PacificHydro

Feasibility Study Public Knowledge Sharing Report

Ord Hydrogen

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1. Acknowledgement of Grant Funding

The feasibility study (Study) received grant funding from the Western Australian Government's Renewable Hydrogen Fund, which is administered by the Department of Jobs, Tourism, Science and Innovation (the Department).

Department of **Jobs, Tourism, Science and Innovation**

GOVERNMENT OF WESTERN AUSTRALIA

1.1 Disclaimer

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2. About Pacific Hydro

Founded in 1992, Pacific Hydro is a leading owner, operator and developer of world class renewable energy assets. With its stated purpose of leading Australia to an affordable, clean energy future, Pacific Hydro's team of highly skilled in-house experts operate a high quality, diversified portfolio of wind, solar and hydro assets with an installed capacity of 665 MW.

Pacific Hydro also has a development pipeline of substantial projects across Queensland, South Australia, New South Wales and Victoria totalling over 1100MW of potential capacity, as well as over 300MW of energy storage solutions. It also has a fast-growing energy retail business, Tango Energy, with close to 100,000 customers.

Pacific Hydro was acquired by the State Power Investment Corporation (SPIC) through its subsidiary, State Power Investment Overseas of China (SPIC Overseas) in January 2016. SPIC is one of the top five (5) power generation groups in China, with $US131 Billion total assets and a total installed capacity that exceeds 120 GW. SPIC operates in the generation, coal, aluminium, logistics, finance, environmental protection, and high technology industries. SPIC has a presence in 36 countries and regions abroad, including Australia, Chile, Malta, Japan, Brazil, Turkey and Vietnam. The recent investment in Pacific Hydro has resulted in priority growth in solar development.

Pacific Hydro's operating assets in Australia currently abate over 1.2 million tonnes of greenhouse gas pollution every year.

Pacific Hydro has built a strong reputation for engaging with the communities within which it operates and has a track record of collaborating with local communities to deliver lasting, and sustainable benefits.

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3. Introduction

3.1 Project background

Pacific Hydro (PH) owns and operates the Ord Hydro Power Station in Western Australia (WA). The Ord Hydro Power Station is situated on Lake Argyle, approximately 45 km south of Kununurra in WA. The plant supplies the township of Kununurra and the Argyle Diamond Mine via a transmission network owned and maintained by Pacific Hydro.

The anticipated diamond mine closure will result in between 15 and 25MW of power becoming available for alternate applications. Pacific Hydro is seeking alternative applications for the available power, including the opportunity to develop a hydrogen production facility.

Australia has significant potential to become a leader in the emerging hydrogen industry, both as a domestic producer and user, and as a key exporter of renewable energy from abundant solar, wind and hydro power. To support subsequent investment decisions, Pacific Hydro commissioned GHD to undertake a study to investigate the feasibility of a hydrogen plant near Kununurra. The study also considered the potential for a hydrogen and ammonia facility. This report contains the results of the study which considers the potential options for production and storage of either hydrogen or ammonia.

3.2 Glossary

Table 1 Glossary

Term/Abbreviation	Definition
ANSI	American National Standards Institute
ADM	Argyle Diamond Mine
ARENA	Australian Renewable Energy Agency
AS	Australian Standard
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ASU	Air Separation Unit
barg	Bar gauge (1 MPag = 10 barg)
BLEVE	Boiling Liquid Expanding Vapour Explosion
BS	British Standards
Capex	Capital Expenditure
EEHA	Electrical Equipment for Hazardous Areas
EOI	Expression of Interest
EPC	Engineering, Procurement and Construction
EPCM	Engineering Procurement and Construction Management
FEED	Front End Engineering Design
FIFO	Fly In Fly Out
FTE	Full Time Equivalent
H_2	Hydrogen
HIPAP 4	(NSW) Hazardous Industry Planning Advisory Paper No. 4: Risk Criteria for Land Use Safety Planning

Term/Abbreviation	Definition
HMI	Human-Machine Interface
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
kg	Kilogram
kPag	Kilopascal Gauge
kV	Kilovolt
kW	Kilowatt
LOHC	Liquid Organic Hydrogen Carrier
m	Meter
MHF	Major Hazard Facility
mg	Milligram
mm	Millimetre
MPag	Megapascal gauge
MW	Megawatt
MWh	Megawatt hour
NFPA	National Fire Protection Association
NH_3	Ammonia
Nm^3	Normal cubic meter
NZS	New Zealand Standards
O&M	Operating and Maintenance
OEM	Original Equipment Manufacturer
Opex	Operating Expense
PEM	Proton Exchange Membrane
QRA	Quantitative Risk Assessment
SAFETI	DNV GL SAFETI v8.23, a commercial software package for QRA
SCADA	Supervisory Control and Data Acquisition
SoW	Scope of Works
TBC	To be confirmed
TDS	Total Dissolved Solids
tpd	Tonnes per day

4. Plant overview

4.1 Introduction

Hydrogen is essentially considered as an energy storage medium for this study. While it is the most abundant element in the universe, it exists only in combination with other elements, such as oxygen to form water, or carbon to form hydrocarbons. Hydrogen stores approximately three times more energy per kg than conventional fuels (120 MJ/kg vs 44 MJ/kg for gasoline). However, hydrogen gas and liquid have very low density compared with conventional hydrocarbon liquid fuels.

Combining nitrogen with hydrogen in a Haber-Bosch synthesis plant produces ammonia, which can be used as an industrial chemical (fertiliser) feedstock, or as a fuel. Ammonia is liquefied and stored, either at ambient temperature under pressure (>7.5 barg and 20°C), or at low temperature (-33°C) and ambient pressure. The latter offers a potentially lower risk profile and more efficient storage format. Where ammonia is used as a hydrogen carrier, technology is required at the point of use to separate hydrogen from ammonia.

4.2 Plant description

4.2.1 Hydrogen production only

Hydrogen production is the core process technology using electrolysis to split water into a hydrogen and oxygen stream. The oxygen stream is assumed to be discarded for the purposes of the feasibility study. The hydrogen production plant would include:

- Connection to the Ord Hydro Power Station 132 kV power line
- Connection to raw water
- Water treatment to produce demineralised water to make hydrogen in the electrolyser, and utility (cooling) water
- 15/20 MW electrolyser unit
- Hydrogen compression and storage
- Loading of road transport vessels (including loading bay(s), metering and connection skid, booster compression and isolation skid)

The process flow through the plant is shown in the block flow diagram in Figure 1.

Hydrogen is produced from electrolysis, at pressures between atmospheric and 30 barg, based on the specific electrolysis technology selected. Depending on the purity required, the raw hydrogen passes through a separation step, to separate unconverted water from hydrogen gas before compression. According to AS ISO 14687:2020, Hydrogen fuel quality – Product specification, hydrogen should be at least 99.97 vol% pure to be acceptable for most fuel applications. Typically, electrolyser vendors can supply the additional hydrogen conditioning equipment as part of the vendor package, if required, and produce hydrogen with a purity of 99.998 vol%, or higher, following conditioning.

Hydrogen is compressed to high pressure, to increase the energy density before transport. Tube trailers currently found in Australia operate at a maximum pressure of 200 barg and, therefore, the base assumption is that hydrogen is compressed, stored and transported at 200 barg. Typically, diaphragm compressors are used for hydrogen compression, so that no oil contamination occurs during compression. Several stages are usually required with intercooling to improve compression efficiency. (Note: 1MPag = 10 Bar).

Oxygen is produced from electrolysis at between zero and 20 barg. Typically, the oxygen passes through a separator to remove moisture from the stream and is then vented to atmosphere. Compressed hydrogen is loaded into tube trailers. Depending on the assumed number of loading hours, and time to fill a trailer, at least two loading bays - but preferably three - loading bays are required.

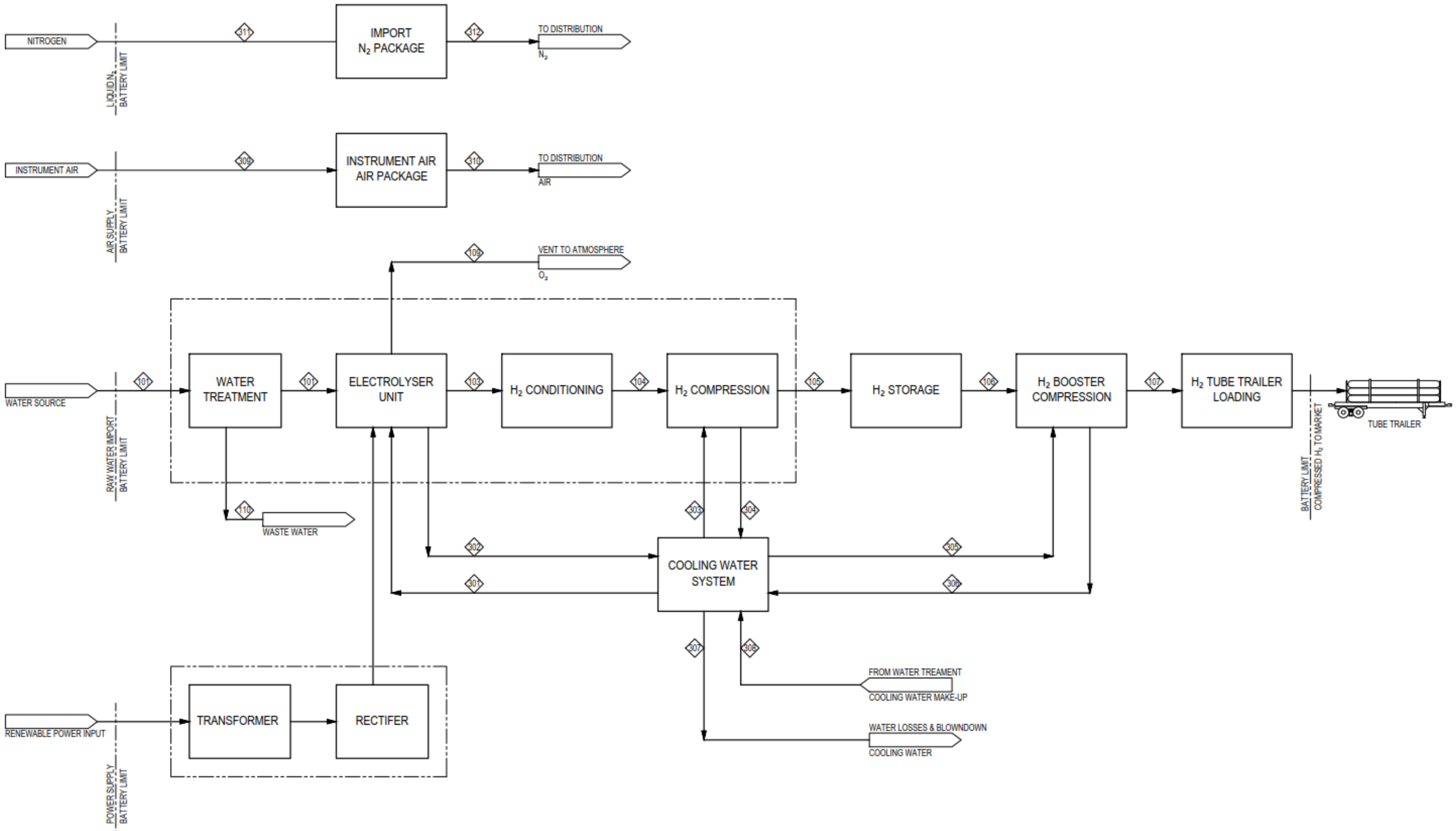

Figure 1 Hydrogen production only – block flow diagram

4.2.2 Hydrogen and ammonia production

In addition to the hydrogen production facility, the ammonia production plant would include:

- Nitrogen generation plant
- Ammonia synthesis plant and storage
- Road transport of liquid ammonia in isotainers

The process flow through the plant is shown in the block flow diagram in Figure 2.

Ammonia synthesis technology (Haber-Bosch reaction) is the same technology used globally to produce ammonia, typically from steam methane reforming (SMR)-derived hydrogen (also known as ‘brown’ or ‘grey’ hydrogen), where hydrogen is produced from fossil fuels, such as natural gas, via catalytic reforming.

Therefore, the technology for ammonia production via this process is mature, and well-known; but still challenging due to the relatively small capacity typically required for green hydrogen and ammonia facilities. The technology vendors are continuing to improve ammonia synthesis catalysts to allow operation at lower temperatures and pressures and find other means of improving the project economics for smaller scale plants.

When selecting the operating conditions for the ammonia converter, two important considerations are the reaction rate and chemical equilibrium. These are a function of the partial pressures of the various species present in the reactor. As the reaction results in a decrease in the number of moles, the reaction shifts towards ammonia, with increasing pressure. In addition, the chemical equilibrium favours production of ammonia at lower temperatures. However, the reaction kinetics also play a role in determining the temperature at which the reactor is maintained, as there are typically faster kinetics at higher temperatures.

A catalyst is used to reduce the activation energy to allow the reaction to proceed at a lower temperature. Most catalysts are iron based. High temperatures are required to accelerate the reaction, typically between 250 and 450 ºC. Ammonia is recovered from the ammonia synthesis gas loop and stored as a refrigerated liquid at near atmospheric pressure in a double skin tank. As the base assumption, ammonia is loaded into isotainers for transport from site. Ammonia filled into isotainers from refrigerated storage requires reheating to avoid ice formation on isotainer fittings. The total fill volume will account for thermal expansion of the liquid to ambient conditions.

