# WHAT ABOUT A ZERO ENVIRONMENTAL FOOTPRINT WASTEWATER TREATMENT PLANT

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**ABSTRACT**

It has been shown that a Zero Environmental Footprint Plant (ZEFP) in the dairy industry is possible using well established technology (Bukauskas et al., 2019). This demonstrated that the required technology is in place and well established for industry to achieve ZEFP.

Looking beyond this to the broader water industry, a key related issue is how to achieve a true ZEFP for a municipal wastewater treatment plant (WWTP). The same model can be applied and developed, looking at full recovery and reuse of all waste streams (liquid and solids). Additionally, the WWTP can become a net exporter of renewable energy, allowing the water entity (council or water corporation) to move towards a zero-carbon cost, but potentially also becoming a revenue generator. The key to achieving this is in understanding the water and energy balance across a WWTP and the ability to breakdown the reuse water into its hydrogen and oxygen elements; utilising the wastewater being treated to produce hydrogen for energy (to offset the WWTP energy need and use, and create revenue) and using oxygen for treatment, (which removes one of the largest energy uses in treatment - aeration).

In this paper we will present how this can be achieved in a municipal WWTP in New Zealand and provide examples where this is being implemented. We will present the benefits of these examples. A strong linkage to the circular and hydrogen economy will be made and we will unpick the barriers that we face at present, demonstrating how these can be overcome.

The concept for a WWTP ZEFP model incorporates much of the same approach as the Dairy ZEFP namely:

- Biogas and co-generation of electricity
- Use of renewable energy
- Carbon neutrality
- Zero liquid discharge treatment of water and recovery of salts
- Biosolids and nutrient recovery to produce a fertiliser or soil improver product
- Minimal to zero production of intractable residuals.

The benefits of a WWTP ZEFP are – it de-carbonises the process, provides cost savings in energy use and waste disposal, improves regulatory compliance with more stringent environmental consent limits, and recovery of resources such as nutrients, carbon, and water. Other benefits include meeting increasing customer desire to minimise carbon emissions and the environmental impacts of the products they use. This paper will demonstrate that the technologies are available, proven and operating.

**KEYWORDS**

**Hydrogen, Decarbonisation, Wastewater, Energy, Environment, Footprint, Closed Loop, Circular Economy**

**PRESENTER PROFILE**

Richard Greenwood is a Chemical and Process Engineer with over 30 years' experience having worked in industry and consulting across including aluminium, fertiliser, dairy, energy generation, construction, and water. Across his career he has been involved in all aspects of minimising the environmental impact and carbon footprint of engineering processes.

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# 1. INTRODUCTION

## 1.1. APPROACH

The Zero Environmental Footprint Plant (ZEFP) model is a fully integrated and systems approach to the recovery of water, nutrients, energy, and waste streams within the footprint of an industrial plant. This vision was first set out by Jacobs in 2019 in the context of the Dairy Industry, where it was proved possible to eliminate environmental discharges by applying existing and emerging technologies to optimise resource recovery (Bukauskas, Greenwood, & Poon, 2019). The purpose of this paper is to apply the ZEFP model to a municipal wastewater plant (WWTP) to see if such gains can be made in the Water Industry.

Like the Dairy ZEFP, the Wastewater Treatment Plant Zero Emission Footprint Plant (WWTP- ZEFP) model focuses on resource recovery and closing these loops. There are many proven technologies within wastewater, water and energy sectors that have been developed for this purpose. The challenge comes with combining these technologies together, investing in unconventional approaches and gaining access to capital in a financially constrained industry with tight margins and cyclical returns (Bukauskas et al., 2019).

This paper will present a review of available technologies for each of the liquid, solid and energy streams in a WWTP. The culmination of these technologies is an integrated process which brings together inputs and outputs to demonstrate that a WWTP ZEFP in a municipal context is possible.

## 1.2 WASTEWATER TREATMENT IN NEW ZEALAND

New Zealand has an estimated total of 323 publicly owned WWTP's (Water NZ, 2020) not including an inventory of industrial and private schemes. A recent report has been produced by the Ministry for the Environment (MfE) that provides a detailed description of the wastewater sector in New Zealand. A breakdown is given in Table 1 below.

*Table 1: Breakdown of New Zealand WWTP's (in terms of size, treatment and discharge methods) by number and population (MfE, 2020).*

| | | No. WWTP | % by No. | % by Pop. |
|---|---|---|---|---|
| Size | Very small & small (<5,000) | 248 | 77 | 6 |
| | Major & large >10,000 | 44 | 14 | 88 |
| Treatment | Ponds & lagoons | 37 | 64 | 15 |
| | Activated sludge | 57 | 18 | 74 |
| Discharge | River | 143 | 45 | 16 |
| | Ocean | 64 | 35 | 74 |
| | Land | 109 | 20 | 8 |

From Table 1 above, the majority of WWTP's in New Zealand are small, pond-based systems. However, these systems represent the minority of the serviced population. Most of the New Zealand population is serviced by a smaller number of large WWTP's with activated sludge treatment. It should be noted that 21% of New Zealand's population is not connected to a reticulated sewer. Although septic tanks are outside scope of this paper, this represents a sizable wastewater load to the environment.

Most WWTP's discharge treated effluent into freshwater bodies, but most of the serviced population (hence wastewater volume) is connected to an ocean discharge scheme. This can be attributed to the coastal locations of our large population centers and the lack of reuse opportunities in New Zealand (MfE, 2020). Biosolids and biogas byproducts have historically been considered waste streams and disposed of or flared. Very few WWTP's have any form of energy capture and reuse, and most sludge is still disposed to landfill.

Originally, wastewater treatment was defined by a public health-based risk approach and discharge to water bodies or land was considered a cheap and effective method of disposal. The introduction of the Resource Management Act (RMA) in 1991 shifted the focus of wastewater management to minimise impacts to both public health and the environment. Increased awareness around sustainability and the effects of climate change have more recently resulted in another focus shift, this time towards the potential of wastewater as a valuable resource.

Issues currently facing the sector include but are not limited to:

- Increasingly stringent water quality standards that cannot be met by existing infrastructure
- Degrading water quality in the receiving environment
- Higher energy requirements (and therefore carbon emissions) for transfer and treatment processes

- Inability to recover and reuse resources
- Cost to transport and dispose of treatment byproducts (screenings and sludge)
- Emerging contaminants

## 1.3 ZERO CARBON ACT AND FRESHWATER POLICY

To a large extent in New Zealand, the impact of wastewater processing on $CO_2$ emissions has been ignored. The dominant greenhouse gases (GHG) generated by a WWTP are methane ($CH_4$) and nitrous oxide ($N_2O$). Direct $CO_2$ emissions are lower as a proportion, depending on the process and whether transport and imported energy costs are factored in.

