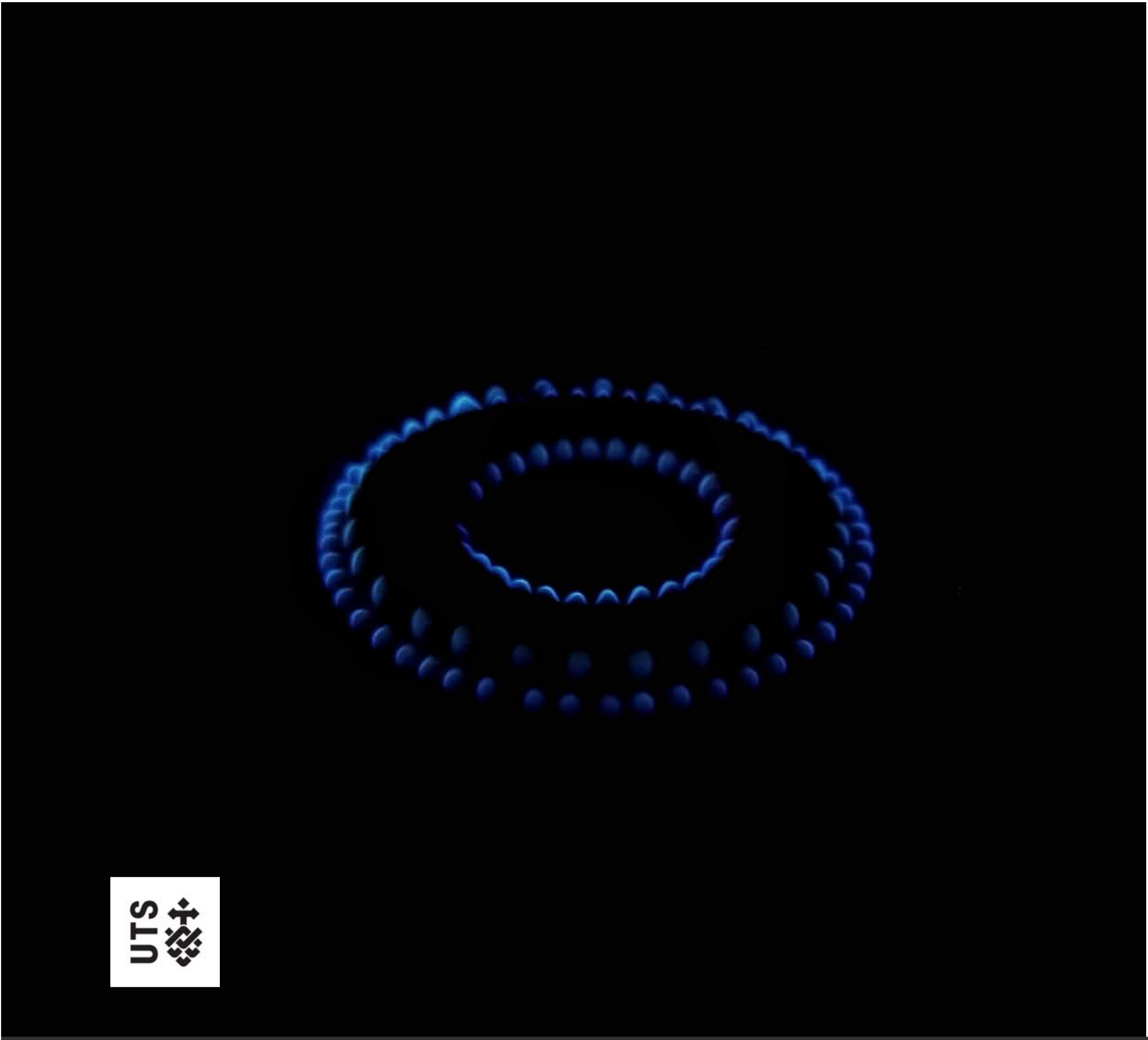

Institute for
Sustainable Futures

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Wastewater gas recovery opportunities in a circular economy

PREPARED FOR:
Sydney Water

About the authors

The Institute for Sustainable Futures (ISF) is an interdisciplinary research and consulting organisation at the University of Technology Sydney. ISF has been setting global benchmarks since 1997 in helping governments, organisations, businesses and communities achieve change towards sustainable futures. We utilise a unique combination of skills and perspectives to offer long term sustainable solutions that protect and enhance the environment, human wellbeing and social equity.

ISF acknowledges and respects the Aboriginal and Torres Strait Islander custodians of Australia and the Gadigal peoples upon which the UTS City Campus now stands. We continue to value the generations of knowledge Aboriginal and Torres Strait Islander Peoples embed within our University and we pay our respect to their Elders past, present and emerging.

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Contents

Introduction

This report

This brief report has been prepared for Sydney Water (SW) by the Institute for Sustainable Futures (ISF), University of Technology Sydney.

The report aims to assist SW in finding potential opportunities for gas recovery from wastewater treatment plants (WWTP) together with potential applications. Thus, aiming to help SW move away from the more traditional linear economy approach, towards a more holistic circular economy perspective, with associated potential new business opportunities.

The circular economy

The concept of the circular economy has been gaining traction over the past decade. The linear economy approach of take-make-waste system has pushed the economy out of the limits of our planet, with the current system is no longer working for business, people or the environment. How we manage resources, how we make and use products and what we do with the materials afterwards needs to transform to a new system where we design out waste and pollution, keep products and materials in use for as long as practicably possible and aim to regenerate natural systems. That is to move to a more circular economy approach in its broadest sense[1].

Circular economy solutions and applications at WWTPs have emerged worldwide focusing on the local context of where the WWTPs are situated, including tailored solutions featuring synergies with local businesses, communities and addressing specific niche needs[2]. Through this transition to a more circular economy approach WWTP systems are being considered from a more holistic perspective including not only the opportunities associated with the water but now also harnessing the opportunities associated with the gases and solids generated. With this broader perspective WWTPs have been identified as a vital piece of the puzzle in tackling climate change, as they can provide not only water but also energy and nutrients to the urban system, as illustrated in Figure 1.[3]

Water has a natural cycle ("nature managed"), but its circularity is impacted by human actions ("human managed"). In the circular economy approach, the human managed cycle aims to be aligned to the natural cycle by: avoiding water use when possible through elimination of ineffective actions; reducing water use through efficient technology and management; reusing water by closed loop systems; and recycling and replenishing by returning water effectively to the basin (Figure 1).

The circular economy approach helps practitioners use system thinking[4]. When water is considered from a system thinking perspective it exists in three dimensions: (1) as a service, (2) as

[1] https://www.ellenmacarthurfoundation.org/circular-economy/what-is-the-circular-economy
[2] Jazbec, M., and Turner, A., 2018 Creating a circular economy precinct, report prepared by the Institute for Sustainable Futures, University of Technology Sydney, for Sydney Water
[3] Ellen Macarthur Foundation (2019) Completing the picture, How circular economy tackles climate change.
[4] Meadows, D., (2008) Thinking in Systems – a Primer. Chelsea Green Publishing, US. (Ed, Wright, D.,)

a carrier of nutrients, chemicals and minerals and (3) as a source of kinetic, thermal and bio-thermal energy.[5]

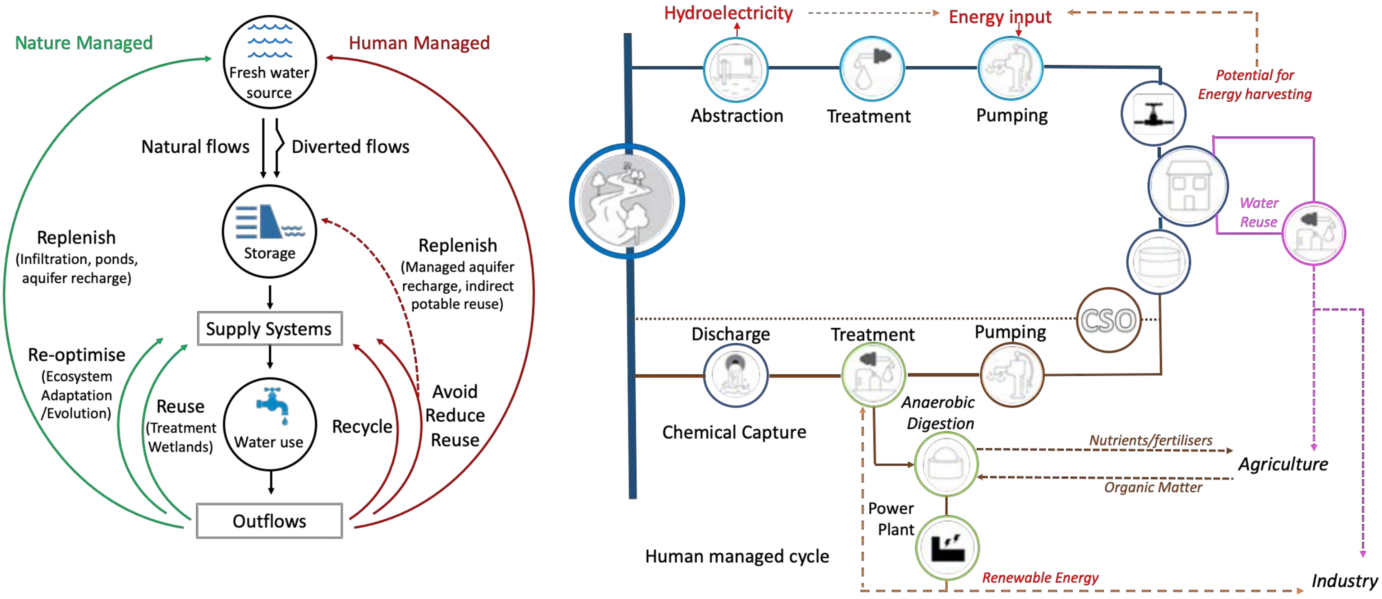


Figure 1: Water and circular economy.[6]

Summary of the case studies and gases collated

A suite of gas use and recovery case studies from around the world have been collated and documented in this report. Some of the examples are currently in operation. Others are still in the construction stage. Several examples are concepts that have been proven on a laboratory scale or pilot scale but, despite significant opportunities, are yet to be applied to wastewater treatment.

Although the main focus of the gas recovery to-date has been tapping into the energy from the carbon cycle of sludge using anaerobic digestion (AD), there are opportunities around other gases generated at WWTPs (e.g. the nitrogen and sulphur cycles). The main focus of these cycles has been the removal of the gases formed as opposed to their utilisation. Hence, this appears to be a gap in knowledge globally and thus a significant opportunity for investigation.

The gas opportunities explored in this report follow the main WWTP treatment stages as highlighted in Figure 2:

- preliminary treatment,
- primary and secondary treatment, and
- sludge treatment

[5] Ellen Macarthur Foundation (2019) Water and circular economy: White paper.
[6] Ellen Macarthur Foundation (2019) Water and circular economy: White paper.