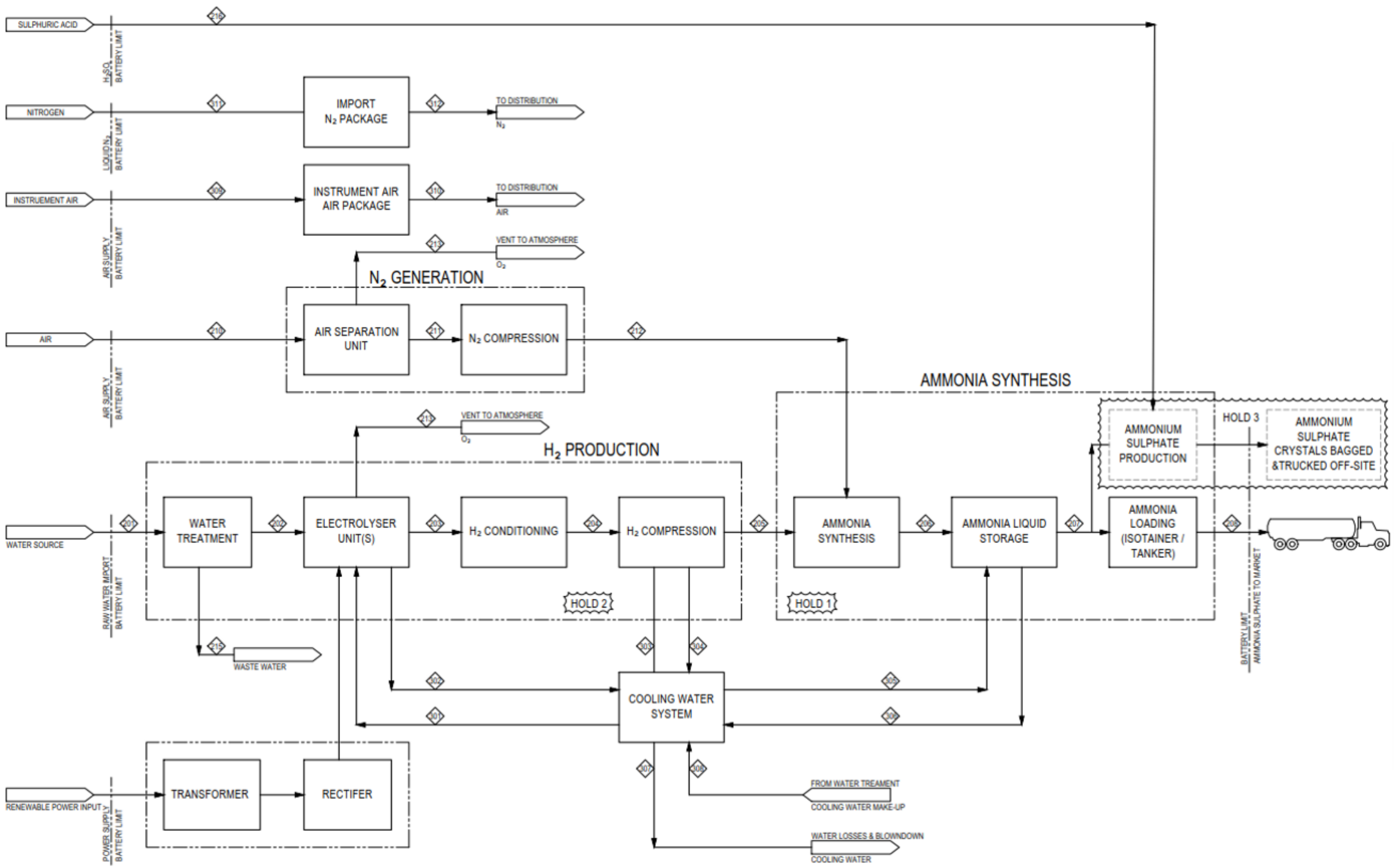

Figure 2 Hydrogen and ammonia production – block flow diagram

4.3 Product transport logistics

4.3.1 Hydrogen transport options

Efficient methods of hydrogen transport over long distances are briefly explored below.

4.3.1.1 Compressed gas

The base assumption is that hydrogen would be transported as a compressed gas in tube trailers. Compressed gas transport vehicles are common for current hydrogen transport applications, for industrial gas uses, and consist of a series of high pressure manifolded cylinders. Current metallic tube trailer configurations, approved for use in Australia, store hydrogen at approximately 200 barg, resulting in a payload of about 255 to 300 kg. Tube tailers may be considered for short transport applications but, based on the low payload, and indicated transport costs for distances beyond 100 km, may be cost prohibitive.

4.3.1.2 Alternate hydrogen transport carriers

While hydrogen has a very high energy density on a mass basis at approximately 120 MJ/kg (typically about 3 x higher than diesel or petrol), it has a very low volumetric energy density, as shown in Figure 3. Even when compressed to high pressures, the energy density on a volume basis remains low.

As a result, cost effective transport of gaseous hydrogen can be a challenge. To improve the logistics and transport efficiency, hydrogen can be converted into a liquid hydrogen carrier format to store and transport hydrogen in a denser form. Ammonia, liquefied hydrogen, and liquid organic hydrogen carriers, such as perhydro dibenzyl toluene (DBT), or methylcyclohexane (MCH), are potential options.

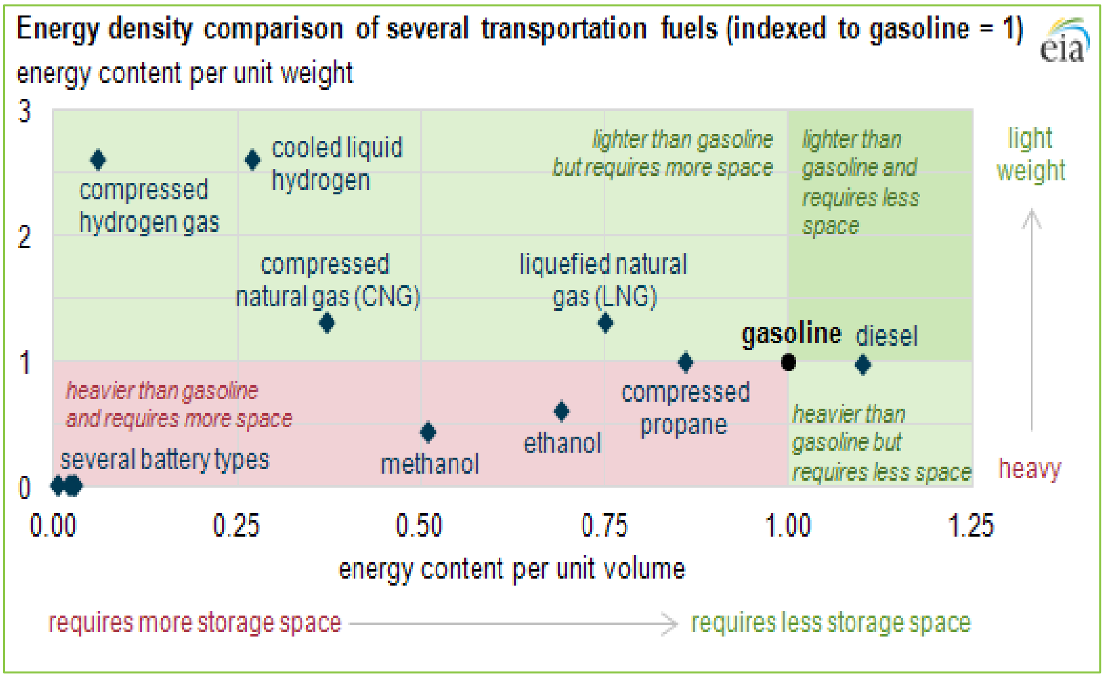

Figure 3 **Energy density of various fuels (volume basis)**[1]

4.3.1.3 Ammonia

Conversion of hydrogen to ammonia is discussed throughout this report. In the context of transport, where ammonia is used as a fuel or feedstock for subsequent processing, storage and handling systems are required at the destination. Road transport of liquid ammonia is relatively efficient compared to gaseous hydrogen, and common in Australia. Road transport options for ammonia include Isotainers or bulk liquid transport options as a pressurised liquid.

If a simple hydrogen carrier mechanism is required for subsequent reconversion to hydrogen, lower cost and less complex technology options exist to achieve this objective for domestic markets.

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[1] https://crudeoilfacilitators.blogspot.com/2013/02/few-transportation-fuels-surpass-energy.html

Transport of hydrogen as ammonia may be considered for export volumes, where international shipping logistics are considered for larger scale operations. If ammonia is required as an industrial feedstock, the hydrogen carrier requirement does not apply, and ammonia would most likely be transported as a pressurised liquid.

4.3.1.4 Cryogenic liquid hydrogen

Hydrogen liquefaction occurs at -253°C, giving a density of 71 kg/m^{3}, which provides a more efficient transport option than compressed gas. However, the systems required to liquefy hydrogen are complex and power intensive, taking a significant fraction of the overall site power demand (approximately 15%).

Based on the power supply availability, potential for long distance logistics and high ambient temperatures at site, the liquefaction of hydrogen is not considered practical for the proposed application.

4.3.1.5 Liquid organic hydrogen carriers

Liquid organic hydrogen carriers (LOHC) consist of a liquid hydrocarbon oil capable of being ‘loaded’ with hydrogen at the source. The hydrogen is chemically bonded with the molecular structure of the carrier, and provides a stable, non-toxic and non-flammable method of transporting hydrogen, using established bulk liquid transport vehicles. The key requirement is to provide the ‘loading’ systems at the production site, with sufficient organic carrier storage capacity to suit the anticipated logistics and delivery models, as determined in conjunction with offtakers.

The offtake destination site must also be fitted with the appropriate infrastructure to receive and store both loaded and spent carrier. The LOHC is received at the destination into storage tanks. The hydrogen is then ‘unloaded’ by reversing the ‘loading’ process. The ’spent’ carrier can then be back loaded into the truck for the return journey to site. Typical offtake applications may include centralised hydrogen vehicle fuelling stations, or industry users. This option also minimises the storage and handling of gaseous hydrogen at the off taker site, but there is a footprint impact for ‘unloading’ systems, storage and liquid transfer infrastructure.

4.3.2 Transport costs

Transport costs for hydrogen have the potential to contribute a significant portion of the delivered costs of the finished product. The costs of hydrogen transport would vary widely, depending on several critical factors, including distance, payload, trailer configuration amongst others.

The total freight cost includes allowances for driver wages and expenses, insurances, fuel, maintenance and depreciation. Transport costs are often quoted in $/km and several freight cost calculators are available online. Transportation of compressed hydrogen or ammonia are less common than traditional goods freight, and the feasibility study has not attempted to predict a specific freight cost, as the destinations and final product configurations are still unknown. However, Figure 4 provides indicative costs per km from the WA Department of Transport[2].

[2] https://www.transport.wa.gov.au/mediaFiles/Freight-Ports/FREIGHT_P_OwnerDriversGuidelineRates_2020.pdf

Heavy Vehicle Type	Metropolitan Based on diesel fuel cost of $1.20 per litre		Regional Based on diesel fuel cost of $1.27 per litre			
	One Driver		One Driver		Two Drivers	
	Hourly Rate (ex GST)	Rate per km (ex GST)	Hourly Rate (ex GST)	Rate per km (ex GST)	Hourly Rate (ex GST)	Rate per km (ex GST)
5 tonne GVM (rigid truck, 2 axles)	57.63	2.66	76.87	1.16		
8 tonne GVM (rigid truck, 2 axles)	59.75	2.76	79.78	1.20		
15 tonne GVM (rigid truck, 2 axles)	65.77	3.04	87.98	1.33		
22.5 tonne GVM (rigid truck, 3 axles)	72.86	3.36	99.19	1.50		
Prime mover (haulier) 2 axles, 31.5 tonne GCM	77.89	3.60	106.87	1.61		
Prime mover (haulier) 3 axles, 1 trailer, 42.5 tonne GCM	84.49	3.41	112.43	1.70	100.76	1.58
Prime mover (haulier) 3 axles, 2 trailers 79 tonne GCM	94.46	3.82	130.45	1.97	116.95	1.83
Prime mover (haulier) 3 axles, 3 trailers 122.5 tonne GCM			143.97	2.17	127.51	2.00
Prime mover + 1 trailer 42.5 tonne GCM	90.02	3.64	119.15	1.80	105.61	1.66
Prime mover + 2 trailers 79 tonne GCM	108.15	4.37	149.40	2.25	132.33	2.08
Prime mover + 3 trailers 122.5 tonne GCM			174.84	2.64	154.39	2.42
B-Double 62.5 tonne GCM	108.68	4.39	149.18	2.25	132.34	2.08
Pocket road train (haulier) 79 tonne GCM	94.68	3.82	130.45	1.97	116.95	1.83

Figure 4 WA freight transport rates (2020)

Based on the nominal transport options presented below, the cost impact per kg of hydrogen is dependent on the distance. To illustrate the economic challenges associated with long distance compressed gas transport, a 100 km round trip (50 km each way) for a 300 kg payload compressed gas trailer would incur a $0.6 cost per kg of hydrogen ($1.8/km x 100 km). But a round trip to Darwin, at 900 km each way, adds approximately $10/kg to the hydrogen cost. In comparison, using an LOHC with a payload of approximately 2850 kg delivering to Darwin (round trip at $2.5/km) would add about $1.6/kg to the cost of hydrogen.

