Towards Energy Self-Sufficient Water Reclamation Plants

A R&D Literature Review on
Used Water Treatment Technologies

First edition (April 2013)

A joint report by:

WATER RECLAMATION (PLANTS) DEPARTMENT
TECHNOLOGY DEPARTMENT

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Preface

This report, "Towards Energy Self-sufficient Water Reclamation Plants", is one of a series of technology reviews prepared by PUB, and was jointly prepared by the Water Reclamation (Plants) Department and the Technology Department. This report was written after extensive scanning of technologies, information analysis and data consolidation, both within published literature and from PUB's data records. It presents the latest developments and discusses future opportunities to increase the process energy efficiency of Singapore's Water Reclamation Plants (WRP), with complete process energy self-sufficiency being the stretch goal for the future.

This report also serves to develop a research roadmap for the WRPs by reviewing potential technologies and identifying research gaps. Strategies have been developed for technology development, both for existing and future WRPs, with the goal of achieving water and energy sustainability in Singapore.

This report is intended as a living document, and will be updated on a regular basis to ensure that it remains current and relevant.

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Executive summary

According to the used water master plan, the upcoming 176 MGD WRP in Tuas (West) is scheduled to be commissioned by 2022, and thus the design must be ready by 2016. In light of the rising population, energy costs and sludge disposal costs, the "business-as-usual" approach is not sustainable. It is thus essential that urgent research and development of new technologies and strategies be undertaken, in order to find and implement more sustainable solutions. This report serves as a first step towards this goal by providing a comprehensive technology review, analysis of possible WRP designs, as well as a technology roadmap for recommended technologies. This report focuses on developing strategies to achieve increasing levels of process energy efficiency for domestic used water treatment, with the stretch goal of process energy self-sufficiency in the future.

During the production of this report, a comprehensive scan of over 80 technologies in literature was carried out. From this list, a group of the 10 most relevant technologies were shortlisted, which can be classified under the three strategic functions of (1) early capture of organics from the influent for anaerobic conversion into energy, (2) reduction of aeration requirements, or (3) Increasing the energy generating capacity of the plant. Through a series of technology combinations based on their strategic role, several WRP configurations were developed and analysed. The recommended WRP configurations and targets are as follows:

Within the short-term (5-10 years) for brownfield projects, the upgrading of existing WRPs can potentially improve the process energy efficiency from the current 25% to over 40%. Recommended technologies for reduction of aeration requirements include: advanced sensors and controls, Variable Frequency Drives (VFD) or Inlet Vane (IV) blower controls, fine bubble diffusers, low energy Membrane Bioreactor (MBR), and Anammox in the side-stream. Recommended technologies for improvement of local energy generating

capacity include: solids pre-conditioning, and upgrading to high efficiency biogas engines (38% electrical conversion). Upgrading of the primary treatment units to Biosorption Enhanced Primary Treatment (Bio-EPT) or Upflow Activated Sludge Blanket (UASB) is not recommended due to the high cost of retrofit and disruption of plant operations.

Within the short-term (5-10 years) for new WRPs built on greenfield land, there is a potential to achieve over 80% process energy efficiency. In addition to the recommended technologies for brownfield projects, the recommended strategy is a Bio-EPT + MBR configuration. The Bio-EPT serves to divert influent organics to the anaerobic digesters, where it can be converted into more biogas for conversion into energy. Additionally, the Bio-EPT reduces the organic load on the secondary treatment process which, together with other aeration energy reduction technologies, serves to reduce the overall energy requirements of the WRP.

For greenfield projects built in the long-term (>10 years), there is a potential to achieve complete process energy self-sufficiency using emerging technologies such as anaerobic MBR (AnMBR) and main-stream Anammox. However, this is subject to the successful development and full-scale implementation of these technologies in the future.

This report has been divided into three major parts for ease of reading. The main report is presented in Part I, and covers the detailed analysis of the configurations described above, as well as recommendations for the technology roadmap towards energy self-sufficient WRPs. Part II covers a brief description of the shortlisted technologies used in the main report, as well as further considerations such as technologies for industrial used water reclamation. Finally, Part III covers the concluding remarks as well as the Appendix section, where detailed reviews on the principles, advantages and challenges for every technology investigated during the literature scan is provided. The Appendix will be subsequently made available in soft format.

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Nomenclature

Abbreviation	Description	First page referenced
AD	Anaerobic Digester	18
Anammox	Anaerobic Ammonium Oxidation	17
AnMBR	Anaerobic Membrane Bioreactor	17
AS-MBR	Activated Sludge Membrane Bioreactor	109
ASP	Activated Sludge Process	10
ATT	Advanced Thermal Treatment	19
BGE	Biogas engines	33
Bio-EPT	Biosorption Enhanced Primary Treatment	33
BOD_5	Biochemical Oxygen Demand (5 days)	21
CHP	Combined Heat and Power engine	17
COD	Chemical Oxygen Demand	17
CWRP	Changi Water Reclamation Plant	10
DAF	Dissolved Air Flotation	28
DEMON®	DEamMONification (a type of Anammox process)	23
DFE	Dual Fuel Engine	12
DHS	Downflow Hanging Sponge (reactor)	61
DTSS	Deep Tunnel Sewerage System	10
EBPR	Enhanced Biological Phosphorus Removal	109
EPT	Enhanced Primary Treatment	17
FST	Final Settling Tank	11
GHG	Greenhouse Gas	31
HTP	High Temperature Pyrolysis	106

ISSA	Incinerated Sewage Sludge Ash	30
IV	Inlet Vane (blower control)	17
IW	Industrial Water	112
JHB	Johannesburg (EBPR process)	111
JWRP	Jurong WRP	10
KWRP	Kranji Water Reclamation Plant	10
LTHW	Low Temperature Hot Water	98
MBR	Membrane Bioreactor	14
MF	Microfiltration	14
MLE	Modified Ludzack-Ettinger (ASP configuration)	110
MLSS	Mixed Liquor Suspended Solids	60
MUCT	Modified University of Cape Town (EBPR process)	111
PST	Primary Settling Tank	11
RAS	Return Activated Sludge	11
RO	Reverse Osmosis	14
SBR	Sequencing Batch Reactor	23
sCOD	Soluble Chemical Oxygen Demand	93
SRT	Solids Retention Time	12
tCOD	Total Chemical Oxygen Demand	93
TPAD	Temperature Phased Anaerobic Digestion	95
TSS	Total Suspended Solids	91
UASB	Upflow Activated Sludge Blanket	17
UF	Ultrafiltration	14
UPWRP	Ulu Pandan Water Reclamation Plant	10
UV	Ultraviolet (disinfection)	14

VFAs	Volatile Fatty Acids	28
VFD	Variable Frequency Drive (blower control)	17
VSS	Volatile Suspended Solids	90
WAS	Waste Activated Sludge	11
WRP	Water Reclamation Plant	2
WWTP	Wastewater Treatment Plant	9

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PART I

Main Report

Chapter 1

Introduction

1.1 Background

Currently, about 322 million gallons per day (MGD) of used water is generated by residential, institutional, commercial and industrial establishments daily. Of this, approximately 80% of the used waters are from domestic sources. This domestic used water is collected in the extensive sewage network before going to the various Water Reclamation Plants (WRPs), where it is biologically converted into biogas, sludge and treated effluent. The biogas is combusted for energy recovery, while the waste sludge is mixed with municipal solid waste before incineration and landfilling. Most of the treated domestic effluent, if not used for NEWater production, is being discharged through sea outfall; however, an increasing portion is being reclaimed as NEWater as part of PUB's efforts to close the water loop.

Almost all of the used water treatment facilities around the world, including those in Singapore, are net energy consumers – i.e. they draw electrical power off the power grid to create conditions suitable for the rapid biological degradation of organics in the used water, as well as for the removal of nutrients to prevent eutrophication in the effluent receiving water body. Energy consumption is a major concern as it constitutes a significant portion of the treatment costs. For the WRPs in Singapore, the current average net energy consumption of 0.648 kWh/m^3 accounts for up to 22% of the plant's total operational costs. Excluding non-process energy requirements (such as air conditioning, lighting, ventilation and inlet pumping) from this figure, the energy used for process operations amounts to 153 GWh/year. In addition, used water treatment currently generates about 49,700 dry tonnes of sludge per year to be disposed of.

Used water generation is estimated to increase to 589 MGD by 2061, over 75% more than the current level. Based on the "business-as-usual" approach, the future process energy demand is projected to reach 300 GWh/year, doubling the current energy consumption. In addition, an increased sludge production to over 90,000 dry tonnes of sludge per year will further amplify the energy required for its disposal. This sludge production rate is not sustainable in the long run due to the increasing shortage of landfill sites. Both the currently employed sludge minimisation processes of sludge drying and incineration, as well as the currently available alternative treatment technologies on the market, are very energy intensive and expensive.

Further adding to the urgency is the upcoming WRP in Tuas (West) which, according to the used water master plan is to be commissioned by 2022, and thus the process design must ready by 2016. In line with this schedule, a 5 MGD demonstration plant is being planned to begin operations in 2015 to identify scaling up issues and to train future operators of the WRP in Tuas. An energy efficient process design for the WRP in Tuas must, therefore, be ready by 2015 for the demonstration plant. A 0.22 MGD Integrated Validation Plant is currently being built to investigate and develop such a process design, based on the technologies shortlisted in this technology review.

From the above considerations, it is essential that urgent developments be made to the current used water treatment system to introduce new technologies and new strategies to mitigate escalating energy consumption. To meet these challenges, PUB will need to leverage on research and development (R&D) for new used water treatment solutions.

1.2 Objectives of the report

In light of the challenges and needs described in section 1.1, the purpose of this report is to provide an updated review of emerging used water treatment technologies for adoption in the WRPs, with the focus on developing strategies to achieve increasing levels of process energy efficiency and minimisation of waste sludge production. The three key criteria used to evaluate the technologies and process configurations are:

1) **Product water quality** – the ability and robustness of the technology/system to consistently produce treated effluent of quality suitable for use as NEWater feedstock;
2) **Energy sustainability** – minimisation of the process energy requirements and maximisation of energy recovery rates; and
3) **Environmental sustainability** – with a focus on the waste sludge aspect, such as the amount and type of waste sludge produced, which affects the disposal costs and future landfill requirements.

Using these criteria as the basis to shortlist and analyse the most relevant used water technologies for PUB, the following energy efficiency targets and corresponding sludge reduction targets have been developed (Figure 1.1):

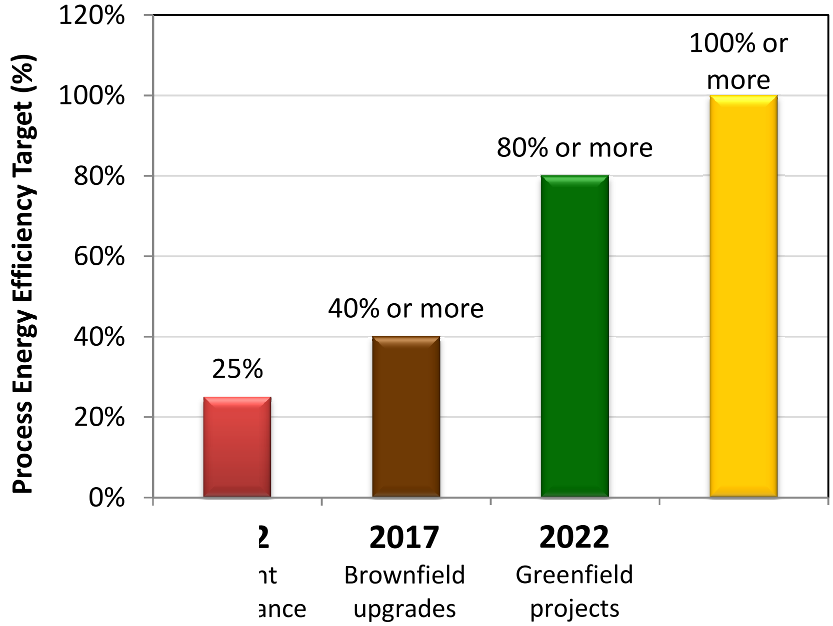


Figure 1.1 Current and targeted future process energy efficiencies

- **Brownfield upgrade target (2017)** – Upgrading of existing WRPs using established and demo scale technologies to over 40% process energy efficiency with about 10% reduction in sludge production compared to current processes.

- **Greenfield mid-term target (2022)** – Design of new WRPs in about 5 years, for instance the future design of the WRP in Tuas, using current pilot/demo scale technologies to achieve over 80% process energy efficiency with about 5% reduction in sludge production compared to current processes.

- **Greenfield long-term target** – By using technologies currently being lab tested (or being proposed) for the achievement of 100% process energy self-sufficiency and beyond, with up to 40% reduction in sludge production compared to current processes.

1.3 Scope and Focus of the report

The field of used water treatment covers a vast number of technologies and related disciplines outside of the WRP, such as policies, sewerage and limnology. In order to keep this report focused, the scope of this report has been restricted to technologies applicable within the boundaries of the WRP, ranging from the point of raw influent entry into the WRP to the point of exit from the WRP as effluent for discharge into the sea or for further purification into NEWater. As for the solids stream, the scope covers technologies for minimization of waste sludge, up to the point of disposal from the WRP. Within the confines of these considerations, technologies related to all treatment streams, including gaseous, liquid, solid and recovered product streams, have been investigated (Figure 1.2).

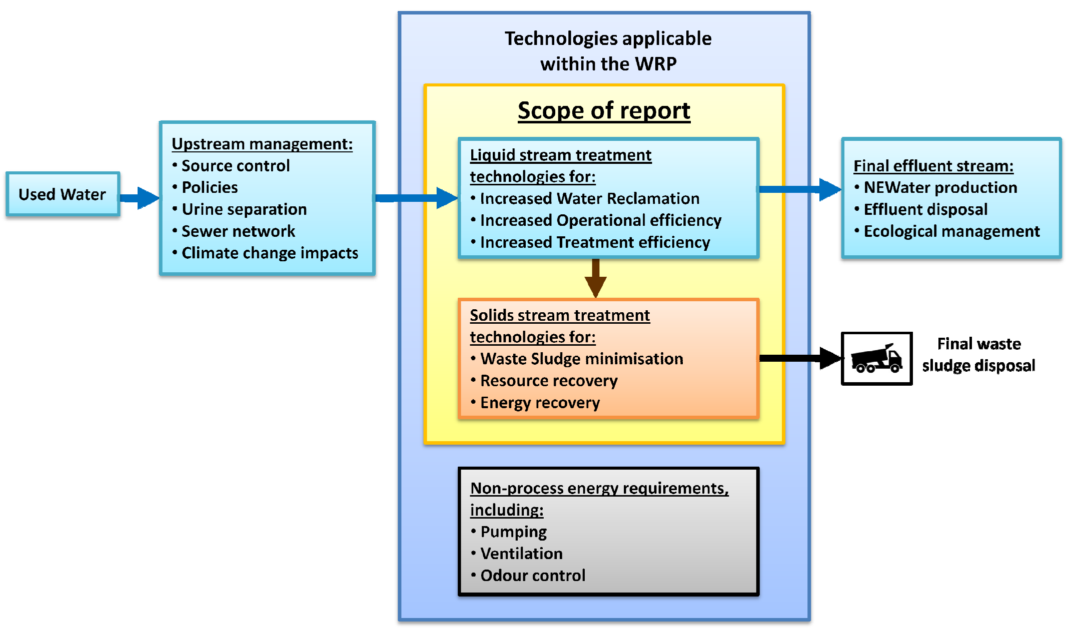


Figure 1.2 Scope of technologies covered in this report.

As the focus of this report is on process energy optimisation within the WRP, excluded from the scope of this report are upstream considerations, such as source control, urine separation and sewer network management. Downstream considerations that are out of the scope of this report include technologies relating to NEWater production, effluent discharge methods, and landfill management.

Excluded also from this report are the non-process systems (such as pumping and odour treatment) of the WRP. While improvements in non-process systems are also important for improving the overall energy balance of the plant, these requirements are highly dependent on local circumstances. For example, a WRP situated near to a residential zone may require a compact and covered design due to the necessity of odour treatment, which will invariably incur higher energy demand than an equivalent plant with no such requirements. While these technologies have been given consideration over the course of the comprehensive literature survey, they will not be covered in detail in this report.

1.4 Methodology and Structure of Literature Review

A comprehensive review of the state-of-the-art technologies was undertaken, with several iterations done to ensure the rigorousness of the selection, based on expert opinion and the context of applicability to PUB's operations. The methodology of the literature review is shown in Figure 1.3 and described as follows:

A review of the current status of used water reclamation in Singapore was first taken in order to establish the baseline from which improvements can be made. This was then compared against global trends and technology roadmaps in the literature in order to identify gaps in the local knowledge base.

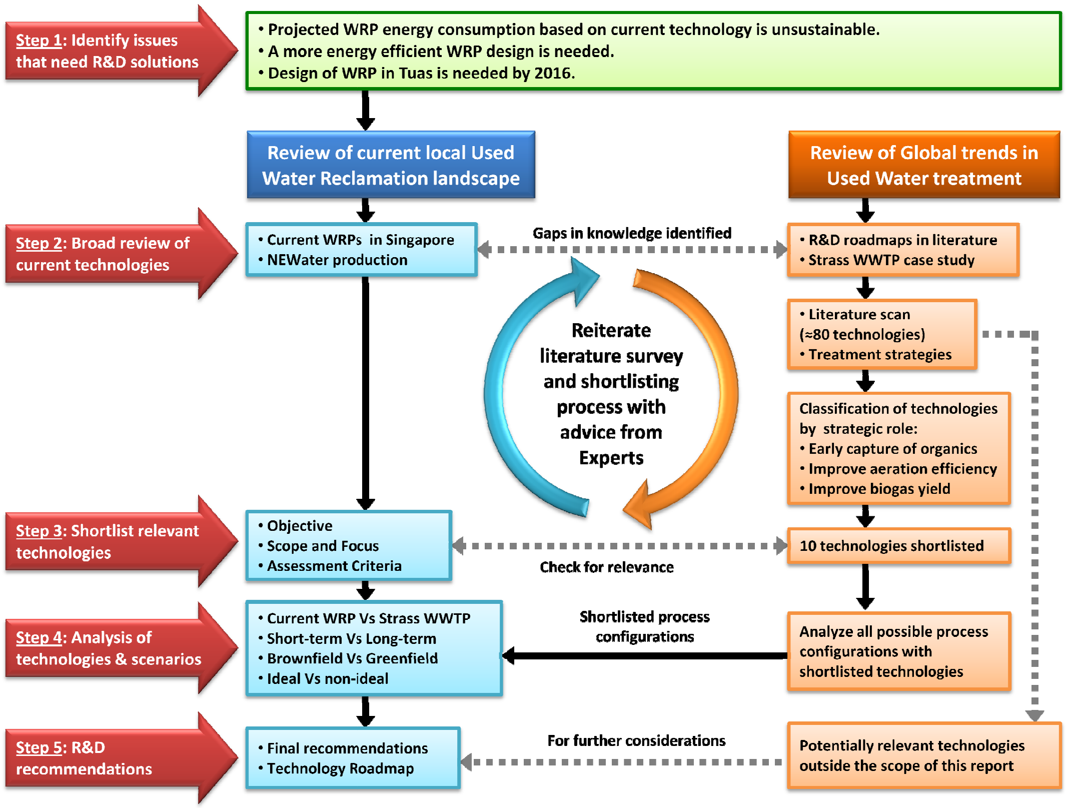


Figure 1.3 Methodology of literature review

From the review of the global trends and roadmaps, the following 3 recurring key strategies were identified and adopted with the aim of improving process energy efficiency:

(1) Early capture of organics from the influent for anaerobic conversion into energy;
(2) Improvements in process energy efficiency (aeration efficiency); and
(3) Improvements in energy recovery (biogas yield).

A total of 80 technologies were reviewed and several were shortlisted for potential application in Singapore. Used water experts were consulted for their advice regarding the relevance and effectiveness of these technologies. The process of reviewing and shortlisting was reiterated several times, until a final list of 10 shortlisted technologies was developed. A detailed description of these technologies can be found in Chapters 5 and 6.

From these 10 shortlisted technologies, 17 possible configurations or permutations were drawn up, of which 8 of the most relevant configurations are assessed in detail in Chapter 3. These shortlisted configurations were benchmarked against the Strass wastewater treatment plant (WWTP), which is the current global benchmark for 100% energy self sufficiency.

In addition, as the proposed WRP in Tuas will have a separate industrial used water stream, a proposed industrial used water treatment process is covered in Chapter 7. Chapter 7 also covers additional considerations for technologies and systems outside the scope of this report. These topics do not form part of the energy efficiency review, but are important nonetheless for a holistic understanding of PUB's aim to close the water loop.

Chapter 2

The current landscape of Used Water treatment

2.1 Singapore landscape

2.1.1 Water Reclamation Plants in Singapore

In Singapore, treatment of used water is carried out at WRPs using the biological activated sludge process (ASP). Currently, there are four WRPs, namely: Changi (CWRP), Jurong (JWRP), Kranji (KWRP) and Ulu Pandan (UPWRP). The WRPs treat used water from both domestic and industrial sources. Changi, Kranji and Ulu Pandan WRPs supply effluent for NEWater production. These three WRPs are also covered and have odour removal facilities. This is to minimise odour emission and to free up land around the WRPs for higher-value development.

Although all the WRPs use conventional activated sludge process, there are local differences between them. For example, Jurong WRP treats high strength industrial used water, while Changi WRP has a sizeable influent pumping station due to the Deep Tunnel Sewerage System (DTSS) and employs a drying system to produce dried sludge with 95% dried solids. In order not to let local variability between the WRPs unnecessarily complicate the analysis, this review will consider Ulu Pandan WRP (UPWRP) as the reference plant. This approach is consistent with that adopted by (Cao 2011b) in his analysis of Singapore's WRPs. General information about UPWRP can be found in Table 2.1, while Figure 2.2 provides simplified process schematics of a typical WRP in Singapore, using UPWRP as a model.

Liquid treatment: In UPWRP, the influent used water first goes through the mechanical screen and vortex grit chamber to remove debris and grit before it is sent to the Primary Settling Tank (PST) that removes part of the organic load as primary sludge by sedimentation. The aeration unit, where the activated sludge process is operated, allows for the aerobic biodegradation of the organic pollutants. At the Final Settling Tank (FST), part of the sludge is returned to the aeration unit as return activated sludge (RAS), and the remaining sludge is collected as waste activated sludge (WAS). The clear supernatant water from the FST is discharged as the treated secondary effluent from the WRP. A part of this effluent is used as feedstock for NEWater production.

Figure 2.1: Aerial photograph of Ulu Pandan WRP, Singapore.

Table 2.1 General information about UPWRP.

Ulu Pandan Water Reclamation Plant	
Design capacity	361,000 m^3/d
Treated flow	≈ 352,000 m^3/d (as of 2010)
Area occupied	46 hectares
Effluent supplied for NEWater production	200,000 m^3/d
Hydraulic Retention time (HRT)	7 h
Solids Retention Time (SRT)	5 d
First commissioned	1961
Last Phase of expansion	2000

Catchments:

≈ 9,600 hectares comprising Queenstown, Clementi, Pasir Panjang, Telok Blangah, Jurong East, Bukit Batok, Bukit Timah and Marina South.

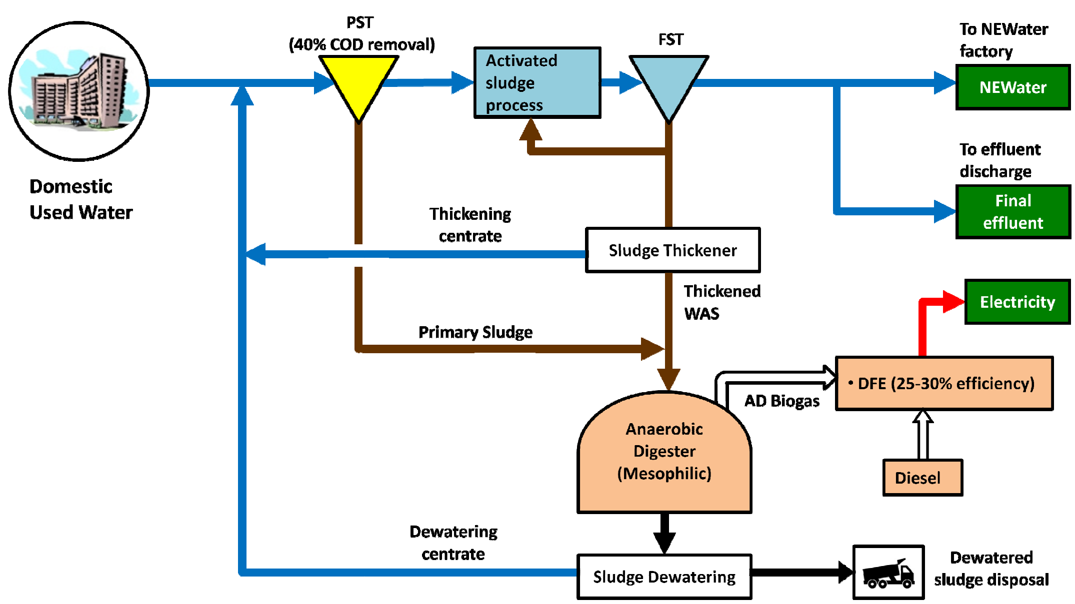


Figure 2.2: Process schematics of a typical WRP in Singapore (PST: Primary Settling Tanks; FST: Final Settling Tanks; DFE: Dual Fuel Engine)

Solids treatment: The solids stream treatment commences with the collection and thickening of the collected primary sludge and waste activated sludge. In the anaerobic digester, organic substances in the sludge are broken down in an oxygen-deficient environment through retention in the digesters for 20 – 30 days. The digested sludge is then dewatered with centrifuges to around 22% dried solids, while the dewatering centrate returns to the headworks of UPWRP. UPWRP produces approximately 160 tonnes/day of dewatered sludge and sludge disposal is achieved by mixing with municipal solids waste to elevate the dry solids content prior to incineration. The sludge disposal cost is around $ 70 per ton of sludge disposed, which includes $60 for incineration and around $10 for transport.