New opportunities through hydrogen have also been documented as an emerging area.

The gas opportunities are provided through six detailed case studies (blue boxes) and twelve shorter highlighted examples (green boxes). Most of the case studies/examples are in the sludge treatment stage as this is where most WWTP gas recovery and use has been implemented. The primary focus area of each case studies is also pictured in the process schematic in Figure 2.

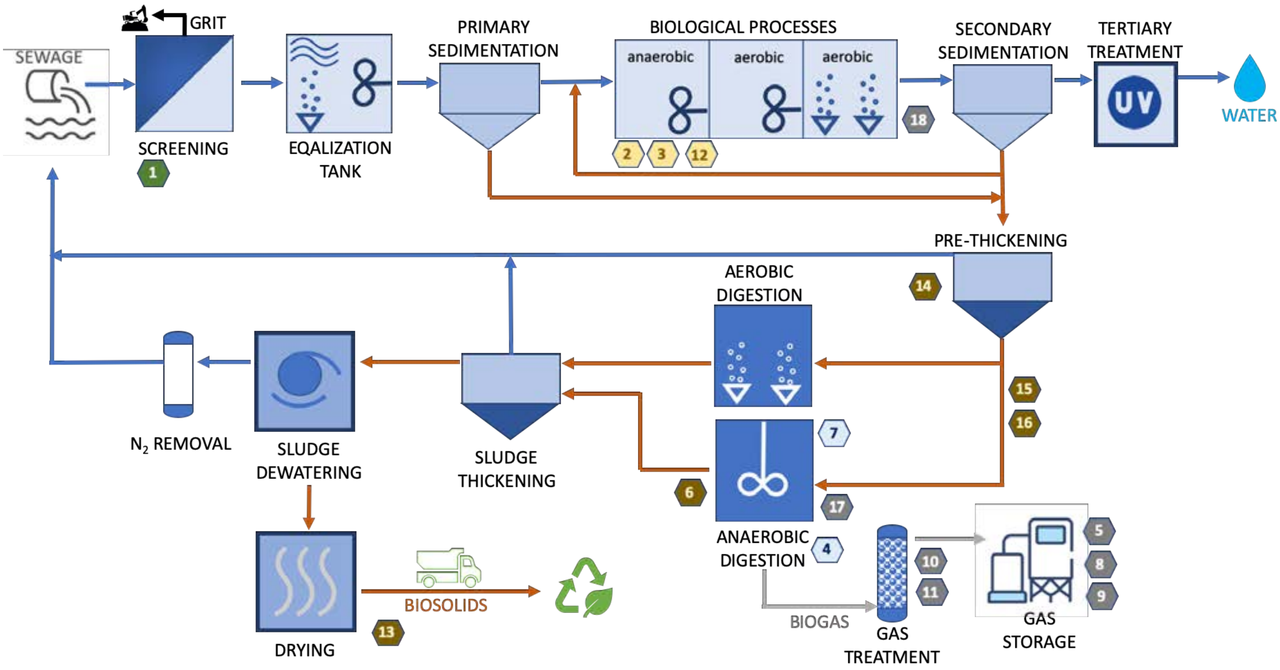


Figure 2: A simplified diagram of the main stages of wastewater treatment plant, including digestion of sludge to produce biogas. Case studies numbered in hexagons indicate their primary area of focus and the colour the phase (green for untreated sewage, brown for sludge, blue for water and grey for gas)

The specific gases reviewed in this report are summarised in Table 1. These are not the only gases found within WWTPs, but are the main gases that need to be considered due to either value of application or the potential adverse effects they have on the equipment and/or environment.

Gases are generated at all stages of WWTPs. The primary focus to-date deals with addressing the environmental and/or operational impacts of such gases. However, with the expansion of focus on the circular economy and development of new products and technologies, new gas-related opportunities (but also challenges) are emerging. Whilst there has been a lot of research at the laboratory scale, there has been limited expansion to large scale implementation which does not always work effectively when scaled up. Hence, it should be noted that this is an evolving field with both great potential but also significant challenges.

Table 1 – Gas case studies/examples explored in this report.

GAS	Stage process	Technologies required	Applications	Postprocessing technologies	Case study
CH_4 (methane)	Sludge treatment	AD	Biogas	Gas scrubbing	2, 6, 7, 8, 9, 13, 14, 16
			Biofuel	Gas scrubbing and upgrade	9
			Electricity	Gas scrubbing	6,7, 9
H_2 (hydrogen)	Preliminary treatment	Gasifier	Syn gas in CHT*	Gas scrubbing	1, 14, 15, 16, 17, 18
CO (carbon monoxide)	Preliminary treatment	Gasifier	Syn gas in CHT	Gas scrubbing	1, 14, 16
CO_2 (carbon dioxide)	Sludge treatment	AD	Food industry	Gas upgrade, e.g. Pressure Swing Adsorption	9, 11, 14, 16
N_2 (nitrogen)	Sludge treatment	ANAMMOX**	Released to atmosphere	Nil	6, 12, 13
O_3 (ozone)	Generated onsite		Not included	Nil	Not included
H_2S (hydrogen sulphide)	Sludge treatment	AD	Sulphur (S_2)	Bio desulphurisation	6, 8, 9, 10, 12
SO_x (sulphur oxides)	Sludge treatment	AD	Not included	Nil	Not included
NO_x (nitrogen oxides)		AD	Not included	Nil	Not included
N_2O (nitrous oxide)	Primary and secondary treatment	ANAMMOX, Real time N_2O monitors	Converted to nitrogen (N_2)	Not included	2, 3
NH_4 (ammonia)	Primary and secondary treatment, treated sludge	ANAMMOX	Converted to N_2	Not included	Not included

**CHP – Combined Heat and Power*
***ANAMMOX – Anaerobic ammonia oxidation*

Preliminary Treatment

Preliminary treatment focuses on screening followed by settling to capture fine and un-screenable solids. In the next step pH is balanced for the following digestion stages. The main gases released in this stage are H_2S and CH_4, from microbiological activity of the raw sludge entering the WWTP. While there was no case study identified focusing on the extraction of H_2S and CH_4 in the preliminary treatment stage, a Crete WWTP, Greece, is developing gasification technology of solids separated upfront as described below. The system appears to be still under construction. It was due to be online by the end of 2019.

Case Study 1 – Crete WWTP, Greece

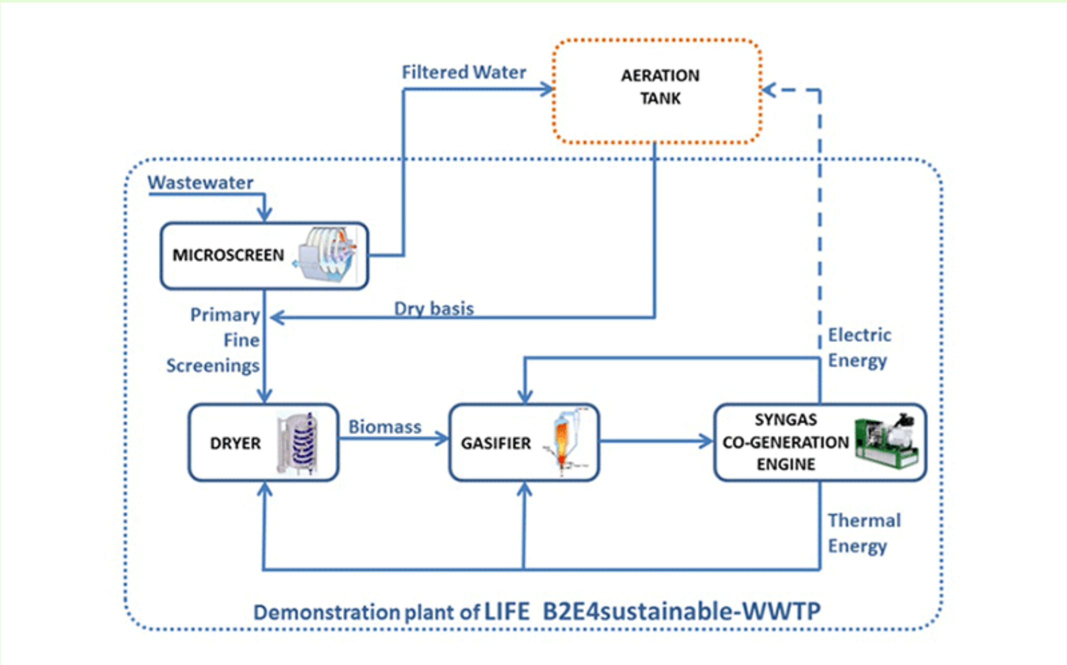
1	**Gasification of biosolids at the upfront stage of WWTPs**		
Gas in Focus	H_2, CO	**Established**	Planned for end 2019

This process removes solids upfront (before the aeration tank) and therefore reduces energy consumption due to omission of the primary clarification step and saving in the aeration. Electric energy is produced by gasification of the solids and makes the process self-sustainable. It addresses biosolids currently disposed to landfill in the demonstration case study of Crete WWTP, Greece. Removing solids upfront has a high reduction of footprint (up to 20 times compared to primary clarification) and results in an improvement in secondary treatment of wastewater due to lower concentration of Total Suspended Solids (TSS) and Biological Oxygen Demand (BOD).

Solids are removed with microscreen (fine mesh sieve) producing biosolids with solid content of 45%, which are dried (optimal moisture content is 15-20% - providing oxygen for the carbon/oxygen ratio) and fed to the gasifier producing syngas (CO, H_2 and small amounts of CH_4). Gasification can be a more efficient process from the energy yield point of view and utilisation of carbon compared to AD, as it uses almost all carbon in the sludge, compared to AD using only 50-60% of carbon, and the energy yield from the gasifier is 190% of the energy typically produced by the AD.

Gasification is preferable when biosolids content is high. While AD is more favourable with wetter biosolids (80% moisture). However, AD residues contain a relatively large fraction of organic matter that requires further treatment.

Circularity of the process *– efficiency of process carbon generation, efficiency of energy use in the process and use of energy generated in the process.*



Sources: http://www.biosolids2energy.eu/home.html; https://futurenviro.es/en/greene-builds-gasification-plant-at-elche-business-park-to-treat-sludge-at-crete-wwtp/

Primary and Secondary Treatment

In the primary and secondary treatment stages, the biosolids are separated from the water. Water is purified by microbial aerobic reaction before it is released to the environment. The gases generated in this stage are due to microbial activity, which is optimised for the operating conditions. Significant N_2O emissions emerge from this step.

