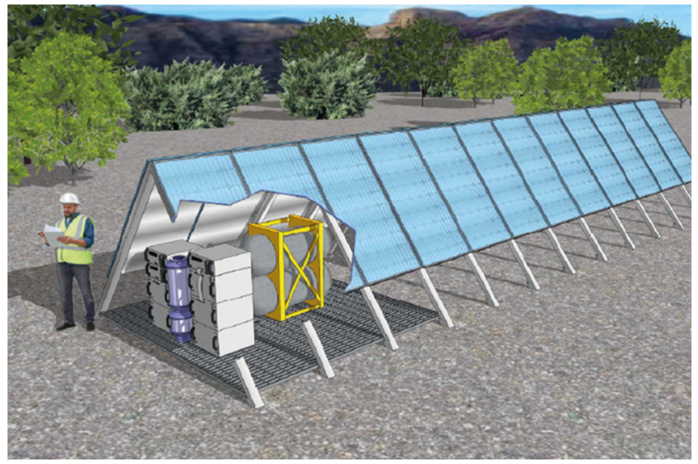
Figure 26: LAVO™ Green Energy Storage System. Image courtesy of LAVO™



Direct Air Capture coupled Methanation (Southern Green Gas)

As highlighted above, APA Group and Southern Green Gas with funding from ARENA is developing a state-of-the-art facility in Queensland to generate renewable methane. The CO_2 feedstock is captured from air using University of Sydney patented Direct Air Capture Technology. The water feedstock is captured from air using Hydro Harvester technology developed at the University of Newcastle. The demonstration plant (**Figure 27**) is expected to generate 74 GJ of synthetic methane every year. The plant will be installed at the Wallumbilla Gas Hub in Queensland, for injecting the methane into the existing gas network.

Figure 27: Illustrated design of the APA Methanation Process. Image courtesy of ARENA.

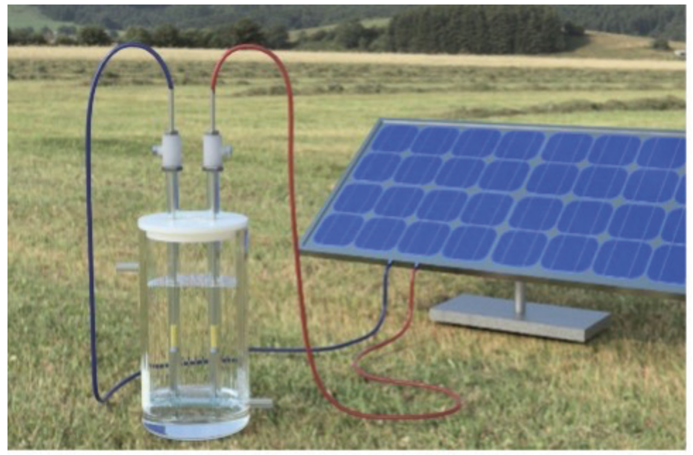


Plasma driven hydrogen and ammonia generation (Plasma Leap - UNSW)

Plasma Leap Technologies (spinoff from University of Sydney) have developed a proprietary system to generate plasma at very high energy efficiency. This system is used by the Particles and Catalysis Research Laboratories based in UNSW to generate NOx that is then converted to ammonia using a hybrid patented electrolyser system (**Figure 28**).

The creation of the NOX intermediate has been a significant technological challenge, and these developments are expected to open avenues for scalable electrochemical ammonia generation to replace Haber-Bosch process.

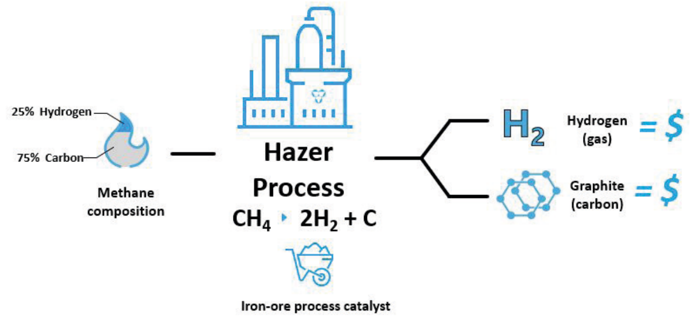
Figure 28: Schematics of hybrid plasma electrolyser system for ammonia production. The process uses plasma to generate the NOX intermediate from water and nitrogen from air (reactor on the left), the NOX is then converted to ammonia by co-electrolysis with water in an electrolyser (shown on the right).[132]



Hazer Process (Hazer Group)

Hazer Group in collaboration with University of Sydney have developed the Hazer® Process which aims to generate emission free hydrogen from natural gas. The process (**Figure 29**) utilises an iron ore-based catalyst to convert natural gas into carbon (retrieved as high-quality graphite that can be retailed) and release hydrogen gas. The process is environmentally (50% lesser emissions) and economically competitive with Steam Methane Reforming (SMR).

Figure 29: A process flow diagram of Hazer Process®. Image courtesy of Hazer Group



Solid Oxide Electrolyser for Syngas and Hydrogen (CSIRO)

CSIRO is developing a proof-of-concept solid oxide electrolyser (SOE) that will enable conversion of carbon emission and water into syngas and hydrogen by harnessing solar energy. The key advantage of using SOEs is that they can utilise solar energy as both electrical and heat to drive the electrochemical reactions improving the process efficiency. The syngas will then be converted to liquid fuels using catalytic converters that are also being developed by CSIRO. The process is expected to be scalable to achieve economic competitiveness, with 40% savings in required electricity to drive the electrolysis process and enable consumption of upto 8 t hr^{-1} of waste CO_2 emissions.

Wastewater Electrolysis to produce Hydrogen (SwitchH2)

SwitchH2 has developed a catalyst and electrolyser system that is able to partially oxidize organic-rich wastewater from the food and beverages industry (i.e., breweries, wineries, and distilleries) into hydrogen. The benefits of SwitchH2's process for NSW includes reducing reliance on clean water for hydrogen production, allowing scarce pure water reserves to be utilised for domestic applications. The company has developed their pilot system, which is shown in **Figure 30**.

Figure 30: SwitchH2's pilot system. Image courtesy of SwitchH2.

HERO® Hydrogen Energy Optimizer

Hero® - Hydrogen Energy Optimizer is a proprietary catalyst system developed by Star Scientific Limited, in collaboration with University of Newcastle. The catalyst allows for generation of thermal energy (Temperatures close to 700°C within three minutes) using Hydrogen and Oxygen with no harmful by-products.[133] The company is also developing special heat exchangers that can then use the heat generated for energy intensive processes like electricity generation (replacing coal-based steam generation), developing heating systems for domestic and commercial use, to fulfill industrial energy especially for water desalination.

The catalyst is being championed as a key driver for a hydrogen economy by providing an opportunity for bulk offtake of hydrogen. The company has recently entered an agreement with the Philippines Government to use their technologies to assist the country in developing their hydrogen economy.[134]

AquaHydrex Pty Ltd

AquaHydrex, is a technology start-up based on research at the University of Wollongong (UOW). The company is working to develop proprietary low cost and highly efficient electrolyser systems for commercial use as a means of renewable electricity storage by generating hydrogen that can then be injected into the natural gas grid. The company was provided funding by ARENA in 2017 to develop such electrolysers.[135] Since then, the company has shifted their operations to the US.

HydGene Renewables

HydGene Renewables is a Macquarie University spin-off that is commercializing hydrogen generation from biomass using a patented bioreactor onsite. The company expects their system to be used as an offsite energy generation system to replace diesel powered system by using the hydrogen produced in a fuel cell generating electricity. The key advantage of their system is that the hydrogen can be generated and used at the same site, reducing the cost of transportation and storage which are major cost drivers of generating and supplying hydrogen.

Hydro Harvester

Hydro harvester is a technology designed to extract water from air by heating the air using solar energy/heat, causing it to absorb more moisture from the surroundings. The heated air is then cooled to condense the absorbed water and extract it for use. The technology though currently in prototype phase, is inherently different from commercialized harvester which tend to refrigerate air to separate water out, a costly and less efficient method. By using solar and waste heat, the hydro harvester is more efficient and can generate water for below 5 cents per L.

The developers also foresee the use of their system for use in hydrogen generation. The technology can provide pure water for electrolysis, with the excess solar and heat energy generated by the system used for splitting water. The company has partnered up with Southern Green Gas and are providing support for their project to generate synthetic methane in Queensland (mentioned earlier).

The developers have also secured seed funding through the NSW Physical Sciences Fund (A$330k) to conduct a commercial demonstration unit.[136]

Mineral Carbonation International (MCi)

MCI is an Australian based company, that is developing technology to capture and convert CO2 into construction material. The company has been active over the last 7 years, raising over $20 million for R&D and have built a pilot plant at the University of Newcastle. Their process enables transformation of captured CO_2 into cement, concrete, aggregates and plasterboards, with conversion into advanced materials like fire retardants and clothing being currently explored. The company claims they now have the ability to assess a potential industrial site and explore the viability for CO_2 conversion, and are now seeking potential opportunities to commercialize their technology.[130,131]

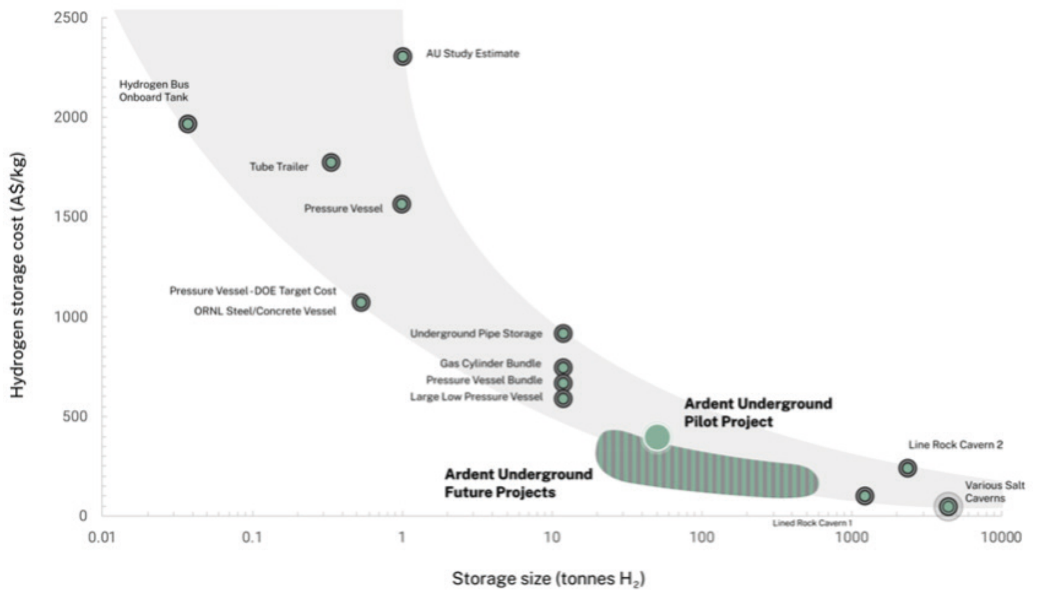
Hysata

Hysata, a spinoff from the University of Wollongong (UoW), is developing an 'advanced' electrolyser technology targeted at generating hydrogen at a cost <$2/kg. The company has recently secured A$5 million in funding through the IP group with support from the Clean Energy Finance Corporation (CEFC) to commercialise their electrolyser design.[137]

Ardent Underground

A key aspect of a hydrogen supply chain is the need for intermediate storage between the generation and utilisation steps. To address this, Ardent Underground in partnership with ITP Renewables is commercialising hydrogen storage at site underground via drilling shafts. The naturally occurring rockbed is used to seal and keep hydrogen from leaking out and in maintaining high pressure, thereby negating the need for costly storage tanks (**Figure 31**)

Figure 31: Cost comparison of Ardent Underground's H_2 storage solution versus alternatives. Image courtesy of Ardent Underground. Image courtesy of Ardent Underground.[138]



5. Suitable Locations for the Development of a 'P2X Hub'

5.0. Suitable Locations for the Development of a 'P2X Hub'

In this section, we explore the possibility of developing P2X hubs in different regions in NSW. It must be noted that the business cases are developed as hypothetical representative scenarios for P2X deployment and do not reflect the intent or plans of the respective companies.

5.1. Three-tiered Framework to Assess 'P2X Hub' Opportunities in NSW

Table 1: Framework to assess 'P2X Hub' opportunities in NSW.

Tier	Target Market	Benefit to NSW's Economy
Tier 1: Embedding of P2X feedstocks into heavy industry (ammonia, steelmaking, gas blending)	Gas blending, heavy manufacturing and mineral processing within NSW	Revives the heavy industry through the embedding of 'green chemical' feedstock into their chemical process, allowing for the generation of green commodities. As green commodity mandates increase in East Asian countries (Japan, China and South Korea), UK, USA and EU, this presents an opportunity for NSW to become a powerhouse exporter of green commodities (i.e., green steel, ammonia, methanol and ethanol) Heavy industry and mineral processing will require the generation and production of high volumes of P2X products allowing for the creation of new jobs in rural locations in NSW.
Tier 2: Transitioning NSW towards 'green fuels'(powerfuels for mining, transportation and process industries)	Transportation, chemical and mining operations and thermal heating industries	Green fuels such as hydrogen, ammonia, methanol and methane produced from P2X present an opportunity to transition NSW's transport infrastructure towards low-carbon/zero-emission alternatives. This is a significant step forward for NSW as it brings us closer to our zero emission targets. Alternatively, the green fuels can be used directly in mining operations in NSW to transition to fuel cell electric vehicles. Thermal heating is an attractive application for P2X products in the food and beverages industry in NSW. Industries such as dairy and meat/poultry predominantly use natural gas for heating applications. Large scale production of green fuels, followed by distribution to NSW transport network or thermal heating network will therefore potentially create regional jobs.
Tier 3: Decentralised P2X microhubs for local end-users	Creation of precincts within NSW to create micro-economies.	Stimulates local job creation and allows for each dollar of NSW funding to be split into numerous smaller projects increasing the velocity of P2X technology adoption, i.e. the development of micro hydrogen (for transportation) and ammonia (fertiliser) hubs in regional NSW, where the offtakers are businesses that are in proximity to the microhub.

5.2. Overview of the Key Locations in NSW to Deploy a 'P2X Hub'

A preliminary investigation was performed to understand the geographical regions within NSW that present the greatest opportunity for P2X adoption. The geographical locations were selected based on existing NSW government initiatives such as the development of manufacturing capabilities (Special Activation Precincts), renewable energy generation zones (REZs) and infrastructure investment (Aerotropolis in Badgerys's creek). The geographical locations were then qualitatively assessed on their feedstock availability (pure water etc.), co-location with industries and access to port infrastructure for export opportunities. In **Table 2**, a summary of these findings are presented.

The focal point of the pre-feasibility investigation will be Illawarra-Shoalhaven, Hunter and Parkes, as these regions represent a synergy between renewable energy generation, existing industries/government stimulated emerging industries, therefore, providing an immediate opportunity for P2X adoption. The other regions in the desktop investigation such as Wagga Wagga, Dubbo, Botany and Badgerys's Creek are markets that are in a very early stages of development, presenting a more long-term outlook for P2X adoption, hence have not been investigated in detail for this version of the report.

NSW Power to X (P2X) Industry Pre-Feasibility Study

Table 2: Summary outlook of potential NSW 'P2X Hubs'

	Feedstock Assessment		Existing Industry Assessment	Tier 1 & 2 Opportunity Assessment	Tier 1 & 2 Opportunity Assessment	Tier 3 Opportunity Assessment
Location	**Access to Renewable Power Generation**	**Access to Pure Water Feedstock**	**Existing Industry in the Region**	**Opportunity to P2X to Decarbonise Heavy/ Light Industries**	**Access to port infrastructure**	**Opportunity to Develop a Micro–P2X Economy**
Illawarra – Shoalhaven	●	●	●	●	●	●
Hunter	●	●	●	●	●	●
Parkes	●	◑ Parkes has 2 major water reservoirs (Burrendong and Wyangala) but the region is prone to droughts	◑ Parkes has a mining sector and will be the intermodal point for the 'Inland Rail'	◕ The 'Inland Rail' and mining operations present an opportunity for power fuel application	◕ The 'Inland Rail' can be used for potential power fuel export	●
Wagga Wagga	◑	●	◑ Wagga Wagga has a large agricultural and food processing sector	◑ Power fuels can be utilised for thermal and transportation applications	◑ Freight and logistics pathways can be created	●
Dubbo	●	◑	◑ Dubbo has a mining sector	◕ Mining operations present an opportunity for P2X application	◑ Freight and logistics pathways can be created	◑
Badgerys Creek	◑	●	◑ The aviation industry and Aerotropolis	◑ The aviation industry and Aerotropolis present an opportunity for power fuels adoption	◑ Freight and logistics pathways can be created	●

5.3. Illawarra-Shoalhaven Precinct

Illawarra-Shoalhaven region is the third largest regional economy within NSW with an annual revenue of A$15.5 billion.[139] The key sectors that contribute to this economy include:

- Port Kembla's shipping port, which is NSW's largest grain export hub and 2nd largest port for coal export. Port Kembla provides A$543 million of revenue to the state through the port.[140]
- Hosts one of Australia's largest manufacturing strongholds with key industries like steel manufacturing and fuel production.[141]

Figure 32: Map of Illawarra-Shoalhaven Region.

