GREEN HYDROGEN PRODUCTION AND WASTEWATER TREATMENT ENABLING THE DELIVERY OF THE UN SUSTAINABLE DEVELOPMENT GOALS

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ABSTRACT

The United Nations 17 Sustainable Development Goals (SDGs) are a comprehensible call to action to realise a sustainable future for everyone. Hydrogen has recently gathered significant momentum as a versatile energy carrier and combined with wastewater treatment, green hydrogen production has the potential to amplify the contribution of the water sector to the SDGs. In this paper, we explore the synergies of an integrated hydrogen production and wastewater treatment facility. In particular, we review some of the technologies relevant to a wastewater treatment plant that will not only facilitate a tangible contribution to the SDGs but could also meet other objectives that may contribute to reducing the cost of wastewater treatment.

INTRODUCTION

The effect of greenhouse gas (GHG) emissions on climate change has been identified as a significant threat to humanity by intensifying hazards such as heatwaves, drought, floods, fires and sea-level rise, to which humanity is vulnerable (Mora et al., 2018). GHG emissions have increased by 57% between 1990 and 2018, but over the same time period, GHG emissions per capita have also increased by 14%, with the combustion of coal, oil and natural gas, representing 89% of global CO_2 emissions and the production of these fossil fuels contributing one third of global methane emissions (Olivier & Peters, 2020).

While replacement of fossil fuels by other energy sources generated by renewables is an attractive proposition to meet environmental objectives, energy still needs to be provided to the geographical location required by the consumer, when the consumer needs it, and at a competitive price. In addition, the fluctuating nature of renewable power generation has already given rise to overproduction of electricity at certain time periods (Niermann et al., 2019). To overcome this issue, there has been considerable focus on energy storage systems such as pumped hydroelectric, batteries, compressed air, thermal energy, and chemical storage such as hydrogen, but also on renewable energy sources such as photovoltaic (PV) systems and wind. Hydrogen produced by renewable energy sources such as solar PV systems is a particularly attractive proposition to reduce fossil fuel consumption while allowing for the intermittent nature of renewable energy supply.

Municipal wastewater treatment is one of the cornerstones of public health management and water resources protection, but treating wastewater is energy intensive. The increasing pressure to treat wastewater to higher standards has been a key driver of the increasing energy consumption in a wastewater treatment plant (WWTP) and, whether motivated by cost or environmental improvements, there is significant focus by WWTP managers to reduce their energy use. The management of water resources, and particularly wastewater treatment, is inextricably linked to, and has a significant impact on, the SDGs.

Sector coupling opportunities for wastewater treatment with hydrogen production has been reported for specific configurations and benefits (Schäfer et al., 2020), including power to methane (Michailos et al., 2020; Patterson et al., 2017) and reduction of organic micropollutants (Gretzschel et al., 2020). However, details of the relationship between an integrated electrolytic hydrogen production and wastewater treatment plant and the resulting effects on the SDGs has not been widely analysed and this paper investigates this further and presents technology opportunities to facilitate this integration. In this paper, we first review the SDGs, with a focus on outcomes of specific goals. An overview of renewable hydrogen developments is provided, with a brief review of commercially available technologies and infrastructure. The case for integrating green hydrogen production with wastewater treatment is examined, and the role of oxygen in wastewater is explored, with a review of new oxygen utilisation technologies.

SUSTAINABLE DEVELOPMENT GOALS

Following the success of the United Nations' (UN) 8 Millennium Development Goals which brought a major worldwide focus to reducing poverty and child mortality, the UN Conference on Sustainable Development in Rio de Janeiro in 2012 was a significant catalyst in developing the 17 Sustainable Development Goals (SDGs) that were agreed amongst its 193 member countries at the COP21 Paris Climate Conference in September 2015 (United Nations General Assembly, 2015). The SDGs have been designed to balance the three main pillars of sustainable development: social progress, economic growth and environmental protection, with a strong focus on addressing poverty, inequality, climate change, environmental degradation, and peace and justice. Each SDG shown in Figure 1 has between 5 and 24 corresponding targets, providing a robust framework.