Energy recovery: The digestion process converts the organic matter into biogas, which is used to power dual-fuel engines (DFE) to generate electricity with conversion efficiencies of typically 25% – 30%. The electricity generated (In-Plant Power Generation) is used to supplement the electrical energy required for the operation of the plant. The in-plant generated power is only suitable to be supplied to equipment which works on constant loading.

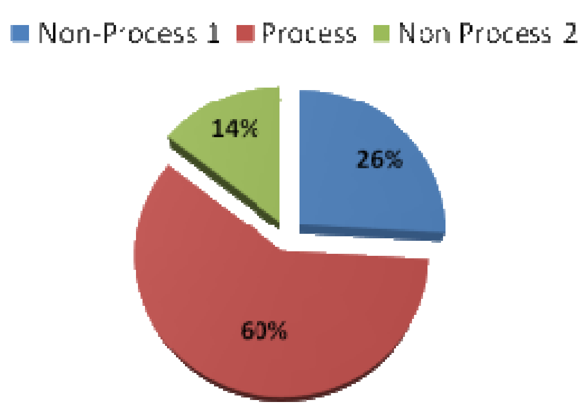


Figure 2.3: Typical energy consumption pattern of UPWRP

An overview of the typical energy consumption pattern of UPWRP is shown in Figure 2.3, where:

1) **Process energy requirements** refer to: Primary Settling Tanks, Final Settling Tanks, Biological process, Sludge Thickening, Digestion, Power Generation, Sludge Dewatering and Drying (where applicable)

2) **Non-Process 1 energy requirements** refer to: Inlet and effluent pumping and Equalisation tanks, NEWater feedstock, Industrial Water production and Greasy Waste Treatment (where applicable)

3) **Non-Process 2 energy requirements** refer to: Odour Removal, Building Air-Conditioning & Mechanical Ventilation and Lightings

2.1.2 NEWater production

In Singapore, an increasing fraction of the treated effluent from WRPs is being further treated in facilities known as NEWater factories using advanced technologies comprising micro-/ultrafiltration (MF/UF), reverse osmosis (RO) and ultraviolet disinfection (UV) to produce high grade water called NEWater. A typical process scheme is shown in Figure 2.5. Currently, NEWater meets 30% of Singapore's current water demand, and there are plans to increase this supply to 50% by 2060 (PUB 2010b).

Figure 2.6 shows a typical energy consumption pattern in a NEWater factory, where the reference energy consumption value for the entire process is 0.7 kWh/m^3. The MF/UF system has energy consumption between 0.10 and 0.15 kWh/m^3 (DHI-NTU 2009; PUB 2010a). For the purpose of comparing against the membrane bioreactor (MBR) technology for NEWater production, the reference energy consumption for MF/UF system has been taken as 0.13 kWh/m^3.

Figure 2.4: Photograph of Bedok NEWater factory

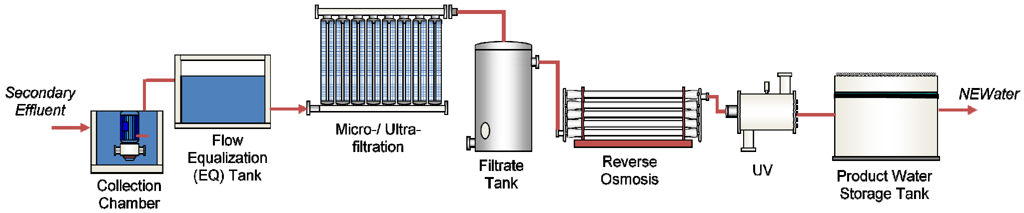


Figure 2.5: Process overview of a NEWater factory

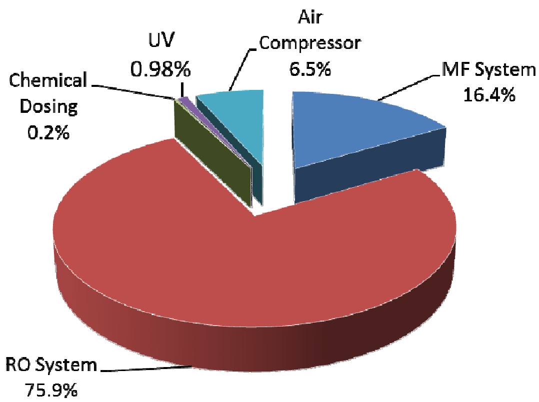


Figure 2.6: Typical energy consumption pattern in a NEWater factory

Although technologies related to the NEWater process fall outside of the scope of this review, the reference energy consumption of 0.13 kWh/m^3 for UF/MF process is important for process analysis in chapter 3. This is because one of PUB's goals is to increase NEWater production. During the technology review, it was found that the membrane bioreactor (MBR) is able to replace both the FST and MF/UF stages to produce an effluent with quality suitable for direct RO filtration in the NEWater factory, at a lower combined energy cost and smaller footprint. Due to these benefits, all future process configurations in Singapore's WRPs have been assumed to utilise MBR technology. In order to present an equal analysis between the future MBR process configurations with the current WRPs and Strass WWTP (both of which treat domestic used water to FST effluent quality only), a value of 0.13 kWh/m^3 has been added to the energy consumption figure for current WRPs and Strass WWTP during the analysis in Chapter 3.

2.2 Global landscape

2.2.1 Global trends in Used Water Treatment technologies

In general, the following 5 global trends in used water treatment technologies towards achieving energy self-sufficiency can be observed:

1) **Early capture of organics from the influent for anaerobic conversion into energy.** The aeration process used to biologically degrade organics in a conventional used water treatment plant is typically the largest energy consumer, up to 42.4% in the case of UPWRP. Hence, reducing the organic loading on the aeration system will improve the energy balance of a plant. Currently, there are two main ways to achieve this:

i. Enhanced Primary / Pre- Treatment (EPT) – This involves removing as much organics as possible at the earliest stage (typically in association with the Primary Settling Tanks) to achieve the twin goals of a) reducing aeration requirements in the Secondary treatment, and b) transferring energy-rich sludge to the anaerobic digesters for enhanced biogas production. Trends in this area include the A-stage process (Biosorption) as practiced at Strass WWTP, chemical and adsorbent pre-concentration methods, and physical filtration methods.

ii. Anaerobic pre-treatment – Here, the organics are not pre-concentrated instead it is diverted from the main-stream to the anaerobic reactors and directly converted into biogas in the anaerobic main-stream processes. Examples include Upflow Anaerobic Sludge Blanket (UASB) and Anaerobic MBR (AnMBR).

2) **Reduction of aeration requirements** – Currently, biological nitrification and denitrification processes remain the most cost effective method of nitrogen removal. Consequently, aeration processes will continue to be employed in future plants. Aeration efficiency may be improved by installing fine bubble diffusers, inlet vane (IV) control or variable frequency drive (VFD) for pumps and blowers, high efficiency combined heat and power (CHP) engines and sophisticated control systems to regulate them. Innovative methods for nutrient removal, such as the Anammox process, can also indirectly reduce aeration requirements.

3) **Energy recovery via biogas generation.** From the organic content in raw domestic used water, it is estimated that one cubic metre contains about 2 kWh-equivalent of energy (Keller, 2008) depending on the Chemical Oxygen Demand (COD) concentration and that 18% of the influent energy value is sufficient to operate most conventional used water treatment plants (Johnson et al., 2009). Biogas generation and subsequent

conversion to electricity and heat via CHP engines remains the current best practice for energy recovery in a WRP. Trends in this areas include:

i. Improvements in Anaerobic Digester (AD) operation for better biogas generation – this includes improvements to feed sludge quality, such as using organics-rich EPT sludge, and applying solids pre-conditioning (e.g. ultrasonic sludge disintegration), as well as improvements to AD efficiency, such as operating in the thermophilic range. However, the effectiveness of solids pre-conditioning and thermophilic digestion remains a topic of debate and research.

ii. Improvements in CHP operation – When biogas is combusted to drive an engine, a significant fraction of the energy is converted into waste heat. A CHP engine improves on the conventional engine by capturing and recycling this heat, thus improving the overall energy efficiency of the plant. In the UK, AD methane-powered CHP recovers only 11% of the influent energy value, which is already about half the energy required to operate a conventional WWTP (Johnson et al., 2009).

4) **Best practices in energy management** – This includes achieving energy efficiency for the non-process systems not directly related to treatment, such as inlet and effluent pumping, Equalisation tanks, NEWater feedstock, Industrial Water production and Greasy Waste Treatment, as well as Odour Removal, Building Air-Conditioning, Mechanical Ventilation and Lightings. There is, however, a limitation in the implementation of best practices across all used water treatment facilities, as these practices are dependent on local circumstances. For example, WRPs with compact and covered design will invariably have higher energy demand for non-process items.

5) **Resource recovery** – In addition to energy self-sufficiency, resource recovery is of prime importance for the development of sustainable WRPs.

Due to increasingly stringent landfill regulations and the growing shortage of resources (e.g. phosphorus and nitrogen), a WRP could potentially serve important functions for producing a wide range of resources covering water, biofuels, nutrients and minerals. Trends in this area include:

i. Water reclamation – Membrane Bioreactor (MBR) and other membrane-based technologies for water reclamation,

ii. Biofuels – Upgrading of biogas to remove sulphur, halogenated hydrocarbons and siloxanes and thereby enhance heat value of the biogas, advanced thermal treatment (ATT) for converting biosolids into biofuels, and

iii. Nutrient and Mineral resources – Recovery of phosphorus and nitrogen as fertilizer additives, ATT technologies for recovery of minerals and by-products for reuse as construction material.

2.2.2 Strass Waste Water Treatment Plant case study

The Strass WWTP in Austria (Figure 2.7) is often used as the international benchmark in terms of energy efficiency for used water treatment. The Strass WWTP is distinctive, because it has proven that energy self-sufficiency is a feasible concept for used water treatment. The total energy consumption of the Plant is 0.314 kWh/m^3, and the energy recovered from In-Plant power generation is 0.34 kWh/m^3. The plant therefore produces more electrical energy than it requires for its operation at 108% energy recovery (Wett et al. 2007). This section introduces the Strass WWTP and explores its key technical features to understand how these may contribute to its high energy efficiency.

Figure 2.7: Photograph of Strass WWTP, Austria.

The Strass WWTP serves 31 communities in the Achental and Zillertal valleys east of Innsbruck, Austria. It provides used water treatment for a population that ranges from approximately 60,000 PE (Population Equivalent) in the summer to 250,000 PE during the winter tourist season, and has treatment requirements that include organic and nitrogen removal. The hydraulic flow to the plant is variable, and may range from 17,000 m^3/d to 38,000 m^3/d depending on season, with an average flow of 26,500 m^3/d. In terms of its average flow, the Strass WWTP is about 13 – 14 times smaller compared to UPWRP[1].

A process overview of the Strass WWTP is shown in Figure 2.8, while the typical used water characteristics and plant performance is shown in Table 2.2.

[1] Source: http://www.aiz.at/betriebsdaten.htm, downloaded from the worldwide web on 16 April 2012

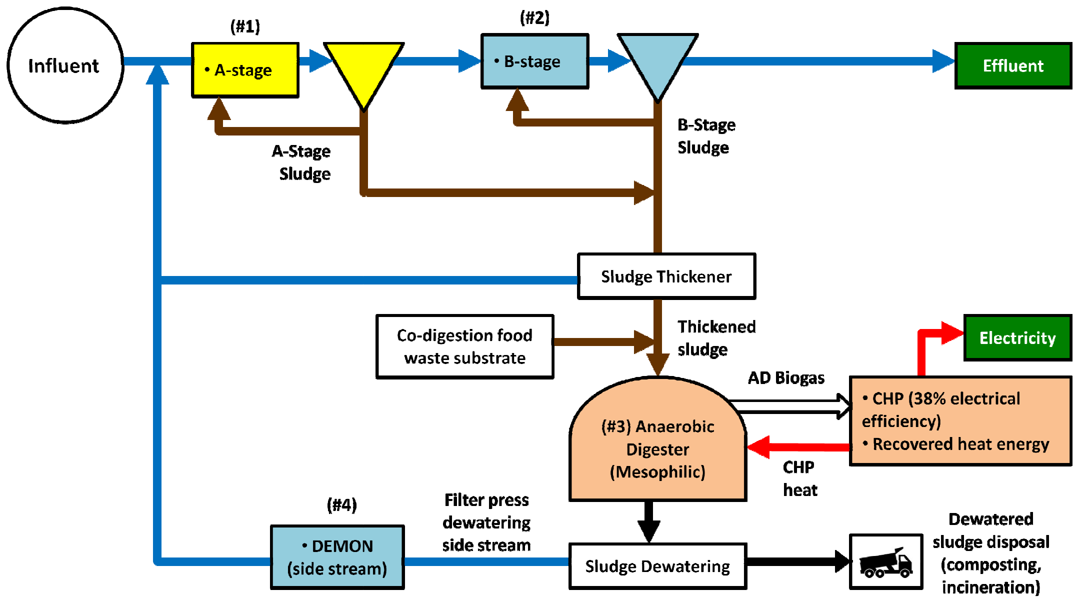


Figure 2.8: Process overview of Strass WWTP.

Table 2.2: Typical used water characteristics that may apply for Strass WWTP (adapted from Jonasson, 2007).

Parameter	**Influent**	**Effluent#**
BOD_5	291 mg/L	15 mg/L
COD	605 mg/L	75 mg/L
Total Nitrogen, N	44 mg/L	≥ 70%, T > 12℃
Phosphorus, P	7.5 mg/L	1-2 mg/L
NH4-N	26 mg/L	5 mg/L, T > 12℃

Based on Austria's emission legislation values

COD – Chemical Oxygen Demand

BOD_5 – Biochemical Oxygen Demand (5 days)

The key technical features that differentiate Strass WWTP from PUB's WRPs include the following (Jonasson 2007; Wett et al. 2007; Fillmore 2010; http://www.aiz.at/betriebsdaten.htm):

1) The Strass WWTP has a two-stage biological treatment known as the A-stage and the B-stage with specific treatment objectives. The A-stage (indicated as #1 in Figure 2.8) works on high-rate entrapment of organics without excessive aerobic stabilisation. This is achieved by operating the plant at reduced solids retention time (SRT) and hydraulic retention time (HRT) of around 0.5 d and 0.5 h, respectively. The A-stage allows organic compounds to be quickly removed by adsorption onto solids and immediately conveyed through thickening and digestion to produce biogas for power generation. The A-stage has been highly effective and could remove 55% to 65% of the influent organic load compared to around 40% achieved in the PST of UPWRP.

2) The B-stage (indicated as #2 in Figure 2.8) is the most energy intensive unit process that has an electricity demand at 47% of the total consumption. It is operated as a conventional activated sludge process with SRT and HRT around 10 d and 10 h, respectively, with a volume of 10,456 m^3. As a result of the enhanced pre-treatment achieved by the A-stage, a significantly reduced organic load enters the subsequent B-stage for nutrient removal and for further aerobic treatment to produce effluent that meets discharge standards. Furthermore, the B-stage employs a "swing zone" control strategy for aeration to minimise air supply and energy requirements. This control strategy works on intermittent aeration of the swing zones by operating between two set-points of the on-line ammonia control to maximise denitrification volume while still achieving full nitrification in relation to the instantaneous actual load.

3) Strass WWTP has a relatively high In-Plant power generation at 0.34 kWh/m^3 compared to UPWRP's 0.11 kWh/m^3. This is not only due to the

use of high-efficient co-generation engine units that provide 340 kW of power with average conversion efficiency of 38% (as compared to typical conversion efficiency of 25% - 30% at UPWRP), but also due to the higher anaerobic digester temperature at around 35℃ for enhanced biogas production (indicated as #3 in Figure 2.8).

4) Strass WWTP applies the DEMON® process (DEamMONification), a type of Anaerobic Ammonia Oxidation (Anammox) process, on the side-stream of the Plant (indicated as #4 in Figure 2.8). The Anammox process is conducted using Sequencing Batch Reactor (SBR) and is able to remove nitrogen without the need for organic carbon source while concomitantly exerting significantly less oxygen demand. The application of the Anammox process achieves two favourable outcomes: a) aeration energy requirement for nitrification of the side-stream ammonia is reduced, and b) the organic carbon that would be required for denitrification of the side-stream was now available for conversion to biogas in the digesters.

Aside from the above key technical features, there are other non-technical factors that contribute to the success of Strass WWTP. These include (Fillmore 2010):

- A highly educated, well-paid workforce operations staff who are experienced tradesmen and/or university graduates with degrees. It may be noted that the plant superintendent was a licensed, Ph.D. engineer;
- High level of automation that allowed for a smaller, more specialized operations team;
- Use of advanced process analysis tools for process optimization;
- Tolerance for process risk, such that the plant could be operated dynamically by providing the necessary level of treatment and minimising resource consumption;
- Quantification of gains with extensive sub-metering in the plant.

Table 2.3: Comparison of overall energy data between Strass WWTP and UPWRP.

Plant	*Process Energy*	*Non-Process 1 Energy*	*Non-Process 2 Energy*	*Total energy consumption*	*Energy recovered*	*Net energy requirement*	*Energy recovered as % of total*
	[kWh/m^3]	**[kWh/m^3]**	**[kWh/m^3]**	**[kWh/m^3]**	**[kWh/m^3]**	**[kWh/m^3]**	**[%]**
UPWRP	0.306	0.13	0.07	0.506	0.11	0.396	21.7
Strass WWTP	0.211	0.09	0.01	0.311	0.34	-0.029	109.3

Table 2.3 provides a comparison of energy data between Strass WWTP and UPWRP. The table shows that the greater energy efficiency achieved in Strass WWTP as compared to UPWRP is due to a number of factors, including process (0.1 kWh/m^3 less in Strass WWTP), non-processes (combined difference of 0.1 kWh/m^3 less in Strass WWTP) and energy recovery from In-Plant generation (0.23 kWh/m^3 more in Strass WWTP).

To improve on the energy efficiency of the WRPs, it is important that efforts are directed at all of these factors. However, as explained in section 1.3, non-process energy requirements have been excluded from the scope of this report because it is highly site-specific and dependent on the local conditions.

Table 2.4: Comparison of process energy data between Strass WWTP and UPWRP.

Process configuration	**Process energy consumption (kWh/m^3)**				**Sludge generation (Dry tonne)**
	Total consumption (standardized to MF/UF permeate effluent quality)	**In-plant power generation**	**Net energy consumption**	**Process energy efficiency (%)**	**Per 100,000 m^3 used water**
UPWRP	0.436 (0.306 + 0.13)	-0.11	0.326	25.2%	9.3
Strass WWTP	0.341 (0.211 + 0.13)	-0.34	0.001	99.7%	18.8

From Table 2.4, we can compare the process energy efficiencies of UPWRP and Strass WWTP, which have been normalised to MF/UF permeate effluent quality for purposes of this discussion. UPWRP has a process energy efficiency of about 25% while for Strass WWTP it is close to 100% even when the MF/UF factor has been added in. The most significant contributor to the energy balance is the diversion of organics to the anaerobic digester using the A-stage process, resulting in three times the energy recovery of UPWRP. However, the sludge production of Strass WWTP is actually double of the yield of UPWRP due to the operation of the A-stage process, but disposal costs are mitigated through composting of a portion of waste sludge, as well as through the installation of a sludge dryer in the future.

In the next chapter, we shall briefly discuss the various process configurations that will enable us to move closer to Strass WWTP level of efficiency and beyond.

Chapter 3

Analysis of Process Configurations

3.1 Outline of chapter

In chapter 2 a comparison between Singapore's WRPs and Strass WWTP (the current global benchmark for energy efficient used water treatment practices) was given in order to identify potential areas for improvements in WRP process design. Using the literature review methodology described in section 1.4, 10 technologies have been shortlisted for further process analysis.

This chapter presents an analysis of these technologies in various combinations and configurations. In order to focus on the relevant options from among the large number of possible combinations, the organisation and scope of the analysis has been defined as follows:

(i) **Assessment criteria** – Several criteria, such as final product water quality, Brownfield and Greenfield scenarios, maturity of technologies, and priority of different criteria, have been used to shortlist suitable technologies for consideration and to develop process configurations for short and long term adoption. These assessment criteria are described in detail in Section 3.2.

(ii) **Organisation of technologies by strategic function** – As described in section 1.4, the following general strategies can be adopted for the development of energy efficient used water reclamation plants:

1) Early capture of organics from the influent for anaerobic conversion into energy.
2) Reduction of aeration requirements
3) Improvement of energy recovery via biogas generation

The shortlisted technologies have been categorized according to their strategic function in these areas and, through a process of combining these technologies for synergistic benefits, a list of 17 possible process configurations were drawn up and briefly discussed in Section 3.3. From this list, 8 of the most relevant process configurations have been shortlisted for detailed calculation and discussion in Section 3.4.

Section 3.5 concludes with a summary of the results of the analysis. Detailed descriptions of the shortlisted technologies for the liquids and solids treatment trains used in this chapter are covered in chapters 5 and 6 respectively. Further noteworthy items for consideration, but outside of the main scope of discussion, are covered in Chapter 7.

3.2 Assessment Criteria

The following assessment criteria were used in this literature review:

3.2.1 Policy considerations:

- **Final product water requirements** – The reclamation of domestic used water as NEWater is the top priority of future WRP operations. Hence, in all the scenarios considered, the final product water quality has been standardised to MBR or MF/UF permeate quality for use as RO feedstock.
- **Nutrient removal** – The process configurations considered must be able to achieve ammonium removal to NEWater feedstock standards. Denitrification

is not a priority as the RO membranes are able to reject nitrate ions. However, denitrification remains valuable as a method to recover alkalinity that is consumed during nitrification and reduce oxygen demand, thus saving the cost of chemical pH correction. Biological phosphorus removal is desirable, but not a priority.

- **Co-digestion of food waste** – Co-digestion of sludge and food waste is able to improve biogas generation in the anaerobic digesters, as shown in the case of Strass WWTP. However, co-digestion of food waste has been omitted from detailed analysis in this review because the management of food waste falls outside PUB's core operations. There are also currently several challenges to co-digestion. Firstly, the recycling of food waste in Singapore is still limited, with only 102,400 tonnes (16%) recycled in 2010 (NEA, 2011). Most of the Food waste generated in Singapore is incinerated (Khoo et. al., 2010). Secondly, the segregation and collection of food waste from food establishments is a challenge (Ong, 2012). Thirdly, care must be taken not to overload the co-digester with food waste, as it may result in rapid build-up of VFAs (volatile fatty acids) and souring of the digester (Lim, 2011). That said, however, PUB collects greasy waste from grease traps around food establishments, which is then fed to anaerobic digesters in Jurong WRP, thus serving as a form of co-digestion feedstock. Greasy waste is more readily managed than food waste as it is devoid of bulk material. After removal of colloidal material using dissolved air-flotation (DAF) the greasy waste, which has high calorific content, is a valuable resource for improved biogas production in the anaerobic digesters.

- **Increased sensors and automation** – In order to improve plant stability and response time to events, sensors and automation will likely play a greater role in process control and plant management in the future. This would also reduce manpower requirements for basic operations and allow the diversion of manpower to more strategic process control roles.

3.2.2 Application for Brownfield and Greenfield scenarios:

- **Greenfield plants** – This refers to the design and construction of a new WRP, without consideration of pre-existing structures. According to the Used Water Master Plan, the proposed WRP in Tuas is to begin construction in 2016 and to be completed by 2022, with a design treatment capacity of 800,000 m^3/day (176 MGD).

- **Brownfield plants** – According to the Used Water Master Plan, Jurong WRP and Ulu Pandan WRP will be decommissioned by 2022, while Changi WRP will continue to remain in service. This review also covers the potential upgrading of these plants to improve their energy efficiency, taking into consideration the individual service life of each plant.

3.2.3 Operational considerations:

- **Maturity of technology** – The shortlisted technologies have been classified as suitable for adoption in the short term (5-10 years) or long term (>10 years), depending on the maturity of the technologies. Technologies that are currently being pilot or demo tested in Singapore are considered ready for adoption for WRPs being designed within the next 5-10 years, while technologies currently being lab tested in research institutes in Singapore are considered ready for pilot testing within the next 5 years, and ready for full-scale application in about 10 years.