The Illawarra-Shoalhaven region (**Figure 32**) supports an ecosystem with large heavy industry agglomerates such as BlueScope Steel and Manildra Group. These two businesses provide a great opportunity for the establishment of a 'Tier 1 P2X Hub' in the region. We explore resource availability and P2X price points to provide an assessment of the suitability of creating a P2X hub in the region.

There is also considerable interest from the NSW government to develop a hydrogen hub in the Port Kembla region. Very recently, the government has provided funding to EnergyAustralia to develop a 300 MW dual hydrogen/natural gas fired power plant in the region.[142] Fortescue Metal Group through its subsidiary Squadron Energy have also expressed their interest in developing a A$1 billion power station that will power NSW industries.[143] These businesses provide opportunity to also develop a 'Tier 2 P2X Hub' in the region.

Opportunity to Support 'Green Steel'

BlueScope Steel operations in Australia produce A$5 billion worth of steel annually, a major proportion being generated at Port Kembla Steelworks.[144] The steelworks facility produces 2.6 million tonnes of steel annually and supports 10,000 jobs in Illawarra.

BlueScope has announced as part of its sustainability commitment, to reduce Scope 1 and Scope 2 GHG emissions intensity for its steelmaking sites by 12% before 2030. BlueScope has made great strides in achieving this target through the introduction of a 7-year power purchase agreement (PPA) with ESCO Pacific to source 88 MW of renewable solar electricity. This PPA commenced in 2019 and provides 20% of BlueScope's energy demand.[145]

Another area of exploration for BlueScope is the decarbonisation of its steelmaking operations. One opportunity for the steel industry is *"increasing primary steel production using Direct Reduced Iron (DRI) plants accompanied by Electric Arc Furnaces (EAFs)"* – 2020 Sustainability Report.[146] The transition to this process of steelmaking is likely to be met initially using a blend of fossil fuel based hydrogen from SMR and green hydrogen, before transitioning completely to green hydrogen.

Current Steel Making Process

The current processing route for steel/ironmaking (**Figure 33**) involves the following steps:

1. Lump and agglomerated fine iron ores (iron oxides such as hematite) are smelted in a blast furnace (BF), producing pig iron (liquid iron saturated in carbon). The process involves direct and indirect reduction using predominantly carbon from metallurgical coke and other auxiliary fossil fuels.[147]
2. Basic Oxygen Furnace (BOF) is used to convert 'pig iron' into steel with low-carbon content. The process of blowing oxygen in the presence of heat accelerates its reaction with residual carbon (and other impurities) in the pig iron to produce carbon monoxide.

   Steps 1 & 2 uses ~24.5 GJ of energy (both heat and electric) to produce 1 ton of steel. So, for the BlueScope Illawarra facility, 64 PJ of energy is required, assuming all the steel is from primary operations, meaning it is based on virgin iron ore units.[148]

The use of fossil fuels for thermal heating and reduction is a significant stream of carbon emissions in the current process. Blast furnace top gas typically has a composition of 22-23% carbon dioxide, 22-23% carbon monoxide, 4-6% hydrogen and the remainder is nitrogen.

Figure 33: Schematics showing current steel making process followed in Industry.[149]

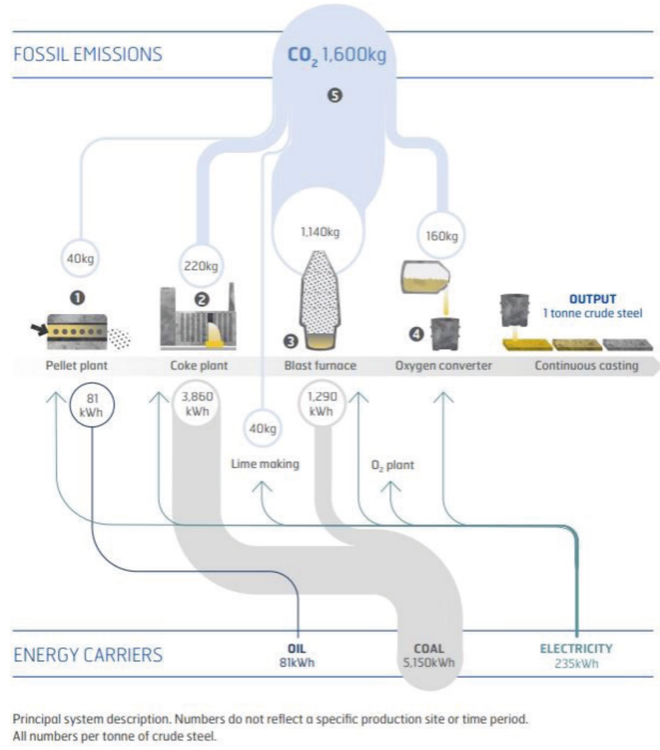
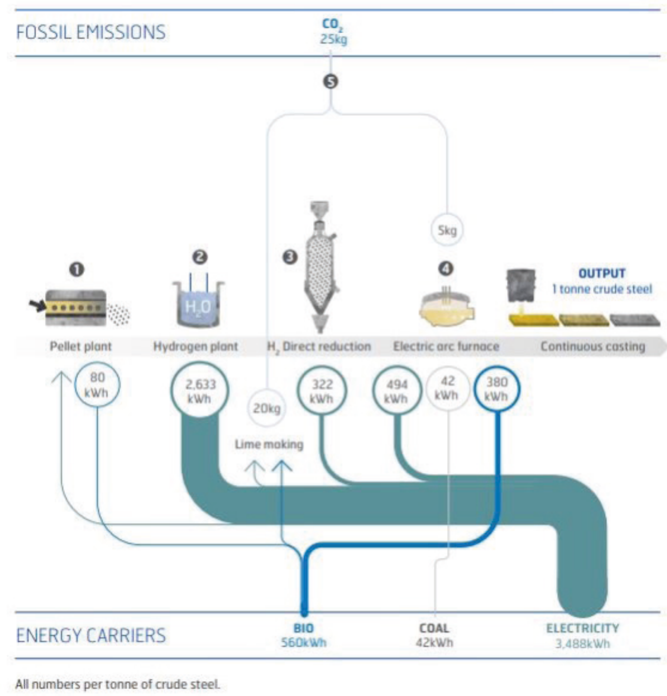


Figure 34: Schematics of Project HYBRIT. The plant is being developed in Sweden for testing use of green hydrogen to produce green steel.[153]



Steel Production Using Scrap Steel as the Feedstock

Electric Arc Furnaces (EAFs) are growing in adoption for the conversion of scrap steel into steel. The basic principle involves the melting a mix of recycled scrap steel and direct reduced iron (DRI) with scrap steel using energy supplied by electrical current in the EAFs. Scrap steel on average contains 0.2% copper which if not diluted using the addition of DRI, exposes the steel to surface cracking during the hot rolling process (hot shortness).[150]

Current DRI production (~76% of global production in 2019) is centred around gas-based furnace processes, where natural gas is converted into syngas (CO & H_2) using SMR and the syngas constituents are used to reduce the iron ore.[150] The transition of the gas input from syngas constituents, to only green hydrogen, will be one of the key enabler in transitioning the secondary steel industry to low-carbon processes.

What does this mean for BlueScope?

BlueScope currently produces 15-20% of their annual steel using scrap steel.[151] In the medium term, as outlined in BlueScope's 2020 Sustainability Report, there will be a transition as *"the industry will see greater contribution from secondary steel electric arc furnace (EAF) facilities as the supply of scrap steel increases in certain markets, as well as an increase in primary steel production by Direct Reduced Iron (DRI) plants accompanied by EAFs"*. BlueScope will await the outcome from the HYBRIT project (**Figure 34**) in Sweden, which aims to demonstrate green steel deployment.[152]

How much Hydrogen is Required for a Low-Carbon Secondary Steel facility, the size of BlueScope's Illawarra Facility?

Traditionally EAF for secondary steel production uses a blend of 75% scrap steel and 25% DRI, to bring the copper concentration to <0.15%, which is the industry mandate.[154] For instance, BlueScope Illawarra produces approximately ~390 kT (representing 15% of BlueScope's annual production) of their steel using secondary steel manufacturing process. This requires ~97.5 kT of DRI. Current estimates suggests 54 kg of hydrogen is required in the reduction process to produce 1 ton of crude steel. Therefore, a low-carbon secondary steel facility such as BlueScope's Illawarra facility will require ~21 kT of green hydrogen per year for their operations.[147]

Feedstock Assessment for a 'Low-Carbon Steel' facility in the Illawarra-Shoalhaven region

The core P2X pathway for green steel production will involve the production of green hydrogen. Therefore, access to water and renewable energy will be one of the critical factors in determining the viability of this opportunity.

Access to renewable energy: The Shoalhaven Scheme in Southern Highlands was commissioned in 1977 to provide hydroelectricity to the Illawarra-Shoalhaven region. Today, the scheme includes two interconnected power stations in Kangaroo Valley and Bendeela. Origin Energy, the owner of the power plants, supported the distribution of 240 MW of electricity to the Illawarra-Shoalhaven region.[155]

In May 2020, Origin Energy completed a feasibility study for the introduction of a further 235 MW of new capacity. The outcome of the study showed, *"technical feasibility, however it is not commercially feasible in the current economic environment. Origin will continue to consider this expansion project for our portfolio in the future"* – Origin's public announcement for the project.[156]

The primary concern for Origin Energy at this stage is due to the economic uncertainty following COVID-19, resulting in balance sheet pressure on the business. The creation of a Tier 1 P2X Hub in the region provides opportunity for the NSW Government to re-activate Origin's plans of adding the additional hydro capacity to their network, as the demand for the energy will come from the electrolysis plants required to produce hydrogen for a green steel facility amongst other applications.

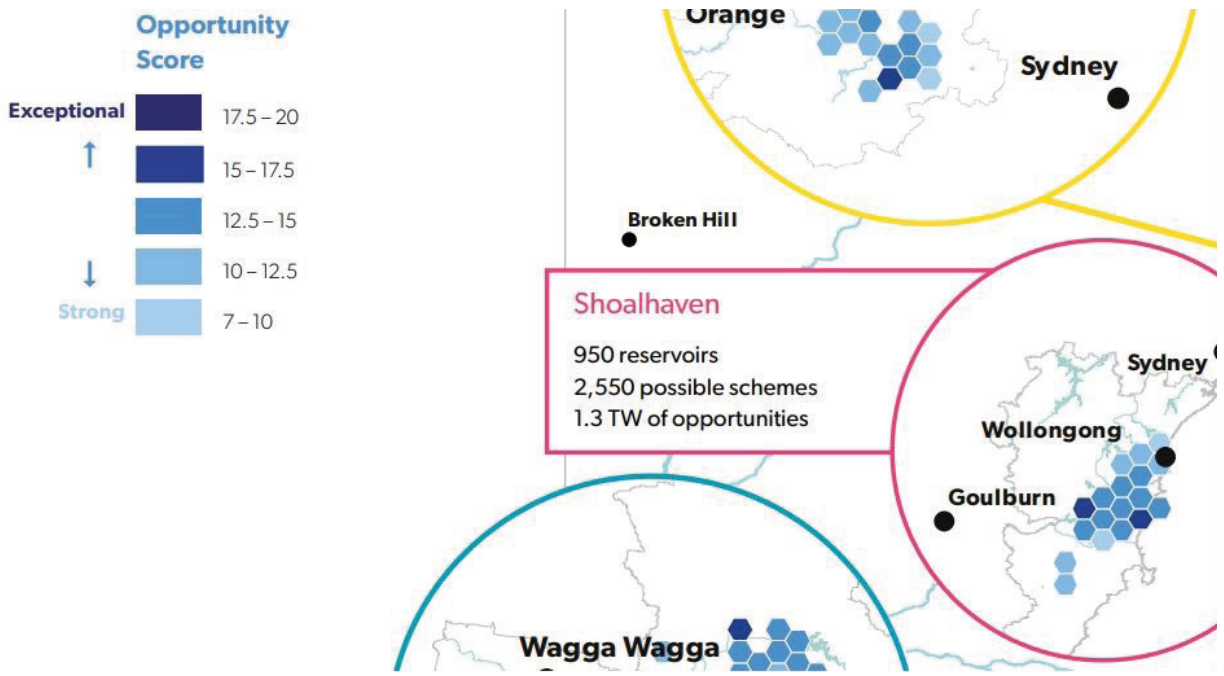
The NSW Government's 'Pumped Hydro Roadmap' identified a further untapped potential of 1.3 TW of hydro capacity if required in the Illawarra-Shoalhaven region (Figure 35).[157]

This untapped hydro capacity can be used to fulfill even BlueScope Steel's complete transition to renewable hydrogen and its long-term targets.

Access to Fresh Water to Produce Hydrogen:
Currently the Nepean and Shoalhaven systems support the water demands for the Illawarra-Shoalhaven region and are further supported by 6 water treatment facilities.[158] The Tallowa Dam is strategically positioned to enable any hydrogen production activities in the region as it is at 100% capacity (8.5 GL).[159]

If a large-scale secondary green steel facility (matching BlueScope's current scale for secondary steelmaking) is established in the region, this will require ~211 ML of water per year, which can be sourced from a combination of the Avon Dam (capacity of 147 GL, currently 83% full), Tallowa Dam as well as from recycled water from Wollongong wastewater treatment facility (capacity 15 ML/day) to reduce operational strain.[160] Note that desalianted seawater can also be used to support the P2X economy within this region to match future requirement.

Figure 35: Shoalhaven's hydro capacity opportunity.[145]



Opportunity Beyond 'Low-Carbon Steel' for Heavy Industry Decarbonisation in the Hunter Illawarra-Shoalhaven Region
Manildra Group has one of the world's largest wheat starch and gluten production plants in the world. The output from the Nowra facility are mainly used for the production of fast moving consumer goods (FMCG) products and paper industries.[161]

To maximise wheat feedstock utilisation, Manildra Group incorporated a biorefinery process to produce bioethanol. The Nowra facility produces 110 ML of bioethanol annually and is Australia's largest provider of bioethanol.[162] Currently, the ethanol consumers are spread across the food & beverage, pharmaceutical and transport fuel sectors.[163]

NSW Power to X (P2X) Industry Pre-Feasibility Study

Bioethanol production process: The residual starch from the core production process is converted into a slurry through the addition of water. The slurry is then heated up to break-down the slurry into smaller chains. Enzymes are used to convert the small chains into glucose, which is a simple sugar.[164] The sugar is the key feedstock that yeast uses to biologically convert into 'crude bioethanol', during the fermentation step. The output solution has a concentration of 10-15% bioethanol.[165] Manildra's 7 distillation columns are used to concentrate the bioethanol to 100% purity by dehydrating the solution using distillation.[165]

Carbon emissions from the ethanol production process:
The fermentation step during bioethanol production is a key source of carbon emissions. Current bioethanol studies have shown that 1.5 kg of carbon dioxide are emitted per litre of bioethanol.[166] Therefore, Manildra's bioethanol production facility is estimated to produce, 165 ktpa of carbon dioxide emissions.

A key P2X fuel Manildra can develop to valorise their carbon dioxide outputs is methanol. The process for producing 'low emission methanol' is described in **Section 3.5**, where carbon dioxide and 'green hydrogen' are reacted together to produce methanol. The Manildra site can produce ~120 ktpa of methanol, which can be sold as a value-added chemical product.

Increasing the reach of renewable electrons in NSW to generate methanol: NSW is home to one of Australia's largest biodiesel operations and one of the key chemicals used to synthesis biodiesel is methanol. The biodiesel production process consumes 20 kg of methanol per 100 kg of biodiesel synthesised.[167]

The transesterification process involves the conversion of methanol and vegetable oils into biodiesel and glycerine. The process usually has an 80% recovery rate for the methanol.

For instance, the Bioenergy Industries Australia facility in Northern NSW produces 20 ML of biodiesel a year, requiring a methanol demand of ~2.7 ktpa, a demand that can be met through Power-to-Methanol. This could be a great pilot initiative to start embedding 'low emission methanol' into the biodiesel supply chain.

Note: The viability and pre-feasibility assessments is performed for the low-carbon steel production case study, due to the scale of operation and socio-economic benefits for the NSW economy. The scale of the low-carbon secondary steel facility has been estimated based on the renewable generation capacity of Origin's expansion project (the project is currently on hold), as access to 'behind the meter' renewable energy is a key driver for green hydrogen economics and therefore impacts the feasibility of secondary steel. A ~230 kT/yr secondary steel facility can be developed in the Illawarra-Shoalhaven region and this facility will be capable of producing equivalent to ~60% of BlueScope's current secondary steel operations.

Viability Assessment for a Low-Carbon Steel production facility in the Illawarra-Shoalhaven Precinct

Table 3: Assessment of key drivers for Low-Carbon Steel Production.