According to the MfE 1990-2019 GHG Inventory report, 2019 wastewater treatment and discharge contributed 372.5 kt $CO_2$-e to the environment, an increase of 22.8% on 1990 levels and a contribution of approximately 0.45% to New Zealand total GHG emissions that year. This value includes $CH_4$ emissions from rural septic tank usage and industrial waste treatment. It excludes the contribution from sludge processing and disposal, which is included in the solid waste disposal source category (MfE, 2021).

This paper considers only emissions arising from the treatment of wastewater at a WWTP. It excludes transport (pumping, networks) and untreated wastewater emissions, such as those from overflows and septic tanks. Although a minor contributor to the New Zealand Carbon Emissions Inventory, it is important to recognise and consider these emissions in the context of the new Climate Change Response (Zero Carbon) Amendment Act. Under this act, each council or WWTP owner/operator will require an emissions reduction plan and have targets set for $CO_2$, $NO_X$ and $CH_4$

The Freshwater National Policy Statement (NPS) 2020 sets out the objectives and policies for freshwater management under the RMA 1991 (New Zealand Government, 2020). Requirements include but are not limited to:

- Managing freshwater in a way that gives effect to Te Mana o te Wai
- Improving degraded water bodies in line with defined "bottom lines "
- Expands the national objectives setting more consideration to the health and wellbeing of our water bodies and encouraging restoration

## 1.4 CIRCULAR ECONOMY

The New Zealand wastewater sector is currently a linear economy whereby the use of raw materials (water) generates waste that is discharged to the receiving environment. A circular economy is based on regeneration, use of renewable energy and the transformation of waste products into valuable resources. There are many arguments for a shift from a linear to a circular economy to maximise the use of finite resources and encourage greater intergenerational equity in the sustainable management of natural assets (Bukauskas et al., 2019). The circular economy is based on three key principals (MfE, 2018):

- Design out waste and pollution
- Keep products and materials in use
- Regenerate natural systems

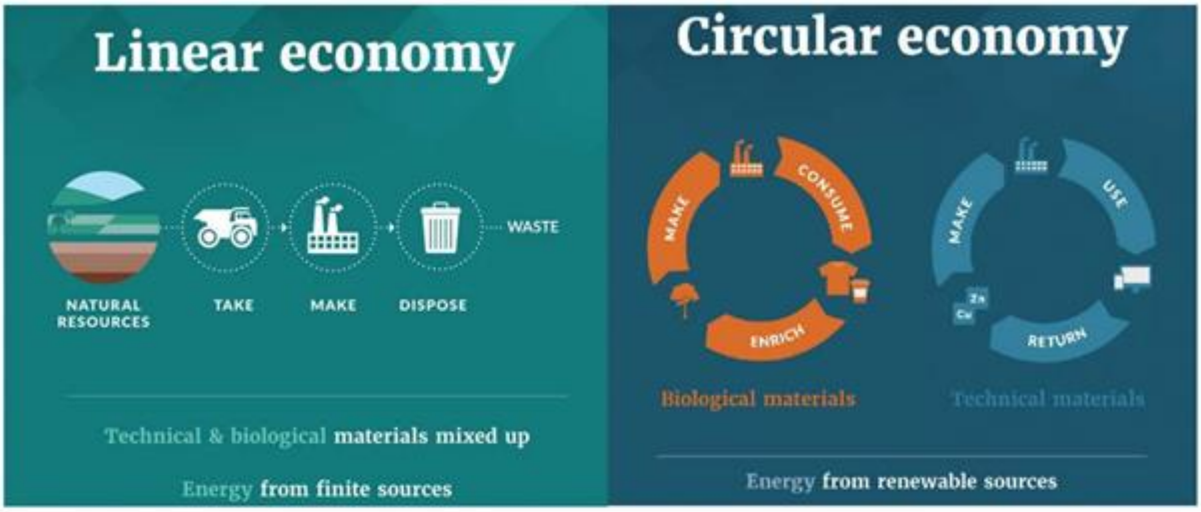


*Figure 1: Linear Economy vs Circular Economy (MfE, 2018).*

The circular economy model is most applicable to biosolids and byproducts management at a WWTP. It aligns with Zero Waste concept which has been growing rapidly around the world. In New Zealand, this concept has recently been championed by the New Zealand Business Council for Sustainable Development (NZBCSD, 2021). The ultimate vision is a 100% resource efficient economy where, as in nature, material flows are cyclical, and everything is reused or recycled harmlessly between society and the natural world.

# 2. CURRENT WWTP

## 2.1 GENERAL PROCESS

At their core, WWTP's in New Zealand rely on biological processes to remove contaminants. The treatment process can vary according to the WWTP type, influent characteristics, and discharge requirements. Municipal WWTP's in New Zealand are typically comprised of some form of the following:

1. **Preliminary treatment** e.g. screening, to remove coarse solids and grit
2. **Primary treatment** e.g. primary settling tank, to remove suspended solids
3. **Secondary treatment** e.g. activated sludge process, for further removal of organic matter and suspended solids
4. **Tertiary treatment** e.g. filtration and UV, for polishing and disinfection
5. **Waste treatment** e.g. sludge treatment, for disposal.

In New Zealand, waste stabilisation ponds (WSP) have formed the basis of municipal treatment for decades and are still the most common form of WWTP for smaller communities. However, these systems are passive, relying entirely on natural processes, and as such the treatment effectiveness is susceptible to climatic conditions. Mechanical WWTP's, such as activated sludge processes, enhance the natural biological processes providing increased control over the treatment processes, improved treatment reliability, and a higher level of treatment is possible. Increasingly stringent discharge conditions to meet modern expectations, in combination with our changing climate, are resulting in a shift from WSPs to mechanical WWTP's.

Mechanical WWTP's utilise the same biological processes that occur naturally within WSPs but provide mechanical means to control and fine tune these processes. They have a significantly smaller footprint than WSPs and are therefore well suited for larger urban communities. There are a number of established and emerging technologies for liquid, solid and energy streams that can be applied to Mechanical WWTP's to minimise the environmental footprint of the treatment process.

