Guiding Principles in the Design and Operation of a Wastewater Sludge Digestion Plant with Biogas and Power Generation

Marlene vd Merwe-Botha, Karl Juncker, André Visser, Robert Boyd

WATER RESEARCH COMMISSION

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THIS REPORT IS DEDICATED TO SHAUN DEACON

In memory and as tribute to Shaun Deacon, an excellent professional considered by most of his peers as the best specialist of wastewater treatment in South Africa with excellent vision of both financial and technical issues – a rare combination in the sector, this report is dedicated.

Never satisfied with the status quo, stagnation was not an option, only continuous improvement. He had the amazing ability to see things clearly, to sort through the clutter greyness and ambiguity. A courageous, decisive and strong decision-maker who put theory into sustainable practice.

The go-to man for wastewater in Johannesburg Water, many would say in South Africa. All the papers and articles that he authored or co-authored were for the purpose of knowledge sharing. Glory and self-aggrandisement did not enter into it.

This research project was conceptualised by Shaun Deacon, who completed his life journey before being able to see this work to the end. Without Shaun, the Northern Works CHP plant, this research study and its findings would not have realised. He was instrumental in the production of the Standards Documents as the basis of design of wastewater treatment plants to assist future generations. His teachings and emphasis on the integrated management of the entire sludge treatment value chain and caution against handling sludge process units in isolation set a benchmark for the South African wastewater sector.

His work ethics and legacy is carried forward in the work of many engineers and scientists in the country.

EXECUTIVE SUMMARY

Background

The South African industry is widely acknowledged for its excellence in process design. However, some disconnect have been identified between the work of the design engineer, the process manager and the process controller (Deacon & Louw, 2013). Opportunity presents itself to align the work of the Process Designer, who considers design criteria but often exclude operational optimisation of the system, and the Process Manager, who may lack design knowledge but are well conversed with operation of the plants.

This study aims to not only align and optimise the process design and operation, but also to unlock the opportunities presented by integrated- and advanced sludge treatment methodologies. One of the value adds of sludge treatment is the generation of energy, which is gaining interest as the price of electricity increases and interrupted supply impact on the ability of treatment facilities to meet regulatory targets. Anaerobic digestion, coupled with Combined Heat and Power generation is becoming an attractive technology. The study explores the case of the City of Johannesburg's full-scale CHP installation.

Scope of Study

This research study departs from the premises that:

- sludge is a recoverable resource that can be developed;
- sludge treatment is a consecutive and interdependent process which, if one process unit fails, the entire production chain is compromised; and
- understanding the link between the design criteria, the operational criteria and performance measurement of each process unit, will build capacity on various levels.

The purpose of the project is to:

- provide a practical guideline for the design and operation of a sludge treatment plant, with enhanced CHP generation; and
- identify and quantify the opportunities to replicate this approach across the South African industry, at municipal WWTW which already incorporate anaerobic digestion.

Local and international references

Interviews with professional engineers that design and construct sludge treatment facilities in South Africa, indicated that:

- South African engineers do not follow any specific or prescribed local- or international design standard for wastewater or sludge process design.
- Engineering design is typically based on 'in-house' preference and design criteria which are regarded as proprietary.
- Larger municipalities tend to base their preference for design on previous experience with systems and processes that had, or not, worked in the past. Existing plants thereby often becomes the basis or the design standard prescribed by the client to the engineer.
- Suppliers of equipment are typically prescriptive regarding the sludge handling practice and designs are often done to accommodate the supplier's requirements and specification, which then become the design standard.
- Local engineers often revert back to textbooks such as Metcalf and Eddy ('Wastewater Engineering Treatment and Reuse') to source typical design parameters for use as guideline.

Johannesburg Northern Works as case study

The City of Johannesburg and Johannesburg Water identified the rising cost in electricity, interrupted power supply via ESKOM's load shedding practices, and the need to comply with Class A1a biosolids as primary risk to the City's wastewater business. The City embarked upon a strategy to develop the potential value of wastewater as a resource, by establishing an integrated sludge management plan that incorporated the optimisation of the various sludge handling process units, combined with the implementation of beneficiation processes such as CHP, phosphate recovery and sludge beneficiation.

By the time of approval of the strategy (2013), Johannesburg Water treated 998 Ml, 249 dry tons of sludge and consumed 17.5 MW electricity per hour at 6 WWTW. It was estimated that the five large WWTW had the potential to generate 9.5 MW through CHP and electricity by optimising the overall sludge treatment efficiency. This would reduce the electrical power requirement by 54% and have amounted to a saving of about R160 million per year by 2020.

The Northern WWTW serves a population of 1 058 000 people and has an ADWF design capacity of 435 Ml/day, receiving 420 Ml/day. The WULA requires the plant to discharge an effluent quality which meets Special Limits (P of <1 mg/l) and produce a Class A1a sludge.

Design Principles

The Johannesburg Water's "*Project Standards Document: Guidelines for the design of wastewater treatment unit processes*" contains the norms and standards for the various process units mentioned above. This report provides a Process Flow Diagram and describes the design principles of the various process units that are involved in sludge processing: sludge thickening, cell lysis, anaerobic digestion, biogas to electrical energy (CHP), struvite (MAP) recovery, solar drying beds, sludge composting and offsetting of the final biosolids product.

Performance versus design expectation

Operational data from the Johannesburg Northern plant, but also Olifantsvlei WWTW, were collected for each process step involved in producing, thickening, conditioning, treating and digesting sludge related to the biogas production for the CHP system. Performance was analysed for each process unit by considering the sludge quality input to the process unit, the outflow from the unit and the expected design performance of each particular process unit. A summary of the results are as follow:

Electro-kinetic cell lysis: Electro-kinetic cell lysis is expected to improve biogas production in the order of 10% to 20%. No data was available to confirm or deny this enhanced biogas production.

Digester feed: Northern Works have four 2 000 m^3 heated and mixed anaerobic digesters for the digestion of sludge generated by the plant. The combined elutriated primary and thickened waste activated sludge solids concentration in the digester feed was 3.4%, somewhat lower than expected.

Power potential: The theoretical power available was in the order of 1 200 kWe and thermal power in the order of 1 325 kWt if all process steps are optimised. Actual power generated was only 201 kWe (electrical) and 222 kWt (thermal). Areas identified for improved performance and utilisation of this renewable energy source, were the feed sludge solids content, the feed cycle, optimised mixing and digester temperature control.

Struvite precipitation: The ammonia (as N) and phosphate (as P) concentrations in the anaerobic digesters indicate that induced struvite precipitation would be phosphate limited and could produce approximately 590 kg of mono ammonium phosphate per day.

Sludge dewatering: Combined digested primary and WAS sludge mixed with undigested WAS sludge is fed to Belt Filter Presses at a solids content of 2-12%. The solids content of the cake varies between 11-21%

Sludge drying and composting: Compost produced at the plant has been demonstrated to comply with the requirements of a class A1a product in terms of the 2006 WRC Sludge Guidelines.

Mapping of anaerobic digesters and biogas potential at municipal treatment plants:
Anaerobic digestion is widely applied in the South African wastewater industry for the treatment of wastewater solids. Evaluation of the Green Drop data on technologies that are employed for sludge treatment (2014) indicated that drying beds are the pre-dominant technology type (353 plants) followed by anaerobic digestion (217 plants). From these 217 WWTW, 108 plants confirmed the use of anaerobic digestion for the stabilisation and treatment of sludge.

Total biogas production is estimated at 282 671 m^3/day, which translates to electrical energy of 657 765 kWh/day. At a unit cost of 60 cents per kWh electricity, this energy value represent a potential saving of R144 million per annum.

The energy recovery and monetary savings potential can be adjusted upward when considering the following improvement and adjustments:

- Full use of each plant's design capacity;
- Upgrading or refurbishing all anaerobic digesters with heating and mixing equipment;
- Structural refurbishment of anaerobic digesters; and
- Improved operations of the various sludge handling processes, especially primary settling and waste sludge handling from activated sludge plants.

Biosolids classification

On average, 3 594 kg primary sludge and 2 289 kg secondary sludge is produced per plant on a daily basis, resulting in a total sludge production of 548 302 kg/d primary sludge and 368 917 kg/d secondary sludge.

Twenty-five (25) of the 108 plants confirmed that the final sludge is classified (23%), whereas 77% of the plants either did not classify the final sludge or did not provide this information. Of the 23% component, the majority of classified biosolids fell in the Class A category (microbial) and in the Class 1a and 2a categories (stability and pollution).

Uptake of CHP in South Africa

'Minimum feasibility' is defined as '*a CHP project with an assumed lifespan of 15 years that will pay back the investment including financing cost over the project life cycle of 15 yea*rs'. By extrapolation of the kWe data of 108 WWTW, the study showed the following feasibility profile:

- 31 plants (28.7%) do not have sufficient generating capacity (produce < 70 kWe), irrespective of the type of financing of loading scenario;
- 77 plants (71.3%) have a generating capacity of >70 kWe and will potential be feasible for CHP uptake, subject to the financing model applied.

Sector consultation and recommendations from the study

Research focus

- The study report be used as a Guideline by municipalities who are in the planning- or design stage of a biogas recovery project.
- The Report serve as guide for best practice in the design, management and monitoring the individual processes responsible for sludge handling in South Africa.
- The data collected during this study on the status of anaerobic digestion and sludge classification be expanded, further processed and documented as a separate WRC.
- Development of a national business case on biogas to energy from WWTW.
- Development of a detailed business case, including cost benefit analysis, for the Gauteng WWTW anaerobic digesters for full-scale biogas to energy/CHP implementation.

- Further research include for an energy balance to illustrate the actual- and potential energy recovery from raw wastewater.

Regulation focus

- The Regulator consider the introduction of a compliance standard or guideline for digester performance or digestate quality, and deserves equal attention to that of the requirement for treated effluent. This is imperative given the link between in efficient sludge treatment and the knock-on on final effluent quality.
- Further research for setting of operational and critical limits and best practice for the operation of anaerobic digesters and the monitoring of performance on a continuous basis. The inclusion of these as part of the Green Drop 10-year plan bodes well for a positive change in the industry.
- Development of a Guideline to assist municipalities to compile a Sludge Management Plan that considers the various sludge handling process units, sludge monitoring and management, legal requirements, energy generation potential, greenhouse impacts, best practices, performance comparison and benchmarking.

Operational focus

- Adoption of best practice and optimization of biogas production through optimisation of the various process units. The current study showed that the majority of municipalities do not operate or monitor sludge management according to best practice, which impact negatively on biogas yield and quality;
- Upskilling of operating skills, especially focussing on:
  - infrastructure to enable and maintain effective process control with regard to pH, VFAs, alkalinity and temperature
  - facilities to thicken feed sludge to optimal solids concentration
  - feed sludge flow monitoring per digester and appropriate feed distribution
  - quantitative and qualitative biogas monitoring per digester to ensure a healthy process as well as to optimise digester feeding and mixing strategies while maximising biogas production.

Strategic focus

- Raising awareness on the value proposition for biogas recovery at municipal plants in South Africa, as well as the constraints perceived by municipalities hampering the uptake of CHP technology in the municipal environment.
- Quantifying the impact of unused biogas as a greenhouse gas and the potential contribution of SA wastewater treatment plants towards the climate change debate.
- Communicating the CHP development minimum requirements at WWTW for biogas to energy potential.
- Informing policy and strategy, as well as the regulation and legislation pertaining to energy recovery, sludge management, appropriate technology selection and licensing (water use and waste) in South Africa.

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This document was written at a level which assumes a reasonable degree of technical understanding of wastewater treatment and sludge handling/management.

Table of Contents

EXECUTIVE SUMMARY v
Acknowledgements ix
Table of Contents xi
List of Figures xiv
List of Tables xvi
List of Abbreviations xviii
1. CHAPTER 1 – Introduction 1
1.1. SCOPE 1
1.2. OBJECTIVES 2
1.3. CASE STUDY SELECTION 3
1.4 RESEARCH APPROACH AND METHODOLOGY 3
2. CHAPTER 2 – LITERATURE STUDY 6
2.1. SUSTAINABLE WASTEWATER MANAGEMENT 6
2.2 OVERVIEW OF SLUDGE TERMINOLOGY AND TECHNOLOGY 7
2.3 WASTEWATER AND SLUDGE TREATMENT IN SOUTH AFRICA 7
2.4 REGULATION OF SLUDGE MANAGEMENT 9
2.4.1 Legislative requirements 9
2.4.2 Permissible Sludge Guidelines 11
2.4.3 Green Drop requirements 15
2.5 KEY DRIVERS FOR ENHANCED SLUDGE TREATMENT 16
2.5.1 Regulatory compliance 16
2.5.2 Energy and costs 17
2.5.3 Resource recovery 21
2.6 KEY ROLEPLAYERS 27
2.7 WASTEWATER RESIDUAL TREATMENT TECHNOLOGY 28
2.7.1 Sludge origin and composition 28
2.7.2 Sludge treatment technology 29
2.8 GUIDELINES FOR THE DESIGN AND OPERATION OF SLUDGE TREATMENT 39
2.8.1 South Africa 39
2.8.2 International 42
2.9 WRC RESEARCH PORTFOLIO: ANAEROBIC DIGESTION, ENERGY, SEWAGE SLUDGE 43
2.10 REFERENCES 46

3. CHAPTER 3: PROJECT PLAN, PLANT design AND OPERATION 51
3.1. PROJECT BACKGROUND 51
3.2 REGULATORY REQUIREMENTS 51
3.3 DESCRIPTION OF SLUDGE TREATMENT PROCESS UNITS 52
3.3.1 Sludge pre-thickening 52
3.3.2 Sludge pre-conditioning 53
3.3.3 Digestion optimisation 54
3.3.4 Struvite control and precipitation 54
3.3.5 Sludge drying 56
3.3.6 Sludge utilisation and disposal 57
3.3.7 Combined Heat and Power Production (CHP) 57
3.4 DESIGN PRINCIPLES AND SPECIFICATION 62
3.4.1 Sludge Thickening 62
3.4.2 Cell lysis 63
3.4.3 Anaerobic digestion 64
3.4.4 Biogas to Electrical Energy 66
3.4.5 Struvite recovery plant 70
3.4.6 Belt filter press 72
3.4.7 Solar Drying Beds 73
3.4.8 Sludge composting 74
3.4.9 Compost offset 75
CHAPTER 4: FULL-SCALE PLANT PERFORMANCE ANALYSIS 77
4.1 JOHANNESBURG NORTH WASTEWATER TREATMENT PLANT 77
4.1.1 Performance Analysis of Sludge Thickening 78
4.1.2 Performance Analysis of Sludge Pre-Conditioning 79
4.1.3 Performance Analysis of Anaerobic Digestion 80
4.1.4 Performance Analysis of Struvite Control and Precipitation 83
4.1.5 Performance Analysis of Sludge Dewatering 84
4.1.6 Performance Analysis of Sludge Drying and Composting 86
4.2 REFERENCES 91
CHAPTER 5: THE POTENTIAL FOR BIOGAS-TO-ENERGY TECHNOLOGY UPTAKE IN SOUTH AFRICAN MUNICIPALITIES 92
5.1 STATUS OF MUNICIPAL WASTEWATER AND SLUDGE TREATMENT IN SOUTH AFRICA 92
5.2 ASSESSMENT OF ANAEROBIC DIGESTION IN SOUTH AFRICA 95

5.3 ASSESSMENT OF BIOGAS TO ENERGY POTENTIAL 96
5.4 SLUDGE MONITORING PRACTICES 98
5.5 COMPARATIVE ANALYSIS OF WRC 2009 AND 2016 ENERGY RECOVERY STUDIES 99
5.6 MINIMUM FEASIBILITY REQUIREMENTS FOR CHP 100
5.7 RECOMMENDATIONS 102
5.8 REFERENCES 103

ANNEXURES 104

List of Figures

Figure 1: Sludge generated at wastewater treatment plants in SA 8
Figure 2: *The sludge guideline series used to manage, classify and regulate sludge in South Africa* ... 12
Figure 3: Waste (sludge) hierarchy for integrated sludge management 14
Figure 4: The top electricity reliant industries in South Africa. The insert (top right) shows energy demand across water supply chain. 18
Figure 5: Energy demand for different wastewater treatment technologies, plotted against typical demand in South Africa 19
Figure 6: Impact of a 25% price increase on the output of various sectors in the long run (Pan_African Investment & Research Services, Eskom, May 2011) 20
Figure 7: The Projected electricity cost escalation to year 2020 at three treatment plants in the City of Johannesburg 20
Figure 8(a): Plan-Do-Check-Act of ISO 50001:2011 as Figure 8(b) applied in a typical WWTW (adapted, Stamatelatou & Tsagarakis, 2015) 21
Figure 9: *Process flow diagram showing the conversion of primary sludge to VFA via an anaerobic process to produce biomass and PHA (Heidrun Steinmetz, 2014).* 25
Figure 10: A flow diagram showing a typical energy recovery systems with engines and turbines (Metcalf & Eddy, 2014) 26
Figure 11: Generalised sludge processing plant (Metcalf & Eddy, 2014) 30
Figure 12: Photo image of struvite : $MgNH_4PO_4 \bullet 6\ H_2O$ 55
Figure 13: Struvite formation on a pipeline (City of Johannesburg NWWTW) 55
Figure 14: Struvite Precipitation plant from Sludge in Amsterdam, Netherlands 56
Figure 15: View of the NWWTW anaerobic digesters and CHP plant 58
Figure 16: Typical output from a toolkit, used to calculate the energy potential from anaerobic digestion. 59
Figure 17: The use of modelling or simulation to determine the amount of phosphate removed, as well as typical performances to be achieved from the thickening, digestion and drying unit processes. 60
Figure 18: A Process Flow Diagram illustrating the consecutive process units involved in the treatment of sewage sludge at Johannesburg's WWTW 61
Figure 19: The battery limits applicable to a supply where the WSP is responsible for gas supply to the CHP plant (ring-fenced CHP supply only) 69
Figure 20: Flow process and sizing of the proposed Driefontein Struvite Removal Plant 72
Figure 21: Open air solar drying at the NWWTW 74
Figure 22: Sludge DS of 70% achieved at NWWTW 74
Figure 23: Recent acquisition of tractor-mounted sludge turners with lower capital costs, fuel consumption, local service backup and parts availability. 74
Figure 24: Composting of sludge without a bulking agent. 75
Figure 25: Layout of the Johannesburg Northern Works 78
Figure 26: Cumulative probability graph for the anaerobic digester's sludge solids content 81
Figure 27: Cumulative probability graph for the anaerobic digester's %VSS 82
Figure 28: Cumulative probability graph for the anaerobic digester's ammonia concentration 83
Figure 29: Cumulative probability graph for the anaerobic digester's phosphate concentration 83
Figure 30: Cumulative probability graph for the BFC solids content 85

Figure 31: Layout of the windrows and composted sludge at Johannesburg sludge drying and composting plant 89
Figure 32: CHP electrical power over time as a function of HRT and % solids in digester feed 90
Figure 33: Graphic illustration of the distribution of design capacity and operational flows of municipal wastewater treatment plants in South Africa 92
Figure 34: National spread of wastewater (liquid) treatment technologies at municipal treatment plants 94
Figure 35: Minimum CHP feasibility requirement for a fifteen year payback period for various loading, sludge routing and financing scenarios 101

List of Tables

Table 1: Calculated energy potential and estimates for South Africa from domestic wastewater sources 8
Table 2: The disposal options used by wastewater treatment facilities in South Africa 9
Table 3: Sludge Classification System 12
Table 4: Preliminary classification according to Microbiological Class: High microbiological quality is associated with acceptable pathogen content and vector control which would allow the disposal of sludge beneficially 12
Table 5: Preliminary sludge classification according to Stability Class: The increased stability of sludge with associated lower odour risk should enable more wastewater treatment facilities to dispose of sludge beneficially 13
Table 6: *Preliminary sludge classification according to Pollutant Class: The organic and inorganic pollutant limits and load restrictions will determine the use of the sludge* 13
Table 7: Criteria 5 of the Green Drop Certification 10-year plan, showing the various requirements that will be used to audit wastewater institutions under the KPI "Sludge/Solids Management" (presented at the WISA Conference Workshop, May 2016) 16
Table 8: Typical energy demands for wastewater treatment facilities 19
Table 9: The *Canadian government's sludge regulation guidelines includes, promotes and regulate the beneficial uses of sewage sludge* 22
Table 10: Typical nutrient values of biosolids compared to commercial fertiliser, with typical fertilizer use rate for various crops in South Africa (Metcalf & Eddy, 2014; Adapted; Un-habitat, 2008; Sappi, 2015; Natural Resources Management & Environment Department, 2015)* 23
Table 11: *Typical electricity and heat generation efficiency from various co-generation systems* 27
Table 12: Typical chemical composition ranges for the main streams of sludge 29
Table 13: A summary of the typical sludge treatment methods used, with their function, generic design considerations and expected output (Referenced) 31
Table 14: An analysis of the various thickening technologies as preferred by Johannesburg Water was conducted and is shown in the table below 62
Table 15: A typical mass balance for sludge handling units, as applied to the Driefontein WWTW 63
Table 16: Anticipated energy generation for each of the Johannesburg WWTW 70
Table 17: Cost to treat and transport sludge during 2009 (actual) and 2015 (calculated): 76
Table 18: Composition of feed sludge to anaerobic digesters taken over period 2014-2015: 80
Table 19: Composition of sludge outflow from the anaerobic digesters taken over period 2014-2015: 81
Table 20: Heavy metal concentrations of the final biosolids product, as compared to the Sludge Guideline limits for Class A1a sludge: 86
Table 21: A comparative table depicting the composition of the final biosolids product vs the standards contained in the Sludge Guidelines, specific to Class A1a biosolids 88
Table 22: A summary of the spread of WWTW, design capacity and operational flow across the different Provinces in South Africa 93
Table 23: Summary of wastewater (sludge) treatment technologies reported at 152 WSAs across South Africa (Green Drop Progress Report 2014) 94
Table 24: Sludge classification of the final biosolids produced from the WWTW that formed part of the AD research study 98

Table 25: Energy potential estimates from the WRC study in 2009 99
Table 26: Comparison between energy potential from municipal wastewater sources based on WRC research findings reported in 2009 and 2016 99

List of Abbreviations

AD	:	Anaerobic digestion
ASTM	:	Anaerobic Stabilisation Themorphilic/Mesophilic
BFP	:	Belt Filter Press
BOO	:	Build, Own and Operate
BOOT	:	Build, Own, Operate and Transfer
BPC	:	Belt Press Cake
BtE	:	Biogas to Energy
CAPEX	:	Capital Expenditure
CHP	:	Combined Heat and Power
COD	:	Chemical Oxygen Demand
DBSA	:	Development Bank of Southern Africa
DEA	:	Department of Environmental Affairs
DWS	:	Department of Water and Sanitation
EBPR	:	Enhanced biological phosphorus removal
FOG	:	Fats oils grease
GBT	:	Gravity Belt Thickeners
GHG	:	Greenhouse Gas
GIZ	:	Deutsche Gesellschaft fuer Internationale Zusammenarbeit
GtG	:	Gas to Grit
GWP	:	Global Warming Potential
ISO	:	International Organisation for Standardisation
KPI	:	Key Performance Indicator
MAP	:	Magnesium, Ammonia, Phosphate
MDS	:	Millennium Development Goals
MLSS	:	Mixed liquor suspended solids
NRWRS	:	National Water Resource Strategy (2nd edition)
OPEX	:	Operating Expenditure
PHA	:	Polyhydoxyalkanoate
RRR	:	Resource Re-use Recovery
SA	:	South Africa
SAGEN	:	South African-German Energy Programme
SALGA	:	South African Local Government Association
SCP	:	Single cell production
SDG	:	Sustainable development goals
SEV	:	Specific Effluent Volumes
SRT	:	Sludge retention time
SS	:	Suspended Solids
TDS	:	Total Dissolved Solids
UN	:	United Nations
VFA	:	Volatile Fatty Acids
VOC	:	Volatile Organic Contaminants
VSS	:	Volatile Suspended Solids
WAS	:	Waste activated sludge
WEF	:	World Environmental Federation
WISA	:	Water Institute of Southern Africa
WRC	:	Water Research Commission
WSA	:	Water Service Authority
WSP	:	Water Service Provider
WUL	:	Water Use License
WWTW	:	Wastewater Treatment Works

Unit Abbreviations

%	:	percent
°C	:	degrees Celsius
Dt	:	dry tonnes
DS	:	dry solids
kg/s	:	kilogram per second
kJ/kg	:	kilojoules per kilogram
MJ	:	megajoules
mg/kg	:	milligrams per kilogram
ML/d	:	megalitres per day
mg/l or ppm	:	milligrams per litre or parts per million
kW or MW	:	Kilowatt or Megawatt (where: 1 W= 1 J/s)
kWh or MWh	:	kilowatt-hour or megawatt hour (where: 1 kWh = 1 kW expended for 1 hour), (1000 Wh = 3.6 MJ)
tDS/d	:	tonnes dry solids per day
t/ha/yr	:	tonnes per hectare per year
wt	:	wet tonnes

1. CHAPTER 1 – INTRODUCTION

1.1. SCOPE

Management of wastewater residuals and solids throughout the world has never been more challenging or dynamic as it is today. Science and technology develop rapidly to meet ever changing regulatory and environmental goals and the next generation of wastewater sludge management is rapidly advancing in South Africa. Sludge management strategies encompassing nutrient and resource recovery, new stabilisation methods and energy recovery, are featuring as part of municipal planning processes to upgrade and expand infrastructure.