Criteria	Status	Assessment
P2X product need	✓	Green hydrogen is required for low-carbon steel production
Heavy Industry to Off-take the P2X Product	✓	Green hydrogen is required for the reduction of iron ore to produce DRI, which can be blended with scrap steel to produce 'secondary steel'.
Renewable Resources in the Region	✓	Shoalhaven Scheme (hydro-powerplant) has the potential to further upgrade operations by 235 MW.
Renewable Energy Supplier for the 'P2X Hub'	!	Origin Energy has put a hold on the Shoalhaven Scheme expansion, due to the economic landscape, post May 2020. Note Illawarra REZ may provide electricity supply for this P2X hub.
Feedstock Availability - Water	✓	~124 ML/yr of water will be required to produce ~12 ktpa of hydrogen. The Tallowa Dam in Shoalhaven is suitably positioned to facilitate for this demand. The region can also source water from the ocean.

Pre-Feasibility Assessment for Low-Carbon Steel Production in Illawarra-Shoalhaven Region.

Table 4: Pre-feasibility assessment for producing low-carbon steel in Illawarra-Shoalhaven Region.

Pre-Feasibility Assessment to Service the Production of ~230 kT of 'Secondary Steel' p.a.	
Feedstock Requirements	
Constant	**Value**
Hydrogen Demand	**12 ktpa** (limited by current renewable generation capacity)
Energy Demand	1,298 GWhpa
Water Demand	124 MLpa
Hydro Power Plant Capacity Factor	37%
Hydro Power Plant Capacity	235 MW
Electrolyser Capacity Required	**84.5 MW**
'Grey Hydrogen' Procurement Price	A$2 kg^{-1}
'Blue Hydrogen' Procurement Price	The National hydrogen roadmap suggests cost of blue hydrogen (Steam methane reforming + CCS) to range between A$2.27 to 2.77 kg^{-1}, we assume an average cost of A$2.5 kg^{-1} for comparison.
Estimated 'Green Hydrogen' Procurement Price	**A$4.39 kg^{-1}**
Estimated Summary of Costs for P2X Technology	
Total Equipment CAPEX (Electrolyzer CAPEX of A$750/kW at 10 MW scale with 10% decrease in cost per 10-fold increase in capacity)	**A$51.7 million**
Total OPEX	**A$47.1 million pa**
Estimated Feasibility Outcome	
Current Price Differential Between 'Grey Hydrogen' and 'Green Hydrogen'	**A$2.39 g^{-1}**
Current Price Differential Between 'Blue Hydrogen' and 'Green Hydrogen'	**A$1.89 kg^{-1}**
Electricity Price Required for Project Feasibility	
Current Electricity Price	A$60 MWh^{-1}
Electricity Price Needed for 'Green Hydrogen' to be Competitive with 'Grey Hydrogen' in NSW for Secondary Steel facility	**A$4 MWh^{-1}** (@Electrolyser CAPEX of A$2,000 kW^{-1}) **A$11 MWh^{-1}** (@Electrolyser CAPEX of A$1,500 kW^{-1}) **A$18 MWh^{-1}** (@Electrolyser CAPEX of A$1,000 kW^{-1}) **A$21 MWh^{-1}** (@Electrolyser CAPEX of A$750 kW^{-1}) **A$25 MWh^{-1}** (@Electrolyser CAPEX of A$500 kW^{-1})
Electricity Price Needed for 'Green Hydrogen' to be Competitive with 'Blue Hydrogen' in NSW for Secondary Steel facility	**A$12 MWh^{-1}** (@Electrolyser CAPEX of A$2,000 kW^{-1}) **A$19 MWh^{-1}** (@Electrolyser CAPEX of A$1,500 kW^{-1}) **A$26 MWh^{-1}** (@Electrolyser CAPEX of A$1,000 kW^{-1}) **A$29 MWh^{-1}** (@Electrolyser CAPEX of A$750 kW^{-1}) **A$33 MWh^{-1}** (@Electrolyser CAPEX of A$500 kW^{-1})

5.4. Hunter Precinct

The Hunter region is NSW's largest regional economy with a revenue contribution of A$34.7 billion.[168] Hunter's economy is diversified across multiple sectors such as mining, advanced manufacturing, food processing and tourism.

The Hunter region hosts Australia's 3rd largest port, Port of Newcastle, which generates A$1.2 billion in revenue and supports ~8,000 jobs.[169] Port of Newcastle is the primary terminal for coal export to the Asian and Pacific markets.

The NSW government has introduced a 20-year strategic blueprint to promote economic growth in the region through investment in advance manufacturing, renewable energy and infrastructure.[170] A major part of this transition could possibly be driven by hydrogen and the NSW government has recently announced the establishment of a Hydrogen Hub in the region, as part of the $70 million hydrogen hub initiative for NSW.[171] These plans could see a revival of the region's steel industry and growth in ammonia generation. A report by Grattan Institute shows that a hydrogen-based ammonia and steelmaking industry can contribute up to tens of thousands of jobs in the region.[12]

Figure 36: A map of Hunter's existing export infrastructure.[172]

Key opportunity for P2X adoption in Hunter Region

The Hunter region provides the ideal scaffold for the mobilisation of a P2X economy due to the existing export supply chain through Port of Newcastle (**Figure 36**).

Orica's Kooragang Island facility in the Hunter region is one of Australia's largest ammonia production facilities, with an annual production rate of 360 ktpa of ammonia. As described in **Section 3.3**, ammonia presents a unique opportunity to embed P2X technologies into the global chemical supply chain.

Orica's facility currently uses ammonia for the production of ammonium nitrate, which is used as an industrial explosive for the mining and construction sector. Currently, Orica's sustainability report do not explicitly describe a requirement to transition to 'green ammonia' production for their ammonium nitrate business. However, 'green ammonia' presents a unique value proposition for Orica to produce a green commodity for global export.

This value proposition to generate renewable ammonia for export extends to new projects (as revealed by our stakeholder consultation), specifically targeting at the Asian market.

Overview of Ammonia Production Process

Orica uses the steam reforming technique to obtain hydrogen from natural gas.[54] The process commences with sulphur removal followed by the steam methane reforming process to produce hydrogen, carbon monoxide and carbon dioxide.

A shift convertor is then used to convert the effluent carbon monoxide and residual water into hydrogen and carbon dioxide, using the Fischer-Tropsch process which is described in the **Section 3.6**. This process ensures the maximisation of hydrogen production.

The gas that exits the reforming process needs to be stripped of carbon dioxide using an amine solution, as carbon dioxide has the potential to attack the catalyst used for the Haber-Bosch process.

The hydrogen that exits the reformer is compressed and mixed with compressed nitrogen to produce ammonia in the synthesis reactor. The stochiometric ratio of hydrogen to nitrogen is 3:1.[62]

Why should the NSW government develop a 'P2X Export Economy' in Hunter?

The Hunter region provides the ideal backbone for Orica and other industry stakeholders to mobilise a new value creation business through the development of a 'green ammonia' export network. Japan would be the ideal first customer to consume 'green ammonia', due to their forecasted ammonia demands in their 'Japanese Hydrogen Roadmap'. Japan requires 30,000 ktpa of ammonia from 2050 onwards.[173] Japan's ambition for this renewable ammonia is to blend it with coal in a ratio of 1:1 for power generation.

Introducing 10% 'green ammonia' into Japan's current ammonia imports, would provide the ideal first step in the development of an export relationship between NSW and Japan. A 10% blend of green ammonia with Japan's current ammonia demands, will result in ~20 kt of carbon emissions abated.[174,175] Japanese industries will be heavily incentivised by their government to purchase 'green ammonia', as it ensures embedding of low-carbon feedstock into their agricultural and chemical supply chains.

Japan currently imports 213 kt of ammonia p.a., which is sourced primarily from Indonesia. As an immediate milestone, 10% of that demand can be substituted with 'green ammonia', produced in the Hunter region, requiring ~3.8 ktpa of green hydrogen.

The Port of Newcastle can be the centre piece for this export network as existing shipping terminals for exports from NSW to Japan will be leveraged. In 2018, ~70% of Japan's thermal coal demand was provided by Australia with the Port of Newcastle being a 'crown jewel' port for thermal coal export.[176]

Potential Outcome of NSW's Government Support
The support of the NSW government in the development of this export economy will deliver the following benefits:

1. Creation of local jobs across the value chain.
2. Long-term establishment of an export relationship with Japan, which will foster recurring revenues into the government.

Feedstock Analysis for the Hunter Region
Access to cheap renewable energy will be a key driver in the development of this export economy. The 'P2X Hub' will require ~233 GWh p.a. of energy to produce ~3.8 kt of hydrogen.

The Bowmans Creek wind farm that is being built by Epuron (~300 MW wind farm with 60 wind turbines) can be used to meet the P2X energy needs of this precinct. 89 MW of wind capacity will be required to produce the hydrogen and the ammonia generation process will require an additional 122 MW of capacity. In total ~70% of the wind farm's capacity needs to be directed to Kooragang to produce the required ammonia.

Water Requirement
The Hunter region has three major dams that support the water demands in the region: Grahamstown, Tomago and Chichester. The dam closest to port facility is Tomago and it currently has a capacity of 54 GL. To produce ~3.8 kt of hydrogen ~37 ML (mega litres) of water will be required annually, which is 0.6% of the capacity. Note that there may be access to suitable wastewater stream from the Hunter water plant. Given the region's proximity to coast, it is also possible to use desalinated seawater in the future to support the P2X economy in the region.

Additional Opportunities for the Hunter Region
The Hunter region has a plethora of high-profile mining, mineral, steelmaking and smelting operations, that present an opportunity for decarbonisation using P2X fuels.

The BHP's Mount Arthur coal mine can transition to using fuel cell powered light and heavy mining equipment, which provide the same operational flexibility as fossil fuel equipment, however with no operational emissions. Anglo American which is one of the largest mining companies in the world is preparing to deploy a hydrogen powered mining truck in 2021.[177]

The introduction of an incentives program to pivot the like of BHP, Yancoal, Glencore, Centennial Coal, Peabody and Tomago operations from fossil fuel mining equipment to low-carbon alternatives powered by P2X fuels presents a great opportunity for the NSW Government to slowly transition the mining sector into a low-carbon economy.

Viability Assessment for the Development of an Export Hub in the Hunter Region

Table 5: Assessment of key drivers for a Hunter Region hydrogen export hub.

Criteria	Status	Assessment
P2X product need	✓	The NSW Government can assist a business such as Orica in the establishment of a 'green ammonia' export economy. As an immediate milestone 10% of Japan's current ammonia import demand is recommended. This will require ~21 kt of ammonia p.a.
Heavy Industry to Off-take the P2X Product	✓	Japan has expressed the desire to import 'green ammonia' in their 'National Hydrogen Roadmap' as a thermal fuel to blend with their power plants.
Renewable Resources in the Region	✓	Bowmans Creek Wind Farm is planned to be operational by 2025 and will have 300 MW of energy capacity. 70% of that capacity will be required to produce the 3.8ktpa of hydrogen required to produce ~21 kt of 'green ammonia' p.a.
Renewable Energy Supplier for the 'P2X Hub'	!	This data isn't publicly disclosed yet. Note: New England and Central West Orana REZs can provide renewable resources to this hub,
Feedstock Availability - Water	✓	38ML of water will be required to produce ~3.8 kt of ammonia. The Tomago Dam in Hunter is suitably positioned to facilitate for this demand. Note that access to seawater is also available for this region given proximity to coast.

Pre-Feasibility Assessment for the Development of an Export Hub in the Hunter Region to Transport Ammonia to Japan

Table 6: Prefeasibility assessment of a Hunter Region Hydrogen Export Hub.

Pre-Feasibility Assessment for the Development of an Export Hub in the Hunter Region to Transport Ammonia to Japan	
Feedstock Requirements	
Constant	**Value**
Hydrogen Demand	**3.8 ktpa**
Energy Demand	233 GWhpa
Water Demand	37.8 MLpa
Wind Farm Capacity Factor	30%
Wind Farm Capacity	235 MW
Electrolyser Capacity Required	**26.7**
'Grey Hydrogen' Procurement Price	A\$2 kg^{-1}
'Blue Hydrogen' Procurement Price	The National hydrogen roadmap suggests cost of blue hydrogen (Steam Methane Reforming plus CCS) to range between A\$2.27 to 2.77 kg^{-1}, we assume an average cost of A\$2.5 kg^{-1} for comparison.
Estimated 'Green Hydrogen' Procurement Price	**A\$4.98 kg^{-1}**
Estimated Summary of Costs for P2X Technology	
Total Equipment CAPEX (Electrolyzer CAPEX of A\$750/kW at 10 MW scale with 10% decrease in cost per 10-fold increase in capacity)	**A\$17.3 million**
Total OPEX	**A\$143.3 million pa**
Estimated Feasibility Outcome	
Current Price Differential Between 'Grey Hydrogen' and 'Green Hydrogen'	**A\$2.98 kg^{-1}**
Current Price Differential Between 'Blue Hydrogen' and 'Green Hydrogen'	**A\$2.48 kg^{-1}**
Electricity Price Required for Project Feasibility	
Current Electricity Price	A\$69 MWh^{-1} (@Wind LCOE at 30% capacity factor)
Electricity Price Needed for 'Green Hydrogen' to be Competitive with 'Grey Hydrogen' for a clean ammonia export facility in Hunter.	**A\$2 MWh^{-1}** (@Electrolyzer CAPEX of A\$2,000 kW^{-1}) **A\$10 MWh^{-1}** (@Electrolyzer CAPEX of A\$1,500 kW^{-1}) **A\$17 MWh^{-1}** (@Electrolyzer CAPEX of A\$1,000 kW^{-1}) **A\$21 MWh^{-1}** (@Electrolyzer CAPEX of A\$750 kW^{-1}) **A\$25 MWh^{-1}** (@Electrolyzer CAPEX of A\$500 kW^{-1})
Electricity Price Needed for 'Green Hydrogen' to be Competitive with 'Blue Hydrogen' for a clean ammonia export facility in Hunter.	**A\$11 MWh^{-1}** (@Electrolyzer CAPEX of A\$2,000 kW^{-1}) **A\$18 MWh^{-1}** (@Electrolyzer CAPEX of A\$1,500 kW^{-1}) **A\$25 MWh^{-1}** (@Electrolyzer CAPEX of A\$1,000 kW^{-1}) **A\$29 MWh^{-1}** (@Electrolyser CAPEX of A\$750 kW^{-1}) **A\$33 MWh^{-1}** (@Electrolyzer CAPEX of A\$500 kW^{-1})

5.5. Parkes Precinct

Parkes presents a multi-tiered opportunity for the development of a 'Tier 2 P2X Hub', as it is home to a thriving mining and agricultural sector. In addition, the emergence of a new 'freight hub' in the region, presents the ideal scaffold for development of a P2X synthetic fuels industry.

The development of a 'P2X Hub' in NSW addresses the key targets set by the NSW Government for the 'Special Activation Precinct', as a P2X economy will promote opportunities for job creation in rural NSW, incentivise private sector investment and promote state-wide decarbonisation.[36]

Parkes is situated in the heart of Central-West Orana, which is a 'renewable energy zone' (REZ).[178] The NSW government has established 5 major REZ's in the state to promote the adoption of clean energy into the transmission infrastructure to smoothen the transition from coal-fired power stations. This zone is expected to install 3 GW of renewable energy capacity over the next 5-10 years, prompting NSW to transition into a low-emission future. This access to cheap renewable electricity will be the foundation for a P2X economy in NSW.

Feedstock Analysis for the Parkes Region

Since majority of the REZ infrastructure is in the early stages of development, projects that are nearing completion will be used to design the 'base scenario' for the development of a 'Tier 2 P2X Hub' in Parkes.

The Suntop Solar Farm, which is being developed by Canadian Solar will be the ideal renewable energy asset to power a 'P2X Hub' as the energy generation potential is 395 GWh from a 189 MW solar farm.[179] The solar farm is expected to be operational from Q3 of 2021 with the full operation capacity being rolled out in the months following. If all of Suntop Solar Farm renewable energy is used for hydrogen production, ~6.4 ktpa of hydrogen can be produced in Parkes.

The production of 6.4 ktpa of hydrogen will require ~64 ML/yr of water, which can be sourced from the Lake Endeavour Dam, which currently has a capacity of 1.8 GL of water.[180] 4% of the Dam's capacity will be consumed annually to produce green hydrogen.

Parkes Shire Council however has strict mandates for water consumption, due to the drought concerns in the regions every decade. Therefore, a contingency plan need to be in place for potential procurement of water from the other 2 major water reservoirs in the region: Burrendong[181] and Wyangala dam[182], in the scenario that Lake Endeavour reaches critical levels. The dam is currently at 80% and has maintained that level in the recent history. Further to these sources, there are opportunities to access local saline aquifers for water feedstock.