N_2O, produced during the biological wastewater treatment process, is a potent greenhouse gas, 298 CO_{2eq} and emissions from N_2O accounting for 6.2% of global anthropogenic GHG emissions. Wastewater treatment sector is assumed to be responsible for 4-5% (N_2O) of the total anthropogenic emissions[7]. It is generated by nitrification and denitrification processes used to remove nitrogenous compounds from wastewater. Its production occurs mainly in the activated sludge units (90%), while the remaining 10% comes from the grit and sludge storage tanks. It predominantly occurs at low pH conditions and low dissolved oxygen concentrations and is mainly emitted in the aerobic tank. To minimise N_2O emissions, biological WWTPs should be operated at high solid retention times to maintain low ammonia and nitrate concentrations in the media. There have been a number of approaches studied to address N_2O formed in WWTP[8], namely:

1. Nitrogen treatment: 75-99% of N_2O is removed in the denitrification processes. Use of a bioscrubber (biofilter), or alternatively collected at the top of a nitrifying unit and then used as an oxidiser to burn methane produced in the anaerobic sludge digester.

2. Partial nitritation and Anammox (anaerobic ammonium oxidation) process to remove ammonia: In principle, Anammox bacteria are not directly involved in N_2O production. However, in a two stage partial nitritation-Anammox process, N_2O emissions occur as some of the ammonia-oxidising bacteria are carried over. If a one-reactor nitritation-Anammox system is used and operated at low dissolved oxygen concentrations, the emissions are reduced. This on the other hand favours oxidation of ammonia to nitrate instead of the desired conversion to N_2, which has led to two stage reactor configurations with control of limiting nitrite-oxidising bacteria.

3. CANDO process (Coupled Aerobic-anoxic Nitrous Decomposition Operation): In this nitrogen removal process, ammonia is converted to N_2O, which is then used to oxidise CH_4 over a metal oxide catalyst to recover energy, with the end product N_2. The innovation consists of utilising N_2O as a renewable energy source and reducing the requirement of organic matter which is consumed during denitrification. Combustion of CH_4 with N_2O releases about 30% more heat than oxidation with O_2.

There has been a substantial development in addressing operation conditions focusing on the nitrogen cycle, especially in conjunction with AD. The standout case study is VARGA in Denmark, shown below due to the holistic and sophisticated overall approach. The project also focuses on CH_4 and N_2 in addition to N_2O.

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[7] https://doi.org/10.1371/ journal.pone.0209763

[8] Campos, J.L., Valenzuela-Heredia, D., Pedrouso, A., Val del Rio, A., Belmonte, M. and Mosquera-Corral, A., Greenhouse Gases Emissions from Wastewater Treatment Plants: Minimization, Treatment, and Prevention, Journal of Chemistry, Volume 2016

Case Study 2 – Avedøre WWTP, Denmark

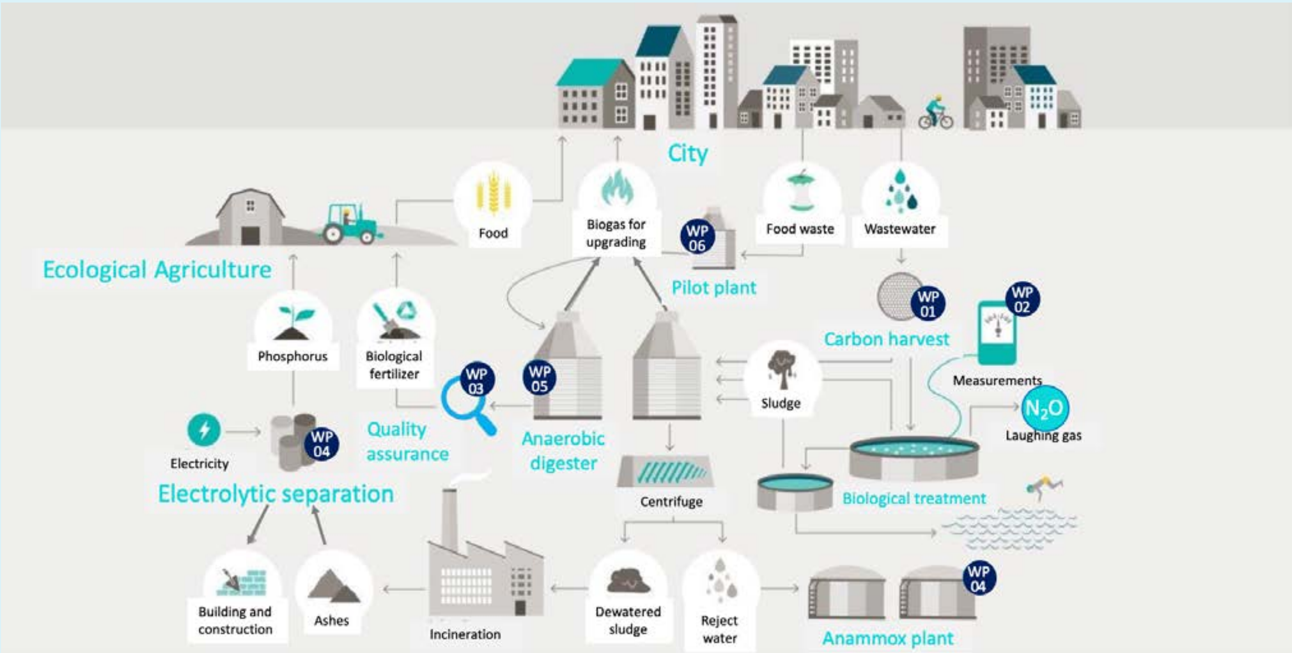
2	**Project VARGA Water Resource Recovery Facility (Avedøre WWTP)**				
Gas in focus	N_2O, CH_4, N_2	**Location**	Avedøre, Denmark	**Established**	To be completed by mid-2020
Financials	AU$18m (Danish EPA grant: AU$4m); market potential is estimated to be AU$1200m of which export of knowledge is estimated to be AU$144m.				

Input
- Wastewater
- Organic waste (agricultural, industrial or household)

Output
- Biogas to be deployed to natural gas network
- Fertiliser

Scale of Operation
- 400,000 Population Equivalent
- 6000m3 AD size

Technology
- Salsnes Filter System (separation, thickening and dewatering) – carbon harvest
- ANAMMOX (Anaerobic Ammonium Oxidation)
- AD
- Real time N_2O monitors (Unisense Environment sensor)
- Electrodialysis separation of phosphorous from ash



Scope – VARGA is a full-scale project that will demonstrate Danish expertise within water and environmental technologies in the wastewater sector. It addresses multiple issues at multiple stages. Better distribution of organic matter (carbon harvest) is achieved by fine filtration of raw wastewater and concentration of primary sludge. This increases biogas production (optimised energy and CO_2 balance) and reduces energy consumption for water purification. GHG effect from aeration processes is reduced with the control for minimization of N_2O emissions. Low oxygen levels and carbon depletion in the aeration tanks significantly increase the emissions of N_2O. The emissions are monitored in real time and real time footprint is calculated using a model. With data collection, the system can be optimised based on the environmental impact, by increasing carbon harvesting to digesters, minimising carbon loading for the biological nitrogen removal, better control of the biological nitrogen removal in relation to oxygen level and phase control, and better control of the side stream process for nitrogen removal (Anammox) minimising N_2O. The CH_4 emissions are also modelled in real time in the form of discharged unburned CH_4 from the digestors. Remaining discharge of CH_4 is not monitored online but is captured on the spot metering the total emission of GHG from the plant. In a traditional Danish WWTP, phosphorous is recovered from the ash produced in sludge incineration. In this project, phosphorous is recovered from wastewater and/or sludge in the Anammox plant and modular electrodialysis technique that can be scaled up. In a traditional WWTP nitrogen is removed and released to the atmosphere in N_2 form with no intent and application to recover nitrogen. The Anammox plant will be constructed providing a stable nitrogen removal without use of a carbon source, which will be further minimised, and the remaining carbon converted to energy in the digestor. The Anammox process is a prerequisite for increased carbon-harvest in the raw wastewater. To ensure complete nitrogen turnover to free nitrogen, the emission of N_2O needs to be monitored. Energy is optimised in the nitrogen removal in water from dewatering of digested sludge. More energy-saving or upgraded biogas are achieved by the addition of hydrogen resulting from the gasification of the added organic streams in the pre-treatment stage. Biogas production is increased by addition of source-sorted organic waste and the residual product is used in ecological farming. The added organic waste needs to be pre-treated to remove unwanted impurities and partially decomposed and mixed with water to ease pumping. Selection of the added household organic waste will depend on the fertiliser application, which will be tested to fulfil the requirement for the application and ecological farming. The project started in 2017 and its completion is expected by mid-2020.

2	Project VARGA Water Resource Recovery Facility (Avedøre WWTP)
Circularity	• Process efficiency, recovery and utilisation of by-products (gases, biosolids, phosphorous) • Knowledge transfer
Drivers	• Scarcity of resources, increased energy cost and increased environmental awareness • Transformation of a conventional WWTP (Avedøre WWTP) into a recycling plant
Environmental Impact	• Utilisation of nutrients in agriculture • Reduction of carbon footprint
Partners/Cooperation	• BIOFOS, MUDP, ARC, EnviDan, Unisense and DTU Environment • Subcontractors: SEGES, Krüger A / S and Vestforbrænding
Sources	https://projekt-varga.dk/en/front/

N_2O monitoring

Denmark has been emerging as a leader in the world in wastewater treatment technology development and application. Unisense Environment has developed the world's only N_2O wastewater sensor for direct measurement in wastewater treatment processes.

Case Study 3 – Unisense Environment N_2O Sensor, Denmark

3	Direct measurement of N_2O in wastewater treatment processes		
Gas in Focus	N_2O	**Established (sensor)**	2013

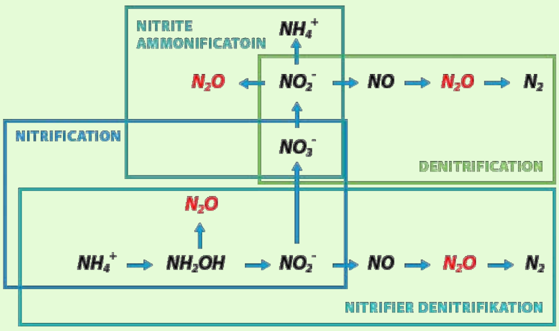
The N_2O Wastewater System from Unisense Environment enables real time and onsite quantification of dissolved N_2O and emission from wastewater treatment processes. New state of the art bioprocess and emission mitigation controls can be developed using N_2O sensor input yielding a clear environmental advantage over standard control regimes.

The N_2O Wastewater Sensor is placed directly in the activated sludge where it measures the production of N_2O during both nitrification and de-nitrification processes. The sensor's waterproof casing can either hang directly in the water which allows it to move freely with the current flow or it can be fixed in position. With its built-in temperature sensor, the N_2O Wastewater Sensor delivers post normalized data.