- **Robustness of technology** – Due to the final treated product water being used as NEWater feedstock, the treatment process needs to be extremely robust. It also needs to be simple and easy to operate and maintain, so as to reduce the possibility of process failure due to hardware malfunction or operator error.

3.2.4 Scope of review

- **Segregation of industrial and domestic used water streams** – According to the Used Water Master Plan for the proposed WRP in Tuas, the domestic stream (600,000 m^3/day, or 132 MGD) and industrial stream (200,000 m^3/day, or 44 MGD) will be segregated and each will receive its own dedicated liquids and solids treatment systems. The scope of this review will focus on the reclamation of domestic used water. A brief discussion of industrial used water reclamation is given in Chapter 7.

- **Process Vs Non-process energy requirements** – This review covers the optimisation of process energy requirements only. While improvements in non-process systems (such as pumping and odour treatment) are also important for improving the overall energy balance of the plant, these requirements are highly dependent on local circumstances. For example, a WRP situated near to a residential zone may require a compact and covered design due to the necessity of odour treatment, which will invariably cause it to have higher energy demand than an equivalent plant with no such requirements.

- **Resource recovery** – In Singapore's context, the major resources to be recovered are water and biogas, and the technologies related to their recovery have been extensively reviewed in this article. While there is potential to recover other resources, such as phosphorus for fertilizers, or incinerated sewage sludge ash (ISSA) as a concrete additive, there is limited local market demand for such products. Thus, the recovery of these resources will not be a major consideration in this review.

3.2.5 Environmental considerations:

- **Sludge disposal** – Minimisation of waste sludge production would reduce disposal costs and alleviate the strain on the limited landfill space available.

- **Greenhouse gas emissions** – In recent years there has been increasing concern about the contribution of used water treatment plants to the release of greenhouse gases (GHG) such as methane (CH_4) and nitrous oxide (N_2O), in addition to CO_2, to the atmosphere. While the level of GHG emissions from various processes is not a high priority in the evaluation of technologies in this review, these concerns have been highlighted for future consideration.

3.3 Analysis of process strategies

The shortlisted technologies described in Chapters 5 and 6 can be classified under the functions of:

(1) Early capture of organics from the influent for anaerobic conversion into energy,
(2) Reduction of aeration requirements, or
(3) Increasing the energy generating capacity of the plant.

Figure 3.1 shows a process flow diagram of these shortlisted technologies according to their strategic role. From this diagram, a number of possible configurations are shown in Table 3.1. While reducing aeration requirements and increasing energy generation capacity are both fundamental aspects of all the process configurations, the processes differ significantly with regards to pre-treatment. All the process configurations can be broadly categorised as falling under one of two strategies: enhanced pre-treatment treatment strategy, or anaerobic pre-treatment strategy. Both strategies seek to optimise the use of energy stored in the influent organics.

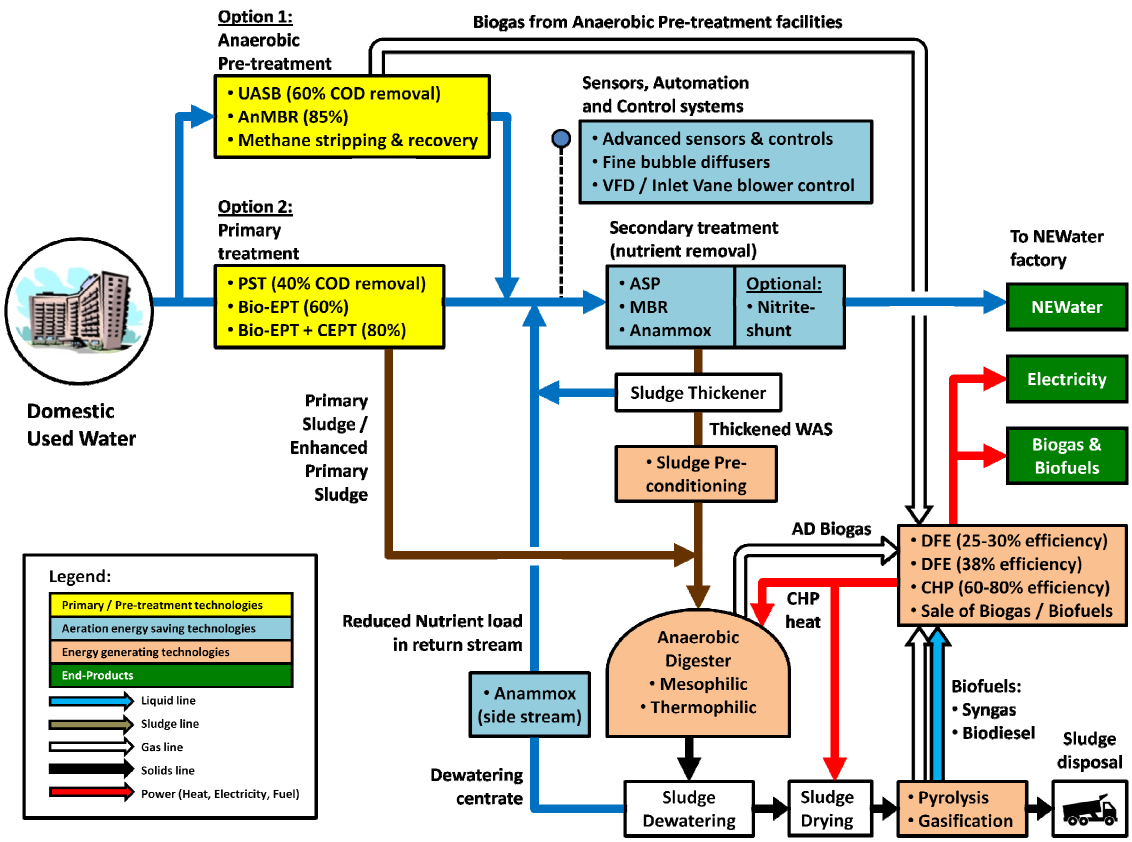


Figure 3.1: Process flow diagram of conventional and shortlisted technologies (colour coded by strategic role in increasing process energy efficiency)

From the organic content in raw domestic used water, it is estimated that one cubic metre contains about 2 kWh-equivalent of energy (Keller, 2008), however Singapore's domestic used water has relative lower COD which contains about 1.7 kWh/m^3 -equivalent of energy. It is estimated that 18% of the influent energy value is sufficient to operate most conventional used water treatment plants (Johnson et al., 2009); some estimates put the influent energy potential, as high as ten times the energy needed to treat it (GWRC, 2008). Currently in the UK, cogeneration powered by methane from the anaerobic digestion in a conventional WWTP recovers only 11% of the influent energy value, which is already about half the energy required to operate a conventional WWTP (Johnson et al., 2009). Therefore, effective conversion of influent organics is a critical component in the design of energy efficient plants.

Table 3.1: Possible configurations of shortlisted technologies for the reclamation of domestic used water

No	Brief description of main configuration	Pre- / Primary-treatment (% COD capture)	Main liquids stream	Waste Sludge stream	AD type	Gas to Energy (% conversion efficiency)	Side liquids stream	Blower control
1	Strass WWTP	A-stage (60%)	B-stage + FST	-	Mp. AD	CHP (38%+heat)	DEMON®	VFD
2	Conventional ASP	PST (40%)	ASP + FST	-	Mp. AD	DFE (25-30%)	-	-
3	Brownfield (basic)	PST (40%)	ASP + FST	Pre-cond.	Mp. AD	BGE (38%)	Anammox	VFD/IV
4	Brownfield (MBR)	PST (40%)	MBR	Pre-cond.	Mp. AD	BGE (38%)	Anammox	VFD/IV
5	Brownfield (EPT, MBR)	Bio-EPT (60%)	MBR	Pre-cond.	Mp. AD	BGE (38%)	Anammox	VFD/IV
6	Brownfield (EPT,MBR,N-Shunt)	Bio-EPT (60%)	MBR, N-shunt	Pre-cond.	Mp. AD	BGE (38%)	Anammox	VFD/IV
7	EPT (basic)	Bio-EPT (60%)	ASP + FST	Pre-cond.	Mp. AD	BGE (38%)	Anammox	VFD/IV
8	EPT (MBR)	Bio-EPT (60%)	MBR	Pre-cond.	Mp. AD	BGE (38%)	Anammox	VFD/IV
9	EPT (MBR, N-shunt)	Bio-EPT (60%)	MBR, N-shunt	Pre-cond.	Mp. AD	BGE (38%)	Anammox	VFD/IV
10	EPT (MBR, N-shunt, CHP)	Bio-EPT (60%)	MBR, N-shunt	Pre-cond.	Th. AD	CHP (38%+heat)	Anammox	VFD/IV
11	UASB (basic)	UASB (60%)	ASP + FST	Pre-cond.	Mp. AD	BGE (38%)	Anammox	VFD/IV
12	UASB (MBR)	UASB (60%)	MBR	Pre-cond.	Mp. AD	BGE (38%)	Anammox	VFD/IV
13	UASB (MBR, N-shunt)	UASB (60%)	MBR, N-shunt	Pre-cond.	Mp. AD	BGE (38%)	Anammox	VFD/IV
14	UASB (MBR, N-shunt, CHP)	UASB (60%)	MBR, N-shunt	Pre-cond.	Th. AD	CHP (38%+heat)	Anammox	VFD/IV
15	Main-stream Anammox (with EPT)	Bio-EPT + CEPT (80%)	Anammox, MBR	Pre-cond.	Th. AD	CHP (38%+heat)	Aug. / no	VFD/IV
16	Main-stream Anammox (with AnMBR)	AnMBR (85%)	Anammox, MBR	Pre-cond.	Th. AD	CHP (38%+heat)	Aug. / no	VFD/IV
17	WRP in Tuas (domestic stream)	Bio-EPT (60%)	MBR	Pre-cond.	Mp. AD	BGE (38%)	Anammox	VFD/IV

Terms and Abbreviations:

A-stage	A type of Biosorption EPT process	DEMON®	Deammonification, a type of Anammox process
AD	Anaerobic Digester	DFE	Dual Feed Engine
- Mp. AD	- Mesophilic Anaerobic Digester (30-38℃)	EPT	Enhanced Pre-treatment Treatment
- Th. AD	- Thermophilic Anaerobic Digester (50-57℃)	- Bio-EPT	- Biosorption Enhanced Pre-treatment
AnMBR	Anaerobic MBR	- CEPT	- Chemically Enhanced Pre-treatment
ASP	Activated Sludge Process	FST	Final Settling Tank / Final Clarifier
Aug.	Augmentation of main-stream by side-stream	N-shunt	Nitrite-shunt process / partial nitrification
B-stage	Activated sludge process, used after A-stage	Pre-cond.	Solids Pre-conditioning
BGE	Biogas Engines	PST	Primary Settling Tank / Primary Clarifier
CHP	Combined Heat and Power generator	VFD/IV	Variable Frequency Drive / Inlet Vane control

Conventional primary sedimentation tanks (PST) are typically able to remove only 40% of these organics; the remaining organics are degraded in the aeration tanks, which accounts for as much as 40-60% of total energy consumption (Gundry, 2008; WERF, 2009). The EPT strategy seeks to improve upon this by using biological or chemical sludge to adsorb the influent particulate matter. This organics-rich sludge is then sent to anaerobic digesters for conversion into biogas (a detailed description of the biosorption EPT method has been given in section 5.1). In contrast, the anaerobic pre-treatment strategy seeks to directly utilise the influent organics in the main-stream. Biodegradable matter is held in the anaerobic reactor, where it is hydrolysed and converted by anaerobic bacteria into biogas (a detailed description of the UASB and Anaerobic MBR technologies has been given in sections 5.2 and 5.3 respectively).

The application of advanced thermal treatment technologies (ATT), such as pyrolysis and gasification, for the further treatment of waste sludge has been included in Figure 3.1 in order to give a holistic view of how this class of technologies can be used to improve the energy balance of a WRP. However, as the application of these technologies to waste sludge is not yet mature, there is limited reliable information available on the process performance of these technologies. Hence, ATT options have been omitted from the configurations list in table 3.1 and subsequent analysis in section 3.4.

3.3.1 Comparison between Strass WWTP and conventional WRP activated sludge process (Configurations 1 and 2):

Strass WWTP has a higher organics capture rate in the A-stage (a type of biosorption EPT) as compared to the conventional PST. This, together with advanced controls and VFD blowers, reduces the aeration requirements in the B-stage (the activated sludge stage). In addition to the higher COD load in the anaerobic digesters, the highly efficient engines also serve to increase the energy recovery of the plant. A DEMON® process (a patented Anammox system that runs as a Sequencing Batch Reactor process) in the dewatering centrate return stream with high ammonium load further reduces nitrogen load on the main-stream, reducing aeration requirements.

3.3.2 Brownfield upgrades (Configurations 3 to 6):

Configurations 3 to 6 show possible increasing retrofits of Brownfield WRPs towards Strass WWTP's process configuration. In configuration 3, basic upgrades include advanced sensors, VFD blowers and fine bubble diffusers, as well as increasing power generation efficiency from 25-30% to 38% using biogas engines. A side-stream Anammox process reduces the nitrogen load on the main-stream. An additional process, solids pre-conditioning, increases the biodegradability of the feed sludge to the anaerobic digester, improving biogas yield and improving digested sludge dewaterability.

In configuration 4, in contrast to Strass WWTP, a MBR is used to replace the conventional ASP and FST.

In configurations 5 to 6, the existing PSTs are retrofitted into biosorption EPT processes to increase organics capture as is done in Strass WWTP. In the ideal case (scenario 6), aeration controls are sufficiently well developed to allow the implementation of the nitrite-shunt pathway in the MBR, further reducing aeration requirements.

3.3.3 Greenfield EPT process designs (Configurations 7 to 10, and 17 (WRP in Tuas)):

Configurations 7 to 10 are possible Greenfield plant process designs based on utilising EPT as the pre-treatment process. Configuration 7 is the most basic form of the EPT strategy, and is almost identical to the Strass WWTP concept. The difference is the inclusion of solids pre-conditioning, such as ultrasonic sludge disintegration, which would further increase the biogas yield of the anaerobic digester. Also, in this configuration a CHP facility is not included because while Strass WWTP is able to utilise the recovered heat for heating purposes during cold seasons, in Singapore's tropical climate there is no such use for the recovered heat. The heat could, however, be used to partially offset the heating requirements of a sludge dryer, if such a facility is employed.

Configurations 8 and 9 utilise the MBR for secondary treatment, with configuration 9 including the implementation of nitrite-shunt.

Configuration 10 represents the ideal EPT configuration, where organics-rich EPT sludge and pre-conditioned waste activated sludge are digested at thermophilic ranges for maximised biogas generation. The biogas is combusted in a CHP facility, which uses the recovered heat to offset the heating requirements of the thermophilic digester.

The recommended WRP in Tuas design is based on the EPT strategy, and is discussed in detail in section 3.4.2.

3.3.4 Greenfield UASB process designs (Configurations 11 to 14):

Configurations 11 to 14 are possible Greenfield plant process designs based on utilising the UASB as the pre-treatment process. The stepwise improvements from basic to ideal scenarios are identical to that of the EPT configurations, except that the UASB is used in place of the EPT. A major difference between the EPT and UASB strategies is that the UASB directly converts influent organics into biogas. This results in a substantially reduced role of the anaerobic digester and overall reduction in footprint.

3.3.5 Future main-stream Anammox process designs (Configurations 15 to 16):

These two configurations are possible Greenfield plant process designs based on main-stream Anammox. The main-stream Anammox, if successfully applied, would be the most energy and carbon efficient nitrogen removal process currently known. This would also eliminate the usefulness of a side-stream Anammox reactor, unless the side-stream reactor is being used to augment the main-stream reactor with Anammox sludge.

The core function of the pre-treatment process has been changed to remove as much organics as possible in order to protect the Anammox reactor from process upsets. Using the EPT strategy, a biosorption EPT augmented with additional chemical EPT could be used to achieve up to 80% COD removal. This also allows even more organics to be diverted to the anaerobic digesters and thus the generation of more biogas. Using the anaerobic pre-treatment strategy, an anaerobic MBR could be used to remove up to 85% COD, as well as to provide consistent feed quality to the Anammox reactor. After the Anammox treatment, a final polishing stage using an aerobic MBR is required to remove any residual COD and ammonium.

3.4 Comparison of key process configurations

In Table 3.1, eight configurations of special relevance have been highlighted (in yellow) for detailed analysis, and the energy efficiencies of these configurations are shown in Table 3.2.

Strass WWTP and conventional WRP activated sludge process have been highlighted for comparison of the current state of technology. For Brownfield projects, it is considered that biosorption EPT retrofits may not be economically viable, while nitrite-shunt may not be achievable with existing infrastructure. For Greenfield projects, both the ideal scenarios for the EPT and UASB strategies have been analysed to provide an idea of the maximum energy efficiency achievable with short-term (5-10 years) technologies. For long-term scenarios, main-stream Anammox is considered to be the technology with the most potential for energy savings. Finally, an analysis of a possible WRP in Tuas configuration is given to provide an indication of a realistic process energy efficiency target.

Table 3.2: Comparison of key process configurations

No	**Process configuration**	**Process energy consumption (kWh/m^3)**			
		Total consumption (standardized to MBR/UF permeate effluent quality)*	**In-plant power generation**	**Net energy consumption**	**Overall energy efficiency (%)**
Current Technology – based on full-scale operational plant data					
1	Strass WWTP (benchmark)	0.341 (0.211 + 0.13) [a]	-0.34 [b]	0.001	100 % [b]
2	Conventional ASP (UPWRP as reference)	0.436 (0.306 + 0.13) [a]	-0.11	0.326	25 %
Short-term (5-10 years) – technologies currently being pilot / demo tested in WRPs					
4	Brownfield upgrade (MBR)	0.416 (0.306 + 0.11) [a]	-0.181	0.235	44 %
17	WRP in Tuas concept (Bio-EPT + MBR)	0.321	-0.28 [b, c, d]	0.041 [e]	87 % [e]
10	EPT-MBR (Ideal configuration)	0.30	-0.28 [b, c]	0.02	93 %
14	UASB-MBR (Ideal configuration)	0.26	-0.27 (?) [f]	-0.01	104 %(?) [f]
Long-term (>10 years) – technologies currently undergoing (or proposed for) lab tests by Singapore research institutes					
15	Main-stream Anammox with EPT (Ideal)	0.29	-0.3	-0.01	103 %
16	Main-stream Anammox with AnMBR (Ideal)	0.27	-0.39 (?) [f]	-0.12	144 %(?) [f]
<u>Notes and Assumptions:</u>					
[a] The Strass WWTP and PUB WRP secondary effluents are treated to discharge quality, while the future WRP in Tuas domestic effluent is to be treated to MBR permeate quality. In order to compare the performance of existing plants equally with the future configurations, an equivalent MF/UF process (0.13 kWh/m^3) has been added to the energy consumption for existing plants. For Brownfield upgrades to MBR process, the MBR scouring energy of (0.11 kWh/m^3) has been added. [b] Strass WWTP receives a relatively higher organic loading as compared to Singapore (Jonasson, 2007, pg 55). Using the EPT process, this allows a higher amount of organics to be converted into biogas. Thus, Strass WWTP is able to maintain an in-plant power generation of 0.34 kWh/m^3, which is higher than the 0.28 kWh/m^3 achievable by Singapore's WRPs. [c] The improved power generation of the EPT configuration is based on a combination of higher COD fed to the					

Anaerobic Digester (AD) and use of higher efficiency engines. Using Strass WWTP as a reference, upgrading the COD capture from 40% (conventional PST) to 60% (EPT) is projected to improve the CH_4-COD fraction from 17.9% (UPWRP) to 35.9% (Strass). By further increasing engine efficiency from the current 30% to 38% (Strass), this would give a projected increase in power generation of 2.54 times. The power generation of such a configuration is thus = 0.11 kWh/m^3 (UPWRP) x 2.54 = 0.28 kWh/m^3.

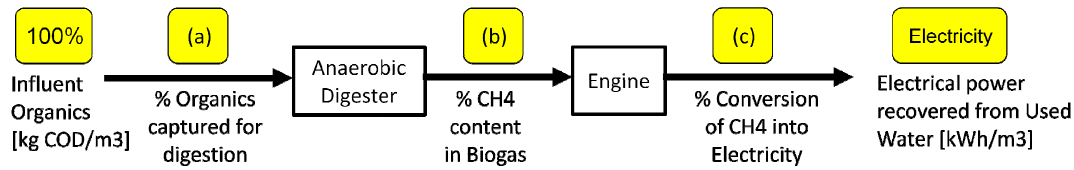
[(d)] Taking into consideration other factors besides energy efficiency, ideally the biogas from WRP in Tuas could be sold to an external contractor or co-located power facility. In this scenario, there would not be any in-plant power generation. However, for purpose of comparison with the other process configurations, a value of 0.28 kWh/m^3 has been used to demonstrate the energy balance, assuming the external power facility utilise equivalent engines with 38% conversion efficiency.

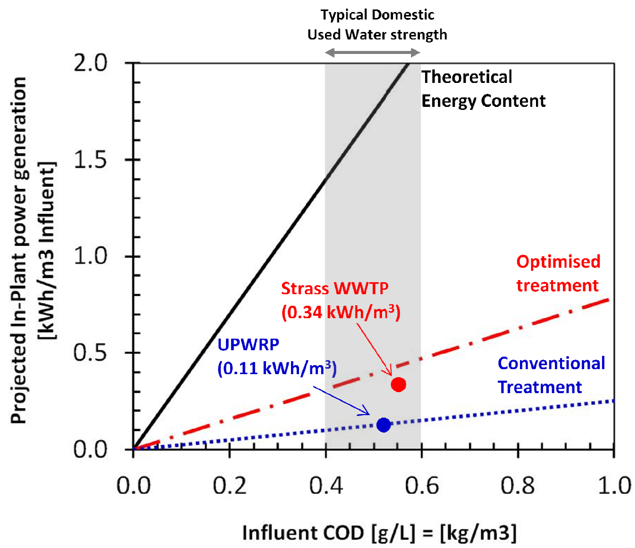
[(e)] The target baseline performance for the WRP in Tuas' net process energy consumption is <0.1 kWh/m^3, or >80% energy efficiency. This target is based on the utilisation of technologies that are proven / likely to be proven within the short term for Singapore conditions. The inclusion of subsequent upgrades (e.g. main-stream Anammox, nitrite-shunt, CHP) could potentially result in further improvement to the energy balance, and bring the performance closer to scenarios 10 and 15.

[(f)] These values are based on the strict assumption that there is an energy efficient method of recovering the dissolved CH_4 in the anaerobic pre-treatment effluent. Without such a process available, a saturated value of 20 mg CH_4/l exits the anaerobic reactor in dissolved state, and is subsequently stripped to the atmosphere during aeration in the secondary treatment system. This would account for as much as 0.225 kWh/m^3 of lost energy. These losses would rise further if the occurrence of CH_4 super-saturation is observed.

3.4.1 Current state of technology (Configurations 1 and 2)

Although Strass WWTP is reported to have achieved energy-positive status, the treatment process is designed to treat domestic used water to discharge limits. In Singapore's case, however, the final product water is to be used as NEWater feedstock, and the RO process should receive feed water of MBR or MF/UF permeate quality. In order to better compare the energy efficiencies of the different configurations, an equivalent MF/UF energy requirement of 0.13 kWh/m^3 has been added to the energy consumption figures for treatment processes using a secondary clarifier. Thus, if Strass WWTP and conventional WRPs were to produce water of MF/UF permeate quality, the plants' respective overall energy efficiencies would be 100% and 25%. Even so, from Table 3.2 it can be seen that Strass WWTP (configuration 1) has both lower energy consumption and higher energy generation than a conventional WRP (configuration 2). The reasons for this have been covered in detail in the Strass WWTP case study in section 2.2.2.





Reference Scenarios	(a)	(b)	(c)	Electricity
Theoretical Energy Content of Used Water – (Benedek, 2008)	100%	100%	100%	1.7 kWh/m³
Optimised reference scenario – projected based on Van Lier (2008)	80%	70%	40%	0.381 kWh/m³
Conventional scenario – projected based on Cao (2011)	40%	62%	30%	0.126 kWh/m³

Figure 3.2 Theoretical and actual electrical energy recoverable from used water

Figure 3.2 shows a comparison of theoretical and actual useful electrical energy recoverable from domestic used water. Dr Andrew Benedek, in his Singapore Water Lecture (2008), noted that used water can possibly contain 1.7 kWh/m^3 of energy. Recent literature publications have indicated that used water from Northeast England (Heidrich et al., 2011) and Toronto, Canada, (Shizas, 2004) have energy content of 2.13 kWh/m^3 and 1.77kWh/m^3 (assuming that 7.6kJ/L and 6330 kJ/m^3) respectively. Hence, Dr Benedek's conservative value of 1.7kWh/m^3 is a realistic number that can be adopted without going into the experimental determination of energy content in Singapore's used water.