'Tier 2 P2X Hub' Opportunity - Fuel for the Inland Rail

The NSW government has set a key target for Parkes to develop a 'National Logistics Hub', as Parkes provides the ideal interlinking opportunity for the east coast of Australia. Current projects that are underway in Parkes include the development of an 'inland rail' line from Melbourne to Brisbane. The inland rail line is being developed to shift the freight load, which is currently transported through road/highways.[183] The freight traffic between this region is expected to reach 32 million tonnes by 2030 and the business case created by ARTC (Australian Rail Transport Corporation) demonstrated, a 35-43% cost reduction by switching from road to rail.[183]

Diesel is the primary fuel used by the rail industry in Australia with a 1 billion litre consumption in 2012.[184] Dimethyl Ether (DME) is growing in consideration as a blending fuel with diesel. Existing diesel engines can be retrofitted to adopt DME blends of up to 13% with diesel.[185] The blending of DME provides combustion benefits as it reduces trace emissions such as SO_x and NO_x, which are a key pain point for the rail industry. In addition, the thermal efficiency of DME blends increases fuel efficiency.

DME is a key product that can be produced using methanol as an intermediate feedstock. The process for producing low emission methanol is described in **Section 3.5**, where carbon dioxide and 'green hydrogen' are reacted to produce methanol. The second step reaction involves the dehydration of methanol to produce DME. Current industrial processes foster these reactions in one process where a bifunctional catalyst is used for the reaction.[186]

Since the inland rail line is currently under construction, consumption data for this rail line is yet to be determined. Therefore, an estimated scenario will be developed using the table below:

Table 7: Key data used for the base case scenario for DME blending with diesel for the Inland Rail project.

Item	Amount
Average Train Fuel Efficiency (km/L)	0.06[187]
Inland rail distance for a round trip (km)	3400[188]
DME blend with diesel (%)	13
DME required per roundtrip (kg)	15.5
Methanol required to produce sufficient DME per roundtrip (kg)	25.4

In the base scenario, we assume that 10 trains will perform a round trip every 2 days using the new Inland Rail track or ~180 roundtrips per train will be performed annually. This will require ~28 tpa of DME, which will need ~45tpa of methanol (requiring ~9 tpa of H_2 and ~63 tpa of carbon dioxide). This will require a ~530 MWh of renewable energy for this project. This is a potential opportunity the NSW government can support for the slow decarbonisation of freight rail.

Tier 2 P2X Hub Opportunity - *Development of a Methanol Export Economy in NSW*

The development of a synthetic chemical export economy in Parkes could be an interesting application of P2X technologies. The production of methanol is a great agent for carbon capture and renewable energy coupling with the chemical synthesis industry. In Parkes ~34 ktpa of methanol can be produced using only the solar capacity from Suntop Solar. In addition, this allows for the valorisation of ~46.6 ktpa of carbon dioxide.

The methanol economy is steadily growing in the Asian markets with the key applications being the production of formaldehyde, acetic acid and more recently fuel blending with petroleum. Japan is increasing their consumption for 'green methanol' as an embedding agent for the decarbonisation of their chemical industry.[189] China is also another alternative option for the sale of 'green methanol' as they consumed 60% of the global methanol imports in 2020.[190] China imported ~12,000 kt of methanol in 2020. Considering recent trade conflict, a China-Australia trade relationship may not be the best launch pad for the P2X economy, but a downstream option.

P2X Hub Opportunity – *Hydrogen gas Blending for NSW's Gas Networks*

Hydrogen gas blending is growing in consideration globally as a sector coupling pathway to embed renewable energy into gas-based application. Natural gas-based power generation is used as a complimentary energy source to provide coverage for the intermittency issues associated with a renewable energy powered grid. Renewable assets such as solar and wind are only operational 15-40% of the year, so to hedge power demand, gas-based power generation is activated.

NSW consumed ~1,400 PJ of natural gas in 2020 and that consumption is expected to increase by ~3% over the next 10 years.[191] The blending of hydrogen with natural gas presents the opportunity for the NSW government to slowly decarbonise the gas grid network.

Studies are being performed globally to identify the upper and optimal blending limit for hydrogen and to understand the retrofitting required to run blended gas through existing gas infrastructure. In addition, blending hydrogen with natural gas presents an additional set of challenges, as natural gas is ~3x as energy dense as hydrogen by volume.

Furthermore, blend train infrastructure is required to homogenise the resultant gas blend to ensure thermal output is consistent.

3 hydrogen blending scenarios (5%, 10%, 15% of hydrogen) with natural gas will be used to calculate the feedstock requirements to facilitate a state-wide gas blending operation.

NSW currently consumes 37 GL/yr of natural gas (NG). Since, natural gas has a higher energy density by volume, the H2-NG blends will have a reduced higher heating value (HHV, i.e. the heat released from fuel combustion with original and generated water in a condensed state), hence a greater volume of the blended gas will be required for the same energy output. **Table 8**, demonstrates the variation in HHV for NG compared to the H_2-NG blends. **Table 9**, describes how NG consumption reduces by blending hydrogen.

Table 8: The higher heating values for 3 blend scenarios (5%, 10%, 15% of hydrogen) that can be adopted by the NSW government.

Gas	HHV (MJ/L)
Natural Gas	~0.038
Hydrogen Gas	~0.013
5% Hydrogen Gas Blend with 95% Natural Gas	~0.036
10% Hydrogen Gas Blend with 90% Natural Gas	~0.035
15% Hydrogen Gas Blend with 85% Natural Gas	~0.034

Table 9: The decrease in natural gas consumption and carbon emissions for the 3 hydrogen blend scenarios for the NSW Government.

Gas	Decrease in natural gas consumption
5% H_2 Gas Blend with 95% Natural Gas	~1.8%
10% H_2 Gas Blend with 90% Natural Gas	~3.6%
15% H_2 Gas Blend with 85% Natural Gas	~5.7%

Hydrogen blending for NSW in the 3 base case scenarios are currently not viable in Parkes, basing of the energy capacity demand, however through a decentralised model for hydrogen blending across the 5 REZs, hydrogen blending can be considered in the near future. The key feedstock required to embed green hydrogen into the gas networks is demonstrated in **Table 10**.

Table 10: Hydrogen and renewable energy demand required to facilitate state-wide gas blending in NSW.

Scenario	Hydrogen Demand (kt/yr)	Renewable Energy Capacity (GW)	Water Demand (GL yr^{-1})
5% Hydrogen Gas Blend with 95% Natural Gas	~173	~5.1	~1.7
10% Hydrogen Gas Blend with 90% Natural Gas	~359	~10.6	~3.6
15% Hydrogen Gas Blend with 85% Natural Gas	~558	~16.5	~5.6

Note: Blending green hydrogen into NSW's gas grid requires more careful feedstock analysis, specifically for water. Opportunity to use saline aquifer and wastewater will need to be explored in detail. In addition, the current plans for the REZs will not be sufficient to produce green hydrogen at the required scale. Therefore, Viability and Pre-Feasibility Assessments will only be performed for the 'Inland Rail' and 'Methanol Export Economy case studies.

Production of P2X Fuel for Inland Rail Consumption in Parkes Viability Assessment

Table 11: Key drivers for producing P2X Fuel in Parkes.

Criteria	Status	Assessment
P2X product need	✓	DME can be utilised up to a blend volume of 13% with diesel for rail application. DME is a by-product of methanol.
Heavy Industry to Off-take the P2X Product	✓	The 'Inland Rail' that is currently under construction for freight transport from Melbourne to Brisbane is a potential off-take scenario for blended fuel produced from P2X technologies. The current base scenario is designed to facilitate a fleet of 10 trains (each train making 180 roundtrips in a year).
Renewable Resources in the Region	✓	The Suntop Solar Farm which is under construction in Parkes is the ideal solar provider for the project. The project will only require ~530 MWh of solar energy.
Renewable Energy Supplier for the 'P2X Hub'	!	*A partner is needed to connect the energy supplier with the project.
Feedstock Availability - Water	✓	The project will require ~90 ML/yr of water which can be sourced from Lake Endeavour Dam which has a capacity of 1.8 GL.

NSW Power to X (P2X) Industry Pre-Feasibility Study

Pre-Feasibility Assessment for Production of P2X Fuel for Inland Rail Consumption in Parkes

Table 12: Prefeasibility Assessment of P2X Fuel generation at Parkes.

Pre-Feasibility Assessment for Production of P2X Fuel for Inland Rail Consumption in Parkes	
Feedstock Requirements	
Constant	**Value**
Hydrogen Demand	**9 tpa**
Energy Demand	530 MWhpa
Water Demand	90 ML pa.
Solar Power Plant Capacity Factor	24%
Solar Power Plant Capacity	189 MW
Electrolyser Capacity Required	**60 kW**
'Grey Hydrogen' Procurement Price	A$2 kg^{-1}
'Blue Hydrogen' Procurement Price	The National hydrogen roadmap suggests cost of blue hydrogen (Steam methane reforming + CCS) to range between A$2.27 to 2.77 kg^{-1}, we assume an average cost of A$2.5 kg^{-1} for comparison.
Estimated 'Green Hydrogen' Procurement Price	**A$4.46 kg^{-1}**
Estimated Summary of Costs for P2X Technology	
Total Equipment CAPEX (Electrolyzer CAPEX of A$750/kW at 10 MW scale with 10% decrease in cost per 10-fold increase in capacity)	**~A$60,000**
Total OPEX	**A$0.014 million p.a.**
Estimated Feasibility Outcome	
Current Price Differential Between 'Grey Hydrogen' and 'Green Hydrogen'	**A$2.26 kg^{-1}**
Current Price Differential Between 'Blue Hydrogen' and 'Green Hydrogen'	**A$1.96 kg^{-1}**
Electricity Price Required for Project Feasibility	
*Current Electricity Price	57 MWh^{-1} (@Solar LCOE at 24% capacity factor)
Electricity Price Needed for 'Green Hydrogen' to be Competitive with 'Grey Hydrogen' for a P2X based refuelling facility in Parkes.	**Not Achieved** (@Electrolyzer CAPEX of A$2,000 kW^{-1}) **A$3 MWh^{-1}** (@Electrolyzer CAPEX of A$1,500 kW^{-1}) **A$12 MWh^{-1}** (@Electrolyzer CAPEX of A$1,000 kW^{-1}) **A$17 MWh^{-1}** (@Electrolyzer CAPEX of A$750 kW^{-1}) **A$22 MWh^{-1}** (@Electrolyzer CAPEX of A$500 kW^{-1})
Electricity Price Needed for 'Green Hydrogen' to be Competitive with 'Blue Hydrogen' for a P2X based refuelling facility in Parkes.	**Not Achieved** (@Electrolyzer CAPEX of A$2,000 kW^{-1}) **A$11 MWh^{-1}** (@Electrolyzer CAPEX of A$1,500 kW^{-1}) **A$21 MWh^{-1}** (@Electrolyzer CAPEX of A$1,000 kW^{-1}) **A$26 MWh^{-1}** (@Electrolyzer CAPEX of A$750 kW^{-1}) **A$31 MWh^{-1}** (@Electrolyzer CAPEX of A$500 kW^{-1})

Development of a Methanol Export Economy in Parkes Viability Assessment

Table 13: Key drivers for producing Methanol Export Economy in Parkes

Criteria	Status	Assessment
P2X product need	✓	Methanol is used as a base feedstock for the chemical synthesis of formaldehyde and acetic acid. The demand for 'low emission methanol' is growing in demand as a base feedstock for chemical industry decarbonisation.
Heavy Industry to Off-take the P2X Product	✓	Methanol is growing in demand in the Asian markets as a base feedstock for chemical synthesis. Japan is a key consumer of 'low emission' methanol and China is the largest exporter of methanol globally.
Renewable Resources in the Region	✓	The Suntop Solar Farm which is under construction in Parkes is the ideal solar provider for the project. The 189 MW solar farm will allow for the production of ~34 ktpa of methanol which is 0.28% of China's annual methanol imports.
Renewable Energy Supplier for the 'P2X Hub'	!	* A partner is needed to connect the energy supplier with the project.
Feedstock Availability - Water	✓	The project will require 64 ML/yr of water which can be sourced from Lake Endeavour Dam which has a capacity of 1.8 GL.

Development of a Methanol Export Economy in Parkes Pre-Feasibility Assessment

Table 14: Prefeasibility Assessment of Methanol Export Economy in Parkes

Pre-Feasibility Assessment for Development of a Methanol Export Economy in Parkes	
Feedstock Requirements	
Constant	**Value**
Hydrogen Demand	**6.4 ktpa**
Energy Demand	395 GWhpa
Water Demand	64 MLpa
Solar Power Plant Capacity Factor	24%
Solar Power Plant Capacity	189 MW
Electrolyser Capacity Required	**45 MW**
'Grey Hydrogen' Procurement Price	A$2 kg^{-1}
'Blue Hydrogen' Procurement Price	The National hydrogen roadmap suggests cost of blue hydrogen (Steam methane reforming + CCS) to range between A$2.27 to 2.77 kg^{-1}, we assume an average cost of A$2.5 kg^{-1} for comparison.
Estimated 'Green Hydrogen' Procurement Price	**A$4.22 kg^{-1}**
Estimated Summary of Costs for P2X Technology	
Total Equipment CAPEX (Electrolyzer CAPEX of A$750/kW at 10 MW scale with 10% decrease in cost per 10-fold increase in capacity)	**A$28.4 million**
Total OPEX	**A$24.0 million pa**
Estimated Feasibility Outcome	
Current Price Differential Between 'Grey Hydrogen' and 'Green Hydrogen'	**A$2.22 kg^{-1}**
Current Price Differential Between 'Blue Hydrogen' and 'Green Hydrogen'	**A$1.72 kg^{-1}**
Electricity Price Required for Project Feasibility	
Current Electricity Price	57 MWh^{-1} (@Solar LCOE at 24% capacity factor)
Electricity Price Needed for 'Green Hydrogen' to be Competitive with 'Grey Hydrogen' in NSW for Methanol export in Parkes	**A$3 MWh^{-1}** (@Electrolyzer CAPEX of A$2,000 kW^{-1}) **A$11 MWh^{-1}** (@Electrolyzer CAPEX of A$1,500 kW^{-1}) **A$18 MWh^{-1}** (@Electrolyzer CAPEX of A$1,000 kW^{-1}) **A$21 MWh^{-1}** (@Electrolyzer CAPEX of A$750 kW^{-1}) **A$25 MWh^{-1}** (@Electrolyzer CAPEX of A$500 kW^{-1})
Electricity Price Needed for 'Green Hydrogen' to be Competitive with 'Blue Hydrogen' for Methanol export in Parkes	**A$3 MWh^{-1}** (@Electrolyzer CAPEX of A$2,600 kW^{-1}) **A$11 MWh^{-1}** (@Electrolyzer CAPEX of A$2,000 kW^{-1}) **A$19 MWh^{-1}** (@Electrolyzer CAPEX of A$1,500 kW^{-1}) **A$29 MWh^{-1}** (@Electrolyzer CAPEX of A$750 kW^{-1}) **A$32 MWh^{-1}** (@Electrolyzer CAPEX of A$500 kW^{-1})

NSW Power to X (P2X) Industry Pre-Feasibility Study

5.6. Other Opportunities

5.6.1. Emerging Technology Precincts in Rural NSW

NSW benefits from a rich culture of innovation in the P2X ecosystem as seen in **Section 4**. Many of these technologies are on the brink of commercialisation and will commence to embed into the domestic market over the course of the next decade.

NSW's rural economy provides the ideal launchpad for these businesses to blossom. This is because key cost centres for emerging technologies such as land lease and labour in rural NSW is far more economical than metropolitan cities.

The NSW government can orchestrate an inter-linking opportunity that incentivises rural industries to adopt/support emerging P2X technologies and to ensure these emerging industries re-locate to rural NSW.

Agricultural Wastewater to Clean Energy in Riverina Region

SwitcH2 is rapidly scaling up operations to deploy a commercial wastewater electrolysis system in the market by 2024. The start-up is uniquely placed to valorise a key cost centre for many agricultural industries, through the conversion of their wastewater into hydrogen, enabling the development of a circular economy.

'Circular hydrogen' presents a unique opportunity for the agricultural sector, as it disrupts the intermittency limitations for 'renewable electrons'. In an agricultural setting, excess solar can be converted into hydrogen, which can be used as the base fuel for fuel cell powered vehicles (tractors, trucks and forklifts), thermal fuel for boilers or energy storage. This provides the agricultural sector with a 'unique hedge' against fluctuating grid electricity and gas prices, as these farms can now go 'off-grid'. For NSW this presents a great option for grid load management and wastewater treatment.

An area that can be a great prospect to launch switcH2 and HydGene Renewables (including other startups) is the Riverina and Wagga Wagga/Moree special activation precinct which has industries such as vineyards, sugarcane, rice and vegetable farms, which provides the ideal feedstock for wastewater electrolysis technology. The region consumed 220 GL of wastewater in 2018/19. Assuming a 75% consumption/recycle rate, this is sufficient for the production of ~2,750 ktpa of hydrogen.

Innovation Coupling to Support a Reverse Supply Chain:

The coupling of renewable hydrogen generation with LAVO's metal hydride storage technology or Ardent's underground storage technology can enable large scale hydrogen storage. This will be a key piece of the puzzle for the creation of a 'reverse energy/chemicals supply chain' for NSW.