The sensors are placed in various sections of the Biological Nutrient Removal (BNR) depending on the design. Flow pattern needs to be taken into consideration (e.g. batch or continuous reactor setup), in the recirculation plant the sensor should be placed in the anoxic and aerated zone monitoring COD*/TN** ratio, which is also monitored by one sensor in sequence batch reactor setup.

Example application: Pforzheim WWTP, Germany.

Circularity of the process *– efficiency of process carbon and nitrogen generation, GHG control*



Sources: https://www.unisense-environment.com; https://www.unisense-environment.com/files/PDF/Application_Report_Pforzheim_%202015_eng.pdf

**COD – amount of oxygen required to chemically oxidise organic matter in wastewater into inorganic matter.*
***TN – Total Nitrogen*

Sludge Treatment

Historically the main focus of sludge treatment has been conditioning biosolids for disposal. However, as the potential of energy generation has been identified through AD, sludge treatment operating conditions and equipment have been modified to aid extraction of energy and nutrients. A range of gases are generated in the process which should be addressed. In this section, the case studies are used to highlight the approaches taken to maximise energy generation, cleaning, application of biogas generated and application of treated sludge from the AD. Alternative technologies to AD are also explored.

Maximising energy generation in AD

WWTPs require significant energy for operation and many have attempted to generate biogas onsite using AD. Their aim is to become energy neutral and to reduce their carbon footprint. When WWTPs generate excess energy, they start to emerge as hubs for circular economy approaches, with the potential of supplying energy to adjacent precincts. However, often this cannot be achieved by digestion of biosolids from the wastewater alone. Additional organic streams, such as food waste, and fats oils and grease (FOG) are required together with collaboration with managers of such waste streams in the precinct and the potential end users of products generated by the WWTP. Energy efficiency can also be achieved by optimising the operating conditions, as demonstrated by Ejby Mølle WWTP in Denmark, which managed to achieve 110% of the WWTP energy required. Similar approaches can be found in a number of examples around the world.

Case Study 4 – Ejby Mølle WWTP, Denmark

4	**Ejby Mølle WWTP, Denmark – Circular Economy approach by optimising operating conditions**		
Gas in Focus	CH_4	**Established**	2011
Ejby Mølle WWTP increased energy production to become self-sufficient with the excess energy. This has been achieved by optimising operating conditions, without major capital investment, through process energy reduction and increased energy process production. The focus extended to enhance nutrient reuse and maximise biogas extraction for additional heat and electricity production. The plant is often used as an example of the circular economy approach. ***Circularity of the process*** *– energy efficiency of the process, nutrient harvest and reuse.*			
Source: https://stateofgreen.com/en/partners/vcs-denmark/solutions/efficient-wastewater-treatment-at-ejby-molle-in-odense/			

Significant energy savings can be also found by installation of heat pumps at WWTP. Katri Vala in Helsinki, Finland, is a sophisticated state of the art application and is illustrated in the example below.

Case Study 5 – Katri Vala WWTP, Helsinki, Finland

5	**Katri Vala Heat Pump – the largest heat pump in the world to produce heating and cooling**		
Gas in Focus	heat	**Established**	2006
The heat pump, located 25 m underground in an excavated rock cave, recycles waste heat from purified wastewater, as well as excess heat from buildings such as data centres. Location of the heat pump is with the outflow of purified wastewater and multi-utility tunnel, transmitting heat and cooling energy to the customers. The plant utilises heat that would be otherwise unused. In 2017 the plant produced 90% of city cooling and 8% of heating requirements. An expansion is planned for 2021, which will cost AU$32m and increase production volume by up to 30%. ***Circularity of the process*** *– collaboration and use of data centres heat in the precinct, supplying heating and cooling to precinct*			
Source: https://www.helen.fi/en/company/energy/energy-production/power-plants/katri-vala-heating-and-cooling-plant			

Energy generation at WWTPs can be increased through AD efficiency. The advanced anaerobic digestion approach taken by WWTPs around the world is in the pre-treatment of the sludge and/or in co-digestion.

The pre-treatment of the sludge can be:

- mechanical, which breaks the cell structure,
- thermal, by destroying cell walls and releasing proteins, achieved at operation at 60-200^{0}C and 10 bar and
- biochemical and chemical treatments.

The common technologies of thermal hydrolysis (THP) used at WWTPs are Cambi, Biothelys and Exelys, which also feature in the case studies through this report. The THP enhancement have been reporting up to 50% higher biogas production at a shorter retention time (12-15 days).

A range of organic feedstocks can be co-digested with the wastewater. However, while the main purpose is to increase biogas yield, the feedstock normally needs pre-treatment before it is combined in the AD and the following properties of different sources need to be considered:

- food waste and dairy products are feedstocks with high fertilizing values (phosphorous, nitrogen, organic matter),
- grease trap wastes (have a low fertilising value but significant biogas yield potential),
- feedstock containing inhibitors (e.g. high NH_4, H_2S, heavy metals, disinfectants, antibiotics) need to be limited,
- feedstock containing impurities, such as plastics, stones, metal, glass, need physical pre-treatment, and

- fibre rich solid feedstock, such as garden waste, which can have high lignin content and low biogas potential, is not appropriate

Basingstoke WWTP is highlighted below as a WWTP illustrating the application of THP to achieve energy neutral operation, with excess supplied to the electrical grid.

Case Study 6 – Basingstoke WWTP, UK

<table>
<tr><td>6</td><td colspan="5">Basingstoke Sewage Treatment Works – Operating entirely on energy from sludge</td></tr>
<tr><td>Gas in focus</td><td>Biogas (CH_4/CO_2), N_2, N_2O</td><td>Location</td><td>Basingstoke, UK</td><td>Established</td><td>2017/18</td></tr>
<tr><td>Financials</td><td colspan="5">AU$100m upgrade trebled energy generation capacity</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">Input
• 53 t Dissolved Solids (DS)/day (capacity 70 tDS/day)
• Mixed sludge 60:40 primary and secondary sludge to AD</td><td colspan="3">Output
• Electric power generation (62 MWh electricity/day) and CHP, excess (50%) is exported to local grid
• Biosolids land application</td></tr>
<tr><td colspan="3">Scale of Operation
• Effluent stream sized for 135,000 population equivalent
• Sludge stream and digestion plant sized for over 500,000 population equivalent (treating sludge from different location either as liquid or cake)
• Digester capacity 9,000 m^3</td><td colspan="3">Technology
• MAD (anaerobic, mesophilic)
• Thermal Hydrolysis Plant (THP) – CambiTHPR – B6
• Dual fuel boiler (biogas or diesel)
• Anammox process</td></tr>
<tr><td colspan="6">Scope – The process is built to accommodate brown-field sludge system allowing treatment of sludge as liquid or cake. THP is the core technology, followed by mesophilic AD and dewatering. Thermal pre-treatment of sludge enhances biogas yield and produces high quality biosolids after dewatering. Dewatering liquors pass through Anammox process, autotrophic method for N-removal. NH_4^+ is directly converted to N_2 under anaerobic conditions. The advantage of this process is that there is no need for an external carbon source and therefore produces less CO_2 emissions. In addition, it uses less energy, produces more CH_4 and a lower amount of sludge compared to conventional denitrification systems. N_2O, an intermediate in denitrifying bacteria is absent in the Anammox bacteria, making N_2O absent from the process.</td></tr>
<tr><td colspan="2">Circularity</td><td colspan="4">• Reduced GHG emissions, production of energy</td></tr>
<tr><td colspan="2">Drivers</td><td colspan="4">• Reduced cost of energy (AU$56m/y)</td></tr>
<tr><td colspan="2">Environmental Impact</td><td colspan="4">• Energy generated from sludge, solar and wind covers a quarter of Thames Water's energy needs and has reduced GHG emissions by 66 per cent since 2015.</td></tr>
<tr><td colspan="2">Partners/Cooperation</td><td colspan="4">• Thames Water</td></tr>
<tr><td colspan="2">Sources</td><td colspan="4">https://wwtonline.co.uk/news/basingstoke-stw-operating-entirely-on-energy-from-sludge
https://www.cambi.com/references/plants/europe/united-kingdom/basingstoke/</td></tr>
</table>

Psyttalia WWTP has been selected as case study demonstrating the energy efficiency achieved on a large scale in addition to removal of sulphur and nitrogen. Further energy is extracted from digested sludge incineration.

Case Study 7 – Psyttalia WWTP, Greece

7	**Psyttalia WWTP – Serving Athens**				
Gas in focus	Biogas (CH_4/CO_2)	**Location**	Athens, Greece	**Established**	2008
Financials	Not publicly available				

Input

- Urban wastewater
- Secondary sludge to AD

Output

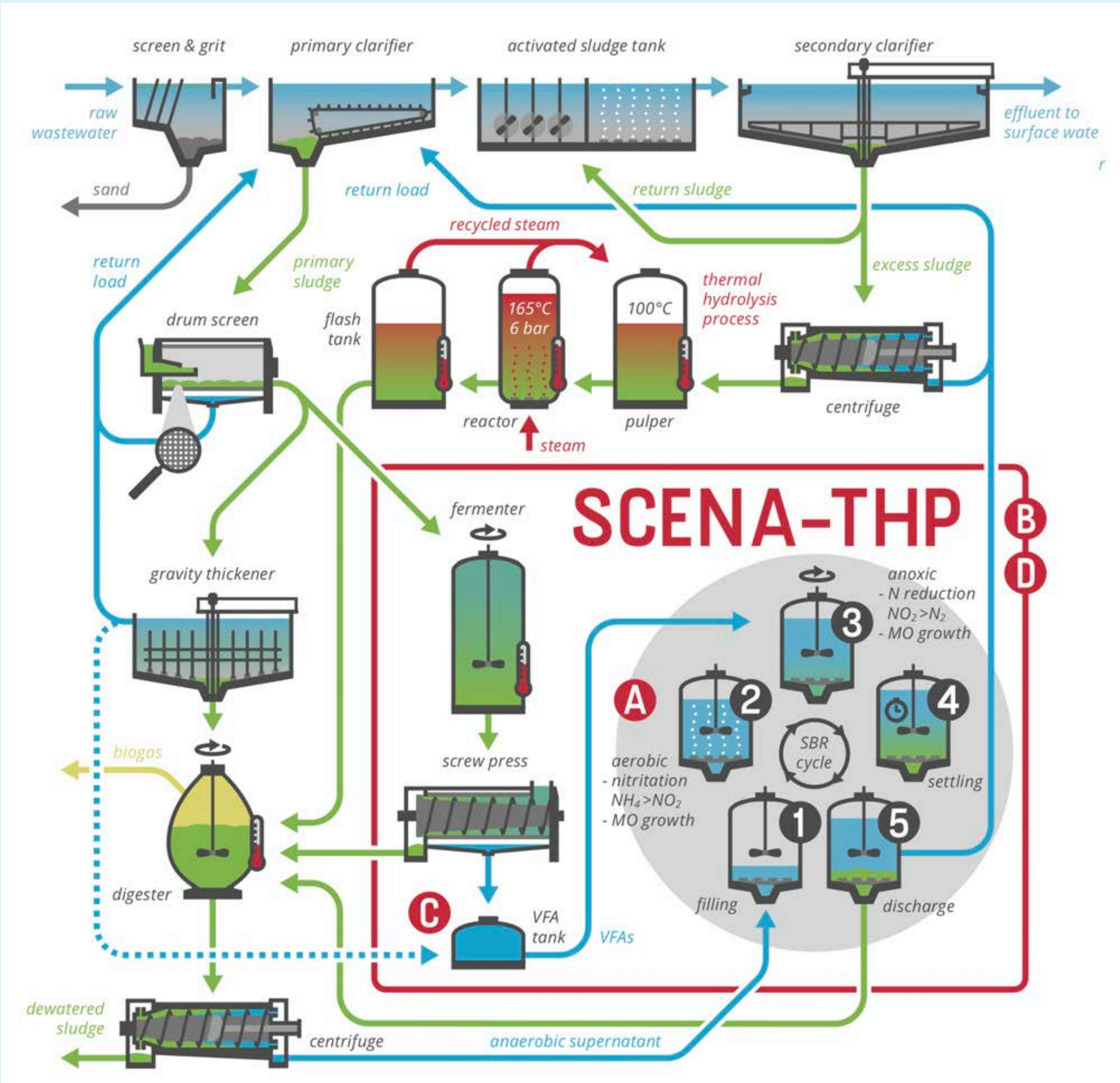
- 61-65% CH_4, 34-38% CO_2 as fuel to CHP plants
- Dry sludge (92%) – secondary fuel in cement factories and power stations (incineration)