Figure 1 - UN SDGs#

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Achieving these goals by 2030 will require a substantial effort, and the consequential impact of water utilities through their everyday business activities feature heavily in many of the SDGs. Australian water organisations, including Water Services Association of Australia and Australian Water Association as well as numerous Australian water utilities have publicly committed their support to the SDGs, with some, including Melbourne Water, Yarra Valley Water, South East Water, City West Water and SA Water being members of the UN Global Compact Network Australia (GCNA) (Global Compact Network Australia, 2020a). Several initiatives by water utilities, have also been featured as part of the GCNA website (Global Compact Network Australia, 2020b), such as Barwon Water, Sydney Water, and Unitywater, to name a few. But despite these commitments and success stories where the Australian water industry can confidently report that high standards of water management are generally maintained, Australians living in remote Indigenous communities have a very different experience (Hall et al., 2020), thus challenging this sense of achievement. There are multiple and complex threads of connection between wastewater treatment and these SDGs, requiring water utilities to apply a holistic and systems-wide consideration of their processes. Minimising energy consumption, achieving high levels of pollutant reduction, and maximising the safe and beneficial reuse of wastewater will make a significant contribution both to the relevant SDGs as well as aligning with community expectations. While it is possible to provide a rationale that describes the impact of wastewater treatment on each and every SDG, the following SDGs have been identified for further review in this paper as being specifically and significantly aligned with and relevant to integrated hydrogen production and wastewater treatment.

Goal 6: Ensure availability and sustainable management of water and sanitation for all – wastewater treatment technologies contribute to advanced water management and sanitation, making a substantial contribution to a healthy community through its water. But high levels of sanitation and water quality is still not available to everyone, and progress is geographically uneven. The wastewater treatment industry has the opportunity to develop new technologies that can be readily deployed to a wide range of locations, particularly in environments where the degree of separation between wastewater effluent and drinking water supplies is shrinking.

Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all – wastewater treatment is an energy intensive process, and with sources of renewable energy becoming more economically viable, wastewater treatment operators have a strong position to determine how these sources of energy can be better utilised for wastewater treatment.

Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation – wastewater treatment is an essential service that must continue to operate effectively during disasters, and be adaptable to a changing environment. Featuring large water retaining structures, usually constructed from concrete and steel, continuing to build larger vessels may not be the answer to sustainable industrialisation, and alternate technologies that are both resilient and sustainable is a key requirement for the water industry to further exploit.

Goal 13: Take urgent action to combat climate change and its impacts – wastewater treatment is a large contributor of greenhouse gases, both directly and indirectly. Direct emissions include carbon dioxide, nitrous oxide, and methane emitted during the treatment of wastewater, and indirect emissions include that resulting from energy use, mainly electricity. Judicious selection of wastewater treatment processes and careful control of the operation presents significant opportunity for wastewater treatment to make a solid contribution to this SDG.

Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development – the quality of treated effluent discharged to the environment has a major impact on marine ecosystems. Concentrations of nutrients released in wastewater effluent affect the health of the receiving water systems, but higher standards of treatment can sometimes be at odds with minimising energy use.

As well as SDGs relative to the water and engineering side of the business, some water authorities are also adopting SDGs for the corporate side of the business, such as SDG5, Gender Equality, which has been adopted by Yarra Valley Water as part of their “Extraordinary Performance” strategy.

HYDROGEN ECONOMY

Hydrogen is often referred to as an energy carrier as it not only serves as a means to store energy for later use, but it facilitates the energy to be used at a location distinct from the primary production site (Abdin et al., 2020). As an energy carrier, hydrogen can take many forms beyond a compressed gas where it can be liquefied at low temperatures, stored in other compounds such as ammonia, methylcyclohexane, methanol, or metal hydrides (IEA, 2019; Makepeace et al., 2019), or it can be contained within metal organic frameworks (Ozturk et al., 2016). There is significant interest and research into storage and transport of hydrogen, with one example being the Australia-Korea Joint H2 R&D Program launched in September 2020; another being the Hydrogen International Collaboration program – Korea Institute of Energy Technology (KAIST), a six step process from hydrogen production in Australia to delivery in Korea using liquid hydrogen. More work is required in this area, but the motivation is in place with several nations.