A mechanical-based WWTP has been selected to represent a typical, urban, New Zealand WWTP and act as a basis for the ZEFP model. The chosen treatment process consists of an activated sludge process with sludge stabilisation for disposal to landfill. An input and output diagram for this system is shown in Figure 2.

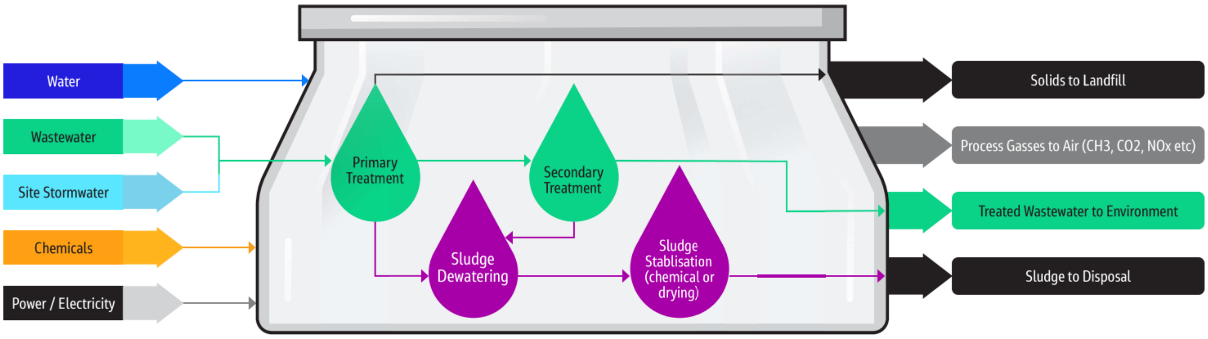


*Figure 2: Example input and output diagram for a typical NZ WWTP.*

## 2.2 LIQUID STREAMS

### 2.2.1 INFLUENT - MUNICIPAL WASTEWATER

Municipal wastewater is generated by a variety of industrial, commercial, and household activities. In addition to human waste it can contain anything that goes down the kitchen sink, including detergents, soaps, food, and other household items. Commercial facilities typically to generate higher strength waste with high fats oils and grease (FOG).

Industrial wastes vary widely from food processing through to heavy industrial and chemical manufacturing. Most significant industrial contributors have a trade waste consent. Food processing facilities include various cleaning chemicals in their waste streams

Wastewater is characterised by key constituents which have environmental and public health concerns. A WWTP's influent stream can vary widely depending on the community it serves and network issues such as septicity. The quantum and type of industrial waste impacts the typical influent composition and therefore the treatment required. An example of the typical municipal composition for a New Zealand town is provided in Table 2.

*Table 2: Municipal wastewater characteristics (MfE, 2020).*

| **Parameters** | **Unit** | **Concentration** |
|---|---|---|
| pH | - | 7–7.5 |
| Alkalinity | mg/L | 250–350 |
| Total suspended solids (TSS) | mg/L | 180–400 |
| Biochemical oxygen demand ($BOD_5$) | mg/L | 180–350 |
| Chemical oxygen demand (COD) | mg/L | 400–600 |
| Total Kjeldhal Nitrogen (TKN) | mg/L | 60–70 |
| Ammoniacal nitrogen ($NH_3$-N) | mg/L | 45–55 |
| Total Phospohorous (TP) | mg/L | 10–12 |
| E. coli | cfu/100mL | $10^7$–$10^8$ |

### 2.2.2 EFFLUENT - TREATED WASTEWATER

The discharge of municipal wastewater requires a resource consent under the 1991 Resource Management Act (RMA). As shown in Table 1, in New Zealand, 74% of WWTP's discharge to ocean, 16% to river and 8% to land. Discharge consents specify conditions for the effluent quality that aim to mitigate adverse effects to human and aquatic life. The treatment processes required at a WWTP are dictated by these conditions, in addition to the influent wastewater characteristics.

The typical effluent quality achieved by an activated sludge process with tertiary treatment is given in Table 3 below.

*Table 3: Typical effluent quality following an activated sludge process with tertiary treatment (MfE, 2020).*

| **Parameter** | **Unit** | **Concentration** |
|---|---|---|
| TSS | mg/L | <5 |
| $cBOD_5$ | mg/L | <5 |
| $NH_3$-N | mg/L | 5–15 |
| Total inorganic N | mg/L | 25–30 |
| TP | mg/L | 4–8 |
| E. coli | cfu/100mL | 100–500[1] |

*1. Pathogen removal achieved by UV disinfection.*

### 2.2.3 FRESHWATER

Freshwater is typically employed to service internal water demand, such as for the washdown of screens and other equipment, some process water requirements, and amenities such as toilets.

### 2.2.4 STORMWATER

Stormwater collected on site is directed into the inlet works for treatment through the WWTP.

## 2.3 SOLID STREAMS

### 2.3.1 SLUDGE

As wastewater passes through a WWTP, solids are generated by the treatment processes and collected in the form of sludge. For the WWTP presented in this paper, sludge is generated by sedimentation in the primary settling tank and the activated sludge process. These primary and secondary streams combine to form an output sludge stream which contains valuable energy and nutrients. Waste activated sewage sludge from an activated sludge WWTP is comparable to wood biomass in terms of energy content with a heating value of 17-18 MJ/kg (Durdevic, Blecich, & Juric, 2019). Many of the emerging technologies discussed in Section 3.2 of this paper are focused around the utilisation of this renewable energy source.

In New Zealand, sludge is disposed of to landfill or treated to form biosolids (see Section 2.3.2). To reduce disposal costs, raw sludge (typically less than 1 wt% solid) is thickened and dewatered to increase the solid particles to 10-25 wt% depending on the dewatering technology used. The water reclaimed from the sludge steam is typically returned to the beginning of the WWTP process.

### 2.3.2 BIOSOLIDS

The 2003 Guidelines for the Safe Application of Biosolids to Land defines biosolids as "sewage sludges that have been treated and/or stabilised to the extent that they are able to be safely and beneficially applied to land" (MfE, 2003). Like many WWTP in New Zealand, the WWTP presented in this paper has no sludge treatment process and therefore outputs its biosolids within this waste stream. Due to global concerns about the increasing volume and hazardous nature of biosolids, there has been a shift away from disposal towards the effective recovery and treatment of these byproducts.