Scale of Operation

- WW flow – 730,000 m^3/d, 5,600,000 population equivalent
- Serving 3.5 million people
- Energy capacity: 5.04MW

Technology

- AD (anaerobic, mesophilic, high-rate)
- Thermal Hydrolysis Plant (THP) – Modular CambiTHP® B6-4 system
- SCENA-THP (Energy efficient nitrogen removal)
- Sulfurex®BF and Sulfurex®CR



7	**Psyttalia WWTP – Serving Athens**
Scope – THP was installed to increase energy production, treating 50% of generated waste activated sludge with thermal hydrolysis and steam explosion before it is anaerobically digested. The thickened primary sludge stream bypasses THP and is mixed with the hydrolysed waste activated sludge before entering AD. The process is separate from the conventionally treated remaining sludge. Overall, the process reports increased dewaterability of mixed digested sludge (from 22% to 31% dry solids; increased volatile solids reduction from 45% to 52%) and increased biogas generation (15.4% increase) and digester efficiency (increased solids destruction). THP process however increases loading of nitrogen and phosphorus of the digested sludge, which is currently addressed with a pilot scale SCENA process ($2m^3$/d). The SCENA process is implemented to remove nitrogen (>80%TN and >90%NH_4-N) and phosphorus from sludge liquors with low energy demand and using an internal carbon source (supernatant from primary sludge thickening or volatile fatty acids (VFA) from fermentation of sludge). Produced biogas is used to fuel two CHP plants (11.4 MWe) and a 12.9 MWe Psyttalia WWTP CHP plant supporting the operation of a sludge thermal drying unit. In addition to drying, the produced biogas provides heat that is needed for sludge digestion and WWTP electric power needs. The surplus power is sold to the National Grid Manager. Biogas is scrubbed from H_2S using a bio-trickling filter, a biological process where H_2S is absorbed in an aqueous solution with a low pH and biologically oxidised to sulphur/sulphate in situ, and with caustic re-use, with a chemical scrubber adsorbing H_2S into liquid with a high pH. H_2S concentration in biogas is reduced from 2000 ppm to less than 70 ppm.	
Circularity	• Energy efficiency, process energy production and use, application of the sludge in the precinct
Drivers	• Improve energy footprint of the WWTP
Environmental Impact	• Sludge storage areas covered with green areas • Protection, revival and enhancement of biodiversity in the Saronic Gulf ecosystem. • Biggest environmental project in Greece (biosolids utilisation, biogas utilisation, reuse of treated effluent)
Partners/Cooperation	• Plant operator Actor, SMART-Plant, DMT Clear Gas Solutions
Sources	https://www.eydap.gr/userfiles/c3c4382d-a658-4d79-b9e2-ecff7ddd9b76/Fact-sheet-PWWTP.pdf

Both, Basingstoke and Psyttalia wastewater treatment plants, produce biogas that is fed into the CHP system and with excess electricity fed into the electricity grid.

There are many more examples of WWTPs around the world that use the THP technology and have successfully achieved energy neutral operation. For example, the Beijing Drainage Group, in Gaobeidian Water Reclamation Plant (with 12 THP units)[9], Huaifang Water Reclamation Plant (2018 IWA Gold Award winner for the largest underground advanced WWTP in Asia)[10] and Tuas Water Reclamation Plant in Singapore[11].

They differ in the application of produced biogas and consequently in the approach of biogas postprocessing and cleaning. This is addressed separately in the following section of this report. In addition, there is a substantial diversity in the approach of treating the digested sludge, which is also discussed further in the report.

Biogas application and cleaning

The most common applications of biogas generated at WWTP are:

- biogas combustion with cogeneration of electrical and thermal energy,
- biogas combustion with generation of electricity only,
- biomethane to be injected into the national grid, and
- biomethane to be used in transport (with compression and storage systems)

[9] https://www.cambi.com/references/plants/asia/china/beijing-gaobeidian/
[10] https://www.cambi.com/references/plants/asia/china/beijing-huaifang/
[11] https://www.pub.gov.sg/dtss/phase2/twrp

Kiselev *et. al.* (2019)[12] compared the application of biogas generated in AD of wastewater sludge at Ekaterinburg WWTP, Russia, using a computational model and circular economy principles and concluded that all options listed above are environmentally favourable. However, where there is an opportunity for the immediate application of the heat generated (e.g. in the plant), then the combustion with cogeneration of electrical and thermal energy becomes the most favourable, which was also the case in the Ekaterinburg WWTP. An additional benefit to consider is the widespread use of the CHP technology. One of the main barriers to the application of biomethane in transport is the availability of the refuelling infrastructure, limiting its application to only corporate transport. Upgrading vehicles to use biomethane, requires special safety equipment due to higher gas pressure compared to propane gas, making the cost of equipment more expensive. In addition, due to the low petrol price the cost reduction becomes insignificant.

Biogas generated in AD in WWTPs is usually composed of CH_4 (55-75%) and CO_2 (25-45%), with impurities such as H_2O, H_2S and siloxanes which need to be removed. H_2S oxidises to SO_2 during the combustion process, forming H_2SO_4 when dissolved in water droplets and damaging the prime mover exhaust system, heat exchanger and stack liners.

Siloxanes are also necessary to remove as they form a glass-like deposit that is harmful to reciprocating engines, gas turbines, microturbines and fuel cells. Siloxanes, organic silicon compounds, present as additives in soaps, shampoos, sunscreens, lotions, hair spray, deodorants and shaving products, pass through the WWTP processes and accumulate in sludge and volatise to form a contaminant in AD biogas. The deposits decrease CHP project efficiency, increase heat rate, reduce power output, form hotspots and cause equipment failure.

Technologies commonly applied to remove siloxanes are adsorption (with activated carbon, polymer beads, silica gel), absorption (physical with water, organic solvent or mineral oil and chemical with strong acids), cryogenic condensation (when the temperature of biogas is decreased, a condensate is formed containing siloxanes), catalytic process (alumina, silica), biological removal and membrane separation[13].

Downers Grove case study below demonstrates how the WWTP was retrofited to accommodate a grease trap FOG stream for co-digestion and the cleaning steps removing H_2S (with traditional iron sponge adsorption) and siloxanes (on activated carbon).

[12] Kiselev, A., Magaril, E., Magaril, R., Panepinto, D., Ravina, M. and Zanetti, M.C., (2019) Towards Circular Economy: Evaluation of Sewage Sludge Biogas Solutions, Resources, 8, 91.
[13] Ruling, G. Shikun, C. and Zifu, L. (2017) Research progress of siloxane removal from biogas, Int J Agric & Biol Eng Vol.10, No. 1.

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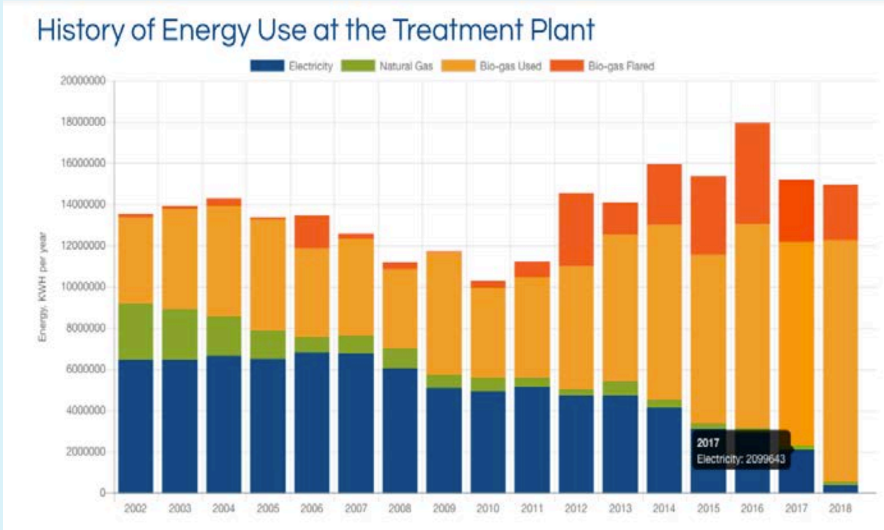
Case Study 8 – Downers Grove WWTP, Illinois, USA

8	**Energy Neutral Downers Grove Sanitary District – Addressing siloxanes**		
Gas in focus	Biogas (CH_4/CO_2), H_2S, Siloxanes	**Established**	2014, 2017 (upgrade)
Location	Downers Grove, Illinois, USA	**Financials**	AU$5.8m



Input

- Urban wastewater (households, industries, institutions, commercial facilities)
- FOG (restaurant grease traps waste)

Output

- CHP (Electric: 655 kW, Thermal: 3,183 kBTU/h)

Scale of Operation

- 60,000 population equivalents

Technology

- 5 AD
- Engine driven generators for heat recovery (280 kW and 375 kW) and gas conditioning system.
- Activated carbon filter for siloxane removal
- Iron sponge reactor for H_2S removal

Scope – The energy efficiency of the operations was increased to reduce cost and environmental impact with the goal to reach site net zero energy consumption. Installation of a turbo blower controlled by measurement of dissolved oxygen (50-75% of facility energy is used for aeration), a sludge biogas cleaning system, biothermal heat pumps and efficient lighting reduced consumption by over 50%.
The CHP system uses internal combustion engines attached to generators to produce heat and electricity. The heat is captured via a hot water system reducing reliance on digester system boilers. The sludge/water heat exchangers were outfitted to preferentially use hot water from the engine before utilizing the old hot water boilers. The gas is conditioned and siloxane filter system using activated carbon removes siloxanes, while an iron sponge reactor tank is used to remove hydrogen sulphide. After conditioning the biogas is ready for injection into the engine CHP. Biosolids are used as a soil amendment.
Batch transfer of sludge between the primary and secondary digesters is affecting variability in biogas production and methane concentration.
A grease receiving station needed upgrades to deal with the problems inherent with grease receiving and handling.

