HYDROGEN SUSTAINABILITY

ENEN2000 – Engineering Sustainable Development

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1. Introduction

On November 10, 2016, Australia ratified its position on the *Paris Climate Agreement*, pledging to reduce the country's greenhouse gas (GHG) emissions to 26-28% below that of 2005 levels by 2030 (Power 2017). According to Climate Action Tracker (2019), Australia is headed for an increase of 8% above the GHG levels of 2005 by 2030 due to its current emission policies. The Australian Government, however, suggest that the 2030 target will be met comfortably as a result of renewable energy schemes implemented by state governments (Power 2017). One exciting and emerging area of renewable energy is that of hydrogen as an environmentally friendly fuel source; with "more than a dozen pilot projects around the country… considering ways to add hydrogen to the mix of natural gas for domestic use", many Australian states are gearing up for a "hydrogen revolution" (Slessor 2020). Reviewing the news article written by Slessor (2020), this study aims to explore the use of hydrogen as a fuel source and its implications on Australia's social, economic and environmental spheres.

2. The use of hydrogen as a renewable fuel source

2.1. Australia's approach – Hydrogen Electrolysis

As stated in section 1, Australian state governments are pushing for projects to incorporate hydrogen into the nation's natural gas mix, as adding just a small amount of hydrogen increases both the efficiency and performance of the mix (Slessor 2020). The first hurdle faced in doing so is acquiring refined hydrogen. To do just that, the South Australian State Government announced the installation of a hydrogen electrolyser in the Adelaide suburb of Tonsley (Slessor 2020). An electrolyser splits water into oxygen and hydrogen using electricity, if said electricity is renewable then so is the hydrogen (Homann 2020). Tonsley's 1.25 MW proton exchange membrane (PEM) electrolyser will use renewable electricity to produce renewable hydrogen as a part of Australia's first trial of 'power-to-gas' technology (Harmsen 2017).

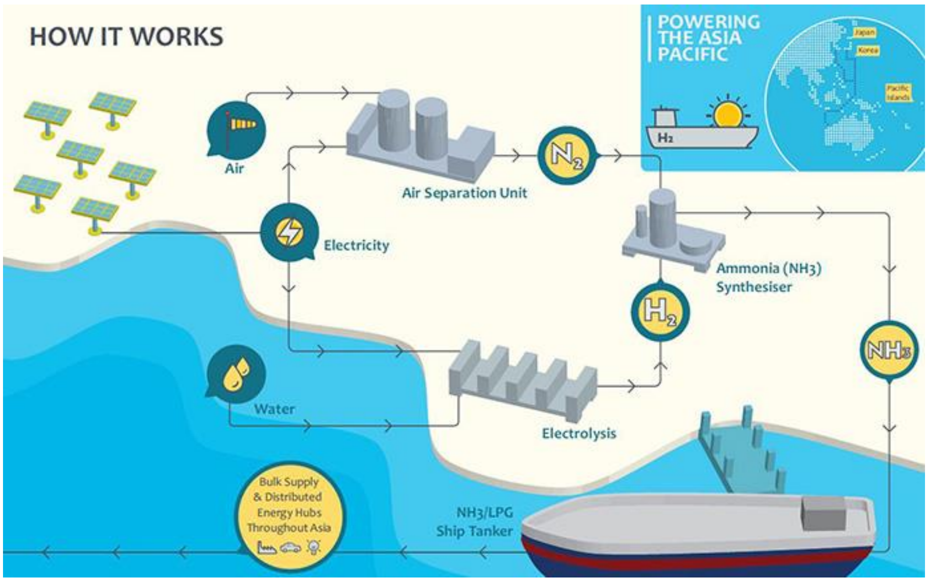

Figure 1. How renewable hydrogen is produced. 2017, Infographic. Reproduced from: ABC News.