4.3.3 Vehicle movements

The total number of vehicle movements per day may affect several project development aspects.

The table below highlights the estimated impact of the finished product format on the number of vehicle movements. The assumptions used for payload and truck capacity are not verified at this stage but are provided for comparative purposes only. The table illustrates the benefit of a densified transport carrier, such as compressed ammonia, or liquid organic carrier.

Table 2 Hydrogen transport format and vehicle movements

Product (rate)	Product format	Road transport format	Assumed Payload	Number of trucks per day
Hydrogen (6tpd/2000tpa)	Compressed gas 200barg	Single tube trailer	250-300kg	24
	Compressed gas 500barg+	Single tube trailer	500-650kg	10
	Cryogenic liquid	Cryogenic Isotainer - single	1500 kg LH_2	4
	Liquid organic Carrier	B-Double (50,000lt/vehicle)	57 kg H_2/1,000 lt 2,850 kg H_2/truck	2
Ammonia (36tpd/12,000tpa)	Compressed liquid (sg0.65)	Isotainer (T50) Single or multiple per vehicle	12t per isotainer	1-3
	Compressed liquid (or low temperature	Bulk carrier	TBA	1

4.3.4 Ammonia transport options

Typically, for small scale ammonia production, isotainers or tankers may be used for transport of ammonia to market. Road transport of ammonia in Australia is typically done as compressed pressurised liquid, rather than refrigerated liquid. For bulk applications, the approach taken for LPG transport may be considered.

5. Process design

5.1 Introduction

The baseline plant configuration considered in this study is ***Gaseous hydrogen production*** from electrolysis, which is then compressed and transported via road in tube trailers, or cylinders on trucks. The low density of hydrogen gas and the potential for long transport distances from the proposed facility to markets are major logistics and economic challenges to overcome.

As alternate transport methods, the following have been considered as part of the study. It should be noted that limited work has been completed on these options, and additional definition would be required to select one of these options for this project:

- Gaseous hydrogen production from electrolysis, loaded into an ***organic hydrogen carrier*** and transported via road in tankers and dehydrogenated at market to extract hydrogen again. There are several conversion technologies and organic carriers under development for commercial applications.
- ***Hydrogen liquefaction*** and transport has been briefly commented on as an alternative hydrogen transport method.
- ***Conversion of hydrogen to ammonia*** via the Haber-Bosch process. Ammonia is usually condensed from the ammonia synthesis process as a refrigerated liquid and can then be stored as either refrigerated liquid at ambient pressure or pressurised liquid at ambient temperature. Road transport in Australia, (tankers or in isotainers), typically only carries ambient temperature pressurised liquid.
- Ammonia could be used as ***fertiliser*** precursor in the local market, given the planned project location is close to an irrigation cropping scheme. Or it could be transported to a nearby mine/market to be ***directly used as an energy source or disassociated into hydrogen*** and nitrogen prior to use.

5.2 Technology review

A technology review has been completed for the main process units in the flowsheet. The processing blocks considered are:

- Water treatment to produce demineralised water of the quality required by electrolysers as feed
- Electrolyser technology, including alkaline and PEM electrolysers
- Hydrogen compressors
- Hydrogen storage
- Nitrogen generation and ammonia synthesis.

5.2.1 Electrolysers

Alkaline and Proton Exchange Membrane (PEM) electrolysers were considered for this study.

5.2.1.1 Alkaline electrolysers

Alkaline electrolysis is the most mature technology of this type. It has been used since the 1920s and was predominantly developed for use in the fertiliser and chlorine industries. For Alkaline electrolysis, the reaction occurs in a solution of water and liquid electrolyte (potassium hydroxide - KOH), between two electrodes. At the cathode, hydroxide (OH^-) and hydrogen molecules (H_2) are produced from water. The OH^- ions travel through the electrolyte to the anode, where they combine and release the extra electrons (e^-) to make water, electrons and oxygen molecules (O_2). Alkaline units require cheaper catalysts and materials of construction compared to PEM units, leading to a lower total installed cost (TIC) and electrode replacement cost.

Typically, alkaline electrolysers use electrodes consisting of steel plates covered with nickel, while PEM units utilise combinations of titanium, iridium, gold and platinum. The electrodes typically last longer than those used in PEM units, due to an exchangeable electrolyte, and lower dissolution of anodic catalyst. These electrodes are also much cheaper to replace when required than a major overhaul of a PEM unit. Due to the maturity of these units, information on operation and maintenance, as well as decline in stack efficiency, is widely available.

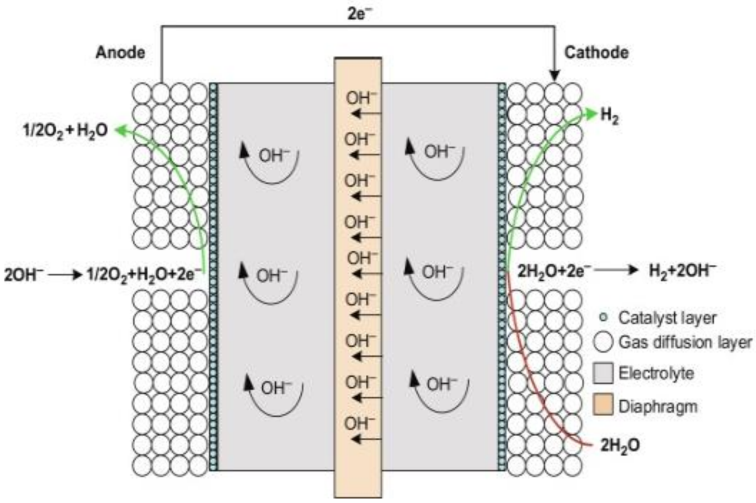


Figure 5 Alkaline electrolysis representation[3]

5.2.1.2 PEM electrolysers

PEM electrolysis was developed in the 1960s by General Electric. PEM units use pure water as an electrolyte, so avoiding the recovery and recycling of potassium hydroxide electrolyte, as required in alkaline electrolysers. A PEM electrolyser utilises ionically conductive solid polymer. Negatively charged oxygen in the water molecules give up their electrons at the anode to produce protons (H^+), electrons and oxygen molecules at the anode. The H^+ ions travel through the proton conducting polymer to the cathode, where they take an electron to become neutral H atoms, which then combine to produce hydrogen gas (H_2) at the cathode. The electrolyte and two electrodes are sandwiched between two bipolar plates. The role of this plate is to transport water to the plates, transport product gases away from the cell, conduct electricity, and circulate a coolant fluid to cool down the process.

PEM electrolysers offer greater flexibility in operation, and can respond to load changes more quickly than alkaline units. In addition, their turndown range is better than that of alkaline units. The higher responsiveness and operating range are of particular advantage, when coupled with dynamic energy sources, such as solar and wind. Expensive platinum group catalysts and membranes require expensive initial and recurring replacement costs. In addition, due to the low technological maturity of larger units, information is not readily available on the potential operation of such units. The performance of smaller models, (around 0.5 to 2 MW), is better understood.

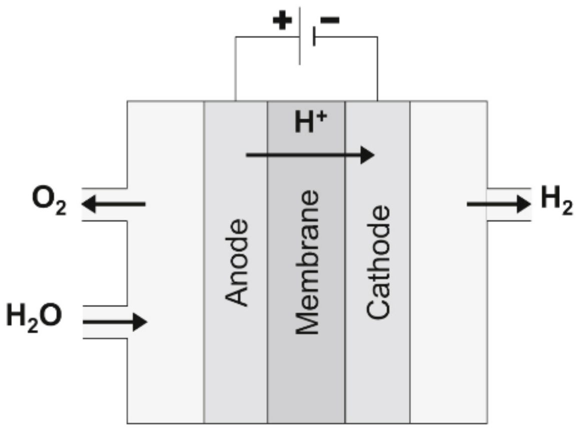


Figure 6 PEM electrolyser representation

[3] Ali Keçebaş, Muhammet Kayfeci and Mutlucan Bayat. Electrochemical Hydrogen Production. Chapter in Solar Hydrogen Production, Elsevier Inc (2019).

PEM appears to be the currently preferred technology for large scale green hydrogen projects around the globe based on the flexibility of the technology to respond to fluctuating load profiles typical of wind or solar generation.

5.2.1.3 Electrolyser technology comparison

Alkaline and PEM electrolysis units present different challenges and benefits to operation.

The minimum load of PEM electrolysers is typically between zero and 10%, while alkaline units can only achieve turndown to 20 to 40%. These values are defined based on the purity of the produced gases at the anode and cathode, and subsequent safety concerns. Gas crossover takes place in every electrolyser. While hydrogen occurrence at the anode, where oxygen is produced, causes no issues.

A brief comparison of alkaline and PEM electrolyser units is provided in the table below.

Table 3 Electrolyser type comparison

Parameter	Alkaline	PEM
Hydrogen Pressure	Lower pressure operation, typically up to 20 barg hydrogen can be produced. Oxygen is produced at lower pressure to keep the gases separated.	Higher pressure hydrogen output can be produced (typically up to 30 or 40 barg) Oxygen (if applicable) can be produced at similar pressure.
Electrolyte	Liquid Potassium Hydroxide (KOH) electrolyte This is a hazardous chemical that has to be handled and stored on site.	Solid polymer electrolyte membrane using pure water
Turn Down Capacity	~60-90% turndown	100% turndown
Ramp Rate	20% in 6 seconds OR 3% / second from 10-100%	10% / second
Impurity Risk	Risk of KOH, H_2O and O_2 impurity in H_2 product. ~99.9% product purity	Risk of H_2O impurity in H_2. >99.99% product purity
Current Capital Cost Comparison	Lower capital cost Typical costs are around US$ 990 -1,270 /kW	Higher capital cost (typically about 1.2 – 1.5 times that of alkaline units). Typical costs are around US$ 1,185 – 2,070 / kW.
Operating and Maintenance (O&M) Costs	O&M costs for PEM and Alkaline units are broadly equivalent. Additional O&M requirements associated with Alkaline units include replacing KOH solution, and more frequent electrode replacement. These additional costs are offset by the higher overhaul (including electrode costs) of the PEM unit.	
Electrode Changes (Approximate)	Eight to 10 years. Stack replacement cost is approx. 5-7% of electrolyser Capex (supply cost) from some vendor sources.	Earliest of 80,000 operating hours or 15 years. Major overhaul costs for PEM units not well defined at present, more operational experience required. Costs of 15-28% of electrolyser capex (supply cost) are quoted in literature[4].
Current Density	Low current density	High current density

[4] Typically, total installed cost is factored from equipment supply cost, for example for electrolysis where the equipment is highly modularised, the total installed cost may be TIC = Equipment Supply Cost * 2.5. Thus to determine major overhaul cost the calculation could be, for example, Major overhaul cost = TIC for electrolyser/2.5 * 0.21

Parameter	Alkaline	PEM
System Efficiency	Potentially higher system power efficiency (70+%). Typical efficiency is around <56 kWh/kg H_2. The theoretical energy consumption to produce hydrogen from water electrolysis is 39.4 kWh/kg H_2. (Although this needs to be assessed on a manufacturer by manufacturer basis)	Potentially lower system efficiency (65-75%). Typical efficiency is around 53-61 kWh/kg H_2. (Although this needs to be assessed on a manufacturer by manufacturer basis)
Technology Maturity	Mature technology commercially available for more than 70 years	Developing technology, commercially available for approximately 20 years

5.2.2 Hydrogen compression

Hydrogen is discharged from electrolyser units at a pressure between 0 and 4 MPag, (depending on technology and vendor selection). The density of hydrogen at normal conditions is very low (0.0813 kg/m^3), so hydrogen must be compressed to minimise the storage footprint. Hydrogen is normally transported from site in tube-trailers pressurised to around 180-200 barg. Therefore, hydrogen from the electrolyser must be compressed to around 200 barg to enable tube trailer filling. To limit the temperature of the hydrogen and improve the compressor efficiency, a multi-stage intercooled compressor system is used.

Two types of compressors - reciprocating piston and diaphragm compressors - are typically offered by hydrogen compressor vendors, with different number of stages, parallel units, depending on the capacity, availability, and reliability of a particular unit: Piston compressors rely on the reciprocating action of one or more pistons to compress gas within a cylinder, or cylinders, and discharge it through valving into high pressure receiving vessels. The compressor has a piston cylinder system, with automatic valves on the cylinder inlet and outlet. A connecting rod links the piston to a crankshaft and the piston transforms the rotary motion of a moving unit into the approximately linear motion of the piston. The piston head moves back and forth in the cylinder to compress the process gas. In most applications, this sequence of movements is driven by a motor connected to two cylinders, in which the compression step follows an expansion step, comprising the working principle of reciprocating piston compressors.

Reciprocating piston compression is a mature technology that can be used to compress almost any gas. They generally have high volumetric capacity and can offer flexibility during compression operation. However, to reduce the influence of mechanical stress, lower speeds are preferred; high compression speeds can only be achieved at small scale, restricting the maximum allowable flow rates. The disadvantages of reciprocating piston compression include the presence of moving parts, which can increase costs due to manufacturing complexities, and maintenance frequencies during operation. Moving parts also generate heat and can lead to a decrease in the efficiency of the system. The reciprocating process of pistons causes pressure fluctuations that can lead to vibration and noise.

