WATER FOR HYDROGEN PRODUCTION: CHALLENGES AND OPPORTUNITIES SUPPORTED BY REAL–WORLD CASE STUDIES

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EXTENDED ABSTRACT

The emergence of the near-zero or zero emission hydrogen industry within Australia has become more of a focus as the country looks to transition away from the current energy dependence on fossil fuels. However, the hydrogen and water sectors will need to take an integrated approach and carefully consider the implications of water for each form or "colour" of hydrogen production. The production colour of hydrogen is dependent on the production method used; however hydrogen is still the same product from each process. The current aim is to shift towards "green" hydrogen where electrolysis is used to produce hydrogen with renewable energy used throughout the entire process. However during the energy transition, "blue" hydrogen which involves steam methane reforming with carbon capture and storage, is expected to play a big role. It is critical for the success of this energy transition towards renewables and a more sustainable future, that the water aspects of hydrogen production are considered in detail. This includes sourcing, disposal, and management of water without impacting or exacerbating local water security concerns and negatively impacting the environment and local communities and industries. It is crucial for the emerging hydrogen industry, for which Australia is well placed to be a key player, that we are aligned with the United Nations Sustainable Development Goals (UN SDGs).

This paper presents the water treatment design experiences from four recent hydrogen projects which cover green and blue hydrogen production at both inland and coastal locations in Australia. In addition to challenges encountered covering water security and water chemistry relating to hydrogen plant siting, opportunities are identified to reduce costs and process complexity. As with most forms of hydrogen production, green and blue hydrogen systems are dependent on demineralised water (typically <0.5 uS/cm) which often, depending on the water source, requires desalination, second-pass RO, and further demineralisation process steps. As a result, a major consideration for any desalination process, are the complexities relating to brine management.

Australia is currently garnering momentum and support from the federal and state governments towards the creation of hydrogen hubs to promote the production and exporting of hydrogen, in particular green hydrogen using renewable energy. Australia is well placed to produce renewable energy due to our climate, however recent floods, droughts and bushfires have increased focus upon water resilience. The implementation of hydrogen hubs in water scarce locations can place additional strain on local water supply creating an industry driver to improve technology advancements and reduce water demands for hydrogen production.

This paper summarises the works from four recent hydrogen production development projects and provides a comparison between the different scenarios observed and lessons learnt. Experience from concept design to pre-FEED (front end engineering design) phases, various challenges and opportunities are identified. The water demands for the various projects are presented with the applied methodology of the various studies and potential areas for improvement are identified.

Keywords: Hydrogen, Demineralisation, Desalination, Brine Management

I. INTRODUCTION

It is estimated that by 2050 that there will be a worldwide hydrogen demand of over 500 million tonnes per year. Australia in a unique position to meet a sizable portion of the hydrogen demand due to its history of exporting resources, the climate to produce consistent and reliable renewable energy for “Green Hydrogen” and natural gas resources to enable production of “Blue Hydrogen”. Both forms of hydrogen production will require a substantial volume of water (in excess of 1000 GL/y assuming Australia will supply 10% of the world’s hydrogen demand) [1]. For perspective, this water demand is more than two-times the capacity of the Australia’s 6 large municipal desalination plants located in Adelaide, Gold Coast, Melbourne, Perth (two plants) and Sydney (i.e. approximately 480 GL/y capacity).

1.1 The Australian Context

To support the future hydrogen industry in Australia, the Australian federal government is looking to create seven hydrogen hubs which include Bell Bay (TAS), Darwin (NT), Eyre Peninsula (SA), Gladstone (QLD), Latrobe Valley (VIC), Hunter Valley (NSW), and Pilbara (WA) [2].

Some of these proposed hydrogen hubs however are in potentially water scare locations. Australia has recently experience extreme weather including bushfires, floods and drought leading to water stress. Water scarcity continues to be a material risk to farming and communities within regional Australia with continual development occurring in quantifying water risk assessment frameworks [3]. Figure 1 below depicts the Australian continent with a comparison made to areas of water stress.