Municipalities and public/private wastewater management institutions are required in terms of their Water Use Licenses, to operate wastewater treatment works and manage sludge in compliance with the Sludge Guidelines (WRC, 2006 & 2009). More recently, this requirement has been included in the Department of Water and Sanitation's Green Drop Certification as a focus area (WISA, 2014). Municipalities are preparing to meet more stringent regulation over the next 10 years pertaining to compliance with sludge management requirements and best practice.

Risk assessments of municipal plants have indicated that sludge management presents a significant hazard within the wastewater business of an organisation and impacts directly on the wastewater treatment processes that need to produce high quality effluent at the point of discharge (WISA, 2014). Sludge which is not adequately treated, monitored and disposed, result in operational- and effluent quality risks throughout the entire wastewater treatment process train, which again result in pollution of ground water, rivers and water impoundments.

Most scientific work or publications relate to individual sludge treatment processes and do not consider the full operational chain of individual processes involved in the complete sludge treatment operation. This is especially true for more sophisticated sludge treatment options, such as Biological Nutrient Removal (BNR) coupled with anaerobic digestion and Combined Heat and Power (CHP) which aim to produce A1a sludge, where the associated risks are high and costly.

Whilst the South African industry is widely acknowledged for it excellence in process design, a disconnect have been identified between the work of the design engineer, the process manager and the process controller (Deacon & Louw, 2013). Information is not readily available to assess the critical link between ***process design and process management*** across the complete sludge treatment process. Opportunity presents itself to align the work of the Process Designer who considers design criteria but often exclude operational optimisation of the system, and the Process Manager who may lack design knowledge but are well conversed with operation of the plants. A disconnect between these elements present a significant risk and would result in an expensive capital installation which will have a reduced asset lifespan as result of inadequate operational practices and non-compliance with the sludge guidelines.

From a financial viewpoint, the capital cost of a comprehensive sludge treatment process is almost 50% of the entire wastewater works, which makes it as expensive as the entire liquids treatment processes. Maintenance cost of the civil, mechanical, electrical and electronic equipment is estimated at 16% of the capital cost (Marx et al., 2004). It makes sense that wastewater treatment be viewed differently going forward, not only to align and optimise the process cycle but also to unlock the opportunities presented by integrated- and advanced sludge treatment methodologies.

One of the value adds of sludge treatment is the generation of energy, which is gaining interest as the price of electricity increases and interrupted supply impact on the ability of treatment facilities to meet regulatory targets. Anaerobic digestion (AD), coupled with CHP generation is but one mean that is attracting attention globally and in South Africa, with various full-scale applications already operational. The latter–utilises the available methane gas produced by the anaerobic digestion process as an energy source to run gas generators and produce power (Burton et al. 2009). Biogas yield and energy recovery depends on the efficient operation of upstream processes, which produces the feed sludge to the anaerobic digester. Hence, the optimisation of the entire sludge treatment train, including sludge withdrawal, thickening, stabilisation and dewatering, becomes critical control unit processes to ensure a high performing anaerobic reactor and biogas-to-energy system.

This study departs from the premises that:

i) sludge is a recoverable resource that can be developed;

ii) sludge treatment is a consecutive and interdependent process which, if one process unit fails, the entire production chain is compromised; and

iii) the link between- and understanding of the design criteria, the operational criteria and performance measurement of each process unit will build capacity of the designer, the manager and the process controller, thereby meeting the objectives of the sludge management infrastructure.

1.2. OBJECTIVES

The WRC commissioned a study to document the design and operation criteria of a full-scale plant which employs an advanced sludge treatment process, with heat and power generation, as well as struvite formation.

The purpose of the project is to:

- provide a practical guideline for the design and operation of a sludge treatment plant, with enhanced CHP generation; and

- identify and quantify the opportunities to replicate this approach across the South African wastewater industry, at municipal wastewater treatment works (WWTW) which already incorporate anaerobic digestion.

The objectives of the study is as follows:

- To develop a comprehensive understanding of the design and operational requirements for a sophisticated wastewater treatment with an anaerobic digestion sludge handling facility, and the requirements set out by the WRC 2006 Sludge Guidelines for A1a biosolids as end-product;

- To evaluate the performance of sludge digestion and enhanced biogas production and electrical power generation in a full-scale CHP plant;

- To assess the recovery of struvite crystals formed after the digestion process for use as a slow release fertilizer and prevent potential blockages in downstream digested sludge treatment plant and equipment;

- To share operational good practice to prevent high concentrations of Nitrogen and Phosphorus from dewatered sludge filtrate being recycled back to the bioreactors, causing effluent non-compliance.

- To illustrate the value of thickening sludge prior to the digestion phase, where higher volatile solids loading rates are used to ensure sufficient digester capacity for sludge treatment.

- To illustrate how sludge stabilisation such as solar drying and composting, as well as final treatment of sludge, produces an A1a class final biosolids product which complies with the 2006 WRC Sludge Guidelines
- To establish the status of anaerobic digestion in SA, and map the suitability for CHP technology in SA

The Final Report contains guiding principles for the design and operation of the various process units responsible for sludge handling and production of value-added biosolids, whereby the focus is on anaerobic digestion with enhanced CHP production.

The Guideline is intended to be used by designers, operators and decision makers to inform decisions pertaining to the use of this technology, as well as the potential uptake of this technology in the South African market place.

1.3. CASE STUDY SELECTION

The City of Johannesburg and Johannesburg Water, own and operate various WWTW, including the Northern, Olifantsvlei, Driefontein, Bushkoppies and Goudkoppies WWTW. The Northern works was used as case study for sludge thickening, cell lysis, anaerobic digestion with CHP, whilst Olifantsvlei presents the case for composting to produce a Class A1a biosolids. Solar drying of solids and composting is done at Olifantsvlei as primary sludge handling methodology. Upgrades to the plant's digester facilities started in July 2015 and will run concurrently with solar drying methodology over a five-year period. The research team worked closely with the Johannesburg Water engineers who are involved in the installation of the full-scale sludge treatment and disposal operations at the NWWTW. The installation of a 1.14 MW CHP unit was completed in 2013 and an agreement was reached in June 2014 to share design aspects and write up the plant data of the full-scale application. The experience gained from the NWWTW will lead to the replication of this technology at the Driefontein WWTW with the installation of 2x376 kW CHP reciprocating units.

1.4 RESEARCH APPROACH AND METHODOLOGY

The research study considers the design, operational, and performance, of various process units involved in the treatment of sludge at 2 full-scale WWTW in the City of Johannesburg. The study focusses on the Sludge Guidelines for the utilisation and disposal of wastewater sludge, as published by the WRC in 2006 and 2009, to illustrate the importance of an efficient sludge treatment train towards rendering a Class A1a biosolids as final product. The research draws attention to the anaerobic digestion and biogas to electrical energy, which presents a focal point of the research. The design guidelines developed by Johannesburg Water set out the basis of the research, in illustrating the importance of design and operation across the entire sludge handling train. The research approach appreciates and adopts the philosophy of 'wastewater as resource', instead of tackling sludge as a 'problem' that needs to be treated and disposed.

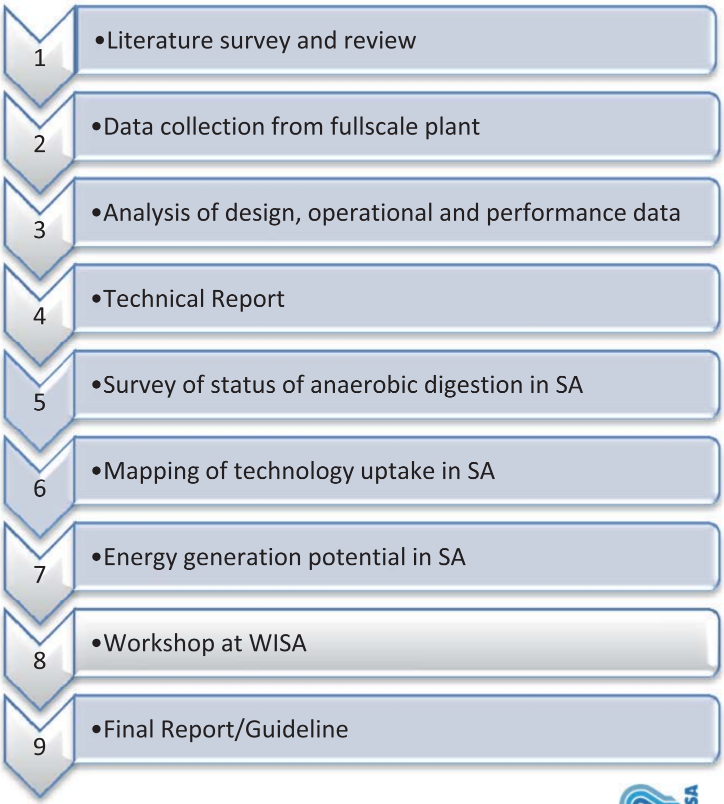
The methodology followed during the study is as follows:

1. **Literature survey and review**

A literature review was undertaken to discuss the type of sludge handling technologies, design standards documentation and research on a global scale.

2. **Collection of data from full-scale plant**

Collection of key design-, operations- and performance data from a full-scale sludge treatment plant for each process unit of an integrated wastewater sludge treatment process, including: primary sludge fermentation, waste activated sludge (WAS) thickening, digestion of the thickened raw and WAS sludge, biological phosphate removal and prevention of struvite formation after the digestion process, dewatering of digested sludge, solar drying of digested sludge, beneficiation of digested sludge, biogas scrubbing and CHP generation.



3. **Analysis of design-, operational and performance data**

Analysis and comparison of the performance of the various process units with its original design specification and expectations, using >6 months operational data, towards the objective A1a sludge type. Where actual results differ markedly from anticipated results, these will be discussed with the Johannesburg Water Engineers in terms of the alterations to the operations necessary to refine the operational element in the study. Results attained prior to and after the operational changes considered in the report where possible, to allow for the determination of best practices.

4. **Technical Report**

The Report includes a comparison between design expectations and actual performance from the full-scale trials pertaining to the design information, the complete treatment operation and CHP generation. The Report also contains guidelines pertaining to the design and operation of the technology, with the main objective being the attainment of a Class A1a biosolids as final product.

5. **Survey of status of anaerobic digestion in SA**

A 1st order survey established the status of Anaerobic Digesters in SA, their design specs and operational status where possible, using available data from the Green Drop. Where information is lacking, site specific enquiries were be made.

6. **Mapping of technology uptake in SA**

Using a set of criteria, a mapping exercise were conducted to assess the potential and suitability for uptake of the AD and CHP technology in SA.

7. **Energy generation potential in SA**

Using known or estimated loading rates, an estimated energy generation were calculated, supported by relevant cost savings that would apply to the existing anaerobic digestion landscape in South Africa, based on the model developed by WEC and GIZ: "A Biogas to CHP tool".

8. **Workshop**

A workshop were held during the WISA Conference in May 2016 to share knowledge on the suitability and potential of the technology, and to seek sector input to the design and operational parameters before finalizing the Final Report.

9. Final Report and guideline

Submission of the Final Report, including guidelines for the design and operation of an integrated sludge treatment process, including CHP, for peer review, print and publication.

2. CHAPTER 2 – LITERATURE STUDY

2.1. SUSTAINABLE WASTEWATER MANAGEMENT

Governments world-wide realise that sustainable growth targets cannot be realised without infrastructure to collect, transport and treat wastewater. As the time limit for the Millennium Development Goals (MDGs) draws to a close in 2015, the new era for Sustainable Development Goals (SDGs) is being introduced (UN, 2015). South Africa's government has communicated messages of commitment and investment in its post-2015 plans for sanitation, emphasizing the need to improve infrastructure, skills and technologies which are efficient, effective, appropriate and sustainable.

Sewage sludge production and management are a central component of water and sanitation engineering. For centuries, wastewater treatment have existed primarily for the protection of human health. Although successful, a reliance was built on infrastructure and management strategies that are not sustainable in the 21st century. The culmination of previous incremental technologies and regulations was aimed at solving a treatment 'problem'. Similarly, wastewater decisions have traditionally been driven by considerations of function, safety and cost-benefit analysis, which have resulted in sludge becoming an economic and social liability (Peccia & Westerhoff, 2015).

South African water- and environmental legislation and the introduction of the Green Drop Certification programme in 2008 have done much to facilitate the upgrading and development of effective treatment plants and improve the final effluent quality. Subsequently, legislation has focussed predominantly on effluent quality and its impact on the resource. It has however become vital to include sludge management for its role in the wastewater treatment process. An appreciation of energy and nutrients has brought about a defined paradigm shift towards viewing wastewater as a renewable recoverable source of energy, nutrients, materials and water (Marx et al*.,* 2004; Tchobanoglous, 2011; Fersi et al*.,* 2015). This would entail that sludge management practice ***shift from treatment of a liability towards recovery of the fundamental energy and chemical assets***, while continuing to protect the environment and human health.

Stamatelatou & Tsagarakis (2015) observed that '*sustainability demands that we acknowledge wastewater as a renewable resource from which water, materials (e.g. fertilisers, bioplastics), and energy can be recovered.The primary problem we face is not the availability of technology for resource recovery, but the lack of a socio technological planning and design methodology to identify and deploy the most sustainable solution in a given geographic and cultural context.*"

Rightly so, for South Africa, this shift will require new research, treatment technologies and infrastructure, and must be guided by operational and design best practice and applying green engineering principles to ensure economic, social, and environmental sustainability. The Department of Water and Sanitation, as Regulator, has already taken steps to communicate sludge as a renewable resource and by including sludge management and resource recovery as a key performance area in the 10 Year Green Drop Plan (WISA, 2014). In this manner, the Regulator incentivise the legislative compliance of sludge treatment, as well as the beneficiation of sludge and its by-products.

Sludge treatment does not exist in isolation, and consist of a train of process units which require an integrated sludge resource recovery philosophy if successful sludge treatment and beneficiation is to occur in a sustainable manner (Guest et al., 2009; Viljoen et al*.,* 2013). Guest et al*.* (2015) emphasises that new perceptions, infrastructure planning and design processes are required to employ technologies that sustainably recover resources from wastewater, such as struvite granules, gas to oil, building materials, etc.

International consensus has largely been reached that sludge management must convert from the traditional regulatory-driven treatment-based approach, to a resource recovery-based enterprise. A future that is concerned with economics, water use efficiency, energy conservation, beneficial re-use, recycling and human and environmental health will demand more from sewage sludge. As the South African wastewater industry is charting a path into a sustainable future, it is contended that wastewater contains resources worth recovering and that the development of technologies, practices, policies, guidelines and finance models that enable cost-effective recovery will have broad implications towards meeting the National Water Resource Strategy (2013) objectives.

2.2 OVERVIEW OF SLUDGE TERMINOLOGY AND TECHNOLOGY

Wastewater is widely defined as a combination of the liquid or water-carried wastes removed from residences, institutions, and commercial and industrial establishments, together with such groundwater, surface water, and storm water as may be present (Metcalf & Eddy, 2014). In the National Water Act (1998), sludge is included under the term 'waste' and defined as follows: "…*any solid material or material that is suspended, dissolved or transported in water (including sediment) and which is spilled or deposited on land or into a water resource in such volume, composition or manner as to cause, or to be reasonably likely to cause, the water resource to be polluted*".

The waste constituents which are typically removed during the wastewater treatment process include screenings, grit, scum, solids and biosolids. The solids and biosolids (collectively called '**sludge'**) is in a liquid or semisolid state, which contains 3%-6% solids (Ross, 1992) or up to 0.25-12% solids by weight (Metcalf & Eddy, 2003), and 2-30% dry solids (Peccia et al*.,* 2015). The terms '**biosolids'** draws from the definition by the Water Environment Federation (WEF, 1998) which reflect that sludge is organic in nature and can be used beneficially (Issac & Boothroyd, 1996). The term 'sludge' is used before beneficial status is achieved, as is usually a process descriptor such as primary sludge. The inorganic constituents are referred to as '**residuals'** and typically consist of the screenings and grit (Ross et al*.,* 1992), and is not considered as part of this study.

Various technologies and unit processes are available for the treatment of wastewater, ranging from BNR for C, P and N removal, to land treatment systems, commonly known as 'natural systems' (Metcalf & Eddy, 2003). These systems have been described in much detail in various reports and studies commissioned by the Water Research Commission and other literature (WRC/DBSA, 2011), and will not be the topic of this Report.

The management of sludge and concentrated contaminants removed by the treatment process is the most difficult and expensive problem in the field of wastewater engineering (WEF, 1993, Marx, 2004). The challenges related to sludge and biosolids are complex because of the offensive nature of the untreated solids and only a small part is solid matter. The objective of any sludge treatment technology is therefore twofold: to reduce the water and organic content in the sludge; and to render the process solids suitable for re-use or final safe disposal (Malina & Pohland, 1992; Herselman et al*.,* 2005).

Sludge treatment technologies have traditionally not been as progressive as the treatment of liquid wastewater. Treatment technologies for sludge processing have focused on conventional methods such as thickening, stabilisation, dewatering and drying. With the advent of regulations that encourage sludge re-use, significant efforts have been directed to produce a 'clean sludge' (Class A1a biosolids) (WRC, 2006). These efforts are largely driven by the need to produce sludge that are clean, have less volume and can be used beneficially. New solutions are however fast gaining momentum in sludge processing. Egg shaped anaerobic digesters are used because of advantages in operation, cost and increased volatile solids destruction (Ashenafi et al., 2014)). Temperature-phase anaerobic digestion and auto-thermal aerobic digestion processes are in use to improve volatile solids destruction and meet high sludge standards (Marx et al., 2004). High solids centrifuges and heat dryers are gaining popularity for their dewatering abilities and producing a dryer sludge cake (Princince et al., 1998). Precipitation of struvite immediately after anaerobic digestion result in recovery of phosphorus and nitrogen (Deacon, 2014).

2.3 WASTEWATER AND SLUDGE TREATMENT IN SOUTH AFRICA

The potential impact of enhanced sludge management and sludge beneficiation in the South African wastewater industry is substantial. In the public sector alone, more than 950 treatment facilities treat approximately 6 550 Ml/d wastewater, with a sludge content of approximately 1 200-1 800 t DS/d. The total mass of sludge could be more if equated to a population of approximately 54 million (Stats SA, 2014), based on a solids production of 50 g/person/day, and an assumed component of 39% from industrial effluent. Marx et al. (2004) estimated total sludge production at 1 750 t DS/d for undigested and 1 375 t DS/d for digested sludge, split as follows:

- 750 t DS/d from primary sludge @ 150 kg DS/Ml;
- 1000 t DS/d waste activated sludge @ 200 kg DS/Ml;
- 525 t DS/d digested primary sludge @ 30% reduction; and
- 850 t DS/d from digester waste activated sludge @ 15% reduction.

Burton et al. (2009) estimated the (total) potential for energy from municipal wastewater treatment plants to be approximately 1 134 MW from municipal wastewater treatment plants and as high as 1 488 MW if accounting for the solids of 48.5 million people in South Africa then. As given in Table 1, Burton et al. (2009) assumed all incoming energy to be available and does not discount the energy consumed by the processes to produce final effluent and sludge.

Table 1: Calculated energy potential and estimates for South Africa from domestic wastewater sources

Wastewater source of energy	Energy potential	Assumptions
Population of SA, incl. domestic black and grey water	1488 MJ/s or 1488 MW	200 l/d sewage per person, population of 48.5 million, COD of 860 mg/l, calculated 96.6 kg/s, energy content of 15 MJ/kg
Municipal WWTW	1134 MJ/s or 1134 MW	7600 Ml/d total flows, COD of 860 mg/l, calculated 75.7 kg/s, energy content of 15 MJ/kg
Domestic blackwater load	824 MJ/s or 824 MW	48.5 million people generate 100 g dry weight faeces with energy value of 15 MJ/d, calculated as 56 kg/s, 842 MJ/s or 842 MW
Total captured domestic blackwater of serviced population	509 MJ/s or 509 MW	60.4% of population with flush toilets = 29.3 million people, 100 g dry weight per person, calculated as 33.9 kg/s, energy content of 15 MJ/s

Sludge generated at wastewater treatment plants in South Africa (dry mass % basis), shows that the majority of sludge accounted for is in the form of anaerobically digested sludge and activated sludge (N-Habitat, 2008 – by Dr H Snyman).

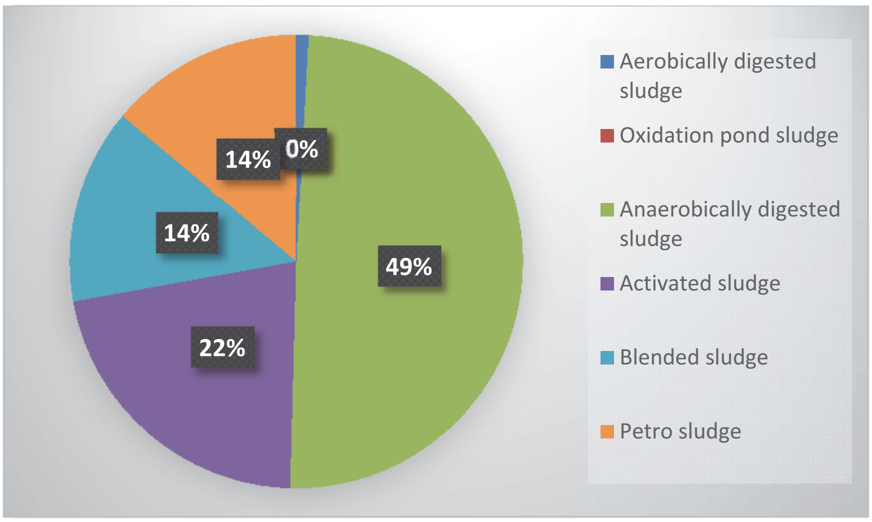


Figure 1: Sludge generated at wastewater treatment plants in SA

Herselman et al. (2004) has quantified the sludge disposal methods applied in South Africa in 2001, and verified these applications again in 2004, and this is given in Table 2.

Table 2: The disposal options used by wastewater treatment facilities in South Africa

Sludge application	% of total in 2001	% of total verified in 2004
Stockpiling of dried sludge	40	33
Sacrificial or dedicated land disposal (incl. dried and flooded sludge)	21	13
Sludge lagoons or oxidations ponds or paddies	16	26
Composting	10	8
Farming activities	7	6
Undisclosed	6	5
Landfill/Co-disposal	4	3
Instant lawn cultivation	3	3
Marine disposal	2	2

The cost of sludge handling, stabilisation, dewatering and land application is generally not well documented by municipalities. Capital cost for sludge handling is estimated at almost 50% of the capital expenditure of the entire treatment infrastructure (WEF, 1993). Marx et al. (2004) calculated the cost of capital, operation and maintenance for various sludge handling technologies, based on a payback period of 25 years at 15% interest rate for civil, mechanical, electrical and electronic infrastructure. Annual maintenance cost of sludge infrastructure is typically 16% of the capital cost.

Indirect cost indicators in the wastewater equipment supply market shows exponential growth, clearing revenues of $66.5 million in 2014, whilst the water and wastewater chemical market is estimated to earn revenues of $129.6 million (≈R1.7 billion) in 2015 (Frost & Sullivan, 2015). Projections favour further growth in this sector as a result of expanding population, new housing development, expanding industrial activity, and upgrade of collection, transportation and treatment infrastructure which surpassed its design life cycle. Moving forward, it appears as if cost and compliance seems to be the two main drivers in a rigorous technology movement geared towards enhanced sludge treatment technology and derive commercial value from sludge-related products (Frost & Sullivan, 2015).

2.4 REGULATION OF SLUDGE MANAGEMENT

2.4.1 Legislative requirements

The Constitution of South Africa assigns the responsibility for provision of water services to Local Government whilst an oversight and performance monitoring duties are delegated to Provincial and National Government. The laws governing the disposal of wastewater sludge in South Africa are as follows:

- National Water Act, 1998 (Act 36 of 1998)
- National Environmental Act, 1998 (Act 107 of 1998)
- National Environmental Management: Waste Act, 2008 (Act 59 of 2008),
- Waste Amendment Act, 2014 (Act 26 of 2014)
- Environmental Conservation Act, 1989 (Act 73 of 1989)
- Fertiliser, Farm Feeds, Agricultural Remedies and Stock Remedies Act, 1947 (Act 36 of 1947), and its regulatory schedule of September 2012
- Hazardous Substances Act, 1973 (Act 15 of 1973)
- Conservation of Agricultural Resources Act, 1983 (Act no 43 of 1983)

- Occupation Health and Safety Act, 1993 (Act 85 of 1993).