2.2. Greenhouse gas emissions of a ‘Power-to-gas’ scheme

A ‘power-to-gas’ scheme uses electrolysers to generate hydrogen that is either injected into the natural gas system or sent directly to hydrogen end users (Walker et al. 2017). Figure 1 illustrates Australia’s approach of using renewable energy to power the production of hydrogen by electrolysis, in its ‘power-to-gas’ scheme. According to Walker et al. (2017), a very similar ‘power-to-gas’ scheme was implemented in Ontario, Canada. Figure 2 shows data from the Ontario study that reinforces that hydrogen via a ‘power-to-gas’ scheme has little-to-no GHG emissions in comparison to other fuels that can be used in a natural gas distribution system.

Contaminants	Natural Gas	Hydrogen via Power-to-Gas (1 vol-%)	Natural Gas (99 vol-%)	Hydrogen Enriched Natural Gas	Renewable natural gas
Greenhouse gas	18.63	0.05	18.58	18.629	−71.8
VOC	0.011	0.000038	0.010	0.0108	0.035
NOx	0.04	0.000015	0.04	0.04	0.013

Figure 2. Table of Greenhouse gas, VOC and NOx emissions, in grams, required to produce 1 MJ of fuel in the natural gas distribution system of Ontario, Canada.

Source: Table reproduced from Walker et al. (2017).

2.3. Effects on land use changes and biodiversity

Some of the current methods of extracting gas from the earth's surface involve a method which is not environmentally friendly. A somewhat popular and hotly contested technique used to extract natural gas from the earth's surface is hydraulic fracking. Australian states have been divided on this subject with some states having a full ban on hydraulic fracking as seen in Victoria and Tasmania. While others have varying degrees of restrictions. This can be seen in states such as South Australia and New South Wales with almost unrestricted legislation regarding fracking (Cullinane 2018).

Some of the environmentally negative effects of fracking is the proposed contamination of nearby water with methane. As contaminating water sources to obtain natural gas is unsustainable, moving towards a domestic green hydrogen gas supply would in turn reduce Australia’s dependence on mining operations. Several proposed ways of generating hydrogen do not involve the use of fossil fuels and therefore have zero emissions. An example of this is electrolysis as previously described. While this is a suitable alternative it is not the only option seeing government investment. The Hazer Commercial Demonstration Plant in Munster Western Australia once completed, will turn Biogas from sewage treatment into hydrogen. The Hazer process will cause zero emissions by turning what would be CO2 into graphite, therefore eliminating the negative environmental impact while recycling a discarded resource (ARENA 2020c).

As displayed in the Hazer Process and electrolysis examples. It is possible to generate Hydrogen gas while avoiding the existing environmental hazards. Moving towards sustainable hydrogen generation will reduce the scope of negative impacts caused by existing mining methods.

The electrolyser requires electricity in order to produce hydrogen. If the methods used to produce electricity for this process are sourced from fossil fuels, then the pollution and C02 emissions are indirectly caused by the electrolyser operation (EIA, 2020). Burning hydrogen causes nitrogen to combine with air which creates NOx, a harmful substance when in excess in the atmosphere. Burning hydrogen produces six times as much NOx emissions compared to burning methane. This can be prevented by burning hydrogen in pure oxygen (not a common commodity in households) (ICAX, 2019). NOx interacts with water in the atmosphere that forms acid rain. This rain is detrimental to sensitive ecosystems in lakes and other waterways. It is also responsible for increased nutrient pollution for coastal waters (EPA, 2016). If Hydrogen is more commonly being combusted within households without means to burn within pure oxygen, NOx emissions from all households using methane gas will increase sixfold. This will severely increase potential for the cause of acid rain, a harmful pollutant to all waterways it enters.

