Jemena Limited

Western Sydney Green Hydrogen Hub (WSGHH) Project

Final Report and Lessons Learnt

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Executive Summary

This report details the **processes and outcomes involved in the development of the Jemena Western Sydney Green Hydrogen Hub** (WSGHH) power to gas (PtG) demonstration project. An account is provided for the processes of the design, procurement, construction, initial testing, commissioning, and operation of the facility. The project outcomes were achieved and are documented, along with the lessons learnt. Recommendations for future projects are also provided.

The WSGHH project began in 2017 with funding from ARENA and the facility began a five year trial period following its commissioning in November 2021. Operations at the facility involve **creating renewable hydrogen from renewable electricity to be injected into the natural gas grid** in the area for testing purposes. The facility was designed to **identify and mitigate commercialisation barriers of hydrogen technology** in Australia, with a specific emphasis on the application of hydrogen blending. The objectives of the project were to gain an understanding of regulatory, environmental, social, and economic barriers to the PtG technology of electrolysis in Australia, as well as to promote awareness of the technology and share insights with stakeholders of the project outcomes.

As the WSGHH facility was the first hydrogen project developed by Jemena, it required a **new pathway to gain regulatory approvals**, paving the way for the rollout of more hydrogen projects in the future. These included new training requirements for operation and maintenance staff, the establishment of a dedicated hydrogen activity permit and accompanied competency assessments, new work instructions and response codes, and new safety requirements for hydrogen related systems.

Key issues discovered during the early operation of the facility included the overheating of thyristor diodes in the electrolyser package and the failure of an air compressor in the electrolyser during a complete electronic stop procedure. The diodes were replaced, and the cause of these issues is currently under investigation. The compressor was also repaired with no further issues. Additionally, as a result of unfamiliarity with equipment rated to the European standard known as ATEX (ATMOSPHERES EXPLOSIBLES; the minimum safety requirements for workplaces and equipment used in explosive atmospheres), an internal review was conducted of the documented processes and installed electrolyser plant to validate compliance with Australian Standards, including AS 3000:2018 - Electrical installations.

A testing program was developed for the WSGHH that aimed to provide operational experience and understanding of the impacts of hydrogen and involved blending hydrogen with natural gas in the existing natural gas network. The testing program included tests relating to the performance of the electrolyser and hydrogen injection panel, hydrogen purity, hydrogen leakage, pipeline materials, safety and compliance and demand response. The results of the testing showed that the electrolyser package operates with an **average efficiency of approximately 60 %**, and at a **maximum efficiency of 62 % when operating at 60 % of the rated capacity** Additionally, the rapid ramping capability of the electrolyser was observed from incremental changes to the load to be **4.5 % per minute ramping up and 25 % per minute when ramping down.**

The outcomes of the project were all achieved and included:

- the overcoming of **substantial project challenges**, such as complying with complex legislative and regulatory hurdles for the injection of hydrogen into the gas network, implementing significant pipeline cleaning procedures to maintain high hydrogen purities and managing the project in light of the pandemic and the associated complications;
- the promotion of **new industry standards and innovations**, whereby the WSGHH facility was the first of its kind in Australia and involved the unprecedented blending of hydrogen gas in the natural gas network, as well as the establishment of industry-first safety and permitting processes for hydrogen systems;
- the **advancing of the regulatory environment** in Australia, where Jemena worked with the NSW Government to amend the legislative regime to include hydrogen gas under the Gas Supply Act and to develop the first distributor’s license for hydrogen in Australia, and;

- the **effective collaboration with the community and project stakeholders**, whereby over 100 commercial and 7 industrial stakeholders were engaged to evaluate the impacts that hydrogen gas would have on their processes.

A Knowledge Sharing Plan was developed by Jemena with ARENA to share insights and lessons from the WSGHH and the testing program on a continuous basis to the wider hydrogen industry. Substantial engagement was undertaken over the course of the project both domestically and internationally in the form of innovation forums, technical workshops, site tours, conferences, and news articles that all involved the WSGHH project. Furthermore, Jemena participated in government processes, such as the National Hydrogen Strategy and Standards Australia to assist in the development of new technical documentation in the field of hydrogen.

A workshop was held to understand the **lessons learned from the WSGHH project**, which involved:

- approvals and stakeholder management;
- health, safety, and quality;
- engineering, scope, and construction execution;
- cost and schedule control;
- procurement and contract management;
- people resourcing and administration, and;
- integration and closeout.

Key positive lessons realised in the workshop included:

- a strong level of engagement with the community, government and other stakeholders allowed for significant promotion of the project delivery and minimisation of rework of documentation;
- the high importance placed on health, safety and quality was realised through frequent and consistent site inspections, audits, engagement with sub-contractors, and drug and alcohol testing (with no positive results);
- the strong adaptability of the project team to manage changes to the design and to rapidly mobilise allowed for the timely completion of the project, despite challenges introduced by the pandemic;
- the ability for the project team to identify and adapt initially non-compliant plant equipment allowed for effective contract and risk management, and;
- the successful early operation of the facility with minimal support from the project team demonstrated the intuitive plant design for existing Jemena gas asset operators.

Key opportunities for improvement that eventuated from the workshop included:

- the need for earlier evaluation of planning requirements prior to detailed design;
- the need to include cost and time impacts in development approval pathways;
- the need to plan for the impacts of complex approval processes in early project phases;
- the need for increased communication with local stakeholders to provide fundamental knowledge of hydrogen production, and;
- the need for a greater analysis of the standards of international equipment with respect to compliance with Australian Standards.

Ultimately, **recommendations for future hydrogen projects** include the following:

- Local support from suppliers is essential for smooth post-commissioning operations.
- The inconsistency between International and Australian Standards can be costly if not appropriately accounted for in the design phase.
- Downrating and sizing of equipment can cause significant reliability issues.
- Highly accurate pipeline blending control is necessary for hydrogen blending projects.

Abbreviations

Term	Definition
ACCU	Australian Carbon Credit Unit
ARENA	Australian Renewable Energy Agency
AS	Australian Standard
ASME	American Society of Mechanical Engineers
ATEX	Atmospheres Explosibles
BOP	Balance of Plant
BtM	Behind-the-Meter
DC	Direct Current
DPIE	NSW Department of Planning and Environment
DUOS	Distribution Use of Service
EPC	Engineering, Procurement and Construction
FEED	Front-end Engineering and Design
FCEV	Fuel Cell Electric Vehicle
FFCRC	Future Fuels Cooperative Research Centre
FID	Final Investment Decision
HazOps	Hazard and Operability Analyses
HSE	Health Safety and Environment
IECEx	International Electrotechnical Commission (Explosive Atmospheres)
IPART	Independent Pricing and Regulatory Tribunal
NEM	National Electricity Market
NGL	National Gas Law
NSW	New South Wales
OEM	Original Equipment Manufacturer
PE	Project Engineer
PEM	Proton Exchange Membrane
PLC	Programmable Logic Controller
PPA	Power Purchase Agreement
PtG	Power to Gas
PM	Project Manager
RGGO	Renewable Gas Guarantee of Origin
SCADA	Supervisory Control and Data Acquisition
TUOS	Transmission Use of Service
WSGHH	Western Sydney Green Hydrogen Hub

1. Introduction

Jemena, supported through co-funding from the Australian Renewable Energy Agency (ARENA), successfully designed and commissioned the Western Sydney Green Hydrogen Hub (WSGHH) power to gas (PtG) demonstration facility, located at Horsley Park, in Western Sydney. Operation of the five year trial period commenced in November 2021.

The uptake in renewable power generation, coupled with growing demand for decarbonising energy sectors in Australia, presents a series of challenges and opportunities to gas transmission and the distribution network in NSW. Jemena, as the owner of the NSW gas distribution network, is seeking to evaluate and enable technologies that allow gas customers to affordably access low or net zero carbon dioxide (CO_2) gases, such as renewable hydrogen. The focus of this project is renewable hydrogen produced using renewable electricity.

The WSGHH is located at the existing Jemena high pressure gas facility at Horsley Park and is well positioned to demonstrate the integration of hydrogen and blending within the existing gas network. The network downstream of Horsley Park supplies approximately 23,500 residential, 100 commercial and 7 industrial customers. The PtG facility is one of the most comprehensive demonstrations of hydrogen blending projects in Australia to date, with the capability to produce up to 10.5 kg/h of green hydrogen from a 500 kW proton exchange membrane (PEM) electrolyser. The facility is grid connected and powered by carbon neutral electricity via a 100 % renewable power purchase agreement (PPA). The produced hydrogen is stored in a 340 metre buffer storage pipeline, which has a capacity to store approximately 4 MWh of energy and can be utilised for multiple applications including:

- controlled direct injection into the existing natural gas distribution network at up to 2 % by volume;
- utilisation by a fuel cell package and or hydrogen microturbine to generate power for export to the grid, and;
- in research and development opportunities, including trialling different hydrogen and natural gas blends.

Figure 1 shows an aerial view of the WSGHH.

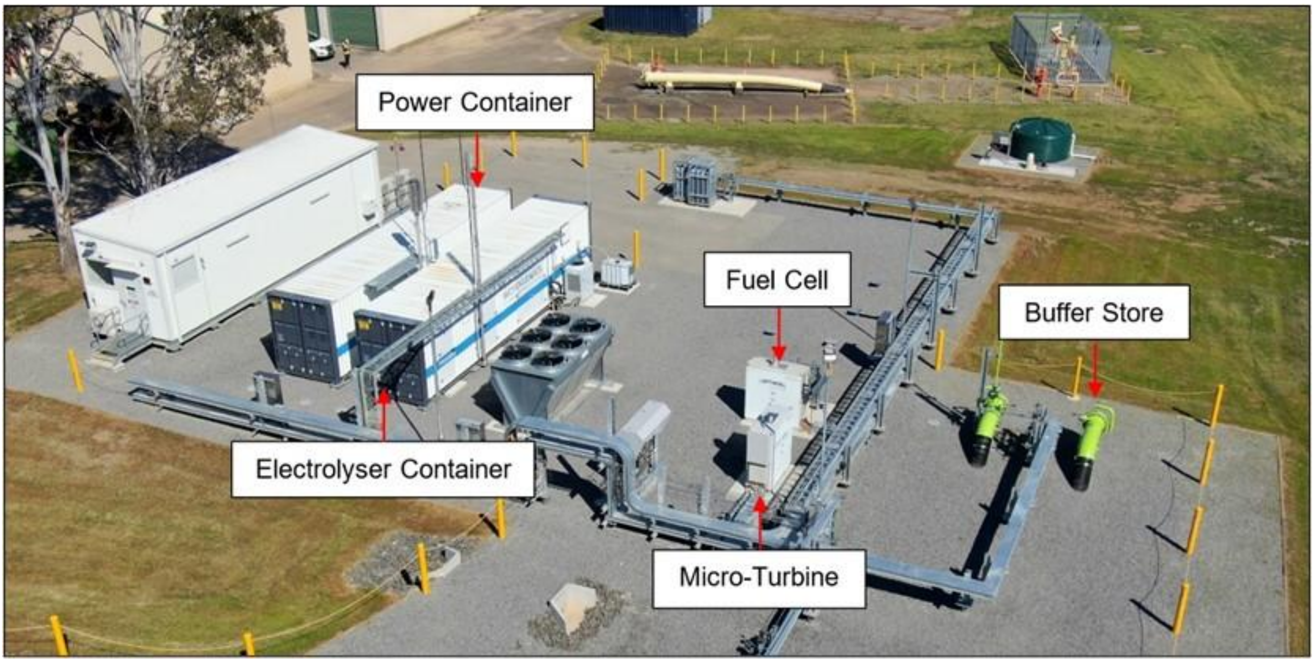

Figure 1: Aerial view of the WSGHH.