Key aspects pertaining to sludge regulation, from the above water- and environmental legislation, are summarised hereunder.

The Department of Water and Sanitation (DWS) is responsible for the regulation of wastewater services as required by Section 155(7) of the Constitution, Section 62 of the Water Services Act (No. 108 of 1997), as well as Section 21 of the National Water Act (No 36 of 1998).

Sludge is included under the term 'waste' in the National Water Act in Section 21 and related sections referred to in it. The Act defines' waste' as: *"…any solid material or material that is suspended, dissolved or transported in water (including sediment) and which is spilled or deposited on land or into a water resource in such volume, composition or manner as to cause, or to be reasonably likely to cause, the water resource to be polluted*".

The conditions for sludge management is contained in Water Use Authorisations, and typically is stated as follows:

i. *Wastewater sludge from drying beds and other solids waste; for instance grit and screening must be handled, stored, transported, utilised or disposed of in such a manner as not to cause any odour, flies, health hazard, secondary pollution or other nuisance.*

ii. *Sludge emanating from the treatment process must be quantified, analysed, dealt with according to the requirements of chapter 5 of the National Environmental Management: Waste Act, 2008 (|Act 59 of 2008) and the Guideline for the Utilisation and Disposal of wastewater sludge (Volume 1-5), dated March 2006 and any updates thereafter, to the satisfaction of the Provincial Head*

iii. *Any wastewater sludge or any other solids waste may be alienated for utilisation or disposal thereof, only in terms of written agreement and provided that the responsibility for complying with the requirements contained in this licence is accepted by Licensee and such other party, jointly and separately.*

The National Environmental Management: Waste Act, 2008 (Act 59 of 2008), and the Waste Amendment Act (Act 26 of 2014) outline the requirements for sludge management. The Act defines waste as "**…** *any substance, whether or not that substance can be reduced, re-used, recycled and recovered-*

(a) that is surplus, unwanted, rejected, discarded, abandoned or disposed of;

(b) which the generator has no further use of for the purposes of production;

(c) that must be treated or disposed of; or

(d) that is identified as a waste by the Minister by notice in the Gazette, and includes waste generated by the mining, medical or other sector, but-

(i) a by-product is not considered waste; and

(ii) any portion of waste, once re-used, recycled and recovered, ceases to be waste.

The Waste Act does make provision for the issuing of an integrated license which "*44(2) (b): issue an integrated license jointly with the other organ of state…. which licence grants approval in terms of this Act and any other legislation specified in the license…"*. However, the issuing of integrated licenses by the two Departments have not been implemented by time of this research (DWS interview, 2015).

The need for a Waste Authorisation is clarified by the Sludge Guidelines, (WRC TT349/2009; Volume 3, Table 7) which stipulates that if the sludge disposal is within the boundaries of the WWTW (on-site), then the sludge disposal is included within the Water Use Authorisation. If the sludge disposal is outside (off-site) the boundaries of the WWTW, then it would require a waste licence. If sludge handling is off-site, but irrigation with sludge takes place, then it will requires a Water Use Authorisation. In terms of marine disposal, a

Discharge Permit is required in terms of the discharges to sea in terms of the Integrated Coastal Management Act.

It is also noted that DWS can dispense in terms of the National Water Act, but the Department of Environmental Affairs (DEA) cannot dispense in terms of NEMWA (DWS interview, July 2015). Section 22(3): *"(3) A responsible authority may dispense with the requirement for a licence for water use if it is satisfied that the purpose of this Act will be met by the grant of a licence, permit or other authorisation under any other law…".*

This means that if an applicant applies for a water use license (WUL), the DWS may dispense in terms of Section 22(3) of the NWA with the requirement for a WUL if DWS is satisfied that the purpose of the NWA will be met by the grant of a waste licence. The applicant still have to submit an application to DWS with a motivation.

2.4.2 Permissible Sludge Guidelines

As previously discussed, the Water Use Authorisation includes the requirement to manage wastewater sludge in a safe and responsible manner and specifies that the water user makes use of the *Guidelines for the Utilisation and Disposal of Wastewater Sludge*, (WRC, 2006 & 2009). The sludge guidelines on its own are just guidelines, but once they have been included in the Water Use Authorisations as a condition, it becomes enforceable.

In order to be discharged and used, sludge need to be characterised or classified. Historically in South Africa, sludge was classified in three main categories in a decreasing order of potential to cause odour nuisances and fly-breeding as well as to transmit pathogenic organisms to the environment. The categories as described in the guide "*Permissible Utilisation and Disposal of Sewage Sludge*" published by the WRC (TT 85/97) in August 1997 (Edition 1), also known as PUDSS 1997, are:

- TYPE A SLUDGE: Unstable with a high odour and fly nuisance potential; high content of pathogenic organisms.
- TYPE B SLUDGE: Stable with low odour and fly nuisance potential; reduced content of pathogenic organisms.
- TYPE C SLUDGE: Stable with insignificant odour and fly nuisance potential; containing insignificant numbers of pathogenic organisms.
- TYPE D SLUDGE: Similar quality as TYPE C but for unrestricted use on land at a maximum application rate of 8 dry t/ha/yr., hence, the metal and inorganic content are limited to acceptable low levels.

This process of classification has been replaced by the Sludge Management Guidelines of 2006 and 2009, which are currently used in Authorisations by the Authorities responsible for water and environmental affairs to stipulate the regulatory requirements for sludge management. The Guideline consists of the following volumes:

- Volume 1: Report TT261/06 Selection of Management Options
- Volume 2: Report TT262/06 Requirements for the Agricultural Use of Wastewater Sludge
- Volume 3: Report TT 349/09 Requirements for the On-site and Off-site Disposal of Sludge
- Volume 4: Report TT 350/09 Requirements for the Beneficial Use of Sludge at High Loading Rates
- Volume 5: Report TT 351/09 Requirements for Thermal Sludge Management Practices and for Commercial Products containing Sludge.

Figure 2: *The sludge guideline series used to manage, classify and regulate sludg*

The sludge classification system is illustrated as follows (Volume 1, Part 6):

Table 3: Sludge Classification System

Microbial class	**A**	**B**	**C**
Stability class	**1**	**2**	**3**
Pollution class	**a**	**b**	**c**

Sludge characterisation and classification should be done annually or as prescribed by a Risk Assessment, and repeated if any major sludge production or processing changes occur that could affect the classification. Such changes could include major extensions or operational changes at the plant or when the raw influent quality changes to such extent that it affects the sludge quality.

Sludge classification is based on three classes: namely the microbiological, stability and pollutant classes (WRC, 2006 & 2009).

Table 4: Preliminary classification according to Microbiological Class: High microbiological quality is associated with acceptable pathogen content and vector control which would allow the disposal of sludge beneficially

Microbiological class	**A**	**B**	**C**
Microbiological constituents	All three samples comply with the following standard	Two of the three samples comply with the following standard	One or more of the samples exceed the following concentration
Faecal coliforms (CFU/g_{dry})	< 1 000	< 1 X 10^6 to 1 x 10^7	> 1 X 10^7
Helminth ova (Total viable ova/g_{dry})	< 0.25 (or one viable ova/4_{gn})	< 1 to 4	> 4

Table 5: Preliminary sludge classification according to Stability Class: The increased stability of sludge with associated lower odour risk should enable more wastewater treatment facilities to dispose of sludge beneficially

Stability class	1	2	3
	Plan/design to comply with one of the options listed below on a 90 percentile basis.	Plan/design to comply with one of the options listed below on a 75 percentile basis.	No stabilisation or vector attraction reduction options required.
Option: 1 Reduce the mass of volatile solids by a minimum of 38 percent. Option: 2 Demonstrate vector attraction reduction with additional anaerobic digestion in a bench-scale unit. Option: 3 Demonstrate vector attraction reduction with additional aerobic digestion in a bench-scale. Option: 4 Meet a specific oxygen uptake rate for aerobically treated sludge. Option: 5 Use aerobic processes at a temperature greater than 40°C (average temperature 45°C) for 14 days or longer (e.g. during sludge composting). Option: 6 Add alkaline material to raise the pH under specific conditions. Option: 7 Reduce moisture content of sludge that do not contain unstabilised solids (from treatment processes other than primary treatment) to at least 75 percent solids. Option: 8 Reduce moisture content of sludge with unstabilised solids to at least 90 percent solids. Option: 9 Inject sludge beneath the soil surface within a specified time, depending on level of pathogen treatment. Option: 10 Incorporate sludge applied to or placed on the surface of the land within specified time periods after application to or placement on surface of the land.			

Table 6: *Preliminary sludge classification according to Pollutant Class: The organic and inorganic pollutant limits and load restrictions will determine the use of the sludge*

Metal limits for South Africa Wastewater Sludge (mg/kg)			
Pollutant class	**a**	**b**	**c**
Arsenic (As)	<40	40-75	>75
Cadmium (Cd)	<40	40-85	>85
Chromium (Cr)	<1 200	1 200-3 000	>3 000
Copper (Cu)	<1 500	1 500-4 300	>4 300
Lead (Pb)	<300	300-840	>840
Mercury (Hg)	<15	15-55	>55
Nickel (Ni)	<420	420	>420
Zinc (Zn)	<2 800	2 800-7 500	>7 500
Benchmark Metal Values (mg/kg)			
Pollutant class	**a**	**b**	**c**
Antimony (Sb)	<1.1	11-7	>7
Boron (B)	<23	23-72	>72
Barium (Ba)	<108	108-250	>250
Beryllium (Be)	<0.8	0.8-7	>7
Cobalt (Co)	<5	5-38	>38
Manganese (Mn)	<260	260-1225	>1225
Molybdenum (Mo)	<4	4-12	>12
Selenium (Se)	<5	5-15	>15
Strontium (Sr)	<84	84-205	>205
Thallium (Ti)	<0.03	0.03-14	>0.14
Vanadium (V)	<85	85-430	>430

Risks are identified throughout the Research Study and indicated using this TEXT BOX indicator.

The poorest sludge quality is defined as a Class C3c biosolids, whilst a Class A1a biosolids represent a high quality sludge with high beneficial value and possible commercial application. The risk, restrictions and management requirements become more onerous with deteriorating sludge quality. Both the Sludge Guidelines, as well as the Green Drop incentive- and risk-based regulation makes provision for a risk-based approach to promote cleaner production, recycling and re-use, in accordance with the risk level of the sludge. The waste (sludge) hierarchy for integrated sludge management as given in Figure 3 has been previously described (WRC Guidelines Volume 3, 2009).

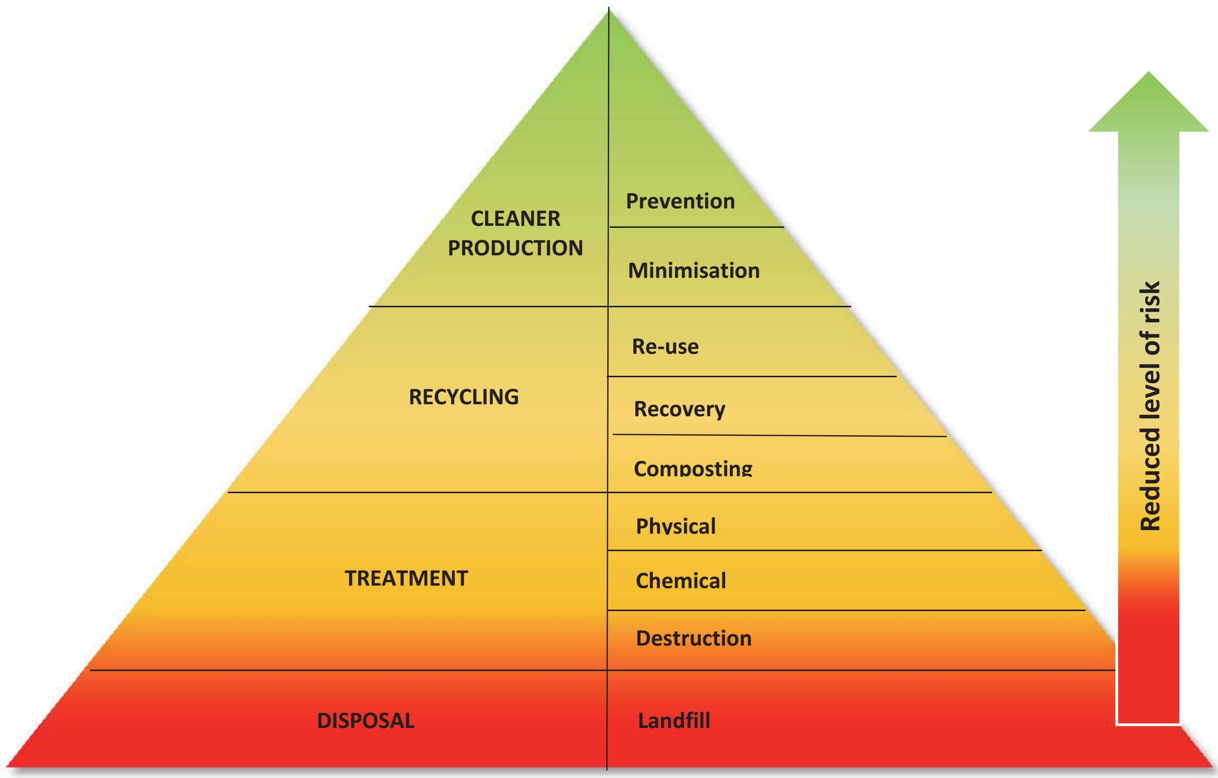


Figure 3: Waste (sludge) hierarchy for integrated sludge management

The Sludge Guidelines, and thereby the Water Use Authorisations, promote beneficial use of sludge and disposal is considered as last resort. Although there is significant potential for the beneficial use of wastewater sludge, it needs to be recognised that not all sludge can be used beneficially and where the wastewater sludge cannot be used as a resource, it needs to be disposed of in a responsible manner. The impact of industrial effluent, through the addition of heavy metals, the domestic sewage and the corresponding sludge could be rendered potentially hazardous.

The following properties and constituents of sludge receive particular attention due to their specific risk association (Van der Merwe-Botha & Manus, 2011). Critical Control Points could be identified for each constituent, to ensure that target limits are not exceeded.

- Nutrients: the agronomic rates of nutrient application to land may not be exceeded;
- Metals: acceptable limits for sludge and for the receiving soil and water environment have been developed and must not be exceeded;
- Odours: odours and vector attraction affect the public negatively and must be addressed in the Risk Assessment;
- Pathogens: local limits exist for sludge to be used for agricultural purposes.

2.4.3 Green Drop requirements

Incentive- and risk-based regulation has been introduced by way of Green Drop Certification in 2009. The initial focus of the Green Drop assessments was directed to technical skills and capacity, treatment technology and compliance, and risk management pertaining to the treatment plants and biased toward wastewater liquid management. The 10 year Green Drop Plan (2015-2025) includes 'Solids/Sludge Management' as a stand-alone Key Performance Indicator (KPI), supported by an incremental scoring that allows up to 30% of the Green Drop score to be allocated to sludge management.

The 3 performance areas which will drive the industry towards compliant and resource-based sludge management strategies include:

- ✓ Sludge classification and authorisation
- ✓ (Integrated) sludge management
- ✓ Beneficial use of sludge and biosolids
- Penalty: if a risk-based approach to sludge management and beneficiation projects are not conceptualised or planned.

Table 7: Criteria 5 of the Green Drop Certification 10-year plan, showing the various requirements that will be used to audit wastewater institutions under the KPI "Sludge/Solids Management" (presented at the WISA Conference Workshop, May 2016)

SLUDGE CLASSIFICATION AND AUTHORISATION	1. Provide the **classification** status of the sludge, in accordance with [the most current Guide for sludge utilisation], 2. Provide the **disposal** practice of the various sludge/solids streams 3. Provide evidence of the **legislative requirements** pertaining to the type of sludge (a) and its disposal practice (b) as pertaining to: i. Authorisation as issued under the National Water Act 36 of 1998, ii. Other relevant legislation.
SLUDGE MANAGEMENT	Provide a **Sludge (Waste) Management Plan** that includes the following: i. A Sludge Flow Balance that shows the recorded volumes and types of sludge produced across the various process units, from intake to discharge of sludge/solids (where type of sludge is e.g. primary sludge, detritus, screenings, grit, waste activated sludge, anaerobically stabilised sludge, desludged ponds, etc.) ii. Disposal methods for each different solids/sludge streams iii. SOP or operational practice pertaining to each solids/sludge stream according to best practice, with specific reference to the technology used for each process unit (e.g. sludge application rate and sand replacement for drying beds, sludge application rate per ha land for irrigation practices, sludge loading rates for anaerobic treatment, etc.) iv. Monitoring points, sampling frequency and analysis of determinands of sludge across the full treatment process v. Reference to Best Management Principles that are applied (i.e. ISO 14000, waste beneficiation and re-use, relevant technical literature) vi. Mass Balance with tonnage input and output of solids, which indicate which % of mass has value-added by-products or uses ***Note:*** *The Sludge Management Plan will* ***only be accepted*** *if demonstrated that it has been used as a primary* ***input to the W_2RAP***
BENEFICIAL USE OF SOLIDS, SLUDGE and EFFLUENT ("Wastewater as Resource)	Provide evidence of projects that have been initiated (with funding) and implemented in the **beneficial use** (re-use, reclaim, recharge, etc.) of sludge, solids and/or effluent in a value-added manner. A maximum score will be attained if the WSI show how the beneficial use increase the balance of usable water and nutrients (e.g. irrigation).
PENALTY **Risk-based Methodology in Sludge Management**	A penalty will apply if the sludge/solids management practice and technology is not based on risk-based methodology. This need to be clearly reflected in the **W_2RAP**.

2.5 KEY DRIVERS FOR ENHANCED SLUDGE TREATMENT

2.5.1 Regulatory compliance

Compliance aims to ensure that business processes, operations and practice takes place in accordance with a prescribed and/or agreed set of norms. Compliance requirements may stem from legislature and regulatory bodies (NWA, NEA), standards and codes of practices (e.g. SANS, ISO) and contractual agreements. Non-compliance to regulations are widely considered as a major business risk with consequential financial, reputational and performance repercussions (WEF, 2010; Sadiq & Governatori, 2014). Whilst compliance is historically viewed as a 'burden', indications are that municipalities now view regulations as an opportunity to improve their wastewater business process and operations (WIN-SA, 2011, WIN-SA, 2012). The majority of municipalities report that they are reaping the benefits from improving their compliance regiments (WIN-SA, 2015).

The notion of making decisions based on risk management and the drive towards preventative maintenance and asset management, is a deliberate strategy towards sustainable approaches for compliance management, whereby 'compliance by design' becomes a fundamental principle (IMESA, 2006; Sadiq et al., 2007). The Green Drop process, by design, advocate that compliance should be embedded into the day-to-day practice of the municipality, rather than being seen as a distinct activity. The inclusion of compliance incentives into Performance Agreements of wastewater managers serves as further motivation to regard regulatory compliance as business driver in the wastewater and sludge management industry.

Legislation and regulation pertaining to the management and disposal of sludge are driven by the National Environmental Management: Waste Act and the National Water Act. The emission of greenhouse emissions are also a powerful compliance driver and is contained in the NEM: Air Quality Act, 2004 (Act no 39 of 2004). The Draft National Greenhouse Gas Emission Reporting Regulations (June 2015) contains the reporting requirements in terms of five sectors, of which the Energy (e.g. CHP generation) and Waste (e.g. wastewater treatment and discharge) are included. Methane (CH_4) is regarded as one of the main 3 Greenhouse Gasses (GHG) with the highest 100-year Global Warming Potential (GWP), whereby 25 GWP of CH_4 are equal to 1 GWP of carbon dioxide (CO_2) (Climate Change Connection, 2015). The Greenhouse Inventory is currently being updated by the Department of Environmental Affairs. The Inventory for 2005-2010 indicated that CO_2 contributed 83.2%, and CH_4 11.4%, of the total CO_2-equivalent emissions. Both these gasses are generated during wastewater and sludge treatment processes.

2.5.2 Energy and costs

For much of the past three decades, electricity prices in South Africa has been low and capacity far exceeded the demand. From 2008, demand outstripped supply and introduced the need for load shedding, with Eskom embarking on a massive building programme to increase South Africa's generation, transmission and distribution capabilities. The impact on the South African water industry is significant:

- Electricity price increase impact on the price of wastewater reticulation and treatment, which translate to higher tariffs to the consumer;
- Pumps, telemetry and process units cannot operate resulting in non-compliant effluent and sludge quality, and compromise the beneficiation benefits;
- Equipment is damaged, back-up generator incur additional cost, sewage spill clean-up costs, and increase pump start-up costs.

The impact of the electricity price is regarded as significant to serious (De Loitte, 2014). Between 2008 and 2011, real electricity prices rose by 78%, and is projected to rise further as part of Eskom's Multi-Year Price Determination process. Wastewater reticulation and treatment relies on electricity as input and is therefore vulnerable to rising electricity prices. The water sector is the 5th most electricity dependent industry in South Africa, together with gold mining (De Loitte, undated). A further breakdown shows that wastewater treatment is by far the highest energy consumer within the water supply chain (Winter, 2011).

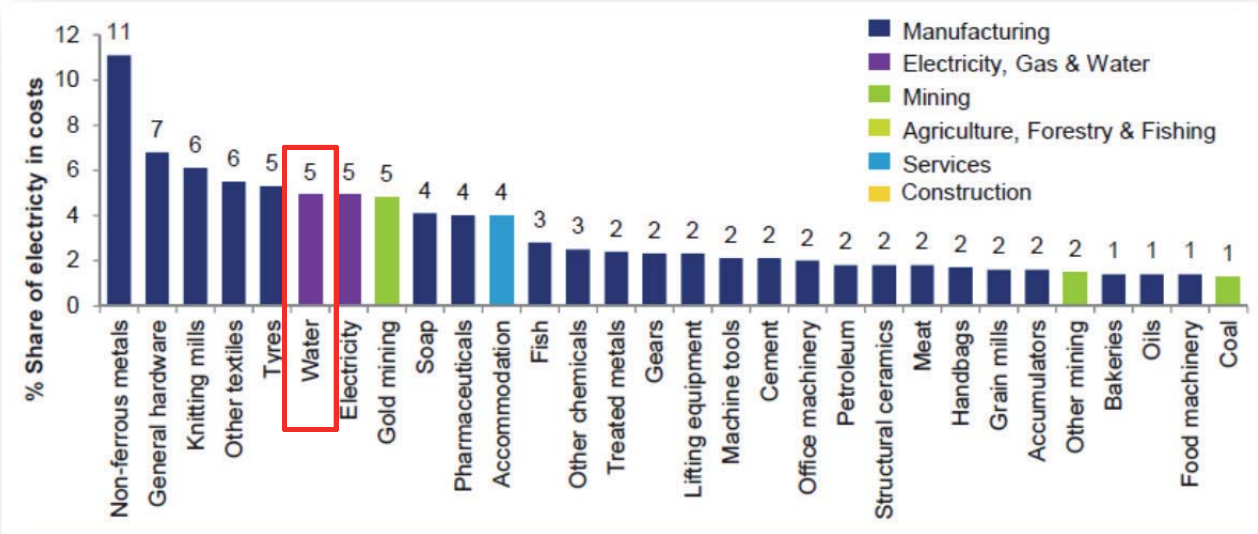


Figure 4: The top electricity reliant industries in South Africa. The insert (top right) shows energy demand across water supply chain.

A WRC study by Winter (2011) found that pumping and treatment of wastewater is highly energy intensive, and hence vulnerable to power outage events. Plant characteristics dictate impact levels, where plants with back-up power supply and overflow dams are generally not impacted by power outages, but less prepared facilities can experience significant environmental, economic, health and social impacts. Various case studies indicated that power outages impacted on financial cost to provide back-up services (Cederberg), loss of revenue and salaries of casual labour (Ugu), economic impact (City of Cape Town), health impacts (Howick, KZN) and environmental impacts (Zandvliet, Western Cape).