Based on domestic used water strength of 0.5 g COD/l and an inherent energy value of 1.7 kWh/m^3, a theoretical line (a) can be drawn representing the absolute limit of energy recovery from domestic used water. In reality, energy losses due to inherent system inefficiencies are inevitable. A more realistic scenario is shown in line (c), where conventional treatment efficiencies are used as a baseline guide: 40% organics capture in the PST; 62% methane concentration in the biogas, with the rest converted into by-products such as carbon dioxide and cellular assimilation; and 30% conversion efficiency of the biogas into useful electricity (Cao, 2011b). An upper limit future scenario is shown in line (b), assuming the following improvements: 80% organics capture rate (possibly through EPT or anaerobic pre-treatment); 70% biogas methane content; and 40% electrical conversion efficiency (Van Lier, 2008).

Based on these scenarios, a lower reference limit of 0.126 kWh/m^3 (1.7 x 40% x 62% x 30%) and an upper limit of 0.381 kWh/m^3 (1.7 x 80% x 70% x 40%) can be established. The UPWRP reference energy generation of 0.11 kWh/m^3 is close to the lower reference limit, as expected due its conventional process configuration, while Strass WWTP's value of 0.34 kWh/m^3 is approaching the reference upper limit. It must be noted however, that Strass WWTP receives an influent with an average COD value 100-150 mg/l higher than UPWRP, thus allowing it to reach a potentially higher energy recovery than UPWRP. It is also noteworthy that Strass WWTP practices co-digestion of sludge and food waste. While the calorific contribution of the food waste has been omitted from this analysis, there remains the possibility of food waste contributing to enhanced digestion rates, thus improving the overall efficiency of the anaerobic digesters. A comparison of Strass WWTP and UPWRP's COD mass balance in terms of % influent COD is shown in Table 3.3 below.

Table 3.3 COD mass balance comparison between Strass WWTP and UPWRP

% of influent COD ► **Plant ▼**	**% COD removed by Primary treatment**	**% COD fed to anaerobic digesters**	**% COD as CH_4 in biogas**	**% COD dissimilated in activated sludge**	**% COD remaining in dewatered sludge**	**% COD remaining in secondary effluent**
UPWRP	39.2	44.9	17.9	52.9	22.3	7.0
Strass WWTP	60.7	74.3	35.9	21.8	37.6	4.7

From Table 3.3 it can be seen that the A/B-stage design of Strass WWTP diverts a combined primary and secondary sludge flow of 74.3% COD to the anaerobic digesters, while in UPWRP this value is 44.9%. Due to the higher biodegradability of the A-stage sludge, Strass WWTP is able to convert 35.9% of the influent COD into methane, almost twice that of UPWRP's value of 17.9%. This equates to 13.6% of the influent COD converted into electricity for Strass WWTP (35.9% x 38% engine efficiency), which is 2.54 times greater than UPWRP's value of 5.4% (17.9% x 30% engine efficiency).

Assuming that equal performance of the biosorption EPT process (35.9% CH_4-COD) and improved engines to the efficiency of Strass WWTP's engines (38%) can be replicated in Singapore, the maximum energy recovery capacity would then be 0.28 kWh/m^3 (2.54 x UPWRP's current power generation capacity of 0.11 kWh/m^3).

3.4.2 Short-term (5-10 years) technologies (Configurations 4, 10, 14 and 17)

Four scenarios were analysed: Brownfield upgrades of existing WRPs, EPT and UASB configurations of Greenfield WRPs, and other options for the WRP in Tuas. These scenarios were analysed using technologies currently undergoing pilot or demo trials, and would be expected to be ready for adoption within the next 5 years.

(i) Brownfield scenario (Within next 5 years)

In the Brownfield upgrade scenario (configuration 4), the focus is on the "low hanging fruit", or improving the current process efficiencies by optimising the existing facilities. These upgrades will be applicable to existing WRPs such as Changi, Kranji and Jurong WRP. Basic upgrades include installation of advanced sensors, blower optimisation through VFD and IV control, installation of fine bubble diffusers, as well as increasing DFE efficiency from 25-30% to 38% using more efficient biogas engines. New facilities include a side-stream Anammox process, which gives about

3-5% energy savings, and solids pre-conditioning, which gives a further 10% COD-CH_4 enhancement (relative to the influent).

An MBR system may be considered, especially for future plant expansions. This is due to the consideration that NEWater production is the top priority for domestic stream treatment in Singapore, and an MBR is able to provide consistent effluent quality for RO feedstock. The MBR also has reduced plant footprint and increased automation, both of which are important advantages. An MBR would add 0.11 kWh/m^3 energy consumption due to membrane scouring requirements. However, it would offset MF/UF requirements downstream, saving 0.13 kW/m^3 and thus resulting in net energy savings when the water reclamation system is analysed as a whole. The upgraded Brownfield plant would have its energy efficiency increased from 25% to 44%.

Other Brownfield scenarios (configurations 5 and 6) would involve upgrading the PST to a biosorption EPT process. While this would further improve the energy efficiency of the plant, it would require a significant retrofit of the PST, aeration and sludge piping system. In addition, further review of the anaerobic digesters must be carried out to ensure that there is sufficient capacity for the increased sludge load. In light of these factors, Brownfield upgrades involving biosorption EPT may not be economically viable if cost savings through energy efficiency is the objective, especially for UPWRP and JWRP, which are due to be decommissioned in 2022.

(ii) Greenfield scenarios (Within 10 years)

Greenfield scenarios, on the other hand, stand to benefit greatly from the biosorption EPT process (configuration 10).

With an influent organics capture rate of 60%, the EPT process reduces the organic load on the secondary treatment by 1/3 (from 60% to 40% of the influent organic load). In the ideal case, the use of nitrite-shunt further reduces aeration requirements by 25% resulting in an overall 50% reduction (2/3 x 75%) in aeration requirements for secondary treatment (not including membrane scouring requirements). As the biosorption EPT process uses biological sludge as an adsorption media, it also has some aeration requirements. Using Strass WWTP as a reference, the Strass A-stage process (a type of biosorption EPT) consumed an average of 810 kWh/day over 10 years (1996-2005) (WERF, 2010). Given that the Strass WWTP average capacity of 23,771 m^3/day, this equates to an average EPT energy consumption of 0.034 kWh/m^3, which is small considering the benefits gained in terms of reduced aeration requirements and increased biogas yield. Based on the ideal EPT configuration, the overall process energy requirements can be brought down from 0.436 kWh/m^3 to 0.300 kWh/m^3. This is accompanied by an increase in in-plant power generation from 0.11 kWh/m^3 to 0.28 kWh/m^3 (as described in section 3.4.1), resulting in a net process energy efficiency of 93%.

Anaerobic pre-treatment was also considered as an alternative pre-treatment process to biosorption EPT. Amongst the options, UASB was identified as the process with the most potential, as it is a well-established process in other countries and it is able to replace the PSTs. In addition, due to the slow growth rate of anaerobic bacteria in the UASB, savings from reduced sludge disposal costs may be gained.

In the ideal UASB process (configuration 14) a minimum of 60% influent COD removal rate is assumed. This puts the savings in aeration energy for secondary treatment equal to that of the biosorption EPT process described above, and the overall process would have very low process energy requirements of 0.26 kWh/m^3. Based on the strict assumption that there is an efficient method to strip and recover the dissolved methane in the UASB effluent, an energy recovery of 0.27 kWh/m^3 (assuming only minor losses of dissolved methane) would make the overall process energy-positive, with a net process energy efficiency of 104%.

Realistically, however, this figure is likely to be lower due to dissolved methane losses in the UASB effluent. As seen in Figure 3.3, at Singapore's ambient used water temperature of 30℃, methane saturation is 20 mg/l. At saturation conditions, this accounts for 0.225 kWh/m^3 of energy stored as dissolved methane. Without employing an effective means of stripping and recovery, the dissolved methane would be stripped during aeration in the secondary treatment system and lost to the atmosphere as wasted energy generation potential. Furthermore, should methane super-saturation be observed, this value may increase up to several times more

(Pauss et. al., 1990; Hartley and Lant, 2006). Due to the large flow rates in the main-stream as compared to the dewatering centrate side-stream, several times more methane would be lost by the UASB as compared to the anaerobic digesters, and would substantially reduce the energy effectiveness of the UASB process configuration.

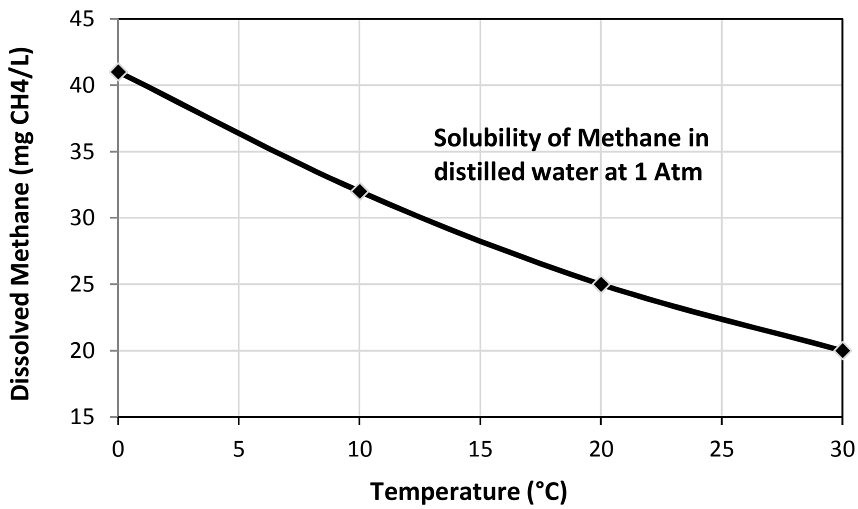


Figure 3.3 Solubility curve of dissolved methane in distilled water at 1 atmosphere (adapted from Yamamoto et. al., 1976)

(iv) Proposed WRP in Tuas process configuration (Within 10 years)

Taking into consideration the assessment criteria in section 3.2 and the analysis of the Greenfield scenarios above, the following strategy is recommended for the design of the proposed WRP in Tuas:

- **Choice of EPT strategy** – Taking into consideration the lost energy generation potential if no effective dissolved methane recovery method is used for the UASB strategy, the biosorption EPT strategy is the more suitable candidate for the WRP in Tuas. In addition, this strategy has already been successfully applied at the full scale in Strass WWTP.

- **Choice of established technologies** – Based on the Used Water Master Plan, the WRP in Tuas is to begin construction in 2016. The technologies likely to be validated under Singapore conditions by that time are: biosorption EPT, side-stream Anammox, solids pre-conditioning, advanced sensors, VFD/IV blower controls and fine bubble diffusers. Provided that the biogas is being combusted on-site for electricity, then biogas engines with 38% efficiency will be recommended.

- **Potential long-term retrofits** – Nitrite-shunt, CHP engines and thermophilic digestion are potential future options for upgrading of the plant and provision will be made for their retrofit into the plant. Although nitrite-shunt is currently being pilot tested, the confidence of successful application will depend strongly on the effectiveness of the advanced sensors and aeration control, which must first be validated. Thus, it may not be suitable during the initial design stage of the WRP in Tuas. With regards to CHP, due to the preference to outsource energy generation to an external party, ideally the raw biogas generated could be sold. However, this limits the possibilities of utilising CHP heat, such as for thermophilic digestion. Hence, mesophilic digestion is the most likely choice for the WRP in Tuas.

- **80% Energy efficiency goal** – Based on the selected design (configuration 17) for the WRP in Tuas design, a process energy consumption of 0.321 kWh/m^3 and energy recovery of 0.28 kWh/m^3 (assuming on-site or off-site combustion with 38% efficiency engines) would give an overall energy efficiency of 87%.

3.4.3 Long Term (> 10 years) Future Plants (Configurations 15 and 16)

This section covers the analysis of envisioned process designs of future WRPs if any were to be built beyond 10 years time. Two long-term scenarios were analysed for emerging technologies currently being tested in the laboratory (or being proposed for testing) in research institutes in Singapore. The shortlisted technologies are main-stream Anammox and anaerobic MBR, both of which are undergoing pilot/full-scale trials overseas and are expected to be validated for full scale application in about 10 years. The two process configurations analysed in this review are built around the main-stream Anammox which, if successfully applied, would be the most energy efficient treatment process currently known.

In the EPT strategy (configuration 15), biosorption EPT augmented with chemical EPT is used to capture up to 80% of the influent organics. This high level of removal serves to protect the Anammox reactor from process upsets, and diverts even more organics to the anaerobic digesters for biogas production. The main-stream Anammox allows for 63% reduction in aeration requirements and almost 100% reduction in carbon demand. After the Anammox treatment, a final polishing aerobic MBR is used to remove any residual COD and ammonium. The large aeration savings result in a low process energy requirement of 0.29 kWh/m^3. Together with an increased energy recovery of 0.30 kWh/m^3, the overall process has a net energy efficiency of 103%.

Using the anaerobic pre-treatment strategy, an anaerobic MBR could be used to remove up to 85% COD, as well as to provide consistent feed quality to the Anammox reactor. This would result in a process energy requirement of 0.27 kWh/m^3, an energy recovery of 0.39 kWh/m^3 (which is around the projected upper limit of 0.381 kWh/m^3) and an overall net energy efficiency of 144%. Again, the energy recovery is contingent on the strict assumption that an effective method of stripping and recovering the dissolved methane is available and implemented.

In both cases, main-stream nitrite-shunt is a necessary precursor technology for the implementation of main-stream Anammox. Also, the main-stream Anammox would eliminate the usefulness of a side-stream Anammox reactor, unless the side-stream reactor is being used to augment the main-stream reactor with Anammox sludge.

3.4.4 Advantages and challenges of key process configurations

In addition to the differences in energy efficiencies between process configurations as discussed in the previous sections, each process configuration has its own advantages and challenges that should be considered. Table 3.4 summarises some of these factors for the eight shortlisted process configurations:

Table 3.4: Advantages and Challenges of key process configurations

No	Process configuration	Advantages	Challenges
1	Strass WWTP (benchmark) 100% energy efficiency	- A/B-stage is a stable, proven process under Strass conditions.	- The performance of A-stage / Bio-EPT processes is currently not known for Singapore's tropical climate and used water conditions. - Final effluent is treated for disposal. In Singapore's case, the necessity for water reclamation makes the MBR a more effective solution than a B-stage + FST configuration.
2	Conventional ASP (UPWRP as reference) 25% energy efficiency	- Stable, proven process under Singapore conditions. - Operators experienced with process.	- Relatively low energy efficiency. - Return stream from the dewatering centrifuge increases nitrogen load on the main-stream treatment processes. - Relatively high waste sludge production. - MF/UF treatment required prior to RO process for production of NEWater.
4	Brownfield upgrade (MBR) 44% energy efficiency	- MBR is a new but relatively well established process, with several membrane suppliers available. - Stable, consistent MBR effluent properties suitable for NEWater production. - Most process energy savings comes from improving existing facilities (e.g. engines, VFD) rather than adding new facilities.	- Extensive retrofitting may be required (including piping, diffusers, sensor networks, blowers and control systems) making the transition period challenging for operators. - Success of retrofit is highly dependent on the effective application and maintenance of the sensor instrumentation. - Extent of improvement in energy efficiency is limited by existing process configuration and facilities. - Any further retrofit (e.g. Bio-EPT, thermophilic AD) would incur high capital costs, making it economically unfeasible to attempt retrofitting into energy self-sufficiency.

17	WRP in Tuas concept (Bio-EPT + MBR) 87% energy efficiency	- Greatly increased energy efficiency. - Very rapid stabilization of Bio-EPT stage due to extremely short SRT. - Stable, consistent MBR effluent properties suitable for NEWater production. - Potential to further upgrade MBR with nitrite-shunt process in the future.	- Due to limited alkalinity in Singapore's domestic used water, COD removal in the Bio-EPT stage should be restricted to about 60%, allowing sufficient organic carbon to pass through to the anoxic zone for denitrification to replenish the alkalinity. Excessive COD removal in the Bio-EPT stage may result in the necessity for alkaline pH correction. - Further pilot / demo testing required in order to gain experience in handling of the sticky, viscous Bio-EPT sludge that is significantly different in properties from conventional activated sludge.
10	EPT-MBR 93% energy efficiency	- High energy efficiency. - Reduced waste sludge volume due to better sludge stabilization in the thermophilic AD. - Reduction in organic carbon requirements in the anoxic zone due to the application of nitrite-shunt process may open the possibility of increasing organics capture rate in the Bio-EPT stage, thus further increasing in-plant power generation.	- Due to limited alkalinity in Singapore's domestic used water, COD removal in the Bio-EPT stage should be restricted to about 60%. - Further pilot / demo testing required in order to gain experience in handling of the sticky, viscous Bio-EPT sludge that is significantly different in properties from conventional activated sludge. - Success of nitrite-shunt depends strongly on effectiveness of sensors and aeration control. - Increased release of N_2O, a greenhouse gas, from the nitrite-shunt process may be of concern. - The increased energy efficiency from the thermophilic AD is dependent on the effectiveness of heat recovery from the CHP system.
14	UASB-MBR 104% energy efficiency	- The UASB has very little operating power requirements, making this potentially the overall most efficient configuration	- By shifting the anaerobic process from the side-stream Anaerobic Digesters to the main-stream, which has a very much larger liquid flow, about 13-35% (at 35℃) of the methane produced is dissolved and subsequently lost to the atmosphere, resulting in increased greenhouse

		implementable within the short-term. - The UASB process produces less waste sludge than the PST or EPT processes, resulting in disposal cost savings. - Reduced plant footprint. - UASB suitable for tropical climates because higher temperatures enhance biodegradation rates. - Stable, consistent MBR effluent properties suitable for NEWater production.	gas emissions and lost energy generation potential. - The surrounding facilities may become affected by corrosive vapours released from the process. The need for additional facilities to strip and treat these vapours, as well as reinforcing the surrounding facilities with corrosion-resistant material, may increase the capital, maintenance and operating costs, offsetting the energy efficiency benefits. - Success of nitrite-shunt depends strongly on effectiveness of sensors and aeration control. - High energy efficiencies achievable only on the strict condition that there is an effective way to recover dissolved methane from the UASB effluent. - Increased release of N_2O, a greenhouse gas, from the nitrite-shunt process may be of concern. - The increased energy efficiency from the thermophilic AD is dependent on the effectiveness of heat recovery from the CHP system.
15	Main-stream Anammox with EPT 103% energy efficiency	- Very high energy efficiency. - Reduced waste sludge volume due to the slow growth rate of Anammox bacteria. - Elimination of organic carbon requirements for the Anammox stage allows the optimization of the EPT process to divert 60-80% COD to the	- Main-stream Anammox is currently an emerging technology at the pilot / full-scale trial, with very limited operating experience currently available. - Main-stream Anammox likely to be sensitive to fluctuations in used water characteristics and flow. System upsets may result in long recovery periods (weeks). - Success of nitrite-shunt and Anammox systems depends strongly on the effectiveness of sensors, aeration control and pH control. - Further pilot / demo testing required in order to

		anaerobic digesters for increased biogas generation.	gain experience in handling of the sticky, viscous Bio-EPT sludge that is significantly different in properties from conventional activated sludge. - The increased energy efficiency from the thermophilic AD is dependent on the effectiveness of heat recovery from the CHP system.
16	Main-stream Anammox with AnMBR 144% energy efficiency	- Very high energy efficiency. - Very low waste sludge generation due to the slow growth rate of anaerobic and Anammox bacteria. - Elimination of organic carbon requirements for the Anammox stage allows the optimization of the AnMBR process to utilise up to 85% COD for increased biogas generation.	- AnMBR and Anammox are both emerging technologies, with very limited operating experience currently available. - Further R&D is needed to study the fouling characteristics of the AnMBR, as well as membrane scouring regimes needed. - Additional safety measures against explosions must be applied should the biogas be used as a membrane scouring gas. - Loss of dissolved methane may be a concern as it is a greenhouse gas. - There is a potential for corrosion of surrounding facilities. - Success of nitrite-shunt and Anammox systems depends strongly on the effectiveness of sensors, aeration control and pH control. - High energy efficiencies achievable only on the strict condition that there is an effective way to recover dissolved methane from the AnMBR effluent. - The increased energy efficiency from the thermophilic AD is dependent on the effectiveness of heat recovery from the CHP system.

3.5 Chapter summary and conclusions

Based on a combination of several shortlisted technologies, a number of possible process configurations were addressed. Of these, eight relevant configurations were analysed in detail to give an understanding of the energy efficiencies potentially achievable under current, short-term and long-term conditions. With regards to applicability in Singapore WRPs, both Brownfield and Greenfield scenarios were analysed, taking into consideration specific local assessment criteria. Recommendations were given for potential Brownfield upgrades of existing WRPs, as well as for the design of the upcoming WRP in Tuas.

In conclusion, a biosorption EPT process followed by MBR is generally recommended as an energy efficient process design for the reclamation of domestic used water as NEWater feedstock. While anaerobic pre-treatment methods such as the UASB are also viable, the energy efficiencies of these configurations are restricted by the condition that an effective method of stripping and recovering dissolved methane must be available.

From the analysis, process energy efficiencies of over 80% are expected to be achievable with Greenfield plants using the EPT or UASB configuration. However, due to the limited influent COD and alkalinity, as well as the product water quality requirements, complete process energy self-sufficiency is not a realistic target in the short-term. In the long-term, main-stream Anammox remains the technology with the most potential for achieving energy self-sufficiency.

In addition to the technologies and issues discussed in this chapter, other issues such as industrial used water reclamation and phosphorus recovery, which are not within the main scope of this review but are nonetheless important for a holistic understanding of how to close the water loop, have been briefly addressed in chapter 7.

Chapter 4

Conclusions and Recommendations

4.1 Summary of Technology Review

4.1.1 Strategy towards WRP process energy self-sufficiency

This report was written with aim of providing an updated review of potential used water treatment technologies for adoption in the WRPs, with the focus on developing strategies to achieve increasing levels of energy efficiency. Relevant technologies and process configurations were evaluated based on a number of criteria, the three primary ones being: suitable product water quality for NEWater production, energy sustainability, and environmental sustainability.

The main strategy for working towards process energy self-sufficiency involves a threefold approach:

(1) Early capture of organics for anaerobic treatment;

(2) Improvements in aeration efficiency; and

(3) Improvements in biogas yield.

Regarding early capture of organics, both biosorption EPT and UASB options were analysed. Although UASB options generally had higher potential energy efficiencies, the problem of dissolved methane eventually led to the conclusion that biosorption EPT is a more feasible option.

As for improvements in aeration energy efficiency, advanced sensor controls, VFD blowers, fine bubble diffusers, and side-stream Anammox are recommended. Nitrite-shunt is a potential short-term upgrade, while main-stream Anammox is a potential long-term technology option. In all cases, MBR is recommended in order to produce a stable effluent of consistent quality for NEWater production.

Regarding improvements in energy recovery through biogas, solids pre-conditioning and high efficiency biogas engines (38%) are recommended, while CHP and thermophilic AD are worth considering. For domestic used water, an upper reference limit of 0.381 kWh/m^3 of power can be generated under ideal conditions.

4.1.2 Process configurations for Brownfield plant upgrades, Greenfield implementations and future WRPs

It is estimated that Brownfield upgrades can raise the process energy efficiency of existing plants from the current 25% to more than 40% using the process upgrades highlighted by red borders in Figure 4.1.

By adopting a side-stream Anammox, high efficiency biogas engines, sludge pre-conditioning and advanced aeration control, we can potentially achieve up to 43.5% process energy efficiency with increased biogas recovery. The side-stream Anammox only contributes a small fraction of improvement (3-5%); however, the main contribution is in terms of R&D value, as the system will allow PUB staff to be equipped with the training and knowledge for potential future main-stream Anammox installations.

The corresponding sludge reduction based on these upgrades will be from 9.3 dry tonnes per 100,000m^3 of used water treated to 8.4 dry tonnes per 100,000m^3 of used water treated. These upgrades will be applicable to the proposed plant expansions and enhancements to Changi, Kranji and Jurong WRPs.