In addition to the above use cases, Jemena has been working with the energy retailer, Origin Energy Limited (Origin) to optimise both the electricity and gas infrastructure, thereby enabling energy network sector coupling opportunities. Future tests are anticipated to leverage both gas and electricity networks for storage and reliability services, allowing network operators to assess the role that electrolysers will play in grid-firming applications.

The basis for this project is to test and demonstrate PtG technology with complementary markets, such as the blending of renewable hydrogen with natural gas. This will allow for the evaluation of future investment of larger scale and commercially viable PtG systems and will promote social licence for the application of hydrogen within Australia’s energy system.

2. Project Objectives

The WSGHH facility was constructed in order to identify, understand, and remove barriers to the commercialisation of hydrogen technology and to understand the application of pipelines and the gas network in the future renewable energy landscape. In doing so, Jemena will provide the opportunity for other stakeholders to confidently invest in the technology, which will create a foundation for a new service for Jemena's gas pipeline infrastructure.

The project's initial focus was to identify solutions to manage real and perceived technical, regulatory, environmental, social, and economic barriers to gas distribution networks being used for large-scale renewable energy storage and distribution. The trial was also a key factor to understand the future integration of the gas and electricity networks and how gas networks can help support a managed transition to a renewable energy future.

The WSGHH objectives are to:

- ensure a sound understanding and address technical, regulatory, environmental, social, and economic barriers to the PtG technology in an Australian context – including knowledge of cost, deployment, utilisation, and scalability;
- promote the awareness of large-scale renewable energy storage and distribution offered by gas pipeline infrastructure, thus providing additional opportunities for the installation of renewable energy generation;
- enable gas pipelines to accommodate renewable gas injection to support the uptake of PtG technology more broadly (as well as other forms of renewable/distributed gas production);
- provide a vehicle for the engagement of stakeholders in the downstream supply chain to accommodate up to 10 % (or potentially greater) of hydrogen and natural gas mixtures;
- share the information gained with industry, and;
- evaluate the application of hydrogen for zero carbon transport fuel applications through third parties.

3. Design Process

3.1 Design Evolution

Power to gas via hydrogen electrolysis is a demonstrated activity with several operational plants around the world producing hydrogen via electrolysis. Some of these plants do so for the purpose of injecting hydrogen into the local gas network, which was happening before the concept began to develop at Jemena. The Jemena gas network, through its predecessor, AGL Energy Limited (AGL), was the first company to produce hydrogen in Australia for the purpose of mixing with natural gas in the gas network. Hydrogen was initially produced via the gasification of coal with multiple other constituents, such as CO, CO_2, blended with the gas, which was known as town gas. While town gas was eventually replaced with natural gas, some of the legacy network design features laid the foundations for re-introducing hydrogen into the network.

The concept of a green hydrogen pilot project operating on the Jemena gas network was considered for many years prior to the ARENA funding application, with growing interest through to 2015, when the drivers for decarbonising the gas network became clear. The design drivers arose from a need to reduce the cost of renewable hydrogen, whilst exploiting the advantages of hydrogen produced via electrolysis. The initial design concepts were developed from scratch, as no specific performance or outcome measures had been defined. Therefore, early concepts focused on sector coupling and storage as key areas to develop.

As one of Australia's largest operators of natural gas and electricity assets, Jemena was well positioned to develop and manage the design process internally, choosing to follow standard project development pathways. This involved managing the project directly and outsourcing front-end engineering and design (FEED) and detailed design activities to third-party engineering consultants. The original design considered a 2 MW electrolyser system directly coupled to the gas network, with limited additional balance of plant (BOP). This design was substituted for a smaller electrolyser with additional site features, allowing greater flexibility to store hydrogen and serve multiple energy markets, rather than just conventional heating, cooking and other commercial uses.

The original storage concept consisted of traditional steel cylinders, however, as one of Australia's largest gas pipeline operators, a logical decision was made to explore the use of a dedicated hydrogen pipeline to store hydrogen at the electrolyser outlet pressure. Ultimately, a 20" steel pipeline was selected as it is identical to the Sydney Primary Main pipeline in size and material and has similar working conditions. Using the stored gas in the pipeline, further features were added to the design, such as a small fuel cell and microturbine, which enable the stored hydrogen to generate power, much like gas power stations are used today. This allows for small scale trials to be conducted, demonstrating the future role of renewable gases in the energy mix. A later addition to the design was high-pressure compression and dispensing equipment, which enables the bulk sale of compressed hydrogen via tube trailer and ultimately access to the highest value market for hydrogen.

Given the additional features and relatively high operating cost, the electrolyser size was reduced to 500 kW, which is adequate for the tests required, and less expensive to operate. Despite this, the facility was designed to accommodate an electrolyser capacity of up to 1 MW without any further site modifications.

Gas network blending remained in scope, however, the design basis changed from an above ground blending skid in favour of below ground injection to an existing pipeline. The pipeline has not previously been proven but is a lower cost approach for the plant. Even after the detailed design phase had commenced, a number of further design changes were considered that primarily focused on accessing renewable resources for electrolysis, such as local behind-the-meter (BtM) solar panels and recycled water. Ultimately, these were not included due to budget limitations and not being essential to the test program requirements.

The current setup of the WSGHH is depicted in the block flow diagram presented in Figure 2. Additionally, a detailed site layout is shown in **Appendix A.**

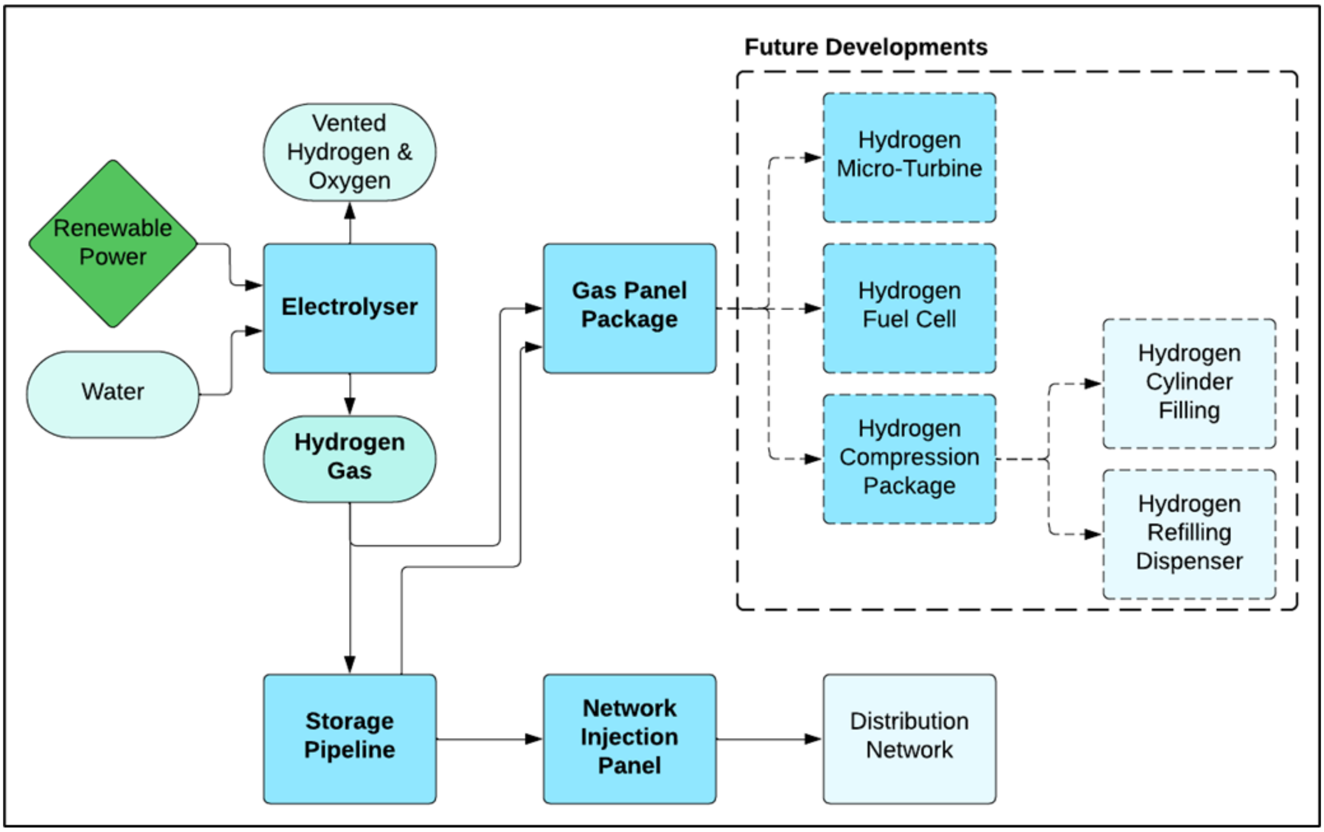

Figure 2: Block flow diagram of the WSGHH.

3.2 Design Governance

The development and management of the design is largely dictated by the drivers established in **Section 5.** The design requirements were owned in accordance with Jemena's Asset Management System, which identifies accountability to specific asset managers, with ongoing design accountability, and approval by the Jemena distribution network licence holder. Day-to-day design responsibility was owned by Jemena's technical lead, who liaised with the project and commercial managers. Together, these managers jointly covered most aspects of the funding, design, delivery, and handover of the asset on behalf of the business managers and steering committee for the project.

Existing controls, such as the asset management system and gated delivery project structure, provided a robust mechanism to ensure all parties, including subcontractors and vendors, delivered services in accordance with the expectations and requirements of the asset owner. From a design perspective, Jemena awarded the detail design work to an external engineering contractor, GPA Engineering, who performed all detailed design work through to project handover, including commissioning support, standards compliance, and safety case justifications. Day-to-day technical aspects were managed between the Jemena technical lead and the engineering consultant. The main reference document used to describe technical requirements was the Design Basis Manual, which is frequently updated and remains a live technical document for the facility.

3.3 Critical Assessment of the Design

The WSGHH is the product of four years of evolution from preliminary concept through to operational asset. During this time, the hydrogen industry in Australia has advanced significantly from a small handful of proposed projects and proponents to being a potential global superpower with strong support from industry and government. Most design decisions were based on the status of the industry at the time and the options available; many of which have changed since. Furthermore, there was no clear single driver providing specific requirements for the design, but rather a collection of concepts of interest with varying levels of merit.

Notwithstanding this, some design decisions have proven to be sub-optimal for the end product in operation, and include the following:

Standard Design Electrolyser

During the electrolyser tender process, Jemena went to market for a 500 kW electrolyser system, with the capacity to upgrade to 1 MW. It was learned that such a system would cost almost the same as a 1 MW system, which is the basic platform that most vendors offered. It was assumed that further demand cases for hydrogen off-take would materialise during the early stages of the project to justify the incremental spend, however, this did not occur. Consequently, the 500 kW electrolyser was ordered, which was fitted with a smaller stack (downrated). As a result, some system issues arose that were believed to be linked to the reduced energy consumption of the package.

Visibility of Electrolyser Human-Machine Interface

The site was designed to be remotely controlled by a programmable logic controller (PLC) via a supervisory control and data acquisition (SCADA) system. The local PLC issues commands to the electrolyser to set operating conditions, however, the system was set up in a way that only key alarms and conditions are communicated back to the remote (central) PLC. In the event of an operational error, the remote (central) PLC is unable to receive the full detail of the error therefore an operator must be on site to resolve the issue. This is a result of design limitation.