It is becoming increasingly difficult for municipalities to balance the regulatory requirement for higher effluent quality standards and sludge quality, which require energy intensive technologies, with the increased cost of energy to sustain these technologies (Bhagwan et al*.,* 2011). One irony is that more municipalities has started to lean towards the implementation of high energy-intensive technologies in order to meet stricter effluent quality requirements. An assessment of 975 treatment plants in South Africa showed a technology distribution of 395 activated sludge, 368 ponds, 145 biofilters, and 100 non-descript type technologies (Scheepers & van der Merwe-Botha, 2012). Higher sophistication level technologies is commonly associated with higher energy cost (EPRI, 1994; Ye Shi, 2011), where land-based systems using 79-277 kWh/Ml have a lower energy demand compared to technologies which rely on high aeration with consumption of up to 1 030 kWh/Ml (EPRI, 1994). Typical technology uses by different sizes treatment plants in SA are indicated in Figure 5 as follows (Winter, 2011):

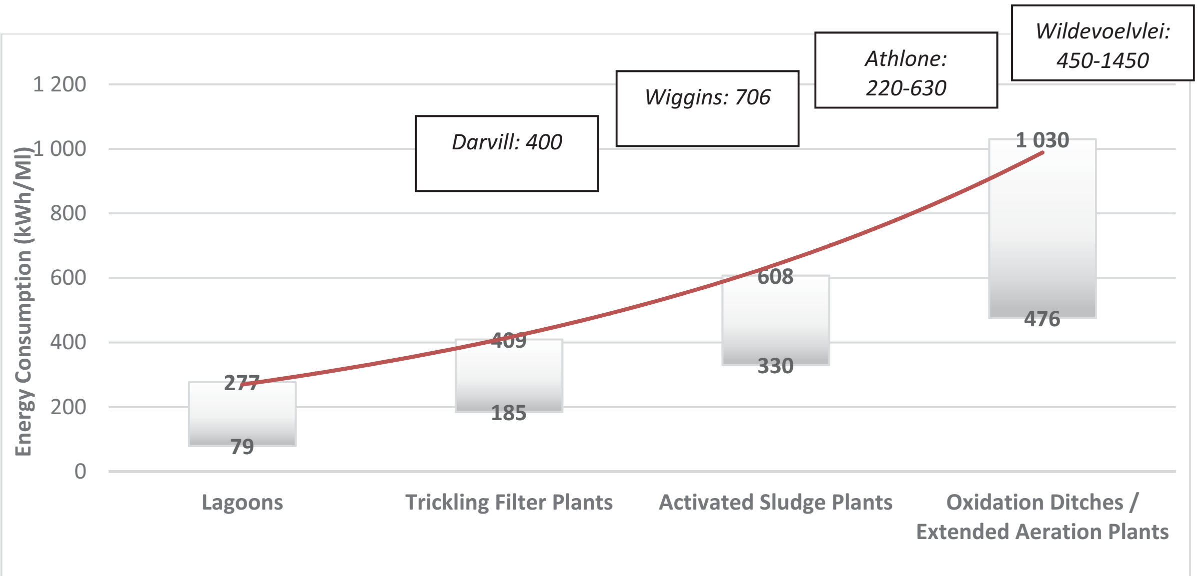


Figure 5: Energy demand for different wastewater treatment technologies, plotted against typical demand in South Africa

Shoener et al. (2014) reported that current energy-intensive approaches to wastewater treatment consumes approximately 0.3-0.6 kWh/m^3. Energy demand distribution across the various treatment processes is summarised in Table 8 (Tchobanoglous et al., 2003). Typical demand distribution for South African plants indicate that 80% of energy is used for aeration, 10% for pumping, 9% for sludge handling and 1% for miscellaneous (Winter, 2011). Tchobanoglous et al. (2003) published another set of energy demand percentages for difference process units across the treatment chain, reporting aeration of the activated sludge process to have the highest energy demand (55.6%).

Table 8: Typical energy demands for wastewater treatment facilities

Process unit	Energy demand (%)
Inlet pumping and headworks	4.9
Primary clarifier and sludge pumps	10.3*
Activated sludge aeration	55.6
Secondary clarifier and RAS	3.7*
Thickener and sludge pump	1.6*
Effluent filters and process water	4.5
Solids dewatering	7.0*
Tertiary treatment	3.1
Heating	7.1*
Lighting	2.2
TOTAL	100

** Process units directly involved with sludge handling can exceed 30% of the energy costs, depending on the technologies employed (study analysis).*

The risk assessment methodology (W_2RAP) adopted for liquid and sludge treatment in the South African water sector, shows that electricity is universally identified as a risk at all municipalities. The treatment operators' ability to mitigate the risk is most commonly found to be as follows: i) installation of back-up generators to power the most essential process units; ii) absorbing the cost or passing on the cost to the consumer and continue business as usual; iii) explore scope for electricity efficiency gains; and iv) explore alternative energy sources to substitute electricity (Interview: DWS Green Drop Inspectors, 2014).

Deloitte (2014) found that water utilities in South Africa are heavily reliant on electricity. However, utilities mitigate this by passing on the cost and thereby emerge as being only 'moderately vulnerable' to price increases. However, the study found that the output of the utilities (water supply) as well as the impact on unskilled employment, are most adversely affected by an increase in price (simulated at 25% increase).

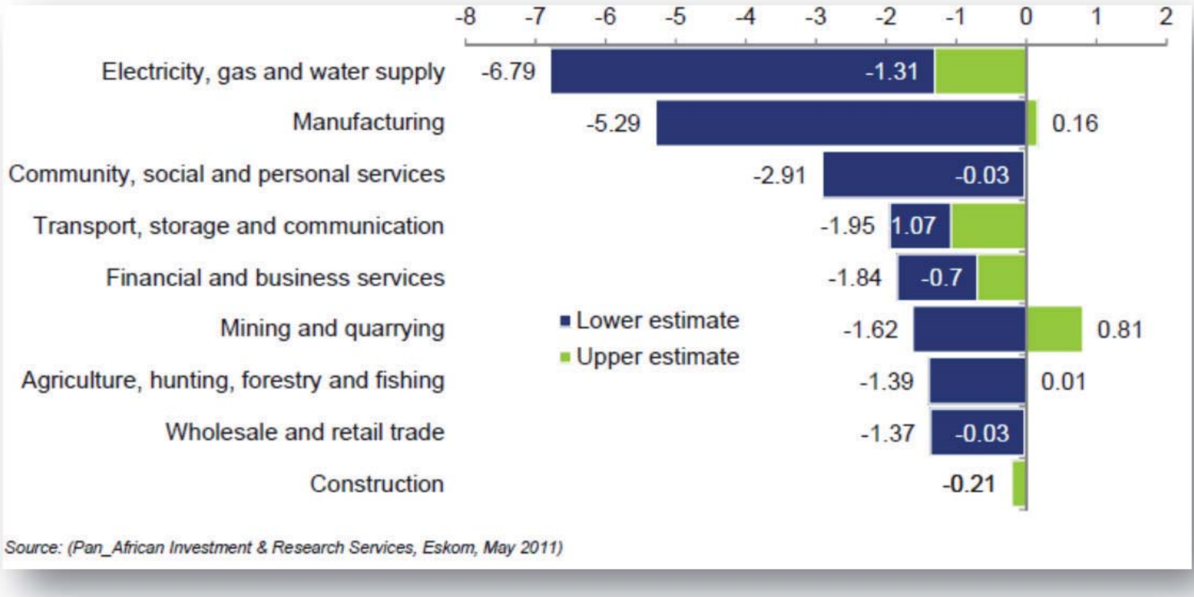


Figure 6: Impact of a 25% price increase on the output of various sectors in the long run (Pan_African Investment & Research Services, Eskom, May 2011)

The City of Johannesburg was one of the metros who identified the rising cost in electricity and interrupted power supply as a primary risk to the operation and treatment of wastewater at the Northern-, Olifantsvlei and Goudkoppies WWTW. It was estimated that the electricity costs would increase from 48 c/m³ in 2007 to about 124c/m³ by 2020 (Viljoen et al., 2013).

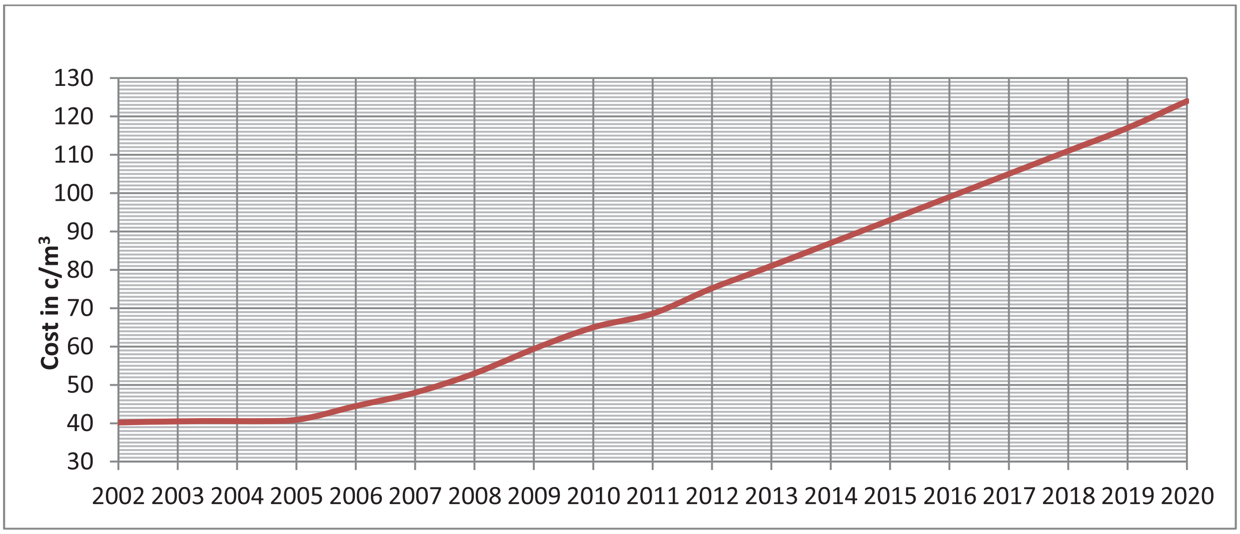


Figure 7: The Projected electricity cost escalation to year 2020 at three treatment plants in the City of Johannesburg

The risk mitigation opted for by the City of Johannesburg was to develop a strategy for the generation of heat and power from the anaerobic digesters, as part of an integrated optimisation process of all process units responsible for sludge handling and treatment. CHP technology utilises the available biogas produced by the anaerobic digestion process as an energy source to run generators and produce electrical power. The approach was that the supply of 'biogas to energy' would ensure that essential processes and equipment would operate continuously and thereby ensuring compliance to effluent quality and sludge disposal, as well as a reduction in energy price, as the plants would be partially energy self-sufficient by producing up to 60% of the plants energy demand (Deacon, 2014).

Fersi et al. (2014) assessed the total cost of energy recovery from sewage sludge with AD and CHP and found that the generated thermal energy meets the needs of the entire WWTW and guaranteed self-sufficiency in heat. The surplus of renewable heat produced by CHP was not a primary factor to improve the economic viability of the process, and the sales of electricity output represented about 76% of the operating cost of the AD process.

From the viewpoint of Best Practice Management and reputation viewpoint, a further driver for energy efficiency is conformance with ISO 50000 (2011). This specification is used by organisations to manage and plan energy efficiencies, reducing costs and improving energy performance. In the case of WWTW, energy production is also an important axis of the energy performance.

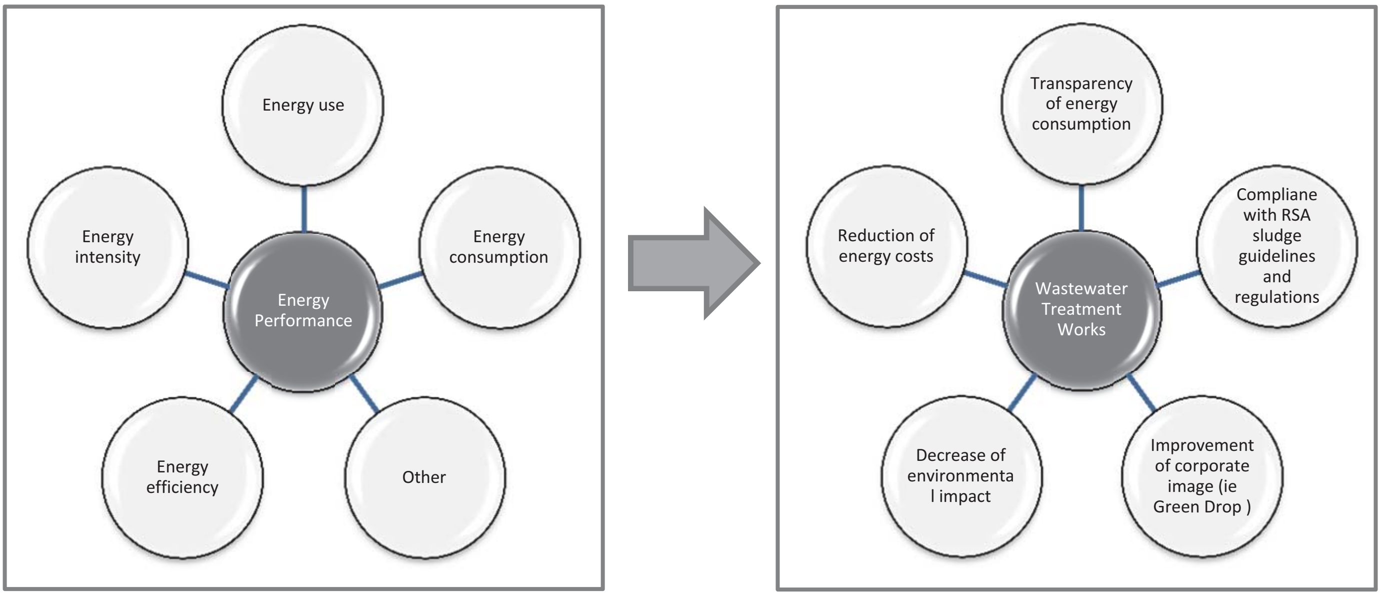


Figure 8(a): Plan-Do-Check-Act of ISO 50001:2011 as Figure 8(b) applied in a typical WWTW (adapted, Stamatelatou & Tsagarakis, 2015)

Various benefits can be derived from implementing ISO 50000 at a wastewater treatment facility, including compliance, cost reduction, energy optimisation, reputational benefit and reduced impact on the environment

2.5.3 Resource recovery

Wastewater sludge has gained significant momentum in recent years. The guest speaker at the WISA 2014 Conference (Mbombela), Prof Eng. Heidrun Steinmetz, stressed the various opportunities related to wastewater as recoverable resource and offset in the market place. The need to feed people, increasing fertiliser prices, land and soil reclamation practices, nutrient extraction, rising sludge treatment cost and stricter regulations underpin the need to explore and develop "resource re-use and recovery (RRR)" from sewage sludge.

A host of literature is available which report on technologies and processes that successfully extract phosphate as fertiliser (Larsen et al., 2009; PCS, 2014), recover energy as biogas (Daigger, 2008; Deacon, 2014), manufacture bioplastics (Kleerebezem et al., 2007), and recover metals from sludge (Pincince et al., 1998). In addition, volatile fatty acids (VFAs), polymer and extracellular polymeric substances (EPS) can be produced for use in the food, cosmetics, construction, pharmaceutical and paint industry (Stamatelatou & Tsagarakis, 2015).

The majority of literature regards nutrients (mostly N and P) and energy (carbon) as the most viable components, technically and economically, in sludge (Tyagi & Lo, 2013). Emerging technologies have been developed to extract this valuable resources including KREPO, Aqua-Recci, Kemicond, BioCon, SEPHOS, and SUSAN, and are based on physical-chemical and thermal treatment to dissolve the P, with final recovery by precipitation (Cordeel, et al., 2011; Tyagi & Lo, 2013).

Other resource recovery include the re-use of sludge for construction materials, heavy metals, PHA, proteins, enzymes, polymers and VFA (Tay & Show, 1997; Tchobanoglous et al., 2003; Yan et al., 2008; He et al., (2015). Proteins in the form of worms, larvae and fungi is fast gaining traction (Stamatelatou & Tsagarakis, 2015). Perez-Cid et al. (1999) reported 98.8%; Ni recovery, 100% Zn and 93.3% Cu. Commercial enzyme production include the production of protease, dehydrogenese, catalase, peroxidase, alpha-amylase, alpha-glucosidase (Tyagi & Surampalli, 2009)

Countries such as Canada, Denmark, Netherlands, Israel, United Kingdom and the United States are building economies around the recycle, re-use and recovery of sewage sludge (and treated effluent), as a renewable resource (CCM, 2012; MARD 2015), often supported by incentives and rebates for energy and nutrient recovery (Ryckebosch et al. 2011). Most of the technologies are available in the South African market place via supplier agreements (e.g. Cambi, Airflex, PHOSPAQ, etc.).

Table 9: The Canadian government's sludge regulation guidelines includes, promotes and regulate the beneficial uses of sewage sludge

Industry	Beneficial use
Forestry	• applications to juvenile or mature forest stands
	• reforestation following harvest or site disturbance
	• establishment of biomass crops including poplar and coppice willow systems
Mine reclamation	• application to aggregate, mineral and coal mines
	• reclamation of overburden stockpiles, waste rock dumps and tailings
Agriculture	• applications to crop and range land
	• application to land with grasses and non-food crops
Disturbed land improvement	• application to landfills to augment the topsoil component of the closure system or mitigate methane emissions
	• brown field reclamation, marginal agricultural land, roadside reclamation
	• application to disturbed areas to promote vegetation establishment for habitat creation and aesthetic enhancement
Value added product development	• utilization as a feedstock in composting, soil fabrication or commercial fertilizer production
Energy recovery and application	• biogas recovery as energy source
	• use as fuel for incinerators, kilns and boilers
Cement manufacture	• use ash from combustion in cement manufacture

A fundamental principle that applies throughout the beneficial use landscape is that the quantity and quality of the wastewater sludge intended for beneficial use is of utmost importance and would determine the commercial viability and the application of the value add product. Improving the quality of wastewater sludge offers flexibility in end use options. In land application programs, improved quality may enable increased application rates or extend the lifetime of an application site (Herselman et al., 2005). For energy recovery programs, which concentrate on the quality and yield of biogas, the effectiveness of the anaerobic digestion process is crucial (Ross et al., 1992; Burton et al., 2009; Swartz et al. 2013). For phosphate precipitation, an optimal pH would give higher P recovery (Marx et al., 2004), and so forth. The general consensus reached amongst the scientific fraternity is that wastewater sludge management need to be dealt with as an integrated process, as one process impacts on the output of the other process units (Viljoen et al., 2013).

An overview of the main beneficiation products are discussed below:

Nutrient recovery:

- Phosphate:

Finite phosphate rock ore reserves are estimated to be exhausted in 100 to 150 years (Bird, 2015) with other estimations projecting that P reserves are available for 300-400 years, depending on future demand (Corbell et al., 2009; Van Kauwenberg, 2010). Once these resources are depleted, agricultural production will be negatively impacted, as there are no alternative phosphorus resources (Bird, 2015). Phosphorus in sludge and return flows is increasingly being viewed as an asset that should be recovered and re-used as fertiliser rather than a nutrient that needs to be treated and disposed (Jeng et al., 2006). Up to 90% of the total phosphorus fraction is contained in the sludge fraction, with only 10% contained in the liquid effluent (Petzet & Cornel, 2011). Typically, sludge contains the following percentages of the major plant nutrients: 1%-8% nitrogen, 0.5%-5% phosphorus (P) and <1% potassium (K as K_2O).

Phosphate is recognised for its contribution to improve the physical and chemical properties of soil (Mondini et al., 2008; WRC, 2006). Sludge also aids in increasing water absorbency and tilth, and reduce the possibility of soil erosion (Meyer et al., 2001).

Phosphorus recovery process, based on crystalisation, is well developed commercially for the recovery of magnesium ammonium phosphate (struvite) and calcium phosphate (hydroxyapatite) (Piekema & Giesen, 2001; PCS, undated). The following full-scale facilities is listed: AirPrex, Cone-shaped fluidized bed crystallizer; Crystalactor®, NuReSys®, Pearl®, Phosnic® and the PHOSPAQ processes (Metcalf & Eddy, 2014).

Table 10: Typical nutrient values of biosolids compared to commercial fertiliser, with typical fertilizer use rate for various crops in South Africa (Metcalf & Eddy, 2014; Adapted; Un-habitat, 2008; Sappi, 2015; Natural Resources Management & Environment Department, 2015)*

Product	Nutrients (%)		
	N	P (as P_2O_5)	K (as K_2O)
Benchmark sludge*	3.5	3.5	0.2
Typical values for stabilized biosolids (based on TS)	3.3	2.3	0.3
Fertilizer for typical agricultural use – global averages	5	10	10
Fertilizer for typical agricultural use in South Africa (For: Eucalyptus trees, maize, lucerne, potatoes)	42 55 15 170	10 30 59 160	10 6 24 120

The main concerns associated with the use of treated sewage sludge as a fertiliser are the loss of nutrients, metals and pathogens to the water body via direct discharges, surface or groundwater discharge. The DWS's concerns with regards to 'emerging contaminants', which may include antibiotics, pharmaceuticals and other zenobiotics, have health related risks associated and need to be considered (and monitored) for its possible adverse impact. A WRC study has been commissioned on this topic, due for completion in 2016.

- Ammonia recovery:

Physio-chemical processes for side stream ammonium treatment are alternatives to biological treatment, which is the norm in South Africa. A number of processes are practiced at fullscale to recover ammonia from wastewater to produce aqueous ammonia or ammonium salts (as sulphate or nitrate) for use in industry and the agriculture.

Ammonia recovery involves a process of air stripping-acid absorption technology, most notably the VEAS in Norway which produce 3.5 m^3/s as N (Sagberg et al., 2006). Another process involves steam stripping, however this technology seems to be limited in its application to wastewater side-streams (Metcalf & Eddy, 2014). Ammonia concentrations of 100 mg N/l is reportedly the practical limit for the process, with cost and energy consumption being the limiting conditions (Teichgraber & Stein, 1994; Gopalakrishnan et al*.,* 2000).

Volatile fatty acids

VFA are short-chained fatty acids consisting of 6 or fewer carbon atoms which can be distilled at atmospheric pressure (*Lee* et al., 2014). Proteins and carbohydrates in sludge can be converted into VFA to enhance methane, hydrogen and polyhydroxyalkanoate production (Yang et al*.,* 2012). The production of VFA is an anaerobic fermentation process involving hydrolysis and acidogenesis (Lahav & Loewenthal, 2001; Su et al*.,* 2009). In hydrolysis, complex polymers in waste are broken down into similar organism monomers by the enzymes excreted from the hydrolytic microorganisms. Subsequently, acidogenesis ferment these monomers into mainly VFA such as acetic, propionic and butyric acids. Both processes involve a mix of obligate and facultative anaerobics such as *Bacteriocides, Clostridia, Bifidobacteria, Streptococci* and Enterobacteriaceae (Ross et al*.,* 1992; Lee et al*.,* 2014). VFA production of up to 60%-70% on COD basis has been reported in high rate reactors at a lower pH of 4.5-5.5 (Tamis et al., 2015).

Polymers

Extracellular polymeric substances (EPS) are the major constituent of organic matter in sewage sludge floc, which comprises of polysaccharides, proteins, nucleic acids, lipids and humic acids (Jiang et al., 2011). EPS occur in the intercellular space of microbial aggregates, specifically on the cell surface (Neyens et al., 2014) and can be extracted by physical (centrifugation, ultrasonication and heating) or chemical methods (e.g. formaldehyde and NaOH, ethylenediamine tetraacetic acids) (Liu & Fang, 2002). The various biotechnological uses for EPS include production of food, paints, oil drilling 'muds', cosmetic and pharmaceutical, surfactants and biological glue (Stamatelatou & Tsagarakis, 2015). Most recent research indicate that a mixed culture bacterial strains produced EPS with excellent flocculation properties, i.e. 93.5% river water turbidity removal, 91.7% for municipal wastewater and 81.8% for brewery effluent (More et al., 2015).