With global hydrogen demand in 2018 estimated to be 74 Mt (IEA, 2019), hydrogen production is already a significant industry but it is almost entirely supplied by coal or gas (often referred to as brown and blue hydrogen, respectively) and is used mostly in oil refining and for the production of fertilisers (IEA, 2019). This is changing however, with the ability to produce green hydrogen from renewable energy such as solar PV becoming more readily available both technically and economically. Indeed, without the increase in solar generation infrastructure, the growth potential of green hydrogen would be less attractive. Concurrent with this, federal and state governments are seeing the hydrogen economy as a significant job creation and export opportunity, as nations such as Korea and Japan express significant interest to import green hydrogen to decarbonise sectors such as transportation and industrial energy whilst provide building heat and power. Korea has a vision to reduce local emissions by 30% and provide 20% of energy demand from green hydrogen (Hydrogen Roadmap Korea November 2018). Australian government policy is also playing a role, forcing the reduction of carbon due to international agreements such as the “Paris Agreement’, a United Nations framework on climate change. This has led to Australia setting targets for renewable energy, with Queensland setting a target of 50% renewable energy by 2030 (Queensland Renewable Energy Expert Panel, 2016).

There is enormous potential for a hydrogen economy to distribute green energy, and hydrogen has recently made a resurgence with the large number of institutional bodies, governments and global corporates becoming more vocal about the role of hydrogen in a low-carbon future (Wollschlager, 2020) and the increasing number of published national hydrogen strategies and roadmaps (Bermudez et al., 2020; Lambert, 2020). The release of Australia’s National Hydrogen Strategy (COAG Energy Council Hydrogen Working Group, 2019) provides a comprehensive description of the opportunity, with a focus on large scale hydrogen hubs to make the development of infrastructure more cost effective, but also to promote sector coupling. The Queensland Government’s Hydrogen Industry Strategy (Queensland Department of State Development & Planning, 2019) supports this vision by describing 17 separate actions across 5 focus areas. In this strategy document, the work being led by Queensland University of Technology at the Queensland Government’s Redlands Research Facility was described, where the state’s first ever delivery of green hydrogen to Japan was manufactured at the site. Other Queensland based projects include the proposed Hills International College Hydrogen Hub at Jimboomba where hydrogen is proposed to be used for fleet vehicles and power, with the oxygen considered for use at the adjacent wastewater treatment plant.

One of the challenges for the full-scale development of a hydrogen supply chain is the development of hydrogen infrastructure (Staffell et al., 2019), but also because hydrogen produced by renewables is not competitively priced compared to fossil fuels (IEA, 2019). While individual financial benefit is not the underlying driver for organisations to pursue implementation of the SDGs, it becomes more challenging to provide motivation for activities that are financially disadvantageous. With renewed vigour, the hydrogen industry is now seeing manufacturing scale up and cost reductions, but there is still a long road ahead. This is being eased with organisations such as the Clean Energy Finance Corporation (CEFC) actively promoting the use of a range of renewable energy systems in partnership with the Australian Renewable Energy Agency (ARENA) via a mix of debt and grant funding to help the water sector reduce operational costs and reliance upon fossil fuels. This allows renewable applications to be implemented with no capital cost increase, using the savings made to fund any amortized costs. Power Purchase Agreements (PPA or SPPA) and Clean Energy Leases or Solar Leases (SL) are examples of commonly used investment models. In a PPA, a finance company owns, manages and maintains the solar farm and agrees to sell the generated power back to the customer at a fixed rate, usually discounted from the grid provider, for a fixed period. An SL is an agreement where a finance company funds the implementation of a solar farm and the customer leases back the infrastructure including access to the generated power. Lease durations of SLs typically range from 7 to 10 years, with options for the customer to buy back the solar farm at a pre-negotiated price at the end of the term, and operation and maintenance costs are usually the customers' responsibility during the term of the lease.