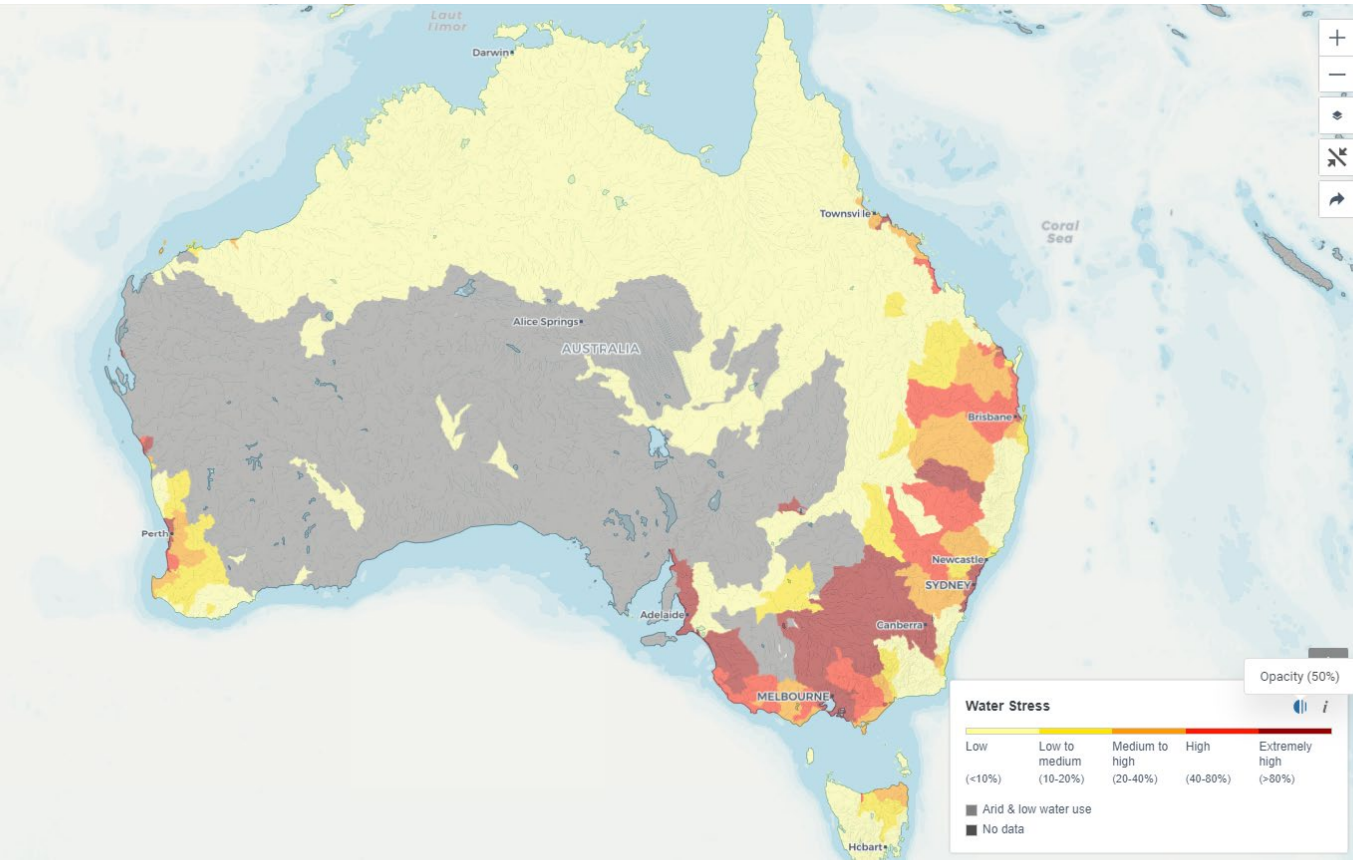

Figure 1: Water stress map comparing demand vs available water within Australia in 2040 [4]

Due to the potentially high requirements for water in the production of hydrogen, it is important to understand how to reduce the dependence on water within the hydrogen economy through the selection and optimisation of hydrogen production, water treatment technologies and opportunities to recycle waste flows to minimise waste discharge. The methodology to undertake this, with associated challenges, have been assessed via the case studies presented in this paper.