Bioplastics

Bioplastics are microbial short-chain polyesters (3-5C) that are widely distributed in nature and accumulate intracellularly in microorganisms in the form of storage granules, with physico-chemical properties resembling petrochemical plastics. These polymers are built from hydroxy-acyl-CoA derivatives via different metabolic pathways (Luengo et al., 2003), with VFA being used for culture growth. Depending on their microbial origin, bioplastics differ in their monomer composition, macromolecular structure and physical properties. The production of polyhydoxyalkanoate (PHA) by microbial enrichment in wastewater have been reported in various studies (Jiang et al., 2012). Microorganisms in ASP can accumulate PHAs ranging from 0.3-22.7 mg polymer/g sludge. Commercial PHAs are available on the market under various product names, such as Biomer, Biocycle, Biogreen, Copolymers, Bioppol, ENMAT and Nodax, of which the production ranges between 50 t/yr. per product up to 50 000 t/yr. (Jacquel et al., 2008)

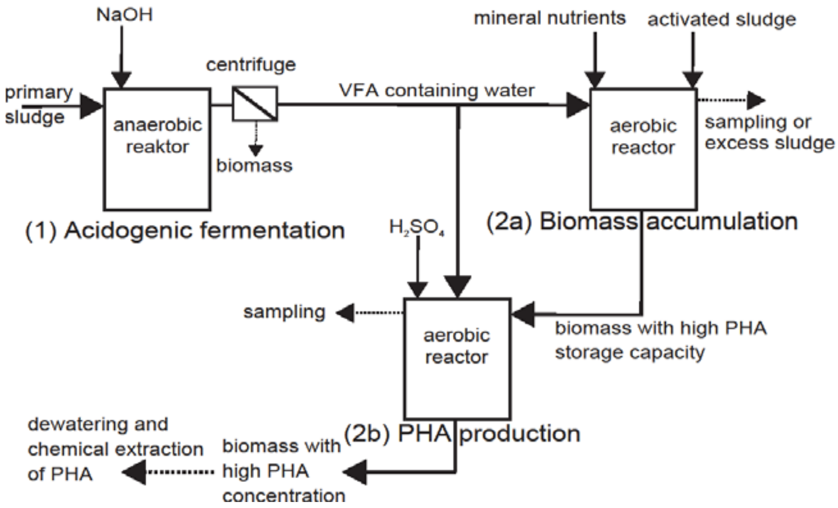


Figure 9: *Process flow diagram showing the conversion of primary sludge to VFA via an anaerobic process to produce biomass and PHA (Heidrun Steinmetz, 2014).*

Proteins

Vermicomposting is sludge reduction by earthworms and produce vermicompost as fertiliser with a high N and microbial component and lower heavy metal content (Ndegwa & Thompson, 2001). Elissen et al. (2010) found that aquatic worms grown on treated sewage sludge produced high protein values with a range of amino acids. These proteins are viable in the animal feed market or technical applications such as coatings, glues and emulsifiers. The dead worm biomass is a valuable source of energy in anaerobic digestion and result in biogas production up to 3 times that of sewage sludge. Another application include fats and fatty acids extraction (Stamatelatou & Tsagarakis, 2015). One of the largest sites is found in Australia with a capacity of >400 m^3/week (Marx et al., 2004).

Bioconversion of biosolids using fly larvae has also been studied for years for their benefit as protein source in animal feed and to replace fishmeal amongst other applications (Lalander et al., 2013). Other uses include the use of the extracted fat for biodiesel production, and chitin for commercial N production (Diemer et al., 2011).

Filamentous fungi has various benefits related to its source of protein, lipids, glycerol, carbohydrates, enzymes and fibre. Other biochemical by-products such as chitin, chitosan, glucosamine, antimicrobials and lactic acids have been produced using substrates such as starch or molasses (Van Leeuwen et al., 2012; Molla et al., 2012; Priyadarshani & Rath, 2012). The most notable example is possibly the SCP process whereby *Fusarium venenatum* fungus is grown by fermentation and is harvested as mycoprotein or fungal protein under the trademark Quorn™, and which is intended for the human consumption market as an alternative to meat products (Ugalde & Castrbllob, 2002). Commercial production of various strains are reported by Priyadarshani & Rath (2012), of which Spirulina 93000 t/yr), Chlorella (2000 t/yr), *Dunaliella salina* (1200 t/yr) and *Aphanizomenon flos-aquae* (500 t/yr.) are the top producers by volume.

Biogas to energy:

Sludge is considered a renewable energy resource as it contains organic material that has a fuel value that can be developed. Under properly engineered and controlled environment, energy recovery and generation from sludge is considered top of the hierarchy of beneficial use due to the increase cost of energy and more stringent air quality regulations. Sludge from wastewater can be processed to generate energy by (WERF, 2008; Metcalf & Eddy, 2014):

- CH_4 production from anaerobic digestion;
- Thermal oxidation;
- Syngas production through gasification and/or pyrolysis;
- Oil and liquid fuel production.

Recovery of energy has been practiced at wastewater treatment facilities primarily by producing biogas from sludge with anaerobic sludge digestion. Typical production of digesters gas through an anaerobic biological process can obtain between 0.75 and 1.12 m^3/kg VS destroyed. Typically, biogas contains 55%-70% methane, 30%-40% CO_2 and small amounts of N_2, H, H_2S, water vapour and other gases. The energy content of digester gas is typically in the range of 22 to 24 MJ/m^3. Gas production can also be estimated crudely on per capita basis, where the norm yield is 15-22 m^3/1000 persons/day for primary treatment plants and up to 28 m^3/1000 persons/day in secondary treatment plants (Metcalf & Eddy, 2014). Methane gas at standard temperature and pressure (20^{O}C, 1 atm) has a lower heating value of 35 800 kJ/m^3, which gives approximately 22 400 kJ/m^3 for a 65% CH_4 content of biogas. Gas needs to be cleaned before use, as it contains various impurities (Deacon, 2014). To access the considerable chemical energy remaining in the sludge after AD, the sludge can also be burnt or dried to produce a solid fuel product (Flaga, 2005; Niu et al., 2013, Deacon, 2014).

Various factors impact on the efficiency of the anaerobic process and biogas production, including:

- pH of the digesters affects CO_2 release to the gas phase, which impact on CH_4 production (Strydom et al., 2009, Barber, 2010).
- heating of digesters affect methane production, where high temperatures typically render higher methane production. Variations of unheated-, mesophilic-, thermophilic- or combinations of temperatures are mostly applied (Osman et al., 2015).
- thickening of the digester feeds sludge or a portion of the digesting sludge to increase the SRT (Slim et al., 1984). Metcalf and Eddy (2014) presents a case study where the HRT is 15 d with a TSS of 3% and the VS loading factor is 1.4 kg/m^3.d. By improving the feed sludge TSS to 6%, the VSS loading can be increase to 2.9 kg/m^3.d. Hypothetically, the digester capacity is doubled.
- co-digestion by using more than one substrate, where substrates such as FOG, spent grain, cow manure, scum, organic solid waste, whey from cheese production, etc. can be used (Remingi & Buckley, 2006; Nielfa et al., 2015). A review on anaerobic digestion (Mata-Alvarex et al., 2014) showed that 50% of all publications are in the field of co-digestion and seemed to be the most relevant topic on a global scale, especially in the field on using fats, grease and algae as substrate with sewage.

Co-generation or CHP is generally defined as a system for generating electricity and producing another form of energy (usually heat in the form of steam or hot water). The most common CHP systems are internal combustion engines or micro-turbines connected to generators. Pumps and blowers can be operated with a direct drive from the engines fuelled by biogas. Fuel cells can also be used to create electricity with the heat recovered for process uses. One of the most critical design aspects of a CHP system is reported to be the cleaning of the biogas.

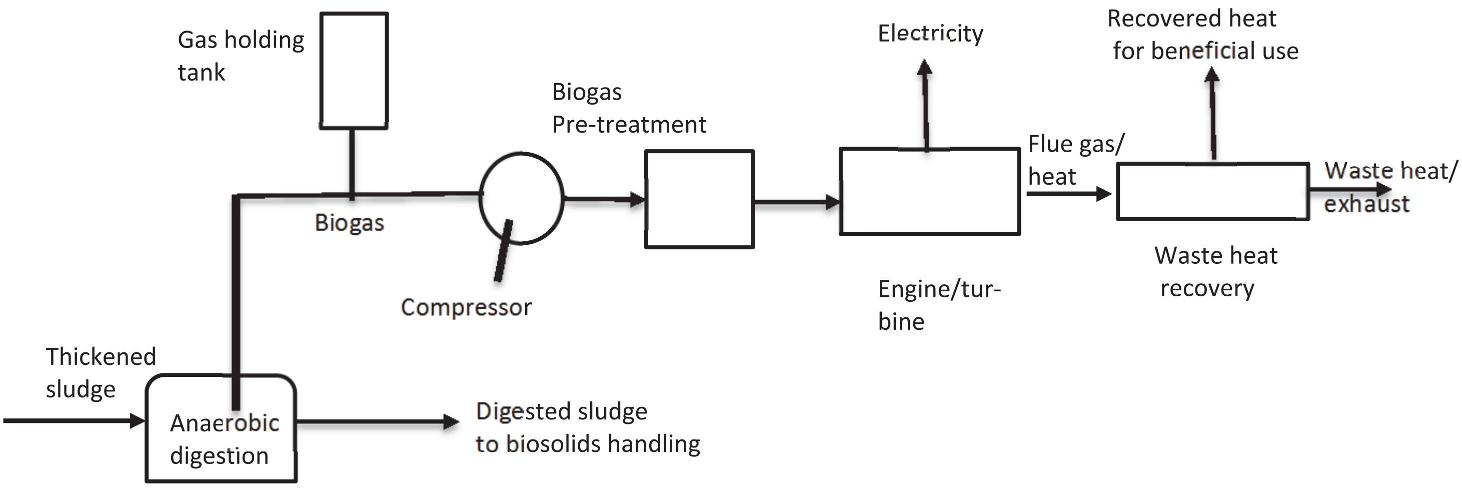


Figure 10: A flow diagram showing a typical energy recovery systems with engines and turbines (Metcalf & Eddy, 2014)

The typical range of total system efficiency from internal combustion engines without CHP is 25%-50%, and with CHP 70%-85%. Typical electricity and heat generating efficiency from various co-generation systems are given in Table 11 (Metcalf & Eddy, adapted US EPA, 2010).

Table 11: Typical electricity and heat generation efficiency from various co-generation systems

Co-generation system	Electricity generation efficiency (%)	Heat recovery efficiency (%)
Internal combustion engine	37-42	35-43
Lean burn internal combustion engine	30-38	41-49
Conventional turbine	26-34	40-52
Recuperated turbine	36-37	30-45
Micro-turbine	26-30	30-37
Molton carbonate fuel cell	40-45	30-40
Phosphoric acid fuel cell	36-40	NA

Mills et al. (2014) conducted an environmental and economic life cycle assessment of current and future sewage sludge to energy technologies and found that advanced AD (THP) has advantages over conventional AD and that CHP is environmentally superior to bio-methane injection in the UK, although incentives support bio-methane and advanced energy recovery. The studies support the current shift from conventional AD to THP AD in the UK. A new practice, Gas to Grid (GtG), clean and inject the methane produced in AD into the gas networks in the UK. This technology is supported under the Renewable Heat Incentive leaving a methane content of >99% (Ryckebosch et al. 2011).

2.6 KEY ROLEPLAYERS

The following stakeholders have active interest and potential benefit from gains from advancing sludge management practices and resource recover in South Africa:

The Regulators:

- The DWS has a stake to see that sludge treatment, disposal and re-use is done in accordance with the Sludge Guidelines in order to minimise pollution to the water resources and to land.
- The DEA has a regulatory role to monitor, regulate and manage against the requirements of the Waste Act and the Air Quality Emission Act.
- DWS and DEA have interest in ensuring that waste minimisation philosophies are followed whereby the hierarchy follows 3 steps:
  - Pollution Prevention -> Minimisation of Impact (re-use, reclaimed, treat) -> Discharge or disposal of effluent (risk-based, polluter-pays)

Other Role players

- The Department of Cooperative Governance and Traditional Affairs (CoGTA) has a role to ensure that local government manage sludge in cost effective and environmental sensitive manner, which are closely link to the management of public perception and potential unrest by communities who feel aggravated by poor services and unsafe conditions posed by sludge handling at local level.
- The South African Local Government Association (SALGA) has an active role to benchmark local government and share best practice and tools that would assist municipalities to improve their performance.

- The agricultural sector has an important stake in terms of the potential benefits associated with the high nutrient and energy value contained in biosolids, in particular phosphorus and nitrogen.
- The Department of Energy (DoE) has a high stake in ensuring that all alternative energy resources are explored and developed. WRC research (Burton et al. 2009) estimated that 7% of South Africa's energy demand could be derived from wastewater sources.
- The Department of Health and Safety takes a critical role in the value chain of sludge and biosolids management, whereby the dangers associated with the hazardous nature of untreated sludge and gas emissions are recognised. The safety of workers and the environmental consequences of inadequate management practices are well documented.
- The research and development fraternity has a critical role to play in terms of sourcing, developing, and communicating technologies and performance achieved via the treatment of sludge, the use of biosolids and generating information that inform policy and strategy in South Africa.
- National Treasury and finance institutions have possibly one of the most significant roles to play. Sludge management hold various benefits and incentives in terms of social and economic good, including aspects of health, environment, commodities, infrastructure development, etc. – for which a business case can be developed. Financing and incentives to drive resource recovery and best management practices in the wastewater sludge industry is key to moving this resource up the Water Agenda.
- The Departments of Trade and Industry, and Science and Technology, recognises the value add and the innovation that is taking place in the sludge/biosolids paradigm. Best practices need to be identified and opportunities created in South Africa to build on the successes that is seen in the sludge/agriculture interface (Israel), the sludge/energy interface (Germany), the sludge/technology interface (Denmark), the sludge/water use interface (Singapore), to mention but a few.
- All national departments that are involved in the water-energy-food nexus addressing issues of climate change, have a function and responsibility to inform policy, strategy and incentives to drive the philosophies contained in this document, i.e. wastewater sludge as resource.

2.7 WASTEWATER RESIDUAL TREATMENT TECHNOLOGY

2.7.1 Sludge origin and composition

The origin, characteristics and quantities of sludge to be handled must be known in order for the process Engineer to design a sludge processing and treatment plant. Residuals* and sludge originate from various sources, including:

- Screenings*
- Grit*
- Scum and grease
- Primary sludge
- Sludge from chemical precipitation
- Activated sludge
- Trickling filter sludge
- Aerobically digested biosolids
- Anaerobically digested biosolids
- Compost.

Typical chemical composition ranges for the main streams of sludge are given in Table 12 (Metcalf & Eddy, 2003, 2014).

Table 12: Typical chemical composition ranges for the main streams of sludge

Item	Untreated primary sludge	Digested primary sludge	Untreated activated sludge
Total dry solids (TS) %	1-6	2-5	0.4-1.2
Volatile solids (% of TS)	60-85	30-60	60-85
Grease and fats (% of TS)	5-8	5-20	5-12
Protein (% of TS)	20-30	15-20	32-41
Nitrogen (N % of TS)	1.5-4	1.6-3	2.4-5
Phosphorous (P2O, % of TS)	0.8-2.8	1.5-4	2.8-11
Potash (K_2O, % of TS)	0-1	0-3	0.5-0.7
Cellulose (% of TS)	8-15	8-15	-
Iron (not as sulphide)	2-4	3-8	-
Silica (% of TS)	15-20	10-20	-
pH	5-8	6.5-7.5	6.5-8.0
Alkalinity (as $CaCO_3$)	500-1 500	2 500-3 500	580-1 100
Organic acids (mg/l as HAc)	200-2 000	100-600	1 100-1 700
Energy content, kJ/kg TSS	23 000-29 000	9 000-14 000	19 000-23 000

The quantity of sludge produced at the various process units will fluctuate from plant to plant. The designer of the plant usually considers: 1) the average and maximum rates of sludge production; and 2) the potential storage capacity of the treatment units within the plant. A limited quantity of sludge may be stored temporarily in the sedimentation and aeration tanks. Most digesters provide for a 15 day solids residence time. If digestion is not used, the solids-treatment process should be designed based on the inherent storage capacity of the systems. For example, mechanical dewatering systems followed by gravity thickening could be based on the maximum 1-3 days solids production. Sludge pumping and thickening must also be sized to handle maximum day conditions.

2.7.2 Sludge treatment technology

A variety of technologies can be employed and are implemented according to regulations, which also drives the different applications in different countries. With regards to sludge stabilization, aerobic and anaerobic treatments are the most widely used methods of sewage sludge treatment (Ross et al*.,* 1992), and 24 of 27 countries in the EU employs this method. Anaerobic digestion is commonly used throughout the world, with specific reference to Spain, Italy, UK and Czech Republic (Kelessidis & Stasinakis, 2012). The classification of sludge according to pathogen levels and stabilisation is particularly feasible in Canada, US and South Africa. In the EU, mechanical sludge dewatering is preferred comparing to the use of drying beds, while thermal drying is mainly applied in Germany, Italy, France and UK. Regarding sludge final disposal, sludge re-use (including direct agricultural application and composting) seems to be the predominant choice for sludge management in the EU (53% of produced sludge), followed by incineration (21% of produced sludge). A summary of technologies employed by different countries can be viewed in the UN-Habitat's "Global Atlas of Sludge Treatment Technologies" (2008). The following flow diagram illustrate the typical treatment unit processes associated with sludge treatment.

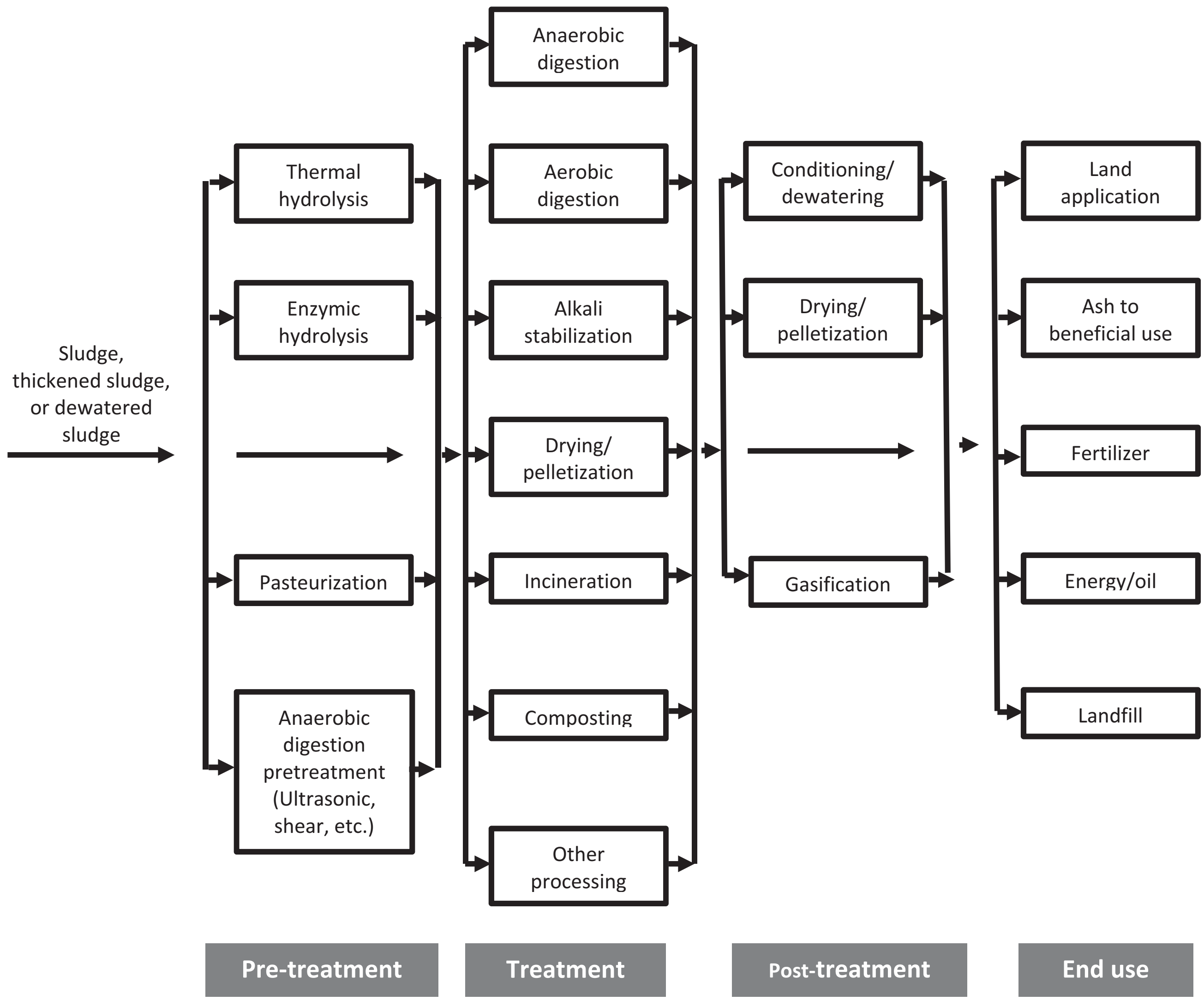


Figure 11: Generalised sludge processing plant (Metcalf & Eddy, 2014)

The following table summarises typical sludge treatment methods found in full-scale applications. The objective of each treatment technology is listed, as well as the key design and operational considerations. Typical performances are provided, with references, to serve as 'benchmark' related to the typical output of each technology from field applications.

Table 13: A summary of the typical sludge treatment methods used, with their function, generic design considerations and expected output (Referenced)

Unit process	Treatment methods	Function	Design and operational considerations (global and local)	Typical output/performance	Ref
THICKENING	Gravity thickening Flotation thickening (DAF) Centrifugation Gravity-belt thickening or linear screens Rotary-drum thickening or Vacuum filtration	Thickening is a procedure used to increase the solids content of sludge by reducing its water content. The direct benefits are downstream: 1) less capacity tanks and equipment required 2) less quantity of chemical required for sludge condition 3) less amount of heat required by digesters *PS: gravity thickening most common internationally and in SA*	• Plants <4 Ml/d seldom practice separate sludge thickening, and use gravity thickening in the PST or sludge digestion units. • Provide adequate capacity to meet peak demands • Prevent septicity • Allow sludge settling times of >12-24h to achieve thickened sludge concentrations in underflow • Avoid retention of sludge as it will reduce TSS and BOD removal and result in septic conditions and gas production • Maintain sludge inventory of 6-12h • As part of gravity thickening, allow VFA production to enhance biological P removal, and VFA need to be elutriated from sludge in separate process • For gravity thickening, design for 0.5-5.5 kg solids/(m^2h) • Provide addition of coagulants (polymer, ferric chloride) to condition sludge for settling • The selection of materials of construction of the centrifuge must be done with care, especially when high-speed machines are used. Consider stainless steel as the abrasion resistance is the principal concern. Consider scroll edges to be 'stellite' tipped and the inlet and wear areas to have ceramic or tungsten carbide tile lining or coating. • Gravity belt or screens typically used ahead of filter-belt press dewatering step	50% TSS removal in 1 hour, 60-70% TSS removal 3-7 hours, Final TSS of 100-200 mg/l Underflow sludge concentrations of 3-5% Solids capture from centrifugation >90% and from linear screen = 95% DAF produce 3-4.5% solids without conditioning Linear screen produce 4-10% solids Gravity thickening produce 2-8% solids in thickened sludge	a b k l k u
STABILISATION	Lime stabilisation	Sludge is stabilised to reduce microbiological activity in the organic fraction of the sludge, in order to eliminate odours, reduce pathogens, and reduce for decomposition/putrefaction. Successful stabilisation is measured by the ability of the process to render the volatile or organic faction of the solids unsuitable for use by the microorganisms. Also, to	• Consider the sludge quantity to be treated • Integration of process with other treatment units • Design according to objectives of stabilisation for the specific plant, as it may be affected by regulatory requirements (e.g. pathogen control for land discharge) • For composting, develop a materials balance to determine the amount of each component (sludge, bulking agents) used during each phase of the process	Degree of attenuation differ per technology/method used: - for pathogens: fair to good - for putrefaction: fair to good - for odor potential: fair to good Lime stabilisation typical solids concentration - 3-6% for primary sludge - 1-1.5% for WAS	a k o p k t u

	Anaerobic digestion Aerobic digestion Composting	improve the dewaterability of the sludge, produce CH_4 and reduce sludge volume. Stabilisation includes the process of composting, whereby organic material are biologically degraded to a stable humus like end product. The process involves the mixing of dewatered sludge with a bulking agent, e.g. wood chips to recreate air voids in the sludge matrix Typical alkaline stabilisation processes (and product recovery) include: Ash recycling, melting furnace process, brick production, cement kiln injection, light-weight aggregate production, OCI waste conversion, Krepro, Noel conversion, Active Sludge Pasteurisation (ASP), Granular fertiliser manufacture	For composting: • temperatures of 50-70^{O}C maintained for 3 consecutive days • moisture content of 50-60% • pH of 6.5-9.5 • C:N ratio of 25:1 to 35:1 • 20-50 m^3/h per ton of dry sludge airflow for a forced aeration system. • For composting, allow aeration for 22 d, followed by screening out the bulking agent for re-use • Control porosity of sludge-compost by control of bulking agent – particle size of 5-15 mm • For aerobic stabilisation: HRT of 10-20; solids loading of 1.6-4.8 kgVS/(m^3/d), 2 kg O_2/kg VS destroyed; 2-40 kW/Ml for mechanical mixing and 1.2-2.4 M^3/(m^3/min) for diffused air. • For auto-thermal thermophilic aerobic digestion (ATAD) design for 45-60^{O}C, HRT of 3-4 d, DS feed >3% • For dual digestion, 50-60^{O}C (aerobic stage, 2 d HRT) and 20-40^{O}C (anaerobic stage, 8-10 d HRT) at solids loading rate of 3.4-7.4 kg VS/m^3 per d; >3% solids feed For lime stabilisation: • pH>12 • retention time of 30 d (unheated) and 3 d (>52^{O}C) • Identify sources of lime: cement kiln dust as by-product of cement manufacture (CaO is 335 g/kg); slagment – a cement with different curing properties as typical cement, contain 5 g CaO/kg slagment; Commercial slaked and unslaked lime – CaO 690 and 840 kg/g, respectively.	- 6-7% for anaerobic digester DS content after lime stabilisation: 50-65% Composting allows for 20-30% conversion of VS to CO_2 and water VS reduction of 40-50% for aerobic stabilisation 70% VS reduction for ATAD 20% and 40% VS reduction in aerobic and anaerobic stages	
CONDITIONING	Chemical conditioning	Sludge is conditioned to improve their dewatering characteristics. The process result in the flocculation (aggregation) of sludge to achieve efficient solid-liquid separation, by using inorganic chemical or water soluble polymers (e.g. lime, ferric chloride- or sulphate, aluminium chloride- or sulphate); or by applying heat/steam at	• Determine the sludge character, mixing conditions and dewatering devices used, to allow selection of the best performing chemical and dosing rate • Lab- or pilot testing is recommended • Solids concentration affect the polymer dosage and dispersion • Use iron salts for sludge that is difficult to dewater • The use of polymers will not increase the DS content, while iron and lime	Heat treatment oxidises 25-30% of VS	a c d k u