4. Procurement

Jemena follows a design and construction pathway for the development of new assets on the gas network, issuing sequential packages of work to suppliers to deliver aspects of design, equipment, and construction services. This allows for complete control over the design and equipment packages used, whilst absorbing the commercial risk directly. This is due to the mature nature of the designs and equipment, and the high familiarity with the environment and supply chain required to complete such works. There was no specific reason to follow the same approach to building the hydrogen assets for the WSGHH, as the risk profile differed from the typical project. However, after a review of the options (such as engineering, procurement, and construction (EPC), or staged construction) the traditional Jemena route was selected to allow for the utilisation of existing project controls and asset management, and to enable a high level of control and learning, whilst managing design risk.

Following the FEED and subsequent final investment decision (FID), long lead items were procured, such as the electrolyser, microturbine and pipeline materials. Design packages were then issued to the market following the completion of detailed design. All remaining material procurement was completed by the principal contactor, Wasco (Australia) Pty Ltd (WASCO). Procurement of services and equipment for hydrogen was a challenge, due to the lack of established suppliers and specialists offering services to a mature level. The electrolyser market was also not well established in terms of vendors, products, and competition, with none of the five vendors that submitted compliant tenders having installed an electrolyser in Australia at the time.

Engineering services were procured from GPA, who offered competitive prices and high quality. A high level of engagement with the project from GPA was noted, as well as a willingness to absorb some development costs, so as to improve the project whilst also developing capability. The engineering designs, free-issue items, and equipment lists were issued for tender and included commissioning activities, such as pipeline cleaning for fuel cell grade hydrogen, for which there is limited precedent for how to achieve this. While the majority of the construction services were typical gas industry practices, some new skills were also required.

The tender response for construction services had varying quality and cost, with only one clear preferred tender response, which was submitted by WASCO. The success of the WASCO bid was due to a clear understanding of the requirements for the project, as well as an acceptable price. WASCO delivered a high-quality product throughout the construction of the project.

Delayed procurement processes were experienced, which was reasonable given project challenges such as the facility being the first of its type in Australia and disruptions due to the COVID-19 pandemic. The electrolyser package was installed and operational within weeks of delivery, demonstrating the successful integration efforts between the Hydrogenics Europe N.V (Hydrogenics)., Energys Australia Pty Ltd (Energys), Jemena, GPA and WASCO. Other equipment packages drew on specialist suppliers, such as Optimal Group Australia (Optimal) for the microturbine and fuel cell packages, as well as the hydrogen gas panels. The fuel cell and turbine are new products to Australia, but in both cases, Optimal made all efforts to ensure the final product was fit for purpose.

Majority of the contracted local suppliers are believed to have received further orders for renewable hydrogen products since the WSGHH project. This underpins the need for ARENA funding for such projects as the impacts can be far reaching across industry in Australia. During the tender phase for services, varied responses were received, which in some cases gave low confidence of the market readiness for hydrogen technology. However, for each package of work, a strong vendor was identified and selected that met expectations.

Throughout the early phases of the project, members of the design and project team frequently met in person, and regular visits to suppliers were conducted. However, the pandemic resulted in the project team working remotely and significantly reduced overall contact. Further impacts of the pandemic were observed across the supply chain and prevented key activities, such as factory acceptance tests, and general site access during construction. The construction of the WSGHH consequently occurred between the two major lock-down periods experienced in NSW. As travel was reasonably unrestricted at the time, representatives from the electrolyser original equipment manufacturer (OEM), Hydrogenics, were able to attend the site for commissioning from Belgium. Through WASCO and Zinfra, Jemena operated strictly in accordance with state and federal guidelines and maintained a safe working environment whilst minimising impacts to the schedule.

Jemena operates with robust procurement and contract management controls to ensure equitable procurement opportunities whilst ensuring scope and quality are known and met. Notwithstanding this, the project was a first of its kind in Australia, drawing on a market largely unfamiliar with the key technology of electrolysis. One observation was the ability of the incumbent market (supplier to the oil and gas industry) to pivot quickly and effectively to hydrogen. This is likely a result of the safety, quality and questioning mindset instilled in the oil and gas market, leading service providers to rapidly focus on new areas, without compromising standard behaviours.

One aspect of procurement expected to continue to challenge future project proponents is access to key equipment, such as electrolysers and compressors. The electrolyser industry is still developing, with vendors increasingly focusing on larger orders. This helps with the scale-up challenges in the hydrogen industry but impacts buyers seeking small-scale solutions that vendors no longer provide. The number of electrolyser vendors available in 2017 in Australia was 10 to 15, which by 2022 had increased to over 30. However, the number of vendors able to meet the exact requirements for a specific project may still be limited.

5. Planning, Approvals & Regulations

Design compliance requirements vary depending on the approvals and operational pathways taken for the delivery and operation of such assets. Jemena typically owns and operates (and designs accordingly to) regulated and licenced utility assets. As such, early regulatory compliance assessments focused on whether the facility could be built and operated under the existing gas network regulatory environment. From a development consent perspective, typical Jemena gas network assets are built under the NSW Gas Supply Act 1996 (**Gas Supply Act**) ,which does not require the continuous application for further development consents from council, state, or federal approval authorities. Upon review, it was considered that the definition of associated equipment (permitted under the Gas Supply Act) would not likely extend to all the scope considered for the project. Therefore, the development consent for the WSGHH was lodged with the state planning authorities.

Operationally however, no specific restrictions or conditions applied to how the new asset would be operated. The precedent set by similar demonstration projects to date varies, with many outsourcing operations to third parties, OEMs, or using in-house dedicated specialists. Early in the design process, it was determined to include all aspects of the facility operation within the control and operational framework of the Jemena distribution network licence. This decision had significant ramifications for the subsequent design, build and operation, as it required the same process and expectations to be followed for the development of the facility, in addition to state development approval requirements.

The Gas Network operates under a safety case, which in turn draws on rigorous processes to assess, identify and manage risks. The safety case references project delivery and operational controls, which cascade to day-to-day tasks and safety measures; all of which had to be reviewed and updated for hydrogen assets. Whilst this process required significant effort across Jemena and Zinfra (responsible for physical operations), the updated process is now embedded in the business, establishing a much-simplified route for incorporating further hydrogen assets in the future.

With the governance requirements for the asset were clarified and agreed, most design standards required were relatively common practice already in Australia, with some notable exceptions. The facility was designed with novel features that were the first of their kind in Australia, and even globally. Thus, the existing standards framework did not comprehensively cover every aspect of the design. These aspects included:

- the hydrogen pipeline, built as a pipeline to both AS 2885[1] and ASME 31.12[2] requirements;
- the hydrogen microturbine, built as a Type B appliance and operable on both natural gas and hydrogen, and;
- the hydrogen gas network injection facility.

Note that the microturbine and fuel cell are connected to the power grid. An overarching safety case approach was taken with regard to the operational safety of the facility. Design compliance was achieved and demonstrated via a range of established methods, such as:

- design reviews;
- hazard and operability analyses (HAZOP);
- safety management studies and formal safety assessments, and;
- quantitative risk assessments, where standards do not comprehensively cover every aspect of design.

Jemena applied for development consent to the NSW Department of Planning, Industry and Environment and was granted approval. Jemena was also successful granted a licence to reticulate hydrogen gas, and ultimately began operations following an internal formal safety assessment and approval to operate by the Jemena distribution network licence holder.

[1] AS 2885.3:2022 Pipelines - Gas and liquid petroleum contains requirements for design, construction, welding, operation and maintenance, testing, and safety for high pressure pipelines in Australia.
[2] ASME 31.12 - 2019 Hydrogen Piping and Pipelines contains requirements for materials, brazing, welding, heat treating, forming, testing, inspecting, examining, operating, and maintaining gaseous and liquid hydrogen pipelines.

6. Construction

The initial phases of construction focused on the procurement of required equipment, parts, consumables, and sub-contractor services, as well as the preparation of documentation required to support approvals. Once construction was approved to commence, the site was mobilised. Site preparation works and access were challenging due to the existing activities on the site, as well as two parallel projects occurring at the site, requiring careful management of multiple contractors.

Construction began with the clearing of the areas required for the new facility, followed by the raising of the site level by 300 mm above the natural grade to prevent overland flooding. Trenching works and stringing of the new 20” pipeline was then conducted, whilst also installing the steel piles for the equipment packages. As the pipeline installation progressed, the installation of cable and pipe support began, as well as the remaining site civil works and the installation of major equipment packages. These included the transformer, control room, electrolyser, reverse osmosis unit, cooling tower and ancillary equipment. Following installation, pipes and cables were fitted between the various packages before the final site finishing works were conducted. The total time for construction of the WSGHH was approximately three months.

Despite some major rain events, disruptions to construction were minimal, and this phase of the project was executed quickly with few issues. This can largely be attributed to the significant planning period prior to mobilisation between Jemena, WASCO, and GPA. Co-ordination of most sub-contractors was completed by WASCO with the exception of some services organised directly by Jemena. To this point, no special considerations were required for hydrogen technologies, other than handling requirements for the electrolyser, and the facility development followed a very similar pathway to comparable sized gas installations. Figure 3 shows an aerial photograph of the construction work at the WSGHH facility.

Figure 3: An aerial photograph of the construction of the WSGHH.

7. Testing & Commissioning

7.1 Pre-Commissioning Activities

For approximately three months following construction, the site underwent a testing and commissioning period under WASCO's supervision, whereby all installed plant was subject to a methodical evaluation. The purpose of this was to ensure all installed equipment met the design criteria and was safe to operate. Simultaneous point-to-point and pressure testing of cables and pipework validated their integrity. Furthermore, the 20" pipeline was subject to hydrostatic tests, which passed at over twice the working pressure.

Following initial integrity tests, the pre-commissioning focused on the pre-conditioning of the site for operations. A key activity was the cleaning of the pipeline following the hydrostatic test to remove all water from within, which is a common process and will be required for all high-grade hydrogen pipelines in the future. This involved draining and pigging[3] the pipe, followed by purging with dry nitrogen. A cleaning agent was then sent through the pipeline between two foam pigs to remove chemical residues left from the manufacturing and welding processes. To remove remaining surface corrosion and solid deposits on the internal pipe walls, a total of 67 foam pigs were pushed through the pipe until no more solid material (dust) could be removed, and the condition of the foam pigs leaving the pipe were completely clean. With the pipe wall then in optimum condition, the pipe was purged again with dry nitrogen to reduce the oxygen content and remove other trace gases. Once filled with nitrogen, the pipeline was reduced to a near vacuum pressure ready for filling with hydrogen gas. Hydrogen was then immediately filled into the pipe to raise the pressure above atmospheric, ready to receive hydrogen from the electrolyser.

Whilst cleaning and preparation activities were underway, the rest of the plant was undergoing control system testing and energisation procedures.

7.2 Site Acceptance Testing & Commissioning

With the general equipment and site connections established, individual packages could then be tested and commissioned. All tests were carried out under the supervision of the appointed Zinfra commissioning manager and project engineers, but in some cases were conducted by the system OEM, such as the electrolyser standard assessment task. Once all individual packages were proven and performance requirements met, the site was handed over from WASCO to Zinfra, who operate the site on behalf of Jemena, and full commissioning commenced, which involved the interconnection of different packages.