Diaphragm compressors use a motor-mounted concentric crank drive that oscillates a flexible disc, which alternately expands and contracts, increasing and decreasing the volume of the compression chamber. The drive is sealed from the process fluid by the flexible disc, so lubricant cannot come in contact with the gas, allowing its delivery at very high purity. Diaphragm compressors are hermetically sealed, the whole compression chamber sealed by metallic, static sealings. This usually achieves very low leakage rates, without additional special action.

The high stage pressure ratio allows for very high final delivery pressures. Typically, piston compressors are limited to a single stage compression ratio of 4-6:1, while diaphragm compressors can theoretically achieve ratios of up to 15-20:1 in a single stage, although this is dependent on the materials of construction, and their associated temperature limits. The units are also energy efficient, in the order of 80 to 85%, and are relatively easy to maintain. They also have lower cooling requirements per increment of compression ratio than piston compressors. Disadvantages of diaphragm compressors include low inlet volumetric flowrates, and, therefore, low capacities, and reduced lifetime of the sealing components, due to lateral forces caused by the crank drive. Durability of these compressors is a critical issue.

Comparing the compressor types, diaphragm compressors are more suitable for the application, despite generally only being able to achieve lower volumetric flow rates than piston compressors, and potentially suffering more frequent failures. This type of compressor is recommended due to its higher efficiency, and the ability to compress the hydrogen gas without any oil contamination. Should the decision be taken to liquefy hydrogen, higher purity hydrogen becomes more important, so that contaminant-free hydrogen production is further favoured.

5.2.3 Hydrogen storage

Hydrogen would be stored at 200 barg to enable trailer filling, with a booster compressor to allow for loading of the tube trailers to 180-200 barg (when being loaded from storage). There are two storage technologies available: tube manifolds and vessels. The manifolded units consist of small, pressurised tubes arranged in stacks. Each tube has a storage volume of approximately 50 litres, with each manifold consisting of about 18 tubes (denoted as MCP-18, where “MCP” refers to “Manifolded Cylinder Pack”) containing 900 litres storage in total. At present, tube storage is considered for high pressure hydrogen storage.

5.2.4 Hydrogen tube trailer loading

Hydrogen tube trailers would access site, to be loaded in loading bays. Approximately 255 kg of hydrogen can be loaded in each tube trailer, (operating pressure is 180 barg, the maximum currently available in Australia). Truck drivers would load the trailers by connecting the loading hose and starting the automatic filling process. The trailer would be filled by flow meter and pressure control, and the fill would be controlled from a local control unit. A minimum of three bays would be required, given a minimum loading time of two hours per trailer, including administration and connection time.

5.2.5 Ammonia production and storage

The Haber-Bosch process combines hydrogen and nitrogen to produce ammonia. This is currently the only commercially available ammonia conversion process and, therefore, has been selected for this project.

Ammonia can be stored as a refrigerated liquid or compressed liquid. Ammonia is produced at 2°C, it would then pass through a chiller unit before being stored in a double skin tank at around -34°C at atmospheric pressure. Two days of production is currently allowed for storage, which is between 100 and 130 m^3 (65 to 85 t) depending on the plant capacity.

5.2.6 Ammonia loading for transport to market.

From refrigerated storage, ammonia is heated through a series of heat exchangers before loading to the isotainers, which operate at ambient temperature and a maximum working pressure of 16.40 barg. A weather-protected isotainer filling station would be constructed at site. The area would be bunded with a dedicated, isolated drainage sump. Load cell filling control is assumed.

5.3 Process scenarios

5.3.1 Scenarios

The following scenarios are considered to utilise the surplus power from the Ord Hydro Power Station.

CASE 1 - An 11 MW (stack consumption only) capacity set of PEM electrolysers would produce high purity hydrogen. It is likely that a number of PEM electrolyser units would be utilised in parallel. The hydrogen would be compressed and loaded into tube trailers for export. The total power consumption for the electrolyser and supporting equipment is 15.6 MW, producing 210 kg/h of hydrogen (operating rate) or five tpd. The total power use is 18 MW, assuming compression to 200 barg plus 10% additional power, as an allowance for utilities, and miscellaneous users.

CASE 2 – A 14 MW (stack consumption only) capacity set of PEM electrolysers would produce high purity hydrogen. It is likely that a number of PEM electrolyser units would be utilised in parallel. Hydrogen would be compressed and loaded into tube trailers for export. The total power consumption for the electrolyser, and supporting equipment, is 20 MW, producing 270 kg/h of hydrogen (operating rate), or 6.5 tpd. The total power use is 23 MW, assuming compression to 200 barg plus 10% additional power, as an allowance for utilities and miscellaneous users.

CASE 3 – An electrolyser set (number of parallel units) and nitrogen generation plant to feed ammonia synthesis, to produce ammonia, aiming for a similar total power consumption as the first two cases. The plant would consume a total of 20 MW (operating), producing 28.5 tpd of ammonia (10,000 tpa), or;

CASE 4 - The electrolyser set (number of parallel units), nitrogen generation plant and ammonia synthesis plant are sized to consume close to 25 MW (operating) power. The plant produces 36.7 tpd, or 12,800 tpa of ammonia.

A summary of key process streams for these scenarios is in Table 4 below.

Table 4 Key process streams (operating)

Parameter	Units	Case 1	Case 2	Case 3	Case 4
H_2 production	tpd	5.0	6.5		
N_2 production	tpd			24.0	30.8
NH_3 production	tpd			28.5	36.7
Cooling duty	MWh	4.7	6.0	8.8	11.4
Power consumption	MWh	18	23	20	25

5.3.2 Additional scenarios/alternate products

The following additional scenarios were briefly investigated. Some of these alternate configurations could have merit and should be further investigated in the next phase of the project:

- Hydrogen liquefaction. Liquid hydrogen has a density of 71 kg/m^3, which is considerably higher than gaseous compressed hydrogen, therefore increasing the mass of hydrogen that can be transported by truck/tanker. However, hydrogen is liquefied at -253°C, adding complexity to transport logistics. In addition, a hydrogen liquefaction unit has to be added to the flow scheme, substantially increasing the capital cost. Hydrogen liquefaction capital costs could contribute an extra AU$ 45 M to AU$ 75 M to the installation of the plant scale under consideration. It also adds considerable complexity, as special coolants, (for example liquid nitrogen), have to be generated on site, and equipment has to be designed for cryogenic service. Also, additional power would be required, typically around 2.5-3 MWh for the plant capacities under consideration.
- Organic hydrogen carrier, where an organic substance is loaded with hydrogen at the plant. Hydrogen is chemically bonded with the organic substance before being transported to the end user. Both the lean (unloaded) organic carrier, and the loaded organic carrier, have to be stored in sufficient quantities, at site. In addition, the hydrogenation plant adds complexity and cost to the facility; although the incremental cost has not been explored yet. While the organic carrier can be transported at ambient conditions, energy is required at the market end to dehydrogenate the organic carrier, as dehydrogenation is an endothermic process. The dehydrogenated carrier can then be returned to site in the same tankers used to transport the loaded organic carrier to market.

5.4 Conclusions

Both green hydrogen production, and green hydrogen and ammonia production, have been considered for this stage of the project.

For hydrogen production only, a key driver will be the typical capacity of electrolysers available.

Typically, between 5 to 6.5 tpd of hydrogen could be produced with the available power, including the electrolyser stack power consumption (10 or 15 MW), auxiliary equipment, water treatment equipment and hydrogen compressors. It was decided to limit the electrolyser capacity to 15 MW, bringing the total power consumption to approximately 23 MW. This still fits into the “traditional” electrolyser unit capacity, rather than extending it to the maximum of 25 MW. The produced hydrogen would be compressed to 200 barg. The power required for this is included in the power consumption for the hydrogen only cases.

There may not be a large advantage regarding capital cost for larger capacity green hydrogen facilities. Electrolysers are expandable in a modular manner, with some advantages to grouping stacks together, depending on the particular technology vendor, while some of the supporting equipment (for example, water treatment) may be less capital intensive at higher capacity, due to scaling. Equipment such as hydrogen compressors are also likely to be relatively small capacity units, with a number of parallel compression trains required.

For ammonia production, the aim was to develop as large a facility as possible to take advantage of economies of scale typically seen for the nitrogen generation and ammonia synthesis units. Usually, vendors recommend 20,000 tpa as a lower threshold for ammonia production from green hydrogen. To produce this volume of ammonia, approximately 36-38 MW of power would be required, depending on the technology vendor.

To maximise ammonia production, a case was developed using 25 MW - the maximum power that may be available for large portions of the year. A smaller facility was also investigated, as the 25 MW facility would be under-utilised at times during the year. However, the more suitable capacity ammonia synthesis plant is likely to be a 10,000 tpa facility, utilising around 20 MW.

6. Power supply and control system

6.1 Overview

The power generated at the Ord Hydro Power Station is transmitted to Kununurra by overhead cables. Initial investigations indicate the transmission network has the capability to deliver the surplus power capacity to the site and, as a result, no significant upgrades are expected. A loop-in-loop-out connection would be made, in the line, at the point of offtake, next to the hydrogen/ammonia site. The parallel would be made at the entrance of the substation via a 132kV bus. Power at the sub-station is stepped down to power the electrolyser plant, and 415V to feed smaller loads of the plant.

The following sub-sections outlines:

- Ord hydro power supply
- Transmission line
- Hydrogen/ammonia facility sub-station
- Power distribution, reliability, availability & power factors
- Power supply for main plant
- Control system architecture
- Site electrical safety

6.2 Ord hydro power supply

The power generated at the Ord hydro power station is transmitted to Kununurra by overhead cables. A connection point would be made in the line, at the point of offtake, adjacent to the hydrogen/ammonia site. Power from the connection point would be sent to an onsite sub-station consisting of stepdown transformers, switch-gear, AC to DC rectifiers that converts AC power to DC power, before being delivered to the electrolyser plant. A small amount of the power would be used for running pumps, compressors, process system packages and general lighting at a Low Voltage (LV) level.

6.3 Hydrogen/ammonia facility sub-station

The new substation would be powered from an existing overhead transmission line, via a cut-in cut-out connection. This involves installing approximately 530 m of double circuit transmission structures, between the new substation gantry and a new termination structure interface with the existing line.

A single transformer is sized to independently supply power to the facility. The transformer supplies a switchboard, which in turn supplies the respective electrolyser banks and ammonia synthesizer. The switchboards also supply a switchboard used to distribute power to the ancillary equipment and site utilities, via 2 x 1 MVA transformers. To minimise costs, the switchboard would be integrated into one of the switch rooms.

Furthermore, emergency backup generation would be required to enhance the reliability of power supply to the site and, in particular, the ammonia synthesizer and ancillary plant, during periods when the supply line to the site fails due to lightning or fault. The emergency generator set consists of one 3 MW diesel reciprocating engine/generator set. The generator unit would be installed with a day fuel tank, which would keep the ammonia plant operating for 24 hours.

Appropriate interconnections between critical infrastructure have also been allowed for, to maintain power availability during planned and unplanned outages

6.3.1 Power distribution

The proposed site layout minimises the cabling and distribution to the major plant users, and the major equipment package suppliers. The electrolyser plant is located to minimise the distance to the sub-station, hydrogen compression and storage facility, and the point of injection for hydrogen to the ammonia plant. The hydrogen compression and storage system has been placed as close as possible to the ammonia synthesiser plant injection point.

Site equipment, utilities and packages, excluding the electrolyser package, require site LV power supply, where at least one site main switchboard would be available for LV power distribution. The LV Main switchboard would also supply Motor Control Centre switchboards (e.g. at the water treatment and cooling water areas), to provide localised power supply to pumps and equipment. Following the HV substation, power distribution would be via underground HD PVC conduits. Cable pits will be available. where appropriate, and in places of heavy cable routing.

6.3.2 Electrolyser supply

Power from the sub-station would be supplied to the electrolyser plant at 11 kV. From there, it is sent to a transformer, before being converted to DC by way of a rectifier. DC power is sent to the electrolyser stack to produce hydrogen. A 415 V supply of power is available for electrolyser utilities, such as:

- Water purification unit
- Process water circulation pumps
- Controls and instrumentation
- Process water cooler
- Hydrogen water separator
- Hydrogen purification modules
- Site safety systems

6.3.3 Ammonia synthesizer supply

Power from the substation would be supplied to the ammonia synthesiser at 11 kV, and 415 V for utilities. The 415 V supply of power is available for synthesiser utilities, such as:

- Air separation unit
- Ammonia generation unit
- Refrigeration unit
- Controls and instrumentation
- Cooling water system
- Ammonia storage and dispensing system

6.3.4 Site lighting

Suitable lighting will be designed for operators and drivers to navigate the site during non-daylight hours. Lighting would be available in all areas and buildings on site, and lighting power distribution would be provided from the site LV switchboard.

6.4 Control system architecture

A central control room would provide a single, local source of operator monitoring control for the site, and a secure location to house the site main control system processor, and essential infrastructure. This would include control panels, for the electrolyser and synthesiser packages and other systems, for site operator monitoring and control. The site main control system will communicate with the main Pacific Hydro SCADA network, to allow suitable site data logging and remote accessibility. The control system must achieve the following functionality:

- Automated control of plant and facilities
- Start-up/shutdown logic based on input energy availability.
- Replicated local/remote functionality (i.e.: remote control via HMIs)
- Manual and automatic start/stop of generation sources.