	Heat conditioning	170-200^{O}C and reactor pressures of 22-25 bar for 20-30 minutes (e.g. ZIMPRO process).	increase the DS by 20-30% • Mixing must not break the flocculated material and detection to be kept to minimum to ensure sludge reaches the dewatering unit soon after conditioning • Two locations for chemical conditioning often advised • Typical dosage rates of 2-6 kg polyelectrolyte/ton DS • Use polyelectrolyte in powder form to prepare own solutions on site to a strength of 0.1-0.5%. • Selection of wetting device is important when preparing poly-solution to ensure that no 'fish eyes' form		
DISINFECTION	Pasteurisation Long term storage	Pasteurisation involves heating wet sludge to 70^{O}C for 30 minutes to inactivate the pathogenic organisms. Heat is usually applied through direct injection of steam or indict heat exchange.	• Temperature at 70OC, retention time >30 minutes • Batch process preferable to avoid re-inoculation if short-circuiting occurs • Equipment to be corrosion-resistant • High operating skills required	Total destruction of pathogens	k q
DEWATERING	Centrifuge Belt filter press Rotary press/Rotary vacuum filters Screw press	Dewatering is a physical treatment to separate the solid matter and water in the sludge resulting in a high solids content stream called 'cake' and a liquid stream. Main reasons for dewatering: 1) cost for trucking sludge is lower when volume is reduced 2) thick sludge easier to handle than liquid sludge 3) increased calorific value when incinerated 4) Reduce demand for bulking agents prior to composting 5) less moisture result in less cost when applying thermal drying	• Bench and pilot testing is recommended to determine the optimum dewatering device and polymer dosage • Do not rely on published industry standard performance data, but rely on field testing • Technology is chosen based on type of sludge, properties of dewatered product, down-stream processing, disposal, space available • The liquid stream contain fine solids and high nutrient levels when anaerobic sludge is dewatered and is typically returned to the mainstream treatment plant. • Different design consideration are applicable depending on technology selection • Energy considerations are important, e.g. electro dewatering is 3-5 less energy intensive than thermal drying • Design low speed centrifuge machine for >1600 rpm, centrifugal force of 750 g; and high speed machine for 2500 rpm and 1100-1200 g Poly consumption at 3-8 kg.t DS	Polymer dosing of 1-25 g/kg of sludge For centrifugation (at 1-8% feed solids): - Solids capture 95%+ - 25-50% cake solids for untreated primary & WAS - 16-25% for WAS - 22-40% for anaerobically digested sludge - 18-25% coke solids for aerobic WAS For belt filter (at 1-8% feed solids) = >96% solids capture - 15-30% cake solids for untreated sludge - 20-2% cake solids for anaerobic sludge - 18% cake solids for aerobic WAS - 12-25% for chemically conditioned sludge	a e f g k r s u

	Filter press	6) reduced odor 7) reduced leachate production when sludge is landfilled *PS: Sludge drying beds are most common method in South Africa and globally, due to low capital and operational cost, simple operation, high solids content in final product*	• Design belt filter press for solids loading rate of 100-300 kg/m belt width/h, width of screen cloth 0.5-3 m, polyelectrolyte consumption 2-6 kg.t DS • Filter presses (or chamber of presses) design at operating pressure of 500-1500 kPa • Rotary drum vacuum filters 15 kg DS/m^2h) and rotational speed of 52 m/h for chemically conditioned sludge; 75 kg DS/m^2h) and 70 m/h for thermally conditioned sludge • *Fell out of use, more advanced technology* • Design of beds based on sludge loading rate, typical 50-125 kg.m^2.year for open beds and 60-200 for closed drying beds • Sludge loading of 70-150 kg DS/(m^2/yr.) or 0.07-0.09 m^3/capita, retention time of 2-4 weeks • Reeds beds appropriate for plants with capacities <0.2 m^3/s, design loading rates up to 100 kg/m^2.year, at sludge application rates of 75-100 mm every 7-10 days • Lagoons is best applied as substitute for dryng beds for dewatering of digested sludge, and not suitable for untreated or limed sludge. Solids loading rate of 36-39 kg/m3.year, sludge pumped to lagoon for 18 months and rest for 6 months.	- 25-40% for thermally conditioned sludge For screw press: Solids capture 88%+ - 15-40%TS cake solids for untreated sludge - 15-28% for anaerobic sludge - 15-20 for aerobic WAS For centrifuge: - Solids capture of >96% - Solids content 12-25% for chemically conditioned sludge - Solids content 25-40% for thermally conditioned sludge For filter press: 50% cake solids For linear electro-dewatering - 29-49%TS for untreated sludge - 12-23% TS for anaerobic sludge - 16-20%TS for aerobic WAS Electro dewatering achieve 23-47% filter cake solids concentration For sludge drying beds: 40-60% solids in dried sludge	
	Electro-dewatering				
	Drying beds				
	Reed beds				
	Lagoons				
HEAT DRYING	Dryer variations - Direct - Indirect - Flash	Heat drying involves the use of heat to evaporate water and reduce the moisture content of sludge to that below conventional dewatering methods.	• Consider energy source for heating, heating (dried sludge can also be used) • For direct drying-retention time of sludge20-60 min, rotation speed of drum 5-8 rpm. Gas velocities 1.2-3.7 m/s (otherwise dust entrainment with exhaust gas) • For flash drying – Gas velocities of 20-30 m/s • Consider high commercial value • Equipment design and operation mostly supplier specific	- Dry solids content of 90-95% - 92-98% for storage - 2-4 mm pellet size (marketable) - N = 5%, P = P_2O_5 of 5%	a
INCINE RATION /ATO	Multiple-hearth incineration	ATO involves total combustion, conversion organic solids to oxidised end products. It is a high-temperature process in which the	• Prepare detailed heat balance to include heat losses through walls and in the stack gases and ash. • 4-5 MJ required to evaporate 1 kg of water in the sludge.	Typical heating values for sludge (in kJ.kg of TS): - 20 000 for biological filter and	a

	Fluidised-bed incineration Co-incineration with solid wastes	carbonaceous material in the sludge feed is ignited and burnt to produce CO_2, water vapour and an ash residue. Combustion is the rapid exothermic oxidation of combustible elements in fuel. Heat is introduced through auxiliary fuel and combustion of volatile matter in the sludge	• Most appropriate for medium to large size plants with limited re-use options • Dewatering needed to produce 30-35% solids • No stabilisation required to keep volatile content at maximum for reduced fuel demand • Co-incineration not effective at moisture levels of 70-80% • Operational ratio of 1: 4.6 kg dry sludge to solid waste • For multiple-hearth furnace: solids in feed sludge 15-30%, loading rate of 25-75 kg.(m^2/h) • For fluidised bed incineration: operating temperature of 760-820OC, loading rate of 30-60 kg.(m^2/h)	activated sludge - 12 000-16 000 for anaerobic sludge - 25 000 for raw primary 10-15% moisture for co-incineration with municipal solid waste Ash residue from multiple hearth is 25-35% of DS feed Ash residue from fluidised bed is 20-30% of DS feed	
RESOURCE RECOVERY	Nutrients	Solids can serve a source of nutrients to be used as fertiliser, as feedstock for the production of energy and in the manufacture of value-added commercial products. Nutrient rich side-streams can be harvested to recover phosphorus, using crystalisation to recover magnesium ammonium phosphate (struvite) and calcium phosphate (hydroxyapatite). Vermiculture is an application using various worm species to biodegrade sewage sludge and produce N and P.	• Due diligence is required for N and P recovery vs costs and offset in market place, i.e. regulatory conditions • For P recovery, the most critical operational parameters include: pre-treatment, 2) pH and temperature control, 3) chemical requirements 4) seed.	- 90%/178 kg/d P recover with Crystallisation, 92% DS high quality struvite - 90%/178 kg/d P recover with Crystallisation, 20% DS low quality struvite - 90%/178 kg/d P recover with chemical precipitation, 25% DS - 75 kg/d dry struvite fertiliser in most optimal studies in SA, City of Cape Town	A v
ENERGY RECOVERY	Anaerobic digestion (biogas to energy)	Production of methane rich gas by anaerobic digestion is used to recover energy from sludge. Combined heat and power involves the recovery of heat from the biogas and use as energy source to further dry and stabilise the cake solids (for beneficial purposes).	• pH control is crucial for optimal biogas production • Feed sludge of 3-6% to reactor • Retention times of 20-30 days (low rate and 10-20 days (high rate) • Solids loading of 0.5-1.6 kg VS/day per m^3 digester capacity for low rate, unheated digesters and 1.6-4.8 kg VS/day per m^3 for heated and mixed digesters	- 0.75-1.12 m^3/kg VS destroyed for biogas production - 55-77% CH4, 30-40% CO_2, trace N_2, H_2, H_2S - Energy content of 22-24 MJ/m^3 - VS destruction is 45-60% - Typical biogas production is 0.75-1.1 m^3/kg VS destroyed - Biogas composition of 65-70% methane (by volume) and 25-30% CO_2	a k m u

	Temperature-phase anaerobic digestion	Thermophilic and mesophilic digestion can be combined to stabilise raw sludge and reduce pathogens. The aim is to improve digestion performance ito solids reduction and gas production as compared to a single-phase process. The thermophilic process increase the digestion rate (increase microbial activity) meaning higher VS can be achieved at lower HRT. Various process configurations can be explored, e.g. ASTM and Schwarting/Uhde processes.	ASTM: ● 2-3 d retention time in thermophilic stage at 55-60^{O}C ● 12-15 days retention time in mesophilic stage 35-37^{O}C ● Basic design is independent of solids, provided that <6% DS in raw sludge ● Special care required in civil design of thermophilic stage for higher temperatures – steel or concrete may be used for reactor construction ● Mixing of large size digesters (>1 500 m^3) need attention. Best results achieved with draft tube mixers. Friction losses in the pumping of high solids will increase due to the non-Newtonian behaviour of the sludge ● Foaming often occurs with thermophilic sludge which requires special overfall weirs inside the reactor and foam traps in the gas line ● Gas injection is not recommended for reactor mixing ● Energy efficiency is optimised by recovering the heat of the thermophilic sludge to heat up the raw sludge feed via heat exchangers. Schwarting/Uhde: ● Retention times of 37^{O}C in mesophilic and 55^{O}C in thermophilic digesters are 5-6 days each ● 40-60% reduction in digester volume as result of high loading rate combined with plug flow conditions	- 50-60% degradation of organics solids for both processes - 55% for Schwarting/Uhde process within 10-12 d HRT compared to 40% and 20-30 days HRT in conventional AD.	k n u
	Thermal oxidation /hydrolysis	The combustion process (see above) produces hot flue gas where energy can be recovered for air pre-heating and other energy needs or electrical production. The ash is an inert material that can be used in commercial application such as cement making, asphalt, etc. P can be recovered from the ash. Excess heat from thermal oxidation of dewatered sludge can be used to generate steam for electricity generation Example: Cambi THP process			a u

	Thermal conversion/Gasification and pyrolysis	Thermal conversion processes utilise high temperatures to stabilise sludge and to change its physical characteristics, typically producing gases, ceramics and metals. The term ‘gasification’ is applied when converting organic materials to fuel gas called syngas, composed of CO, CO_2, H_2 and CH_4, which has a low heating value of 4500 5500 kJ/m^3. Processes include: catalytic extraction, co-gasification, electric-arc gasification, sludge pyrolysis, Syngass-Thermanetic and Renugas, microwave gasification, supercritical water oxidation, total bio-combustion, deep-shaft wet air oxidation, oxygen injection (incineration), RHOX, ATHOS Pyrolysis is the 1st step that occurs in gasification and combustion reactions. It is used in the chemical industry to produce charcoal, activated carbon and methanol.	• Dried sludge with >75% solids in granular form required. For wet air oxidation: • Operating temperature of 175-315^{O}C • Operating pressure <20 MPa • Allow treatment of high COD (10 000-15 000 mg/l) recycle stream		j
	Oil-from-sludge	Sludge can be converted to liquid and oil fuel as energy source, and comprise mostly of patented processes, such as the Enersldudge™. The conversion is achieved by pyrolysis, a highly endothermic process, where the sludge is heated in an oxygen-free atmosphere. As most organic material is thermally unstable, it is split into gas, liquid and solids fractions via thermal cracking and condensation reactors.	• Capital and operational cost evaluation needed to determine feasibility of option • Operate process at atmospheric pressure and temperatures of 350-500^{O}C • Sludge to be dewatered to DS of 95%		k
ULTIMATE DISPOSAL	Land application/reclamation	Sludge/biosolids can be applied to agricultural land, forest land, disturbed land and dedicated land disposal sites in liquid or dry form. Due to the extended coastline of SA, sewage can be discharged to sea, but is not	• Refer to WRC Sludge Guidelines for operating criteria in SA • For sea discharge of ‘sewage’: head of works and outfall with pump station – noting that strong sea currents are required. • Technology analysis to consider regulatory requirements and application that meets the pollutant ceiling concentrations.	• 20-30% solids concentration for application to land • Up to 40% DS for landfilling	g h

	Landfilling	strictly prescribed as sludge disposal, as the sewage is not treated and hence no sludge is formed	• The characteristic of the site will determine the actual design and influence the overall effectiveness of the land application concept. • Consider topography, soil character, soil depth to groundwater, proximity to critical areas • Consider loading rates over long term applications (usually N and heavy metals) • Establish the Permissible Application Rate (PAR) or load prior to application to ensure that the metal content of soil will not increase above the Maximum Application Rate (MAR): 60 ton DS/ha over 2 years for animal feed and 120 ton DS/yr for industrial sites or crops. • Sludge loading rates to dedicated land range from 12-2250 tonne/ha • Stabilisation and dewatering is commonly required is sludge is to be landfilled, coverage with 350 mm clean soil layer		
	Disposal to sea				

Literature Sources:

a = Metcalf & Eddy, 2014, P392; b=Albertson&Waltz, 1997; c=Abu-Orf et al., 2001; d=WEF 1988; WEF 2010; f=Crites & Tchobanoglous, 1998; g=Cooper et al, 1996); h=Herselman 2205; i=WRC (2006/Vol2); j =WRC (2006/Vol5); k=Marx et al., 2004; l=Haarhoff, j. & van Vuuren, L. 199; m=Ross et al. 1992; n=Schafer, P.L. & Farrel, J.B. 2000; o=Pitt & Ekama (1995); p=WRC-189 (1992); q= Morrison, I.R. (1986); r=Ceronio et al. (1999); s=Slim et al. (1984); t=La Trobe et al. (1994), u=Pincince et al. (1998), v=Malanda et al. (2016).

2.8 GUIDELINES FOR THE DESIGN AND OPERATION OF SLUDGE TREATMENT

2.8.1 South Africa

Interviews with randomly selected professional engineers that design and construct sludge treatment facilities in South Africa, outlined the following:

- South African engineers do not follow any specific or prescribed local- or international design standard for wastewater or sludge process design.
- Engineering design is typically based on 'in-house' preference and design criteria which are regarded as proprietary.
- Larger municipalities tend to base their preference for design on previous experience with systems and processes that had, or not, worked in the past. Existing plants thereby often becomes the basis or the design standard prescribed by the client to the engineer.
- Suppliers of equipment are typically prescriptive regarding the sludge handling practice and designs are often done to accommodate the supplier's requirements and specification, which then becomes the design standard.
- In the absence of the above, local engineers often revert back to textbooks such as Metcalf and Eddy (Wastewater Engineering Treatment and Reuse) to source typical design parameters for use as guideline.

The following Guidelines have been sourced from SA-based reports, which contain design- and operational specifications and considerations for sewage sludge treatment processes:

- Johannesburg Water: "***Project Standards Document: Guidelines for the design of wastewater treatment unit processes***". The document summarises the City's norms and standards for their treatment plants, including liquid and sludge.

- WRC Report 1240/1/04: "***A technical and financial review of sewage sludge treatment technologies***" *by Marx, Alexander, Johannes and Steinbach.* The document serve as a tool for local authorities and other institutions involved in the treatment and disposal of wastewater sludge. The document describe technology and cost options associated with various stages of sludge handling, including pre-treatment, thickening, stabilisation, dewatering, drying, thermal conversion, and product use and disposal. The report guide the sludge producer through the different disposal or utilisation options and highlight relevant technical, legislative and first-order cost estimates with each decision. Valuable design and operational criteria are provided for each technology discussed, including reference sites.

- WRC Report TT107/99: "***Guidelines for the design and operation of sewage sludge drying beds***" *by Ceronio, A.D, van Vuuren, L.R.J & Warner, A.P.C.* This document contain the fundamentals of sludge treatment and practical design and operational aspects. The report concludes that: i) designs must be based in site and plant specific variables; ii) designs should be based on worst-case scenarios in terms of climatic conditions unless alternative dewatering procedures were available; and iii) plant operators should try to optimise operation through experimentation – a log of activity and statistics on the beds' performance are crucial.

- WRC Report **No: TT 389/09: "*Process design manual for small wastewater works*" by** *SD Freese & DJ Nozaic:* The motivation for this project was that 'A Guide to Design of Sewage Purification Works' was first published in 1973 by the then Southern African Branch of the Institute for Water Pollution Control (IWPC) and over the years this useful reference document has become known as the *Black Book*. This guide was revised and republished in 1987. The purpose of the 1987 revised publication was to update outdated information, include new processes and provide the information in a more user-friendly manner. The 1987 revision of the Manual was intended to be less of a guide to design, and more of a manual to assist firstly designers, and secondly engineers and/or chemists who may be required to approve the designs for smaller domestic sewage works treating up to 5 M*l*/d.

- WRC Report TT 261/06 (Volume 1); TT 262/06 (Volume 2); TT 349/09 (Volume 3); TT 350/09 (Volume 4); TT 351/09 (Volume 5): "***Guidelines for the utilisation and disposal of wastewater sludge: Volumes 1 to 5***" *by HG Snyman; JE Herselman & P Moodley*. This guideline series contain a comprehensive overview of wastewater sludge management practices, including an alignment with the South African laws and regulations pertaining to the environment, waste and water. The guidelines support the principles of sustainable use of resources and are in line with international trends and practices. Each sludge management option is being developed as a separate guideline document, and each document focuses on the management, technical and legislative aspects associated with a particular option.
  - *Volume 1* focuses on selecting the appropriate management options for the sludge streams generated by a specific wastewater treatment plant.
  - *Volume 2* deals with the requirements for agricultural applications. This volume may also be used to manage compost containing sludge that is not distributed to the general public for use. The potential benefits of the nutrients (nitrogen, potassium and phosphorus) as well as the high organic carbon content of sludge have been well demonstrated. Sludge can also assist in increasing the organic content of the soil.
  - *Volume 3* is dedicated to sludge disposal options. The volume has been developed specifically to minimise the detrimental effect of sludge disposal to land, the water and the marine environment.
  - *Volume 4* deals with the requirements for the beneficial use of sludge at high loading rates,
  - *Volume 5* deals with requirements for thermal sludge management practices and for commercial products containing sludge.

- WRC Report No: TT 405/09: ***"A Simple Guide to the Chemistry, Selection and Use of Chemicals for Water and Wastewater Treatment"*** *by P Leopold & SD Freese.* The report takes departure from the fact that an estimated R500-million is spent on chemicals used in the treatment of drinking and wastewater in South Africa. Most of this money is allocated on the basis of tenders issued and contracts awarded. The decisions regarding which chemicals to use, how much to use, how much should be paid, who is the most professional supplier – are important ones and should be taken while in possession of the most factual and impartial information. This guide is a chemistry handbook, and aims to provide decision-makers and other users of water treatment chemicals with specific and useful information about water treatment chemicals.

- WRC Report 1540/1/10 "***The Influence of Sludge Conditioners on the Soil Conditioning Properties of Sewage Sludge"*** *by JJ Schoeman JJ & M Murigwathoho*. This report is not a comprehensive guideline document, however it contains valuable operating guidance for the use of dewatering agents for sewage sludge treatment. The report is based on observations from previous studies which found that sewage sludge conditioned with polyelectrolytes was hard and difficult to crush. If this is the norm for all polyelectrolyte treated sludge, a change in the properties of the sludge may reduce the soil conditioning abilities of sewage sludge that are applied to agricultural land. The study investigated the effect of various conditioning agents (organic and inorganic) used in sludge treatment at different concentrations on the properties (dewatering, wettability, chemical composition, hardness, biodegradability, mineralization, etc.)

- WRC Report No: TT 472/10. ***"Guide for operations and maintenance of a waste stabilisation pond system"*** *by P de Souza & U Jack*. This guideline takes departure from the premises that the operation and maintenance of a waste stabilisation pond system is relatively simple, but that it needs to be performed to ensure proper functioning and a long system lifetime. This guide provides practical guidelines for the persons responsible for the operation and maintenance of waste stabilisation pond systems; understanding typical failures experienced within waste stabilisation pond systems, as well as how to attend to and rectify such failures.

- WRC Report TT 471/10 ***"Guide for Management of Waste Stabilisation Pond Systems in South Africa"*** *by P de Souza & U Jack*. This guide provides assistance in terms of planning for construction of an appropriate wastewater treatment pond system and determining what is appropriate; management to understand what to expect from the contractors and/or consultants in designing a waste stabilisation ponds system; good operations and maintenance of waste stabilisation ponds system; possible re-use of treated wastewater from waste stabilisation ponds system; and upgrading waste stabilisation ponds systems.

- WRC Report No: K5/1869. ***Guideline Document: Package Plants for the Treatment of Domestic Wastewater"*** *by A van Niekerk, A Seetal, P Dama-Fakir, L Boyd & P Gaydon*. Previous WRC studies found that package plant manufacturers and operators face a number of challenges. Both within South Africa and abroad, package plant failures are most commonly ascribed to poor design and construction, insufficient or no maintenance, and mechanical breakdown. Legislation must be adhered to before such plants can be installed. The purpose of this study was to develop a guideline document for use by Water Service Authorities, Department of Water Affairs, and suppliers and owners of package plants. The authorities would use the document as a guide when authorising and subsequently inspecting package plants and the package plant suppliers and owners will use the document to understand their roles and responsibilities regarding the authorisation, operation, maintenance, monitoring, and reporting on these plants.

- WRC Report No: TT 375/08 **"*Guideline to the Inspection of Wastewater Treatment Works"*** *by LA Boyd & AM Mbelu.* This guideline document deals with the requirements for undertaking an inspection at a wastewater treatment works. The purpose of the guideline document is to assist the process controller to prepare for an inspection at the works and take corrective action where a problem is identified. It also allows the inspector to undertake an inspection and give guidance where a problem is identified.

- WRC, Publication: 1994 "**Guidelines for the design and operation of sewage sludge consolidation tanks".** Sludge consolidation is used by most wastewater treatment works to reduce the sludge volume and hence lessen the cost of downstream processing and disposal. Traditionally the design of consolidation tanks have not allowed for the wide variations in consolidation properties that can occur, even for the sludge's of the same type. This guide describes a procedure which has been developed for the design and operation of tanks which improves the efficiency of the process. A mathematical model is used to predict the performance of sludge in a consolidation tank and hence optimise the process.

- WRC Report TT55/92 "***Anaerobic digestion of waste-water sludge: Operating Guide***" *by Ross, Novella, Pitt, Lund, Thomson, Kind and Fawcett*. This guideline covers all steps of sludge treatment and handling. It gives wastewater operators/process controllers with regard to the monitoring, control, trouble-shooting, and maintenance aspects of the anaerobic digestion process. It is particularly useful to identify problems and seek solutions regarding aspects of loading, mixing, heating, gas and toxicity parameters. Practical examples on the calculation of sludge mass balances and others are found in this valuable guideline.

2.8.2 International

A number of guidelines are available globally which deals with design and operational aspects of sludge treatment. The following list guidelines most recently developed and released:

- ***Land Application of Sewage Sludge: A Guide for Land Appliers on the Requirements of the Federal Standard for the Use or Disposal of Sewage Sludge***" by the US EPA-40 CFR Part 503; EPA/831-B-93–002b; Washington, DC, 1994.