Early commissioning activities focussed on incrementally filling the buffer store with hydrogen from the electrolyser and observing the functionality of the control system to perform autonomous pressure control. Following the first fill of the pipeline, gas samples were taken at the outlet of the buffer store and sent for lab analysis. The results demonstrated that the gas composition was 99.97 % hydrogen, which meets the necessary quality requirements for fuel cell applications. The remainder of the commissioning focused on the acceptance and registration of the microturbine, gas panels, and ancillary equipment, with the fuel cell planned for commissioning at a later date.

Once the packages were demonstrated to work as a connected system, the final commissioning activities focused on the control system and the various modes of operation of the plant. This involved accessing the site PLC via SCADA and executing controlled tests from the main control room. During this period, design and equipment deficiencies were observed, in addition to the typical punch-list issues experienced for such projects. The key issues identified included the following:

[3] Pigging - a process involving pumping a device (known as a pig) through a pipe at high pressure to clear or clean the pipe from all liquids, solids and or obstructions.

- Leaking 2” valve - each of the two risers on the buffer store are fitted with 2” isolation valves. These are both soft-seated ball valves in steel housings with only welded (carbon steel) pipe fittings back to the 20” pipe, and a flange outlet coupled to a stainless steel (insulated) reducer down to 1” stainless steel tubing. On the outlet valve, the downstream tubing experienced a rapid increase in pressure (within a minute for 1.5 m of 1” tube) once depressurised and isolated by closing the valve, indicating a leak past the valve. Upon investigation, it was determined that the cause of the leak was likely pipeline debris that was blown through the valve during the cleaning process, becoming entrapped between the ball valve and the seat. Subsequently, the debris would have scored the soft seat and created a small leak path. However, this could neither be visually confirmed nor repaired, as this is the primary isolation valve to the pipeline and is completely welded. Such a repair would therefore require the entire pipeline to be depressurised and purged. Due to the manageable nature of the leak and with no hazards identified, it was agreed to accept the valve with the leak until the pipeline was depressurised next. This issue could have been prevented with a sacrificial throttling valve installed downstream to the isolation valve, which was used throughout the cleaning and purging processes to control the gas flow out of the pipe and is the suspected cause of the damage.
- Few minor leaks in fittings – some external hydrogen leaks were found, which was expected and therefore required tightening of the fittings (still within gauge tolerances). A combination of portable sniffers and snoop devices[4] were used on all hydrogen fittings, which identified a few minor leaks. The site is routinely inspected for leaks with no further issues identified since.
- Check valve chatter – once the electrolyser was set to fill the onsite buffer store, a high-pitched vibration was noted in the pipework between the electrolyser and main gas panel. The noise was identified as a check valve that appeared to be chattering and occurred when the electrolyser was operational. The exact reason for the chatter is unknown, with possibilities including pulsing flows from the electrolyser or incorrect sizing and harmonics. The issue has not been resolved and remains under investigation.
- Passing regulator – on the gas injection panel that controls gas flow and pressure to the network, a regulator that reduces the buffer store pressure from up to 3.0 MPa to 1.1 MPa operated normally during use. However, following a shutdown, the regulator was found to pass a very small volume of gas, causing the downstream pressure to rise. The panel is rated for full inlet pressure and the outlet was isolated, meaning the leak did not pose any hazards, however, it did require a manual bleed of the panel before resuming operation. It was suspected that the cause of the issues was dust or debris on the regulator diaphragm, although upon an overhaul of the regulator, no contaminants or damage was identified. New seals and parts were fitted and upon re-commissioning, the valve has continued to operate without issues.

All issues identified in the commissioning process were consistent with new build plant facilities and were considered minor in nature.

[4] Sniffers - a gas detection sensor that can measure the amount of a specific gas in ambient air.
Snoop - a liquid soap that is applied to potential leak sites and bubbles due to gas leaks pushing through the substance.

8. Handover & Early Operations

Jemena owns many assets in Australia that are operated by Zinfra, with both entities well aware of the importance of a good project handover. As it was known that the site would be operated by Zinfra from the outset, the relevant teams were engaged and provided insights for working with hydrogen. As the design progressed from engineering to construction, Jemena and Zinfra entered into a phase of operational readiness, holding weekly meetings to go through the many changes and artefacts that would need to be set prior to operation. This is standard procedure for all Jemena facilities and included the following:

- Training requirements – Zinfra, through its key suppliers, developed a number of training packages for both hydrogen and plant specific safety, with all high pressure technicians required to undergo the training.
- Control room changes – new control screens, response procedures, and training were implemented in the main control room for the facility.
- Permitting system and a hydrogen authority – a dedicated permit was established for hydrogen activities that can only be approved by control room approved technicians before working at the facility.
- Work instructions – all maintenance activities at the site follow a dedicated work instruction that is attached to a work order. These were developed as well as response codes that capture the outcome as data in System Applications and Products.
- Test program requirements – the facility was intended to be used as a test and demonstration site; however, the design of tests and general schedule was developed well before the site became operational.
- Safety requirements – general issues and concerns were discussed, such as appropriate personal protective equipment and other procedures, as well as equipment suitability for hydrogen and oxygen systems.
- Maintenance and management of subcontractors – while Zinfra perform most tasks directly, some were outsourced, where the skill set required was different to the training of the technicians. For example, maintenance of high voltage transformers or electrolyser plant overhauls.
- Competencies – before operators can interact with the plant, they must undergo a competency assessment to ensure they can apply their training correctly and safely prior to requesting a permit to operate.

Prior to entering operation, a period of familiarisation provided operators an opportunity to operate the plant and run maintenance procedures, with some under the supervision of OEM vendors. Mock scenarios were run, as well as actual system failures, which provided a positive learning experience. Given the non-commercial nature of the plant, delays to production had relatively few impacts. There were a number of un-planned delays during the initial months of operation that resulted in a reduced supply of hydrogen.

Jemena has benefited from having close support from the new owners of Hydrogenics, Cummins, who have responded to issues with the electrolyser, with the support of Energys and using local resources with input and support from overseas OEM offices. Despite this, a few issues arouse from the early phases of operation of the electrolyser package, which included the following:

- Diode failure – during a full-load test on a warm night, the electrolyser tripped at approximately 11 pm. Control room operators suspected this was due to the buffer store approaching maximum pressure, however, the electrolyser failed to restart as the pressure began to drop (hydrogen was being injected into the gas network at the time). Technicians were called to the site and found that the electrolyser was unable to start. Upon investigation and with support from the OEM, one of the three thyristor diodes was discovered to have over-heated with external evidence, and a separate test confirmed the failure. A new diode was subsequently installed, however, some overheating issues persisted, and are subject to an on-going investigation by Cummins and Zinfra.

- Air compressor failure – a planned full-load e-stop was conducted from the main control room, which forced all systems into a safe shut-down procedure. When restarting, the electrolyser flagged an alarm. Upon investigation, the electrolyser air compressor (a reputable international brand) was found to have a failed fitting on the outlet, which had sheared off, meaning the air pressure could not be maintained. It is believed the air compressor was operating at load when all air operated valves closed simultaneously due to the e-stop, which resulted in a spike in pressure. The fitting was downstream of a pressure relief valve, which could have operated, although the pressure was not recorded. Given the condition of the fitting, the failure was put down to poor workmanship. An immediate repair was made with no further issues since. This highlighted the need to consider all sub-systems and not just the primary plant.
- Hazardous area compliance – The electrolyser product was issued as a compliant equipment package, with a number of reviews and assessments completed. Once operational, electrical technicians familiar with IECEx[5] rated equipment were not confident of the status of the equipment and fittings rated to ATEX.[6] Lack of access to documentation and approval processes, coupled with the lack of familiarity with compliance processes led to an internal review of both the documented process and a review of the installed plant. It is understood that similar issues have occurred at other electrolyser facilities in Australia, with a lack of certainty on the compliance status of electrolyser installations, potentially with different views in different jurisdictions. Compliance to specific Australian Standards, including AS 3000, has also been identified by overseas vendors as an issue, with different approaches being adopted by different vendors, however, it is believed most will move to supplying compliant equipment packages in the future to avoid these issues and delays.

Overall, the construction commissioning and handover predominantly proceeded according to plan. The early phase of the operations experienced a temporary reduction in output and some impacts to the test schedule. Despite this however, early test results demonstrated that the network injection design meets all expectations with regards to accuracy and consistency of hydrogen blending in the network. Further tests will be run during the trial, with details on testing provided in **Section 9.**

[5] IECEx - International Electrotechnical Commission (explosive atmospheres): refers to an international certification for the safety of equipment and services for use in explosive atmospheres.

[6] ATEX - Atmospheres Explosibles: refers to a certification that is mandatory in Europe for the safety of equipment and services for use in explosive atmospheres.

9. Plant Performance

The focus of the WSGHH testing program is set on acquiring operational experience, understanding optimal design configuration, and improving maintenance and asset management expertise. Additionally, in order to understand the accuracy of blending hydrogen with natural gas and the impact of hydrogen on Jemena's existing gas network and its ancillaries, the following activities were set out as the main drivers of the testing program:

- Training/Emergency Response Testing
- Hydrogen Production and Electrolyser Performance Testing
- Hydrogen Injection Panel Performance Testing
- Hydrogen Purity Testing
- Leakage Testing
- Material Testing
- Safety and Compliance Tests
- Seasonal test activities
- Testing for regulatory and standards development
- Customer Focused Testing – Demand Response Testing
- Future Fuels Cooperative Research Centre (FFCRC) projects

Figure 4 summarises the Testing Program Plan developed for the WSGHH to understand the viability of operating the facility, blending hydrogen into the gas network, and investigating the impact on the network and its ancillaries.

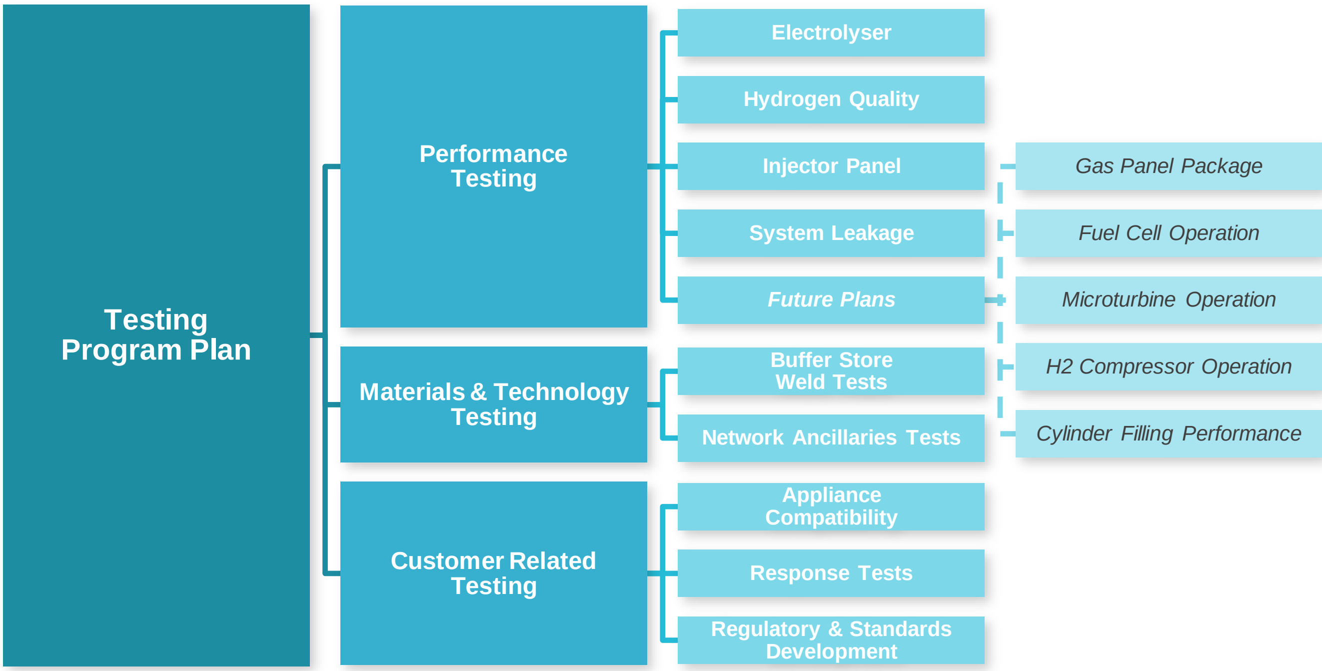

Figure 4: The WSGHH Testing Program Plan.