This is an exciting prospect for the agricultural sector as traditionally the industry is viewed as a 'net consumer of resources', hence the valorisation of wastewater to produce hydrogen, will enable that equation is reversed.

The coupling of LAVO's metal hydride or Ardent underground storage solution with renewable hydrogen generation will ensure the maximisation of 'circular hydrogen' utilisation. Both LAVO/Ardent present a disruptive alternative to traditional storage pathways.

- LAVO's technology allows for energy storage footprint maximisation,
- Ardent minimises storage costs for hydrogen.

Note that these business models are not restricted to technologies covered within this study.

Hydrogen the 'hedge' against overflowing grids in NSW

Emerging P2X technologies can be mobilised in the development of 'decentralised hubs' with systems that are <500 kW. These systems have quite versatile functionalities, which mean various feedstock profiles can be used for operation, this will be pivotal in re-directing surplus renewables to produce 'circular hydrogen'. The complementary use of these systems with smart meters will ensure the energy operator dictates when the systems should be operational, and the intent will be for these assets to be owned and operated by local governments. These hubs can be scattered throughout NSW in regions with significant surplus renewables.

The hydrogen that is produced can then service the local government's energy needs such as low-carbon mobility fleets (i.e. buses) or localised gas blending. This project could be pivotal in assisting the NSW government tackle grid management issues in the long run (such as supply matching) whilst allowing for deep-rooted decarbonisation opportunities.

Carbon dioxide valorisation for methane production

APA Group and Southern Green Gas have developed a solution to valorise rich carbon dioxide emissions streams for industries such as cement, mining and food processing into synthetic methane. Their process is able to directly convert carbon dioxide from the air into methane.

The technology is currently being tested at scale to generate 27 ML/yr of synthetic methane. The plant will be installed at the Wallumbilla Gas Hub in Queensland, for injecting the methane into the existing gas network.

The successful scale-up of this technology will allow for the creation of a 'decentralised low-carbon loop' for industries that face difficulty in reducing their carbon footprint.
The thermal fuel industry is a key sector where the transition away from natural gas is still posing economical constraints. Therefore, the use of a 'decentralised low-carbon loop' bares merit as an intermediate step in NSW's transition to a zero-emission economy in the coming years. Industries such as the dairy and pet foods industries in central-west Orana are an ideal short-medium term market for this emerging solution.

Additional Opportunities

Technologies such as HERO, present a unique opportunity to accelerate the transition away from fossil fuels by increasing the combustion efficiency for hydrogen. The technology will play an increasing role in the long-term decarbonisation of NSW's thermal fuel industry. The mining sectors in NSW presents the ideal region for the scale-up and embedding of this technology in the long-term.

UNSW's hybrid ammonia technology in the mid-term will accelerate the migration from centralised to decentralised ammonia production. The current feasibility limitations of the Haber-Bosch process at small scale, presents a great hurdle for the ammonia industry. Further advancements in efficiency optimisation and scale-up of UNSW's hybrid ammonia technology will ensure further penetration of 'renewable electrons' for NSW.

The scale-up and embedding of these technologies in NSW, will establish NSW as a market leader in P2X technologies. Therefore, enabling NSW to become a 'beacon' for clean energy innovation, resulting in recurring revenue for the government and ensuring job creation remains in local markets.

5.6.2. Biomass to Renewable Hydrogen Opportunity in Northern NSW Region

The Northern Rivers region of NSW encompasses the catchments and fertile valleys of Clarence, Richmond and Tweed rivers, extending from Tweed Heads in the north (adjacent to the Queensland border) to the southern extent of Clarence river catchment. Home to a population of ~300,000 and an economic activity of $32 billion, the region boasts 107,411 jobs.

Within the region, Cape Byron Management (CBM) operates two, 30 MW biomass power stations at Condong and Broadwater in the Northern Rivers district of New South Wales producing 350 GWh of electricity annually, supporting local industries including agriculture, fisheries and tourism.

The power plants are attached to the local sugar mills and provide year-round, baseload electricity to the National Energy Market (NEM). During the sugar season, the plants, in addition to electricity provided to the NEM, provide intermediate and low-pressure steam to the two mills for use in their processing of sugar. CBM's provision of power and steam to the two local sugar mills is critical for the local sugar industry and the associated 2,500 jobs.

CBM is exploring the feasibility of producing green hydrogen from biomass with the goal of demonstrating the ability to utilise this hydrogen as a mobility and logistics refuelling option in the regional area. The plants are located on major transport and industrial routes. This would assist in expanding the available network of hydrogen for use in transport across NSW by providing a key refuelling option in the Northern Rivers precinct. Businesses such as Hiringa Pty Ltd in New Zealand are currently demonstrating the feasibility of similar projects, to support commercial, industrial and agricultural routes across New Zealand.

The CBM trial sites present an excellent opportunity to develop a model for smaller scale hydrogen production units across NSW regions and shires. The current trial focus on biomass but also allows for investigations into a wide variety of fuels, including waste streams, to be the power source for green hydrogen. This project will assist in opening up opportunities for other council districts to take advantage of the developed technology and their biomass options, including household refuse, landfill gas and green waste, to be utilised in hydrogen production, supporting a state-wide transport network, and potentially reducing landfill waste.

5.6.3. Opportunities in Port Botany

The Botany Industrial Park is a major location for the NSW petrochemical industry, operating on the northeastern side of Botany Bay in Banksmeadow, adjacent to Port Botany. Today, the main industrial businesses operating at the park are Qenos Pty Ltd, Indorama Ventures Oxides Australia Pty Ltd and IXOM Ltd. Other minor operators at the site include Air Liquide Australia Ltd and Elgas Ltd.[192]

Existing Operations

Qenos is Australia's largest plastics manufacturer and their facility at Port Botany produces olefins, manufacturing around 290 ktpa of ethylene from ethane piped to Botany Bay by the Moomba to Sydney Ethane Pipeline.[193] At Moomba, South Australia, Santos processes natural gas, separating ethane from other constituents for transport over the 1,375 km pipeline.[194] Subsequently, processes such steam cracking, further treatment and fractionalization are then undertaken to produce ethylene at the Botany site.[194] This ethylene is subsequently used to produce either Alkathene® or Alkatuff®, transported to the Indorama Ventures Oxides Australia plant for ethylene oxide production or transported to Port Botany for export.[194]

Overall, 88 ktpa of LDPE (Alkathene®) is manufactured using a high-pressure autoclave process.[193] Further, 100 ktpa of linear low-density polyethylene (LLDPE) and HDPE, which combined make Alkatuff®, are produced using the Unipol™ Gas Phase Process.[194,195] Qenos is also responsible for the provision of utilities for the Botany Industrial Park. Two coal-fired boilers and a natural gas-fired boiler are onsite for the production of steam. Also, cooling water and effluent treatment are provided for other occupiers.[196] Electricity is imported from offsite.

The Indorama Ventures Oxides plant takes ethylene produced by the Qenos plant and oxygen sourced from Air Liquide, feeding this to a 40 ktpa ethylene oxide plant.[197,198] The carbon dioxide produced in the manufacture of ethylene oxide is transported to Air Liquide and BOC for use. The ethylene oxide is then used as a feedstock, reacted with water to produce 16,000 tpa of ethylene glycol.[197] The ethylene oxide is also reacted with alcohol to produce 5,000 tpa of glycol ethers.[197] Additionally, ethylene oxide is reacted with fatty organics to produce 35,000 tpa of non-ionic surfactants.[197] Other specialty chemicals are subsequently produced with these range of chemicals as inputs, with the plant manufacturing over 300 products.[198]

The final major operator at the site is IXOM. In 2015, IXOM separated from Orica to become a stand-alone company. The IXOM Botany ChlorAlkali facility produces 31 ktpa of chlorine, from the electrolysis of brine from seawater, using mercury-free membrane technology.[199,200] The hydrogen, produced as a byproduct from electrolysis, is combined with chlorine in an HCl burner to produce 55,000 kLpa of hydrochloric acid.[199] Chlorine is reacted with iron and ferrous chloride to produce 21,200 tpa of ferric chloride.[199] Caustic and Sodium Hypochlorite are produced at 36,000 tpa.[199]

Role of P2X to Decarbonise Botany Industrial Park

Existing operations at the Botany Industrial Park are unsustainable in the long run. The chemical industry at the site is heavily reliant upon petrochemicals as the base feedstock for production, as well as provision of site utilities. Fossil fuel-based ethane is a core feedstock for products produced at the site, while coal and natural gas are the crucial source of heat energy for steam production. Estimates suggest that 0.3 tonnes of CO_2 are emitted per tonne of site product.[198] This represents a halving from 1996 as process efficiencies improved, however, significant progress must be made to transition the industry going forward.[198]

Currently, the fuel used in the furnaces and boilers accounts for over 90% of total energy consumption and onsite greenhouse gas emissions by Qenos.[201] In particular, it is estimated that Qenos's natural gas consumption for energy, excluding the ethane used for ethylene production, is 8 PJ annum^{-1} for the combined Altona (205 ktpa) and Botany Bay sites (290 ktpa) in 2015.[193,202]

Conservatively assuming the natural gas use of each site is split proportionately to the ethylene production capacity, 4.69 PJ p.a. would be required for the total utilities at the Botany Industrial Park. Using the heating value of natural gas and density of hydrogen, an estimated 9,600 tpa of hydrogen would be required to completely replace the natural gas energy source. It should be noted, further hydrogen could be used to replace the coal-based boilers and renewable electricity would be required to further reduce emissions.[201]

Port Botany Renewable Hydrogen Export Opportunities

In May 2021, Port Botany handled imports of chemicals totaling 9,141 twenty-foot equivalent units (TEU), with exports of 2,304 TEUs, representing 90% of NSW's bulk chemicals.[203] Port Botany is home to 2 bulk liquid berths, currently used for handling refined oil, gas, chemicals and bitumen.[204] The precinct handles 5.5 million kL of bulk liquids and gas annually.[204] This contains direct pipeline access to the nearby industrial precinct as well as storage facilities, including the Elgas cavern which has a capacity of 65,000 tonnes of LPG.[205] There is also railway access to and from the port.[204]

Consequently, Port Botany has potential as a hydrogen-based export hub. However, significant adjustments would need to be made to existing port infrastructure and the adjacent industry to facilitate this. For example, for direct export of liquid hydrogen, liquefaction facilities and cryogenic infrastructure would need to be constructed. Furthermore, the existing Moomba to Sydney Pipeline can be connected to a green hydrogen source. Alternatively, blue hydrogen facilities in Moomba, South Australia, would need to be constructed to provide the hydrogen.[206] Furthermore, for liquid hydrogen carriers such as ammonia and methanol, new onsite industrial processes would be required for their production. These changes would bring new environmental and safety threats to Botany Bay area, and, consequently, the high population density near Port Botany may make this a less desirable hub location.

Alternatively, transitioning the existing infrastructure and industry to handle hydrogen as both a feedstock and fuel could aid significantly in the decarbonisation of the Botany Industrial Park. However, to maintain the existing product range, costly alterations to existing facilities with new and innovative technologies would be required.

6. Roadmap for the Deployment of NSW Power-to-X Eco-Precincts

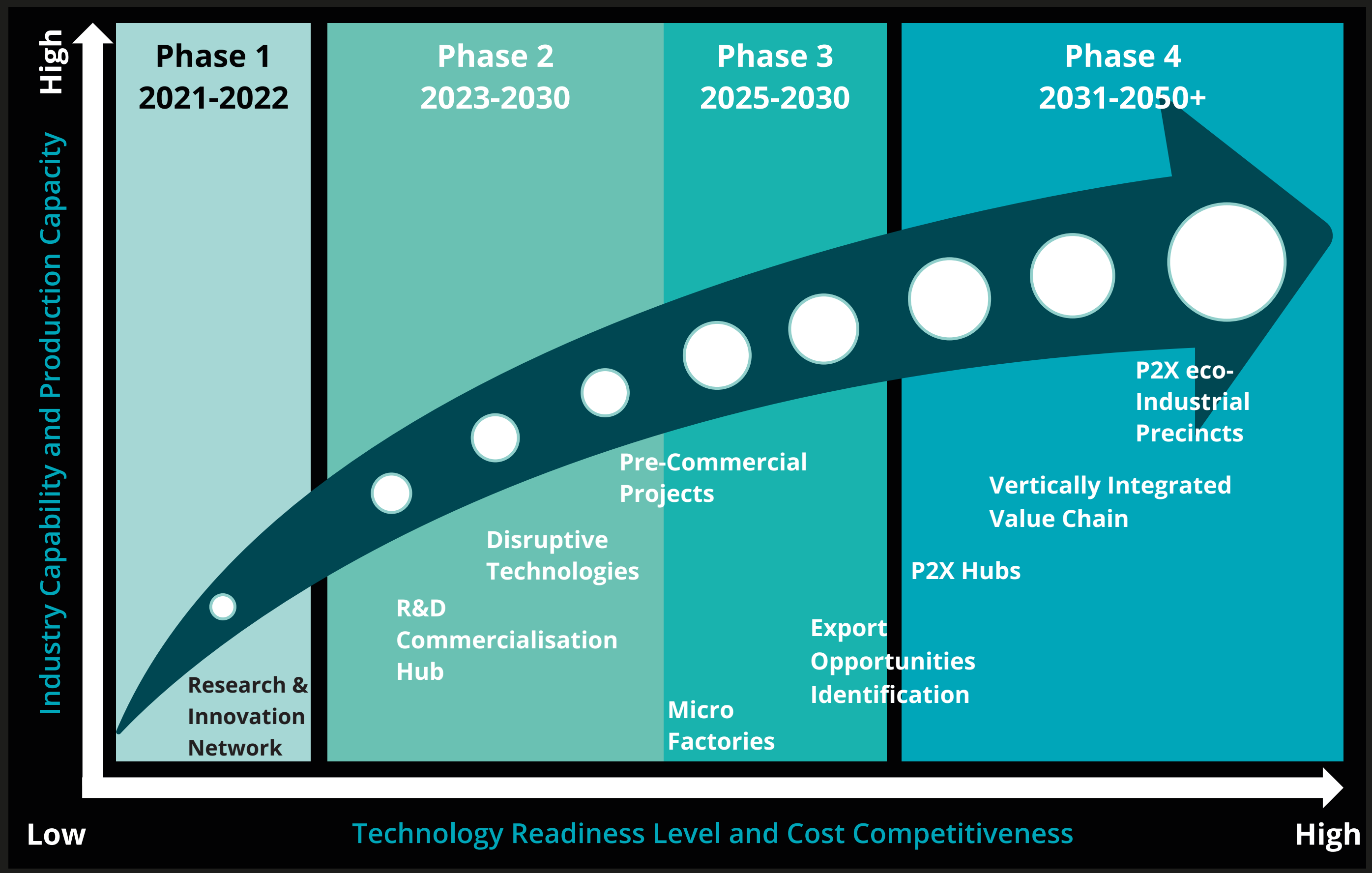
NSW Power to X (P2X) Pre-Feasibility Study

6.0 Roadmap for the Deployment of NSW Power-to-X Eco-Precincts

NSW has a strong business case to establish a P2X Economy in realising the enormous economic and environmental benefits. The state is well positioned to lead the P2X industrialisation, having all the essential ingredients of success. The scenarios analysis in **Chapter 5** presented NSW's potential in building multiple P2X Hubs. These P2X Hubs will have industry scale production capacity to supply domestic demand and export to global market. The materialisation of these P2X Hubs will not happen in the short-term, their development will need to follow the technological pathways and take necessary steps of capability and capacity building over time.

Guided by findings from the pre-feasibility study and insights from stakeholders, a four-phase roadmap is proposed with sequential steps to develop a future NSW P2X economy. The roadmap adopts the P2X technological pathways commencing with collaboration and collective efforts in R&D, through technology commercialisation and demand aggregation phase, and eventually reaching critical mass with the wide technology adoption by industry as bankable assets. The roadmap is demonstrated in **Figure 37** and steps under each phase are explained in detail below.

Figure 37: A Roadmap for NSW P2X Economy in NSW.



Phase 1 (2021-2022): Collaboration and Knowledge Sharing

1 Formalising a NSW P2X Research & Innovation Network that acts as the central coordinator for collaborative efforts from industry, research and government in technology advancement.

Research and Innovation Networks are communities, physical and virtual spaces and/or clusters of research, development and commercialisation expertise that support and coordinate innovation. Typically, new innovation networks are established to tackle emerging problems and provide an independent forum for capacity building and collaborative efforts. Successful innovation networks deliver tangible outputs, such as accelerating the commercialisation and uptake of innovative technologies and services, creating new partnerships between parties with shared interests, providing evidence-based and practical advice to industry and government, attracting private and public investment, and creating economic, social and environmental benefits.