The 2003 Guidelines, which are currently being updated, define two stabilization and two contaminant classification grades that dictate how the biosolids may be reused. Beneficial reuse pathways include a secondary sludge treatment process such as thermal drying, composting or lime addition. The extent to which biosolids processing occurs in New Zealand is limited, the most common product being digested biosolids that have been dewatered to approximately 20 wt% dry solids content. The Mangere WWTP produces 45% of New Zealand's biosolids that are used in quarry rehabilitation and land restoration, however the capacity of this end use is finite, and another end use will need to be identified and implemented. It is important to note that 32% of New Zealand biosolids are still disposed of as waste, either to landfill (27%) or onsite storage (5%) (Tinholt, 2019).

### 2.3.3 OTHER SOLIDS

Solids removed by preliminary screens and grit chambers are collected and disposed of to landfill. The composition of this material varies widely from mineral (grit) through to plastics and rag making beneficial reuse very difficult to achieve.

## 2.4 ENERGY STREAMS

Energy requirements for a WWTP vary according to the treatment processes employed. Typically, the main energy input to a WWTP is electricity to drive the mechanical WWTP and processes, as well as electrical utility requirements (lighting, power for amenities and control systems). WWTP's with sludge treatment facilities have higher energy demands but there is potential to off-set these demands with the heat and biogas generated by the treatment process itself (see Section 3.3.1).

For secondary treatment WWTP's with a conventional activated sludge system, the energy consumption is approximately 0.3 kWh/m$^3$. The aeration process in the secondary treatment stage is the most energy intensive and accounts for approximately 50-60% of all electricity consumption. Sludge treatment (if present) can account for approximately 15-25% and primary treatment, including recirculation pumps, is approximately 15% (Gu, et al., 2017).

In New Zealand, most WWTP input electrical power from the national grid. As of June 2021 79% of all electricity generated in New Zealand is renewable (MBIE, 2021) and it has been higher in the past. However, the 2019 MfE WWTP GHG Inventory reports that scope 2 emissions (due to grid electricity use) from New Zealand WWTP's is approximately 21 kilotonnes/year $CO_2$e (MfE, 2021). Thus, grid electricity use by WWTP's is still a contributing factor to overall carbon emissions.

Some New Zealand WWTP's generate their own renewable energy on site by the installation of solar panels and wind farms. A solar array installed by Watercare at their Rosedale WWTP can generate approximately 1,500 MWh each year and off-set a quarter of the WWTP total energy demand (Watercare, 2020). These technologies still require an external energy input and therefore, whilst renewable, represent a linear model of electricity generation at the site level. A fully circular approach to on-site electricity generation utilises the energy available within the WWTP itself. This typically occurs via biogas cogeneration, discussed in Section 3.1.1.

Increasing energy costs and growing concern about climate change has highlighted the need to realise self-sufficiency in WWTP's. Self-sufficient WWTP's exist and, in some cases, a net positive energy balance has been achieved. The USA is leading in this field, to the extent that many North American WWTP are being rebranded as "Water Resource Recovery Facilities" (Macdonald & Crawford, 2017). In the Australasia region, Yarra Valley Water is leading in this space with their ReWaste facility, which exports excess energy to the electricity grid (Yarra Valley Water, n.d.).

# 3. AVAILABLE TECHNOLOGIES

This section of the paper considers available technologies for liquid, solid and energy streams at a WWTP and how these may be implemented to achieve a WWTP ZEFP.

## 3.1 LIQUID STREAMS

As discussed in Section 2.2, liquid streams pass through the WWTP process in a linear sense, with outputs directly to the environment. This section focuses on how these liquid streams may be most effectively treated, recovered, and reused to minimise WWTP outputs and channel this valuable resource.

### 3.1.1 MEMBRANE AERATED BIOREACTOR

Conventional activated sludge delivers oxygen to micro-organisms by pumping air through diffusers to create bubbles. This is energy intensive because air only has a small portion of oxygen, requiring large volumes to be supplied. The bubbles also rise too quickly for most of the oxygen to be absorbed (Jacobs, 2020). As such, there are limits to the efficiency of this treatment process and high associated operating costs.

A membrane aerated bioreactor (MABR) process applies a gas permeable membrane to deliver oxygen to a biofilm that is attached to the membrane media surface. Experience has shown that nitrifiers preferentially grow at the surface of the media, differentiating the MABR from conventional biofilm technologies in which BOD removal is considered a necessary step prior to nitrification (Houweling, Peeters, Cote, Long, & Adams, 2017).

The key advantage to this technology is that the biofilm is formed on the membrane itself and the oxygen goes straight into the biomass. Therefore, the usual mass transfer limitation for oxygen transfer of 10% to 40% in conventional fine bubble diffuser aeration no longer applies (Houweling et al., 2017). MABRs can also be fed with pure oxygen, a by-product of hydrogen electrolysis (see Section 3.3.2). This results in ever greater efficiencies in the treatment process. The MABR technology therefore has the potential to greatly reduce the energy and capital costs of wastewater treatment and allow WWTP to expand capacity without the need for additional space (Jacobs, 2020).

Another advantage is that an intensified biological nutrient removal (BNR) process can be achieved by an MABR within an activated sludge bioreactor. The MABR zone is unaerated thereby creating an environment with aerobic conditions in the biofilm and anoxic conditions in the suspended biomass around the media. This enables simultaneous nitrification and denitrification (Houweling et al., 2017).

### 3.1.2 NUTRIENT RECOVERY

Nitrogen (N) and phosphorous (P), which are present in wastewater, are essential nutrients for plant growth and therefore global food security. For synthetic fertilisers, N is usually manufactured through the Haber-Bosch process and P is extracted from finite mineral reserves (mining). These processes are energy intensive, unsustainable in the long term and overutilization has also led to eutrophication (Lorick, Macura, Ahlstrom, Grimvall, & Harder, 2020).

Recovery of the nutrients from municipal wastewater for use in agricultural fertiliser reduces the burden on reactive N and mining to produce P and mitigates their escape into environment (Sengupta, Nawaz, & Beaudry, 2015). In New Zealand, WWTP's with sludge treatment facilities may dispose of their biosolids to land, though this accounts for only 19% compared to 90% achieved by the UK and Australia (Tinholt, 2019).

"In process" N emissions from WWTP's is a significant contributor to the total emissions footprint with 1 tonne of $N_2O$ equivalent to 298 tonnes of $CO_2$. Reducing the emission of $N_2O$ has a disproportionally large impact on the calculated carbon footprint of the WWTP. Whilst there is currently little reliable data available and the data that is available varies between sites, it is generally accepted that $N_2O$ emissions occur in the aerated zones of the WWTP due to the presence of $NH_3$-oxidizing bacteria, rather than heterotrophic denitrifiers (Law, Ye, Pan, & Yuan, 2012).