Performance tests were conducted that involved investigating different modes of operation and output capacities of the electrolyser package. The nameplate hydrogen production rate and electricity consumption were tested over a period of approximately five hours, whereby the electrolyser was incrementally ramped up to its rated output. The test was conducted with a fixed output pressure (pressure control mode) with the maximum output hydrogen flowrate calibrated to 100 Nm^3/h (or 9 kg/h), and with both the input electricity consumption and output hydrogen flowrate metered. Figure 5 shows the results of the test and indicates that the electrolyser power consumption closely matches the output hydrogen flowrate while the load increases from 15 % to 100 %, which was expected. Additionally, the rapid ramping capabilities of the PEM electrolyser were also observed as the load was increased from 15 to 50 % in the first 20 minutes of the test, whereby the electrolyser was able to respond within minutes of the load change, at a rate of approximately 4.5 % per minute. This was further seen at each incremental increase in the load and moreover as the machine was powered down, where the most rapid change of the entire test was observed of approximately 25 % per minute.

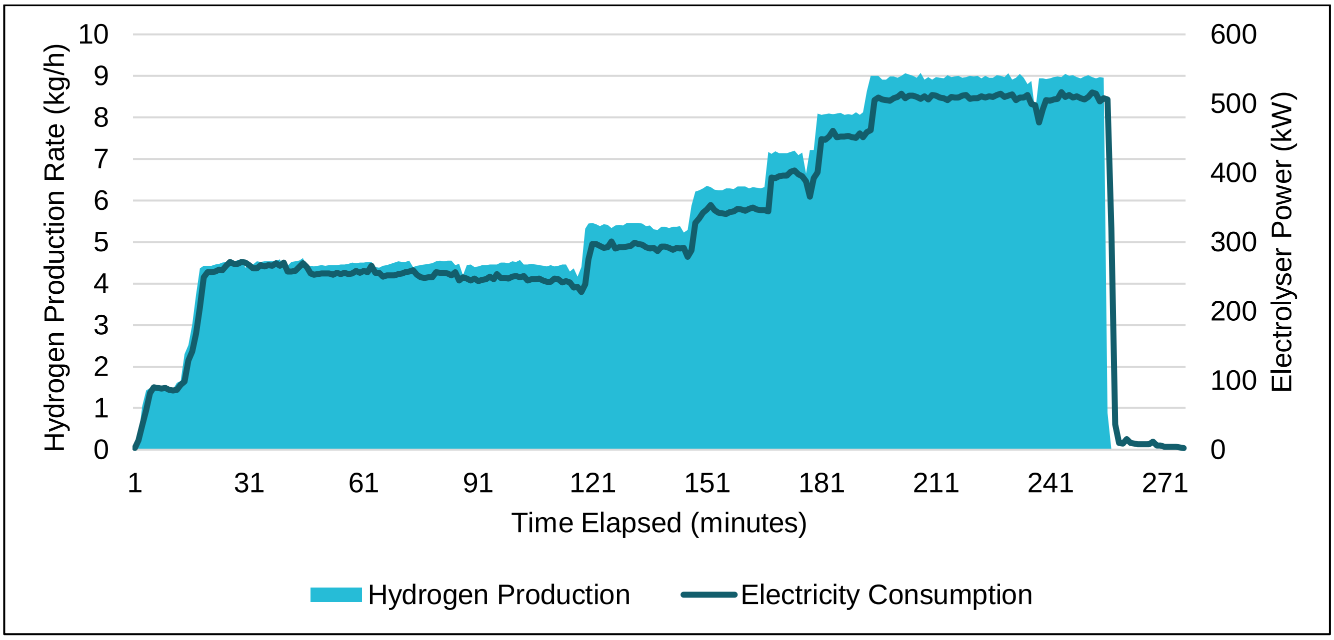

Figure 5: The electrolyser hydrogen production and electricity consumption recorded during the performance test.

Following this test, the average efficiency of the electrolyser was computed for the various load levels tested, with the results summarised in Table 1. From the values calculated, the efficiency during the test was observed to fluctuate around an average of 55.5 kWh/kg of hydrogen, or 60.2 %. It was also observed that the average efficiency of the electrolyser rose to a maximum of 54.2 kWh/kg or 61.6 % at a load level of 60 % (corresponding to 60 Nm^3/h or 5.4 kg/h of hydrogen production and 300 kW of power draw). This indicates that the electrolyser's performance is not proportional to the load level, however, the difference between the greatest and lowest average efficiency was only 2.8 %.

Table 1: The calculated average electrolyser efficiencies from the performance test for different load levels.

Load Level (%)	Time Period in Graph (minutes)	Average Efficiency (kWh/kg)	Average Efficiency (%)
15	1 - 17	56.7	59.8
50	18 - 120	56.6	59.0
60	**121 - 147**	**54.2**	**61.6**
70	148 - 167	54.4	61.4
80	168 - 180	54.8	60.9
90	181 - 194	55.4	60.2
100	195 - 255	56.7	58.8
Average		*55.5*	*60.2*

Further tests found the specific water consumption of the electrolyser to be 12 to 13.2 L/kg of hydrogen, as well as a cold start-up time of 25 minutes including a nitrogen purge, and hot start-up time of 8 minutes.

Further performance information, including blending results, can be found in the **WSGHH Performance Report.**

10. Demonstration of Project Outcomes

10.1 Challenges

The growth of green hydrogen and integration within the existing natural gas network has the potential to play a significant role in the renewable energy transition. The novel nature of the technology and limited frameworks around hydrogen presented significant challenges to the project, which included:

- complex legislative and regulatory hurdles for the production and injection of hydrogen into the gas network;
- cleaning steel pipelines to achieve a hydrogen purity of 99.97 % or higher for fuel cell applications;
- compliance with applicable standards, and developing and accessing new standards;
- commissioning and integration of novel technology and assets into an operating gas distribution business;
- stakeholder advocacy and engagement to increase confidence in hydrogen;
- long lead items (such as the electrolyser) and the fragility of supply chains as a result of the pandemic;
- coordinating international travel and exemptions during the pandemic, aligning with the tight delivery timeframe of the project to ensure the successful commissioning of the electrolyser;

The above challenges were overcome through significant collaboration between key stakeholders and delivery partners to ensure the successful delivery of the project.

10.2 Promote New Industry Standards & Innovation

10.2.1 Pipelines & Injection

Hydrogen produced by the electrolyser is stored within a 340 metre long, 500 mm diameter buffer store pipeline that can store approximately 120 kg of hydrogen (approximately 4 MWh of energy storage), before injection into the secondary gas network or generation of electricity via the microturbine or fuel cell. With the support of GPA, Jemena was able to utilise a hybrid of two standards for the buffer store pipeline, which were AS 2885 for general pipeline design and ASME B31.12 for specific material and weld considerations with respect to interactions with hydrogen gas. The pipeline material used is similar to that in the Jemena gas network, thereby allowing for the understanding of potential implications of hydrogen within the existing gas network.

In addition to managing the integration of Australian and International standards, the existing standard approach for pigging and cleaning steel pipelines was also innovated to ensure stored hydrogen would remain at a fuel cell acceptable purity of 99.97 %. This was the first of its kind for carbon steel pipelines in Australia. Furthermore, the project also introduced the first direct injection blending of hydrogen into a natural gas steel pipeline, which involved injection after a pressure reducing station into turbulent flow conditions.

10.2.2 Improving Safety

Given Jemena's involvement across both the electricity and gas sectors in Australia, in which hydrogen will play a significant role, it was important that the project was not treated just as a trial, but as an opportunity to expand internal capabilities and upskill the workforce. Natural gas safety systems exist within Jemena and Zinfra for the standard gas network operations, however, hydrogen acts differently to natural gas. The project teams therefore investigated how safety systems are applied across the industry and built on these with the implementation of new processes and procedures developed for risks related to hydrogen, specifically at the WSGHH.

During integration with operations, the team undertook a comprehensive integration process, ensuring all existing controls and procedures were amended to reflect the nuances of hydrogen. New safety training systems were developed, included a hydrogen familiarisation program and the hydrogen authority permit system discussed in **Section 8.** The aim of which was to ensure workers attending the facility understand the way hydrogen interacts with the environment and how to safely complete maintenance tasks on hydrogen equipment. The new permitting system ensures tasks can be completed safely, by allowing operational personnel experienced and trained with hydrogen to obtain hydrogen work permits. All training is completed and overseen by a registered training organisation with certificates provided to personnel.

These developments will allow Jemena to rapidly role out hydrogen training across its gas network operation teams, which is a critical capability given the rapidly changing energy landscape in Australia.

10.3 Advancing the Regulatory Environment

An important objective of the project was to understand the regulatory impacts that the facility would have. Through collaboration with the gas technical regulator in NSW, the following strides were made in the regulation of hydrogen within NSW, particularly around the gas network and its role in the energy transition:

- Working with NSW Government and stakeholders to include hydrogen within the Gas Supply Act, and;
- The application to the Independent Pricing and Regulatory Tribunal (IPART) for the first Distributor's Licence for hydrogen.

One of the key project objectives was to understand what improvements were required to existing regulatory frameworks to facilitate the development of future hydrogen projects across Australia. The current technical and economic regulatory frameworks do not contemplate the injection and distribution of hydrogen through a network, requiring an extensive stakeholder engagement program to obtain the appropriate approvals and social licence.

A key learning from the project was the importance of early engagement with stakeholders, including community and technical regulators, given the innovative nature of the project. Constraints existed within the Gas Supply Act 1996, which was unclear on the permissibility of hydrogen within the network. To overcome this, the project team worked closely with the NSW technical regulators to understand how the project could be enabled within the current regulatory framework. Ultimately, the Gas Supply (Safety and Network Management) Amendment (Hydrogen Gas) Regulation 2020 was made in December 2020. This provided clarity on how hydrogen is to be treated under the Gas Supply Act and was able to be applied by IPART for granting Jemena the first distributor's licence for the distribution of hydrogen in NSW. This licence was granted in June 2021, authorising the injection of renewable hydrogen into Jemena's gas distribution network.

10.4 Community & Stakeholder Engagement

Jemena's ambition is to achieve net zero emissions by 2050, which the WSGHH will play a key role in accomplishing, by providing an understanding of the network's capability to facilitate decarbonisation through the application of hydrogen. As part of the project involves driving change alongside innovation, an inclusive approach was adopted that took stakeholders through the development of the facility from the concept to commissioning.

The project team worked collaboratively and transparently with a wide range of stakeholders, including energy customers, governments, and the broader community. During the course of development, over 100 commercial and 7 industrial stakeholders were engaged to evaluate if hydrogen blending would negatively affect end uses or processes of customers in the area. Type B appliance users were the most likely to see changes to operations, however, not with the low blending ratios of less than 2 % that were planned for the demonstration. If approvals are obtained in the future to increase the ratio to 10 %, then a detailed engineering review of these appliances will likely first be required. No adverse reactions or changes in use have occurred at the current 2 % blend.