RENEWABLE ENERGY AND WASTEWATER INFRASTRUCTURE

Traditionally, Australia's WWTPs are powered from the electricity grid infrastructure, but the ability to shift to renewable energy, including green hydrogen, has developed significant interest and can combine several technologies. A brief description of some of the available technologies is provided in this section. Solar PV systems have significantly reduced in cost over the past two decades and forecasts have been made that the capital cost of hydrogen electrolysis will also significantly reduce, potentially up to 75% over the next 3 decades for large scale systems (Böhm et al., 2020). With some of the highest solar irradiance levels on the planet, significant land availability, and an advanced economy and a comparatively stable political environment, Australia has a natural advantage for generating green hydrogen using solar PV. Not only does investment by the water sector in these technologies significantly advance the SDGs, but it can also play a fundamental role for water utilities working on an energy reduction program.

Photovoltaics – Green Energy Source

PV systems have made significant advances in Australia, with access to green hydrogen through surplus solar production beginning to emerge. PV energy can be generated through three common configurations, all of which have been used at wastewater treatment plants:

- Roof top and shade structures
- Solar farms
- Floating Solar on Water Bodies

Roof top solar on buildings or car park shade structures at WWTPs (Figure 2) is an easy way to produce green energy, albeit peak energy generation may not coincide with peak electricity use. Several WWTPs have implemented solar systems and concurrently shifted power load activity such as pumping. Of course, roof top area or suitability at some locations is a limiting factor and other forms of solar need to be considered.

Solar Farms are also found at WWTPs where they have available land area or adjacent land with agreement of the landowner. Investment in ground mounted solar needs to be considered with future plant expansion requirements.

Figure 2 – Roof top solar

Floating Solar on water bodies (Figure 3) are becoming a commercial reality and have the benefit of providing area for power generation whilst reducing evaporation and the proliferation of algae that can affect water quality. In Australia, Lismore wastewater treatment plant commissioned a 100 kW floating solar system in 2018 (Lismore City Council, 2018), and in New Zealand, Vector Group and Watercare recently announced the start of construction of a megawatt-scale floating solar array at the Rosedale wastewater treatment pond (Vector Ltd, 2020).

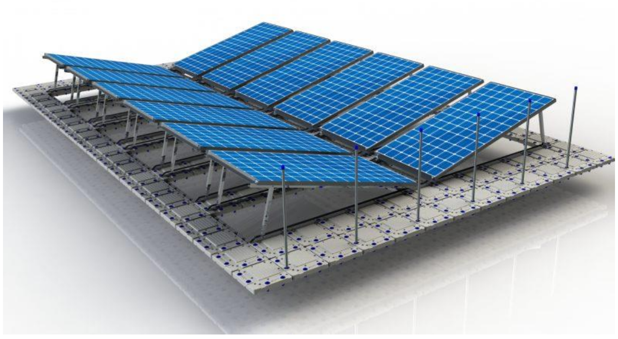

Figure 3 – Float Pac Floating Solar

Electrolysers – Producing Hydrogen

Hydrogen electrolysers are commercially available in Australia in many sizes and often with minimal integration requirements whereby water and a clean energy source are simply connected, the electrolyser having all the necessary componentry integral to a containerised solution (Figure 4), making the implementation of hydrogen systems at WWTPs less complex. The electrolyser container includes the electrolyser stack, process equipment (including water filtration), hydrogen purification and a PLC control system. The power supply container includes power distribution within the equipment and rectifiers for the electrolyser stacks.