2.4. Economic and social consequences

The expansion of the hydrogen industry comes with the decline of the fossil fuels industry as it effectively replaces the resources they produce. This will result in the creation of a potentially booming industry with thousands of work opportunities but will also collapse another huge industry. Not all pipelines are capable of carrying hydrogen so for hydrogen to replace current natural gas, the entire pipeline network will have to be insured that safe for hydrogen transportation (Camron, 2020). Although some pipes already hydrogen capable, large sections will need to be replaced to completely allow for a safe hydrogen network. This means an expensive infrastructure project that will be a large investment by governments and funded by the taxpayer.

Because the hydrogen production being environmentally friendly is entirely reliant on the development and use of green energy production. If recyclable energy production is not able match needs for consumption by the electrolysers in the future, the new gas being used in households will still be taxing on the environment due to the necessity of fossil fuels for operation (Camron, 2020). If this is the case it may spark outrage in environmental communities as the new gas is not actually solely produced by environmental means.

Some of the general population may be wary of hydrogen because of the well-known Hindenburg disaster. Certain groups may be against the use of seemingly dangerous gases in their households leading to protests for the project - an anti-hydrogen movement. While anti-hydrogen sentiments may exist, a survey and report issued by the University of Queensland on behalf of COAG energy council found that the public's trust in hydrogen is overall neutral. Members of the public displayed interest in the jobs and opportunities an energy boom may bring (Ashworth et al. 2019). The public's opinion was also positive towards Australia's possible stance as a major exporter of domestically produced hydrogen as demand is set to increase in China, Japan and Korea (Deloitte 2019). Indigenous interviewees showed a keen interest in supporting a green industry. Although this seems mostly positive some concerns for the future of the fossil fuel industry were displayed by people with an ongoing relationship with said industry (Ashworth et al. 2019).

3. Engineering Challenges

The use of hydrogen as a sustainable, renewable fuel source poses many engineering challenges. This section aims to outline, analyse, and discuss the challenges faced when considering the sustainability system. These challenges include: The development of a sustainable industry able to produce hydrogen while avoiding unsustainable methods; upgrading pipelines and infrastructure as required to work with the 10% hydrogen mix; and ensuring the public opinion remains neutral to positive towards hydrogen. The major focus of each challenge will be considered, be that economic, technological, environmental, or social impact, as well as whom is responsible for the managing of each challenge.

3.1. Analysis

3.1.1. Achieving renewable hydrogen

As stated in section 2.3, the use of an electrolyser to produce hydrogen gas as a *renewable* fuel source entirely depends upon whether the electricity used in the electrolysers process was produced *renewably*. If the electricity used in electrolysis is completely renewable, such as that of the Tonsley electrolyser (Slessor 2020), the greenhouse effects of the production of the hydrogen are considered negligible. The focus of the Australian Government on creating renewable hydrogen, by the means of renewable electricity, highlights the continued and growing consideration of the impact the gas sector has on the environment. As renewable energy has become more affordable in recent years (Slessor 2020), this positive change towards consideration of the environment is not wholly benevolent and partly driven by the industry's monetary gain within the sector.

3.1.2. Upgrading infrastructure

Australia had a dependency on natural gas. Only in recent years has hydrogen been seriously considered by the Australian government. Hydrogen has moved into the spotlight due to Australia attempting to meet its emissions target set at the 2016 Paris Agreement, with no small part due to hydrogens secondary aspect as a major export good (Deverell and Hartley 2020). Engineers working on integrating hydrogen into the natural gas mix may find that the existing infrastructure isn't up to the task or that industry isn't able to use the hydrogen mix in gas machinery. These are some issues considered by the COAG Energy Council who commissioned GPA Engineering to investigate infrastructure and industry. Findings showed that existing infrastructure would be suitable for a 10% hydrogen and natural gas mix with some adjustments required for industry machinery (GPA Engineering 2019).