Conventionally, wastewater treatment has focused the removal of N and P to protect receiving water bodies, rather than recovery of these nutrients for a beneficial end use. There are many nutrient recovery options available for organic waste streams which have been proven at large scale. The two considered for the WWTP-ZEFP are struvite precipitation and $NH_3$ stripping.

Struvite is an effective slow-release fertiliser which can replace other fertilisers produced from phosphate rock (Lorick et al., 2020). Significant quantities are produced in the USA, Japan, and China. Due to the potential benefits in aiding global food security, the process is under continuous research and improvements are being made worldwide (Siciliano, Limonti, Curcio, & Molinari, 2020).

Struvite is a crystalline mineral composed of equimolar concentrations of magnesium (Mg), ammonium ($NH_4$) and phosphate ($PO_4$) ($MgNH_4PO_3*6H_2O$). Precipitation occurs when the concentrations of these ions overcomes the solubility product under an alkaline environment. In general, struvite precipitation is aimed to remove and recover $PO_4$ from wastewater as only chemicals for Mg supply and pH setting are required. Due its excess in concentration, targeting the removal of $NH_4$ requires more reagents and is less sustainable (Siciliano et al., 2020).

$NH_3$ stripping can be applied to wastewater streams with high $NH_4$ concentration. High temperature and pH are required to ensure most the presence of N as gaseous $NH_3$. Stripped $NH_3$ is recovered by acid absorption, most commonly sulphuric acid. The resulting product is a low pH ammonium sulphate which can be used as fertiliser on soils with alkaline or neutral reaction (Siciliano et al., 2020).

### 3.1.3 WATER REUSE

Due to increasing water scarcity and demand, water reuse is becoming a necessity in communities around the world. Water reuse consists of taking water that has been 'used' in some way, treating, and reusing it for a beneficial purpose. Such schemes are being implemented in the United States where municipal wastewater is being treated and employed for non-potable uses such as agriculture, irrigation, groundwater replenishment, industrial processes, and environmental restoration (EPA, 2020).

One example of water reuse is Melbourne Water's purple pipe network, which distributes recycled water to homes and businesses for non-drinking purposes, such as flushing toilets and watering gardens. Recycled water is produced from municipal wastewater at Melbourne Water's Western and Eastern WWTP's, requiring advanced tertiary treatment processes involving filtration, UV, and chlorine. Other uses for recycled water include refilling aquifers (Melbourne Water, 2020).

Water reuse has once again become a topical issue, spurred on by events such as the Auckland 2020 drought. At present, the concept of water reuse in New Zealand is narrowly used. Instead, the conventional approach for treated wastewater is application back to ocean, land or freshwater. Land-based discharge is typically adopted as a treatment disposal option in line with tangata whenua desires for treated wastewater to pass through land before it reaches a water body (MfE, 2020). Only a few systems are operated nationally that maximise irrigation or nutrient benefit of these applications. Examples include Southland District Council's Te Anau WWTP, Queenstown Lakes District Council's Cardona WWTP and Synlait Milk Ltd's Dunsandel Milk Factory, which all discharge treated wastewater to land via irrigation. Historic barriers to water reuse in New Zealand include the low cost and easy access to high quality water, infrastructure limitations, cost, and public perception (Lowe, 2009).

## 3.2 SOLID STREAMS

Solids generated by the WWTP process have historically been considered waste streams and disposed to landfill, where they break down, resulting in the uncontrolled emission of $CH_4$ and other pollutants to the atmosphere. As discussed in Section 2.3, the solids stream has a high carbon content and therefore high potential for beneficial reuse, especially as a fuel. Emerging technologies for WWTP solids are therefore primarily focused on the effective pre-treatment of and conversion of WWTP solids to biofuel. These technologies make up the first stage of waste-to-energy (WtE) solutions. Alternative solutions for WWTP biosolids include thermal drying to produce fertiliser products suitable for land application.

### 3.2.1 ADVANCED ANAEROBIC DIGESTION (THERMAL HYDROLYSIS)

At the heart of biosolids processing improvements is high performance anaerobic digestion (AD) (WEF, 2019), The use of AD in the water industry can be traced back over a hundred years. However, it was historically employed as a method of sludge stabilization and minimization, only more recently have the energy benefits been realised. AD is now being considered the engine of water resource recovery facilities in WWTP across the world (Parry, 2019).

Anaerobic digestion of sludge is a complex biological process whereby acid forming bacteria break down the organic materials into organic acids, which are then converted into $CH_4$ and $CO_2$. As a result, the sludge organic content is reduced by up to 50%. Gas output depends on temperature, contact time and the stabilisation of the volatile matter that undergoes digestion. A properly balanced system will produce 900-1100 L of biogas for each kg of volatile matter destroyed (Petitpain, 2006). This biogas can be used as a fuel in combined heat and power (CHP) units to produce heat and energy (see Section 3.3.1). Co-digestion of sewage sludge with other waste streams offers additional opportunities for additional waste minimisation and the potential for enhanced $CH_4$ production.

There is a plethora of technology available to enhance the biodegradability of sludge and therefore the inherent biogas production and energy generation. The thermal hydrolysis process (THP) involves the application of heat above sterilization temperature (120 °C) coupled with pressure to break down the cellular content of sludge. The fundamental benefit of THP is a change in sludge rheology to a lower viscosity which allows for feed a high solids concentration at higher loading rates, while still being able to mix the digestor (WEF, 2019). This results in reduced digester volume or increased throughput. THP pre-treatment also increases the volatile content entering the digestor, resulting in increased methane production and reduced biosolids output. When compared to traditional anaerobic digestion, the additional of THP pre-treatment typically achieves 10-20% higher methane generation and 5-15% greater cake solids in the output biosolids (Viswanathan et al., 2020).

### 3.2.2 INCINERATION / COMBUSTION

Sludge incineration involves the combustion of municipal sludge into ash, flue gas particulates and heat which can be used to generate electricity. It is therefore both a landfill reduction method and a WtE technology. Due to the historically high levels of air emissions, sludge incineration has gained criticism that, as a process, it does nothing more than convert water pollution into air pollution (Yang & Meier, 2011). However, stricter regulations have driven advances in emissions control and flue-gas treatment technologies now remove contaminants from the environmental cycle.