- ***Process Design Manual: Land Application of Sewage Sludge and Domestic Septage***" by the U.S. EPA., 625/R-95/001; EPA: Washington, DC, 1995.

- ***"Guidance Document for the beneficial use of municipal biosolids, municipal sludge and treated septage".*** By the Canadian Council of Ministers of the Environment (CCME) Biosolids Task Group, 2012. This guideline outlines the beneficial use and sound management of municipal biosolids, municipal sludge and treated septage and contains information to assist Canadian regulators and generators to manage these three categories of wastewater residuals in an environmentally beneficial and sustainable manner. Beneficial use options include combustion to capture energy contained in municipal biosolids, municipal sludge and treated septage (generating heat and power) and land application to utilize the nutrients and organic matter contained in municipal biosolids and treated septage. Beneficial use options must adhere to jurisdictional standards, requirements or guidelines.

- ***"Design Report for Egg-shaped Anaerobic Digesters: Wyoming Clean Water Plant"***: Biosolids Management Final Report (May 2014). By Ashenafi et al. (Blackwards Team 7). This report consist of design and operational considerations for an egg-shaped AD for sludge stabilisation. The client's design specifications were: Class A biosolids product; progressive technology and nutrient recovery options. The report includes aspects of: sludge thickening, predigestion by thermal hydrolysis, sludge holding tank design, biogas production, co-generation, post-digestion dewatering, biosolids storage tanks, nutrient removal and recovery, bench-scale experiments and cost. The report compares various technologies under each heading, rendering it a particularly useful report.

- **"Guidelines for Using Activated Sludge Models" By IWA Publishing, 2013.** The document gives guidance in the process of planning and conducting simulation projects and can be used as an introductory book to learn about good Modelling practice (DMP) in activated sludge modelling and will be of special interest to process engineers who have no knowledge of modelling. The STR presents a framework to deal with the practical application of commonly used process models such as the activated sludge nodes.
- **"Guideline for granular sludge reactor design"** By: C.M. Castro-Barros, revised by E.I.P. Volcke, 2013. The partial nitritation-anammox pathway is an innovative alternative for nitrogen removal from wastewater compared with conventional nitrification-denitrification. Granular sludge reactors are suitable systems to develop partial nitritation-anammox that present several advantages compared with floc-based systems such as lower footprint and higher settleability. A review on granular sludge technology is given to provide a guide for reactors design, focusing on aerobic granular sludge systems to carry out the partial nitritation-anammox pathway. Microbial kinetic factors as well as hydrodynamic and operational parameters involved in aerobic granular sludge systems are described. Fundamentals of sequencing batch reactor design for aerobic granular systems are provided and modelling is put forward as a useful tool for biofilm system design. The outcome of the review shows that an appropriate selection pressure is essential to develop proper granules,

mainly short sludge settling times and relatively high shear stress. Modelling granular sludge has to take into account physical-chemical and biological aspects.

- **"Guidelines for the implementation and operation of biogas upgrading systems"** by Michael Beil and Uwe Hoffstede, 2010. This report gives stakeholders willing to implement a biogas upgrading plant an overview about the state-of-the-art of all technologies that are available for cleaning and upgrading of biogas to biomethane. It includes expenses of BIOGASMAX and project external plant operation as well as technology providers, and gives recommendations to avoid faults in both the planning and operating stages of plants.
- **"Energy from waste – a guide for decision-makers."** By: Rea's bioenergy, biogas and gasification & pyrolysis groups. 2011. This guide has been produced to demonstrate how much energy can be recovered from waste, after recycling has taken place. It illustrates how EfW contributes to the UK's energy needs and renewable energy targets and gives an overview of the various types of technologies used. Financial incentives is discussed which aim to promote deployment of EfW. The guide assist decision-makers what high-level actions need to be taken in order that the UK can convert more residual waste to energy.
- **"Assessing the use of activated sludge process design guidelines in wastewater treatment plant projects: A methodology based on global sensitivity analysis".** Elsevier B.V, 2012. Design inputs (wastewater characteristics, operational settings, effluent requirements or safety factors,…) need to be supplied when using activated sludge process design guidelines (ASPDG) to determine the design outputs (biological reactor volume, the dissolved oxygen demand or the different internal/external recycle flow-rates). The values of the design inputs might have strong effects on the future characteristics of the plant under study. For this reason, there is a need to determine how both design inputs and outputs are linked and how they affect wastewater treatment plant (WWTP) designs. In this paper, the ASPDG is assed with a methodology based on Monte Carlo (MC) simulations and Global Sensitivity Analysis (GSA). The novelty of this approach relies on working with design input and output ranges instead of single values, identifying the most influential design inputs on the different design outputs and improving the interpretation of the generated results with a set of visualization tools. The variation in these design inputs is attributed to epistemic uncertainty, natural variability as well as operator, owner and regulator decision ranges. Design outputs are calculated by sampling the previously defined input ranges and propagating this variation through the design guideline.
- **The** *"National Plan for the Management of Sewage Sludge from Municipal Wastewater Treatment Plants in Bulgaria"* (November 2013), includes sections dealing with "***Technical guide on the treatment and recycling techniques for sludge from municipal wastewater treatment with references to Best Available Techniques (BAT)***'; and a guideline titled "***Preparation for decision-making in the field of sewage sludge disposal."*** The reports form part of a national plan which outlines the various technologies and methods for sludge disposal and re-use, supported by key considerations for decision-makers in respect to the management of sewage sludge.

2.9 WRC RESEARCH PORTFOLIO: ANAEROBIC DIGESTION, ENERGY, SEWAGE SLUDGE

Mass balances modelling over wastewater treatment plants III
Authors: Ikumi DS; Harding TH; Vogts M; Lakay MT; Mafungwa H; Brouckaert CJ; Ekama GA; 2015/01/01; Research Report No.1822/1/14

Addressing the Challenges Facing Biological Sulphate Reduction as a Strategy for AMD Treatment: Reactor stage – raw materials, products and process kinetics

Authors: Harrison STL; Van Hille RP; Mokone T; Motleleng L; Smart M; Legrand C; Marais T; 2014/11/01; Research Report No.2110/1/14

Mass balances and modelling over wastewater treatment plants

Authors: Ekama GA; Mebrahtu MK; Brink IC; Wentzel MC; 2011/04/01; Research Report No.1620/1/11

The use of hydrodynamic disintegration as a means to improve anaerobic digestion of activated sludge

Authors: Machnicka A; Grübel K; Suschka J; 2009/01/31; Water SA Manuscript

Anaerobic digestion of dairy factory effluents

Authors: Strydom JP; Mostert JF; Britz TJ; 2007/11/27; Research Report No.k5/455

The influence and mechanism of influent pH on anaerobic co-digestion of sewage sludge and printing and dyeing wastewater

Authors: Wang J; Zhang Z-j; Zhang Z-f; Zheng P; Li C-j; 2007/07/01; Water SA Manuscript

Co-digestion of high strength/toxic organic effluents in anaerobic digesters at wastewater treatment works

Authors: Remigi EU; Buckley CA; 2006/01/06; Research Report No.1074/1/06

A steady state model for anaerobic digestion of sewage sludges

Authors: Sötemann SW; Ristow NE; Wentzel MC; Ekama GA; 2005/10/01; Water SA Manuscript

Integrated biological, chemical and physical processes kinetic modelling Part 2 – Anaerobic digestion of sewage sludges

Authors: Sötemann SW; Musvoto EV; Wentzel MC; Ekama GA; 2005/10/01; Water SA Manuscript

Anaerobic digestion of high strength or toxic organic effluents in available digester capacity

Authors: Sacks J; Buckley CA; 2004/01/03; Research Report No.762/1/04

Anaerobic digestion of dairy factory effluents

Authors: Strydom JP; Mostert JF; Britz TJ; 2001/04/01; Research Report No.455/1/01

Rapid communication: Measurement of VFA in anaerobic digestion: The five-point titration method revisited

Authors: Lahav O; Loewenthal RE; 2000/07/01; Water SA Manuscript

Two-phase anaerobic digestion of three different diary effluents using a hybrid bioreactor

Authors: Strydom JP; Britz TJ; Mostert JF; 1997/04/01; Water SA Manuscript

Treatment of exhausted reactive dyebath effluent using anaerobic digestion: Laboratory and full-scale trials

Authors: Carliell CM; Barclay SJ; Buckley CA; 1996/07/01; Water SA Manuscript

The evaluation and improvement of the anaerobic digestion ultrafiltration (ADUF) effluent treatment process

Authors: Nell JH; Kafaar A; 1995/01/11; Research Report No.365/1/95

Laboratory-scale treatment of acetic acid effluent by the anaerobic digestion ultrafiltration (ADUF) process

Authors: Strohwald NKH; 1993/09/01; Research Report No.459/1/93

An investigation into the application of the anaerobic digestion ultrafiltration (ADUF) process to fruit processing effluent

Authors: Strohwald NKH; 1993/09/01; Research Report No.460/1/93

Anaerobic digestion of waste-water sludge: Operating guide

Authors: Ross WR; Novella PH; Pitt AJ; 1992/08/01; Research Report No.TT 55/92

Anaerobic digestion of landfill leachate

Authors: Lin CY; 1991/10/01; Water SA Manuscript

Application of ultrafiltration membranes for solids-liquid separation in anaerobic digestion systems: The ADUF process

Monitoring and control of anaerobic digestion

Authors: Ross WR; Louw LM; 1987/08/01; Water SA Manuscript

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- **A South Africa design guide for dissoved air flotation**.
- Authors: Haarhoff, J. & van Vuuren, L. WRC Report 332/1993

Mass balances modelling over wastewater treatment plants III

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Authors: Morrison, I.R. WRC Report 86/1/86, Pretoria

Guidelines for the design and operation of wastewater sludge treatment works.
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Evaluation and optimisation of dual digestion of sewage sludge.
Authors Water Research Commission, WRC report 189.1.92

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Forced Aeration composting of sewage sludge for rural communities.
Authors: La Trobe, B. WRC Report 341/1/94, Pretoria

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Authors: Swartz CD; van der Merwe-Botha M; Freese SD; 2013/06/01; Research Report No.TT 565/13

Energy from wastewater: A feasibility study

Authors: Burton S; Cohen B; Harrison S; Stafford W; van Hille R; Welz P; Kome K; Pather-Elias S; 2011/08/31; Conference Proceedings – Presentation

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Authors: Malanda, N., Sikosana, M., Randall, D.G., Peterie, D.G., Oelofse, M., Russo, V. & von Blottnitz, H.; WRC Report K5/2218/3. WISA Presentation, May 20160

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3. CHAPTER 3: PROJECT PLAN, PLANT DESIGN AND OPERATION

3.1. PROJECT BACKGROUND

The City of Johannesburg (WSA) and Johannesburg Water (WSP) identified the rising cost in electricity, interrupted power supply via ESKOM's load shedding practices, and the need to comply with Class A1a biosolids as primary risks to the wastewater business at their WWTW's.

The City embarked upon a strategic road of approaching the risk by developing the potential value of wastewater as a resource. The City concluded that the identified risks could be mitigated and that benefit could be derived by establishing an integrated sludge management plan that incorporated the optimisation of the various sludge handling process units, combined with the implementation of beneficiation processes such as Combined Heat and Power (CHP), phosphate recovery and sludge beneficiation.

By time of approval of the strategy (2013), Johannesburg Water treated 998 Ml, 249 dry tons of sludge and consumes 17.5 MW electricity per hour at their 6 WWTW. It was estimated that the five large wastewater treatment works had the potential to generate 9.5 MW through CHP by optimising of the overall sludge treatment efficiency. This would reduce the electrical power requirement by 54% and have amounted to a saving of about R160 million per year by 2020.

In order to comply with the new sludge guidelines, Johannesburg Water embarked on a sludge treatment optimisation and refurbishment programme in 2013 that included optimisation of the various process units responsible for collection and thickening of sludge streams, as well as structural repair and the installation of heating and mixing equipment at Northern and Olifantsvlei Works. The digester upgrade project commenced in July 2015, and the Goudkoppies project is in planning phase. New mesophilic digesters were commissioned in 2013/2014 at the Driefontein and Bushkoppie WWTW. The successful implementation of a 1.14 MW CHP unit at the Northern Works in 2013 led to a decision to extend the CHP programme to Driefontein WWTW by installing of 2 x 376 kW CHP reciprocating engines.

This chapter provides context in terms of the City's legal requirements pertaining to its sludge management practices, and provides an overview of the various process units and design philosophies followed.

3.2 REGULATORY REQUIREMENTS

3.2.1 Northern Works and Driefontein Works

The Northern- and Driefontein WWTW hold a Water Use License (WUL) issued in 2015 which outlines the requirements by the DWS in terms of Sections 21(e), 21(f) and 21(g) of the National Water Act (Act 36 of 1998):

- License carries a 20 year validity, subject to review every 5 years
- "…Sewage sludge or any other solids sewage waste may be alienated for utilisation or disposal thereof, only in terms of a written agreement and provided that the responsibility for complying with the requirements contained in the license is accepted by the Licensee and such other party, jointly and separately
- The areas used to compost dry sludge should be lined with appropriate geo-liners to prevent ground water contamination
- Sludge emanating from the treatment process must be quantified, analysed, dealt with according to the requirements of Chapter 5 of the National Environmental Management: Waste Act, 2008 (Act 59 of 2008) and the Guideline for the Utilisation and Disposal of

Wastewater Sludge (Volume 1-5), dated March 2006 and updates thereafter, to the satisfaction of the Provincial Head…”.

3.3 DESCRIPTION OF SLUDGE TREATMENT PROCESS UNITS

The Northern WWTW serves a population of 1 058 000 people with wastewater services, which include the residential areas of Bedfordview, Modderfontein, Western Klein Jukskei catchment, Delta catchment, Cydna catchment, Bruma catchment, Vorna Valley and Diepsloot. The plant incorporates activated sludge technology with BNR and trickling biofilters for handling of liquid wastewater, and anaerobic digestion and agricultural land application for sludge handling. The plant has an Average Dry Weather flow (ADWF) design capacity of 435 Ml/day and receives 420 Ml/day with a peak WWF of 590 Ml/day. The license requires the plant to discharge an effluent quality which meets Special Limits (P of <1 mg/l) and produce a Class A1a sludge.

A generic process flow diagram which depicts the sludge handling process units are illustrated in Figure 18, outlining the various process units that will be discussed and evaluated during this case study (Refer Process Flow Diagram).

The Northern WWTW sludge plan comprises of the following sludge treatment units:

- Sludge pre-thickening for sludge thickening from 2.5% DS to 6%;
- Sludge pre-conditioning for cell membrane destruction;
- Anaerobic digestion for the production of biosolids and biogas;
- Struvite control (including phosphate removal from sludge) to prevent blockages in post-digestion operation;
- Sludge drying to reduce the sludge volume (to obtain a TS of > 50%) and forming heaps to generate high temperatures >55°C for pathogen and seed kill and render a value-add product; and
- Digested biosolids utilisation and disposal to meet Class A1a legal requirements.

Whilst the focus point of this case study is CHP, it is of importance to consider that Johannesburg Water has considered the **entire sludge treatment train** as part of its sludge management strategy. It was envisioned that the enhancement and optimisation of each pre-digestion processes would ultimately increase the solids retention, resulting in greater production of biogas, increased potential for heat and power production (CHP) and producing Class A1a biosolids.

3.3.1 Sludge pre-thickening

All of Johannesburg’s wastewater treatment works have implemented enhanced biological nutrient removal through the fermentation of primary sludge for volatile fatty acid production and therefore most of the digester feeds consist only of thickened waste activated sludge (WAS). The WAS on all WWTW is thickened in concrete gravity thickeners from 0.35% to between 1-2.5% dry solids prior to anaerobic digestion.

In the case of the Olifantsvlei WWTW, the WAS is fed to the anaerobic digesters at a concentration of around 2.5% with a Volatile solids concentration of 82%. In order to increase the loading on the digesters and the effective volumetric use of the digesters, it was recommended to thicken the sludge to around 5-6% DS content before feeding the sludge to the digesters.

The benefit of sludge pre-thickening is an increase of solids retention time and more effective use of the digesters (more sludge can be digested with the same digester volumes).

The rationale is that the increase in sludge concentration would result in:

- An increase of volatile solids loading rate by reducing the digester volume requirements;

- Increase in the solids retention time in the digesters;
- increase in biogas production and electrical energy generation at a reduced digester volume requirement;
- Reduction in the mass of digested sludge to be further treated before final disposal;
- Reduction in the cost of digested sludge dewatering and disposal;
- A more stable final product with reduced potential for odour and vector attraction would be produced;
- Reduction in the digester heating requirements due to digester feed volume reduction.

Downstream of the existing gravity thickeners, an enhanced thickening of the sludge was recommended using a mechanical thickening process. Typical mechanical thickening processes could include gravity belt thickeners, volute or press type of thickeners or centrifugal thickeners. It is important that a consistent feeding regime of sludge to the digesters is prescribed and maintained.

Johannesburg Water have standardised on gravity belt thickeners, with moderate capital and operational costs and good performance results as the process selection for sludge thickening. Ease of operation, inexpensive maintenance costs and low cationic dosing rates were important factors of consideration when selecting this technology.

The level of thickening is an important design and operational consideration, as sludge that is too thick becomes difficult to pump, mix or heat within the digesters. It is therefore not desirable to thicken the feed sludge to above 7% DS content.

3.3.2 Sludge pre-conditioning

Sludge conditioning or cell-lysis was considered to enhance anaerobic digestion efficiency. Cell lysis is the destruction or breaking down of the cellular structure of the sludge in order to release further readily available volatile solids and nutrients within the sludge which enhances the digestion process by releasing more readily available digestible matter as substrate for the anaerobic bacteria. Cell lysis or disintegration increases the biogas yield at the anaerobic digester facilities which translates into increased electricity output at the downstream cogeneration/combined heat and power in installations.

It is important to note that no additional COD is produced during the cell lysis/disintegration process; only COD previously not available to the anaerobic bacteria is made available to the anaerobic bacteria by the lysis/disintegration processes. Therefore the cell lysis/disintegration process is most effective when treating thickened WAS, although some manufacturers claim that their processes are also effective when treating thickened primary sludge (thermal, mechanical and biological methods).

Cell lysis can be done in various forms with varying levels of effectiveness (usually proportional to the capital costs of the lysis type) and various degrees of operational complexity and costs. For the NWWTW, the following processes were evaluated:

- thermal hydrolysis,
- mechanical disintegration (including cavitation),
- chemical hydrolysis,
- thermo-chemical,
- ultrasonic,
- electro-kinetic, and
- electrical pulse lysis technology.

Each of these processes was considered for their advantages and disadvantages. Cell lysis was the preferred option as it offered enhanced sludge treatment in terms of VSS destruction and dewaterability, as well as projected biogas production. As result, the design engineers considered electro-kinetic cell lysis as a relatively low-capital and easy to operate process. This selection was investigated to determine the operational savings as well as increased power production from CHP from the WAS sludge produced at NWWTW.

The sludge pre-conditioning can be retro-fitted to an existing works as an 'add-on' in-line process between the sludge holding tanks and the digesters. The thickening outcome can be modelled by specialists to simulate the anticipated improvements provided by the respective process. This allowed Johannesburg Water to consider the beneficial effect of including such process to their works.

3.3.3 Digestion optimisation

The NWWTW incorporated anaerobic digestion from the initial design of the activated sludge plant. Digester operation and optimisation remain a critical part of a successful integrated sludge treatment process. Digesters are inherently sophisticated infrastructure with biological processes and need to be checked, serviced and maintained continuously. Inadequate operation and understanding of the process will result in poor digestion, unstable sludge and low biogas yield, which holds an environmental risk.

The NWWTW incorporates 6 anaerobic digesters in Unit 2 digester complex with a design capacity of 2 175 m^3 sludge/day. The digesters have a regular (non-continuous) feed from the sludge holding tanks at 2.5%DS providing a sludge retention time of only 5 days. A consistent feed is ensured via the regular withdrawal of WAS from the BNR reactors and the regular desludging of the WAS thickeners.

A key risk identified for the NWWTW, was that grit settles with the sludge (particularly the primary sludge) which subsequently settles out in the digesters, creating volume reductions and ineffective mixing. It is best practice to check and service the digesters every 5-6 years and remove grit and solids if necessary. Best practice would be to ensure that the degritting system functions properly and not create problems downstream with grit deposition in the digesters.

The simplest manner in determining if the digesters are operating efficiently is by evaluating the biogas production, where the theoretical versus practical gas production is compared. Poor practical gas production is indicative of an inefficiently operating digester.

Similar shaped and sized digesters should incorporate gas flow-meters on each individual digester in order to monitor the performance of the digesters by comparing each digester's individual gas production. Any reduction in a digester's gas production indicates a potential problem with the operation of the digester. Hence, the importance of fitting each digester with a flow meter to monitor the equal distribution of the sludge feed.

Increased gas and power production can be achieved by adding additional external carbon source (high-organic matter) to the digesters. This should only be done with consideration to adequate digester capacity as well as potential change in gas quality effect that such an external source can have.

3.3.4 Struvite control and precipitation

Struvite (magnesium ammonium phosphate) is a crystalline deposit that is formed when magnesium, ammonium, and phosphate ions react with one another and precipitate tiny crystals

Phosphates removed from a biological nutrient removal process are taken up in the sludge. However, in the digesters (anaerobic environment), PO_4^{3-} is released due to the hydrolysis of polyphosphates. This is where the PO_4^{3-} becomes available for the formation of Struvite crystals.

Under the right conditions, struvite crystals form on almost any surface, which can include in pipes or on mechanical equipment causing restrictions in pipes or damage to rotating equipment.

Figure 12: Photo image of struvite : $MgNH_4PO_4 \bullet 6\ H_2O$

Furthermore, during the sludge dewatering process (post digestion), the highly concentrated phosphate-containing filtrate is usually returned to the head of the works, which can load an additional 15% phosphate loading onto the plant. This phosphate recycle will eventually lead to the overloading and failure of the biological phosphate removal process.

Phosphates can effectively be removed from the sludge or filtrate by means of a controlled struvite precipitation process, where the struvite crystals are formed under a controlled environment, settled out and removed from the system. The phosphates are simultaneously removed from the sludge/filtrate.

Figure 13: Struvite formation on a pipeline (City of Johannesburg NWWTW)

Phosphates also have water-absorbing characteristics, which typically deteriorate the sludge dewatering rates. Removal of phosphates from sludge can increase sludge dewaterability by around 20% (DS content) and reduces polymer consumption in the dewatering process by around 10%. (W. Ewert – P.C.S. Hamburg).

Johannesburg Water considered the processes available and opted for a process that precipitates the Struvite from sludge directly after the digesters, which would provide the following benefits:

- The achievable P removal rate of 85%-90% on a permanent basis with a positive effect on the overall sludge treatment and dewatering process
- Simplicity of operation of the system
- Capital costs are easily justified by savings created
- Prevention of struvite crystallisation downstream of the Struvite Precipitation plant
- Improvement of sludge dewatering rates and
- Prevention of recycle PO_4^{3-} loads
- Reduction of recycle ammonia loads
- Production of Struvite as a saleable fertiliser product with commercial value
- Low operating costs covered by sales of Struvite

The phosphate (as P) and ammonia (as N) removal rates as well as quantity of struvite produced from the processing plant can be accurately determined and maintained.

Figure 14: Struvite Precipitation plant from Sludge in Amsterdam, Netherlands

Nitrogen and Phosphate Recovery

The precipitated struvite can be harvested, washed and recovered for commercial benefit in the fertiliser industry (Malanda et al*.,* 2016).

The typical composition of the struvite is: MgO (12%), N (5%), and P_2O_5 (23%)

Note: Phosphate is a depleting resource (Malanda et al., 2016) and struvite is harvested from sludge for commercial sale in Berlin and Amsterdam. Struvite can be sold in bulk for around R4 000 per ton (market value as at 2015) or more if individually packaged.

3.3.5 Sludge drying

After digestion and struvite removal the sludge is dewatered in a mechanical dewatering facility. Commonly used mechanical dewatering facilities include Belt Presses or Centrifuges.

Mechanical dewatering would result in a final sludge thickness of between 16% and 25% DS content after dewatering (increased if PO_4^{3-} O_4 is removed from sludge).

An improvement in dewatering efficiency has a significant effect on the further drying of sludge, handling and disposal costs of sludge. (i.e. drier sludge results in a reduced volume to dispose of and therefore reduced disposal costs).

Johannesburg Water has standardised on belt presses for the final sludge dewatering at all their works.

Further drying of sludge through mechanical or thermal processes has high energy and operational costs. In dry weather climates such as is common for the South African inland areas, solar drying on sludge drying beds is a cheap and simple method for sludge drying.

3.3.6 Sludge utilisation and disposal

In terms of the guidelines for utilisation and disposal of sludge; (1) sludge as a saleable product, (2) sludge for crop production and (3) sludge for beneficial use are three of the five recommended methods of disposing sludge. This study encourages these options by managing the sludge process effectively and providing a workable and beneficial solution to the sludge train.