NSW Government has adopted the model of research and innovation networks in areas that NSW has strong R&D capabilities and is of strategic importance for new industry development. For instance, the Office of NSW Chief Scientist & Engineer has set up innovation networks in advanced sensing, defence and circular economy and NSW Department of Planning, Industry and Environment has established research hubs in bushfire, energy efficiency and climate change. Some mature networks have demonstrated their success in coordinating R&D and attracting significant investment to NSW. For example, the Defence Innovation Network attracted over $22 million R&D investment to NSW innovation ecosystem by leveraging a $3.5 million funding from the NSW Government.[31]

A NSW P2X Research & Innovation Network can accelerate the technology pathways by providing the organisational platform to bring stakeholders and interested groups together. Through such a platform, technology inventors and industry end-users can collaborate to develop solutions to address both discrete and systematic barrier for the technology development and industry transformation. The Network will provide the opportunity for a wide variety of 'problem owners' in industry and government to collaborate with a wide variety of 'problem solvers' including other businesses, entrepreneurs, researchers, thought leaders, scientists, engineers, investors and policy makers. These collaboration and coordination services offered by the Network can accelerate the technology pathways to deliver impactful, practical and even disruptive P2X technologies for the future industries. Knowledge sharing and information communication through formal and informal channels provided by the Network could maximise the benefits of investment in R&D by stakeholders.

During the consultation for the pre-feasibility study, NSW P2X stakeholders pressed strong interest for collaboration and partnerships in the technology development and capability building in NSW. To seize the momentum, a consortium (NSW_{P2X}) was initiated with more than 40 members (**Appendix D**) and the network is growing. Current members are from Commonwealth and NSW State Government agencies, local industries including startups and SMEs, NSW research and technology inventors, global P2X supply chains, multinationals, and NGOs. The NSW_{P2X} Consortium has formed membership foundation for the NSW P2X Research & Innovation Network. The Network could be formalised with clear objectives, a robust governance structure and measurable deliverables for effective operation and sustainable growth in the long-term.

Phase 2 (2023-2030): Technology R&D and Commercialisation

2 Establishing a P2X R&D Commercialisation Hub that provides research infrastructure, expertise and resources to technology inventors and end-users for commercialisation-driven R&D projects.

Research equipment, facilities, infrastructure are vital for technology development and commercialisation. These 'hardware' capabilities are essential for researchers and innovators to translate fundamental research into pre-commercial projects. Investment in new research infrastructure for P2X is necessary to deliver the research excellence needed for the future P2X industries. This will equip technology inventors with the facilities to prototype, pre-manufacture, assess and validate their R&D results. The knowledge and data generated through these pilot and pre-commercialisation trials can de-risk the technology industrial translation from financial and technical perspectives. Research facilities will employ and train engineers, scientists, technicians, financial controllers and project managers. This highly skilled and specialised workforce will have adequate experience and expertise to work on industrial projects in P2X areas, building up the state's capability. Further, high quality and accessible research infrastructure is vital to boost NSW's P2X capability in attracting international players across the P2X value chains and institutional investors to the state. Investment made in research infrastructure could lay the foundation for long-term industry-research-government partnerships to deliver further collaboration in P2X industry development. The establishment of the R&D Commercialisation Hub will be benefited from the matured collaboration and partnership through the P2X Research & Innovation Network.

3 Investing in locally invented P2X technologies that have the potential to accelerate the technological pathway and disrupt the global value chain.

The incubation period for deep technology is rather long and generally over 30 years for clean technologies. The International Energy Agency (IEA) stated in their Net Zero by 2050 report *that most of the clean technologies for emissions reduction through 2030 are already commercialised and on the market today*. But to achieve net zero targets by 2050 or before, almost half of the decarbonisation need to come from new technologies such as P2X that are currently at their early demonstration or prototype phase. This brings the need of both public and private investment to accelerate the R&D development for P2X. NSW has strong P2X R&D capabilities where many technologies have gone through the knowledge accumulation and fundamental research phase. Targeted investment in P2X technologies in their development and demonstration phase (i.e. Technology Readiness Level (TRL) between TRL3 – TRL6) could deliver accelerated incubation and bring forward commercialisation timeline for early industry adoption. As identified in **Chapter 4**, NSW and Australia have disruptive P2X innovation that could potentially change the landscape of global powerfuels and clean chemical market. Once commercialised, these disruptive technologies will create new products, services and customers across the value chains. This presents NSW the opportunity to invest in locally invented disruptive P2X technologies that could potentially displace established market-leading technologies and firms. The R&D Commercialisation Hub will support the development of these disruptive P2X technologies with research infrastructure, expertise and resources.

4 Deploying pre-commercialisation project such as feasibility studies and demonstration projects to pave the wave for early technology adoption and deployment at industry scale.

As highlighted in **Section 3** and **Appendix A**, there are a number of projects underway in NSW (and worldwide) in the P2X domain, including demonstration projects and feasibility studies. Feasibility studies could de-risk investment decisions through initial assessment on P2X technical and economic viability for technology end-users. The deployment of demonstration projects will translate the P2X technologies from controlled laboratory environment to real industry conditions. These pre-commercialisation projects could test, validate and improve these P2X technologies for their commercial adoption. Essential data and knowledge will be generated for full-scale industry projects in technical and financial aspects as well as preparing the social license to operate. The deployment of these projects will be benefited from established partnership, infrastructure and early investment provided through the P2X Research and Innovation Network and R&D Commercialisation Hub.

NSW Power to X (P2X) Pre-Feasibility Study

Phase 3 (2025-2030): Market Preparation

5 Deploying decentralised micro-manufacturing facilities for small scale P2X production in meeting local demand.

The first wave of adoption of P2X in NSW on a commercial scale are anticipated to be small-scale and decentralised projects. Building on pre-commercialisation projects under Phase 2, these projects are relatively small in production scale, most likely in <10MW in terms of electrolyser capacity, to meet local demand of power fuels and clean chemicals. Their geographically dispersed nature makes these projects ideally positioned to supply remote mining and agriculture operations in replacing their current demand for fossil fuels that come with transportation costs. The modularity and mobility design could enable these micro-production facilities moving their operations following demand and being flexible in production. These projects have less logistic requirement, low demand in feedstock, minimum impacts to environment due to their small scales. This means they could fast-track approval process, shorten construction and deployment timeframe, and commence operation with relatively low capital investment and operation costs. Both green built and brownfield retrofitted operation are expected for micro-manufacturing facilities leveraging new planning and existing infrastructure.

6 Identifying the export opportunities of P2X products to build investment confidence and seek off-take agreements for large scale production in the longer term.

NSW enjoys established trade relationship with major economies in the Asia-Pacific region for energy resources. Many of these countries, such as Japan, South Korean and Indonesia, have limited local renewable resources and have signalled a strong P2X demand to decarbonise their economies. There are emerging demand of green powerfuels and chemicals from Singapore, Germany, Neverlands and UK. Better understanding of the P2X supply chain and associated barriers in technology, regulation, logistics between NSW and these potential P2X 'buyers' could de-risk large scale production projects. Leveraging NSW Government's trade and investment initiatives like Global NSW, negotiation of long-term contracts for P2X products with these 'buyer' governments and industries could offer off-take agreements. This will inevitably further de-risk large-scale P2X projects, which will translate to more industries setting up their P2X operations within the state.

Phase 4 (2031-2050): Industry Deployment

7 Deploying P2X Hubs for large scale production

P2X Hubs will be deployed for centralised large-scale production, expected in tens of MW to GW in terms of electrolyser capacity. As outlined in **Chapter 5**, these P2X Hubs have access to major transport infrastructure, renewable energy with low-cost electricity, abundant feedstock (i.e. water), close to existing heavy industries and new industrial precinct and preferably have the export potentials to overseas markets. Adopting the Hub and Spoke model, micro-facilities and decentralised small-scale P2X production facilities deployed under Phase 2 will evolve into spokes to support the centralised P2X Hubs. These Hubs and Spokes will have continuous movement of P2X products and enhanced productivity through shared infrastructure, customer-base, expertise and resources. The P2X Hubs could produce sufficient powerfuels and clean chemicals to meet regional demand and significantly replace fossil fuels, and some export-focused Hubs will explore shipping to overseas market.

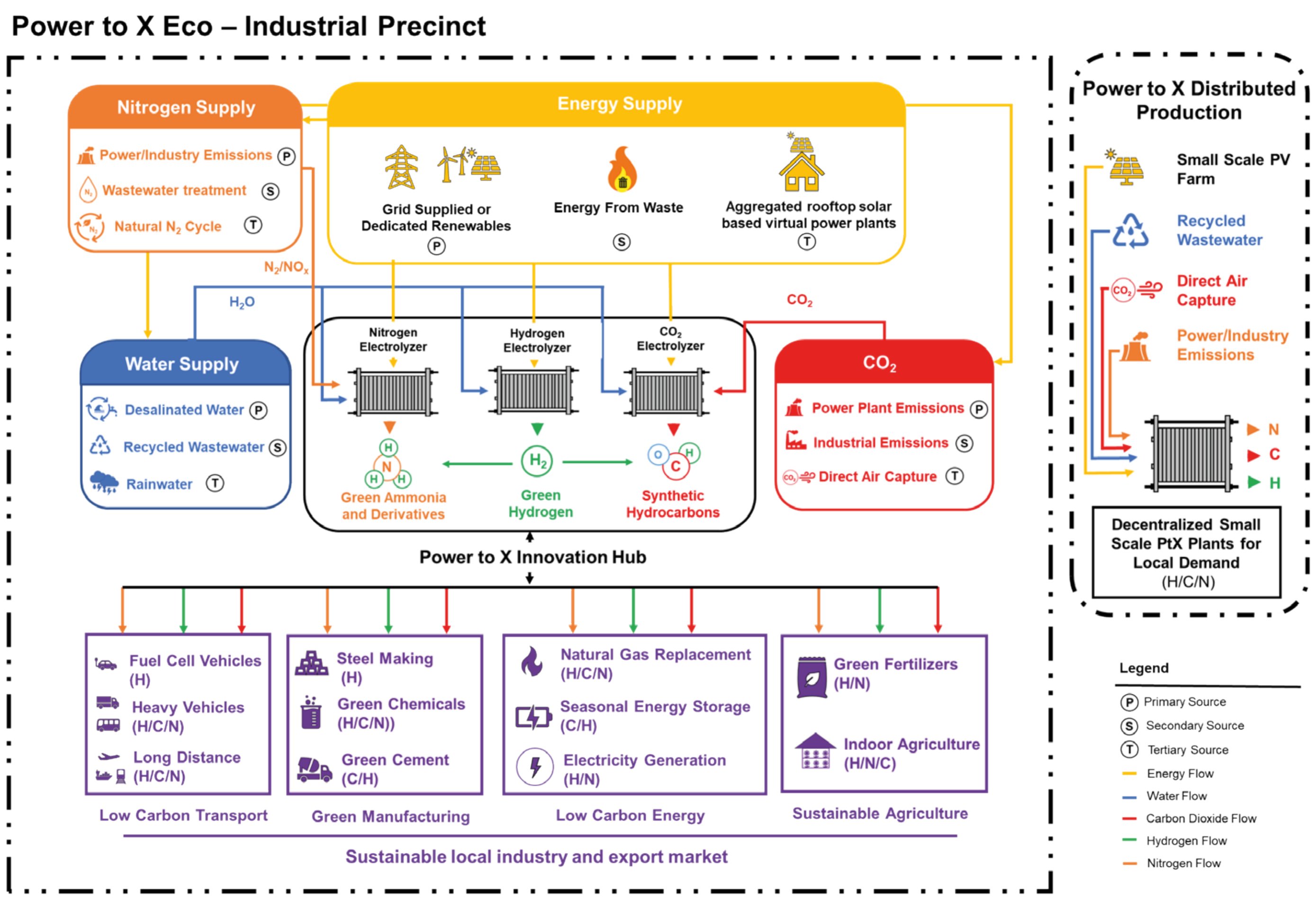
8 Building vertically integrated P2X value chains and local manufacturing capability

Renewable mining through P2X should not follow the 'dig and ship' model of mining and mineral industry. NSW will investigate where the state has comparative advantages to establish local manufacturing for P2X industries across the production, transport and utilisation. Moving local manufacturing capability up the value chain will bring wider economic benefit and job creation as well as opening up new market and export opportunities in P2X technologies, services and skills. For example, P2X production will require a wide range of equipment and machineries involving electrolysers, reactors, critical mineral processors, compressors, separators, purifiers, etc. While these may be imported to NSW from international suppliers in the short run, NSW have the potential to develop local manufacturing capability of these technologies and equipment. P2X technologies that are invented and commercialised locally would have drawn significant investment and resources from both public and private sector. With the support of strong capabilities in advance manufacturing, automation, sensing and digitalisation technologies, NSW could explore opportunities of local manufacturing of these technologies or components that have the most economic benefits and job growth for the state.

9 Developing P2X eco-industrial precincts

Building on the P2X Hubs, the P2X eco-industry precincts will attract industries and business across the P2X value chains to co-locate and collaborate for industry development. The precincts will be designed for P2X-intensive industries such as powerfuels production, green steel, and chemical and fertiliser manufacturing. These heavy industries are expected to be the anchor tenants of the precincts. A diverse range of P2X industries, including producers, feedstock suppliers, equipment manufactures and service providers (e.g. electrolysers) and downstream customers, will be attracted to the precincts. Precinct tenants will have access to low-cost P2X products, shared infrastructure and skilled workforce. The precincts could achieve enhanced productivity and cost-saving through P2X industrial symbiosis. This means tenants gain competitive advantages through physical exchange of P2X products, services, feedstocks and by-products for inclusive and sustainable development as a community. As shown in **Figure 38**, these precincts could achieve self-sustainable and low or net-zero emissions as well as deliver significant economic benefits and employment opportunities across energy, industry, transport, and agriculture sectors through P2X technologies.

Figure 38: Schematics of a proposed P2X precinct.



Appendices

Appendix A: Current and Announced P2X Projects

A.1. Green Hydrogen Projects

Table 15: List of ongoing and announced Green Hydrogen Projects

Project Name	Location	Capacity	Status	P2X Feedstock	Investment	Project Type	Ref.
Australia							
Jemena Western Sydney Green Gas Project	Western, Sydney, New South Wales	500 kW PEM Electrolyser	Under construction (Operational Mid 2021)	Water, Grid supplied renewables	A$15 million	Demonstration Project (H_2 Gas injection into natural gas grid).	22
Project NEO – (Infinite Blue Energy)	Hunter Valley, New South Wales	1,000 MW	Prefeasibility Analysis (Operational by 2027)	Water, Dedicated Renewable	Expected cost: A$2.7 billion	Commercial Plant (Baseload electricity generation power plant).	207
Neoen Australia Hydrogen Superhub	Crystal Brook, South Australia	50 MW	Under Construction (Operational: Q2,2023)	Water, Dedicated Renewables	A$24 million	Demonstration Plant (Grid Firming).	208
Murchison Renewable Hydrogen Project	Kalbarri, Western Australia	NA	Development stage (Pilot Plant)	Water, Dedicated Renewables	A$10 Billion (Full complete three stages)	Commercial Plant (5000 MW solar and wind capacity for generating H_2 using Siemens PEM technology)	209
AGIG Hydrogen Park South Australia	Tonsley District, South Australia	1.25 MW PEM Electrolyser	Operational (Q1,2021)	Water, Grid supplied Renewables	A$11.4 million	Commercial Plant (Siemens' Sylizer PEM for injection into gas grid.	210
Hydrogen Park Gladstone (HyP Gladstone)	Gladstone, Qld	175 kW PEM Electrolyser	Final stage of project development	Water, Grid supplied Renewables	A$4.2 million (A$1.7 million in grant funding from Qld Government)	Demonstration Plant (Hydrogen gas injection into natural gas grid.	211
Hydrogen Park Murray Valley (HyP Murray Valley)	Wodonga, Vic	10 MW Electrolyser	Under Development	Water, Grid supplied Renewables	A$32.1 million (Funding provided by ARENA – Renewable Hydrogen Deployment Fund)	Demonstration Plant (Hydrogen gas injection into natural gas grid.	212,213
Clean Energy Innovation Park	Warradarge, WA	10 MW Electrolyser	Under Development	Water, Grid supplied Renewables	A$28.7 million (Funding provided by ARENA – Renewable Hydrogen Deployment Fund)	Demonstration Plant (Hydrogen gas injection into natural gas grid.	212,213
Asia							
Fukushima Hydrogen Energy Research Field	Fukushima, Japan	10 MW Electrolyser	Operational (2020)	Water, Dedicated onsite Renewables	A$243 million	Commercial Plant (H_2 retail for refuelling fuel cell vehicles)	214
Europe							
H&R Ölwerke Hamburg-Neuhof Project	Hamburg, Germany	5 MW PEM Electrolyser	Operational (2017)	Water, Grid supplied Renewables	A$15 million	Commercial Plant (Hydrogen utilised by nearby refinery).	215
H2FUTURE Project (FCHJU)	Linz, Austria	6 MW PEM Electrolyser	Operational (2020)	Water, Grid supplied Renewables	A$29 million	Pilot Plant (Siemens' Sylizer 300 PEM for steel making operation)	216
Energiepark Mainz Project	Mainz, Germany	6 MW PEM Electrolyser	Operational (2017)	Water, Surplus Renewables	A$26 million	Pilot Plant (Hydrogen storage using Siemens PEM electrolyser)	217
Linde Leuna Chemical Complex	Leuna, Germany	24 MW PEM Electrolyser	Under Construction (Operational Q3,2022)	Water, Grid supplied Renewables	Not Disclosed	Commercial Plant (ITM PEM Electrolyser for H_2 suppl for fuel cell vehicles)	218
Westküste 100 Project	West Coast, Germany	30 MW – Stage 1 (700 MW – Final)	Final Stage of Project Development	Water, Dedicated Renewables	Initial: A$46 million (Final: 136 million)	Commercial Plant (ThyssenKrupp Electrolyser for H_2 Merchant Plant)	219
Americas							
Air Liquide Quebec Plant	Bécancour, Canada	20 MW PEM Electrolyser	Operational (2021)	Water, Renewable electricity	Not Disclosed	Commercial Plant (Cummins' HyLZER electrolyser for H_2 retail)	220
Nikola Corporation Project	Utah, United States	85 MW	Electrolyser Purchased	Water, Renewable Electricity	A$109 million	Commercial Plant (Nel Alkaline Electrolysers for H_2 refueling operations)	221
Florida Power & Light Project	Okeechobee, United States	20 MW	Proposed	Water, Surplus renewables	A83 million	Pilot Plant (Electrolyser to supply H_2 fuel supplement for natural gas powerplant)	222