- The setting of process variable values, status and alarm monitoring of all instrumented process variables, and instrumented protection
- Local and remote control of the plant, including balance of plant items and ancillary equipment, where appropriate
- Fault annunciation and alarm dispatch.

6.4.1 Site automation

The hydrogen/ammonia production design will aim to minimise the requirement for operator interaction for ongoing production, where the operator may adjust process control set points (e.g. flow rates, operating levels, dose rates etc.) and adjust operational control, (e.g. duty selection, process on/off time of day, process enable/disable etc.) as desired, but is not required to perform manual control to maintain production. The operator may, however, use local manual control of select equipment, where available. The option for remote manual control of equipment over SCADA may be considered, as part of the site SCADA interface and control programming.

6.4.2 Remote/SCADA access

The site operator would be able to access a remote interface, for the site process monitoring feedback, and pre-defined control functionality, via remote SCADA system. This will communicate with the site central control system via a site telemetry system. The remote SCADA interface would be secure. It would only provide access and varying degrees of control to authorised personnel.

6.4.3 Package communication

All site packages would primarily use available Fieldbus communication, between the package controller/control devices, and the site central control system.

7. Site layout

7.1 Overview

The overall process area is determined by the products and volumes to be produced, and the product storage inventory to be held on site. The site layout for ammonia production indicates the required footprint for the ammonia synthesis building, which includes air separation, refrigeration and feed to storage, for truck loading applications.

The indicative site layouts have been developed, based on initial assumptions about building sizes, and appropriate separation distances between structures and storage facilities. For more detail on the layouts refer to Appendix A - Feasibility design layouts.

When developing the site layouts, GHD was asked to maintain the majority of the process site on the existing disturbed land area and set back in the block, generally understood to be the former quarry area. This allows the process facility to be set back from Crossing Falls Road and accessed via an entry road from Crossing Falls Road, leaving a buffer from the main road, and space for truck parking. The facility layout provides adequate buffer and separation distances between operational areas, buildings, site boundaries and neighbouring properties. Subject to the final site configuration, buffer distances may be reduced for a more compact layout and smaller overall footprint.

7.2 Site layout considerations

Appendix A contains the indicative site layouts for a hydrogen only facility (Cases 1 & 2) and a hydrogen and ammonia facility (Cases 3 & 4). The buildings on the site include:

- An administration and control building, housing the reception, meeting rooms and control room.
- Maintenance and stores building, including work facilities, overhead crane, and store rooms. The storage facility is sized to accommodate the potential increase to spares storage, and onsite repairs due to remote location.
- A water treatment building housing filtration and demineralisation systems
- An electrolyser plant building containing the power conditioning, electrolysis modules, controls, hydrogen clean-up, drying and compression.
- An ammonia synthesiser/ASU structure consisting of an open sided, multi-storey steel framed structure.

In addition to the above, the site also contains:

- Two evaporation ponds for brine treatment
- A substation containing transformers, switchgear, control panels and emergency back-up generation capability.
- Fire water storage tank, complete with electric and diesel pumps and fire hydrants
- An ammonia loading station.
- A hydrogen loading station (for hydrogen-only option)
- A flare for ammonia releases
- Storage areas for both hydrogen and ammonia.

The layout considers the following key safety and operability factors to support a flexible, and safe site.

- Adequate spacing and separation distances between plant facilities, allowing for hazard incidents, constructability, maintenance access and isolation.
- Perimeter access road for emergency services access
- Appropriate road surface finishes to manage storm water run-off, traffic movements and accessibility during weather events.

- Administration facilities, parking and associated amenities
- Separate controlled access to the main process plant area, via fenced and secured gates.
- Perimeter access road for offtake vehicle access, including dedicated filling stations for hydrogen and ammonia, where required. This avoids vehicle access to the core process facility and provides increased access control and security for the core process plant.
- The large liquid ammonia production and storage inventory is stored as far as possible from the nearest neighbouring properties as well as the main administration facility.
- Cooling water supply and distribution is assumed to be provided from a centralised bank of cooling towers, with the majority of demand from heat rejection associated with the electrolysis plants. So, the towers are located on an allocated block, convenient for the electrolysis and ammonia synthesis units.
- Incoming power distribution is sited to minimise the distance from the main transmission line, and to be located as close as possible to the main user (electrolysis)
- Low hazard, non-process infrastructure, including water treatment, maintenance sheds, and fire systems, are within the same 'block'. They are separated from the process infrastructure to allow access for non-process related personnel.
- Additional area has been allocated to increase the evaporation pond footprint if required.
- The plant occupies much of the disturbed area of the site, minimising encroachment on undisturbed land.
- All loading bays have concrete bases; roadways are asphalt.

7.3 Administration and control room

The number of personnel on site, at any given time, will depend on the final product configuration. Sufficient operational and administration resources are required to maintain the business operations and maintenance of the facility. Fewer operations staff would be required for hydrogen-only production.

The admin and control room would be housed in the main site building, along the site entry road. This building would house the administrative offices, amenities, IT infrastructure and associated hardware. The building would be designed to include staff office facilities, meeting rooms, kitchen facilities, operator and contractor change rooms, essential amenities, a training facility, and reception area. The total footprint, and internal floor area, are to be confirmed subject to anticipated staffing levels and uses (e.g. onsite training, or potential integration of other Pacific Hydro business units).

8. Environmental assessment

8.1 Overview

An initial review of potential environmental impacts has been undertaken based on the preliminary assumptions for the indicative site layouts, and estimated water demands.

Air emissions are not considered at this early stage, because the main process emission would be oxygen. While there may be temporary minor emissions from a backup diesel generator, and the emergency ammonia flare (if ammonia is included), they occur only infrequently, under upset conditions (and start-up), so are considered to have a negligible environmental impact.

Water supply is critical to the ongoing plant operations. A bore water assessment is required to confirm if a bore(s) can meet the forecast demand of the selected plant configuration, over the designated operating period. Water use reduction, recovery, conservation and reuse processes would be likely to reduce overall demand.

Land tenure including Native Title considerations will be addressed by Pacific Hydro independently and are not covered in this technical report. Similarly cultural heritage surveys and considerations will be addressed by Pacific Hydro if the project proceeds beyond this feasibility study.

8.2 Project development

The project concept is predominantly on a disused quarry site. It is approximately 30 ha in total. Depending on the final footprint chosen, the site would require clearing up to 15 ha of native vegetation, but likely much less. The environmental approval requirements will be refined following further assessment but may require assessment on the basis of up to 15 ha impact.

Areas with native vegetation appear to be predominantly grasses, with sparsely distributed trees. The vegetation, (and inferred habitat types for terrestrial fauna), is consistent with the surrounding area. If the project proceeds beyond this feasibility study, further environmental assessments including flora and fauna surveys would be undertaken. The final design may also need to incorporate a bushfire protection area on appropriate Department of Planning advice.

The site would be set back from Crossing Falls Road, which would mitigate visual impacts. Landscaping and screening vegetation may further reduce visual impacts if required, although this may not be necessary at this site.

8.3 Water

8.3.1 Water supply

Water (and power) supply is a critical feedstock for the process. While variability in water quality is manageable, to an extent, the demand from the electrolysis and cooling systems is essential to maintain the operating status of the site.

Bore water is the preferred source option but the selection of the plant water source would be based on availability, viability, cost, and waste stream management. If bores cannot meet demand, other options would be assessed.

Use of bore water may require a licencing application to WA Department of Water and Environmental Regulations (DWER). An assessment of the potential supply capacity for bore water is required, based on the forecast demand from the site. Once the final site configuration is determined, a more detailed assessment of the water demand can take place, with the intention to match bore supply capability and site demand, or consider alternative supply options. This assessment will also identify any key water supply constraints.

8.3.2 Water quality

Assuming that sufficient bore water can be obtained at the site, it would be collected in raw water tanks to feed the onsite water treatment facility. The raw water tanks would have capacity to store two days' requirements. Bore water quality assumptions are below, in Table 5. They are taken from the Kununurra Water Reserve - Drinking water source protection review (Dec 2012)[5].

Table 5 Expected raw water quality

Parameter	Units	ADWG aesthetic guideline value*	Kununurra Borefield Raw water sample point	
			Range	Median
Chloride	mg/L	250	17 - 23	21
True Colour	TCU	15	<1 - 1	<1
Hardness as CaCO3	mg/L	200	160 -160	160
Iron Unfiltered	mg/L	0.3	<0.003 – 0.008	<0.003
Sodium	mg/L	180	37 - 40	38
Total filterable solids by summation	mg/L	600	429 – 437	433.5
Turbidity	NTU	5	<0.1 – 0.1	<0.1
pH	N/A	8.5	7.37 – 7.84	7.58

* An aesthetic guideline value is the concentration or measure of a water quality characteristic that is associated with good quality water.

Water treated in the treatment plant would be used for:

- Electrolyser water supply (demineralised)
- Potable water including cooling water system make up, site building supply, sanitary water supply and firewater system (subject to confirmation)

Most of the water is used for cooling water makeup; most of the waste water is produced from cooling tower blowdown. All cooling is presumed to be evaporative water cooling. Cooling water accounts for approximately 80% of the total water demand, followed by water for demineralisation, for electrolyser feed. Other small water users include potable water for safety showers, and wash water demand. Fire water requirements (storage and demand) have not been assessed as part of this feasibility study, but they are not expected to be an ongoing daily demand requirement.

It was calculated that 2.4% of the cooling water would be lost in any circulation, mainly due to evaporation. The water demand for the main cases studied is shown below, in Table 6.

Table 6 Raw water requirements and wastewater production

Parameter	Units	Case 1	Case 2	Case 3	Case 4
H_2 production	tpd	5.0	6.5	(5.0)	(6.5)
NH_3 production	tpd			28.5	36.7
Demineralised water required	m^3/d	50	65	50	65
Raw water for demineralised production	m^3/d	***71***	***92***	***71***	***92***
Cooling duty	MW	4.7	6.0	8.8	11.4
Circulating cooling water	m^3/h	337	431	634	818
Cooling water make-up	m^3/d	***194***	***248***	***365***	***471***
Raw water import	m^3/d	***265***	***340***	***436***	***563***

[5] https://www.water.wa.gov.au/__data/assets/pdf_file/0013/4315/104266.pdf

To reduce the total water demand and subsequent waste water production, air cooling, or dry cooling, of process stream may be considered. From preliminary calculations, dry cooling could cost 20 to 30% less than evaporative cooling. The cost of raw water supply to site, and efficient disposal of waste water, are dominant costs for evaporative cooling (operating cost), while higher capital investment is required for dry cooling.

The decision as to whether water or air cooling would be used is typically driven by process economics, and site layout. Air cooling equipment requires a larger footprint. Additional considerations include the general climatic conditions, and water scarcity in the area. At this stage, no scarcity of water is foreseen for this project, informing the decision to employ water cooling which is reflected in the cost estimate.

8.4 Findings and summary

The potential environmental impacts are summarised below:

- Vegetation and clearing of the site. Vegetation appeared to be predominantly grasses and sparsely distributed trees. Based on the habitat, the appropriate approval pathway would be via a Native Vegetation Clearing Permit.
- Vegetation surveys to support a clearing permit for the site, should be planned and take place at specific times of the year to avoid potential delays to project execution. They should be considered in the next stage of the project.
- Groundwater. Appropriate groundwater testing would need to be undertaken to determine groundwater availability and quality parameters, depending on the specific sources of water identified for the project.
- Visual impact. Some of the taller equipment, such as the ammonia synthesis reactor module structure cooling tower(s), and the security fences, would create some visual impact. The site location, setbacks from roads and existing vegetation and topography, would significantly mitigate these visual impacts, but additional screening may also assist.

9. Contracting and procurement strategy

9.1 Overview

The contracting and procurement strategy employed in subsequent phases of project implementation will have a significant effect on the front end engineering and project development, and the plant performance, operations and maintenance considerations. The strategy would be structured to align with Pacific Hydro's risk profile over the development lifecycle of the project. Key factors affecting the strategy selection include:

- Remote location of Kununurra
- Source of core process technology and packaging strategy
- Availability of skilled operational and maintenance staff

A range of options were analysed which are presented in this section below.

9.2 Strategies considered

The contracting strategies considered were:

- BOO – Build Own Operate
- Full EPC – Turnkey package with delivery managed by EPC contractor
- EPC – Contractor manages all inside the fence, with an Owner's Engineer appointed in a project support role
- EPCM - individual EPC packages plus an installation contract

A range of evaluation factors were considered, reaching the conclusion that EPC would be the best delivery approach.

9.3 EPC strategy discussion

Based on early stage discussions, an EPC contracting strategy is considered the most appropriate for the development of the project in subsequent stages. Although EPC can be a fully integrated package managed by the owner, EPC with an appointed Owner's Engineer is recommended.

Successful integration of the key parties in subsequent project implementation stages will be considered critical to deliver an operating facility, with clear understanding of performance and risk allocation.

- Project developer - Pacific Hydro
- Owners Engineer – technical support through project delivery
- Core equipment/technology supplier – supply of process systems, from water treatment to finished product storage
- Constructor – supply of balance of plant, civil, and supporting infrastructure (e.g. power, fire systems, lighting, security)
- Operator

The recommended EPC model would consist of an Owners Engineer acting on Pacific Hydro's behalf to provide technical and construction support services throughout the project lifecycle. The EPC model also includes an Australian based constructor working closely with the selected technology supplier. The assessment of the constructor should include previous experience in remote area (ideally WA) construction such as mine sites and a history of project delivery in oil and gas or allied sectors such as chemicals.