11. Knowledge Sharing

A Knowledge Sharing Plan was developed with ARENA to amplify Jemena's ability to share insights and lessons learnt from the WSGHH project on a continuous basis. This plan includes the provision of performance and cost data, as well as specific development learnings.

Since the project approval, extensive engagement has been undertaken across domestic and international innovation forums, technical workshops, community events, site tours, conferences, and news articles with regards to the WSGHH project. Additionally, engagement with consumer groups, local community, industry bodies, retailers, specialist gas industry, and government, has allowed for the promotion and acceleration of the safe deployment of affordable renewable gas.

Jemena has proactively participated in a range of industry and government processes, including the National Hydrogen Strategy. Furthermore, Jemena has also actively contributed to Standards Australia, developing both existing standards and the development of new technical documentation in the field of hydrogen. Jemena continues to work with Energy Networks Association, the Australian Hydrogen Council, the Clean Energy Council, the Hydrogen Directorate, and the Future Fuels Co-operative Research Centre, utilising the WSGHH and its capabilities for research and development to be conducted live on the gas network, which is a first-of-its-kind.

12. Lessons Learnt

A Lessons Learned Workshop for the WSGHH was held to review the works completed and resultant outcomes relating to the integration on the project. The objective of the workshop was to contribute to the continuous improvement and learning scope of the facility. The review covered:

- approvals and stakeholder management;
- health, safety, and quality;
- engineering, scope, and construction execution;
- cost and schedule control;
- procurement and contract management;
- people resourcing and administration, and;
- integration and closeout.

12.1 Methodology

Participants were asked to complete prework for the workshop to identify activities and processes that were executed well by the project team, as well as those that could be improved. During the workshop, the group focused on items that the project team has direct control over and discussed how such activities could be better managed in future projects.

12.2 Detailed Lessons & Discussion

Table 2 summarises the lessons learned and opportunities for improvement

Table 2: Lessons learned and opportunities for improvement identified at the Lessons Learned Workshop.

Topic	Positive Lessons	Opportunities for Improvement
Approvals & Stakeholder Management	▪ Increased communication with NSW Department of Planning and Environment (DPIE) enabled a better understanding of expectations, minimising rework of documentation and improving outcomes in a manageable timeframe. ▪ Regular and open communication with stakeholders was advantageous in promoting the significance of the project and assisted the project delivery. ▪ Continued sharing of the positive nature of the project, including the potential opportunities for renewable gases in the local gas network. ▪ Early and continual engagement with local community during works.	▪ Earlier evaluation of planning requirements prior to detailed design. ▪ Inclusion of cost and time impacts in development approval pathways. ▪ Recognition and planning for the impacts of the complex approval processes in early project phases. ▪ Increased communication with local stakeholders, such as councils, to better understand and address concerns of a lack of knowledge about hydrogen production and gas infrastructure.
Health, Safety & Quality	▪ Ownership of stewarding safety by senior team members, supported by HSE resource. ▪ Early engagement with sub-contractors to align safety protocols with Jemena's requirements. ▪ Dedicated weekly inspections and audits, with other HSE issues addressed by their on-site HSE resource. ▪ Contractor and Jemena audit and inspection programs. ▪ Regular drug / alcohol testing programs conducted throughout the project with no positives results. ▪ Regular review of quality control documentation to ensure a high standard.	▪ Improved management and supervision of works in close proximity to non-energy buried services, such as telecommunication cables, to mitigate the risk of strikes.

Topic	Positive Lessons	Opportunities for Improvement
Engineering, Scope & Construction Execution	▪ The agility of the project team during detailed design and site works, to manage late changes to the scope whilst maintaining a successful project budget and outcome. ▪ The ability of the project team to replace concrete piles with steel to save approximately three weeks in the schedule and significant budget. ▪ A strong relationship with the detailed design consultant, ensuring both teams had aligned objectives. ▪ The rapid mobilisation of the project team, allowing for the effective management of the commissioning process following a misalignment of responsibilities with the construction contractor.	▪ Better communication with contractors regarding Permit to Work procedures and isolation and lock-out-tag-out procedures during commissioning to reduce delays. ▪ Ensuring future project include the provision of a significant amount of hardware, licences, and programming software for SCADA and control systems.
Cost & Schedule Control	▪ The ability of the project team to successfully deliver the facility despite resource challenges from the pandemic. ▪ The ability to ensure the electrolyser commissioning engineer from Belgium was able to attend the commissioning, despite having to quarantine.	▪ Informing of stakeholders during initial project phases to understand realistic delivery timeframes of long lead items. ▪ Aligning expectations on the integration of unprecedented technologies.
Procurement & Contract Management	▪ The ability for the project team to specify standards and compliance requirements for novel technologies. ▪ The ability for the project team to identify non-conformances in equipment and to complete subsequent compliance work. ▪ Weekly and monthly meetings with the contractor and equipment suppliers allowed for effective contract and risk management and limited scope variations. ▪ Strong teamwork with the Project Manager (PM) ensured contract obligations from both sides were met and that budget, schedule, and relationships were maintained. ▪ Good rapport and working relationship throughout the entirety of the project with the contractor and suppliers. ▪ Strict oversight of payment claims, extensions of time and variations allowed for a detailed monitoring of the contractors' works and the ability to successfully manage contractor commercial risks.	▪ Greater emphasis on the standards that international equipment is held to in order to ensure compliance with relevant Australian Standards upon procurement. ▪ Delineation of commissioning should be better defined in the construction contractor documents to mitigate potential issues.
People Resourcing & Administration	▪ Combined project team worked efficiently and respectfully together to successfully deliver the facility. ▪ Internal resources successfully allocated time to facilitate the project's complex integration requirements.	▪ Adequately provisioning resource funding corresponding to the nature and level of complexity of the project.
Integration & Closeout	▪ A dedicated integration and commissioning lead for the project was paramount for the integration of the facility. ▪ The development and delivery of the detailed hydrogen awareness and facility operation training programs for the operation team, enabled a process for the demonstration of competency. ▪ The positive feedback from stakeholders on the level of upskilling provided through the classroom and hands-on training sessions delivered to ensure operations personnel were trained and familiar with novel processes.	▪ The provision for adequate allowances to allow the appropriate integration resourcing time for all stakeholders involved. ▪ The provision of all required specialised maintenance equipment in the maintenance program.

Topic	Positive Lessons	Opportunities for Improvement
	▪ The availability of the project team during the handover process to Jemena Gas Networks. ▪ Successful early operations with minimal support required from the project team, demonstrating the ability of operations to draw on their existing knowledge of gas assets and newly acquired skills.	

12.3 Lesson Learnt - Workshop Discussion

Table 3 shows a summary of the actionable items to be applied to projects in flight as a result of the workshop discussions.

Table 3: Summary of actionable items that can be applied to projects in flight.

Topic	Discussion	Executable Gem
HSE / Accountability & Resourcing	The PM and Project Engineer (PE) took ownership of the stewarding safety, supported by HSE resources. Jemena's PM, PE & HSE Advisor are regularly present on site and built a reputation on mutual respect. Jemena's team were able to build rapport with the contractor and their subcontractors, enabling a change in culture towards safety and good practices.	Maintain site presence during construction and build a positive relationship with all contractors to enable a safety culture that is reinforced by peers. Be clear on expectations within the statement of work and during engagement to ensure high standards.
Engineering, Scope & Construction / Early Engineering	The project scope underwent several design changes, including site location, size, and configuration. These were driven by changing responses from external stakeholders and an internal refinement of the scope. During this period, which included the FID, the project budget was not always aligned with the scope, leading to misalignments of the budget in further project stages.	Begin all projects with the end in mind. Allocate the appropriate budget required at the beginning of the project that is required to deliver the desired outcomes and clearly define the scope.
People Resourcing & Administration / Resourcing	Internal resources across multiple business areas were able to successfully allocate time to facilitate the complex integration of the project.	Internal stakeholder management is fundamental to deliver projects like the WSGHH. Project teams can avoid rework through early engagement.
Integration & Close / Handover	A dedicated integration and commissioning lead for the project was paramount for the integration of the facility. The development and delivery of the detailed hydrogen awareness and facility operation training programs for the operation team, enabled a process for the demonstration of competency.	Ensure a dedicated integration lead is appointed who has knowledge of the internal operational requirements. Additionally, deliver projects with training and safety as the first priority, ensuring operational and maintenance staff members have a complete understanding of the facilities to be operated.

13. Future Recommendations

There is significant change ahead in the energy landscape and hydrogen will play an important role in contributing to the solution of the energy trilemma of reliability, affordability, and sustainability. The learnings from the WSGHH project will support future renewable hydrogen related activities, including understanding commercialisation requirements and providing insights into the application of chemical energy storage and electricity generation.

A summary of key learnings from the project includes the following:

- Local support from suppliers is essential for smooth post-commissioning operations.
- The thorough alignment of International and Australian Standards can be costly if not appropriately accounted for in the design phase.
- Downrating and sizing of equipment can cause significant reliability issues.
- Ensuring European designs are appropriate for typical Australian operating conditions is important.
- Highly accurate pipeline blending control is necessary for hydrogen blending projects.

13.1 Regulatory

A significant project challenge was the lack of existing legislation and regulations to enable the injection, blending and distribution of hydrogen into gas distributions networks. Whilst the facility was designed to limit hydrogen injection to less than 2 % (by molecular volume) to remain within the physical requirements of the gas quality specifications in the National Gas Rules (AS 4564:2020), hydrogen itself is not a natural gas for the purpose of the National Gas Law (NGL) and the Gas Supply Act. Predominately, the issue stems from the definition of a natural gas as a substance that consists of naturally occurring hydrocarbons, or a naturally occurring mixture of hydrocarbons and non-hydrocarbons. To resolve this issue, the NSW DPIE amended the Gas Supply (Safety and Network Management) Regulation 2013, declaring that the definition of “gas” under the Gas Supply Act can include hydrogen gas and blends of hydrogen gas with other natural gases to which the Gas Supply Act applies (section 34 of the Gas Supply Act).

Under this amendment:

- network operators conveying hydrogen and hydrogen blends are regulated by Part 3 of the Gas Supply Act;
- network operators conveying hydrogen and hydrogen blends require a distributor’s licence to operate;
- network operators conveying natural gas, or a natural gas hydrogen blend require a distributor’s licence and a reticulator’s authorisation, and;
- network operators conveying a natural gas or natural gas and hydrogen blend to customers receiving gas intended to be compliant with AS 4564 should, in the Safety and Operating Plan, nominate to comply with equivalent requirements to those of Part 4 of the Gas Supply (Safety and Network Management) Regulation.

Jemena continues to recommend and support a number of changes to the NGL, regulations and gas quality standards in light of better enabling renewable gases, such as biomethane and hydrogen. Jemena acknowledges the supportive engagement from State and Federal Government, as well as industry stakeholders through consultation. Key changes that are yet to be made include the definition of a gas and limits on hydrogen as impurity.

13.2 Technical

During the design, construction, commissioning and early operation of the facility, a number of challenges arose that required technical and operational solutions. These challenges were primarily related to the electrolyser procurement, hydrogen pipelines and gas network injection, and are discussed further below.

13.2.1 Electrolyser Procurement

The current market for electrolysers remains in an early stage of development in terms of production volumes and cost reductions. Australia currently has limited manufacturers with only a small group of existing manufacturers and a small stream of new market entrants available for selection for the WSGHH project. Future projects should consider how investment and procurement support the development of local supply chain and skills.