Circularity	• Energy neutral, utilisation of FOG, partnership in the district
Drivers	• Utilising digester gas • Easy to retrofit existing sludge heating system to accommodate new CHP system • Energy savings • Supplementing digester heating with waste heat • Ability to receive high strength waste from haulers
Environmental Impact	• Net zero energy consumption
Partners/Cooperation	• ComEd Energy Efficiency Program, US DOE Midwest CHP Technical Assistance Partnership, energySMART, Nicor Gas Program.
Sources	http://www.chptap.org/Data/projects/DownersGrove-Project_Profile.pdf

Depending on the application of biogas, different levels of biogas “cleanliness” are required. Below, the three most common applications of biogas are compared, at three different WWTPs. The scrubbing process and technologies used are also listed. H_2S normally present in concentrations of 2000-5000 ppm needs to be reduced to below 100 ppm and for vehicle fuel below 5 ppm[14].

Case Study 9 – La Farfana WWTP (Chile), Trebal-Mapocho WWTP (Chile) and Hendriksdal WWTP, Sweden

9	**Treatment of biogas for the three most common applications**	
Use in the city gas (biomethane)	In cogeneration – CHP (biopower)	For transport (biofuel)
Wash tower: scrubber and biological reactor (95% removal of H_2S)	H_2S removal (biological and chemical washing) – 50 ppm	Biogas precooling
Cooling (exceeding water elimination by condensation)	Condensed water elimination	Biogas compression (8 bar)
Compressing to 14 bar (CO_2 is removed through membranes)	Volatile organic compounds and siloxane removal through activated carbon filters	Biogas cooling, removal of H_2S, VOC and Siloxanes
CH_4 concentration increases from 63% to 96%		Methane enrichment in (Pressure swing adsorption) PSA
Source: WWTP La Farfana, Santiago de Chile (recipient of United Nations award, aiming to achieve zero waste, zero environmental impact and zero consumption of fossil energy) *https://www.suezwaterhandbook.com/case-studies/wastewater-treatment/La-Farfana-wastewater-treatment-plant-Chile*	*Source: WWTP Trebal-Mapocho, Santiago de Chile* *https://www.suezwaterhandbook.com/case-studies/sludge-treatment/El-Trebal-Mapocho-wastewater-treatment-plant-Chile*	*Source: Biogas upgrading at Hendriksdal WWTP (underground WWTP)* *https://bioenergyinternational.com/biogas/swedens-largest-biomethane-producer*

While sulphur is predominantly removed via H_2S, due to its corrosive and adverse health features, it is normally lost through waste. However, it is possible to capture sulphur in its elemental form and use it as a fertilizer as demonstrated in Case Study 10.

CO_2 removal from biogas technologies are normally based on absorption, where CO_2 is transferred into certain fluids, adsorption, where CO_2 is transferred through solid material, or separation by membranes[14]. In the Case Study 11 is illustrates one of the most widely applied processes for CO_2 removal from biogas.

[14] IRENA (2018), Biogas for road vehicles: Technology brief, International Renewable Energy Agency, Abu Dhabi.

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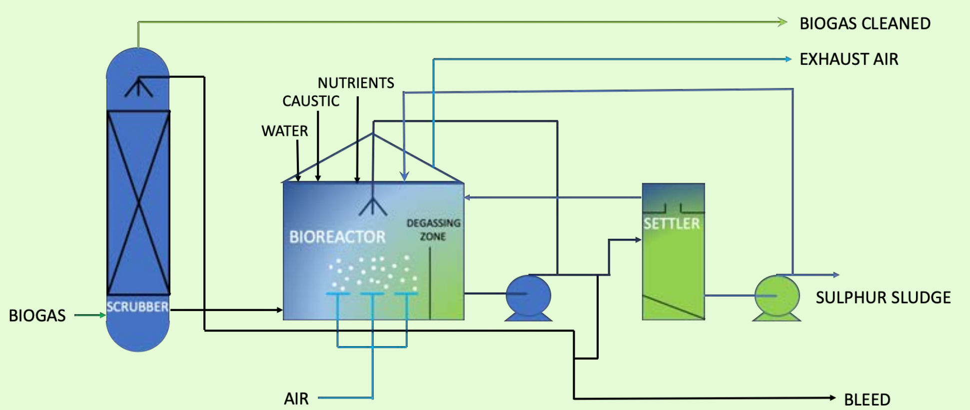
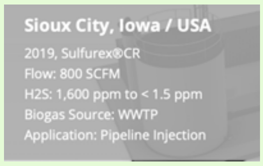
Case Study 10 – Sioux City WWTP (Iowa, USA) and Cactus WWTP (Texas, USA)

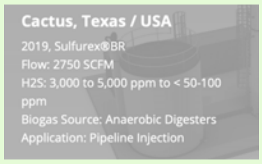
10	**H_2S convertion into elemental sulphur – Desulphurisation process (Sulfurex® BR)**		
Gas in Focus	heat	**Established**	2006

Combined chemical desulphurisation at medium to high pH with biological regeneration of the solvent (caustic). The system consists of a packed column, biological reactor and settler. The biogas enters the scrubber at the bottom of the packed column and flows upwards. A caustic solution is distributed on top of the column in a counter-current direction of the gas. The biogas leaves the column free of H_2S at the top. The saturated process liquid, collected at the bottom of the scrubber, is biologically oxidised into elemental sulphur by Thiobacillus bacteria in the bioreactor. The bioreactor is supplied with oxygen by an aeration system. During oxidation, the caustic solution is regenerated before being reused for another washing step in the scrubber. Under optimal conditions, 98% of the H_2S is converted into S_2 collected in the settler and used as a high-quality fertilizer.

Circularity of the process – *utilisation of wasted sulphur*







Sources: https://www.dmt-cgs.com

Case Study 11 – Carbotech biogas upgrade technology, Essen, Germany

11	**CO_2 removal from biogas – Carbotech process**		
Gas in Focus	CH_4	**Established**	2006

Carbotech uses pressure swing adsorption (PSA) process for biogas upgrade. The biogas is compressed, catalytically cleaned H_2S and other trace gases using activated carbon and cooled to remove as much water as possible. The biogas is then passed through an adsorber filled with carbon molecular sieve, where CO_2 and other contaminants (H_2O, remnant H_2S, siloxanes, NH_3, odorants and fractions of N_2, O_2, etc.) are removed from the gas prior to the production of biomethane.

In order to make the process continuous, production is switched to a second adsorber after a predetermined interval, allowing the first adsorber to be fully vacuum regenerated. Programmable logic control (PLC) and on-line gas analysis make plant operation automatic, safe and reliable.

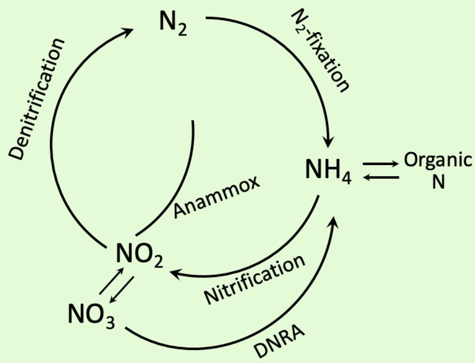
Circularity of the process – *allows biogas to be used instead of natural gas*

Sources: http://www.carbotech.info/en/Products/gasupgrading.html

Applications and treatment of the digested sludge

While digested sludge is commonly de-watered, dried and conditioned for land application, nitrogen (usually present as ammonium) is commonly removed and released to the atmosphere from the process water in the form of N_2 through the nitrification/denitrification process. Alternatively, digested sludge is incinerated and phosphorous and metals are recovered from the ashes. In the Case Study 12 the ANAMMOX process discovered by Delft University of Technology in The Netherlands is explained.

Case Study 12 – ANAMMOX, Delft University of Technology, The Netherlands

12	**Anammox Process – minimising formation of N_2O**		
Gas in Focus	NH_4	**Established**	1995
The aim of the Anammox process is removal of ammonium in wastewater treatment, consisting of nitrification step by ammonia oxidising bacteria, which converts some of the ammonium (NH_4) to nitrite (NO_2), which are both converted to nitrogen gas (N_2) by anammox bacteria. Both processes take place in one reactor (sequencing batch reactor, moving bed reactor or gas-lift-loop reactor). The process was developed by Delft University of Technology and the concept is patent as ANITA Mox Anammox (Veolia), ANAMMOX (Paques, Netherlands), NAS (Colsen, Netherlands) and EssDe (Switzerland) ***Circularity of the process*** – *reduction of N_2O GHG emissions*			
			
Sources: http://www.veoliawatertech.com/news-resources/datasheets/45999.htm https://en.paques.nl/products/featured/anammox https://www.colsen.nl/en/services/nitrogen-removal https://www.essde.com/deammonification			

The focus of capturing phosphorous and nitrogen from the sludge to manufacture fertilisers impacts the generation of gases. The whole process needs to be modified. Below, Ostara technology, Netherlands, is highlighted as an example of such an approach. Sludge that is fed to the AD system needs to be further pre-treated, in addition to thermal or co-digestion set-up.