3.1.3. Public opinion

The general public's perception of hydrogens safety is mixed as 35% believe that hydrogen is a dangerous energy source according to an anonymous social media survey. This sceptical view of hydrogen likely stems from the infamous historical disaster of the Hindenburg in 1937, the destruction of a hydrogen-filled airship that combusted due to unknown reasons other than several hypotheses (Ong and Kolodziejczyk 2019). Another fresh disaster still in the hearts and minds of majority of the world was the catastrophe of the 1986 Space Shuttle Challenger launch. The obliteration of a NASA space shuttle broadcast worldwide to helpless onlookers as all seven crewmates aboard the shuttle perished in the hydrogen related explosion. Although investigations concluded O-rings were the point of failure, the worlds firsthand view of the disastrous effects of hydrogen in an accident did not improve public opinion (Ong and Kolodziejczyk 2019).

3.1.4. Role of engineers in creating existing challenges

Pure 100% Hydrogen has never been supplied to homes and businesses, it has been limited to industrial applications and there are currently no example networks in the world that can demonstrate how such a system could work. To cause a significant effect in reducing GHG, a large deployment to homes and business would require implementation over 30 years. As engineers have limited their current hydrogen systems to purely industrial means, there are currently no engineers who are skilled in providing and developing consumer friendly models that can be established for households and business (Robert et al. 2020). A project so ambitious for engineers with little experience and such a short time span will require highly convincing evidence to give any reason to proceed.

3.2. Discussion and Suggestions

When considering possible solutions to such challenges outlined in section 3.1, all aspects will need to be investigated. A strong economic policy with a weak social outlook will fail due to public distrust. While an environmentally sustainable policy with low economic success will lead to the industries demise. Only by investigating all challenges will a suitable policy emerge.

3.2.1. Economic

Future economic and environmental issues rising due to how the government tends to fund in the far future. For example, if Hydrogen cannot be generated fast enough to meet domestic and export needs the industry may turn to fossil fuel generation methods to meet demand. This would negate the effect of sustainably generated clean hydrogen. Alternatively, the Australian government has a history of bailing out dirty industries (Lannin 2014). If hydrogen export demand exceeds supply the government may choose to fund fossil fuel generation methods.

The government should regulate industry to ensure that the price is controlled both domestically and internationally for export. To support the emerging industry the government may choose to lower export tariffs. Establishing ongoing trade relations will be the responsibility of both government and industry.

3.2.2. Environmental

Investing into emerging hydrogen technology will ensure the industry is able to freely innovate. Government funded taskforces such as the Australian Renewable Energy Agency (ARENA) can supply funding to projects that accelerate the renewable energy in Australia. One such project is a project in Western Australia which turns Biogas into hydrogen with zero emissions. With the ability to fund fringe projects Australia will be able to ensure its ability to adapt to new technology as it becomes available removing dependency on outdated and damaging methods, such as fossil fuels, in the future.

To ensure a push to environmentally friendly, sustainable fuels sources the Australian Government must follow the guidelines set by the Australian Hydrogen Roadmap if it intends to meet the 2016 Paris Agreement targeted emissions (Deverell and Hartley, 2020). There are economic reasons for the government to keep producing hydrogen sustainably with some sources stating that potential importers of Australian hydrogen will only be interested if the hydrogen is generated from sustainable sources (Hamilton 2020). As such the government will be responsible to ensuring that the industry is working in a sustainable manner.

3.2.3. Social

While surveyed Australians remain mostly neutral towards hydrogen, a sharp increase in the industry is likely to cause negative social effects within the public. This sentiment was discussed in a University of Queensland study which quoted how the public grows to distrust a swiftly growing industry (Ashworth, Ferguson and Sehic 2019). This same study suggested several ways to ease the social aspect of establishing and developing this new industry. Some notable suggestions were to manage expectations and communicate realistic timeframes, costs, risks, and benefits. Engage with the community, especially with traditional owners and ensure that Hydrogen will be used domestically so the average Australian can see the positive impact firsthand.