1.1 Water for Hydrogen Case Study Projects

The case studies presented here are based on real-world concept design to pre-FEED projects where the hydrogen production unit (HPU) and their respective water treatment plants (WTPs) were selected and designed. These projects have a cross-section of attributes: both inland and coastal located and blue and green hydrogen projects. A summary of the case studies is provided below:

1. Green Hydrogen Inland
    - Co-located with a windfarm
    - Located 50km inland in a semi-arid location with some nearby agriculture and townships
    - Brackish groundwater source (3,000 ppm salinity)
2. Green Hydrogen Coastal
    - Multiple projects at the same location with, and without, ammonia production for export
    - Wind & hydropower from grid
    - Coastal location on a river estuary, near population centres and agriculture
    - Multiple potential water sources including sea water, dam water, sewage effluent, saline estuary water (30,000 ppm salinity for the latter source)
3. Blue Hydrogen Inland
    - Located several 100kms inland, no agriculture or population centres nearby
    - Brackish water groundwater (limited) & brackish produced water (water from oil/gas wells) (2,000-4,000 ppm salinity)
4. Blue Hydrogen Coastal
    - Located at a relatively remote coastal location, small population centre nearby and no agriculture
    - Sea water only available (40,000 ppm salinity)

These projects allowed for comparison and the identification of various challenges and opportunities.

1.2 Water Requirements for Green & Blue Hydrogen

The following summarises the various feed water and waste stream volumes and characteristics for green and blue hydrogen projects informed by the case study projects undertaken:

1. Green Hydrogen
    - Feed Water Streams
        a) Hydrogen Production
            - Volume and water quality requirements dependent upon technology used
            - Approximately 10-12 L of demineralised water is required per kg H_2 produced (best case scenario)
            - PEM Electrolyser <0.25 ppm salinity, most individual analytes <0.005 ppm (e.g. sodium, chloride) largely based on ASTM standard D1193 Type III B for de-ionised water
        b) Cooling Water Make-up
            - 50-300% of electrolyser volumetric demand depending on several location specific variables (i.e. humidity, temperature, wind) and electrolyser requirements
            - <500-1000 ppm salinity, low scale/biofouling potential, stable (i.e. pH buffered)
    - Waste Streams Produced
        a) Water treatment waste streams
            - Dependent on water quality / salinity of the raw, recycled & treated water streams
            - High solids streams normally via pre-treatment, high salinity streams via desalination
            - Some readily recycled, some not and require appropriate management or disposal

    b) Hydrogen production waste streams
        - Condensate from electrolyser & compressors
        - Small flows and relatively high quality

2. Blue Hydrogen
    - Feed Water Streams
        a) Hydrogen Production
            - Volume and water quality requirements dependent upon technology used
            - Approx. 3-8 L demineralised water per kg H_2 produced
            - Steam Methane Reforming: generally <0.5 ppm salinity, individual analytes <0.1 ppm (e.g. sodium, chloride)
        b) Cooling Water Make-up
            - Air cooling or even chilling often used in dry locations if water resources are lacking
            - Air cooling may require adiabatic cooling leading to very high short water demands
    - Waste Streams
        a) Water treatment waste streams
            - Dependent on water quality / salinity of the raw, recycled & treated water streams
            - High solids streams normally via pre-treatment, high salinity streams via desalination
            - Some readily recycled, some not and require appropriate management or disposal
        b) Hydrogen production waste streams
            - Small to medium flows, various condensates (turbine, process, blowdown) some high in amines/ organics

1.3 Methodology Used for Each Project

Table 1 below outlines the approximate 6-step process followed for each project which form the basis of the case studies; note that that the process is iterative and often repeated during each phase.