Sludge incineration is a mature and well-known technology. Historically, the primary use of this process was to burn off harmful elements from clinical or municipal waste prior to final disposal or reuse of ash in the construction industry. Municipal sludge incineration is once again gaining attention, due to need to reduce waste to landfill the ability to generate heat or electricity from the process. It is widely practiced overseas with large WtE investments in France, Germany, the UK, Italy, and Sweden. Incineration allows these countries to reduce the volume of waste to landfill by 90% (Perrot & Subiantoro, 2018). However stringent legislation, perceived risk of emission and public perception has made this option very unpopular in New Zealand, with no new incinerators constructed in recent years.

### 3.2.3 PYROLYSIS

Pyrolysis, often referred to as incomplete gasification, is the thermal degradation of fuel without any oxidation agent in an inert environment. It involves the conversion of sewage sludge without air at moderate operating temperatures (350–600 °C) to produce biofuel as char, oil, or gas. The process temperature dictates the output products, with high temperatures promoting more liquid and gas product. Application of this technology is mostly used to maximum liquid fuel (bio-oil) yield, which has a slightly higher heating value than bio-oil from biomass (Oladejo, Shi, Luo, Yang, & Wu, 2018).

The pyrolysis process has large heat requirements. The sludge must be dried to less than 10% moisture content and a heat source to initiate the reaction. Heat may be sourced from the partial combustion of biogas or bio-oil derived from the process itself to ensure its self-sufficiency. Pyrolytic products of bio-oil, biochar and non-condensable gases can all be utilised as fuel for heat or electricity generation. Bio-oil and gas can also be upgraded to synthesis gas for chemical production. Biochar is a promising product with potential as solid fuel for combustion applications, adsorptive capacity in catalyst applications and agricultural applications (Oladejo et al., 2018).

### 3.2.4 GASIFICATION

Gasification is the thermochemical conversion of organic content into high value gases such as $H_2$ and CO, or synthesis gas (syngas), as well as $CO_2$, $CH_4$ and $H_20$. This reaction occurs in a partially oxidised atmosphere at high temperatures (800–1000 °C). Either or a mixture of air, $CO_2$, $O_2$, and/or steam is employed as the gasifying agent. This significantly impacts the calorific value of the syngas, with the highest heat value obtained from oxygasification.

For the WWTP-ZEFP, oxygen could be sourced from hydrogen electrolysis (see Section 3.3.2) and used as a gasifying agent to obtain syngas with a high-heat syngas. This can be used directly for heat and electricity generation. Ash generated by this process can be reused in agricultural or construction applications (Oladejo et al., 2018).

### 3.2.5 SLUDGE DRYING

Another beneficial end use for WWTP solids, alternative to energy production, is application to land as a fertiliser product. As discussed in Section 2.3.2, the 2003 Guidelines for the Safe Application of Biosolids to Land in New Zealand is the recommended approach to the management of biosolids discharge to land under the RMA. These guidelines define a grading system for biosolids based on stabilization and contamination requirements. Grade Aa biosolids are suitable for "unrestricted use", meaning that no consent is required (MfE, 2003). An Aa biosolids grade can be achieved by thermal drying processes such as flash, spray, rotary and steam driers.

A local example of this is New Plymouth District Council's BioBoost product, a natural organic fertiliser made from waste activated sludge generated by the New Plymouth WWTP. The sludge is concentrated in sludge thickeners and excess water is removed through a belt press. The thickened and dewatered sludge is then dried, sterilised and palletised in a rotary drier. The result is a commercial fertiliser product that is high in N and P, and contains other nutrients potassium, calcium, magnesium, sulphur and iron (New Plymouth District Council, 2017).

## 3.3 ENERGY STREAMS

WWTP's require electricity to drive their mechanical treatment processes, particularly for the aeration treatment stage. Solids processing technologies, such as those discussed in Section 3.2, require heat to dry the sludge and drive the decomposition reactions. As highlighted in Section 2.4, there is a need to realise self-sufficiency in WWTP due to increasing energy costs and growing climate change concerns. This section presents two technologies that can harness the embodied energy within WWTP output streams to generate the heat and power required to drive internal processes.

### 3.3.1 COMBINED HEAT AND POWER (CHP)

Section 3.2 presented emerging technologies for the effective pre-treatment and conversion of WWTP solids to biofuel as part of the first stage of a WtE solution. The second stage of a WtE is the conversion of the biofuel to energy in the form of heat and/or electricity. This is most often achieved by a combined heat and power (CHP) unit fueled by biogas.

In addition to its energetic benefits, burning biogas produces $CO_2$ from $CH_4$, which has more than 80 times the atmospheric warming power. This process therefore significantly reduces a WWTP's greenhouse gas emission. It also ensures that the $CO_2$ generated is from renewable source, not fossil fuels. Internal uses for heat and power include sludge treatment, aeration, and hydrogen electrolysis (Section 3.3.2). Surplus electricity can be sold to the national electricity grid.

It is currently estimated that a total of 50 $MW_e$ of $CH_4$ is collected and used as biogas in New Zealand, enough to power 40,000 homes, although it is mostly used in industrial scale, CHP applications. New Zealand has a growing biogas sector, with 31 key biogas generation sites with a total capacity of 57 MW or 5.7 PJ. An additional 6 PJ of potential capacity has been identified, of which 2.5 PJ comes from municipal solid waste. There are currently only 11 municipal bio-digestion WWTP able to process sewage sludge in New Zealand, with potential to upgrade a number of others for biogas production (Biogas, n.d.)

### 3.3.2 HYDROGEN ELECTROLYSIS

As part of a global drive towards a sustainable and decarbonised future, hydrogen has gained attention as a flexible energy carrier and enabler for the international trade of renewable energy (Jacobs, 2020). Hydrogen is a clean burning fuel and can be produced by electrolysis, the process of using electricity to split water in hydrogen and oxygen. If the electricity used comes from renewable sources, the hydrogen produced from this processed is known as 'green'.

With water and renewable energy from biogas readily available, WWTP's can supply the resources required for green hydrogen production. They are also uniquely placed to improve the financial viability of this process. Pure oxygen is a valuable resource for WWTP's as it can increase the efficiency of energy-intensive aerobic treatment processes. This gives value to what has traditionally been described as a 'by-product' of electrolysis and offers an opportunity to partially subsidise hydrogen production and increase its commercial viability (Jacobs, 2020). Another use for the oxygen byproduct in a WWTP-ZEFP could be oxy-gasification, as discussed in Section 3.2.4.