Its already been suggested that controlling the growth of the industry will prevent negative public outlook therefore the government and industry will need to ensure that this growth is controlled. Providing communication to the public will also be a government and industry responsibility ensuring that the public knows the benefits of the industry will be of great importance to achieve high public opinion.

4. Life Cycle Analysis

When addressing sustainability challenges, it is critical to consider the entire life cycle of a product or process. Failing to do so can lead to unforeseen challenges or overlooked consequences that are only discovered long after implementation.

4.1. Hydrogen Enrichment Life Cycle

The life cycle of hydrogen enrichment for natural gas begins with electrolysis. An electric current is passed through water from a submerged anode to cathode, causing the water to decompose into oxygen and hydrogen (Homann 2020). This hydrogen is collected, while the oxygen can be safely released as it is not a GHG. As long as the electricity to perform electrolysis is sourced renewably, this stage of the process has negligible environmental impact (Slessor 2020).

The collected hydrogen is then mixed with natural gas and distributed throughout the natural gas distribution pipeline, where it is delivered directly to homes (Slessor 2020). Not all existing natural gas distribution pipes may be capable of carrying high concentrations of hydrogen however (Slessor 2020), so levels may need to stay below 5% hydrogen by volume until these concerns can be properly investigated (Walker et al. 2017).

Having been distributed to households via the pipeline, this hydrogen-enriched natural gas can be combusted as a source of heat for various home gas appliances. Combustion of hydrogen reacts with oxygen in the air, forming water and releasing heat. Assuming the electricity to perform electrolysis comes from renewable sources, the hydrogen enrichment process forms a renewable life cycle, where water is initially consumed to form hydrogen and oxygen, and then this hydrogen is consumed along with oxygen to form water.

The hydrogen enrichment life cycle can have indirect effects environmental effects, however. When combustion occurs in air rather than pure oxygen, the heat can cause oxygen atoms to react with nitrogen in the air to form NOx (ICAX 2019). Typically, the fuel for combustion is high in carbon, and so a large portion of the excited oxygen atoms will instead react with the released carbon to form CO_2. Hydrogen-enriched natural gas is significantly more carbon efficient as a fuel source, so less carbon is released for the excited oxygen atoms to react with. Consequently, more of these atoms will react with nitrogen, forming greater amounts of NOx (ICAX 2019).

4.2 Triple Bottom Line Hotspots in production and processes that are creating sustainability challenges

The triple bottom line (TBL) is a form of indicators which not only focuses on the economic implications of business operations but also consider ecological, and social impacts of business operations (Rosano and Biswas 2020). The social indicator will reflect upon the people involved in the respective business operation such as customers, the wider community, and the employees involved in the project (University of Wisconsin n.d.). Ecological will involve anything pertaining the planet specifically the effects of global warming caused by the conduction of business activities, a project must try its best to minimize its ecological footprint as much as possible (University of Wisconsin n.d.). Economic is the pursuit of profitability while still maintaining sustainable business operations without forgoing ecological and social efforts (University of Wisconsin n.d.).

To produce hydrogen gas in Australia the TBL hotspot for the economy can be the construction of the hydrogen plant, and the manufacturing of the hydrogen. The ecological hot spots can be the production of nitrous oxides into the atmosphere through the manufacturing of the hydrogen gas. The social hot spots can be thought of as the end-user satisfaction, and the number of jobs created.