The specification and performance characteristics of different electrolyser vendor equipment, as well as system definitions often vary between vendors, making direct comparison of cost and performance difficult. This includes inconsistency in units of measurement, nominal ratings (i.e., stack versus system) and performance definitions (energy in versus hydrogen out). A standardised product specification for use in the Australian market is recommended, whereby vendors specify the product performance details in line with a consistent set of metrics, enabling clear interpretation of performance for the specified price.

13.2.2 Hydrogen Pipelines

The design and construction of hydrogen pipelines must consider the impacts of hydrogen on the pipeline material, as well as the impacts of the pipeline on the quality of the gas. This will be particularly important for fuel cell applications, which require hydrogen purities of at least 99.97 %. The Standards Australia committee, ME 038 (AS 2885), is providing guidance on applying existing standards for hydrogen use, which has been partly due to the experience from the WSGHH project. Jemena developed a cleaning methodology for the pipeline following the commissioning of the plant to remove construction debris and purge the gas via a complete removal of contaminants, which led to a hydrogen purity of 99.97 % from the first sample at the outlet.

13.2.3 Gas Network Injection

As the first project in Australia to inject hydrogen into the main gas network, Jemena developed a low-cost method for blending that avoided withdrawing the entire gas stream above the ground into a blending skid. The method involves a traditional “hot tap” connection of a branch onto an existing pipeline with a regulated hydrogen flowrate to provide a consistent blend rate from an above ground injection skid. This approach was validated through testing, and the methodology has been consolidated into a guideline document that will be released by Standards Australia, known as, “HB 225 Guideline for blending hydrogen into pipelines and gas distribution networks”.

13.3 Commercial

Large scale renewable hydrogen from electrolysis is not yet commercially viable due to the relatively high cost of the electrolyser at the early stages of market development. However, the commercial stream of the project aimed to evaluate all potential revenue streams attributable to an electrolyser integrated into gas and electricity networks. The key commercial findings and future recommendations are summarised below.

13.3.1 Renewable Energy Supply

The assessed benefits of a behind-the-meter solar PV connection as opposed to a direct grid connection (with a 100% renewable PPA) include:

- a reduction in line losses (transmission and distribution);
- an improved overall efficiency of up to 10 % as a result of utilising the direct current (DC) supply from solar generation directly for the electrolyser, rather than converting alternating current to DC, and;
- the avoidance of Transmission and Distribution Use of System (TUOS and DUOS) network charges.

Despite these benefits, some limitations were also observed in relation to the BtM solar for the WSGHH, including:

- the complexity of enabling a DC-to-DC connection that was not a part of the original scope of the electrolyser;
- the five-year demonstration period limiting the capital cost recovery period of the onsite solar and thereby limiting the utilisation of the electrolyser to align with solar production only (approximately 17 %), and;
- the future site or land availability limiting the long-term viability of the onsite solar.

Due to the small scale of the project and the limited five-year demonstration period, the decision was taken to make the WSGHH grid connected and powered by carbon neutral electricity via a 100% renewable PPA, rather than a BtM solar installation. The basis of the decision was the increased utilisation of the electrolyser and the potential to evaluate electricity market services, such as demand-side management and ancillary services. This option also provides the facility with the ability to assess the potential to load follow complementary renewable sources, such as wind and solar, as well as responding to wholesale electricity market pricing.

It was also noted that the NSW Government released discounts for DUOS and TUOS network charges for renewable hydrogen projects accessing under-utilised network capacity in the NSW Hydrogen Strategy in October 2021. Such discounts offer further reasons to choose a grid connection over BtM, as the discount in network charges will see a direct reduction in the cost of hydrogen production by approximately $0.60 per kilogram. A recommendation for future projects is to assess the viability of electrolysers with both a direct grid and BtM connection to evaluate the potential benefits of the increased efficiency of a DC-to-DC connection, as well as the increased capacity factors enabled via the grid connection.

13.3.2 Revenue Assessment

Renewable Gas – Hydrogen Injected into the Network

Injected hydrogen is blended with natural gas and is therefore not discernible as hydrogen at the point of application. At the low blending rate of less than 2 %, little-to-no difference is experienced by customers, however, similar to how electricity customers can access renewable electricity from the grid via renewable PPAs irrespective of where the electrons are actually generated, the same could exist for gas customers. This will involve customers contracting renewable gas via future renewable gas certificates and guarantee of origin schemes.

Jemena is currently working with GreenPower to trial a Renewable Gas Guarantee of Origin (RGGO) scheme, which will include both hydrogen injection into the network and biomethane. It is intended that RGGO certificates will be created for all hydrogen utilised to abate fossil fuels. The inclusion and sale of RGGOs adds another revenue stream that was not previously explored or discussed in the initial business case for the WSGHH. Figure 6 shows the proposed process flow diagram for obtaining RGGO certificates.

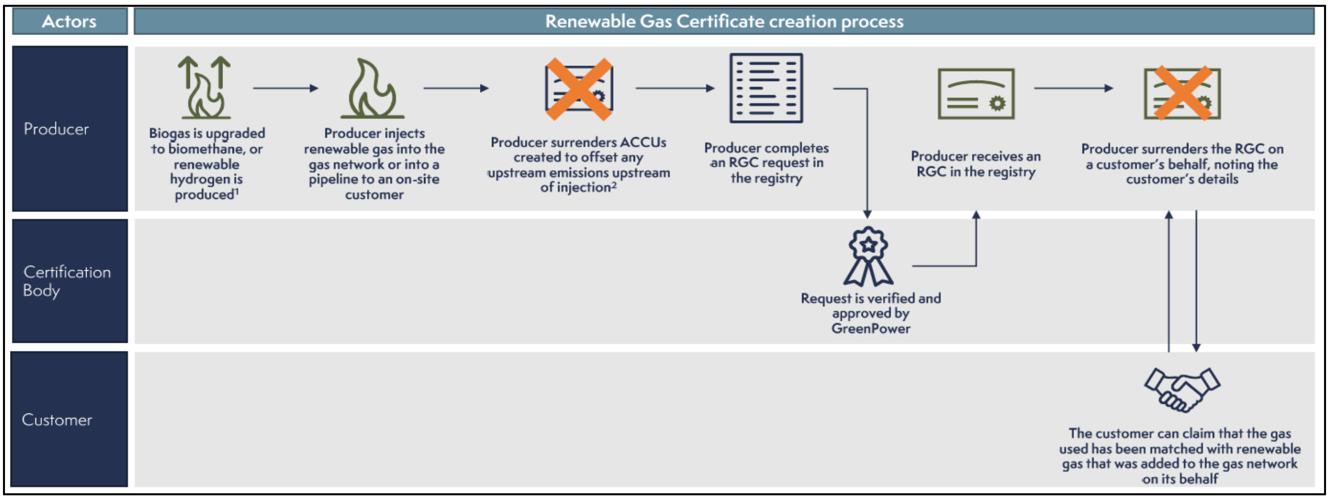

Figure 6: Process flow diagram for obtaining RGGO certificates.

The value of renewable gas is expected to surpass that of natural gas on the basis that it provides a decarbonisation pathway for customers. A low range estimate of the potential additional value of renewable gas is described in the National Greenhouse Gas Emissions Reporting's measurement of determination for natural gas multiplied by carbon offset price such as an Australian Carbon Credit Unit (ACCU). However, a higher range estimate could be equated to the Large-Scale Renewable Energy Target shortfall charge if there was an equivalent Renewable Gas Target. Hence, it is recommended that the benefits of a renewable gas target be evaluated in supporting scaled investments in the supply and blending of renewable gas (including both hydrogen, biomethane and other forms of renewable gas).

Renewable Storage in Existing Gas Infrastructure

An increasingly important element of the energy transition is renewable energy storage to decouple energy demand from variable and intermittent renewable electricity generation. By converting excess renewable electricity to hydrogen and injecting it into the network, the energy system can leverage existing gas infrastructure to store large volumes of renewable energy. This can then provide end users with greater flexibility and responsiveness for meeting their energy demands. For example, the NSW Gas Distribution Network has over 25,000 km of buried pipework and can provide more than 6 GWh of energy storage (equivalent to approximately 7 million Tesla Powerwall residential batteries). Additionally, the gas network is interconnected to gas transmission and storage across the entire east coast of NSW, providing further flexibility, reliability, and responsiveness. To evaluate the storage as a service, it is worth treating the electrolyser as a flexible and unlimited charging cycle device, with the gas network equivalent to the storage capacity and the end user application as an unlimited discharge cycle. The scale of this solution and the ability to utilise existing infrastructure and appliances is an important differentiation from batteries or pumped hydroelectric energy storage that warrants further investigation.

Jemena and its project partners will continue to evaluate the potential to develop renewable storage solutions that can provide the market with relatively low-cost solutions. Such solutions will provide real time renewable energy supplies to complement further large-scale investments in wind and solar generation. Following the commission of the microturbine and fuel cell at the WSGHH in 2023, further operational data will be supplied.

Renewable Storage in Dedicated Hydrogen Infrastructure

Renewable storage in a purpose built 100 % hydrogen pipeline and responsive renewable power generation from a microturbine and fuel cell will be trialled as part of the ongoing WSGHH project. Currently the hydrogen pipeline demonstrates a relatively low-cost storage solution, capable of providing up to 4 MWh of energy storage. Further investigation is required to investigate the round-trip efficiency of regenerating electricity, as well as the levelised cost of hydrogen production, to assess the commercial viability of the storage option for renewable electricity generation.

Hydrogen for Transport

One design challenge for the WSGHH was the immaturity of the hydrogen fuel cell electric vehicle (FCEV) market. Low utilisation of high-cost infrastructure, such as a refueler, adversely impacts the viability of hydrogen as a transport fuel. However, it is noted that the value of hydrogen as a renewable transport fuel is a much higher value than displaced natural gas in the near term and as FCEVs become more prevalent.

Demand Response and Ancillary Services

The selection of a PEM electrolyser provides significant responsiveness and enables the electrolyser to load follow wind and solar resources, as well as rapid fluctuations in the wholesale market price. At the current scale and cost of electrolysers, the commercial benefits of targeting low electricity prices are outweighed by the need for high utilisation, however, as the cost of electrolysers reduce and market volatility increases, the ability to access lower cost energy will have an increasing impact on the levelised cost of hydrogen production. The WSGHH facility was entered into a demand response contract with Origin, which is typically only activated when the grid is in excess of capacity.[7] The voluntary reduction allows Origin to scale down electricity use at a time chosen and arranged by them, without interrupting operations.

This payment allows for an additional revenue stream for the WSGHH and presents a positive opportunity for grid firming the National Electricity Market (NEM). Large scale electrolysers could play a significant role in grid firming and reliability, particularly for the common demand response events during summer from 3 to 9 pm. The project continuously evaluates demand response revenues and potential applications for electricity network support. Furthermore, there is also the potential for large-scale electrolysers and BOP to connect directly to transmission infrastructure to derive ancillary services revenue, such as frequency control services.

All of these revenue streams are captured and categorised in Figure 7.

[7] Demand response refers to a mechanism whereby a business voluntarily reduces electricity consumption in exchange for a financial benefit.