A.2. Green Ammonia Projects

Table 16: List of ongoing and announced Green Ammonia Projects

Project Name	Location	Capacity	Status	P2X Feedstock	Investment	Project Type	Ref.
Australia							
QNP Prefeasibility Study	Moura, Queensland	20ktpa	Study Completed (Q2,2020)	H_2 (Electrolysis), N2 (Air)	Proposed: A$150 – 200 million	Pilot Project (H_2 from 30 MW electrolyser to retrofit existing Haber Bosch Plant)	223
Project Geri Feasibility Study (BP – GHD)	Geraldton, Western Australia	20ktpa - 1st Stage 1000 ktpa - Final	Prefeasibility Analysis (NA)	H_2, Renewables from Grid, Water, N_2	Study Cost: A$4.4 mil. (ARENA & BP)	Pilot/Commercial Plant (Green ammonia generation for export – H_2 electrolyser + HB Process)	224
Eyre Peninsula Gateway™ (H2U Group)	Eyre Peninsula, South Australia	120tpd	Under Construction (Pilot phase by 2022)	H_2, Renewables from Grid, Water, N_2	A$240 million	Pilot/Commercial Plant (Green ammonia generation for export – 75 MW electrolyser + HB Process)	225
Yuri Green Ammonia Project (Yara Fertilisers)	Pilbara, Western Australia	Phase 0 – 1% of Ammonia Supply (2023) Phase 1 - 2 – 6% of Ammonia Supply (2026) Phase 2 – new 800ktpa green ammonia plant (2028) Phase 3 – 80% - 100% of Ammonia Supply (2030)	Pilot Plant under Construction (Operational: Q2,2023)	H_2, Renewables from Grid, Water, N_2	A$70 million (Cost of phase 1 anticipated) Project has secured A$42.5 million in funding from ARENA – Renewable Hydrogen Deployment Fund for Stage 1 (10 MW electrolyser)	Demonstration Plant (10 MW electrolyser to supply H_2 to existing HB process to make 3.5ktpa – 1% of total ammonia production).	212, 213, 226
Origin Energy Renewable Ammonia Plant	Bell Bay Precinct, Tasmania	420 kpta	FEED Study (Q1,2022)	H_2, Hydropower, Water, N_2	Currently: A$3.2 million	Commercial Plant (500 MW electrolyser and HB plant for green ammonia export).	227
Fortescue Metal Group Green Ammonia Plant	Bell Bay Precinct, Tasmania	250 kpta	Envisioned by 2030	H_2, Hydropower, Water, N_2	A$500 million	Commercial Plant (250 MW electrolyser and HB plant for green ammonia export).	228
Eco Energy Green Ammonia Project	Gladstone, Western Australia	NA	NA	H_2, Dedicated Renewables, Water, N_2	A$500 million	Commercial Plant (300 MW solar plant + 200 MW electrolyser and 100 MW storage for green H_2/ ammonia export)	229
Asia Renewable Energy Hub	Pilbara, Western Australia	NA	NA	H_2, Dedicated Renewables, Water, N_2	NA	Commercial Plant (26 GW solar/wind generation for H_2 and ammonia export)	7
H2-Hub™ Gladstone	Gladstone, Qld	NA	Prefeasibility Phase (Commercial Plant)	H_2, Dedicated Renewables, Water, N_2	NA	Commercial Plant (3 GW electrolyser for green ammonia export)	230,231
Asia							
NEOM Green Ammonia Project (Air Products)	Neom, Saudia Arabia	1.2 Mtpa	Under Construction (Operational 2025)	H_2, Dedicated Renewables, Water, N_2	A$6.5 billion	Commercial Plant (H_2 conversion to NH_3 for export of H2 for retail by refueling fuel cell vehicles in Japan)	232
Europe							
Retrofit of Porsgrunn Facility (Yara)	Porsgrunn, Norway	500ktpa	Under construction (Operational 2026)	H_2, Grid supplied Renewables, Water, N_2	A$1.5 billion	Commercial Plant (Conversion of existing natural gas based haber bosch process to electrolyser supplied by Nel).	233,234
Puertollano Plant Project (Iberdrola)	Cudaid Real, Spain	20kpta (20 MW electrolyser)	Operational (2021)	H_2, Dedicated Renewables, Water, N_2	A$230 million	Commercial Plant (10% of 200ktpa facility converted to green, 100 MW solar + 5 MW battery and Nel 20 MW electrolyser)	235
Americas							
Donaldsonville Nitrogen Complex (CF Industries)	Louisiana, USA	20ktpa	Under Construction (Operational 2023)	H_2, Renewable Electricity, Water, N_2	A$580 million	Commercial Plant	236

A.3. Green Methane Projects

Table 17: List of ongoing and announced Green Methane Projects

Project Name	Location	Capacity	Status	P2X Feedstock	Investment	Project Type	Ref.
Australia							
APA Group and Southern Green Gas Renewable Methane Pilot Plant	Wallumbilla, Queensland	35 GJ of methane per year.	Under Construction	Dedicated Renewables, CO_2 and water from air.	A$2.2 million	Pilot Plant (Proprietary design for use of direct air capture to separate CO_2 and water from air, H_2 electrolyser and reactor)	237
ATCO Renewable Methane Project	Albany, Western Australia	NA	Prefeasibility Analysis	Renewable electricity, CO_2 and water.	Feasibility Cost: A$20k by Western Australia Government.	Demonstration Plant (injection of renewable natural gas into ATCO owned pipeline)	84
Asia							
Hitachi Zonsen's Shaanxi Project	Shaanxi Province, China	3.5 million m^3 yr^{-1}	Operational (2020)	Renewable electricity, CO_2 and water.	N/A	Demonstration Plant (Conversion of waste CO2 emissions into methane using Hatachi Zonsen's technology)	238
Europe							
Audi e-gas plant	Wertle, Germany	325 Nm^3 h-1, (max 1,000 t y^{-1})	Operational (since 2013)	CO_2 sourced from biomass (2,800 tonnes), Renewable electricity and water	N/A	Demonstration Plant (Generation of natural gas for Audi's natural gas operated fleet)	239
Store&Go Demonstration Facilities **(27 partner organizations supported by EU)**	F1: Solothurn, Switzerland F2: Falkenhagen, Germany F3: Troia, Italy	Switzerland Facility: 173 (LNG) Germany Facility: 192 kWh (LNG) Italy Facility: 33 kWh (LNG)	Operational (2019) Operational (2019) Operational (2019)	Water, Grid supplied Renewables, CO_2 from Air	A$43 million (total)	Demonstration pilots for storing surplus renewables as SNG	240

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A.4. Green Methanol Projects

Table 18: List of ongoing and announced Green Methanol Projects

Project Name	Location	Capacity	Status	P2X Feedstock	Investment	Project Type	Ref.
Australia							
ABEL Energy Bell Bay Powerfuels Project	Bell Bay, Tasmania	60,000 t yr-1	Under Construction	CO_2 from biomass and captured industrial emissions, H_2 from renewable electrolysis	Feasibility Study (A$20 million grant by Tasmanian Gov.)	Commercial plant (Methanol for export)	241
Europe							
George Olah CO2 to Renewable Methanol Plant **(Carbon Recycling International)**	Grindavik, Iceland	5 Million Liters per year	Operational (Since 2012)	CO_2 captured from a Geothermal plant, H_2 from renewable electrolysis	A$10 million	Demonstration Plant (R&D of process and explore viability of manufacture and transport of methanol)	242
MefCO2 Project	Niederaussem, Germany	1 tpd	Operational (Since 2019)	CO_2 and renewable H_2 from electrolysis	A$12 million	Demonstration Plant (R&D of process to develop thermal catalysts for methanol generation)	243
FreSME Project	Sweden	1 tpd	Operational (Since 2019)	CO_2 captured from a steel making plant, H_2 from renewable electrolysis	A$17 million	Demonstration Plant (Scale up of technology currently at TRL 6)	244
Swiss Liquid Future	Mo I Rana (Mo Industrial Park), Norway	1 Million Liters per year	NA	CO_2 captured from a biomass plant and industry, H_2 from renewable electrolysis	A$460 – 540 million	Commercial Plant (For refuelling and industrial use)	245
Liquid Wind Project	Gothenburg, Sweden	50ktonnes (over total project life)	Under Construction (Operational by 2024)	CO_2 captured from a biomass plant, H_2 from renewable electrolysis	A$225 million	Demonstration plant	246
Power2Met – Renewable Energy to Green Methanol	Aalborg, Denmark	300,000 liters per year	Operational (2020)	CO_2 from biomass/H_2 from solar/wind operated electrolysis	A$3 million	Demonstration Plant	247

Asia							
KIST Project	Japan	100 kg day-1	Operational (Since 2004)	Power plant CO_2 and H_2 from electrolysis	N/A	Demonstration Plant	97
Mitsubishi Methanol Project	Hokkadio, Japan	20 tpd	NA	Captured CO_2 and H_2 from electrolysis	N/A	Commercial Facility	248
Dalian Institute of Chemical Physics Project	China	NA	NA	Captured CO_2 and H_2 from electrolysis	N/A	Commercial Facility	249

A.5. Green Syngas Projects

Table 19: List of ongoing and announced Green Syngas Projects

Project Name	Location	Capacity	Status	P2X Feedstock	Investment	Project Type	Ref.
Europe							
Norsk e fuel (Climeworks and Sunfire GmbH)	Oslo, Norway	10 Million liters per year (Scale upto 100 Million liters)	Under Construction (Operational by 2023)	CO_2 from DAC, H_2 from renewable electrolysis for co-electrolysis to generate methanol	A$775 million (Total expected cost after upscaling)	Commercial plant (Liquid fuels generation for retail)	250

Appendix B: Feedstock Technologies for P2X Production

In this section, we highlight the available technologies that can be used to source P2X feedstocks and their costs. As outlined in earlier sections, hydrogen generation (**Section 3.2.**) would require a sustained availability of water and renewable energy while its subsequent conversion to methane (**Section 3.4.**), methanol (**Section 3.5.**), syngas (**Section 3.6.**) will require carbon dioxide. Further, the generation of renewable ammonia will require water as well as nitrogen (**Section 3.3**). We further provide a higher-level commentary on water availability in the state for Power-to-X applications.

As discussed in the case studies above, there is significant availability of feedstocks in NSW, with the costs of sourcing these feedstocks on the decline. Further, the scaling of these capture technologies is also reducing their costs (economies of scale). Altogether, these factors further strengthen the case for P2X technologies and their economic future.

B.1. Overview of Carbon Feedstock Technology for P2X

A key aspect of some key P2X pathway is sourcing the required CO_2 feedstock. In this regard, waste CO_2 emissions from industrial and power generation sectors provide significant opportunity for utilisation through P2X and enable emission abatement by closing the carbon loop. The IEA expects carbon capture and utilisation (CCU) for generating fuels and industrial feedstock to play an essential role in achieving long term climate goals.[19]

CO_2 Sources

An important consideration for establishing carbon capture technology is the emission source, as this defines the composition of the CO_2 containing stream and pressure. As a rule of thumb, emission streams with low CO2 content and partial pressure will require larger capture infrastructure and hence require higher input energy to generate a pure stream for downstream applications. As such, streams with high CO_2 content are better suited for direct utilisation in P2X without the need for any pre-treatment.

Table 20 compares potential CO_2 sources, highlighting the CO_2 content, potential impurities, and conditions (temperature and pressure) in the waste streams. There exist several CO_2 capture technologies that are capable of capturing carbon emissions from power plants and industrial processes (TRL 5–9). **Table 21** and **Table 22** provides a comparative outlook and indicative costs of different capture technologies, respectively.

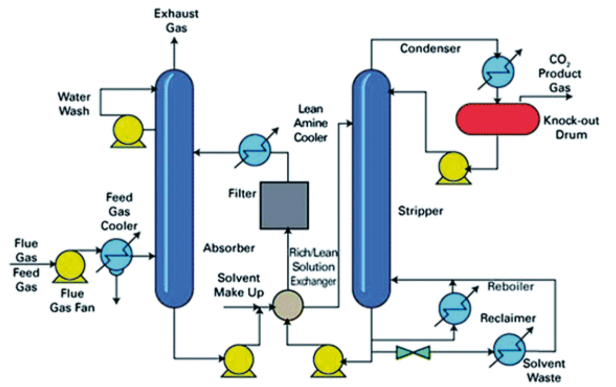
Absorption Technology

CO_2 absorption technology involves interacting a CO_2 rich stream (i.e. flue gas) with a solvent (typically amines) that has a high affinity towards CO_2 (**Figure 39**). This allows the absorption of CO_2 from the flue gas, which can then be separated from the solvent for application or storage. At present, monoethanolamine (MEA) is reported to show high capture efficiencies >90%.[251]

The technology is highly mature and is actively utilised for post combustion capture in power plants and industrial process. It is also used actively in capturing CO_2 emissions at gas processing facilities, like the Gorgon LNG project in WA where CO_2 emissions (3 – 4 Mtpa) are being separated from natural gas for subsequent storage.

A key disadvantage of absorption technology is the need for regeneration of the absorbent that adds to energy consumption and the absorbents tend to suffer from degradation over time.

Figure 39: Simple schematics of the Amine based process.[252]



Adsorption Technology

CO_2 adsorption technology works in a similar principle as absorption technology with the exception that the liquid solvent is replaced by physical adsorption of CO_2 with the surface of a solid phase sorbent. These sorbents are usually designed to have a large surface area and selectivity towards CO_2. Typical sorbents include molecular sieves, activated carbon beds and porous material such as zeolites.

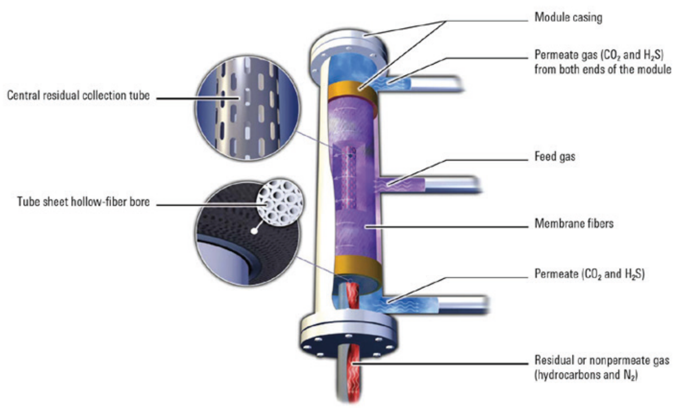
Commercially, these adsorbent beds are retrofitted into Pressure Swing Adsorption (PSA) or Thermal Swing Adsorption (TSA) where cycling of pressure and temperature assists in adsorption and desorption of the captured CO¬2. In PSA, increased pressure leads to adsorption, while a decrease in pressure leads to desorption. In a TSA, low temperature assists in adsorption and increase in temperature leads to desorption. Both PSA (Figure 40) and TSA are commercially utilised with CO2 recovery efficiency of 80 – 85% and high purity (>90%).[253]

Figure 40: PSA unit installed at a Steam Methane Reforming Facility for hydrogen generation. The 13 small cylindrical vessels are the PSA columns equipped with the absorbent beds. Image courtesy of Linde Engineering.

Membrane Separation

Membrane separation technology uses selective membrane that allows CO_2 to pass through while excluding other components of waste streams. They are often used in high pressure applications such as power plants and natural gas processing sites, for instance the CYNARA Membrane system developed by Schlumberger (**Figure 41**) where the high pressure assists in the permeation of CO_2 through the membrane.

Figure 41: Schematics of the CYNARATM process, a commercial membrane system for CO2 separation from natural gas. Image courtesy of Schlumberger.