4.3 Diagnose of the causes of Triple Bottom Line hotspots

The economical TBL hotspot is mainly found in the manufacturing (electrolysis) process of hydrogen as mentioned in section 6.1, to produce hydrogen it’s required to split hydrogen from water molecules this requires a great magnitude of current energy, and due to the small molecular makeup of hydrogen, it’s required for the hydrogen to be compressed through very low temperatures (ICAX 2019). These processes will require a great magnitude of energy and electricity which incur large costs to the project (ICAX 2019). Arguably, the costs of electrolysis can be mitigated by only running the process when electricity is the cheapest which is typically in off-peak times (ICAX 2019). Furthermore, the electrolysis process or any other hydrogen extraction process is not going to be 100% efficient therefore, these efficiencies must be paid for (Bochum 2016) (ICAX 2019). Furthermore, due the different molecular sizes and properties of hydrogen molecules relative to the commonly used fossil fuels, the necessary modifications to the pre-existing pipelines must be made to fully accommodate hydrogen in-order to stop the pipelines form embrittlement, and combustion (Walker et al 2017). Additionally, further research and development needs to be conducted to ensure that the hydrogen gas can be handled safely, and the appropriate complementary technologies can be bought which in itself is an expensive process (ICAX 2019). Using, the stream-reforming method for hydrogen production the purchase of a carbon capture and storage (CCS) unit is needed to make the process sustainable, as carbon dioxide is released through the burning of methane and steam (ICAX 2019). In which the CSS unit is still research and development, and it’s expensive to produce (ICAX 2019). Other, economic considerations may include the cost of installing the specialised technologies, the cost of labour, the cost of maintenance of the hydrogen applications, feedstock cost, auxiliary inputs, plant overhead, construction costs, and utilities (Chanhee et al 2020).

The ecological TBL hotspot is mainly found in the manufacturing of hydrogen gas, containment, and transportation. To manufacture hydrogen copious amounts of electrical energy and heat must be produced to successfully produce hydrogen, and to transport hydrogen gas the use of either ships or trucks is required. If the production of hydrogen is conducted through the combustion of natural gas (methane) and air this will lead to excess production of nitrous oxides and carbon dioxide contributing to global warming (ICAX

2019). Albeit, if the production of hydrogen is conducted through the electrolysis method the resultant product will be free from nitrous oxides and carbon dioxide thus, this method would be the preferred method for decreasing the ecological footprint (ICAX 2019).Furthermore, The resultant product of this process will be water, and heat which is the greatest advantage of this method as those products can be used to make more hydrogen or to power another renewable energy source (ICAX 2019). On the other hand, the greatest disadvantage of this process is the incurred cost of electricity and heat when splitting water molecules into hydrogen and oxygen as the production of extra electricity and heat implies sometimes extra production of greenhouse gasses (ICAX 2019). Therefore, depending on the process partaken in providing the necessary electricity and heat will determine the size of the ecological footprint created. If the extra electricity is created from burning fossil fuels the ecological footprint will be significant contrarily if the extra electricity is provided from the excess energy from other renewable sources the footprint will be negligible. Therefore, it can be inferred that electricity won't be provided from renewable energy 100% of the time as renewable energy is heavily dependent on uncontrollable factors, therefore, sometimes it will be required to burn fossil fuels to produce hydrogen hence, producing a small amount of carbon dioxide, sulphates, and nitrogen oxides contributing to global warming. Additionally, greenhouse gases would have been produced when manufacturing the components of the hydrogen plant and transporting all the equipment to the site (Chanhee et al 2020). Looking, at alternative fields which hydrogen can be used in we can see major ecological footprint reductions such as hydrogen cars will be able to avoid 0.2 kilograms of carbon dioxide per kilometre travelled, and replacing grid electricity with electricity from hydrogen electricity will avoid 15 kilograms of carbon dioxide per kilogram of hydrogen used (COAG Energy Council 2019).

The production of hydrogen in Australia has a plethora of positive social implication including greater job opportunities, and greater savings for the end-user. The production and manufacturing of hydrogen can generate a surfeit of jobs residing in regional areas (COAG Energy Council 2019) inferring that a greater proportion of families and individuals will have an income, therefore, allowing individuals to better educate themselves and invest into their communities. Additionally, with a greater proportion of individuals with jobs, this will consequently increase the GDP in the economy therefore implying that the standard of living will increase (Hall 2018). Furthermore, it's estimated that 1 litre of hydrogen will be able to travel 100 kilometres in a hydrogen car (COAG Energy Council 2019) inferring great cost savings for the end-user hence, leading into greater customer satisfaction.