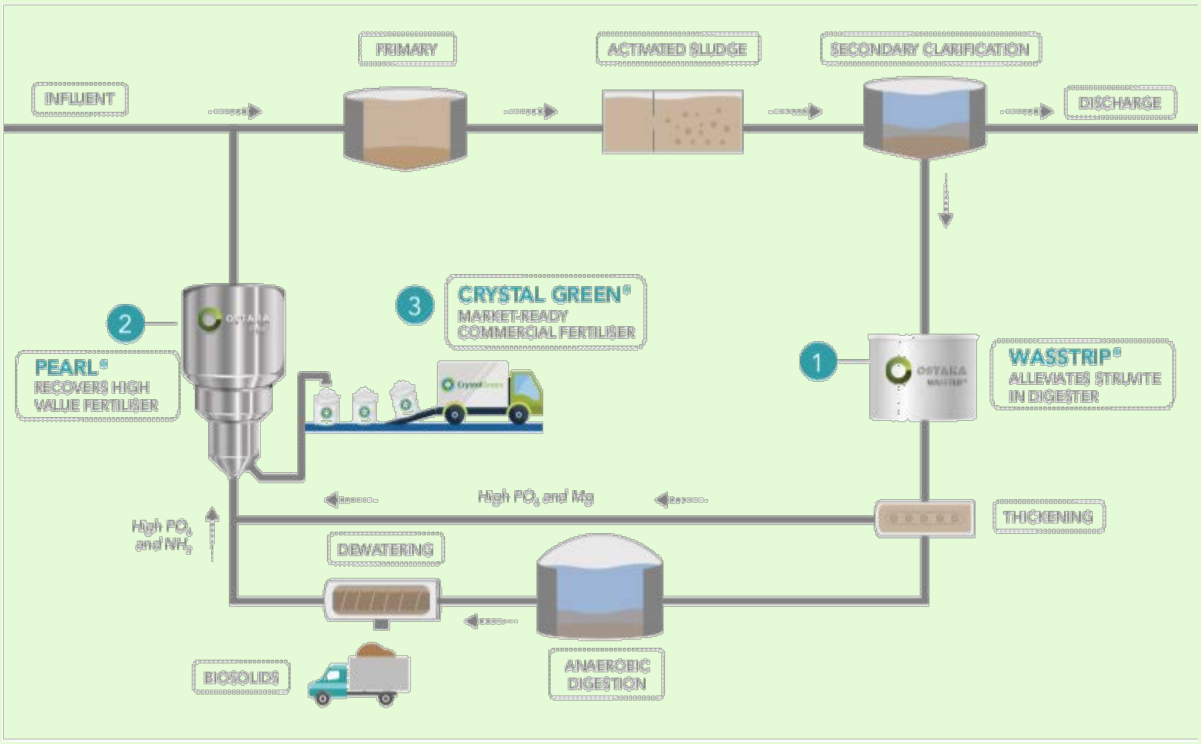
Case Study 13 – Ostara Technology, The Netherlands

13	**Ostara Nutrient Recovery Technologies**		
Gas in Focus	H_2, CO	**Established**	Planned for end 2019

In this process phosphorous and nitrogen are recovered and operational and maintenance costs are avoided due to struvite precipitation. WASSTRIP releases phosphate (with magnesium and potassium) from waste activated sludge (under anaerobic conditions and in the presence of volatile fatty acids) and diverts it through a thickening process from the AD (reducing digester struvite by 90%), where ammonia is formed creating conditions for struvite precipitation. This also reduces sludge production and reverses the negative impact that enhanced biological phosphorus has on dewaterability. The PEARL process recovers phosphorus and ammonia, with the addition of magnesium in a controlled pH setting, from the sludge dewatering liquor and waste activated sludge thickening liquors by growing high purity crystalline granules of struvite under controlled fluidised bed reaction conditions. Phosphorus, nitrogen and magnesium are combined into fertiliser, which Ostara as a part of business model buys off the WWTP. The process recovers 50% of total plant influent phosphorus that would accumulate as struvite in the process equipment.

Example application: Amersfoort WWTP, NL

Circularity of the process *– utilisation of process by-products, more efficient, environmentally friendly process*



Source: https://ostara.com

Alternative technologies to AD

Alternative, and complimentary, technologies to AD have been proposed with the focus towards zero sludge disposal and efficient extraction of valuable resources of water, energy and nutrients from the sludge.

Only 35-45% of energy contained in raw wastewater is converted to CH_4 during AD of primary and secondary sludge, the remaining is wasted under aerobic conditions due to conventional nitrification and denitrification processes to remove nitrogen and organic matter simultaneously. Instead, an autotrophic process can be applied to remove nitrogen, e.g. partial nitrification with the Anammox process (illustrated in Case Study 12), or use of microalgae, to facilitate separated removal of nitrogen compounds and organic matter. This way, oxygen requirements are minimised and CH_4 production is maximised[15].

Microalgae can be used as a biogas purification or for post-combustion CO_2 capture, which is then used as biofertilizer. Microalgae can also be used to remove nitrogen, addressing aeration requirements and therefore assuming lower N_2O production. However, the requirements of large ponds, has a limiting application. In addition, microalgae have poor settling properties and require use of coagulants and flocculants for separation from treated wastewater.

The concept of use of microalgae was widely pursued reaching WWTP full scale demonstration application almost 10 years ago[16], but due to the decline in the price of petroleum, coupled with on-going low prices for natural gas and the absence of consistent policies on carbon pricing, it has caused a significant challenge for the technology to develop. In the review by IEA Bioenergy[17], it can be seen that many projects, pilots and companies have shut operations. Nevertheless, potential algae technology applications still exist, especially from the carbon capturing perspective.

An example of conversion of sewage sludge into crude - biofuel (renewable diesel, aviation fuel) has been installed in Southern Oil's Northern Oil Advance Biofuels Pilot Plant in Yarwun outside Gladstone, QLD.[18] Other technologies producing biocrude in Australia are Muradel (converting marine microalgae to biofuel)[19] and Licella converting of inedible plant material (biomass) into bio-crude oil with similar characteristics to traditional fossil crude in a Cat-HTR process.[20] While none of these technologies is currently applied to WWTP, they could be explored in the WWTP context, especially in combination with the use of microalgae to treat waste waters.

An alternative technology to AD is gasification. In the Case Study 14 an example of gasification technology that could be applied to WWTP is highlighted. While the supercritical pilot scale water gasification has been applied to biomass with high water content to produce syngas rich in H_2 and CH_4 with high calorific value, it is yet to be demonstrated on a pilot or industrial scale to WWTPs.

[15] Campos, J.L., Valenzuela-Heredia, D., Pedrouso, A., Val del Rio, A., Belmonte, M. and Mosquera-Corral, A., Greenhouse Gases Emissions from Wastewater Treatment Plants: Minimization, Treatment, and Prevention, Journal of Chemistry, Volume 2016.
[16] Craggs, R.J., Sutherland, D. and Campbell, H., National Institute of Water and Atmospheric Research, World-first wastewater algal bio-crude oil demonstration.
[17] IEA Bioenergy (2017), State of Technology Review – Algae Bioenergy.
[18] https://arena.gov.au/blog/sewage-sludge-to-jet-fuel/
[19] https://arena.gov.au/projects/advancing-marine-microalgae-biofuel-to-commercialisation/
[20] https://www.licella.com.au

Case Study 14 – Super Critical Water Gasification

14	**Super Critical Water Gasification (SCWG)**		
Gas in Focus	H_2, CO, CH_4 and CO_2	**Established**	
The SCWG process consists of gasifying biomass waste in aqueous medium under supercritical conditions (22.1MPa, $374^{O}C$), allowing transformation of wet biomass in high calorific syngas (H_2, CO, CH_4 and CO_2) and intermediate organic salts that can be recovered through a selective precipitation process. The process is applicable to all kinds of sewage sludge, (primary, secondary or mixed), also including digestates and every composition, local condition, circumstance or contaminant. The process allows 30-40% reduction of energy consumption of WWTP. The system can be configured to produce either renewable natural gas (ready for direct natural grid injection, available from the process at high pressure, clean and purified) or renewable power generated through microturbines. ***Circularity of the process*** *– This process will provide savings in energy by omission of dewatering of the sludge step, lower generation of the by-products and providing replacement to use of the natural gas.*			
			
Source: https://cadeengineering.com/proprietary-technologies/zerosd/			

Focus on Hydrogen

Hydrogen is gaining traction in Australia as an alternative fuel and a national hydrogen strategy[21] has just been released. The strategy ambitiously presents Australia as a one of the future significant suppliers of hydrogen in the world[16]. The strategy highlights the identified demand on the international scale, specifically in South Korea and Japan. The application of hydrogen is seen in transport, gas networks and for remote power supply in addition to industrial applications. Germany launched the world's first H_2 powered trains[22] and California is building a hydrogen-fuel-cell ferry to serve the San Francisco Bay Area[23]. ARENA has just recently funded two projects for WWTPs with a focus on H_2 production, illustrated in Case Studies 15 and 16.

In addition, there has been some interesting research on a pilot plant scale attempting to generate H_2 from AD instead of CH_4 and is highlighted in the Case Study 17. A Swedish research group just recently published a review paper demonstrating the concept of production of H_2 and volatile fatty acid instead of CH_4[24], indicating that this is potentially a feasible and interesting area worthwhile to perusing in an the attempt to reduce the carbon footprint and supply H_2 for the future predicted demand. The Royal Society, United Kingdom, also identified the microbial process technology as advantageous in H_2 production due to lower operating temperatures, simple technological basis and the ability to be used with a wide range of wet and dry biomass types, such as straw and sewage.[25] Hydrogen is produced by selective inhibition by changing the conditions, such as pH and temperature to prevent the conversion of H_2 to CH_4.

On the laboratory scale, a Princeton group, in the USA, has been studying the formation of H_2 in wastewater in a hydrogen biofuel cell. While these experiments are under negotiation to scale up the process, they offer tremendous potential of a neat production of H_2 while also reducing carbon footprint. The study is demonstrated in the Case Study 18.

[21] https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf
[22] https://www.alstom.com/our-solutions/rolling-stock/coradia-ilint-worlds-1st-hydrogen-powered-train
[23] https://watergoround.com
[24] Wainaina, S., Lukitawesa, Awasthi, M.K., and Taherzadeh, M.J., (2019), Bioengineering of anaerobic digestion for volatile fatty acids, hydrogen or methane production: A critical review, Bioengineered, *Vol. 10*, pp. 437-458.
[25] The Royal Society (2018), Options for producing low-carbon hydrogen at scale.