The selection of the constructor is expected to take place following the definition of the preferred plant configuration and shortlisting of technology suppliers. The selection of constructor would be discussed with the technology supplier and, subject to the preferences expressed by the technology supplier, an early contractor involvement process is expected to provide valuable input to the subsequent stages of project design and construction planning.

9.3.1 Constructor scope

The delineation of scope is likely to be a relatively straightforward process between the technology supplier and constructor with direction from PH and the owners' engineer. The constructor scope is assumed to include:

- Site preparation and establishment including site ground works, clearing and construction site establishment (sheds, amenities, temporary power etc).
- Civil works (including roads, foundations, buildings, landscaping)
- Balance of plant (including power infrastructure, Non process infrastructure such as compressed air, cooling towers, fire systems.
- Security, lighting, fencing, building fit-out.
- Piping and process connections as determined by the process technology supplier.
- Support for technology supplier to transport, and unload at site.

9.3.2 Technology supplier scope

The technology supplier would be responsible for:

- Core process design working with the EPC contractor to establish the balance of plant sizing and selection.
- Equipment construction and fabrication including development of modular structural design.
- Quality management and factory acceptance testing,
- Packaging and shipping including coordination of Australian based delivery to site.
- Supervision of site delivery and offloading.
- Supervision of process and utility connections
- Development and implementation of site-based commissioning and testing
- Coordination of training and start up in conjunction with the operator.
- Ongoing technical support, performance and warranty obligations

9.3.3 Operators scope

Several scenarios may be considered to select and engage potential operating contractors. The operating contractor is expected to prepare and contribute to the commissioning protocols, operation and maintenance standards and asset management plans, with the technology supplier. Operational safety management is considered critical to the ongoing business continuity. Plant performance would be intrinsically linked to safe operating performance, as measured by key indicators set by Pacific Hydro, and the operating contractor.

The responsibility of the operator includes:

- Health, safety and environmental management, including compliance with licence conditions.
- Production management including target production output.
- Business and financial performance reporting and auditing.
- Asset management and maintenance protocols.
- Compliance with regulations, standards and mandatory reporting requirements (MHF).
- Staffing and shift operations.
- Security.
- IT support.

- Business operations including the interface with clients/customers
- Implementation of safety, and management of change systems
- Training and recruitment

10. Construction, transport and logistics

10.1 Overview

Kununurra's remote location will dictate the transport and logistics strategy for the construction of a complex industrial facility, such as the renewable ammonia production plant. The feasibility study considers the implications of the site location for the movement and supply of materials, resources and packaged systems, from local, national and overseas suppliers.

Site construction would consist of Non-Process Infrastructure (NPI), including roads, buildings, foundations, power supply connections, and evaporation ponds. The core process infrastructure includes the main electrolyser plant and ammonia synthesis plant, with associated storage. The EPC model, discussed in this report, is assumed to consist of a local constructor working with the technology supplier.

Subject to the selected procurement and contracting strategy, NPI supply and construction would use an Australian based contractor, with knowledge of the region, and capable of mobilising a skilled workforce consisting of local, state and national resources. The availability, or lack, of locally sourced materials may have a significant impact on the overall project budget and schedule, particularly where supplies would be sourced from Darwin, or further afield.

The balance of plant is expected to be supplied in a modular format, from overseas, via sea and road transport. Sea transport would unload at Darwin, or Wyndham.

10.2 Modular build strategy

The core process technology for hydrogen and ammonia production would be made overseas, most likely in South East Asia, regardless of the selected vendors. A modular build strategy allows the equipment to be constructed and tested largely offsite, before deconstruction and packaging for transport. Modular design and construction is increasingly common across industries, with significant benefits, including reducing site construction effort, and minimising testing and commissioning activities. The incremental cost of modular fabrication is expected to be offset by the construction cost and schedule savings, and overall project delivery risk reductions.

When preparing equipment specifications for procurement, the requirement for a modular build style would be a key element. All equipment would be transported by road from either Port of Wyndham, or Port of Darwin. Specifications would need to factor road conditions, maximum load requirements and costs associated with escorted loads. Early contractor involvement (ECI), in collaboration with the equipment supplier, is considered essential to support an integrated delivery model, that considers the local conditions and transport constraints.

Modularisation allows the plant to be shipped in standard 20 ft or 40 ft containers, allowing straightforward handling at ports, and transport by standard vehicles. Containers also give weather and impact protection. Oversize equipment transport may be required, and needs to be sized to suit route load, and dimension, limits. If the final plant output is hydrogen only, the overall construction strategy would be simpler. The supply of the core electrolyser technology is relatively straight forward, consisting of a series of modular electrolysis packages, to be housed in an appropriate building for weather protection. Water treatment and balance of plant packages can also be readily containerised.

Hydrogen storage and unloading is largely dependent on the transport methodology. Compressed hydrogen storage vessels are likely to be fabricated overseas, either in one piece for smaller vessels, or several pieces for larger systems, with final welding at site. A series of smaller connected vessels would remove the site welding requirements, with all QA completed before shipping. A series of pressure vessels are easier to fabricate and transport, and may provide a lower overall risk profile at site, with the capability to isolate individual units.

If LOHC are used, the fabrication of standard bulk liquid storage tanks is readily achievable in remote locations. Several innovative options may be considered to minimise site-based fabrication. The equipment required to load the hydrogen into the carrier is assumed to be a relatively small component cost of the overall budget, and may result in long term operation savings, and a reduction in complex high pressure hydrogen storage CAPEX.

The ammonia plant construction would also be delivered in a modular style, with the majority of process systems within the plant footprint. Ammonia storage vessels would need to be constructed at site, but most of the plant and equipment would be packaged.

10.3 Construction resources

Subject to the site's final configuration, the construction resources required on site would be as follows:

Construction phase	Hydrogen facility expected range (FTE)	Hydrogen + Ammonia facility expected range (FTE)
Initial Site Preparation	10-15	10-15
Civil Works	10-15	10-15
Power Connection	30	50
Equipment and Building	30	50
Piping and Electrical	30	50

Table 7 Construction full time equivalents

During operation, the total amount of FTEs would be as follows:

Construction phase	Hydrogen facility expected (FTE)	Hydrogen + Ammonia facility expected (FTE)
Operators	9	15
Support Personnel	3	3
Total	12	18

Table 8 Operation full time equivalents

The regional agricultural industry, and the proximity of the diamond mine, means the area has labour available, mostly earthmoving-related, and the capacity to support a short term construction workforce. Skilled resources may be deployed on a fly in fly out basis (FIFO), drawing on personnel from east and west coast Australia. The constructor is assumed to allocate at least one construction manager, safety manager and some discipline (e.g. electrical, mechanical, civil) site superintendents to supervise site works on site on various work fronts, to optimise the schedule.

10.4 Construction schedule

An indicative construction schedule can be found in Appendix B - Construction schedules and indicates a possible order of works. The basic order of construction is earthworks, roads, foundations, buildings, and then equipment installation. The construction would take place in the dry season, with many work fronts to maintain progress. Equipment commissioning would start following immediately after installation.

10.4.1 Long lead items

The core process technology, (electrolysers, air separation unit, ammonia synthesis packages), are expected to represent the long lead equipment packages. Vendor responses suggest a required lead time of approximately 12 to 18 months. Subject to the selection of the final plant configuration and technology suppliers, the electrolysis and ammonia synthesis packages could be ordered early in the design development programme, when throughput and power availability are confirmed. The significant increase in renewable hydrogen and ammonia projects, globally, may put pressure on equipment supply chains, particularly the more innovative PEM electrolysers.

10.4.2 Site construction considerations

The construction strategy discussions noted the potential for weather to affect the construction schedule. The site-based works should be timed to avoid the tropical wet season, and mitigate the risks of delays and hazardous conditions. The wet season is from October to April, when northern Australia is vulnerable to the cyclones, heavy rainfall, and flooding. These conditions would affect the ability to transport goods and personnel to and from the site by road. Construction activities are likely to be adversely affected, including delays, and weather-related risks to crews and equipment, such as flooding and lightning strikes.

Construction planning should account for the wet season by scheduling works at other times, though higher demand may mean contractors are booked in advance. Project planning would consider this. For the hydrogen only option, a site construction period of less than nine months is considered feasible. Timing of site preparation and preliminary site works can coincide with the later stages of the wet season, providing access for key civil works, and foundations, to begin, when ground conditions are more suitable. The ammonia production unit is more complex and would require additional schedule and specialised contractors. The modular construction strategy, however, aims to minimise onsite works.

The hydrogen-only option is not expected to result in significant structural and foundation requirements which may support the local supply of concrete and civil contractors to undertake the building foundations. Several works front could be established to prepare and construct a prefabricated structure, housing the electrolysis.

10.5 Road transport

Modular packages are assumed to be delivered and unloaded at Darwin port. Subject to Port of Wyndham constraints, packaged modular systems, or containerised equipment, may be delivered directly to the port, or barged from Darwin to Wyndham. Oversize load routes are provided on the NT government website. Further definition of package systems would support the development of a comprehensive transport strategy.

The transport distances from ports and major centres, as noted below, would be expected to add cost and risks to the overall construction strategy. These can be managed through early definition of requirements and routes. The closest major transport centres to the Crossing Falls Road site are:

- Kununurra, WA: 5 km
- Wyndham Port, WA: 116 km
- Darwin, NT: 821 km
- Broome WA: 1053 km

All major centres are accessible via major Category 1 roads. This high standard two-way, two-lane road type, of national or state importance, can accommodate oversize and heavy loads. The final 2 kms to site, along Crossing Falls Road, is a Classification 2 road, with a lower capacity for heavy vehicles. The site inspection indicates oversize vehicle clearance is good, due to the absence of roadside utilities.

10.6 Port of Wyndham

The Wyndham Port is the only deep-water port between Broome and Darwin. Cambridge Gulf Limited operates and manages the port. The Department of Transport owns the port, and regulates it alongside its transitioning successor, the Kimberley Ports Authority.

Figure 7 Wyndham port berth structure (https://www.cgltd.com.au/cgl-wyndham-port/)

Port of Wyndham has a maximum tidal range of 8.2 meters, and tidal streams run at up to 7 knots through the narrower sections of the Cambridge Gulf passage. The port has one of the longest pilotages in Australia, at 45 nautical miles north of the jetty. The jetty is 13m wide with 314 m of berth face. The south berth is generally used for deep draft cargo vessels. The port advises that unloading of equipment packages should be undertaken by the ship's crane onto low link loaders and deposited in the container park. The container park is bitumen with full security.

Port of Wyndham can support a modular supply and construction methodology, via direct shipping from international locations, if required. The port advises it can unload any cargo capable of being transported by road.

11. Operations and maintenance

11.1 Overview

The contracting strategy workshop considered possible operation and maintenance (O&M) strategies, and which would be optimal for this project. There are a number of models that can be adopted, including:

- Full operations and maintenance by the owner
- Operation by the owner, and maintenance outsourced
- Operations and maintenance outsourced

11.2 Strategies of vendors and industry

11.2.1 Full operations and maintenance by owner

Under this model it is envisaged that, as part of the procurement process for the facility, Pacific Hydro would request the successful technology provider is retained for two years and operate and maintains the facility. During this time, the technology provider would train Pacific Hydro's own staff. After the two year period, the technology provider would hand over operation and maintenance duties to Pacific Hydro.

11.2.2 Operation by owner, and maintenance outsourced

Under this model, Pacific Hydro has the responsibility for operating the facility, outsourcing the routine and scheduled maintenance to a maintenance contractor. The term of the maintenance contract could be a five year term, for example, renewable by PH, if the contractor satisfies contract KPIs. Alternatively, PH could choose another contractor.

11.2.3 Operation and maintenance fully outsourced

Under this model, Pacific Hydro would engage a contractor to operate and maintain the facility for an agreed period. The contractor would be fully responsible for day to day operations and all necessary routine and scheduled maintenance. The contractor would be monitored using agreed contract KPIs. An indicative term may be five years, renewable if the contractor meets the contract KPIs.

11.3 Defects liability

The defects liability period can vary but is commonly 24 months post commissioning. During that period, the contractor is responsible for any defects during facility operation. It is common to engage the contractor to remain on site for the defects liability period, to operate and carry out maintenance as required, and attend to any defects.

The structure of O&M contract would be negotiated between Pacific Hydro, (and/or the designated operating organisation), the technology supplier and construction contractors. The operating contractor would be responsible for KPIs related to overall plant safety and performance. Alongside the anticipated performance warranty provided by the technology supplier for a given period, this is expected to drive the maintenance strategy and schedule, and the operational handover from the constructor to the operator.

11.4 Remote location

The Kununurra region has limited industrial capability (ADM is a notable exception). The highly automated facility would operate 24/7, with the capability to remotely operate the site where required. The initial assumption is that the site would be manned during operation, based on the hazardous nature of hydrogen and ammonia.

This assumption may be challenged during subsequent stage of the project, with a view to unmanned operations where no personnel access is required, and sufficient safety integrity levels can be demonstrated, subject to continuous remote monitoring. This may be more feasible during out-of-hours periods, where vehicle access to the site is not required (e.g. hydrogen collection)

Skilled technical services may need to be sourced from regional centres such as Perth or Darwin to provide specialist maintenance services.