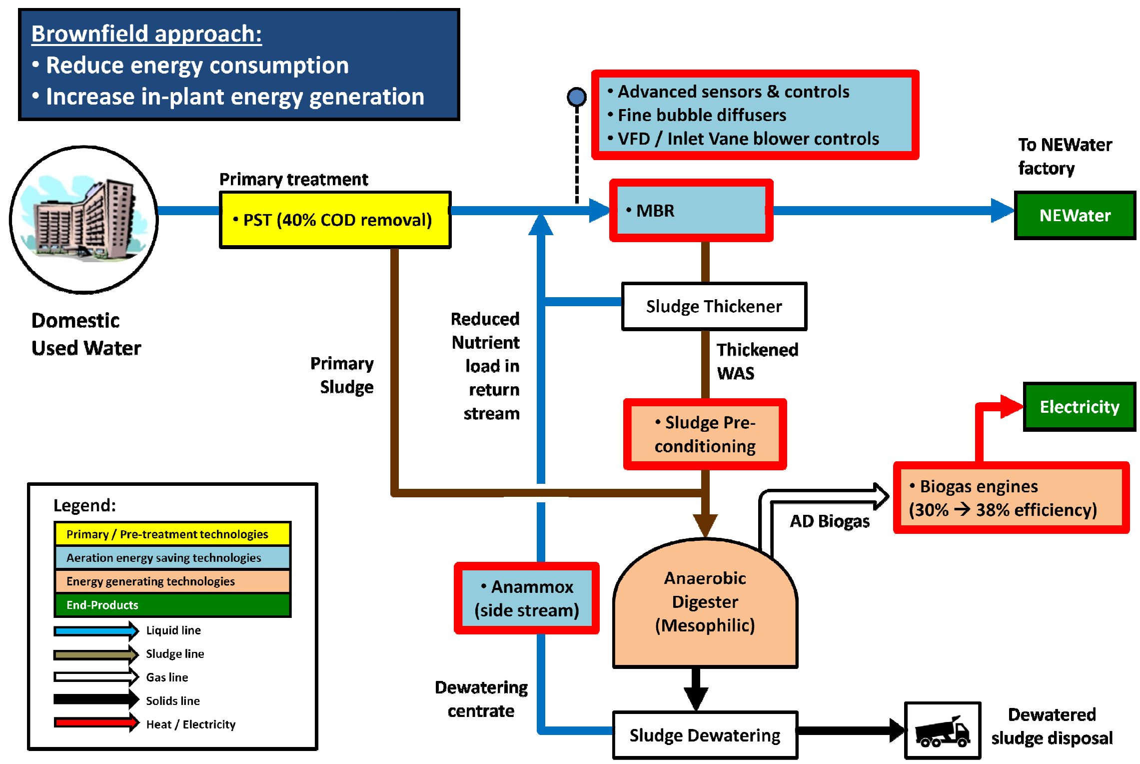


Figure 4.1 Recommended Brownfield WRP process upgrades for domestic used water

Table 4.1 Brownfield upgrade comparison table

Process configuration	Process energy consumption (kWh/m^3)				Sludge generation (Dry tonne)
	Total consumption (standardised to MBR/UF permeated effluent quality)	In-plant power generation	Net energy consumption	Process energy efficiency	Per 100,000 m^3 used water
Brownfield upgrade (MBR)	0.416 (0.306 + 0.11)	-0.181	0.235	44%	8.4
UPWRP (Baseline reference)	0.436 (0.306 + 0.13)	-0.11	0.326	25%	9.3

For Greenfield projects in the 5 - 10 years time frame such as the proposed WRP in Tuas, it is estimated that a process energy efficiency of 80% is achievable. Complete energy self-sufficiency is not a feasible target due to the requirement to treat the used water to MBR permeate quality. Figures 4.2 and 4.3 shows the recommended process configurations for the WRP in Tuas for both domestic and industrial (segregated) used water streams:

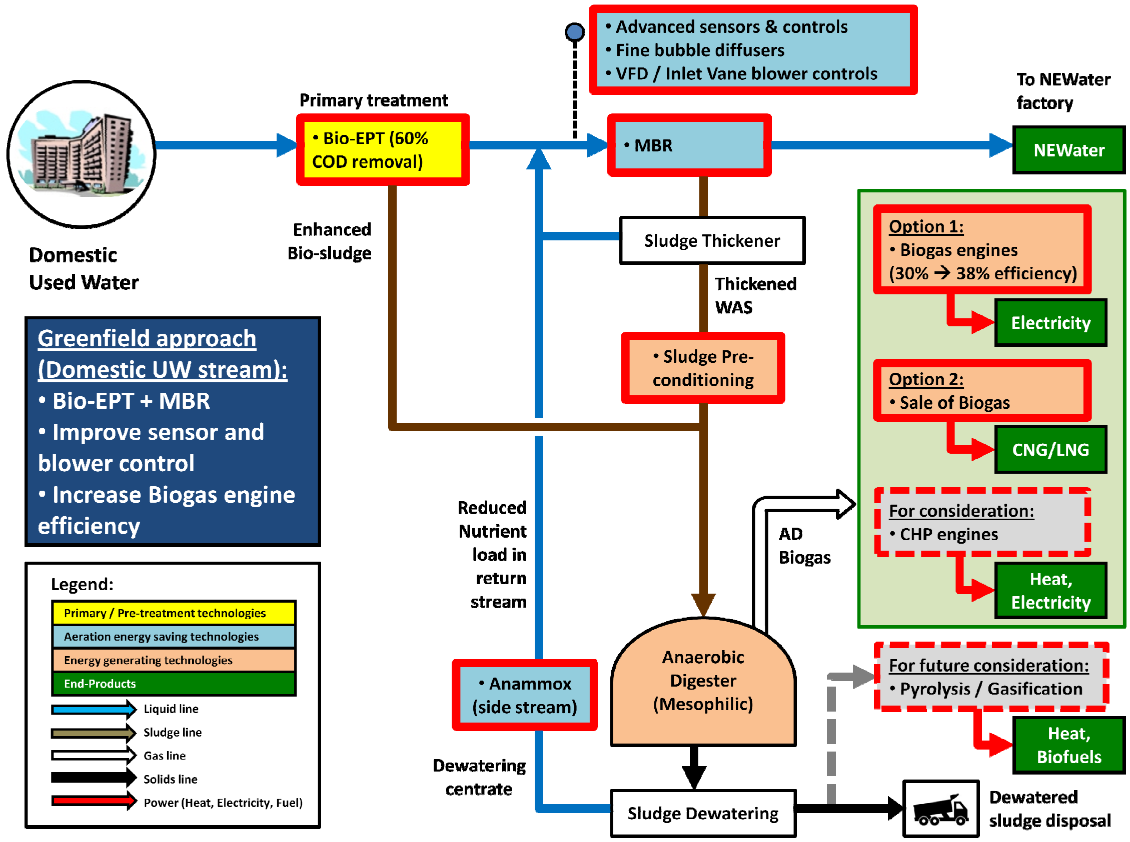


Figure 4.2 Recommended WRP in Tuas process configuration for domestic used water

Table 4.2 Bio-EPT with MBR comparison table

Process configuration	Process energy consumption (kWh/m^3)				Sludge generation (Dry tonne)
	Total consumption (standardised to MBR/UF permeated effluent quality)	In-plant power generation	Net energy consumption	Process energy efficiency	Per 100,000 m^3 used water
Bio-EPT + MBR	0.321	-0.28	0.041	87%	8.8
UPWRP (Baseline reference)	0.436 (0.306 + 0.13)	-0.11	0.326	25%	9.3

With the recommended processes highlighted by the red borders in Figure 4.2, the target is to achieve process energy efficiencies beyond 80% in the domestic stream of the proposed WRP in Tuas. This will be done using the increased conversion of organics to biogas through enhanced pre-treatment with the corresponding optimisation of process energy use in the aerobic MBR system. One drawback is that the reduction in dry sludge production will be only be about 0.5 dry tonnes per 100,000m^3 of used water treated due to the nature of the Biosorption EPT process applied. However, there is a possibility that advanced thermal treatment such as pyrolysis and gasification can be applied to the dewatered sludge to provide an energy neutral solution for sludge minimisation and disposal.

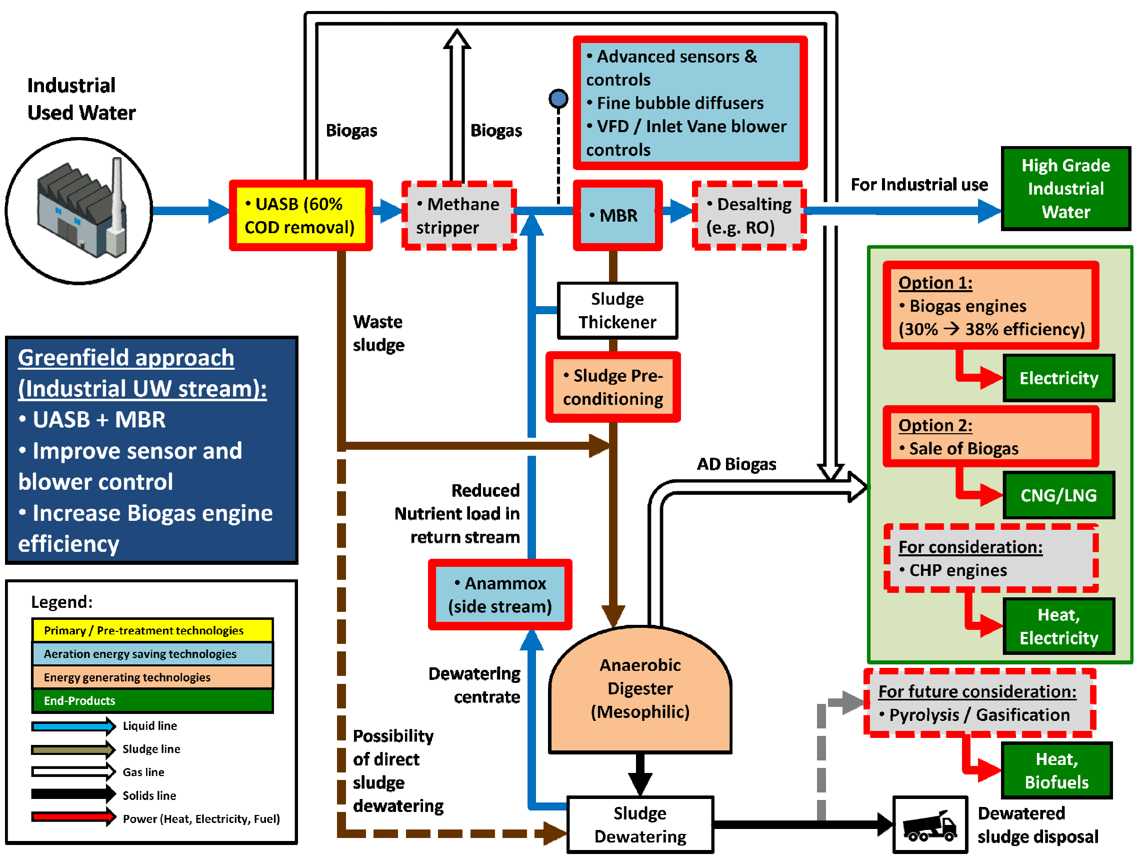


Figure 4.3 Recommended WRP in Tuas process configuration for industrial used water

With regards to the industrial stream, the target is to treat the industrial used water to the high grade industrial water for supply back to the industries, using the recommended processes highlighted by the red borders in Figure 4.3. By using the Upflow Anaerobic Sludge Blanket (UASB) reactor and other process optimisations, the process energy consumption is projected to be reduced by 0.15 kWh/m^3, along with a 20% reduction in excess sludge production. The drawback of this process is the presence of dissolved methane in the UASB effluent, and the presence of salts in the MBR effluent due to the high conductivity (~3000 µS/cm) of the industrial used water influent. In order for this proposed process to function efficiently, an effective and energy efficient methane stripper post UASB treatment is required to recover the dissolved methane in the UASB effluent stream and also to prevent methane emission to the atmosphere. Also, a desalting process may be needed in the post treatment to reduce the conductivity of the treated effluent so that it is suitable for industrial water use. Alternatively, a blending line from the treated domestic used water stream may be used to dilute and improve the quality of the treated industrial used water stream.

Table 4.3 Future configurations comparison table

Process configuration	Process energy consumption (kWh/m^3)				Sludge generation (Dry tonne)
	Total consumption (standardised to MBR/UF permeated effluent quality)	In-plant power generation	Net energy consumption	Process energy efficiency	Per 100,000 m^3 used water
Main-stream Anammox + EPT	0.29	-0.3	-0.01	103%	6.3
Main-stream Anammox + AnMBR	0.27	-0.39	-0.12	144%	5.5
Conventional ASP (UPWRP as reference)	0.436	-0.11	0.326	25%	9.3

In the long-term (>10 years), complete process energy self-sufficiency or even net energy positive WRPs may be achievable through a combination of main-stream Anammox and either EPT or AnMBR pre-treatment. The possible configurations and the energy efficiencies are shown in Table 4.3. With main-stream anammox and

AnMBR, it may be possible to have net energy production from the plant processes along with a 40% reduction in sludge production per volume of used water treated. However, as these are currently emerging technologies, these figures will be subjected to the successful maturation and implementation at full scale installations.

4.2 Technology Roadmap

A summary of the status of the technologies discussed in section 4.1 and the recommended actions for R&D are listed in Table 4.4, according to the strategic role of each technology group (Pre-treatment, Secondary treatment, Energy recovery and Other technologies). From this, a WRP technology roadmap has been developed according to timeline (Table 4.5) and at each individual WRP (Table 4.6).

Table 4.4: Summary of technologies recommended for development

Technology	**Status**		**Notes / Recommendations**
	Singapore	**Worldwide**	
Pre-treatment Technologies			
Biosorption EPT	Pilot-scale	Full-scale (e.g. Strass WWTP)	Strongly recommended for further R&D Pilot plants: - “Energy+” plant (KWRP), - Integrated Validation Plant (UPWRP)
Chemical EPT	None	Full-scale	Recommended for lab-scale jar test studies to compare with Bio-EPT results. Conventionally done using polymer and ferric chloride coagulants.
UASB	Demo-scale	Full-scale	Recommended for further investigation of industrial used water treatment. Not recommended for domestic used water reclamation.

AnMBR	Lab-scale	Pilot-scale	Recommended for further R&D by local research institutes. Focus should be on mitigation of membrane fouling.
Secondary Treatment Technologies			
Advanced sensors and controls	Ongoing trials	Full-scale	Strongly recommended for further trials. Focus is on mitigation of sensor fouling. Currently ongoing trials at KWRP and CWRP.
VFD / Inlet Vane blower controls	Full-scale	Full-scale	Strongly recommended for implementation. R&D must also be combined with sensor and control studies.
Fine bubble diffusers	Full-scale trials	Full-scale	Strongly recommended for further trials. Focus is on mitigation of diffuser fouling.
MBR (aerobic)	Demo-scale	Full-scale	Strongly recommended for further R&D. Focus is on determining optimal Mixed Liquor Suspended Solids (MLSS) & SRT levels, as well as minimising aeration requirements for membrane scouring.
Nitrite-shunt	Pilot-scale	Full-scale	Strongly recommended for further R&D. Pilot studies: - "Energy +" plant (KWRP)
Anammox (side-stream)	Pilot-scale	Full-scale	Strongly recommended for further R&D. Although side-stream Anammox does not contribute much to energy savings (only 3-5%), the R&D experience gained will open up options for further R&D into main-stream Anammox technologies. Pilot studies: - Anammox pilot plant (CWRP) - Integrated Validation Plant (UPWRP)

Anammox (main-stream)	Lab-scale (proposed)	Range from Lab-scale to Full-scale trials	Strongly recommended for further R&D at local research institutions. To closely monitor full scale trials at: - Strass WWTP (Austria) - Glarnerland WWTP (Switzerland) To monitor closely lab scale trials at: - Blue Plains (Washington D.C., USA) STOWA and WERF are currently leading amongst the GWRC members, both of which have full-scale trial projects.
Energy Recovery Technologies			
Solids Pre-conditioning	Full-scale (planned at UPWRP)	Full-scale	Recommended to closely monitor the performance of ultrasonic sludge disintegration at UPWRP, as well as monitor the development of other solids pre-conditioning options. Actual effective energy savings from this group of technologies remains debated by experts.
Thermophilic AD	None	Full-scale	Recommended for consideration at the lab- and pilot- scale.
High efficiency Biogas Engines (38% and beyond)	None	Full-scale	Strongly recommended for further R&D and for implementation.
CHP systems	None*	Full-scale	Recommended for future consideration for Greenfield projects. *Currently only electricity is being recovered in dual-fuel engines in UPWRP, KWRP and JWRP. In CWRP, biogas is combusted only for heat, which is used for sludge drying.
Dissolved Methane Recovery	Pilot-scale	Full-scale	Recommended for further monitoring of development of technology. Downflow Hanging Sponge (DHS) system employed in UASB pilot plant (JWRP).

Advanced Thermal Treatment (ATT): Gasification and Pyrolysis	None	Full-scale	Recommended for further monitoring of development of technology.
Other Technologies			
Phosphorus recovery	None	Full-scale	Recommended for future consideration for Greenfield projects, on the assumption that phosphorus discharge limits will become more stringent.
Greenhouse gas (GHG) emissions characterisation (N_2O, CH_4)	Planned	Full-scale studies	An R&D agreement has been signed with NUS to conduct N_2O emission studies at the WRPs. Proposal pending. Dissolved CH_4 emissions recommended in order to quantify energy losses from UASBs and other anaerobic pre-treatment systems.
Sludge drying	Full-scale (CWRP)	Full-scale	Although sludge drying is an energy-consuming process, by raising the dry solids content of sludge from 22% DS (dewatered sludge) to over 90% DS (dried sludge), significant savings in disposal costs can be achieved due to the sludge volume reduction. Sludge drying synergises well with CHP units, where the recovered heat from the CHP is used to partially offset the required heat for sludge drying. Sludge drying is also a pre-requisite process to prepare the sludge (to at least above 50% DS) before Pyrolysis or Gasification. However, care must be taken during the storage of dried sludge as it can continue to generate heat, especially if in contact with ferric chemicals. This may pose an explosion and fire hazard.

Biogas scrubbing & upgrading	Dosing of ferric into AD to suppress H_2S formation	Full-scale	Adding a dehumidifier and activated carbon unit to remove siloxanes will improve the effective lifespan and efficiency of biogas engines. If biogas is being sold as vehicle fuel or piped gas, the methane content must be upgraded from 60% to above 95%. The stripped dissolved biogas from anaerobic pre-treatment effluent is expected to be dilute in methane (30% or less) and requires upgrading to increase its concentration to useable levels.
Plant mass balance modelling and optimisation	Basic mass balance	Full-scale	Regular mass balance studies will be able to show the impact of plant improvements and activities. Optimisation using modelling techniques is subject to the availability of sensor data.
Co-digestion (also called Co-fermentation) of food substrates	Greasy waste (JWRP)	Full-scale	Adding food waste to anaerobic digesters has been shown to increase the digestion effectiveness as well as biogas production, at minimal or even no increase in final dewatered sludge volume. The food waste must be of good quality (free of hard matter such as metal cutlery) and must be pre-processed into a pumpable slurry prior to feeding into the anaerobic digester. Although the benefits are well proven in plants such as Strass WWTP, co-digestion has been omitted from the scope of this report as it is not part of the used water stream. However, it is highly recommended for further study and consideration for inclusion in future plants, where a co-located food waste pre-processing facility can be sited.

Table 4.5: Technology roadmap towards energy self-sufficient WRPs

Timeframe:	Existing WRPs	Ready for implementation (<5 yrs)	Short-term (5-10 yrs)	Long-term (>10 yrs)
Primary / Pre-treatment	- PST (40% COD capture)		- UASB - Bio-EPT and Chemical EPT	- AnMBR
Secondary Treatment	- Conventional ASP (overall 25% energy efficiency for treatment to MF/UF quality)	- MBR (aerobic) - Anammox (side-stream) - Fine bubble diffusers	- Advanced sensors and VFD/IV blower controls	- Anammox (main-stream) - Nitrite-shunt
Energy recovery	- AD (mesophilic) - DFE (25-30% electrical conversion efficiency) - Heat recovery for sludge drying (CWRP only) - Incineration (≈49,700 dry tonnes of sludge per year)	- Solids pre-conditioning - High efficiency biogas engines (>38% electrical efficiency) - CHP engine for both electricity and heat recovery	- AD (thermophilic)	- ATT (Pyrolysis, Gasification) - Dissolved methane recovery
Other technologies	- Sludge drying (CWRP) - Basic mass balance	- Phosphorus recovery - GHG studies - Sludge drying - Biogas scrubbing (siloxanes) - Regular basic mass balance	- Food waste co-digestion	- Plant mass balance modelling and optimisation - Biogas upgrading (increasing methane content)

Table 4.6: Recommended technologies for adoption in individual WRPs

WRP	Technologies recommended for implementation / consideration			
	Pre-treatment	**Secondary Treatment**	**Energy Recovery**	**Other Technologies**
***Common technologies for adoption in all WRPs**		- MBR (aerobic). - Advanced sensors and controls. - VFD / Inlet Vane blower controls. - Fine bubble diffusers. - Anammox (side-stream).	- Solids pre-conditioning. - High efficiency Biogas engines (38%).	- Regular mass balance studies - Plant mass balance modelling and optimisation (subject to availability of sensor data)
Kranji WRP	- N/A	- As above*	- As above*	- As above*
Ulu Pandan WRP	- N/A	- As above* - 1000 m^3/d Integrated Validation Plant (IVP) to test Bio-EPT + MBR concept. - IVP studies: to consider options for testing of nitrite-shunt and main-stream Anammox.	- As above* - Testing of more solids pre-conditioning technologies.	- As above*
Changi WRP	- N/A	- As above*	- As above*	- As above* - P-recovery technologies (for consideration).

Jurong WRP	- Bio-EPT for industrial used water stream (pilot studies). - UASB (pilot/demo studies). - Methane stripping and recovery (to consider for lab/pilot testing).	- As above* - Demo scale plant for Bio-EPT + MBR concept.	- As above* - Methane stripping & recovery studies (to recover dissolved methane from UASB effluent) - Biogas scrubbing and upgrading studies (to improve quality of recovered dissolved methane from UASB effluent)	- As above* - GHG emissions study to characterise loss of dissolved methane from anaerobic pre-treatment units under Singapore conditions.
WRP in Tuas (future)	- Bio-EPT (domestic stream, also for consideration for industrial stream). - UASB (industrial stream). - Methane stripping and recovery. - Potential for upgrading to AnMBR if the technology is mature	- As above* - Potential for upgrading activated sludge process to nitrite-shunt or main-stream Anammox in the future.	- As above* - Thermophilic AD (for consideration). - CHP (for consideration). - ATT (Pyrolysis / Gasification), for consideration if technology is mature.	- As above* - P-recovery technologies (for consideration). - Sludge drying (to consider for use with CHP) - Food waste co-digestion (for consideration)

PART II

Shortlisted Technologies

Chapter 5

Potential Technologies for adoption – Liquids stream

A brief description of the shortlisted used water treatment technologies for the liquid train is given in this chapter. Detailed reviews of these technologies will be updated in the appendix.

5.1 Biosorption Enhanced Pre-treatment Treatment (EPT)

Enhanced Pre-treatment Treatment (EPT) is a general class of technologies that increase the efficiency of the primary clarifier to capture COD and other pollutants. In general, raw municipal used water consists of about 25% COD present in stable and soluble forms (< 0.08 µm), 15% of the organic matter as colloids (0.08-1.0 µm), about 25% as supracolloidal (1-100 µm) and about 35% as settleable solids (> 100 µm) (Ødegaard, 1998). Conventional primary clarifiers are only designed to remove the settleable fraction. EPT technologies however, allow the primary clarifier to further capture the colloidal and supracolloidal particles, thus diverting more COD to the anaerobic digesters. This results in higher biogas production from the anaerobic digesters, and less aeration demand in the main liquid treatment stream. EPT technologies have been recognised as a critical strategic component of the GWRC roadmap towards an energy neutral plant (GWRC report, 2010).

Principles of the technology

Several methods of EPT have been tested, including chemical coagulation (Parker et. al., 2001), physical filtration and biosorption processes. Among these options, chemical and physical methods are relatively more chemical (cost) and/or energy intensive. Thus, biosorption appears to be the most suitable EPT method for improving plant energy efficiency.

The Strass WWTP A-stage process is a type of biosorption EPT. The A-stage activated sludge process has the features of short sludge retention time (SRT) (≈0.5 d) and hydraulic retention time (HRT) (≈0.5 h). Under such conditions, the A-stage sludge becomes populated by fast-growing microorganisms that produce high quantities of sticky extracellular polymeric substances (EPS). When brought into contact with raw used water, the sticky A-stage sludge adsorbs particulate matter, with up to 55%-65% of the organic load eliminated at this stage (Wett et. al., 2007).

Advantages and challenges of the technology

In addition to the main advantages of increasing biogas production and reducing aeration requirements, a further advantage of biosorption EPT is the potential for retrofit into existing conventional treatment facilities (Versprille et. al., 1984) and the reduction of any potential toxicity it may impact downstream nitrification process. Also, as EPT is designed to work in conjunction with the anaerobic digesters, improvements to anaerobic digester operation (such as upgrading to thermophilic digestion) synergises well with EPT processes. A future potentially synergistic combination of technologies is EPT and main-stream Anammox, where the EPT is used to improve the operational stability of the Anammox system by protecting it from large organic loadings.

There are two main challenges of biosorption EPT. Firstly, when treating relatively dilute domestic used water stream, care must be taken to retain sufficient organics in the used water for effective denitrification. This can be achieved by designing an influent bypass line to the secondary treatment process. Secondly, the effectiveness of biosorption EPT relies on the settleability of the EPT sludge. Due to the low sludge age, EPT sludge contains high levels of loosely bound EPS (Li and Yang, 2007), giving it relatively poor settling and dewatering properties, as well as potential for bulking (Sun et. al., 2005). Thus, the properties of biosorption EPT sludge needs to be carefully characterised and controlled.