Case Study 15 – Loganholme WWTP, Australia

15	Logan City Council Biosolids Gasification Project – Transforming sewage sludge to energy				
Gas in focus	H_2, CO, CH_4 and CO_2	**Location**	Loganholme, QLD, Australia	**Established**	2020
Financials	AU$17.28m (AU$6.22m funded by ARENA), Saving in operation costs: AU$0.5m/y				

Input	**Output**
• 34,000 t/y biosolids (treated and partially dewatered sewage sludge)	• Biochar (soil conditioner) • Synthetic gas (H_2, CO, CH_4 and CO_2)
Scale of Operation • Serving 300,000 people • Energy capacity: 5.04MW	**Technology** • Gasification

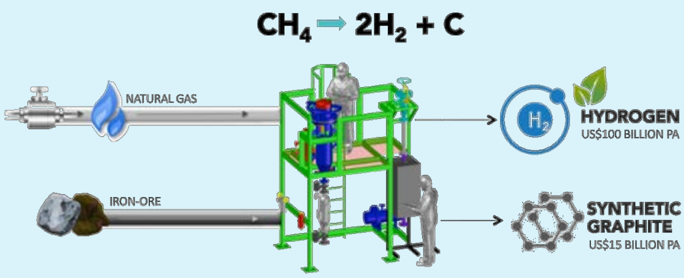
Scope – Sewage sludge will be dewatered in a centrifuge, dried in a paddle dryer and treated at high temperatures (600^{0}C) and low oxygen environment in a gasifier producing biogas. Recovered energy in the biogas will be used to power the drying and heating processes. 70% of the energy need will be covered by the gasification process and the remaining 30% will be sourced from the onsite solar array. Biosolids volume will be reduced by 90%, and biochar containing carbon, phosphorus and potassium will be produced in the gasification process. A demonstration facility will be expected to be operating in February 2020 and full-scale facility by July 2021.The technology is simple and can be fitted to the existing or new WWTP. There is potential for partial to full destruction of pollutants such as PFAS and microplastics[2].

Circularity	• Generation of energy from the process by-product and recovery of nutrients
Drivers	• Transport of biosolids for 300km to Darling Downs to be used as soil improver costs AU$1.8m/y (30% of WWTP operating costs) • Increasing cost of biosolids treatment and disposal (rising electricity cost and increasing population) • Tightening government regulations associated with carbon reduction and managing organic pollutants in soils
Environmental Impact	• Reduced carbon footprint (carbon sequestered in the biochar) • 4,800 reduction of CO_2/y
Partners/Cooperation	• Downer Utilities Pty Ltd, WSP Australia Pty Ltd, Cardno (QLD) Pty Ltd, Pyrocal Pty Ltd
Sources	[1]https://arena.gov.au/projects/logan-city-biosolids-gasification-project/ [2]https://www.pyrocal.com.au/biosolids-to-energy

Case Study 16 – Woodman Point WWTP, Australia

16	Hazer – Transforming biogas from Woodman Point WWTP sewage into hydrogen and graphite				
Gas in focus	H_2	**Location**	Munster, WA, Australia	**Established**	Planned for December 2020
Financials	AU$15.8m (AU$9.41m funded by ARENA)				

Input	**Output**
• Biogas from sewage	• H_2 • Graphite
	**Scale of Operation** • 100t/y **Technology** • Hazer Process



Scope – The Hazer process converts bio-methane to renewable hydrogen and graphite, using an iron ore catalyst, creating an alternative hydrogen pathway to the traditional approach of steam methane reforming and electrolysis. Hydrogen will be sold to industrial applications and end markets for graphite are being explored with potential carbon black, activated carbon or battery anode applications. The construction of the facility is planned by December 2020 and will begin operations in January 2021. The technology could set Australia up as an exporter of hydrogen and open up new opportunities from the graphite produced as a by-product of the hydrogen production process.

Circularity	• Production of useful by-product: graphite
Drivers	• Conversion of low value biogas stream from WWTPs (or landfill sites) to produce higher value hydrogen and graphite.
Environmental Impact	• CO_2 capture
Partners/Cooperation	• Hazer, Western Australian Water Corporation
Sources	https://arena.gov.au/news/world-first-project-to-turn-biogas-from-sewage-into-hydrogen-and-graphite/

Case Study 17 – Generation of H_2 in AD, Pilot Plant in India

17	**Modification of AD to produce H_2**		
Gas in Focus	H_2	**Established**	2017

Based on the pilot of AD using ground food waste, filtering large particles, draining the oil and feeding into the AD, the plan is to build a 10 times larger plant to treat municipal waste in Delhi and Mumbai. The AD does not produce conventional biogas but based on the Mohan's group innovation, produces gas rich in hydrogen (5kg H_2/day). This is one of the small group of researchers around the world who are finding that various organic waste streams—such as food waste, agricultural waste, and wastewater—can be viable sources of hydrogen gas.

Typical AD uses a mix of acidogenic and methanogenic bacteria that naturally occur together in food waste to turn organic compounds into CH_4. The acidogenic bacteria generate H_2 and short-chain carboxylic acids from the food, along with small amounts of CO_2. The methanogenic bacteria in turn convert the H_2, carboxylic acids, and CO_2 into CH_4. But the acids produced in the first step—acetate, propionic acid, and butyric acid among them—are valuable as feedstocks, and if those chemicals and the H_2 could be preserved, it would help make H_2 more cost competitive as a fuel. Hence, Mohan set out to arrest the digestion process to make H_2 the main product by inhibiting the methanogens. For close to a decade, Mohan adjusted the bacterial populations in digesters, steering them by varying the organic content of food waste, pH, temperature, and other parameters. He found that exposing the bacterial culture to acid before digestion helps reduce the population of methanogenic bacteria, tripling hydrogen production.

Circularity of the process – *Generation of gas for energy from the process, lower emissions of carbon*

Source: https://cen.acs.org/energy/hydrogen-power/Turning-organic-waste-hydrogen/97/i14

Sarkar, O., Kumar, A. N., Dahiya, S., Krishna, K. V., Yeruva, D. K., Mohan, S. V. (2016), Regulation of acidogenic metabolism towards enhanced short chain fatty acid biosynthesis from waste: metagenomic profiling, *RSC Advances, Vol.6(22)*, pp.18641-18653.

Case Study 18 – H_2 Biofuel Cell, University of Colorado, USA

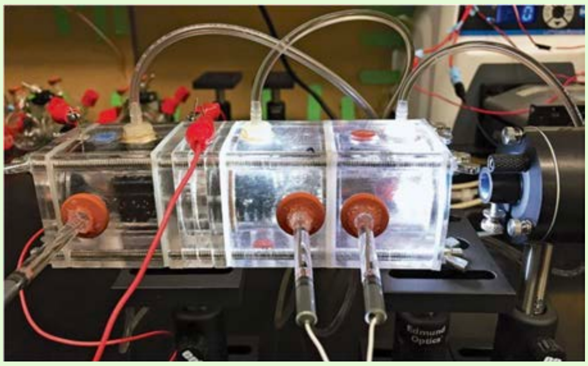
18	**H_2 biofuel cell**		
Gas in Focus	H_2	**Established**	2017

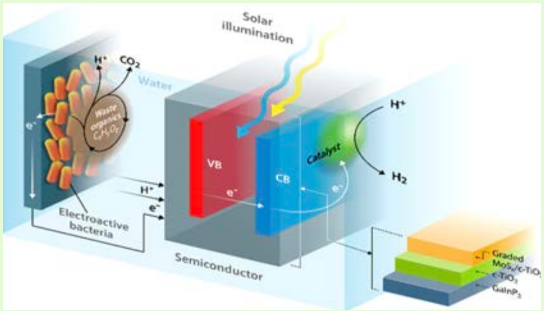
This laboratory study is working on ways to use electroactive bacteria to produce hydrogen from wastewater while treating it. Electroactive bacteria occur naturally in sewers and WWTPs, where they consume organic matter and produce electrons that are immediately taken up by other bacteria. Researchers have learned to harvest these electrons by letting the electroactive bacteria grow on the anodes of so-called microbial fuel cells; the electrons produced flow through the fuel cells to the devices' cathodes, generating current. They combine these electroactive bacteria with a photoelectrochemical cell to split wastewater and generate hydrogen.

In a proof-of-concept experiment, Ren's team has set up a photoelectrochemical cell with a bioactive anode coated with a naturally occurring mix of electroactive bacteria and a photoactive gallium-indium cathode. When light shines on the cathode, excited electrons reduce hydrogen ions in the wastewater to form hydrogen, leaving positively charged holes. The holes are then filled with electrons from the anode, produced by the electroactive bacteria munching on the organic waste.

The researchers are now trying to push their technologies toward commercialization.

Circularity of the process – *Future potential: system taking sewage in and producing H_2 and clean water.*





Source: https://cen.acs.org/energy/hydrogen-power/Turning-organic-waste-hydrogen/97/i14

Lu, L., Williams, N. B., Turner, J. A., Maness, P-C., Gu, J., Ren, Z. J. (2017), Microbial Photoelectrosynthesis for Self-Sustaining Hydrogen Generation, *Environmental science & technology, Vol.51(22)*, pp.13494-13501

Conclusions

In the context of the circular economy, there are significant and growing opportunities to more beneficially use water as a service, opportunities for utilisation of water as a carrier of nutrients, minerals and chemicals, and as a source of kinetic, thermal and bio-thermal energy. This report illustrates, using 18 international and national Case Studies, how WWTPs have capitalised on the opportunities that arise from the gases generated in the wastewater treatment process.

The main identified focus has been on the energy extraction from the CH_4 formation in the anaerobic carbon cycle and the research and development that has evolved to maximise the yield of generated CH_4. The technologies have concentrated on the pre-treatment of sludge to AD and co-digestion of sources of carbon with higher calorific values such as food waste and FOG. With the limited capture of carbon in the AD, alternative technologies have also been also explored, addressing the efficiency of CH_4 extraction but also disposal of the remaining biosolids and potential future regulatory restrictions to the application of biosolids to the land. The gasification process has been applied in a few case studies utilising sludge in different stages of WWTP.

In addition to the carbon cycle, complex nitrogen and sulphur cycles occur in the wastewater treatment bioreactions. While the understanding and scientific study has strongly focused on the efficiency of wastewater treatment, there is also an opportunity to explore further the generation of desirable gases and minimisation of undesirable gases, as demonstrated with the ANOMMOX process which lowers N_2O formation. The alteration of biological treatment processes step has implications on the following sludge treatment steps as well, requiring finetuning of the desirable outcomes.

In an attempt to address CO_2 emissions, pilots focussing on the generation of H_2 instead of CH_4 and capturing carbon in the char or as graphite are the most recent applications. Generation of H_2 in the WWTP has only recently caught attention outside the laboratory scale, where a successful biofuel cell has also been demonstrated, with significant potential.

In addition, ammonia and generation of ammonia at the WWTP should be studied further as it has a significant application as a hydrogen carrier for the overseas export.

While the main focus of the biosolids treatment so far has been stabilisation and disposal to land, the extraction of valuable materials, such as phosphorous and sulphur has already been pursued. The biosolids, as a source of gases and energy have also already been explored around the world. However, it would be beneficial to identify the whole range of utilisation options of biosolids in the WWTP context as well as being cognisant of regulatory limitations and implications.

There are case studies illustrating the capitalisation of additional gases, however there are still significant untapped opportunities in the gases that can be generated and used onsite at WWTPs, at a local adjacent precinct scale and even potential exportable scale. Whilst there has been a lot of research at the laboratory scale, there has been limited expansion to large scale implementation which does not always work effectively when scaled up. Hence, it should be noted that this is an evolving field with both challenges but also significant potential.

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