Co-locating a green hydrogen facility at a WWTP presents an opportunity to generate value from the treated wastewater and biogas electricity produced on site. A case study on Yarra Valley Water's Aurora WWTP found that implementing an oxygen-based MABR (see Section 3.1.1) could deliver net capital and operating cost savings whilst also generating a guaranteed demand for oxygen that is sufficient to enable a co-located hydrogen facility to be commercially viable while hydrogen within a competitive price range ($2-6/kg) (Jacobs, 2020).

# 4. ZERO ENVIRONMENTAL FOOTPRINT WASTEWATER TREATMENT PLANT

The concept for a WWTP-ZEFP is shown in Figure 3. The WWTP-ZEFP treatment process includes:

- Nutrient removal (e.g. struvite precipitation and/or $NH_3$ stripping) to produce fertiliser.
- MABR or similar treatment of wastewater to achieve high quality effluent suitable for reuse and significantly reduce energy demand.
- Sludge treatment (e.g. advanced digestion or thermal decomposition) to produce biofuel for cogeneration and biosolids suitable for beneficial land application.

To complete the WWTP-ZEFP model, the following supporting infrastructure would be required:

- On site biogas cogeneration to supply heat and electricity to wastewater and sludge treatment processes.
- On site and grid-based renewable energy generation.
- On-site electrolysis facility that utilises renewable energy to produce green hydrogen from treated wastewater. Oxygen byproduct supplies the MABR treatment process.

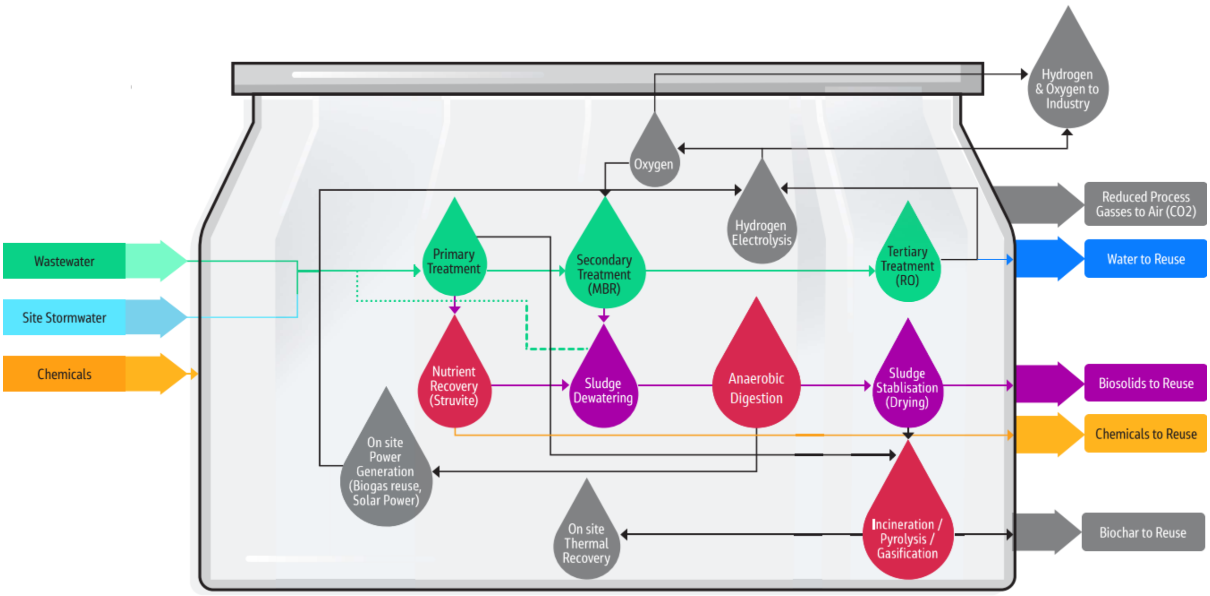


*Figure 3: Example input and output diagram for a WWTP-ZEFP.*

The WWTP-ZEFP model offers direct benefits to the WWTP internally in addition to the wider community that it serves. Knock-on effects may benefit the entire planet. These include:

- Environmental emissions to water, land and air are minimised or eliminated.
- The use of advanced, modern technology enables more stringent environmental consent limits.

- Cost savings achieved by increased treatment efficiency, diverting waste from landfill, and generating revenue from resources previously considered as waste streams.
- Nutrient removal processes produce beneficial fertiliser products, reducing the need for non-renewable and energy intensive synthetic processes.
- $N_2O$ emissions are reduced, reducing the overall environmental footprint.
- High quality effluent can be readily reused for non-potable applications, reducing impacts to the receiving environment and the wider demand for potable water supply.
- On site sludge digestion captures the renewable, embedded carbon and energy in high-strength organic waste streams and prevents $CH_4$ at the WWTP and further emissions at landfill.
- Biogas cogeneration minimises the importation of electricity and use of non-renewable fuels. There is potential to eliminate this input stream if the overall energy balance has been optimised by other means.
- Hydrogen electrolysis provides a reuse opportunity for treated effluent as well as a cost-effective oxygen supply to increase aerobic treatment efficiency and reduce demand on non-renewable electricity generation.
- Guaranteed water supply and demand for oxygen by the WWTP provides an opportunity to subsidise hydrogen production and increases the commercial viability of this fuel source.

# 5. CONCLUSIONS

The ZEFP vision was first set out by Jacobs in the context of the Dairy Industry, where it proved possible to eliminate environmental discharges by applying existing and emerging technologies to optimise resource recovery. The purpose of this paper was to apply the ZEFP model to a municipal wastewater setting to see the same outcomes could be achieved within the Water Industry.

The WWTP-ZEFP model considers the full recovery and reuse of waste streams to minimise outputs to the environment and generate beneficial byproducts. On-site energy generation can ensure self-sufficiency. Beyond this, there is potential for the WWTP-ZEFP to become a net exporter of renewable energy and a revenue generator. All of this may be achieved by applying available, proven technologies with a circular economy approach.

WWTP are uniquely placed to take full advantage of resource recovery methods. As posed by the Water Environment Federation (WEF) in 2011, "WWTP are not waste disposal facilities, but rather water resource recovery facilities that produce clean water, recover nutrients, and have the potential to reduce the nation's dependence on fossil fuel through the production and use of renewable energy" (WEF, 2011). The WWTP-ZEFP model provides a framework in which their full potential may be realised.