Evaluation of technology

Biosorption EPT is a well established technology in Europe, with Strass WWTP being the most important case study of a successful application. This technology shows much potential and is highlighted in several R&D roadmaps in literature as one of the fundamental strategies for energy efficient future WRP design.

In Singapore, there are currently a few pilot projects in the WRPs investigating EPT, one of which is the Environment & Water Industry Programme Office (EWI)-funded "Energy+" project in Kranji WRP that is being done in collaboration between DHI Singapore, NTU and Suez Environnement. The project seeks to replicate the Strass WWTP A/B-stage process under Singapore's used water and climate conditions. The project has just completed its baseline studies and is currently undergoing A-stage (biosorption EPT) studies.

Another pilot project of note is the Integrated Validation Plant, which seeks to validate the combination of biosorption EPT and MBR technologies as a feasible concept for the WRP in Tuas. The proposal has been approved and is scheduled to begin construction in early 2013.

5.2 Upflow Anaerobic Sludge Blanket (UASB)

The primary objective of anaerobic pre-treatment is to reduce the majority of the influent COD (60-80%) in an energy efficient way, leaving a much reduced residual COD for the aeration stage. This significantly reduces energy consumption for aeration, as well as reduces the volume of waste activated sludge produced and allows for direct conversion of influent COD into recoverable biogas. Among the anaerobic pre-treatment systems reviewed (including Expanded Granular Sludge Bed reactors, Anaerobic filters, etc.), the most suitable configuration appears to be the Upflow Anaerobic Sludge Blanket (UASB) as it is suited for treatment of higher strength used water with lower energy requirements.

Principles of the technology

UASBs are anaerobic biological treatment systems employed in the main-stream, with typical loading rates of 4 to 15 kg COD/m^3/day (Mutombo, 2004). Raw influent is fed through the inlet at the bottom of the UASB, passes up through a sludge blanket and exits at the top of the reactor. A three phase separator at the top of the reactors is used to retain the sludge (by gravity settling in a quiescence zone), extract the biogas (from the gas headspace) and allow the treated effluent to exit the reactor.

UASBs are commonly built to a height of 4.5-6.5m (Mutombo, 2004) with a typical upflow velocity of 0.5-1.0 m/h which is maintained by an internal recycle pump that recycles the reactor effluent back to the inlet[2]. By regulating the upflow velocity, the system can be controlled such that the sludge is not washed out, but remains as a fluid blanket in the lower section of the reactor. When operated at higher upflow velocities, anaerobic granular sludge can also be cultivated, conferring additional resistance to toxic shocks. Slow degradable particulates are trapped in the blanket and degraded over time, while inert solids are readily removed by direct sludge wasting (Marchaim, 1992; Jördening and Buchholz, 2008). Like an anaerobic digester, part of the degraded organics is converted into biogas, which can then be combusted for energy.

[2] Source: Lim S.J., "Comparisons between the UASB and EGSB Reactor". Downloaded from the worldwide web on 29-Sep-2012, http://home.eng.iastate.edu/~tge/ce421-521/seungjoo.pdf

Advantages and Challenges of the technology

In addition to the advantage of reducing organic loading on the secondary treatment system, UASBs are able to significantly reduce plant footprint, capital and operating costs. This is because UASBs can receive raw sewage, thus removing the need for primary clarifiers. It produces 3-20 times less sludge than an equivalent conventional activated sludge system when applied to high strength used water, resulting in significantly reduced disposal costs (Lew et. al., 2004) and reduced anaerobic digester requirements. Furthermore, as the speed and efficiency of anaerobic treatment processes improve with increasing temperature, the consistent, warm tropical climate in Singapore is favourable for the application of UASBs.

The greatest challenge facing UASB technology is the presence of dissolved methane in the effluent. As much as 13% to 35% (at 35℃) of the methane produced is dissolved in the effluent and lost to the atmosphere during the aeration process of the subsequent activated sludge treatment (Bandara, 2010). The negative impacts are twofold: firstly, the methane lost to the atmosphere is a greenhouse gas, and secondly, the methane lost directly translates to lost potential energy recovery. There are currently no cost effective means of recovering and upgrading this dissolved methane for energy recovery. Besides methane, UASBs can also release corrosive vapours into the atmosphere. Special care must be taken in the design and operation of UASBs to mitigate corrosion of the surrounding equipment and facilities. Furthermore, UASBs require seeding for effective start-up and, in the event of a complete sludge washout or system break down, may require a complete re-seeding of the reactor (Edelmann et. al., 2004).

Evaluation of technology

Anaerobic pre-treatment is a well established technology globally, and is especially effective in tropical climates such as Brazil. It forms the other fundamental treatment strategy besides EPT, in that it captures organics early in the process for conversion into biogas. However, concerns regarding loss of dissolved methane and maintenance against corrosion may limit its attractiveness.

One of the key advantages of the UASB is the ability to treat high strength industrial used water. In light of this, several pilot and demo scale plants are being tested in Jurong WRP for the treatment of the Tuas industrial stream. The largest of these is the EWI-PUB-Meiden funded 1 MGD UASB-MBR demonstration plant by Meiden Singapore. The duration of the demonstration study is 26 months starting Q3 2012 and the scheduled completion is Q1 2015.

A brief discussion on the role of UASB in industrial used water treatment is covered in chapter 7.

5.3 Anaerobic Membrane Bioreactor (AnMBR)

Background

The anaerobic membrane bioreactor (AnMBR) is a membrane bioreactor (MBR) that is operated under anaerobic conditions. The AnMBR concept is not new, having been investigated at the full scale since the mid 1990's, and some full scale plants operating since 2000 (McCarthy, 2010). While it has not received widespread use due to inherent challenges in operation and quality of the effluent, in recent years there has been renewed interest in the AnMBR as a possible solution in the increasing drive towards development of sustainable, energy-neutral used water treatment plants.

Advantages and Challenges of the technology

The impetus behind the development of the AnMBR was to overcome a disadvantage of early anaerobic technologies; the long hydraulic retention time needed for slow growing methanogenic bacteria that resulted in the necessity of large capacity tanks. By employing the excellent biomass retention capabilities of an MBR, the AnMBR is able to achieve a substantially smaller plant footprint (Kanai et. al., 2010). The second disadvantage the AnMBR seeks to overcome is the relatively high blower energy requirements that conventional aerobic MBRs need in order to maintain adequate dissolved oxygen (DO) levels in the high mixed liquor biomass concentrations and for air scouring of the membranes. By eliminating the need for DO, the AnMBR significantly reduces the energy requirements of the plant. The emitted biogas is typically used in place of air for membrane scouring, and is also recovered as an energy source.

The main challenges of the AnMBR are: firstly, the mitigation of membrane fouling; secondly, the removal of nutrients; and finally, the issue of dissolved methane. Membrane scouring can be achieved with biogas scouring or by adding granular activated carbon (GAC), although more R&D is required to establish a robust, cost effective method. The second challenge is that the AnMBR does not perform nutrient removal. Moreover, as is typical of anaerobic treatment systems, residual COD can be high. As such, while the effluent from the AnMBR is particularly suited for agricultural applications, it is usually not good enough to meet nutrient discharge standards. Finally, the stripping and recovery of dissolved methane in the effluent is a common challenge that must be overcome for all anaerobic pre-treatment processes.

Evaluation and R&D Collaborations

AnMBR is an emerging technology that has several challenges to overcome. However, if these issues have been overcome and the technology proven successful, it could potentially play an important role in the anaerobic pre-treatment strategy. While there are no pilot scale plants in Singapore, NUS and NTU have expressed interest in developing AnMBRs at the bench scale.

5.4 Nitrite-shunt (partial nitrification)

Background

Conventional nitrification-denitrification systems operate by oxidizing ammonium fully to nitrate in an aeration stage, then reducing the nitrate to nitrogen gas in an anoxic stage (Metcalf and Eddy, 2004). This process consumes oxygen (in the nitrification step) and carbon (in the denitrification step). In the nitrite-shunt pathway (also known as partial nitrification), ammonium is only partially oxidized to nitrite, which is subsequently reduced to nitrogen gas. By skipping the nitrate step, both oxygen and carbon requirements can be reduced.

Nitrification **Denitrification**

Conventional system: $NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^- \rightarrow NO_2^- \rightarrow NO + N_2O \rightarrow N_2$

Shortcut

Nitrite-shunt pathway: $NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^- \rightarrow NO_2^- \rightarrow NO + N_2O \rightarrow N_2$

Principles of the technology

Conventional nitrification in activated sludge is carried out by two main groups of microorganisms. The Ammonium Oxidising Bacteria (AOB) are responsible for converting ammonium (NH_4^+) to nitrite (NO_2^-), and the Nitrite Oxidising Bacteria (NOB) are responsible for converting nitrite (NO_2^-) to nitrate (NO_3^-). In order to exploit the nitrite-shunt pathway, operating conditions must be controlled to promote growth of AOB and suppress growth of NOB, so that there is an accumulation of nitrite instead of nitrate.

The most important operational parameter to control is reported to be the dissolved oxygen (DO) level. AOB have a lower DO saturation concentration as compared to NOB, and thus can tolerate lower DO levels (Painter, 1977; Alleman, 1984). Hence, a low DO environment can be used to promote the growth of AOB over NOB. In a pilot study by Wang et. al. (2007), a maximum nitrite accumulation ratio of 90% was observed at a DO of 0.6 mg/l, and in a subsequent pilot study by Ma et. al. (2009), Fluorescent In-Situ Hybridization (FISH) tests revealed that the NOB population gradually reduced to negligible levels when the system was operated at a DO of 0.4-0.7 mg/l. However, during trials at Strass WWTP, DO was not found to be a reliable control factor, as the NOB were found to be capable of adapting to low DO conditions in the long term.

The second important parameter is temperature. At higher temperatures, AOB have a significantly higher growth rate than NOB. Thus, by operating at higher temperatures and reducing the SRT, the slower growing NOB can be washed out of the system. An operating range of 30℃ to 40℃ coupled with a SRT in the aerated zone of 1-2 days is suitable (Mulder et. al., 2006).

To a limited extent, pH can be used to control nitrite accumulation. At higher pH, there is an increase in the presence of free ammonia (NH_3) that may inhibit NOB. As a result, NOB prefer lower pH environments than AOB (Painter, 1977; Alleman, 1984) and thus by operating at a higher pH range, the growth of AOB over NOB can be promoted. The importance of pH may be dependent on nitrogen loading. For example, the SHARON® (Single reactor High Activity Removal Over Nitrite) process, which performs partial nitrification on high nitrogen loaded (0.5 g N/L) dewatering centrate at the Rotterdam Dokhaven Wastewater Treatment Plant, operates at a pH of 7.5-8.5 and achieves 90% treatment efficiency (Mulder, et al., 2001). However, in the pilot study by Wang et. al. (2007) on an Anoxic/Oxic process treating domestic used water, pH was not found to be a useful operational parameter to realise partial nitrification.

Advantages and Challenges of the technology

Bypassing the nitratation[3] step yields the following key benefits:

[3] Nitratation is the second part of the nitrification where the NOB uses the enzyme nitrite oxidoreductase (NOR) to conduct the process.

(i) 25% less oxygen is required for nitrification as there is no need to oxidise nitrite to nitrate (Hellinga, et al., 1998). As a result, savings can be gained from the reduction in air supply;

(ii) An estimated 40% reduction in carbon demand for denitrification (Giraldo *et. al.*, 2011). This allows the available carbon to be better utilised in other reactions, such as biological phosphorus removal. Alternatively, when used in conjunction with EPT, it would allow more carbon to be captured by the EPT process for conversion into biogas.

(iii) Similarly, a 40% lower waste sludge generation as compared to the conventional nitrification / denitrification process (Bott, 2011; Pennsylvania Department of Environmental Protection, 2002).

(iv) Possibility of synergising with main-stream Anammox processes: partial nitrification is an essential step before the Anammox process can be carried out. In this configuration, only half the ammonium load will need to be converted into nitrite, further reducing aeration and operating costs (Bott, 2011).

The main difficulty in applying partial nitrification is that it is an operationally challenging process. Careful control of aeration and pH is necessary in order to inhibit NOB growth, and even then a long period of time is still required to wash out the NOBs from the activated sludge consortium. In the pilot study by Ma et. al. (2009), a lag phase of several SRTs operating a low DO levels is required before the onset of the nitrite-shunt pathway. However, once partial nitrification is achieved, the system is stable enough such that if DO were to be raised to 2-3 mg/l, there is a lag period of one to two SRTs before the recovery of the nitratation pathway. However, in light of the unsuccessful inhibition of NOBs under low DO conditions at Strass WWTP, further studies are needed to better understand NOB suppression.

A second challenge is that partial nitrification appears to negatively impact sludge settleability (Ma et. al., 2009), potentially limiting the applicability of the nitrite-shunt pathway in conventional WRPs that use final clarifiers. However, this may not be a problem for MBR systems where the biomass is effectively separated by membranes from the final effluent without utilising a clarification process.

A third challenge is that continuous aeration can lead to the germination of protozoa, which may negatively impact the stability of the system (van Dongen et. al., 2001).

A final concern with partial nitrification is that the emission of nitrous oxide (N_2O) and nitric oxide (NO) in such a process are statistically higher than that of a conventional full-nitrification process, resulting in a higher carbon-footprint (Ahn et. al., 2011).

Evaluation of technology

Nitrite-shunt is a promising technology with significant potential to reduce WRP energy consumption. It is also a prerequisite technology for the implementation of Anammox (both side- and main- stream variants). However, stable operation is still a concern and the process requires strict system control. As such, the successful application of advanced sensors and aeration controls is a requirement before nitrite-shunt should be investigated.

Currently there are two groups investigating nitrite-shunt at the pilot scale in Singapore's WRPs. The second is the DHI-NTU-Suez "Energy+" project at Kranji WRP. Both projects are currently monitored to assess the potential for application of nitrite-shunt in the short term.

5.5 Anammox (side-stream and main-stream)

Background

ANaerobic AMMonium OXidation (Anammox) is a process whereby ammonium is oxidised using nitrite as an electron acceptor and carbon dioxide as the energy source. Utilising this unique process can result in a significant reduction in oxygen and carbon requirements as compared to a conventional nitrification-denitrification process. Anammox was developed in Delft University of Technology (TUD) (Rittmann and MaCarty, 1999) and has been successfully applied at the full scale in Strass WWTP for the treatment of high ammonium loaded dewatering centrate (Wett, 2007b). In recent years, several research groups have also begun investigating the potential of applying Anammox in the main liquid treatment stream (Winkler et. Al., 2012; Bott, 2011).

Nitrification **Denitrification**

Conventional system: $NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^- \rightarrow NO_2^- \rightarrow NO + N_2O \rightarrow N_2$

Partial nitrification: $NH_4^+ \rightarrow NO_2^-$

$\downarrow$

Anammox pathway: $NH_4^+ + NO_2^- \rightarrow N_2$

Principles of the technology

The Anammox pathway is always preceded by partial nitrification, which is used to convert half of the influent ammonium into nitrite. The Anammox bacteria then take one part ammonium and oxidise it with one part nitrite to produce nitrogen gas. Five genera of Anammox bacteria have thus far been defined. Anammox bacteria are autotrophic, that is, they utilise CO_2 as a carbon source instead of organic carbon. They are further characterised by their brown-reddish colour, slow maximum specific growth rate (μ=0.00648/day) and a long doubling time of 10.6 days (Strous, et al., 1998; Jetten, et al., 1999) leading to low biomass yields (0.11-0.13 VSS/gNH_4^+-N) (Strous, et al., 1997). The Anammox operating conditions of pH, temperature, presence of organics and nitrite must be tightly controlled in order for the process to be effective.

Currently, there are several commercial variations of the Anammox process. In a 2-stage partial nitrification-Anammox system (such as the SHARON®-ANAMMOX® process), the generation of nitrite and the Anammox processes occur in separate, specialised reactors. The Anammox bacteria are typically grown as granules in continuous upflow reactors. In a single-stage system, both AOB and Anammox bacteria are cultivated in the same sludge and their activities regulated by aeration control. These systems are commonly called deammonification processes. One example is the ANITA™-Mox process, where the bacteria are grown on plastic biofilm carriers in a moving bed biofilm reactor (MBBR) design. Partial nitrification is maintained in the outer layers of the biofilm by carefully controlling the level of aeration, while the Anammox processes occur in the deeper, oxygen limited layers of the biofilm (Plaza *et. al.*, 2011). Another novel single-stage system is the DEMON process used at Strass WWTP (Figdore, 2011), where the partial nitrification and Anammox processes are controlled in a sequencing batch reactor (SBR).

Currently, Anammox has been proven in full scale operations for treatment of dewatering centrate in the side-stream, where there is sufficiently high ammonium loading to maintain stable growth of the Anammox bacteria population. A full scale side-stream Anammox plant in Rotterdam that has been operational since 2006 has demonstrated both consistently stable operation as well as ability to quickly recover from operating faults (Abma *et.al.*, 2011). However, savings gained from side-stream Anammox are limited due to the relatively small flow volume. If Anammox were to be successfully applied in the main-stream, the impact of the operation cost savings are potentially much more significant (Jetten et al., 2005). As a result, main-stream Anammox is regarded as one of the key breakthrough technologies to be developed towards achieving energy positive used water treatment (Bott, 2011) and is currently being investigated at the lab, pilot and full-scale trials by several research groups (Cao, 2011b).

Advantages and Challenges of the technology

The advantages and limitations of side-stream Anammox are as follows:

- The key benefit of adopting Anammox is to reduce aeration energy requirements for nitrogen removal. Full-scale data from Strass WWTP indicates that the electrical consumption per kg of N removed in the side-stream was 1.16 kWh $(kg\ N)^{-1}$, several times more efficient as compared to 6.5 kWh $(kg\ N)^{-1}$ for the main-stream (nitrification-denitrification) treatment ([2]Wett, 2007). Oxygen consumption for side-stream nitrogen removal was reduced by 50% (Wett et al., 2007a).

- A second benefit is that the Anammox process requires almost no organic carbon input when stringent total nitrogen requirement is required. When applied in the side-stream, it eliminates the need for addition of external carbon (typically added in the form of methanol). By reducing the nitrogen load from the side-stream on the main-stream treatment processes, it also frees up the influent organics for use in other important processes such as biological phosphorus removal or for conversion into methane in the anaerobic digesters.

- The main limitation of side-stream Anammox is that the side-stream flow is relatively small, thus while the Anammox process is energy efficient, the actual benefit in light of the full plant process energy usage is only about a 4% increase in energy efficiency. However, additional yield in biogas production could be gained from the influent organics that were previously used to denitrify the side-stream nitrogen load, on the condition that these organics could be effectively channeled to the anaerobic digesters (for example, through an EPT process). In the case of Strass WWTP, the combined impact of side-stream Anammox, A-stage (a type of EPT) and upgrading to high efficiency engines was as high as 12% (Wett et. al., 2007).

The advantages and challenges of main-stream Anammox are as follows:

- Similar to the side-stream Anammox, the key benefit of the main-stream Anammox is the potential reduction of up to 60% aeration requirements for nitrogen removal.
- The second main benefit, elimination of organic carbon requirements, can be maximised in an EPT-Anammox (main-stream) combination, where the EPT can be used to channel almost all of the organics to the anaerobic digesters for maximum biogas generation.
- A third benefit is the large reduction in carbon dioxide emissions as compared to conventional nitrification-denitrification, which helps to reduce the carbon footprint of the plant (van Loosdrecht, 2008).
- A fourth benefit is the Anammox bacteria's very long doubling time of 10.6 days (Strous, et al., 1998; Jetten, et al., 1999), leading to a low biomass yield of 0.11-0.13 VSS/gNH_4^+-N (Strous, et al., 1997) and savings in sludge disposal costs.
- On the other hand, the low biomass yield also leads to the challenge of long process start-up time (up to one year) (Trigo et al., 2006), and uncertainty regarding the robustness of the system in quickly recovering from process failure events.
- Another challenge in application of main-stream Anammox is the strict operational conditions required, namely an optimum pH range of 6.7 to 8.3, optimum temperature range of 20 to 43 ºC (Strous, et al., 1999), as well as achieving stable and effective partial nitrification.

Evaluation of technology

Side-stream Anammox is a relatively recent but already well proven technology. Although the energy savings from side-stream Anammox is small due to the small flow volume of the dewatering centrate, when applied to a large WRP such as

Changi WRP and the upcoming WRP in Tuas, the cost savings can still be substantial. The main value of installing a side-stream Anammox is to gain R&D experience, which can be used to further R&D efforts into main-stream Anammox technologies.

Of greater importance than the side-stream Anammox is the main-stream Anammox, which is currently being regarded by many global experts as the technology with the most potential to achieve energy-positive WRPs. While there are several overseas groups researching it in various scales from lab to full-scale trials, the technology is still emerging and is thus not likely to be available for full-scale adoption in the short term.

5.6 Advanced aeration systems

Background

Aeration is the largest energy consumer of a municipal used water treatment plant, accounting for 40-60% of total energy consumption (Gundry, 2008; WERF, 2009). In practice, aeration capacity is determined by three factors: (i) oxygen demand (OD) (ii) the design of biological process, especially the selection of sludge retention time for the aerobic compartment; and (iii) the efficiency of aeration facilities, including types of the facilities, control and maintenance. Despite large advances in plant process design that have reduced the aeration requirements in the biological stage, aeration will continue to play an integral role in future WRPs due to the necessity of nutrient removal. Therefore, there is an opportunity for significant improvements in energy efficiency through the optimisation of the aeration system.

Principles of the technology

Optimisation of the aeration system consists of improvements in the following three areas: (i) the sensor systems, which govern the aeration control strategy, (ii) the ability to control the level of aeration (blower mechanical efficiency and control strategy), and (iii) the effectiveness of the diffusers in promoting oxygen mass transfer into the liquid phase.

Dynamic sensor systems – In recent years dynamic control by the application of on-line sensors has been widely used in full-scale plants in Europe and United States, allowing effective air supply to be regulated under a dynamic state. Reportedly, dynamic aeration control through on-line DO and NH_4-N measurement can save up to 30% of the original aeration energy (Pakenas, 1995).

Dynamic blower controls – Dynamic sensors can be used to control the level of aeration supplied via variable frequency drives (VFD) for centrifugal blowers, and inlet vane control for positive displacement blowers (Cao, 2011b). Intermittent aeration based on sensor technology has been adopted at the full-scale in Strass WWTP, which saved 15% aeration energy (Wett, 2007a). Intermittent mixing

(Jonasson, 2007) and optimal air scouring in Zenon membrane processes are other examples of aeration control strategies based on dynamic sensor controls.

Fine bubble diffusers – The specific oxygen supply capacities of various types of aerators are quite different: 4.0-8.0 lbO_2/hp-hr for fine diffusers (Pakenas, 1995); 2.0-4.0 lbO_2/hp-hr (Pakenas, 1995; Monteith et al., 2007) for coarse diffusers and surface aerators. Adoption of fine-pore systems could reduce energy consumption from 40 to 50%, and overall life-cycle from 10 to 20% compared to other diffused-air systems (Pakenas, 1995). However, regular maintenance and cleaning is essential in order to maintain high aeration efficiencies, which may offset its potential benefits.

Advantages and Challenges of the technology

The direct advantage of dynamic aeration control is the increase in aeration system efficiency, which results in energy savings. A secondary benefit from the dynamic sensors is the increased operating data available to the plant operators, which may enable them to make further optimisations to the plant process. A third benefit is that successful implementation of the control system opens up the opportunity to investigate advanced biological processes with strict aeration regimes, for example the nitrite-shunt process. This, in turn could lead to further energy savings.

The main challenge of advanced aeration systems is implementing a suitable maintenance regime. This is especially so for the sensors, which govern the operation of the whole system. Sensors operating within activated sludge in particular are at risk of fouling and providing erroneous feedback, which would then cause the blowers to supply the wrong amount of aeration. Impacts may range from simply oversupplying aeration and offsetting the desired energy savings, to causing the effluent to not meet discharge standards, or even alter the whole microbial community in the case of sensitive processes like nitrite-shunt and Anammox. Thus, robust sensor hardware, a suitable maintenance regime and skilled operators to maintain it are essential for the successful application of advanced aeration systems.

Evaluation of technology

Advanced aeration systems are fundamental prerequisites for any future Greenfield WRP. Currently, the most challenging aspect remains the maintenance of advanced sensors. Trials are currently being carried out in Kranji and Changi WRPs.

Chapter 6

Potential Technologies for adoption – Solids stream

A brief description of the shortlisted used water treatment technologies for the solids train is given in this chapter. Detailed reviews of these technologies will be updated in the appendix.

6.1 Solids Pre-conditioning (Sludge Pre-conditioning)

Background

Activated sludge processes in general produce large amounts excess waste activated sludge (WAS) that must ultimately be disposed of, representing up to 50% of the operating costs of a used water treatment plant (Koners et. al., 2007, Appels et. al., 2008). Prior to disposal, waste sludge is typically treated with anaerobic digestion for energy recovery as biogas, as well as to reduce final sludge volume and stabilize the sludge (Appels et. al., 2008). However, WAS is largely composed of microbial biomass. While the intracellular material is biodegradable in the anaerobic digester, it is also encased in a durable cell wall which must first be hydrolysed before it becomes bioavailable. This cell wall is a semi-rigid peptidoglycan cross-linked structure that provides resistance to osmotic lysis and biodegradation (Appels et. al., 2008). The slow rate of WAS hydrolysis is thus a significant bottleneck in anaerobic digestion (Rittmann et. al., 2008), resulting in long sludge retention times of 20-30 days and low overall degradation efficiency of the organic dry solids of 30-50% (Appels et. al., 2008).