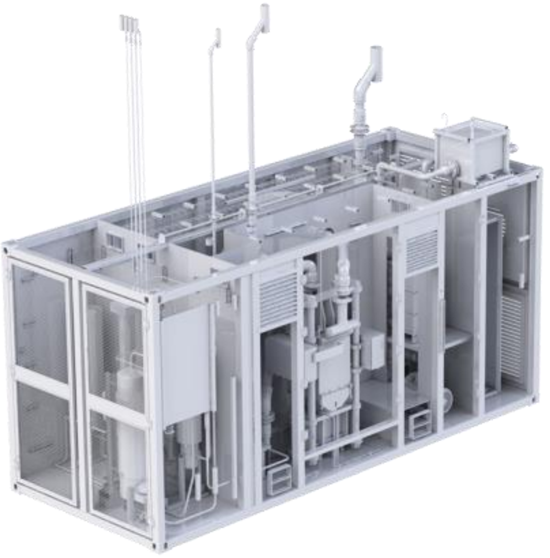

Figure 4 - Containerised Hydrogen Electrolyser

Hydrogen Microturbines – Power Generation

Hydrogen produced by electrolysis using renewable energy sources can be used as a means for power storage where electricity can be generated at the desired rate. Using hydrogen, micro-turbines produce clean, efficient, and low-cost electricity, providing independence and insulation from the grid. They are a type of combustion turbine, ideal for small-scale power generation. Micro-turbines can also power heating and cooling needs and can be used in conjunction with waste heat recovery. Products such as "Capstone Micro Turbines" (Figure 5) can achieve over 80% combined heat and power efficiency, down to 10 kW in size.

Figure 5 - Hydrogen Micro Turbine

Micro-turbines can deliver power from a wide variety of fuels including hydrogen and biogas and can be easily implemented in WWTP applications. As well as generating electricity, micro-turbines can be linked with absorption chillers using waste heat to generate cooling. This type of central energy plant using green hydrogen and biogas can make for a particularly clean solution.

Fuel Cells – Power Generation

A fuel cell is a device that can convert chemical potential energy into electricity. A PEM (Proton Exchange Membrane) fuel cell uses hydrogen gas and oxygen gas as fuel. The products of the reaction in the cell are water, electricity, and heat. Fuel cells can be used for backup power, power for remote locations or for infrastructure, such as a WWTP, as well as being part of distributed power generation. An example of this is already installed at the Sir Samuel Griffith Centre – Nathan Campus, Griffith University, Brisbane using stored hydrogen energy to generate electricity. Another type of fuel cell relevant to a WWTP is a solid oxide fuel cell (SOFC) which is particularly suitable for use with biogas because carbon dioxide, water vapour, and ammonia do not need to be removed, as is the case for internal combustion (IC) biogas engines. Electrical efficiency of SOFCs can reach 50%, exceeding that of IC biogas engines, particularly in small scale applications (Wasajja et al., 2020).

Hydrogen for Fleet

Most water utilities run a significant fleet of vehicles, making a publicly visible contribution to greenhouse gas emissions. Hydrogen's versatility as a means of energy storage and use in vehicles can be combined as part of an overall strategy for wastewater treatment plants, reservoirs, offices, depots and water bodies.

INTEGRATION OF HYDROGEN PRODUCTION AND WASTEWATER TREATMENT

A focus on making currently mature technologies cheap enough for large scale deployment without compromising on the main environmental and social benefits is likely to be a key enabler for launching the hydrogen economy into mainstream energy use. Within the hydrogen supply chain, the cost of production is a major component (Bruce et al., 2018), and considering hydrogen producing technologies currently ready for deployment on a large scale, electrolysis is likely to be an economically competitive option in the near future (Abdin et al., 2020). Finding commonality between hydrogen technologies and other industries might be a way to reduce the cost of hydrogen: rather than industrial sectors operating in isolation, a higher level of integration where one industry reuses waste products from another may be the key to driving down the cost of hydrogen. The concept of sector coupling has been described in hydrogen strategy documents (Bruce et al., 2018; COAG Energy Council Hydrogen Working Group, 2019) and various literature (Buttler & Spliethoff, 2018; Schäfer et al., 2020). Using electricity and water as the main feedstocks, hydrogen production by electrolysis also generates oxygen and heat. Instead of being discharged to the environment, these by-products could be better used. Electricity and water are also critical: electricity can be supplied by renewable energy sources such as solar and wind, and an economic and sustainable source of water is crucial. While economics are a strong determining factor in the feasibility of any production process, social issues have the potential to derail otherwise viable projects. If water electrolysis is considered a promising technology for near-term widespread deployment, the source of water must be identified.