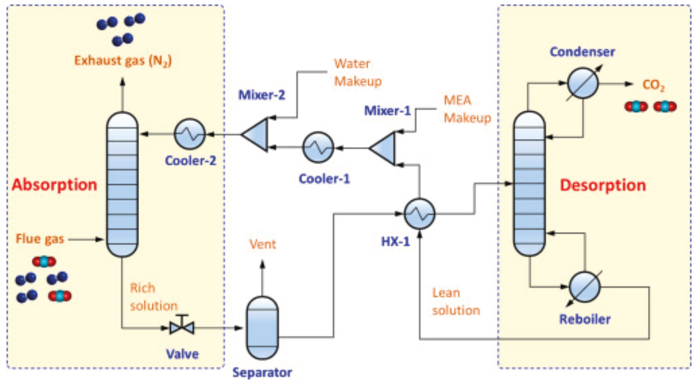


Cryogenic Distillation

Cryogenic Distillation, like the conventional distillation process, separates a mixture on basis of the boiling points of the constituent components. However, as the process is used for gas separation, it must be carried out at very low temperatures and high pressures to be able to liquify the gases and then separate them on their boiling points (which otherwise are very high at ambient conditions). To separate CO_2, the air is cooled to -110ºC to -135ºC at high pressures (100 – 200 atm). This causes the CO_2 to liquify/solidify as it is heavier (lower boiling point) than other lighter components of flue gas such as NOX (-152ºC) or CO (- 192ºC). The solid/liquid CO_2 can then be separated and converted back to gas by reducing the pressure. Cryogenic distillation can achieve up to 90 – 95% of CO_2 separation from flue gas.[253] However, the big drawback is the energy consumption required for reducing temperature and increasing pressure, ~600 kWh to 660 kWh of energy is required per ton of CO_2 recovered.[253]

Commercially, cryogenic distillation is being actively used for separating oxygen and nitrogen from air. However, the same principles are being extended to CO_2 separation from industrial waste streams (**Figure 42**).

Figure 42: Schematics of cryogenic distillation-based separation of CO_2 sepaaration from industrial flue gases.[254]



Direct Air Capture

One emerging CO2 capture technology is the direct capture from ambient air. IEA analysis revealed that the CO_2 concentration in air crossed ~400 ppm as global energy related emissions rose above 33 Gt_{CO2} per year by 2019.[255] Hence, direct air capture (DAC) techniques provide opportunity to reduce atmospheric CO_2, leading to the creation of a circular economy. IEA expects ~10 Gt CO_2 of emissions would have to be captured per year by 2070 in the sustainable development.[19] Of which roughly ~2 Gt per year would be removed through DAC. Overall, 90% of all captured emissions are expected to be stored underground, but 10% (1 GtCO2 yr^{-1}) would be converted to power fuels like synthetic kerosene for aviation.[19]

DAC utilises big fans to induce air flow through a CO2 separation process that uses reversible chemical and physical sorbents to trap the gas. Chemical sorbents include aqueous hydroxides (like NaOH, KOH, $Ca(OH)_2$ etc.) and carbonate forming solvents (CaO)[256]. These chemicals bind the CO_2 on interaction with air and can then be later regenerated by thermal heating to release CO_2 (**Figure 43**).

Figure 43: Schematics of chemical sorbent-based DAC process. In the first step, an aqueous alkaline sorbent (KOH) absorbs the CO_2 to make a carbonate (K2CO_3). The carbonate is then reacted with calcium hydroxide ($Ca(OH)_2$) to make calcium carbonate ($CaCO_3$), which can be thermally decomposed to release the captured CO_2.[257]

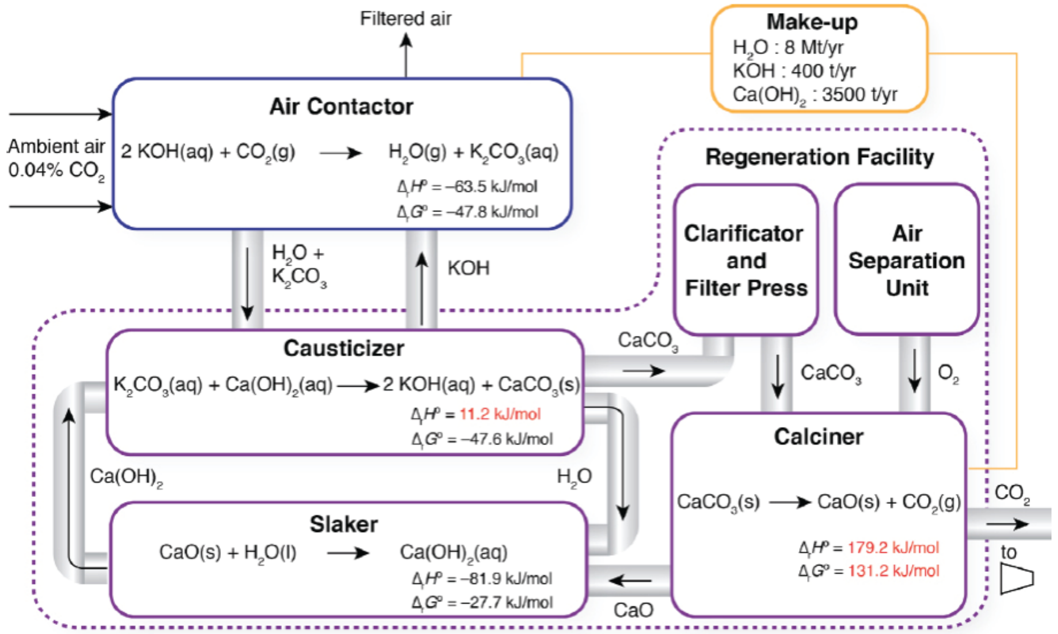


Table 20: Comparison of various CO_2 sources.[258]

Source	CO_2 Comp in Flue Gas (%)	Major Impurities	Minor Impurities	Pressure	Temperature
Power Generation Sector					
Gas Fired Plant	7 – 8%	H_2O, O_2 & NO_2	CO & NO_x		
Coal Fired Plant	12 – 20%	H_2O, O_2 & NO_2	CO, SO_2 & NO_x	1 Bar	50 – 75ºC
Oxy – Combustion Plant	75 – 85%	H_2O	NO_x & SO_x		
IGCC Power Plants	~40%	O_2, CO & N_2	H_2, N_2 & CO		
Industry					
Steelmaking Plant	20%	CO & N_2	CO & N_2	33 Bar	37ºC
Cement Kiln Plant	14 – 33%	H_2O & O_2	H_2O & O_2	1 Bar	50 – 75ºC
Hydrogen Production Plant (SMR)	70 – 90%	CO		15 – 40 Bar	40 – 450ºC
Gasification Plant	~10%	N_2 & H_2	CH_4 & CO		
Atmosphere					
Ambient Air	≈ 400 ppm	N_2 & O_2		1 Bar	Ambient

Table 21: Outlook of potential technologies for capturing CO_2.[259–264]

Process	Advantages	Disadvantages	TRL
Amines	• Mature	• Corrosion, amine degradation & high energy consumption	9
Activated Carbon	• Fast kinetics, high thermal stability, and low cost	• Low CO_2 capacity at low pressure	3
Zeolites	• Fast kinetics	• Regeneration is energy & time intensive	5
Metal Organic Frameworks	• High thermal stability & adjustable chemical functionality	• Low selectivity in CO_2 mixes with other elements & lack of long-term performance data.	3
Membrane	• No regeneration required, low capital cost and compact design.	• Gas must be compressed (15 – 20 bar) prior to separation, high temperature degrades membrane & mutli stages need to be installed to maintain efficiency.	5 - 7
Cryogenic Distillation	• No regeneration required & captured CO_2 is delivered at high pressure.	• High energy consumption	5 - 7
Direct Air Capture	• Scalable • Does not require a point source	• High energy requirement • High Upfront Capital Cost	6

Table 22: Cost outlook of Carbon Capture from different point sources.

Carbon Source	**CO_2 capture cost** (USD$ per tCO2 Captured)
Coal Gasification Power Plant	34 – 48
Coal – fired Power Plant	37 – 60
Gas – fired Power Plant	57 – 110
Refineries & NG Processing	22 – 86
Steel Mill	85 – 89
Cement Production	70 – 105
Biogas Plant	0 – 110
Direct Air Capture	270 – 325

Note: The costs were sourced from a review by Dieterich *et al.*[116], the actual costs were quoted in € (2020 basis) and were converted to U$ basis using the conversion factor of 1 € = 1.22 USD $.

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B.2. Nitrogen and NO_x Feedstock for Ammonia Generation

Nitrogen required for ammonia generation is currently sourced from air using air separation units (ASU). ASU units are currently based on two principles:

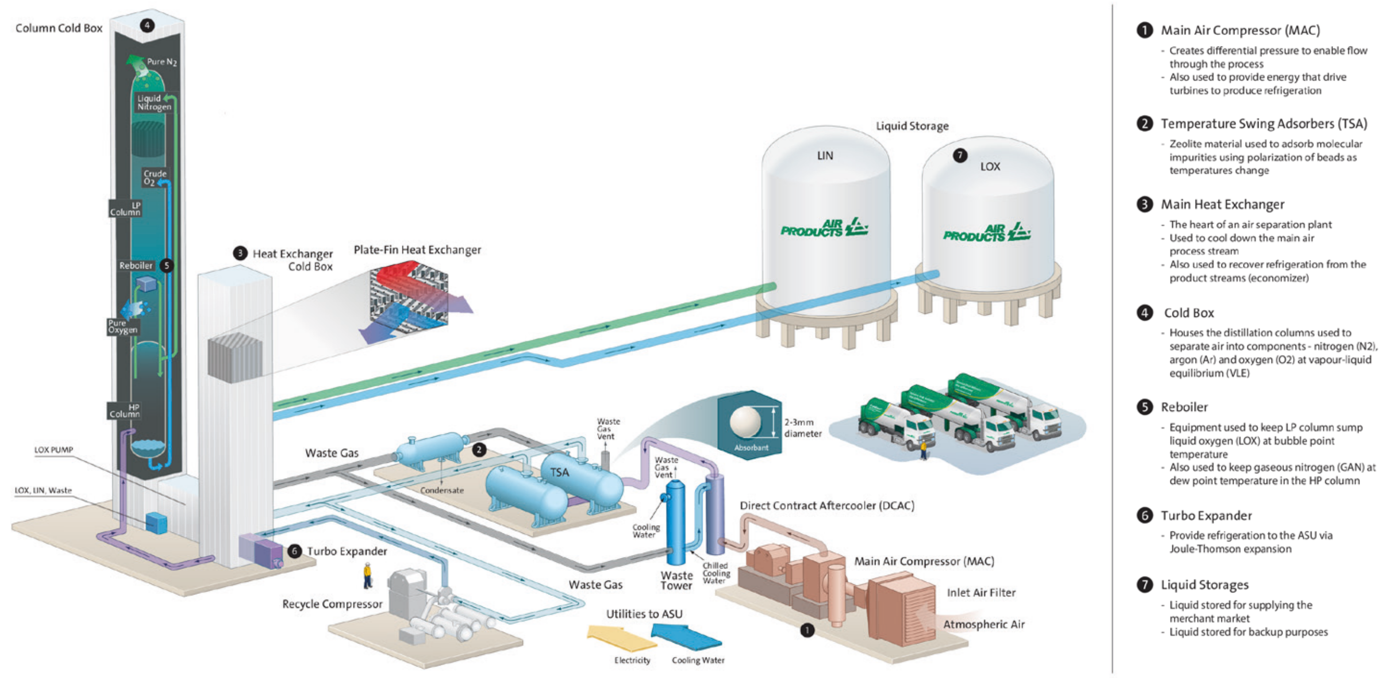
- Cryogenic Distillation: The cryogenic distillation processes the difference of condensation temperatures between the different components in air. In the process, ambient air is passed through a series of coolers and compressors to reduce the temperature required to liquefy the components. The liquid components can then be reconverted to individual gas through distillation. Commercially, ASU plants with capacities between 100 to 1,000 tpd of product are in operation around the world (**Figure 44**). The cryogenic plants deliver N_2 of high purity (>99%) but requires significant amount of energy ~175 – 280 kWh/ton of N_2 which is largely driven by the electricity to operate the compressors.[265]
- Adsorption: The alternate process for N_2 separation is adsorption usually through a PSA unit or a membrane. These units usually have a limited capacity of ~30 tpd of N_2 (beyond this capacity cryogenic processes are more viable) and they are often prone to less pure N_2 (~95%).[265] The process is usually conducted through a membrane or a specially designed adsorption bed installed as a Pressure Swing Adsorption (PSA).

Industrial ASU units of average capacity 135 tpd are reported to cost between USD$ 2.5 million for PSA, USD$ 4.8 million for Membrane Separation and USD $9.5 million for Cryogenic Distillation.[266]

Another potential source of N_2 is in the form of NO_x emissions from industrial and power plants. These NO_x emissions are generated when fuels are combusted to generate energy in presence of ambient air, which results in the N_2 components in the air and fuel to convert to NO_x emissions. The NO_x emissions can then be converted back to N_2 and subsequently into ammonia to close the loop.

Alternatively, direct electrochemical reduction of NO_x can generate ammonia and is being actively explored by UNSW Sydney and University of Sydney. The NOx feedstocks can be directly sourced from the industries or power plants, as NO_x emissions are also capturable using conventional carbon capture technology.[267] In this manner, P2X technologies could be vital in an ammonia energy-based economy, given splitting ammonia to generate H_2 or combusting it for power generation would lead to generation of N_2 and NO_x that can then be recycled through P2X to generate ammonia again.

Figure 44: Schematics of a commercial Air Separation Unit (ASU) process developed by Air Products for generating Nitrogen and Oxygen. Image courtesy of Air Products.[268]



B.3. Water Requirement for P2X

Water is another key ingredient of all the considered P2X pathways, either to generate green H_2, or for secondary conversion processes. Generally, commercial electrolysers operate using high quality water to achieve optimal efficiency and maintain the lifetime of the electrolyser system. Though most of these systems are installed with a water purification system, feedwater must be at least of potable quality (TDS <1,000mg L^{-1}, WHO Standards). This is a potential issue for a water scarce country like Australia, as scaling electrolysis would compete with fulfilling Australia's drinking water and agricultural demand.

To generate H_2 using electrolysis, ~9 L of water are required generate a kilogram of H2. This, as highlighted in the National Hydrogen Roadmap, would translate to 4.5 GL yr^{-1} (gigalitres – 1 x 109 liters) required to service the expected 0.5 Mtpa demand of H2 (hydrogen export market) by 2030.[21] However, if the industry had to be scaled to generate synthetic fuels to replace the 39 million tonnes of liquid fuel that Australia imports, the water demand will increase drastically to 99 billion L yr^{-1} (equivalent to water demand of 1.7 million people).[52] Thus, sustaining an electrolysis economy would have to hinge on sourcing water by either reclaiming wastewater or increasing desalination capacity. Though sourcing water from these sources will be more costly than fresh water, cost of water is expected to only take up ~2% of electrolysis cost.[21] The water feedstock required for the specific locations considered in this pre-feasibility study are elaborated in the respective sections. It must be noted that NSW holds promising reserves of potable water as well as saline aquifers dispersed within the regions that can also be considered in the development of a P2X economy.

Appendix C: Acknowledgement

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Appendix D: NSW P2X Alliance Members

Alliance Members	Sector/P2X Interest
ABEL energy	Industry/Developer
AgBioEn	Industry/Inventor
ARDENT Underground Hydrogen Storage	Industry/Startup
Australian Renewable Energy Agency (ARENA)	Government/Investor
Beyond Zero Emissions	NGO/Community and policy
BOC	Industry/Inventor
CNF & Associates	Industry/Developer
CSIRO	Research/Network
Deloitte	Consulting/Network
Energy Estate	Industry/Investor
Fortescue Metal Group	Industry/Investor and end-user
German Energy National Agency (DENA)	Government/Investor
GHD	Engineering Consultant
Global Alliance Powerfules	Industry/Network
GPA Engineering	Engineering Consultant
H2U™	Industry/Developer and Investor
Hysata	Industry/Startup
Infigen Energy	Industry/Developer and Investor
IP Group	Industry/Investor
Ironside Capital	Industry/Investor
ITP Renewables	Industry/Developer
MAN Energy	Industry/Technology
METS Ignited	Industry/End-user
Mitsubishi Development Pty Ltd	Industry/End-user
NAPEAN Engineering & Innovation	Industry/Manufacturer
Origin Energy	Industry/End-user
PlasmaLeap	Industry/Startup
Qenos	Industry/End-user
Quinbrook Infrastructure Partners	Industry/Investor
Santos	Industry/End-user
Siemens Energy	Industry/Technology
Southern Green Gas	Industry/Startup
Squadron Energy	Industry/End-user
Star Scientific	Industry/Startup
ARC Steel Research Hub	Research/Network Inventor
SwticH2	Industry/Startup
Toshiba	Industry/Technology
University of Newcastle	Research/Technology
University of Sydney	Research/Technology
University of Technology Sydney	Research/Technology
University of Wollongong	Research/Technology

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