In order to overcome hydrolysis as a limiting factor, various solids pre-conditioning technologies are being developed to evoke lysis or disintegration of WAS cells, thus releasing and solubilising intracellular material into the water phase and transforming refractory organic material into biodegradable species (Appels et. al., 2008). These technologies include heat, chemical, mechanical, and ultrasonic methods (Appels et. al., 2008). Recent studies have also investigated the potential of enzymatic (Appels et. al., 2008), electrical (Rittmann et. al., 2008) and microwave (Grübel and Machnicka, 2010) methods as novel sludge disintegration techniques.

Advantages and Challenges of the technology

All solids pre-conditioning methods seek to achieve two primary effects: a more rapid and a more complete degradation of organic matter in the WAS (Phothilangka et. al., 2008). By achieving a more rapid degradation rate, the loading capacity of the anaerobic digester can be increased, or conversely, a smaller anaerobic digester can be designed. By achieving a more complete degradation of the organic matter, more biogas can be produced for energy recovery and less final digested sludge remains. As an alternative to anaerobic digestion, the high organic liquid overflow can be diverted to the main-stream anoxic tank to be used as a replacement carbon source to eliminate the use of methanol in denitrification[4]. Furthermore, by rupturing the cell walls, intracellular water is allowed to drain out during dewatering, resulting in improved dewaterability of the digested sludge and cost savings for sludge disposal.

The key challenge in applying solids pre-conditioning is the generation of undesirable by-products, including ammonia and soluble inert organic matter. Elevated ammonia levels up to 100% more (from simulation results) result due to complete degradation of decay products, causing higher N-loading from the return side-stream (Phothilangka et. al., 2008). An energy efficient side-stream nitrogen removal process, such as Anammox, would be needed in order not to incur additional aeration cost for nitrogen removal in the main-stream. The second undesirable by-product, soluble inert COD, is associated with biological inhibition

[4] Source: http://www.opencel.com/news12302010-1.shtml, accessed on 20-Nov-2012

(Figdore, 2011) and causes acute inhibition of anaerobic digestion, requiring long acclimatization periods before the positive impacts of solids pre-conditioning on biogas generation can be seen (Eskicioglu et. al., 2010).

Principles, advantages and challenges of the technology

A brief summary of the principles of various solids pre-conditioning technologies, as well as their specific advantages and challenges, is given below:

Thermal pre-treatment – under elevated temperatures of 150-200ºC and pressures of 600-2500 kPa, the chemical bonds of cell walls and membranes are disrupted. Although proven to be an effective method, the optimum conditions and magnitude of improvement vary considerably between sludges (Appels et. al., 2008). A further consideration is that the WAS feedstock must be preheated to the operating temperature (at an input of about 700 kJ/m^3) at the expense of using some of the biogas produced, or by tapping off the heat captured from a CHP plant (Panter, 2005). One commercial example is the Cambi process. A full-scale application has shown that Volatile Suspended Solids (VSS) destruction was increased to 60% compared to 40% without pre-treatment, biogas production from WAS in a mixture with primary sludge can be improved by 25%. At the same time dewatering-ability was improved, increasing the dry solids concentration from 22% to 30% (Piat, et al., 2009). However, a side effect of thermal hydrolysis is the production of hardly degradable organic compounds and the solubilisation of inert compounds at high temperatures (Phothilangka et. al., 2008), which are believed to be associated with side-stream biological inhibition (Figdore, 2011). Hence, careful control of operating conditions, side-stream loading rates and acclimatisation periods are necessary to mitigate impacts on sensitive side-stream processes such as Anammox (Figdore, 2011).

Chemical pre-treatment – the addition of acids, bases or oxidants, either at ambient or elevated temperatures, can be used to solubilise sludge. The main drawback of chemical methods is the necessity to alter pH to extreme levels; the Fenton peroxidation (Fe^{2+} ions used in conjunction with H_2O_2), for example, operates at an optimum pH of 3. This gives rise to higher maintenance requirements because of corrosion (Zhang, 2010) and necessitates WAS re-neutralisation before it can be fed to the anaerobic digester, reducing the cost-effectiveness of the process. Among the chemical based methods, oxidative treatment is considered the most promising, although further research is required to avoid the extreme reaction conditions in terms of pressures, temperatures and pH (Appels et. al., 2008). PUB is currently collaborating with the Canada's Ontario's Ministry of Economic Development and Innovation (formerly known as the "Ministry of Research and Innovation" prior to 2011) to investigate possible synergistic effects of combining oxidants with ultrasonication. Ontario's researchers will investigate ultrasonication combined with hydrogen peroxide treatment while PUB led research will investigate ultrasonication combined with ozone treatment.

Mechanical pre-treatment – in this method, high shear stresses are induced through pressure and impact forces to physically disintegrate cellular material. Several strategies have been reported, including variations of colloid mills using grinding discs or beads, Lysat centrifugal technique where tools on the side of the rotor impart shear stresses, and high-pressure homogenizers, also known as the mechanical jet smash technique. The last method is currently the most widespread, and works by pressurising the sludge up to 60 MPa before being depressurised at high speed against an impaction ring to create turbulence, cavitation and shearing forces on the cell walls (Appels et. al., 2008). The advantage of mechanical systems over other methods is that additional heat or chemicals are not required. However, the improvement of anaerobic digester performance is relatively low compared to other pre-treatment methods, with milling methods achieving about 20% increase in VSS destruction (Appels et. al., 2008) and the high-pressure homogenisation method achieving an increase of 50% total Suspended Solids (TSS) (Nah et. al., 2000) or VSS (Choi et. al., 1997) removal efficiency. High-pressure homogenisation systems are also relatively complicated (Zhang, 2010) and high stress components like the impaction ring and nozzle will require frequent replacement.

Ultrasonic pre-treatment – the principle of ultrasonic sludge disintegration is the induced cavitation process. The ultrasonic waves impart a series of compression and expansion waves within the fluid, creating bubble cavities that immediately implode, giving rise to local extreme conditions with temperatures up to about 5000 K (Tiehm et. al., 2001) and pressures up to 500 bar (Appels et. al., 2008). Compared with other sludge disintegration techniques, the ultrasonic method is the most powerful, being capable of achieving 100% sludge disintegration, at the cost of high energy input (Appels et. al., 2008; Zhang, 2010). Practically, an improvement of VS destruction by 40-55% and enhancement of biogas production by 50% can be achieved. Operation and maintenance costs are expected to be minimal, although the ultrasound probes require replacement every 1.5 – 2 years, which may reduce the cost-effectiveness of the method (Appels et. al., 2008). An ultrasonic sludge disintegration demonstration study was carried out in UPWRP in 2005, achieving an average of 35% increase in biogas production for the 9 months of operation with a net energy gain to power consumption ratio of 2.3. UPWRP is currently preparing for full scale implementation of the system.

Electrical (pulsed) pre-treatment – this method was developed from the well established pulsed electric field (PEF) technology that is applied in molecular microbiology and food biology. The principle relies on using a rapidly pulsing high voltage electric field (20-30 kV) to attack the exposed polar molecules of a bacterial cell's surface, such as phospholipids and the peptidoglycan, tearing the cell apart. A key advantage of pulsed electrical sludge disintegration is that, due to the susceptibility of bacterial cells to strong electric fields, the treatment time for WAS can be in the range of milliseconds (Rittmann et. al., 2008). One such system is the OpenCEL system, which is projected to be able to reduce sludge disposal by 40% - 50% and increases biogas generation by 60% - 75%. There are currently two full-scale installations, the first in Mesa, Arizona (operational since 2007) and the second in Racine, Wisconsin (2011)[5].

Enzymatic pre-treatment – the application of microbial enzymes for WAS degradation was first proposed in 2002 for the purpose of pathogen destruction. However, it was observed that, as a side effect, the biogas generation was enhanced during anaerobic digestion, leading subsequent researchers to propose the use of enzyme addition for WAS pre-treatment (Zhang, 2010). The enzymes catalyse reactions with the cell wall, causing cell lysis and speeding up hydrolysis of the WAS cellular material (Appels et. al., 2008). While there have been some positive lab

[5] Source: http://www.opencel.com/news12302010-1.shtml, accessed on 20-Nov-2012

scale results, this technology has not yet been developed for practical application. It also remains to be seen if this technology can be applied in a cost-effective manner.

Microwave pre-treatment – microwaves are a type of electromagnetic wave that can be adsorbed by matter through the dielectric effect (causing heating) and through ionic conductivity. This property can be used to disintegrate WAS cellular material by deforming and depolarising the cell wall, causing lysis and necrocytosis. It can also directly affect the water inside the cells, causing heating and selective ionization of the water. As WAS contains more than 70% water in its mass, it is thus susceptible to the destructive effects of microwave radiation (Grübel and Machnicka, 2011). Both sub-boiling point and pressurised autoclave vessels with operating temperatures up to 190ºC have been studied at the lab scale, with increases in the sCOD/tCOD (soluble COD / total COD) ratio in the range of 12-45% (Eskicioglu et. al., 2010; Grübel and Machnicka, 2011).

Evaluation of technology

Solids pre-conditioning is a suitable technology to enhance the biogas generating capacity of existing WRPs. However, prior investigations are needed in order to determine if the process can cause digester inhibition. A downside of solids pre-conditioning is that it is most suited for treatment of cellular waste activated sludge, and not primary sludge. This may reduce its scope of contribution for future WRP configurations utilising EPT or UASB pre-treatment, which reduce the amount of secondary waste activated sludge. It is also unknown how much impact solids pre-conditioning has on further improvement of EPT sludge, which is already highly biodegradable.

A study on ultrasonic sludge disintegration was previously carried out by the Technology Department and WRP Department, and a full scale implementation is planned for Ulu Pandan WRP.

6.2 Thermophilic anaerobic digestion

Background

Most conventional high rate anaerobic digesters are designed to operate at ambient temperatures in the mesophilic range (30-38℃), with volatile solids destruction in the range of 56-65.5%. In recent years, more attention is being paid to the development of thermophilic digesters (50-57℃) as a means to improve the digestion process (Appels et. al., 2008). This has resulted in various designs and control strategies, of which the single stage thermophilic anaerobic digestion and the coupled thermophilic-mesophilic digestion (known as Temperature Phased Anaerobic Digestion, or TPAD) designs are of particular relevance to the energy efficient WRP concept.

Principles of Technology

Thermophilic digestion is performed by heating the anaerobic digester to 50-57℃ to cultivate a thermophilic bacteria consortium. At higher temperatures, the solubility of organic compounds increase, improving hydrolysis which is the rate-limiting step in anaerobic digestion (WEF White Paper, 2004). Also, biochemical reaction rates are faster at higher temperatures. These factors make volatile solids reduction faster and more complete than at the mesophilic temperature range (Appels et. al., 2008).

Thermophilic digestion can further be classified into single-stage and multi-stage designs. Although the single stage design is the simplest type of thermophilic digestion, intense malodour of the digested sludge and dewatering centrate, due to elevated volatile fatty acids (VFA) and ammonium content, has been frequently cited as a disadvantage of the process (WEF White Paper, 2004). This has led to the design of the multi-stage TPAD (the most common configuration being a thermophilic digester followed by a mesophilic digester) which reduces the odour of the digested biosolids to that of a normal mesophilic digestion product (Schafer et. al., 2002).

Advantages and Challenges of Technology

The key advantage of operating an anaerobic digester at thermophilic ranges is the increased volatile solids reduction, leading to greater biogas generation rates, greater capacity for a given volume (and thus lower footprint designs), and improved dewaterability of the digested sludge (Appels et. al., 2008). This leads to potential improvements in energy efficiency, as well as savings in sludge disposal costs. Another important advantage is the high rate of pathogen destruction, allowing the digested sludge cake to qualify as a Class A biosolids according to EPA's regulations and possible reuse as a soil conditioner (Schafer et. al., 2002).

The challenges of thermophilic digestion are:

(i) Structural stresses – Greater thermal stress on concrete digesters due to higher temperatures (WEF White Paper, 2004).

(ii) Operational challenges at elevated temperatures – An increased moisture content in the biogas results in a substantial increase in condensate. Also, mechanical problems such as plugging of heat exchangers may occur due to caking (WEF White Paper, 2004).

(iii) Lower quality dewatering centrate stream – Increased levels of dissolved VFAs (Appels et. al., 2008) and free ammonia due to the increased rate of VS reduction (WEF White Paper, 2004) will increase COD and ammonia loading in the recycle stream. Also, the increase in free ammonia levels can inhibit the digestion process (Appels et. al., 2008).

(iv) Increased sensitivity to temperature fluctuations – sharp or frequent fluctuations in operating temperatures can negatively impact the methanogenic bacteria, with the possibility of process failure occurring when temperature changes in excess of 1°C/day are encountered. This is because thermophilic bacteria are more sensitive to temperature fluctuations than mesophilic bacteria (Appels et. al., 2008). Thus, careful temperature control is critical for the effective operation of a thermophilic digester.

(v) Intense malodour – This is due to the presence of VFAs and ammonia in the digestate. However, the malodour appears to be temperature sensitive and will reduce to normal (mesophilic digestate) levels once cooled to mesophilic temperatures, either via holding tanks or the TPAD configuration (Schafer et. al., 2002).

(vi) Heating energy requirements – From an energy efficiency standpoint, a challenge in implementation of thermophilic digestion is the high energy input requirements (Appels et. al., 2008), which is not necessarily offset by the increase in biogas generation. The energy balance can be improved by effective utilisation of waste heat, such as for sludge drying or space heating requirements (Schafer et. al., 2002). Alternatively, a co-located Combined Heat and Power (CHP) system may be able to supply part of the heat requirements for the thermophilic digester.

Evaluation of technology

Thermophilic digestion is a generally well studied technology, though the operational challenges involved have limited more widespread applications. In terms of energy efficiency, it is not certain if the energy from the additional biogas generated can offset the digester heating requirements. However, cost savings can be gained from the reduction in sludge volume, which is an attractive advantage. Also, as the digester footprint can be reduced, thermophilic digestion may be a viable option for Greenfield plants with limited space available.

Due to the heating requirements, thermophilic digestion synergises well with CHP systems, where the recovered heat can be used to partially (or possibly completely) offset the heating requirements of the digester.

There are currently no ongoing thermophilic digester studies in the WRPs.

6.3 Combined Heat and Power (CHP) System

Background

In a conventional heat engine, fuel is combusted for electricity only, with over half the thermal energy lost to the atmosphere as waste heat. In contrast, the combined heat and power (CHP) system, also known as cogeneration, is the simultaneous production and utilisation of both electricity and heat, potentially reaching a thermal energy recovery of up to 80% (Shipley et. al., 2008). CHP is a reliable, cost-effective option for municipal used water treatment plants that have, or are planning to install anaerobic digesters (AD), as the two technologies synergise well. Anaerobic digester biogas is used as fuel to generate electricity and energy in the CHP system, and the thermal energy captured by the CHP system is used to meet digester heat loads and for space heating (Cao, 2011b). In general, the electricity generated from biogas of a conventional AD and CHP system can meet 1/3 of the electrical needs of a conventional municipal sewage treatment plant (Wong et al., 2005).

Principles of the technology

There are several grades of heat that can be produced depending on the type of CHP engine, and some CHP schemes can deliver multiple grades of heat at once. In general, the following grades of heat can be defined: Low Temperature Hot Water (LTHW) at 80-95℃, hot oil at about 160℃, hot air at 200-550℃, and steam (Hodges, 2011).

The two primary types of conventional electricity generation equipment are microturbines and reciprocating gas engines. These conventional engines have a biogas-to-electricity conversion efficiency in the range of 20-40%. When combined with advanced AD, achieving a power generation of approximately 1 kWh per 1 kg of AD feed sludge dry solids is a realistic target (UKWIR, 2009). When operated as a CHP, reciprocating engines can further deliver LTHW from the cooling water jacket, with the possibility of steam from engines with large electrical generating capacities greater than 300 kWe. CHP microturbines can typically deliver hot oil, hot air or steam (Hodges, 2011).

A more recent engine development is the fuel-cell technology, which can operate on hydrogen-rich fuel mixtures known as syngas. Syngas can be generated from advanced thermal treatment facilities such as gasification and pyrolysis (Ni et. al., 2006). There are several types of commercially available fuel cells: low temperature (includes phosphoric acid, proton exchange membrane and alkaline types) and high temperature (molten carbonate and solid oxide types).

Advantages and challenges of the technology

In general, upgrading a conventional engine to a CHP system can confer the following advantages:

- **Proven technology** – CHP has been employed in various forms for over a century and it is a proven and effective technology for increasing energy efficiency (Shipley et. al., 2008). A survey of CHP applications in the UK shows that it is well established with up to 41,985 GWh of delivered heat across multiple sectors, including refineries, metal works, food and drink, commerce and transport sectors (Hodges, 2011). As an established technology, CHP systems are commercially available on the market (Shipley et. al., 2008).

- **Economic viability** – CHP produces power at a cost below retail electricity as it can be fed “free” fuel in the form of biogas from the anaerobic digesters, as well as displacing the amount of purchased fuel and electricity for heating requirements (Cao, 2011b). Due to the proximity of the CHP to the point of use, it also eliminates electrical grid transmission losses (Shipley wt. al., 2008).

- **Environmental sustainability** – CHP increases the overall energy efficiency of the plant, therefore lowering external electrical demand. In places where this external electrical supply is generated using fossil fuels, the application of CHP thus contributes to a net reduction in greenhouse gas emissions (Cao, 2011b; Shipley et. al., 2008).

- **Energy security** – A CHP combined with an anaerobic digester provides a local energy solution for WRPs. This relieves power grid congestion and enhances the power reliability of the plant in the event of disruptions to the grid (Cao, 2011b; Shipley et. al., 2008).

However, the following limitations may potentially reduce the effectiveness of CHP installations in certain situations:

- **Heat demand requirements** – The increase in energy efficiency from CHP systems is highly dependent on the ability to effectively utilise the recovered heat. While in temperate climates the recovered heat can be used for anaerobic digester heat loads and office space heating, in tropical climates there is typically no demand for such applications. A possible solution for tropical climates is to utilise the recovered heat to further increase anaerobic digester operating temperatures, or to offset drying energy requirements, depending on the grade and type of heat available from the CHP system.

- **Plant size considerations** – While the payback period of an AD-CHP system can be as short as six years for large plants, the economic viability reduces as plant size decreases. The minimum plant size for an economically feasible biogas-to-energy facility is suggested to be not less than 17,000 m^3/day (Haefke, 2009).

- **Scrubbing and purification of Biogas and CHP flue gases** – Before anaerobic digester biogas can be used, it must first be cleaned of impurities such as siloxanes, CO_2 and H_2S, which reduces the heating value of the biogas and damage downstream equipment (Cao, 2011b). After combustion in the CHP, the flue gases will also need to be scrubbed for fly ash and toxic substances. These additional costs must be considered before installation of an AD-CHP system.

- **Reliability of biogas supply** – The efficiency of an AD-CHP system is also dependent on a reliable biogas supply. Upsets in AD operation could reduce biogas quality or production, in turn reducing the energy output of the CHP. In order to mitigate the impact of such events, the plant will require a reserve electrical supply from the power grid, which adds on to costs.

Specific advantages and challenges of various CHP technologies (EPA, 2008) are shown in Table 6.1.

Table 6.1: Overview of CHP Technologies (EPA, 2008)

<table>
<tr><th>CHP system</th><th>Advantages</th><th>Disadvantages</th><th>Available sizes</th></tr>
<tr><td>Microturbine</td><td>Small number of moving parts.
Compact size and light weight.
Low emissions.
No cooling required.</td><td>High costs.
Relatively low mechanical efficiency.
Limited to lower temperature cogeneration applications.</td><td>30 kW to 250 kW</td></tr>
<tr><td>Spark ignition (SI) reciprocating engine</td><td rowspan="3">High power efficiency with part-load operational flexibility.
Fast start-up.
Relatively low investment cost.
Can be used in island mode and have good load following capability.
Can be overhauled on site with normal operators.
Operate on low-pressure gas.</td><td rowspan="3">High maintenance costs.
Limited to lower temperature cogeneration applications.
Relatively high air emissions.
Must be cooled even if recovered heat is not used.
High levels of low frequency noise.</td><td>< 5 MW in DG applications</td></tr>
<tr><td rowspan="2">Compression ignition (CI) reciprocating engine (dual fuel pilot ignition)</td><td>High speed (1,200 RPM) ≤4MW</td></tr>
<tr><td>Low speed (102-514 RPM) 4-75 MW</td></tr>
</table>

Fuel Cells	Low emissions and low noise. High efficiency over load range. Modular design.	High costs. Low durability and power density. Fuels requiring processing unless pure hydrogen is used.	5 kW to 2 MW

Evaluation of technology

CHP is one of the fundamental technologies recommended by global experts to increase the energy efficiency of the WRP. However, this is dependent on the ability to effectively use the recovered heat. In the Singapore context, due to the tropical climate there are no heating requirements for space heating or for digester heating. In light of this, CHP may be of limited use in Singapore unless it is paired up with alternate heat receivers, such as a thermophilic digester or sludge dryer. Currently, in the WRPs heat is not being recovered from the dual-fuel engines.

6.4 Advanced Thermal Treatment (ATT) – Pyrolysis and Gasification

Background

Incineration is currently the most widely practiced method of treating sludge waste. However, it requires the treatment of large amounts of flue gas, and the disposal of ash remains a concern (Tsang and Sapienza, 2011). Furthermore, the energy efficiency is relatively low (10-30%) and the process results in the formation of undesirable by-products such as heavy metals in the flue gas, dioxins, furans and sulphur dioxide (Ni et al., 2006).

Advanced Thermal Treatment (ATT) technologies are alternative technologies to municipal solid waste (MSW) and waste sludge incineration. ATTs employ high heat and pressure to decompose waste into potentially recoverable liquids, gases and solids, typically for reuse as fuels. Most ATT are already well established technologies for chemical production. However, these technologies are now being considered for novel application on waste biosolids in a "waste-to-energy" role (Hill et. al., 2010). Amongst these technologies, gasification and pyrolysis form the largest groups and are the key ATT being considered for application on waste biosolids.

The distinction between different groups of ATT can be made by the different end-products obtained at various temperature ranges and operating conditions. For example, the main products of Pyrolysis (300-900℃, no oxygen) are bio-oil and bio-char, while the main product of Gasification (550-1450℃, limited oxygen supply) is syngas.

Principles of the Technology – Gasification

Gasification involves the reaction of carbon in the used water solids with air, oxygen, steam, carbon dioxide, or a mixture of these gases at elevated temperatures (550-1000℃, with some applications reaching 1450℃). In contrast to combustion processes (incineration) that work with excess air, gasification processes operate under oxygen-starved conditions, with only enough oxygen added to generate heat to drive the chemical reactions. Under these conditions the process produces heat, which can be used to generate power, and the waste matter undergoes partial oxidation to form syngas and charcoal, which is then finally reduced to form even more syngas. This syngas is composed of H_2, CH_4, CO, CO_2, light and heavy hydrocarbons (Ni et. al., 2006). Typically, the majority of the energy is in the form of CO, which can be converted into CH_4 through the addition of hydrogen (H_2) in a hydro-gasification process or through specialised catalytic gasification (Johnson et al., 2009). Alternatively, the syngas can be further steam reformed and followed by a water-gas shift reaction to maximise H_2 production (up to 60% by volume) (Ni et al., 2006).

The syngas generated through the gasification process may require cleaning prior to its use for power generation or for production of hydrogen, liquid fuel, or chemicals. According to the heat values of the end products and their uses, four types of syngas can be produced, depending on the gasification agent (air, oxygen, or steam), the gasifier operating temperature and pressure, and feed characteristics (type, dry solids, and volatile solids). While it was reported that gasification would have a net energy production of 1.7 GJ/tonne dry solids (Johnson et al., 2009), current operational experience with biosolids gasification in used water treatment plants is still limited (Hake et al., 2006).

Principles of the Technology – Pyrolysis

Pyrolysis is a thermal conversion process where a solid fuel is heated in the absence of an oxidising agent (in an inert atmosphere) at temperatures varying in the range between 300 and 900 °C. Pyrolysis yields mainly CO gas and combustible H_2 gas, a bio-oil liquid, and a solid residue (char). Two classes of pyrolysis exist: (i) the slow heating rate pyrolysis, aimed at producing charcoal (also referred to as carbonisation), and (ii) the flash/fast pyrolysis where the sample is heated at high heating rates (typically at several hundred degrees per minute) or is suddenly exposed to a high temperature in order to produce bio-oil (Johnson et al., 2009). A single commercial application of the pyrolysis process currently in use is the SlurryCarb™ installation in California. The technology converts biosolids into a fuel called E-fuel and CO_2 gas. The plant is designed to process 803 wet tonnes/day. Projected energy balances indicate a net energy production of 8.3 GJ/tonne dry solids (Kearney, 2008).