Considering the inputs and by-products of hydrogen production by electrolysis, wastewater treatment has some close synergies that could be exploited in the following process streams:

1. Wastewater often requires treating with large quantities of oxygen, generally via high volumes of air injected into the aerobic zones. The supply of this oxygen via air can account for 50 to 80%, or more, of the total energy use of a traditional municipal wastewater treatment plant (Baquero-Rodríguez et al., 2018; Drewnowski et al., 2019). High purity oxygen (HPO) systems are an alternate to providing the required oxygen for aerobic wastewater treatment and use of oxygen from electrolysis would contribute to SDG 7 and 13 with respect to energy consumption and climate change action. Further, using high purity oxygen instead of air can reduce the size of wastewater treatment vessels, progressing SDG 9 for resilient infrastructure and at the same time, extending the life of existing assets that could delay the timing for upgrading a wastewater treatment plant in response to population growth.
2. Heat is often needed to increase the temperature of some unit processes in wastewater treatment, such as anerobic digestion, to operate more efficiently (De Vrieze et al., 2016). Electrolysis typically produces waste heat temperature in a range of 60 to 80°C and a waste heat output around 30% of the electrical input power (Zauner et al., 2019) which may be used for heating anaerobic digesters. Using this waste heat from electrolysis instead of using biogas to fire boilers for heating the digesters would allow more electricity generation from biogas, contributing to SDGs 7 and 13 by importing less electricity to the WWTP.
3. The effluent water discharged from wastewater treatment plants could be an appropriate source of water for electrolysis. When 9 litres of high quality water is needed per kilogram of hydrogen (COAG Energy Council Hydrogen Working Group, 2019), or perhaps the equivalent of 15 to 20 litres of potable water taking into account the efficacy of water purification (Arup, 2019), hydrogen production by electrolysis could be challenged by water availability. Although the cost of water has been reported as being proportionally low for hydrogen production (Acil Allen Consulting, 2019), social concerns due to competition for this precious resource are likely (Lambert, 2018), meaning that an assessment of water supply must account for more than economics. Wastewater effluent may be a candidate to supply the high-quality demineralised water required for the electrolyser and eliminate the need to use drinking water, particularly with concerns of water scarcity, thus progressing SDG 6 for sustainable water management.

OXYGEN IN WASTEWATER TREATMENT

It has been reported that approximately 15% of all wastewater treatment in the USA is carried out using High Purity Oxygen (HPO) systems (Linde plc, 2020). Dissolving oxygen in wastewater quickly enough can be challenging, with low dissolved oxygen (DO) levels leading to process upsets in a WWTP. Many WWTPs aerate using fine bubble diffusers, but the efficiency of dissolving oxygen before the bubbles have risen to the surface can be around 15 to 20% under actual conditions, related to factors such as the actual DO level, wastewater impurities, and the effect of suspended solids. Although fine bubble diffusers also provide mixing energy needed for the mixed liquor, the low efficiencies corresponds to considerable waste of energy and explains why a WWTP generally uses more than half of the total electricity consumption to power the blowers supplying this air. Mechanical surface aeration is a popular alternative to fine bubble diffusers, however their energy consumption is usually higher (Tchobanoglous, 2014). Low oxygen transfer efficiency is therefore an area of potential improvement and has attracted the attention of numerous technology developers. With higher economical value being placed on HPO compared to atmospheric air, there is a further incentive to optimise its effectiveness in wastewater treatment, but there is less information available to suggest the most suitable devices for use with HPO (Drewnowski et al., 2019). In this section, we provide some background on the use of high purity oxygen in wastewater treatment and outline some more recent technologies utilising pure oxygen.

The Controversial History of High Purity Oxygen in Wastewater Treatment

HPO as a replacement for conventional aeration in activated sludge wastewater treatment has been the subject of investigation since the 1930's and 1940's (McWhirter, 2019; Skouteris et al., 2020). The motivation for using HPO in municipal wastewater treatment was primarily to reduce aeration power consumption and reduce the size of the treatment vessels by supporting higher mixed liquor concentrations (Kumke & Sutton, 1973). The 1970's and 1980's demonstrated significant interest in furthering HPO development in pilot and full scale WWTPs. In particular, the USA was a strong proponent of HPO systems having around 60 to 70% of the known 248 oxygen activated sludge plants in operation or in design or construction (McWhirter, 2019).