5. Industrial Ecology Strategies

5.1. Eco-efficiency Industrial symbiosis

There are many methods to produce hydrogen. One of which can be through the processing of biogas. Biogas is formed when organic material decomposes in an oxygen-free environment (EESI 2017). This process is known as anaerobic digestion. Anaerobic digestors are utilised to manage waste in facilities which produce organic waste. These facilities include food manufacturing facilities, breweries, farms, municipal waste sites and water treatment plants (Walker et al. 2017). Australia has vast resources for biogas which can be supplied by industrial waste, more specifically, from: food industries, such as dairy and meat; agricultural waste and sludge from water treatment plants (ARENA 2019). The biogas then generally goes through a reforming process which will resultingly produce hydrogen (Galvagno et al. 2012).

This presents a by-product synergy with the external companies as the hydrogen producing facilities are able to take advantage of the waste from varying industries as feedstock to produce further hydrogen and renewable natural gas. Furthermore, this prevents waste going to landfill leading to overall improvement in the environment.

An example of this industrial symbiosis which can already be observed in Australia is with the Water Corporation and Hazer Group Limited (Hazer). Hazer aims to convert biogas, supplied by the Western Australian Water Corporation at Woodman Point Wastewater Treatment Plant, into renewable hydrogen and graphite using an iron ore catalyst (ARENA 2019). This project has aimed to begin operations in January 2021 (ARENA 2019).

With an existing example of industrial symbiosis of hydrogen production and organic waste producing industries combined with Australia's extensive resources in biogas, there is clearly a high potential for further development and application of this industrial ecology strategy. This has the opportunity to further encourage the implementation of hydrogen production to be utilised as a renewable energy.

5.2. Renewable energy

As stated in section 2.3, there are no GHG emissions when hydrogen is consumed with pure oxygen. Hence, the only emissions possible is during the production of hydrogen. This is due to the power source of the electrolyser which is generally electricity generated from fossil fuels. However, this can be mitigated through the use of a renewable energy source for the electrolyser such as wind, hydro or solar (Walker et al. 2017).

Australia currently has more than 100 operating hydroelectric power stations which have been producing 5-7% of Australia's total energy supply for the past decade (ARENA 2020a). Most of which are located in south eastern Australia (ARENA 2020a). While wind energy in Australia has produced enough electricity to meet 7.1% of our nation's total electricity demand, with up to 94 wind farms by the end of 2018 (ARENA 2020b). Furthermore, solar energy has also accounted for 5.2% of our nation's electrical energy production in 2018 (Clean Energy Australia 2019).

In summary, with Australia's current position and growth in the production of renewable energy, there is an abundance of potential for a renewable source of energy for the utilisation of renewable energies for the production of hydrogen. An example of which can be shown from Tonsley's proton exchange membrane (PEM) electrolyser which will be installed in South Australia (Harmsen 2017). This PEM will be powered by one of Australia's largest rooftop solar arrays (Tonsley 2020). As a result, the emissions of GHG during production of hydrogen would be omitted.

5.3. Biomimicry

An alternative carbon neutral process which can be utilised to produce hydrogen is biophotolysis (Walker et al. 2017). This is a biological process which uses the same principles found in plants and algal photosynthesis (Nikolaidis et al. 2017). Photosynthetic processes capture solar energy and store the energy in the form of chemical fuels, with photosynthetic organisms being able to effectively and efficiently capture sunlight and converting it into organic molecules (Allakberdiev et al. 2010). Artificial photosynthesis is a method of which hydrogen can be produced from water through the use of sunlight and biomimetic complexes (Allakberdiev et al. 2010).