11.5 Operations and maintenance

11.5.1 Operations

The facility would be manned on a 24/7 basis, during operations. The number of operating and maintenance staff, however, would be driven by the extent of site automation, and production output. Operational staff would be trained in the maintenance requirements of the facility as a dual skill rather than separate teams, it is expected. The hydrogen-only option, being a simpler process, would typically have lower staffing requirement than ammonia.

Site administration and management would only be required during a day shift, with limited overnight coverage. It is anticipated that remote dial-in support from technical specialists could readily be provided for both operations and maintenance teams. Online analytical services may also be provided as a predictive, or preventative maintenance tool.

The site operating team would be supported by contracting companies able to carry out routine and specialist maintenance, as required. For all scheduled maintenance requiring specialist support by the technology provider (OEM), there would be an arrangement for a FIFO service to conduct the work, as scheduled, over the agreed maintenance cycle.

11.5.2 Maintenance

The facility would be designed to be maintained with minimal support plants and equipment. All required equipment lifts would use simple monorails and lift tackle. Access to the facility would be by a perimeter roadway, to enable access to all buildings.

The workshop would be fitted with a 10 T overhead travelling crane, which can lift the heaviest electrolyser component. The electrolyser building would also be fitted with an overhead travelling crane, to facilitate maintenance duties requiring lifting of heavy components.

The ammonia synthesis facility is also designed to enable easy access and equipment maintenance. the warehouse would be stocked with spares for equipment vital for the facility’s safe and viable operation, as may be required between scheduled maintenance periods.

11.6 Spares inventory

Initially, the procurement process would request the technology provider/contractor provide two years’ worth of spares, to be stored in the facility warehouse. Over time, additional spares may be stored for components likely to fail or have affect production.

As a scheduled maintenance period approaches, the facility supervisor would ensure all necessary replacement plant and equipment are ordered and stored in the warehouse, in advance.

11.7 Recommended O&M strategy

As an emerging industry in Australia, a challenge would be the limited number of contractors with the required operating and maintenance skills and experience to maintain the facility. Contractors with similar skill sets are available for the operation of petrochemical facilities. Experience is also available in large European companies considering entry to the Australia industry. It is common to appoint an O&M Contractor during the construction, testing and commissioning of the facility.

12. CAPEX estimates

12.1 Overview

A capital expenditure estimate (CAPEX) has been developed for the two cases - hydrogen-only, and hydrogen and ammonia together. Engagement of suppliers in subsequent stages of the project, with a well-defined project requirement, is expected to result in more competitive responses, where the vendor perceives a more developed project outcome. The CAPEX estimates developed are classified as Class IV, according to AACE International Recommended Practice No 18R-97. Typically, a Class IV cost estimate has an accuracy of -30+50%.

12.2 Basis of estimate

CAPEX estimates for the two cases are shown in Table 9.

Table 9 Plant configuration and capacity for CAPEX estimates

Case	Hydrogen-only	Ammonia production
Product	Gaseous compressed hydrogen (200 barg)	Liquid ammonia
Capacity	6.5 tpd H_2 (2,150 tpa)	28.5 tpd NH_3(10,000 tpa)
Configuration	Water treatment 15.5 MW electrolyser Hydrogen compression and storage Loading to tube trailers for road transport Utilities to support plant	Water treatment 15 MW electrolyser Nitrogen generation (ASU) Ammonia synthesis unit (including compression) Ammonia storage tank (refrigerated) Isotainer filling unit for road transport Utilities to support plant

The estimate basis is the following:

- The estimate currency is AUD (converted where required from the base currency of Euro or USD).
- The project is in the remote north of WA, which adds cost due to the difficulty of transport of plant and equipment and additional costs for FIFO staff. Engagement with potential contractors, in subsequent stage, would be important to define the strategy and costs associated with construction and operation.
- An EPC contracting strategy. Further investigation is required to identify the scope of supply battery limits, and additional project management requirements, and owner's cost to manage the contract.
- Preliminary quantities.
- Pricing as of third quarter 2020.
- Exclusive of Goods and Services Tax (GST).

The Class IV estimate includes the following:

- Project direct costs:
  - Direct man-hours.
  - Direct labour cost.
  - Plant and equipment cost.
  - Bulk material cost.
  - Contractors distributable costs (allocated per task).
  - Freight cost (included in the supplied cost).
  - Construction equipment cost, (as applicable, and included in contractor distributables).

- Subcontract cost (not identified at this stage)
- Growth (where applicable).

- Project indirect costs essential to support construction, but that cannot be attributed to, nor become a part of, the permanent plant structure, are itemised as indirect costs. Indirect costs include:
  - Common distributables –the overall site indirect costs required to support the direct-cost effort of the project.
  - Professional services – cost of engineering service support during the implementation phase.
  - Owner's costs – cost of project management, and supporting functions, to manage the project.
  - Contingency – an allowance to cover the cost of unknown risks that may occur within the scope, over the project life.
  - Escalation –the allowance for the change in cost due to market conditions, over the project life.

12.2.1 Exclusions

The following factors are excluded from the cost estimate, but may contribute to the overall costs:

- GST
- Cost of funding
- Exchange rate variations
- Costs to date committed
- Land acquisitions
- Operating costs
- Cost impacts, due to change of site locations
- Contaminated materials that may be found during geotechnical survey, or construction

12.2.2 Indirect costs

Indirect costs have been factored based on historical project information. The indirect costs are:

- Common distributable and temporary costs expenses for Engineering Service Providers (ESP)
- Commissioning, testing and handover
- EPC management for cases one and three are consultancy fees for further design and the ESP.
- Owner's costs are for project delivery and operational readiness
- Escalation is the time it takes to complete the project, from estimate completion. Assumed to be 3 years
- Contingency.

Table 10 Indirect cost assumptions

Indirect Cost Description	Allowance
Common distributable, Commissioning, testing and handover, Owner's costs and Operational readiness	16%
EPC management (Cases 1&3)	Consultancy fees plus 2%
Escalation and Contingency	33%

12.3 CAPEX results

The CAPEX estimate assumes the EPC model basis for assumptions relating to the construction and indirect costs.

The EPC model places the overall project delivery risk with the contractor and, as such, incurs a cost premium. This cost premium is expected to vary depending on the technology supplier, technology maturity and the extent of performance warranty required.

12.3.1 Hydrogen-only (15.5 MW 6.5 tpd) EPC CAPEX

The estimated CAPEX is for a Hydrogen production facility, with the EPC contractor providing the required performance and project delivery warranty.

Hydrogen $119,000,000

12.3.2 Hydrogen/ammonia (28.5 tpd) EPC CAPEX

The CAPEX includes ammonia production of 10 tpa, and used the full OEM vendor price, an EPC management structure with the contractor taking the plant performance risks. The total CAPEX for a hydrogen/ammonia plant is in this range.

Hydrogen/ammonia: $260,000,000

13. OPEX estimate

13.1 Overview

Operating costs are typically split between fixed and variable operating costs. Fixed operating costs do not vary with production rate; variable operating costs depend on the amount of product produced. For the green hydrogen and ammonia facility, the operating costs are typically divided into fixed and variable operating costs, as follows:

Fixed costs: maintenance, labour, laboratory and analysis costs, overheads, license fees and plant insurance.

Variable costs: energy costs, raw water import costs, chemicals, catalysts for the ammonia synthesis plant, brine and salt disposals.

13.2 Findings and summary

Table 11 below, shows an estimate for the dollar value of operating costs. These costs are not generally available, so they have been estimated as a proportion of equipment cost. Where possible, a cost is supplied on an annual basis. In each case, the average for each of the hydrogen and ammonia cases were used to calculate the operating cost.

Table 11 Operating cost indicators

Parameter	Units	Hydrogen cases (Case 1&2)	Ammonia synthesis cases (Case 3&4)
Total opex	**M AU$/annum**	**12**	**17**
Breakdown			
Fixed opex			
Maintenance:	% of equipment cost	See Table 12 for typical %	
	AU$/annum	1,300,000	3,400,000
General site costs (assumed allowance)	AU$/annum	1,000,000	1,000,000
Laboratory costs/analysis (assumed allowance)	AU$/annum	500,000	700,000 – 800,000
Labour	AU$/annum	1,800,000	2,700,000
Insurance	AU$/annum	1,620,000	2,980,000
Variable operating cost			
Raw water m^3pd 265-340	AU$/annum	104,940-135,036	172,656-222,948
Catalysts and chemicals		AU$ 300,000 – 500,000/annum.	
Salts disposal (infrequent)		A small portion of produced brine would end up as mixed salts which would have to be disposed by a specialist waste company for a fee. If the decision is to dispose of wastewater/brine as is, the associated disposal costs could be higher.	

Maintenance costs are typically determined as a percentage of equipment cost, depending on the particular type of equipment. The percentages typically assigned to specific equipment types are shown in Table 12.

Table 12 Maintenance cost percentages

Equipment type	Percentage of equipment cost for maintenance cost (%)*
General equipment (utilities, water treatment, brine systems, etc)	1.0
Electrolyser**, ASU, Ammonia synthesis unit and compressor and other rotating equipment	9.0
Storage vessels and tanks	0.5

Notes:

**Costs are determined on an equipment supply cost, not installed capital cost for the plant.*

***The annual electrolyser maintenance cost does not include major overhaul costs incurred every eight to 10 years, depending on the electrolyser vendor. These costs can be 5-15% of the capital cost of the electrolyser, depending on the electrolyser type, with PEM units having higher overhaul costs than alkaline units.*

As expected, operating costs for the ammonia synthesis cases are higher, at approximately 40% higher than hydrogen production only cases. These costs are for production only (i.e. no transport costs have been considered, yet).

14. Conclusions and next steps

14.1 Next steps

The key question for the project to address, before proceeding to subsequent stages, is whether to produce ammonia, or focus on hydrogen production only. This requires an understanding of the specific market demand, the scale of the addressable market, in the local region, and the location of potential offtakers. This report presents the analysis of technical production pathways, risks and costs. The following commentary is intended to guide the decision making process, to determine the most suitable product from the facility.

This report is intended to provide a basis for Pacific Hydro to conduct the subsequent financial, risk and market analysis assessment. The decision to pursue hydrogen only, or to further process it into ammonia, would have a fundamental bearing on the project capex, market options for the sale of the product, the associated logistics, and the overall site risk profile.

The recommended steps are as follows:

- Undertake Planning and Environment studies on site
- Get all Planning and Environmental approvals for the project
- Appoint an owner's engineer
- Owner's engineer to develop a project definition study
- Owner's engineer to carry out a tender process to identify a suitable main contractor
- Main contractor to carry out a FEED study
- Main contractor to carry out a tender process for procurement of specialised plant packages, balance of plant equipment, and contractors to construct the plant
- Main contractor to be responsible for all site related activities, and plant commissioning and testing

14.1.1 Tender process for a main contractor

The owner's engineer would carry out a tender process to secure a main contractor, to be responsible for:

- Undertaking a tender process to engage suitable OEMs, (for specialised packages), and balance of plant (BOP) equipment, and the necessary mechanical, electrical and civil/structural contractors.
- All engineering procurement, and construction activities.

14.1.2 FEED

Following a successful financial analysis, GHD recommends that a FEED be undertaken for more detail to support a more accurate Capex (typically +/-10 to 15%). Potentially, this could include further engagement with technology vendors and construction partners. The FEED study would be undertaken on the basis that the core process technology design is developed by the technology supplier, as a fully integrated package.

The FEED study objective is to develop the design for balance of plant, civil, structural (including buildings) and electrical services, as required to support the core process technology, based on the identified scope inclusions. The completion of the FEED package represents the basis of the engagement of the technology supplier and constructor.

The FEED development is expected to include all relevant disciplines necessary to develop a tender package. Design development at FEED may vary 30 to 50%, but design extent would be guided by the requirements of both the technology supplier and constructor.

The FEED study would also be expected to provide the planning approvals strategy approach, which may be managed separately from the EPC package. Any design requirements imposed by the planning process, however, must be understood at the tender phase.

Risk studies would be completed at various stages of design development. A preliminary hazard assessment/HAZOP would be completed, based on the FEED study design development. The expectation would be that detailed risk assessments would happen during the detailed design phase.

Typical FEED study duration is expected to be between six and nine months, based on the core technology design, if managed by the technology provider. Costs would vary depending on the level of design development required. A value in the region of 2% of capex. However, is considered typical, noting the expected design input required by the technology supplier.

14.1.3 Tender

Once the design is 85% complete, the main contractor would develop specifications and tender documentation. As the design nears completion, lists of potential OEMs, and contracting organisations, would be compiled. Discussion would progress with all interested parties after a short EoI process.

Once issued and received from OEMs and contractors, the tenders would be evaluated. After clarification meetings, involving the main contractor, and the owner’s engineer, the contracts would be awarded, subject to the project reaching financial close. A FEED report would be issued, and a project definition document would be developed, for the purpose of financing, leading to financial close.

After the tender and clarification process is complete, negotiation would proceed with successful tenderers and contracts would be issued subject to successful financial close of the project.

14.1.4 Detailed Design

The detailed design phase, removes uncertainties, and provides a completed project design. The main contractor would do much of the design, but individual, specialist OEMs, and equipment suppliers, would also undertake detailed design, before manufacturing project equipment.