Table 1: Summary of 6 step methodology

Step	Description
1. Water quality sampling	Sampling should occur over an as long as practicable period to ensure data is representative and season variation is observed. All analytes important for design need to be analysed. It is essential that all parameters are tested that may affect design.
2. Process selection and design	For each project EVS: Water Design software was used for process simulation and design. EVS: Water is a WTP process design and process simulation / chemistry software which allows for the configuration of flow sheets to quickly simulate multiple scenarios and inform plant design and sizing. It incorporates a speciation engine which allows for prediction of pH, chemical addition, solubility, density, conductivity, and boiling point rise of each stream within the model. In addition key deliverables including PFD, M&H balances and lifecycle cost spreadsheets can be exported from the model. This allowed rapid development of multiple alternative treatment schemes whilst accounting for process chemistry and costs.
3. Brine management strategy development	Determination of the brine volume minimisation approach (if required), disposal / beneficial use route and end of life management is a key consideration for the desalination process. For inland sites, the determination of brine chemistry behaviour (using software such as OLI Stream Analyzer) and integration with water balance modelling is useful for prediction of bulk crystallisation timing for management of ponds or investigation of aquifer re-injection opportunities.

Step	Description
4. Cost estimation	Often paired with an MCA as cost comparison to influence the decisions made from both a technical proficiency and a cost to the organisation to find a compromise between cost and performance. Typical cost estimation occurs through net present costs (NPC) analysis which feeds into the overall project internal rate of return (IRR) to undertake trade-off studies e.g. air cooling versus chilling versus evaporative cooling.
5. Multi Criteria Analysis (MCA)	Used to compare all facets of an engineering design i.e. cost, technical, environmental, social etc considerations. Commonly used for siting selection (important for space constrained coastal projects), technology selection (e.g. pre-treatment) and brine management strategy decisions including pond storage vs thermal treatment or comparison of complete strategies.
6. Lab or pilot test work	In addition to water quality testing, jar testing, lab testing of technology and even pilot plant testing may be required to determine or prove feasibility of technologies that may be novel.

II. RESULTS

Throughout the development of these case studies, the various demineralised water demands, waste stream production rates and cooling water demands were determined following several design iterations. Table 2 summarises the water demands and waste stream production for the various case studies.

Table 2: Summary of case study water demands

Project	Raw Water (L/kg H_2)	Waste Stream (L/kg H_2)	Cooling (L/kg H_2)	Demin for H_2 & NH_3 (L/kg H_2)
Inland Green H_2 (Brackish Ground Water)	56	11	35	10
Coastal Green H_2+NH_3 (Saline Estuary Water)	176*	114	46	16
Inland Blue H_2 - Steam Methane Reforming (Brackish Ground & Produced Water)	13	5	Chilling	8
Inland Blue H_2 - Auto-Thermal Reactor (Brackish Ground & Produced Water)	5	2	Chilling	3
Coastal Blue H_2 - Steam Methane Reforming (Sea Water)	23	15	Air	8

Note: * indicates additional water required for NH_3 production (i.e. for hydrogen transport).

2.1 Hydrogen Transportation

The transportation method for the produced hydrogen, as demonstrated by ammonia production in Table 2, contributes to the water demand of the system. Typical carrier mechanisms include conversion of hydrogen to ammonia via the Haber Bosch process, liquefication of hydrogen or storage of hydrogen by means of a fuel cell. Whilst the water demand requirements may not be the main driver for the selection of a carrier mechanism, it should not be neglected from a whole system water balance. The current preferred approach for hydrogen transport is as ammonia produced via the Haber-Bosch process, however fuel cells, and liquid hydrogen transportation have both occurred.

2.2 Raw water quality

The water quality of available raw water sources is often brackish to saline in salinity or high in pollutants (e.g. such as oil and hydrocarbons) as fresh water sources are typically locked in for drinking water, agriculture, or existing industry. This often results in specific water treatment technology requirements to remove these analytes prior to feed into the hydrogen production plant and the production of the resultant waste streams. For example, desalination is often required with the resultant production of brine waste.