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## REFERENCES


Biogas. (n.d.). *Using biogas technologies to reduce methane emissions from waste and facilitating circular economies*. Retrieved July 4, 2021, from Biogas: https://www.biogas.org.nz/

Bukauskas, K., Greenwood, R., & Poon, J. (2019). *Moving Towards a Zero Environmental Footprint Dairy Plant.* Auckland: Water NZ.

Durdevic, D., Blecich, P., & Juric, Z. (2019). Energy Recovery from Sewage Sludge: The Case Study of Croatia. *Energies*. doi:DOI:10.3390/en1210927

EPA. (2020, July 8). *Water Reuse*. Retrieved June 26, 2021, from United States Environmental Protection Agency: https://www.epa.gov/waterreuse/basic-information-about-water-reuse

Gu, Y., Li, Y., Li, X., Luo, P., Wang, H., Wang, X., . . . Li, F. (2017). Energy Self-sufficient Wastewater Treatment Plants: Feasibilities and Challenges. *Energy Procedia, 105*, pp. 3741-3751.

Houweling, D., Peeters, J., Cote, P., Long, Z., & Adams, N. (2017). *Proving Membrane Aerated Biofilm Reactor (MABR) Performance and Reliability: Results from Four Pilots and a Full-Scale Plant.* Chicago: WEFTEC.

Jacobs. (2020). *Toward a Zero Carbon Future.* Melbourne: Jacobs.

Law, Y., Ye, L., Pan, Y., & Yuan, Z. (2012, May 5). Nitrous oxide emissions from wastewater treatment processes. *Philosophical Transactions of the Royal Society B*, pp. 1265-1277.

Lorick, D., Macura, B., Ahlstrom, M., Grimvall, A., & Harder, R. (2020, November). Effectiveness of struvite precipitation and ammonia stripping for recovery of phosphorus and nitrogen from anaerobic digestate: a systematic review. *Environmental Evidence*.

Lowe, H. (2009). What is our problem with water reuse: How other countries do it? *New Zealand Land Treatment Collective* (pp. 53 - 62). Palmerston North: New Zealand Land Treatment Collective.

Macdonald, G., & Crawford, J. (2017). *Energy Neutral WWTPS - a Dream or a Reality for New Zealand.* Hamilton: Water NZ.

MBIE. (2021, June 10). *New Zealand Energy Quarterly*. Retrieved from Mnistry of Business, Innovation and Employment: https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-publications-and-technical-papers/new-zealand-energy-quarterly/

Melbourne Water. (2020, August 3). *How we're taking action*. Retrieved from Melbourne Water: https://www.melbournewater.com.au/water-data-and-education/environmental-issues/why-we-need-save-water/how-were-taking-action

MfE. (2003). *Guidelines for the Safe Application of Biosolids to Land.* Wellington: NZWWA.

MfE. (2018, April). *Ōhanga āmiomio - Circular economy*. Retrieved from Ministry for the Environment: https://environment.govt.nz/what-government-is-doing/areas-of-work/waste/ohanga-amiomio-circular-economy/

MfE. (2020). *The New Zealand Wastewater Sector.* Ministry for the Environment.

MfE. (2021). *New Zealand's Greenhouse Gas Inventory 1990-2019.* Wellington: Ministry for the Environment.

New Plymouth District Council. (2017). *How do we make it?* Retrieved from BioBoost: http://www.bioboost.co.nz/

New Zealand Government. (2020). *National Policy Statement for Freshwater Management 2020.* Wellington: New Zealand Government.

NZBCSD. (2021, June 6). *Introducing the NZBCSD Zero Waste Project.* Retrieved from http://www.wasteminz.org.nz/wp-content/uploads/NZBCSD-Zero-Waste-Project.pdf

Oladejo, J., Shi, K., Luo, X., Yang, G., & Wu, T. (2018). A Review of Sludge-to-Energy Recovery Methods. *Energies*. doi:10.3390/en12010060

Parry, D. (2019, September). *Next Generation Anaerobic Digestions.* Retrieved from Water NZ: https://www.waternz.org.nz/Attachment?Action=Download&Attachment_id=4077

Perrot, J.-F., & Subiantoro, A. (2018). Municipal Waste Management Strategy Review and Waste-to-Energy Potentials in New Zealand. *Sustainable Development of Electrical Energy Storage Technologies in Energy Production*.

Petitpain, F. (2006, June 1). Municipal sludge digestion attracts interest as energy prices rise. *WaterWorld Magazine*.

Sengupta, S., Nawaz, T., & Beaudry, J. (2015). *Nitrogen and Phosphorous Recovery from Wastewater.* Springer International Publishing.

Siciliano, A., Limonti, C., Curcio, G. M., & Molinari, R. (2020). Advances in Struvite Precipitation Technologies for Nutrient Removal and Recovery from Aqueous Waste and Wastewater. *Sustainability*.

Tinholt, R. (2019). *The Value of Biosolids in New Zealand - An Industry Assessment.* Auckland: WasteMINZ.

Viswanathan, S., Thomson, C., Dimassimo, R., Garbett, R., Yellin, W., Kim, D., & Landes, D. (2020). *Next Generation Thermal Hydrolysis Process - High Solids THP.* Veolia Water Technologies.

Water NZ. (2020). *Wastewater Treatment Plant Inventory*. Retrieved July 5, 20201, from Water New Zealand: https://www.waternz.org.nz/WWTPInventory

Watercare. (2020, October 2). *New Zealand's first floating solar array unveiled*. Retrieved from Watercare: https://www.watercare.co.nz/About-us/News-media/New-Zealand%E2%80%99s-first-floating-solar-array-unveiled

WEF. (2011). *Water Environment Federation Position Statement - Renewable Energy Generation from Wastewater.* Alexandria: Water Environment Federation.

WEF. (2019). *High Performance Anaerobic Digestion.* Water Environment Federation. Retrieved June 2021, from https://www.accesswater.org/publications/-326649/high-performance-anaerobic-digestion

Yang, C.-L., & Meier, D. (2011). Cleaning Flue Gas from Sewage Sludge Incinerators Using an Electrostatic Precipitator and Polystage Chemical Scrubber. *Journal of the Air & Waste Management Association*, 169-176.

Yarra Valley Water. (n.d.). *Waste to Energy*. Retrieved from Yarra Valley Water: https://www.yvw.com.au/help-advice/waste-energy