14.1.5 Procurement

The procurement phase reviews received tenders, and the main contractor recommends a preferred supplier for each equipment item/package. When PH, and its owner’s engineer, have approved the tender evaluation, the preferred tenderer would go through the contract negotiations process with the main contractor, supported by the owner’s engineer.

14.1.6 Construction

The construction phase would begin ahead of procured items arriving on site. The civil/structural contractor is expected to start several months before equipment arrives on site. Once the equipment has arrived on site, the mechanical and electrical contractors would install, commission and test the facility under the main contractor’s supervision. It is envisaged that the construction phase would take approximately 29 months.

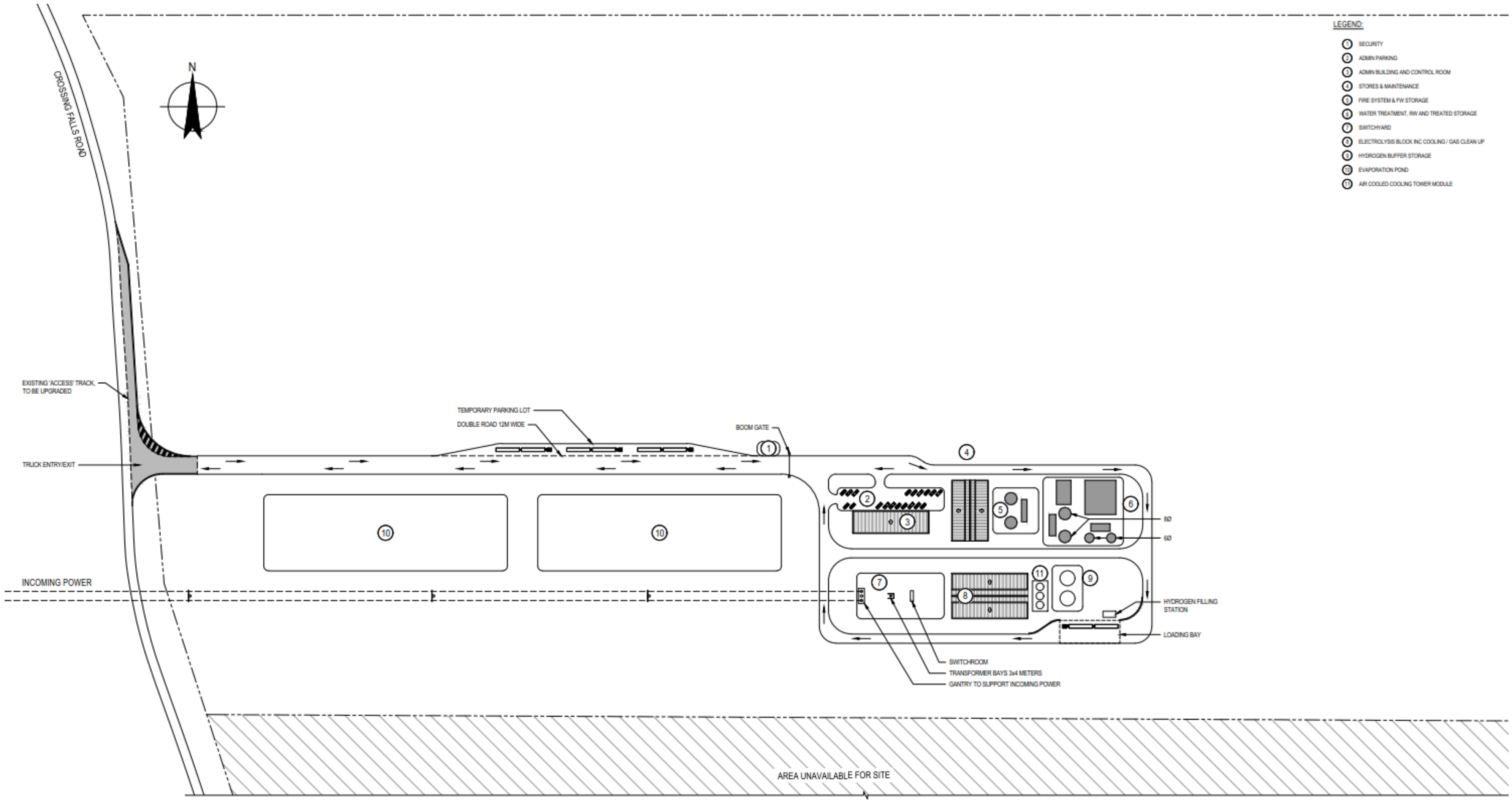
The relevant technology providers and equipment suppliers would undergo a design phase, followed by manufacturing and factory testing, before delivering the relevant equipment to site, as discussed above. The main contractor would mobilise to site, and would be responsible for all site activities, including maintaining safe site practices.

The owner’s engineer would be represented on site, to oversee all activities, and ensure that the main contractor fulfils its commitments, and the plant is commissioned and tested in accordance with the agreed PH procedures.

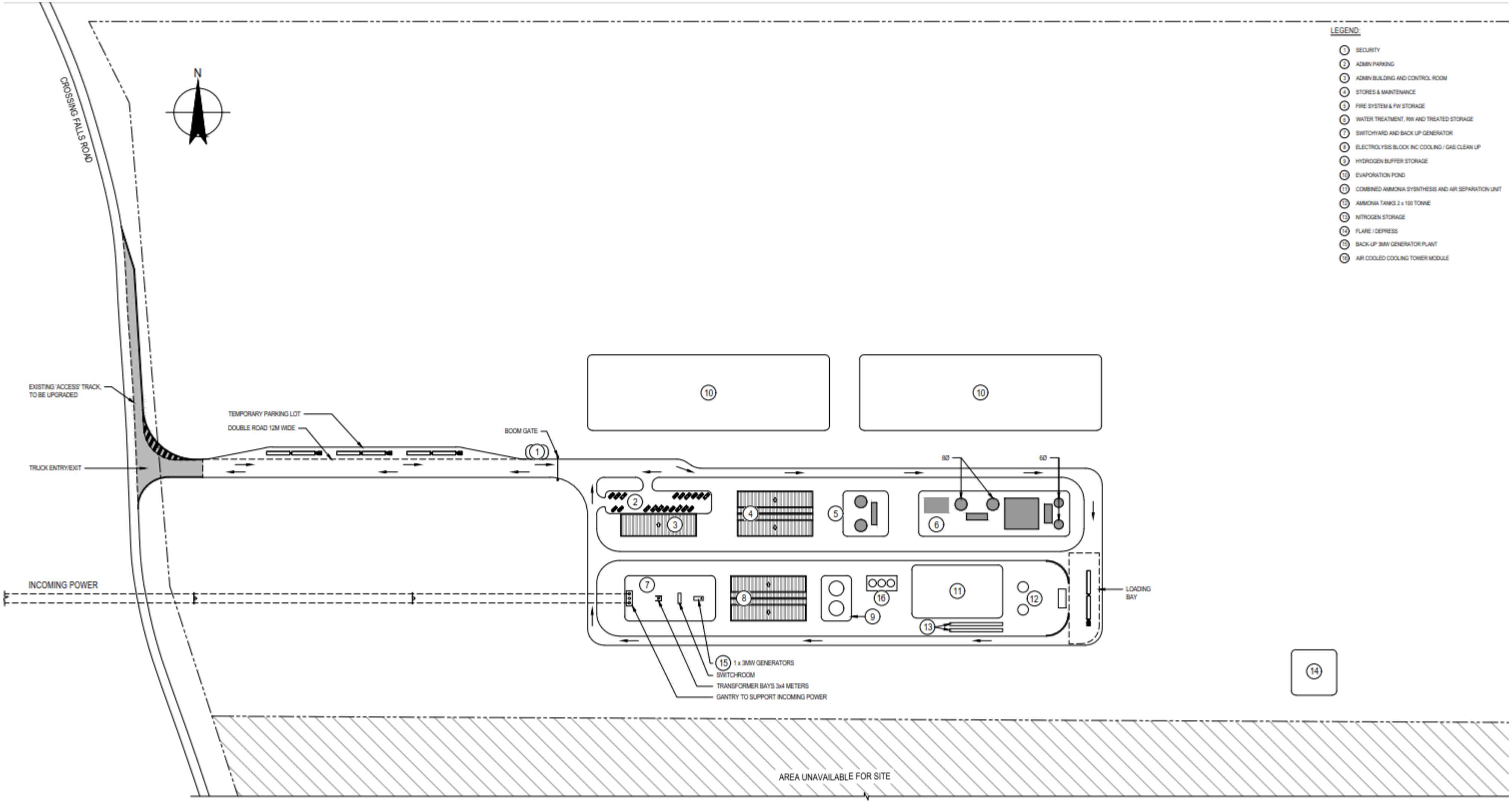
15. Appendix

15.1 Appendix A - Feasibility design layouts

15.1.1 Hydrogen only layout

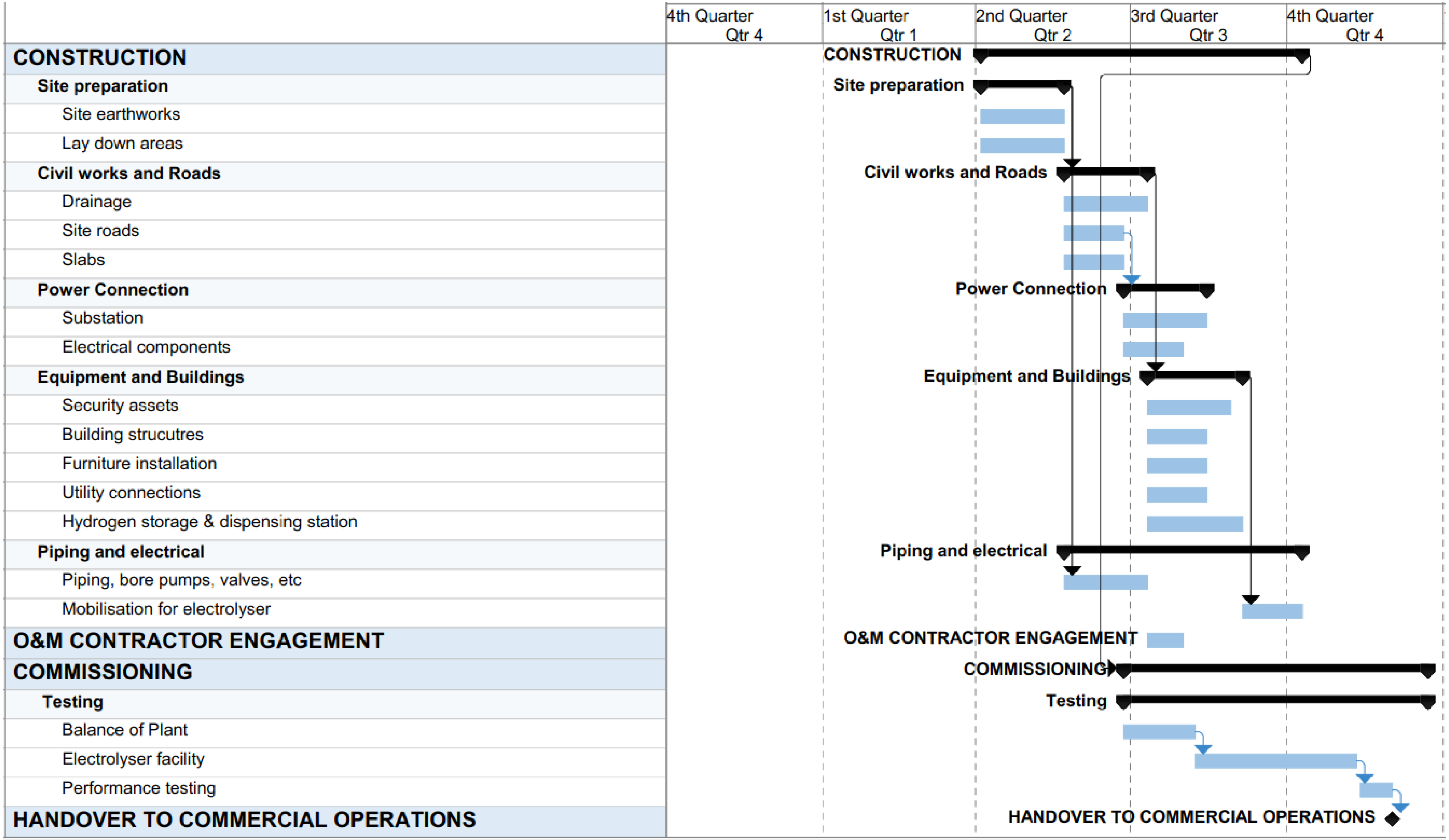


15.1.2 Hydrogen and ammonia layout



15.2 Appendix B - Construction schedules

15.2.1 Hydrogen only schedule



15.2.2 Hydrogen and ammonia schedule

CONSTRUCTION
Site preparation
Site earthworks
Lay down areas
Civil works and Roads
Drainage
Site roads
Slabs
Wet season pause
Power Connection
Substation
Electrical components
Equipment and Buildings
Security assets
Building structures
Furniture installation
Utility connections
Hydrogen storage & dispensing station
Piping and electrical
Piping, bore pumps, valves, etc
Mobilisation for electrolyser
COMMISSIONING
Testing
Balance of Plant
Electrolyser facility
Performance testing
HANDOVER TO COMMERCIAL OPERATIONS