Biophotolysis splits water into molecular O_2 and H_2 with light as the energy source and can occur in two different ways: direct and indirect (Brentner et al. 2010). Direct biophotolysis involves the production of hydrogen through the employment of green algae under anaerobic conditions (Brentner et al. 2010). While, indirect biophotolysis involves the production of hydrogen from water through involvement of cyanobacteria which utilises carbohydrate energy stores from photosynthesis (Brentner et al. 2010). The main advantages of these processes are that $C0_2$ is consumed and 0_2 is the only by-product (Nikolaidis et al. 2017). However, there are major disadvantages as well with some being: low H_2 rates and yields, sunlight requirement and high raw material cost (Nikolaidis et al. 2017).

Consequently, it can be observed that biomimicry can assist in the production of hydrogen in a carbon neutral manner. However, for it to be a feasible process, long term research and design will be required to further increase the efficiency of hydrogen production and decrease the raw material cost.

5.4. Green Engineering

A major principle of green engineering is that "it is better to prevent waste than to treat or clean up waste after it is formed" (ACS n.d., para. 7). An important consideration of natural gas hydrogen enrichment is the concern that high concentrations of hydrogen may cause embrittlement of gas distribution piping (Walker et al. 2017). If these concerns were ignored, there would be the potential for high rates of pipe breaches in the future, releasing large amounts of natural gas into the environment and requiring costly repairs.

This risk can be averted by keeping hydrogen concentrations at the safe level of under 5% by volume (Walker et al. 2017) while concerns about pipe embrittlement can be properly investigated. Once this has been done, higher concentrations of hydrogen can be used if deemed safe, or at-risk pipes could be pre-emptively replaced.

5.5. Closed Loop Production Principles

As outlined in section 2.3, a significant challenge to hydrogen production is the formation of NOx when hydrogen is not burned in pure oxygen. This issue could be alleviated by implementing closed loop production principles. A closed loop electrolysis system could be used as a method of storing excess renewable energy created in times of low demand. Excess energy could be used to perform electrolysis in a closed system, capturing both the hydrogen and oxygen that is created. This hydrogen, in the presence of pure oxygen, could be later burned to power a turbine in times of high demand.

As water and heat are the only products of hydrogen combustion in the presence of pure oxygen, the water produced can be collected and used again for electrolysis, forming a closed loop system. Assuming the components used to create this closed loop are sourced sustainably, this system would be a zero-waste form of energy storage.

6. Life Cycle Management

6.1 Achieving Circular Economy

A circular economy from a sustainability standpoint is one that does away with unnecessary disposals, favouring re-usability and recycling. The benefits to having a sustainable product lifecycle with a carefully planned end of life strategy can be numerous for those willing to invest and endeavour wholly towards a sustainable product lifecycle.

Capitalising on a product’s end of their life cycle has sprouted a new industry. This can be displayed by the actions of ‘Close the Loop’, a sustainability solutions company that has made a business out of providing sustainable solutions to Fortune 500 companies looking to enhance their corporate social responsibilities. Close the Loop has taken advantage of previously discarded printer ink and toner turning it into high performance asphalt roads ("Tonerplas: Close the Loop" 2020).

Although reusability has quantifiable positive values to a company such as increased revenue or the ability to maximize a products value over its lifecycle. It also can drive innovation which may lead a company down a profitable and sustainable pathway. While creating a circular economy may be profitable it requires a strong life cycle management program to be in place before the product is created. This ensures the design is maximising the reusability of the products end of life stage. Products without a planned and existing end of life strategy are wasting their potential, a potential in which Close the Loop was able to turn into profit.

An effective life cycle management system should account for the triple bottom line, a sustainability indicator that weighs in Ecological, Economic and Social aspects. As such a life cycle assessment includes life cycle costing. The act of determining how much a product will cost over its lifetime. While also including the social life cycle cost of a product. (Guinée 2016). Only a product that is conceived with these pillars at the core of its design will be able to wholly capitalize on the end of life phase. Designing and producing without regard for sustainability creates a product that is not maximising value over its lifecycle.

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