2.3 Brine Management

Brine Management has been a challenge associated with desalination and is associated with many industries including unconventional gas production (e.g. coal seam gas industries) and America's inland power stations. This will be no different for the hydrogen industry with the requirement for desalination at both inland and coastal applications. Seawater desalination is often seen to be beneficial when it comes to brine management due to ready disposal via a coastal outfall. However, there are often numerous studies required to determine the environmental impact of brine outfalls (i.e. hydrodynamics studies, extensive water quality testing, ecological studies etc) and significant community engagement required. For inland desalination routes, surface encapsulation or landfill of salt and brine injection are common routes for disposal of large volumes of brine. In some cases, salt recovery may be worthy of investigation. Various treatment methods are available to enable volume minimisation for costs reduction, however, in the context of Australia, solar evaporation ponds are most common due to the preferential climate. It is noted that thermal evaporation methods are, in a holistic sense (i.e. considering both economic and non-economic factors) and in whole life costs, often ranked similarly.

2.4 Sample Process Flow Diagram

Using the methodology outlined above, water treatment designs have been developed for the four recent hydrogen projects covering inland and coastal hydrogen production water treatment plants. Figure 2 presents an example simplified schematic for Green Hydrogen (not based on the case study presented in this paper).

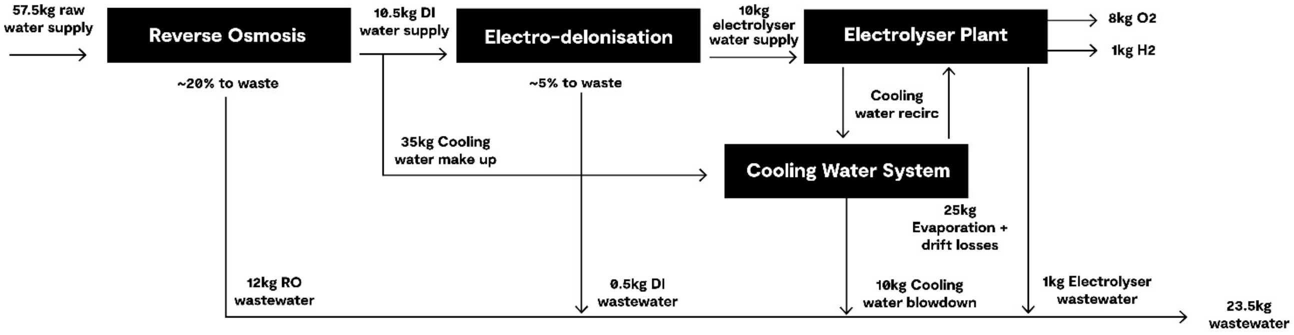

Figure 2: Example schematic for Electrolyser Water Treatment for Brackish Water Supply [5]

Note that the CEDI waste and cooling water blowdown have been shown to go to waste however there is an opportunity depending on water quality to recycle these to the front of the process for reprocessing through the system. The above has been shown as a conservative case in case recycling is not possible.

III. SUMMARISED FINDINGS FROM CASE STUDY PROJECTS

Summarised outcomes from the four case study projects undertaken are as follows:

- Inland Green Hydrogen Project:
    a) Brackish groundwater desalination was the only option at this project site
    b) Lack of source water quality / quantity information evident at the start of the project and additional sampling required
    c) Challenges for brine management exist for this site (i.e. no readily available local disposal route) with investigations continuing
- Coastal Green Hydrogen Project:
    a) Significant water availability constraints at this project site:
        - limited fresh water due to population / agriculture / industry demands
        - drawn out discussions with water suppliers/users
        - challenging alternative sources e.g. saline estuary water with changeable quality and high organics and nutrients
    b) Saline estuary water desalination shortlisted & discussions with surface water supplier ongoing
    c) Significant regulatory requirements / investigations due to saline waste release to river estuary (i.e. toxicology studies, dispersion modelling etc.)
- Inland Blue Hydrogen Project:
    a) Numerous low quality water sources available (brackish ground water and produced water)
    b) Some water sources 40km from WTP
    c) Complex treatment due to requirement for desalination and hydrocarbons / oils in produced water
- Coastal Blue Hydrogen:
    a) Sea water was the only source available
    b) Water quality samples were >10 years old therefore additional sampling required
    c) Significant regulatory hurdles & investigations due to saline water release into a large bay with rare marine fauna identified and challenges due to the potential for warm cooling water release

The various findings from the above case studies enabled identification of challenges and opportunities that are likely valid for most hydrogen production projects.