In one of the more significant full scale trials, Albertsson et al. (1970) analysed the results of the full-scale parallel tests between HPO and air at Batavia treatment plant, New York, using the "UNOX" system developed by the Linde Division of Union Carbide. It was reported that the higher oxygen partial pressure in the enclosed head space provided more than 90% oxygen utilisation levels, with between 27% and 42% sludge reduction and 30% to 85% reduction in energy compared with conventional aeration system. Ball and Humenick (1972) disputed the calculations made by Albertsson et al. (1970) and although accepted that some real benefits may be achievable in HPO systems, noted that the point at which the economic benefits outweigh the costs was unclear. These challenges were further investigated by Benefield et al. (1977) who concluded that the differences observed by Albertsson et al. (1970) at Batavia treatment plant, New York, may have been due to the specific operational characteristics used. Kalinske (1976) also disputed several improvement claims made by HPO system proponents and concluded that the capital and operating costs may not be sufficiently different for any generalisations to be made on the benefits of HPO systems. Following a critical rebuttal by Union Carbide of the investigation made by Kalinske (1976), Parker and Merrill (1976) attempted to settle the conflict through an independent analysis of the data, but was unable to draw general conclusions about economics, although believed the original work at Batavia treatment plant New York, unfairly compared conventional aeration systems at low dissolved oxygen levels.

Following this period of uncertain results in the 1970's, Nelson and Puntenney (1983) undertook a 15-month performance evaluation at the Metropolitan Denver Sewage Disposal District No. 1 to compare the use of HPO with conventional aeration because of the lack of clarity from previous studies. The evaluation calculated that for the oxygen system, the power consumption for mixing and aeration was 44% lower than the air system even using coarse bubble diffusion, but no significant difference was identified for sludge production, although the sludge produced by the HPO system had 44% better settleability.

More Recent Developments in Using High Purity Oxygen for Wastewater Treatment

Since the 1970s and 1980s, developments in using HPO for aeration in WWTPs continued, and although the controversy may have subsided, uncertainty of its benefits using traditional aeration technologies have persisted (Schäfer et al., 2020). This situation is now changing with newer technologies for transferring oxygen to wastewater.

The Speece Cone is a simple device for increasing oxygen transfer efficiency, comprising a submerged cone-shaped hood where oxygen combined with water is injected at the top. The water velocity entering the smaller, top end of the hood is greater than the buoyant velocity of the bubbles and the water velocity leaving the larger, open bottom is less than the buoyant velocity of the bubbles, thus trapping the bubbles inside the hood, achieving oxygen transfer efficiency in excess of 90% with low power input (Speece et al., 1971). The Speece cone configuration has been commercialised (Figure 6) and used in aquaculture and oxygenation of waterways, and also in wastewater applications for odour and corrosion prevention, but to a more limited extent in activated sludge WWTP processes. Ashley et al. (2014) investigated a pilot scale Speece Cone for wastewater aeration and achieved Standard Oxygen Transfer Efficiencies (SOTE) between 66 and 72% and believed further experimentation could increase the SOTE closer to 100%. Barreto et al. (2018) investigated the side stream super oxygenation of wastewater using different oxygen purity levels in a pilot scale Speece Cone and observed SOTE values around 80% to 100%. (Kolekar, 2019) carried out a similar investigation with high mixed liquor concentrations typical of membrane bioreactors and was also able to achieve 100% transfer efficiency in this application.

Figure 6 - ECO$_2$*'s Application of the Speece Cone (ECO2 Oxygen Technologies, 2020)*

Another superoxygenation system called SDOX® developed by BlueInGreen injects pure oxygen into a pressurised headspace where a side stream of mixed liquor is introduced so as to create a large gas to liquid interface in the top of the vessel capable of absorbing more oxygen compared to a low or an unpressurised vessel, thus creating a supersaturated solution. The superoxygenated stream is then reintroduced into the main aeration tank to maintain the required DO level. The SOTE of a laboratory scale SDOX system was reported as 100% and higher alpha factors, particularly at high mixed liquor concentrations experienced in membrane bioreactors, was observed where the energy input required was significantly reduced, thus being a potentially valuable technology in future process intensification (Kim et al., 2020).