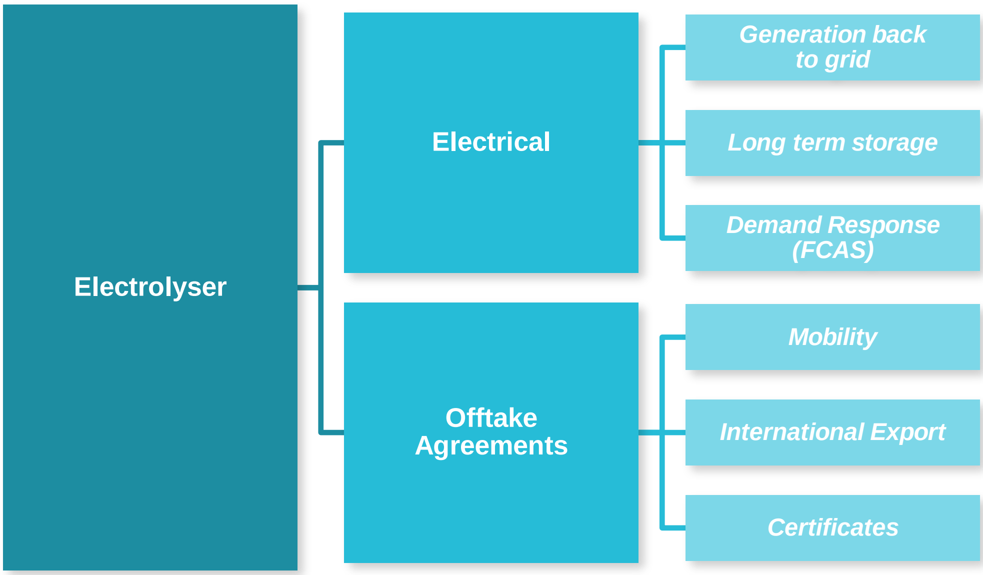

Figure 7: Revenue streams for the WSGHH.

13.3.3 Recommendations

Renewable hydrogen offers the opportunity to integrate the gas, electricity and transport sectors and presents an opportunity for future PtG projects to combine revenues from each. Hydrogen projects thereby provide a low-cost pathway to decouple energy demand from intermittent renewable power generation, which will lead to a more reliable, responsive, and adaptable grid to support greater investment in renewable energy. However, it is currently difficult to commercialise hydrogen projects due to unreliability and a lack of hydrogen demand. Hence, a recommendation is to consider supportive policies to commercialise such projects, which would aid in supporting offtake to further support scaled investment in renewable hydrogen production. Specifically, the following policies could be evaluated:

- time of use emission reporting – supporting demand to shift to lowest emission sources of energy and or investment in renewable energy storage;
- renewable gas certification and renewable energy storage targets, and or;
- load matched renewable PPAs (often referred to as 24/7 renewables).

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- Origin Energy – Electricity Supply and demand side management applications, www.origin.com.au
- Coregas – Hydrogen commissioning support and Gas testing, www.coregas.com.au
- GPA – Detailed design and construction / commissioning engineering support, www.gpaeng.com.au
- Cummins/Hydrogenics OEM for electrolyser supply, www.cummins.com.au
- Energys – Electrolyser supplier, www.energys.com.au
- WASCO – onsite construction, https://wascoenergy.com.au/
- Optimal Group– supply of microturbine and fuel cell, www.optimalgroup.com.au

Appendices

Appendix A - Site Layout

The site layout of the WSGHH is shown in Figure 8 to Figure 10.

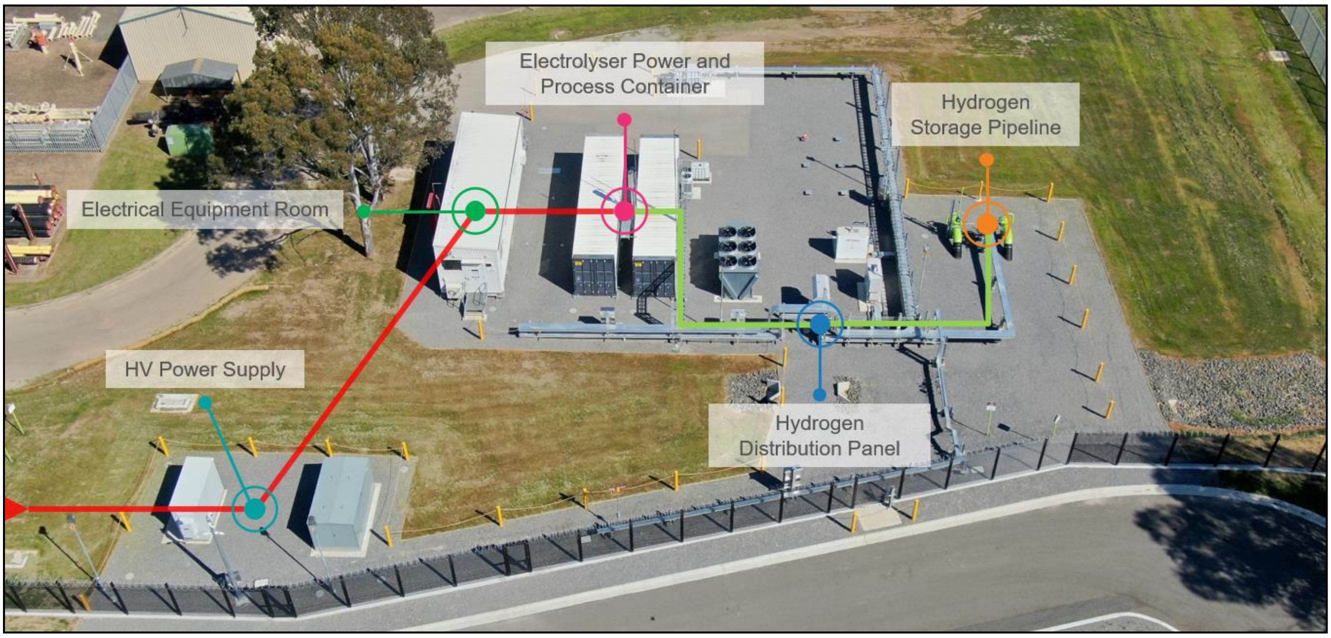

Figure 8: Site layout of the WSGHH (1/3).

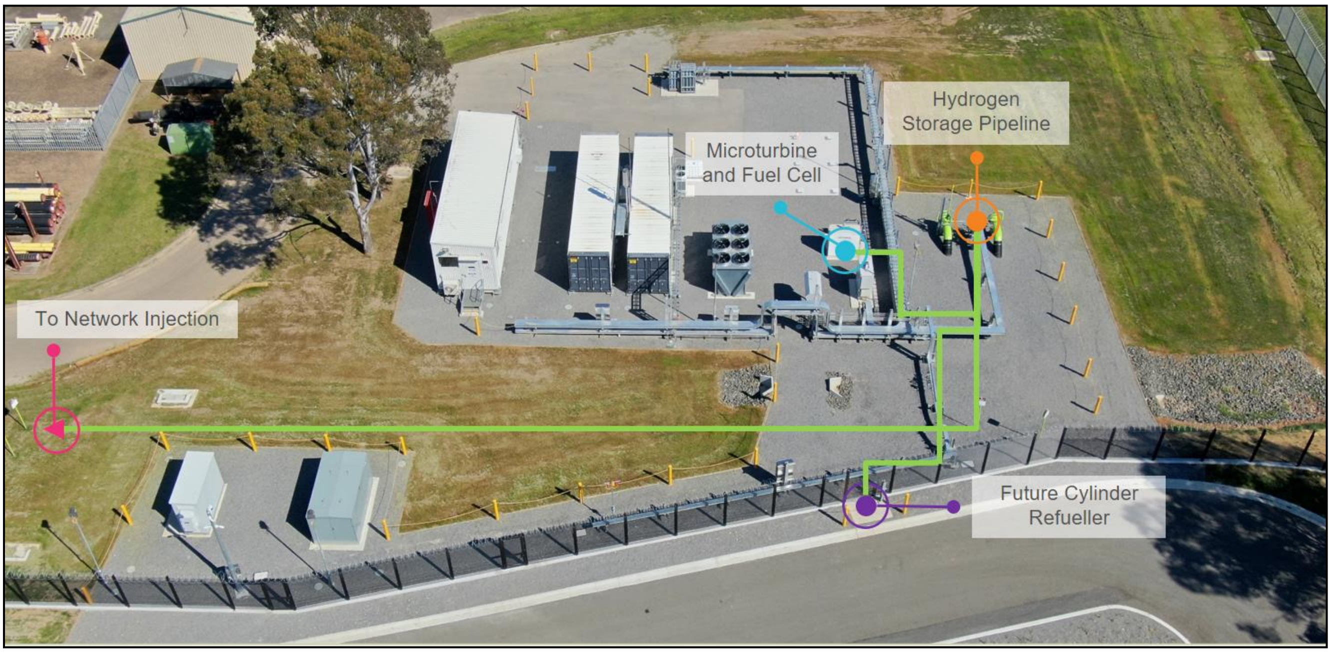

Figure 9: Site layout of the WSGHH (2/3).

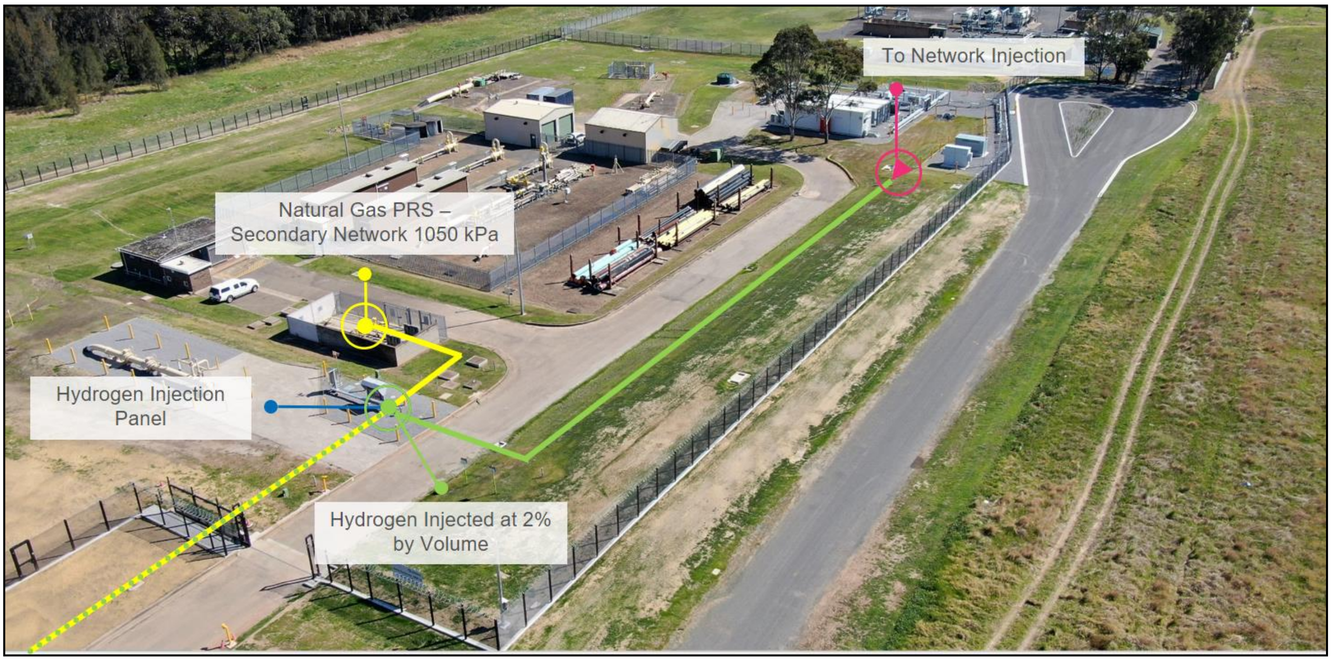

Figure 10: Site layout of the WSGHH (3/3).