It was reported that High Temperature Pyrolysis (HTP) (operated at temperature> 1200^{0}C) has a higher energy efficiency i.e., energy requirements are 400kWh/t of sludge but the process will produce 1200kWh/t of sludge (standard gas engine). The off heat energy from pyrolysis is used for sludge drying and therefore not included in the energy balance (NEPTUNE, 2010).

Advantages and challenges of the technology

There are four key advantages of advanced thermal treatment. Firstly, certain types of ATT have the potential to be autothermic, that is, the temperature at which the reaction proceeds is maintained by the heat of the reaction itself. This allows the process to be self-sustaining as long as it is continuously fed fuel in the form of biosolids, and creates a net output of energy. Secondly, ATT converts waste biosolids into fuels such as syngas and bio-oils, further increasing its net energy output. Thirdly, in addition to biofuel, waste biosolids can be converted into products of value such as biochar and metals, reducing the final ash and solids landfilling cost. Finally, as compared to conventional incineration, because ATT uses much less air to drive the reaction, it produces less fly ash and toxic gases that have to be scrubbed from the flue gases. Thus overall, ATT is regarded as an environmentally sustainable “green technology”.

There are two main challenges hindering the successful implementation of ATT for treatment of waste biosolids. Firstly, although pyrolysis and gasification are proposed as potentially energy positive technologies, currently the typical thermal efficiencies are only about 70-90% (Wallace, 2008). A key issue is that in order for these technologies to be energy efficient, the feedstock must contain a high level of dry solids (>50%) (Brown et. al., 2011), which is significantly higher than that found in dewatered sludge from WRPs. Thus, the excess heat generated must be used to offset heating requirements of the dryer, reducing the overall energy efficiency of the system.

The second main challenge is that ATT systems are operational issues. For example, pyrolytic bio-oils are corrosive in nature and age over time, thus requiring expensive corrosion resistant piping and tanks, as well as quick turnover times to prevent bio-oil properties from degrading (Wallace, 2008). In gasification systems, the presence of tarry vapours in syngas lead to tar condensation on valves and pipe surfaces, causing operational problems. Solutions are complex or require very heat to thermally crack the tar (Prins, 2005). Full scale ATT installations continue to face operational disruptions (Tsang and Sapienza, 2011).

Evaluation of technology

ATT processes are regarded by some global experts as possibly being the next great technological innovation to achieve energy-positive WRPs. A possible configuration is to replace the anaerobic digester with an ATT system, thus producing syngas and bio-fuels instead of biogas, and with the advantage of very little waste product for landfilling. However, in order to achieve net energy generation from this setup, the waste sludge being fed to the ATT system must contain >50% dry solids, which is challenging for undigested sludge. Using wet sludge, the recovered heat from the ATT can only be used to partially offset sludge dryer heat requirements, thus resulting in a net energy input. A greater challenge for ATT implementation is the poor full-scale track record due to maintenance problems. A related challenge is that ATT systems are typically run as a batch process due to the problem of repeatedly shutting down and restarting a continuously-fed process for frequent maintenance.

PUB has been in dialogue with companies offering ATT systems. However, ATT systems are not likely to be ready for adoption within the short term due to infrastructure and process constraints. Although ATT systems are unable to have net energy production/recovery, there is a potential for these systems to be an energy neutral sludge minimisation method in which savings in sludge disposal can be made.

Chapter 7

Further considerations

7.1 Industrial Used Water Treatment

Background

Jurong Water Reclamation Plant (WRP) is the only WRP among the current four WRPs in Singapore which receives a significant proportion of industrial used water. For the first 6 months of 2012, it treated an average of 185,000 m^3 of used water daily; about 40% of total used water hydraulic flow originate from various industrial sources including petro-chemical, chemical, pharmaceutical, manufacturing, electricity generation and food industries, etc., and hence heavily polluted. Based on the Used Water Master Plan, Jurong WRP will be decommissioned by 2022, and the industrial used water stream from the Tuas and Benoi sectors will be treated in the future WRP in Tuas. The industrial stream will be segregated from the domestic stream, and will have its own dedicated liquid and solids treatment systems.

In contrast to domestic used water, which is typically characterised as dilute, relatively easy to biodegrade and consistent in composition, the following factors must be considered in the design of treatment systems for the industrial used water stream at JWRP:

i. **High COD mass loading:** A rough estimation indicated that the COD of the industrial streams could vary from 600 to 6,800 mg / l, making it challenging to optimise the aeration requirements in a conventional activated sludge process and resulting in the necessity to provide strong aeration;

ii. **Refractory and toxic chemicals:** Considering the types of industries which discharge used water to the treatment plant, it is likely that some chemicals in the industrial used water could be refractory and toxic. Early upstream detection of these pollutants and possible mitigating measures should be considered in the process design;

iii. **Nutrients:** The concentrations of ammonia and phosphorus of the industrial used water were in the high range of municipal sewage, and their removal should be considered in the process design, with special consideration for the possible inhibition of nitrification;

iv. **High conductivity:** The high conductivity of the industry used water may imply high TDS in the final effluent, which may affect its suitability for reuse, particularly for cooling water.

v. **High fluctuation in influent quality:** The industrial used water influent quality received by Jurong WRP varies greatly most of the time.

vi. **Foaming:** Sludge overflow affected the normal operation of previous PUB MBR site studies, and should be controlled and prevented.

In the continuing efforts to close the entire water loop by PUB, reuse of used water from Jurong WRP has been investigated since 2002 (Tan, 2004). Several pilot-scale investigations for the treatment and reuse of the mixed sewage (Qin et al., 2004; Qin et al., 2006, Cao et al., 2010) and of the industrial used water (Cao et al., 2009) have been carried out. One such study is the 24 m^3/day UASB-MBR-RO pilot plant for the treatment of industrial used water from the Tuas stream (the most polluted stream entering JWRP, with the influent COD sometimes exceeding 5,000 mg/l) (Cao, 2011). The duration of the site investigation was between May 2008 and August 2009.

Having considered the aforementioned characteristics of the industrial used water stream, an integrated process comprising of a UASB reactor, nutrient removal activated sludge-membrane bioreactor (AS-MBR) and RO process was selected for the pilot-scale investigation (Fig. 6.1). This is one of the few pilot-scale plants reported to use an integrated UASB, nutrient removal AS-MBR and RO process for exploring the feasibility of the reuse of industrial used water. One other such system was previously tested in Australia, as reported in Daigger et al., 2007.

The objectives of the pilot-study were: (i) observation of the performance of the integrated process; (ii) investigation of the feasibility of employing enhanced biological phosphorus removal (EBPR) under different configurations; (iii) biological nitrogen removal, especially on the potential inhibitive effects on nitrification; and (iv) effluent quality and its feasibility for industrial reuse.

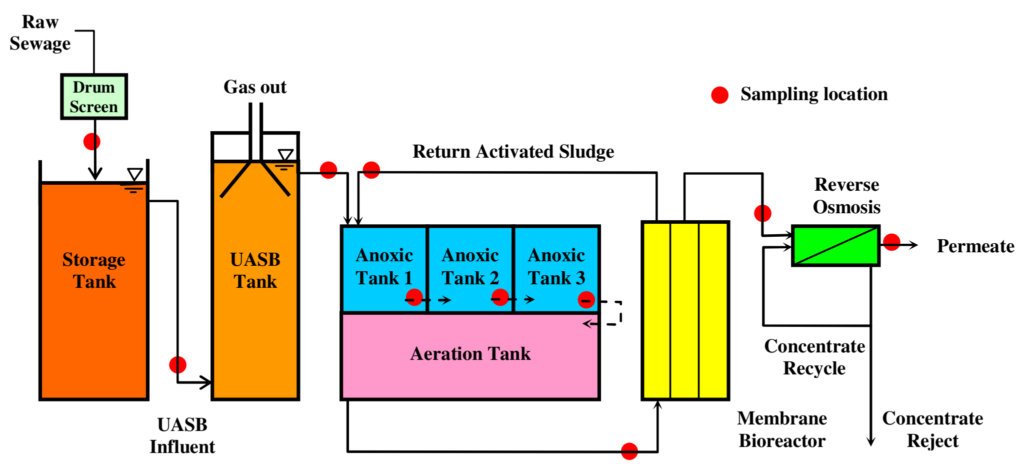


Figure 7.1 Schematic diagram of the integrated UASB-MBR-RO pilot-scale process (MLE configuration).

Figure 7.2 Photo of pilot-scale facilities on-site.

Principles of the technology

The key drivers for the investigation of UASB for industrial used water treatment include: (i) Reduction of the oxygen demand of the subsequent aerobic process, which can result in significant aeration savings in the case of high strength industrial influent; (ii) Increase in biodegradation of the refractory chemicals from industrial sources; and (iii) Reduction of toxic effects of some chemicals on the downstream activated sludge system by adsorbing it onto the UASB biomass.

As previously described in Section 5.2, additional benefits of employing a UASB are: (iv) significant reduction in plant footprint, capital and operating costs; (v) replaces primary clarifiers; (vi) production of 3-20 times less sludge than an equivalent conventional activated sludge system when applied to high strength used water, resulting in significantly reduced disposal costs (Lew et. al., 2004); and (vii) production of biogas while reducing anaerobic digester requirements. Furthermore, as the speed and efficiency of anaerobic treatment processes improve with increasing temperature, the consistent, warm tropical climate in Singapore is favourable for the application of UASBs.

As the UASB is unable to remove nutrients, the subsequent stage in the treatment process was the AS-MBR. In addition to the conventional Modified Ludzack-Ettinger (MLE) activated sludge process, which is designed for nitrogen removal, the AS-MBR system was further modified to investigate the performance of Johannesburg (JHB) and modified University of Cape Town (MUCT) configurations for enhanced biological phosphorus removal. In the last stage of the treatment process, the feasibility of upgrading MBR permeate with an RO system was investigated.

Results of study

The results of the pilot-study showed that the UASB was able to remove up to 70% influent COD. However, due to recurrent illegal toxic discharges there were incidences where the UASB was completely inhibited. For the MBR process, the COD removal efficiency was fairly consistent at about 86%. However, the high average soluble COD (sCOD) of 266 mg/l in the MBR permeate indicated the presence of refractory chemicals that might reduce the lifespan of downstream RO membranes. In general, the overall UASB-AS-MBR process had an average COD removal efficiency of 90.1%.

Very good nitrification performance in the range of 87.2 to 98.3% was observed under an SRT of 5 days. However, the process was also susceptible to the impacts of inhibitors from illegal discharges, with occasional spikes in nitrite or ammonium concentration. The inhibition appeared to be reversible, as evident by the rapid recovery of the system, indicating that the MBR process was sufficiently robust for industrial used water treatment. On the other hand, the performance of EBPR was erratic and unsatisfactory, ranging from 47.6% to 60.9%. This was concluded to be mainly due to the warm temperature and high COD to Phosphorus conditions.

The conductivity and TDS removals of the UASB-MBR process were poor as the dissolved components could still pass through the MBR hollow fibre membranes. However, the TDS and conductivity removal efficiency of the RO unit was > 90% and the quality of the RO permeate was of near-potable quality, which definitely met the requirements for industrial reuse.

Evaluation of technology

The MBR permeate is of sufficiently high quality for floor washing and general cleaning purposes, but the high conductivity and TDS are the major constraints for reuse as cooling water. In order to upgrade the product water to industrial water (IW) grade, two possible measures may be taken: (i) direct blending with the MBR permeate of the domestic stream, or (ii) partial treatment of a portion of industrial stream MBR permeate with RO prior to blending with the MBR permeate of the domestic stream. The choice of final product water and the corresponding MBR permeate treatment approaches are strongly dependent on the type of end users and various economic factors. Due to the presence of high levels of recalcitrant COD in the MBR permeate, it was decided that the RO unit would be dropped from the final design as the rapid membrane fouling would inflate costs significantly.

Pilot results have shown that the UASB unit was not able to perform as well as expected. Possible causes include: (1) occasional inhibition due to illegal toxic discharges, (2) strongly fluctuating industrial used water strength, (3) changes in used water characteristics over time, and (4) presence of sulphates, which promote the growth of undesirable Sulphate-Reducing Bacteria (SRB) that directly compete with methane producing bacteria. Thus, further UASB studies and influent control measures are needed before the suitability of the UASB-MBR configuration for industrial used water reclamation can be determined.

7.2 Phosphorus Recovery

Background

Besides energy recovery, the recovery of resources such as water, nutrients and solids is also of increasing importance for the modern used water treatment plant. One nutrient in particular, phosphorus, has caught the attention of the professional used water community in recent years. The global peak in phosphate rock reserves – estimated to occur in the next 30 years (Cordell et al., 2009) – is expected to detrimentally affect global agricultural yields. As one cubic meter of raw domestic used water is estimated to contain sufficient nutrients for at least one square meter of agricultural production area per year (Keller, 2008), used water has emerged as an attractive source for sustainable phosphorus recovery.

Principles of the technology

Most of the available technologies for phosphorus recovery involve the precipitation of phosphate using magnesium or calcium. Phosphorus recovery through the formation of struvite (magnesium ammonium phosphate) from dewatered anaerobically digested sludge centrate is currently the most popular due to the high concentrations of ammonium and phosphate present in the centrate. Phosphorus recovery by struvite also has the added benefit of reducing the side-stream ammonium load on the main-stream treatment process, resulting in aeration savings.

A typical process is able to produce struvite prills (crystalline pellets) of high purity and different sizes. One example, the Ostara process, is able to reduce phosphorus in the centrate by an average of 82% along with a 14% reduction in ammonia (Baur, 2011). There are at least 6 commercial technology suppliers including Ostara, Paques and Royal Haskoning DHV that are able to implement struvite recovery. While there are other methods of phosphorus recovery from waste streams, such as incinerated sludge ash, these methods are out of scope of current WRP operations and have not been covered in this report.

Evaluation of the technology

Changi WRP currently experiences operational challenges in the centrate pipeline due to struvite scaling choking the pipes. Currently, the pipes are being maintained through a combination of antiscaling agent (which softens the struvite deposits) and routine dismantling for manual cleaning. Although this pipe maintenance regime has been effective, it is labour intensive and the whole cleaning operation must occur within a very tight window of opportunity when there is no flow through the pipe; failure to reassemble the pipe on time would lead to operational delays in the rest of the solids handling systems.

In conclusion, while phosphorus recovery is beneficial for environmental reasons, it is economically unfeasible if the main objective of implementation is the mitigation of struvite build-up in the centrate pipelines. The harvesting and sale of struvite is also economically unfeasible as a business model due to the limited size of the local market. Thus, phosphorus recovery can only be considered if funded by green initiatives to offset the costs involved.

7.3 Dissolved Methane stripping and recovery

Background

Although anaerobic pre-treatment systems such as UASB are well established, a major drawback that has largely been overlooked is the role of dissolved methane in the anaerobically pre-treated effluent (Bandara et. al., 2011). It is estimated that dissolved methane accounts for 30-50% of the methane produced in an upflow anaerobic sludge blanket (UASB) reactor (Cao, 2011). The loss of dissolved methane is believed to result in significant wasted energy recovery potential, while simultaneously contributing to a plant's greenhouse gas emissions (Matsuura et. al., 2010). This is exacerbated by the high hydraulic loading in the main-stream as compared to the much smaller digester centrate side-stream of the conventional primary clarifier – anaerobic digester process. Assuming methane saturation in the used water is reached in both cases, much more dissolved methane will be lost in an anaerobic pre-treatment process due to the much larger volume of used water passing through it.

Among the technologies assessed, the current most applicable are the downflow micro-aeration systems (cascade micro-aeration and Downflow Hanging Sponge (DHS) reactor) due to their relative simplicity, low cost and compatibility with upflow anaerobic systems (e.g. UASB). However, while these systems have the potential to significantly improve methane recovery, the methane concentration in the biogas is low. Unless mixed with high concentration methane gas or further purified (possibly with methane selective membranes), the collected biogas may be of too low a methane purity to be useable as an energy source.

Principles of the technology

Cascade micro-aeration: This method of micro-aeration utilises a conventional gas stripping tower design to strip methane. The anaerobically pre-treated effluent is allowed to cascade down a series of cross-flow channels in a packed tower, increasing the gas-liquid surface contact area. An upflow counter-current air stream is used to strip off the methane, which is collected at the top of the tower. The advantage is that this system couples well with an upflow anaerobic pre-treatment system (such as a UASB) as the pre-treatment effluent can directly enter the stripping tower at the top, reducing pumping requirements. A disadvantage of this system is the build up of solids over time in the tower packing, especially in the event of sludge washout from the anaerobic pre-treatment system.

Downflow Hanging Sponge (DHS) reactor: The DHS reactor is very similar in design and function to the cascading micro-aeration system, being also a downflow packed tower. The key difference is that the DHS additionally utilises aerobic biofilms to oxidise residual dissolved methane after the stripping process and also to perform nitrification, thus functioning as a trickling filter. While the polyurethane sponge media was originally hung in the reactor, subsequent DHS were designed with the sponge cubes bound in laschig rings and randomly packed to a sponge-to-reactor volume ratio of greater than 30% (GEC, 2005). No clogging of sponge pores was observed after one year of continuous operation (Mahmoud et. al., 2010). The reactor has a relatively fast start-up time, with methane removal efficiency of up to 95% achievable within 3 weeks of start-up (Hatamoto et. al., 2010).

In a UASB-DHS configuration, a combined COD and BOD_5 (Biochemical Oxygen Demand, 5 days) reduction of over 90% and effluent SS of less than 20 mg/l can be achieved (Tawfik et. al., 2006; GEC, 2005). Compared with conventional activated sludge treatment, electric power consumption can be reduced to less than 20% and sludge production to less than 40% (GEC, 2005). Although the DHS is able to perform both nitrification and methane oxidation, methane oxidation was found to occur preferentially over ammonia oxidation. In one study, dissolved methane removal efficiencies of up to 95% could be achieved with a nitrification efficiency of only 10% (Hatamoto et. al., 2010). While substantial nitrification (up to 86% in a UASB-DHS reactor study by Tawfik et. al., 2006) can be achieved by substantially increasing air supply, this will have the detrimental effect of diluting the biogas (Bandara et. al., 2011).

A solution to this problem is to adopt a 2-stage DHS configuration, with the first stage designed for methane stripping and recovery, and the second polishing stage designed for biological oxidation. In this way, an average of ≈77% of the influent methane could be recovered as useful gas (containing over 30% methane) by adjusting the air supply rate in the first stage. After polishing in the second stage, the effluent dissolved methane can be reduced by more than 99% to 0.01 mg COD/l (Matsuura et. al., 2010).

Evaluation of technology

Anaerobic pre-treatment focuses on the early capture of energy-rich components from raw sewage and converting it into methane. A major drawback of this method is the significant loss of dissolved methane due to super-saturation and the relatively high flow rate of the main-stream. As a result, in order for anaerobic pre-treatment to be fully effective in terms of energy efficiency, it must be complemented with a dissolved methane stripping and recovery post-treatment system. Among these, cascade micro-aeration and DHS reactors appear to have the most potential.

As PUB's WRPs currently do not employ anaerobic pre-treatment, there are no existing applications of methane stripping and recovery technologies. However, in light of the ongoing studies to evaluate the feasibility of implementing UASB technology for industrial used water treatment, methane stripping and recovery may be a suitable topic for future research.

During SIWW 2010 Prof. Gatze Lettinga was consulted on the management of dissolved methane. He proposed the use of a cascade type micro-aeration setup.

PART III

Final Remarks and Further Reading

Chapter 8

Final remarks

8.1 Report summary

This report was written with aim of providing an updated review of potential used water treatment technologies for adoption in the WRPs, with the focus on developing strategies to achieve increasing levels of energy efficiency.

In Part I, the current landscape of used water treatment, both locally and globally, was described in order to frame the context and scope of this report. An analysis of multiple process configurations was done, concluding with a technology roadmap for increasing the process energy efficiencies of current and future WRPs.

In Part II of the report, a brief description of the shortlisted technologies used in the process configuration analysis was given. In addition, potential treatment solutions for the industrial stream of JWRP and the future WRP in Tuas were discussed. Finally, some process technologies that are potentially important, but outside the scope of this report, were raised for further consideration.

In summary, improvements to brownfield WRPs can potentially increase the process energy efficiency from 25% to 40% within the next 5 years, while for greenfield WRPs such as the upcoming WRP in Tuas, a process energy efficiency of 80% is potentially achievable. Due to the increased reclamation of used water for production of NEWater being a priority target, the MBR has been recommended as a core process unit in all proposed WRP configurations even though it is relatively more energy intensive. As a result, 100% process energy self-sufficiency is currently not a feasible target. However, should some current emerging technologies such as main-stream Anammox be successfully developed, there is the possibility of upgrading WRPs with these technologies for future improvements in energy efficiency.

This report is intended to be a “live” document, and will continue to be updated from time to time as new developments in used water treatment technologies arise.

8.2 Further R&D considerations

8.2.1 Technologies and issues beyond the scope of the report

Due to the complex interactions and large number of used water technologies, as well as space constraints of this report, the focus of this report had been strictly restricted to those technologies applicable within the physical boundaries of the WRP, and the primary method of analysis based on process energy efficiency. However, this is only one component of WRP design; several other factors that still need to be considered include:

1) **Non-process requirements** – These include lighting, pumping, ventilation and odour treatment systems which are not directly involved in the used water treatment process, but are nevertheless vital in the effective operation of a WRP. Energy savings in some areas such as lighting can be achieved by adopting best practices, while in other areas like odour control further R&D can be conducted to improve cost and energy efficiency.

2) **Preventive Vs. Predictive maintenance** – Currently, maintenance in the WRPs is conducted according to maintenance schedules in order to prevent breakdown of equipment. Predictive maintenance, on the other hand, utilizes sensors and trending to monitor the status of equipment, for example, monitoring pressure build-up in the diffuser line to detect the occurrence of diffuser membrane fouling. By adopting predictive maintenance, the WRP is

able to reduce equipment down time and improve the overall efficiency of the plant operations.

3) **Upstream considerations** – The treatment effectiveness and energy efficiency of a WRP is strongly dependent on the characteristics of the influent that the WRP is designed to treat. Should the influent characteristics change over time, or was projected differently during the WRP design phase, the WRP will likely be operating under sub-optimal conditions. To avoid this, further R&D can be done to better understand and control the influent. This can include:

   - Preventive measures – e.g. source control policies and upstream monitoring sensors for detection of incoming toxic substances. Detection of high influent flow during storm events, and the subsequent management of flow and treatment capacity within the WRP, can also be studied.

   - Predictive measures – e.g. impacts of Deep Tunnel Sewerage System (DTSS), greywater recycling, decentralisation etc. on the strength and characteristics of the influent. The impact of climate change on precipitation and rainwater infiltration rates may also be a topic of study.

4) **Expanded role of WRP** – Based on the current model, the WRP treats the influent used water, while the waste sludge is incinerated and disposed of by an externally contracted waste disposal company. However, this arrangement is not necessarily optimal as synergistic benefits, such as heat recovery from incineration / ATT (gasification / pyrolysis), cannot be effectively exploited. Thus, in order to further improve the energy efficiency of the WRP and to minimise waste sludge disposal costs, the following expanded roles of the WRP might be considered:

   - Sludge management and disposal – by co-locating an incineration or ATT facility within the WRP, the recovered heat can be utilized for processes such as heating anaerobic digesters, sludge drying and membrane distillation. Consideration must be made whether the benefits justify the CAPEX and OPEX of the additional facilities required, and whether the facilities should be operated under PUB's scope or as an externally contracted company.

- Waste product management – The final products of sludge incineration / ATT (gasification / pyrolysis), such as ash and biofuels, have potential for further use as Sewage Sludge Ash (SSA) cement additives and engine fuel, respectively.

- Alternative waste streams – There is potential for treatment of alternative waste streams to synergise with used water treatment processes. One example is the inclusion of food waste as a co-digestion substrate for increased biogas production. Another under-utilised waste stream is waste cooking oil from restaurants, which can be segregated from the used water stream through direct collection at the restaurants. In Fritzens WWTP, Austria, this segregated waste cooking oil is purified and subsequently combusted in a biodiesel engine which, together with the biogas CHP engine, has allowed the plant to reach energy positive status. A similar arrangement may be considered for potential adoption in Singapore.

5) **Location considerations** – The location of future WRPs has a significant impact on the design constraints and opportunities for improved energy efficiency. Some of these considerations include:

- Co-location synergies – By tapping on waste streams of co-located facilities, particularly waste heat streams, synergistic benefits can be gained, for example, supplying excess heat from CHP engines or incineration facilities to a membrane distillation unit.

- Design constraints and opportunities – Site locations can affect the non-process energy demand of a plant. For example, an underground WRP would, by necessity, require higher ventilation requirements, and may generally have higher maintenance requirements. An example of an opportunity is the use of hydraulic head (if available) at the final effluent outfall channel for energy recovery with a water turbine. Such a system has been successfully implemented in several plants, such as the Main Treatment Plant Vienna (MTPV) in Vienna, Austria.

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