With the buoyancy of bubbles in conventional fine bubble diffusers reducing the contact time between the gas and liquid, attention has turned to reducing the bubble size enough to disrupt the effects of buoyancy. Nanobubbles having a diameter less than about 100 nm lack buoyancy and randomly drift to remain suspended in liquid for long periods of time until they dissolve, while the surface charge limits their coalescence (Khan et al., 2020). Nanobubble technology deployment has focussed on agriculture, although some case studies in wastewater treatment by Molear Inc., including use in a membrane bioreactor, shows promising economic return on investment based on energy savings alone. The Life Nanobubbles project under a EU grant agreement is another project aiming to reduce energy consumption in wastewater treatment by 70% and reduce sludge production by 50% (Ekotek S.L.) with expected project completion date at the end of 2020.

A Membrane Aerated Biofilm Reactor (MABR) is an attached growth technology that has overcome the problem of transferring oxygen via gas bubbles. An MABR system comprises numerous thin hollow fibres or flat sheet submerged in the wastewater tank, with air or oxygen flowing through the centre of the hydrophobic membrane. Oxygen and substrates are transported into the biofilm in a counter-current diffusion arrangement through the semi permeable membrane wall (Figure 7) and the system supports aerobic, anoxic and/or anaerobic zones, and provides an environment that supports simultaneous COD/nutrient removal in a single step (Lu et al., 2020). MABR technology has been commercialised in the last 5 years, with drop-in modules available from companies such as Suez, Oxymem, and Fluence. Pilot scale MABR tests using air have resulted in oxygen transfer efficiencies ranging from 24% to 69% (Côté et al., 2015; Houweling et al., 2017; Li, 2018). Using HPO instead of air in municipal wastewater treatment appears to be restricted to small scale laboratory trials, and there may be significant opportunity to optimise the oxygen transfer efficiency of MABR using different membrane venting control schemes to approach 100% efficiency (Perez-Calleja et al., 2017).

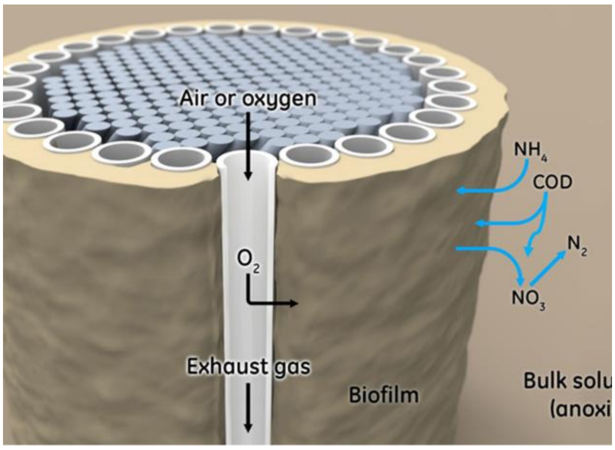

Figure 7 - Schematic of Suez's Zeelung MABR (Suez, 2020) (Used with the permission of Suez)

CONCLUSIONS

The hydrogen economy is rapidly developing as a valuable means to decarbonise industry, and technologies for green hydrogen production are already a commercial reality. Both wastewater treatment and hydrogen play extremely important roles in achieving the UN SDGs, and together, these sectors make an even greater contribution. Integrating green hydrogen production with wastewater treatment has several valuable synergies and can particularly contribute to SDG 6 (water and sanitation), 7 (clean energy), 9 (resilient infrastructure), 13 (climate action), and 14 (aquatic life). Oxygen is an important process stream and although high purity oxygen in wastewater treatment has long been a consideration, a new era has emerged where oxygen availability from hydrogen production combined with new technologies that achieve high levels of oxygen utilisation in wastewater treatment, represents a paradigm shift that provides stronger incentive for integration of these sectors. While there is a community expectation of the wastewater treatment industry making a solid contribution to the SDG's, the integration of green hydrogen production with wastewater treatment has potential for cost reduction as well as being a component of an overall energy reduction program and extending the life of existing assets. Various levels of government have shown particular interest in the development of a hydrogen economy, with CEFC and ARENA providing strong financial encouragement for these developments, and the water industry can be a prominent beneficiary of these incentives.

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