IV. COMMON CHALLENGES AND OPPORTUNITIES

Common issues relating to water treatment for hydrogen production include the impact of hydrogen plant siting, water security (many readily available sources require desalination), feed water chemistry, cooling requirements. In developing the designs for the real-world projects evaluated here, several investigations occur as part of the process. These items incorporate or address the key challenges and opportunities as outlined within Table 3.

Table 3: Summary of challenges & opportunities for water treatment for hydrogen production

Investigations	Challenge / Opportunity
Location Siting	• Proximity to various water sources • Proximity to hydrogen export location • Proximity to feed stock methane • Proximity to energy sources • Cooling considerations
Water Security and Feed Water Chemistry	• Water security and feed water availability i.e. even in high rainfall areas, all available water may already be allocated to drinking water, agriculture or environmental flows • Feed water quality and quality uncertainty (e.g. untested groundwater) • Many available sources but are challenging to treat (e.g. brackish groundwater, oily produced water, treated sewage, brackish water from estuaries, saline seawater) • Regulations related to water access and the end-uses (e.g. for blue hydrogen, a groundwater source may not be able to be used for export) • Information related to the feed water chemistry (e.g. number of available samples, representative samples / correct sampling method, sampling occurring throughout the year, field values vs lab values for pH etc, sampling of the required analytes)
Brine Management Strategy	• Many readily accessible water streams require desalination • Desalination produces a considerable waste stream that is challenging (i.e. costs, regulations, environment) to treat, manage and dispose • Considerations around end-of-life management • Optimisation of beneficial reuse opportunities e.g. downstream sodium bicarbonate plant
Recycling of WTP & HPU Waste Streams from Water Treatment	• At water constrained locations there are drivers to maximise plant recovery via waste stream recycling • Waste stream recycling can be challenging due to quality, lack of information available on Hydrogen Production Unit (HPU) waste streams etc
Cooling Water Requirements	• Air versus water cooled versus chilling dependent on local climate and interplays with siting and trade-off against overall hydrogen project costs • Seawater once-through cooling versus seawater evaporative cooling (although low number of cycles and expensive materials) • Adiabatic cooling requirements at hot inland locations (requires intermittently very high-water usage)
Site Steam Applications	• Potential to use blue HPU steam to drive thermal desalination or thermal brine evaporation / crystallisation
Waste Heat Recovery	• Appreciable amounts of waste heat exist both for green and blue hydrogen projects • Considerable amounts of waste heat exist for ammonia production using the Haber-Bosch process • Waste heat may be used for desalination (e.g. membrane distillation), brine minimisation and/or assist cooling processes
Oxygen Reuse Opportunities	• Reuse the oxygen generated from the electrolyser for water treatment process e.g. aeration of the wastewater treatment processes

V. CONCLUSIONS

Water treatment for green and blue hydrogen projects, whether inland or coastal, all have scenario specific challenges and opportunities. However, as outlined, many of these are common between projects and there are potential integration opportunities to create complementary designs that are advantageous for both water treatment and hydrogen production plants. The methodology covered above has been used successfully to develop designs for each project based on their own circumstances and requirements.

Hydrogen project proponents and the water sector will need to take an integrated approach and carefully consider the implications of water within each form or "colour" of hydrogen production. Water is a key aspect to the emerging hydrogen industry and is crucial for hydrogen production in the form of demineralised water, is often used for cooling and presents challenges relating to the waste streams produced during raw water purification (i.e. a common waste being brine from desalination).

It is important to ensure that water requirements are not underestimated as this may be detrimental for the social license to operate, may affect communities already impacted by water scarcity and, ultimately, may be an impediment to hydrogen production. The variable water volume requirements for the hydrogen projects outlined within this study need to be considered carefully and cannot be removed from project planning from an environmental, cost, or social license perspective.

Water supply and treatment for hydrogen, if not addressed properly, may affect the financial viability of projects, and ultimately may result in projects being abandoned due to the lack of water. Ignoring the intricacies and costs of water management will directly correlate to the ability for proponents to meet the Australian Government target of "H2 under $2" [6].

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