Ideally a sludge that is stable, disinfected and non-pollutant (A1a compliant biosolids) and with 65-75% DS content would have use as agricultural biosolids with commercial value.

The composting process of the sludge provides an A1a product which is in compliance with the guidelines for sludge disposal for crop production. This process requires certain retention times for the composting process to occur, which takes up substantial drying area.

Dried sludge tends to granulate itself in a rough and irregular kernel. A well rounded or conditioned granule with specific hardness shall favour a commercially viable biosolids product; this may require some additional hardening, granulation chemical disinfection and size separation of the sludge to provide a commercial bio solid.

Alternate methods of utilisation and disposal of sludge such as incineration or pyrolysis could also be considered, where the final products revert to ash and additional power can be generated via these processes which can be used for brick or cement production. Although such processes are common in developed countries, they tend to be costly and require more sophisticated operations, which would encourage supplier-operated type of systems where the operator is responsible for performance of the system (BOOT or BOO).

3.3.7 Combined Heat and Power Production (CHP)

The gas produced as a by-product of the anaerobic digestion process is a methane-rich gas. Methane gas is a green-house gas and is harmful to the atmosphere with a typical 25 times the global warming potential of carbon dioxide. Methane should therefore either be utilised for their potential or flared rather than being released to the atmosphere.

Typically the methane rich gas produced in digesters is stored in a gas-holder and used to heat the anaerobic digesters via a water-heating circuit that is heated by a gas-fired boiler, with any excess methane gas flared.

This gas is however a primary fuel and could be utilised to either offset another source of primary fuel or to produce electricity and heat through a CHP plant. At Johannesburg Water's Northern WWTW a 1.14 MWe CHP plant has been installed. Energy is produced through reciprocating piston gas-fired engines with alternators and heat-recovery. The heat is recovered from the engine cooling water as well as the exhaust. The heat produced from the gas engines is used to re-heat the digester content (instead of using methane gas) thereby making more gas available for energy production.

Figure 15: View of the NWWTW anaerobic digesters and CHP plant

The gas does however need to be cleaned prior to direct use to ensure a cleaner fuel, which results in a much longer lifespan of the engines. Digester gas has around 60%-70% methane content and contains moisture (H_2O), hydrogen sulphide (H_2S) and siloxanes which could all potentially damage the gas engines.

Best practice: Johannesburg Water applies best practice by recording power consumption at each plant. Approximately 80% of power is from the bioreactors, the average bioreactor power consumption for all 6 works last year was 408 kWh/ML treated.

The power generated from the CHP plant is used internally by the WWTW to off-set the current power usage. Liquid wastewater treatment is very power intensive (up to 22 kW/ML of sewage treated), but varies widely depending on process configuration). CHP therefore typically produce between 50-70% of the WWTW own energy requirements via sludge digestion. For a trickling filter plant the power produced could exceed the consumption.

If external biomass is added to the digesters to increase the gas production or enhanced sludge processes are considered for the works which could increase gas production (such as hydrolysis, thermophilic digestion, parallel digestion) then the gas production and resultant energy production could be increased. Few plants produce > 100% of its own power requirement, however, there are plants (e.g. Hamburg, Germany) which is known for achieving excess production which is then feed to the grid.

Risks: Interruptions in power supply by the CHP plant for various reasons.
Risk mitigation: Integrate the CHP system with the grid supply.

The benefit of off-setting the power produced from the CHP plant from the works is that no power needs to be exported to the national grid or to the regional power authority (and hence no Power-purchase agreements etc. need to be arranged), but the savings are still realised by the WWTW and any power offset from the utility results in a 'freeing-up' of that equivalent power from the national grid.

If a significant portion of the works power is produced by the CHP plant, then the plant could be operated in either 'parallel' or 'island' mode. Parallel mode is where the CHP plant is feeding the works in 'parallel' with the utility supply (i.e. off-setting of power from utility) and 'island' mode is where the CHP plant is running independently of the utility. Due to the fact that the CHP plant usually does not supply the full works power requirement, 'island' mode is usually only used in periods when there is an interruption in the supply of the utility and critical components on the works are powered only by the CHP plant. This does add complexity to the electrical integration and operation of the plant.

There are also *toolkits* available that can provide a high-level desktop analysis on the generating capacity of a sewage works, the generic capital investment required and the pay-back periods of the CHP plant. Projects which include the use of toolkits are dependent on having a suitable basic infrastructure and basic digestion capability.

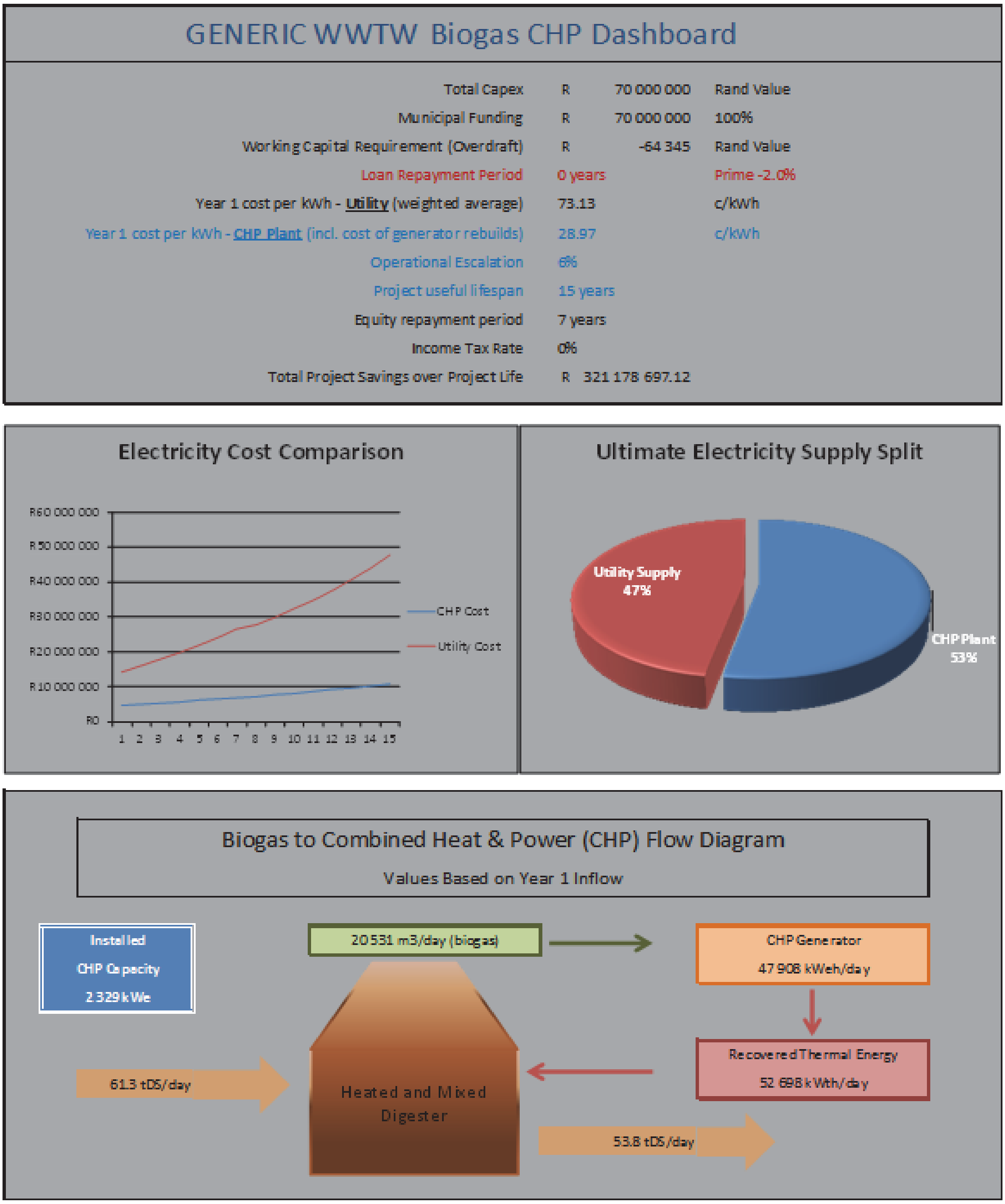

Figure 16: Typical output from a toolkit, used to calculate the energy potential from anaerobic digestion.

The process described above can be fairly accurately sized and theoretically calculated to present the outcomes of the processes. The sludge characteristics do vary from works to works but they can be fairly accurately predicted by the influent flowing to the works.

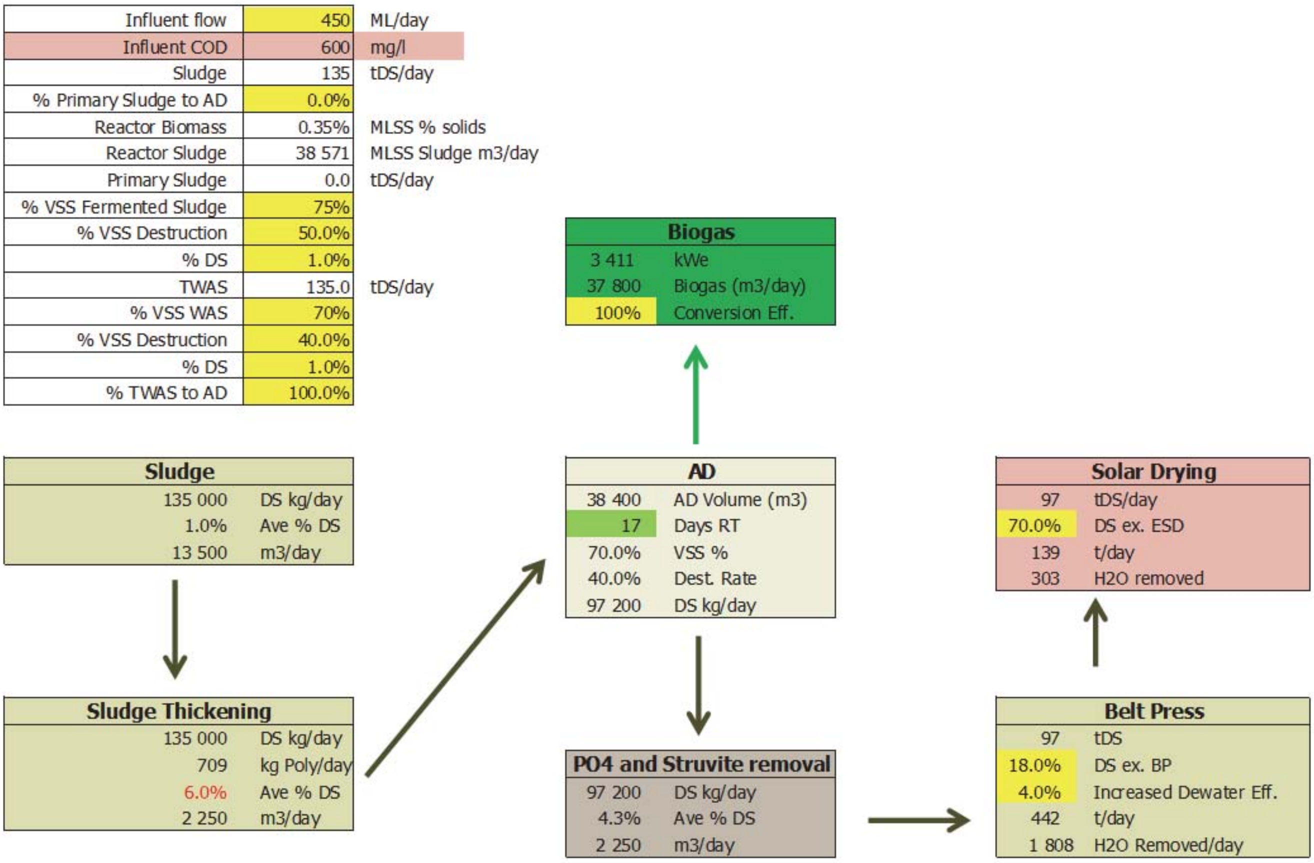

Figure 17: The use of modelling or simulation to determine the amount of phosphate removed, as well as typical performances to be achieved from the thickening, digestion and drying unit processes.

The financial facts which applies to the NWWTW biogas-to-energy project, including the expected production and savings (payback), can be summarised as follows:

- Initial capital costs of the BtE plant (for 1.1 MW)
    - R36 million
    - <u>includes</u> additional civil & electrical infrastructure for future capacity planning up to 4.5 MW
- Operational costs (at award stage in Nov 2012):
    - Fixed monthly charge = R6860.00/month
    - Variable electricity cost = R0.287/kW
- It was originally envisaged that the BtE plant would run as a 'pilot' at a production phase of 900 kWe continuously (or 7 884 000 kW per year), followed by a 'full-scale' production phase of 4 MW (or 35 040 000 kW per year).
- The 4 MW full-scale plant has a payback of 7 years, which is decreasing with the increase in utility electricity tariffs.

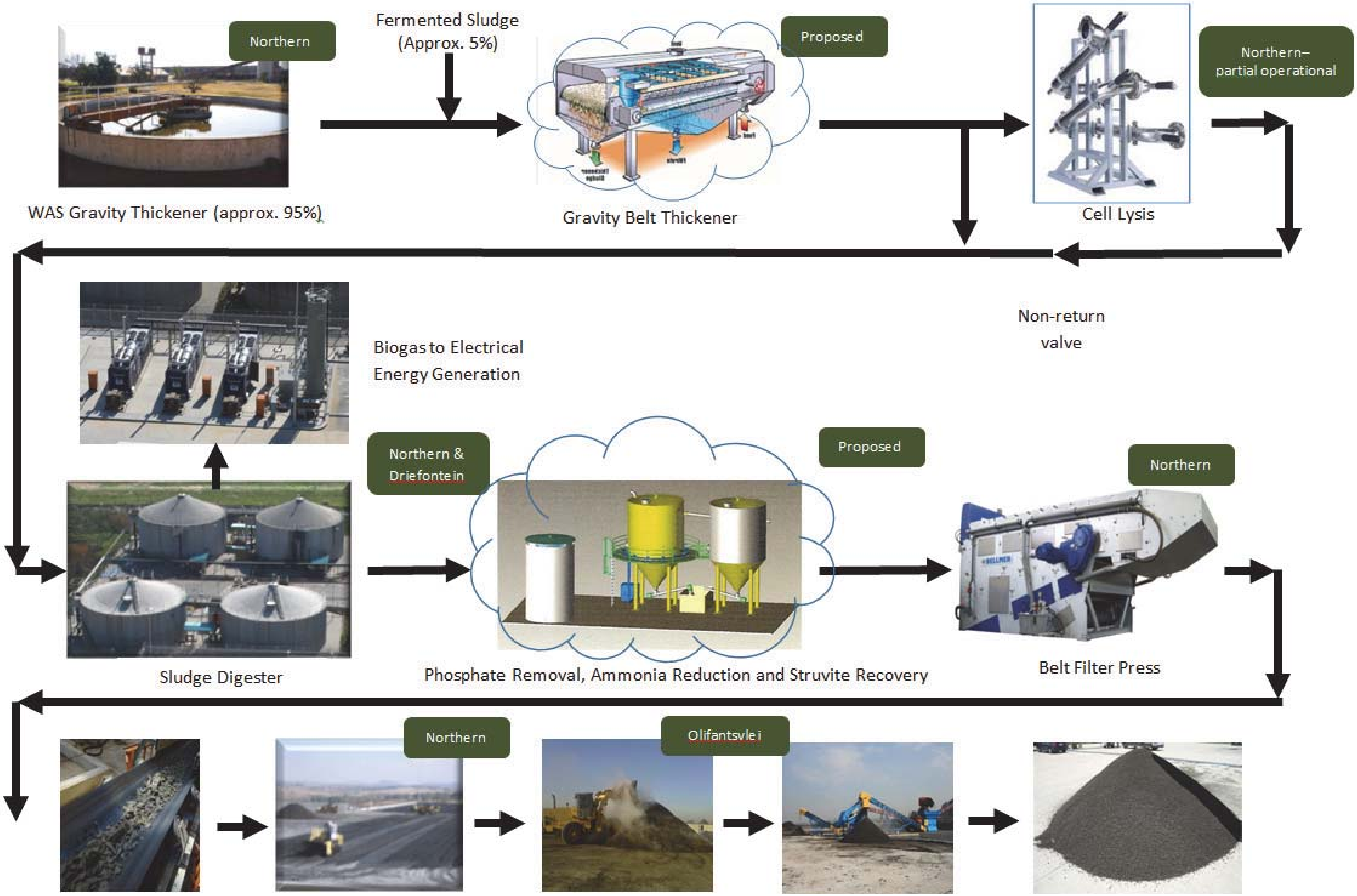

Figure 18: A Process Flow Diagram illustrating the consecutive process units involved in the treatment of sewage sludge at Johannesburg's WWTW

3.4 DESIGN PRINCIPLES AND SPECIFICATION

3.4.1 Sludge Thickening

Sludge can be thickened using various methods, including but not limited to:

- Gravity Sludge Thickening (Conventional circular thickeners)
- Dissolved air flotation
- Gravity belt thickeners
- Dehydrators/sludge presses

Each of these methods have their respective advantages, however the principle behind the thickening of sludge prior to digestion is to increase the sludge thickness as much as possible while still being able to achieve suitable heating, mixing and digestion. Therefore it is optimal to try and achieve a fairly consistent sludge thickness of between 5-7% DS content. An analysis of the various thickening technologies as preferred by Johannesburg Water was conducted and is shown in table 14 (Deacon, 2014).

Table 14: An analysis of the various thickening technologies as preferred by Johannesburg Water was conducted and is shown in the table below

Evaluation criteria	Gravity thickener	DAF thickener	GB thickener
1. Capital investment	High	High	Moderate
2. Operating cost:			
- **Polymer dosing**	-	Moderate	High
- **Electrical power**	Low	High	Moderate
- **Wash water**	-	-	Moderate
3. Operational aspects			
- **Supporting infrastructure/building**	Open installation	Partly enclosed	Enclosed
- **Size of footprint**	Large	Large	Moderate
- **Operational complexity**	Low	High	Moderate
- **Maintenance complexity**	Low	Moderate	Moderate
4. Performance	Poor (2.5-3.5% TS)	Moderate (4-5% TS)	Good (5-7% TS)

Johannesburg Water found that the Gravity Belt Thickeners (GBT's) would be the preferred method of pre-digestion thickening and have standardised on this solution as additional thickening post gravity thickeners. The concluding factors of their decision were the moderate investment costs and the good performance that the Gravity Belt Thickeners offer.

Other sludge enhancement and beneficiation technologies such as Thermal Hydrolysis often require the sludge to be thickened prior to their process, which results in thick sludge being hydrolysed, which would need to be diluted again before being fed to the digesters, thereby eliminating the requirement for a separate pre-thickening process.

Additional considerations that need to be given to all the ancillary equipment associated with adding a sludge thickening process include:

- Sludge pumping to and from the GBT's

- Polymer mixing, handling and dosing
- Effluent wash water pumps
- Associated pipework, valves, strainers and polymer injection device/s, etc.
- Ancillary equipment (air compressor equipment or hydraulic equipment)
- Infrastructure (buildings, etc.)
- Support and access structural steelwork
- Electrical and cabling
- Control and Instrumentation

Some fundamental design considerations by Johannesburg Water include:

- The equipment shall be designed to keep maintenance costs to a minimum.
- The equipment shall be suitable for operation 365 days per year, 24 hours per day under the specified design conditions.
- All materials shall be compatible with the chemicals used and suitable for the intended use and service conditions.
- Flocculent dosing must not exceed desired rates (recommended: 4 kg/ton DS)
- The gravity belt thickener unit shall have an effective belt width of 2.5 m.

The thickening operation should accommodate for the continuous sludge feeding regime to the digesters and consideration should be given on how to monitor sludge thickness as well as to keep sludge mixed, homogenous and 'free-flowing' so that the mixing and heating of the sludge in the digesters can be optimised.

The consideration for Driefontein WWTW's gravity belt thickeners was a design flow rate of WAS production of 338 m^3/day at a feed concentration of 2.5% DS.

A 2 m wide gravity belt thickener (GBT) is expected to handle 100 m^3/h and 2 500 kg DS/hr.

Table 15: A typical mass balance for sludge handling units, as applied to the Driefontein WWTW

Design parameters	Units	/day	/h
WWTW sludge discharge	m^3	338	14.1
No. presses	#	1	1
Days/week	days	7	0
Sludge flow to dewatering	m^3	338	14.1
Feed DS	%DS	3	3
Sludge to all GBT	Units	/day	/h
Mass flowrate	tons	345	14
DS mass flowrate	tons	10	0.4
Water mass flowrate	tons	334	14
Cake from each press	Units	/day	/h
DS mass flowrate	tons	10	0.4
Mass flowrate	tons	49	2.0
Polymer dosing to 1 press	Units	/day	/h
	kg	51.714	2.15475

3.4.2 Cell lysis

The fundamental motivations for Sludge Pre-conditioning (cell lysis/disintegration) include:

- Increases sludge digestibility and enhances biogas generation
- Reduces digester operational challenges – foaming
- Reduces the digested sludge mass/volume

- Improve the dewaterability of digested sludge, resulting in a drier sludge cake and reduced polymer consumption at the dewatering facilities

The selection of an appropriate cell lysis/disintegration technology for Driefontein and Northern WWTW was carefully considered and was primarily driven by the 'business case' and the risks associated with each technology. The points below were taken into account:

- The capital costs of the equipment and financial model to pay for the equipment
  - Funded by Johannesburg Water
- The combined benefit provided by each technology [Note: it is imperative to consider the NETT gains in each system]:
  - increased gas production (and resultant power production)
  - reduction in sludge volumes
  - reduction of operating costs
- The 'payback period' of the technology selected (i.e. return of beneficial savings versus capital and implementation costs)
- Operational cost of the system (consumables, energy, maintenance, etc.)
- level of operation required and if operation can be outsourced
- licencing, environmental or statutory requirements that may be associated with the technology
- interchangeability or compatibility with other technologies or processes and benefits thereof (e.g. certain technologies include thickening and heating processes which could replace or reduce pre-thickening of sludge or digester heating requirements)
- Risks associated with the technology, references and reliability (including guarantees from the suppliers)

The cell lysis/disintegration installation shall be designed to be able to treat the full range of WAS flows and solids loads from minimum to peak flows/loads. However, the installation must be able to treat the average sludge flow and solids load at 100% efficiency.

Where applicable, the cell lysis/disintegration equipment should be positioned downstream of the WAS thickening process. This ensures that the installation treats a lower flow and higher solids load sludge stream, resulting in a smaller installation.

Johannesburg Water opted for the electro-kinetic cell-lysis process at Northern WWTW. The system provided a 5-10% increase in biogas production. However the capital cost of the electro-kinetic system and maintenance and operation costs were relatively low, therefore the system was expected to have an 8-10 year payback period (based on 2012 electricity prices).

At Driefontein WWTW, an Ultrasonic Cell-Lysis system was recommended. The Ultrasonic system is a newer technology associated with low capital cost, but claims to higher to biogas production of approximately 10-15%, resulting in a shorter payback period of < 8 years.

3.4.3 Anaerobic digestion

Anaerobic digestion is most commonly applied as a mesophilic process within South Africa, due to the simplicity of operation. Digestion can also be thermophilic which improves the sludge stability and produces higher biogas yield but is more difficult and costly to operate but is less common. eThekwini Municipality are conducting studies to run thermophilic digesters (interview: S Moodliar).

Digesters are designed to 'stabilise' sludge and reduce volumes; they do so by reducing the amount of volatile solids in the sludge. Heated mesophilic digesters should be designed to achieve an active volatile solids destruction of ≥ 35% for Waste Activated Sludge (WAS) and a VS destruction of ≥ 40% for WAS/primary sludge digestion. The minimum VS destruction required by the WRC/DWS Sludge Guidelines is 38%.

Good digestion design is subject to many parameters including:

- Shape (volume and ratio) of the digesters
- Materials of construction (Steel, Concrete, coating materials)
- heating system and method of the digesters
    - Heat Exchangers
    - Boilers (steam and hot water, JW's preference is hot water)
    - Hot water recirculation
    - Steam injection
- Mixing type and efficiency
    - Draft tube (internal or external)
    - Gas-mixing
    - Jet or nozzle mixing
    - 'Plunger' mixing …
- Sludge recirculation and transfer pumps and pipework
- Gas train (collection and harvesting)
    - Gas Storage and Accumulation System

However one of the most critical considerations regarding effective digestion relates to the control and operational philosophy of the digesters.

The following guide parameters should be considered with digester design and operation:

- Digester volatile solids loading rates shall be 1.6-3.2 kg VS/m^3/day, and
- A minimum of 15 days rolling average solids retention (%TS)
- Regular sludge feeding of the digester units shall be employed to limit and prevent any shock loads or spikes in the production of biogas mass
- Pipe work shall be arranged to allow an even distribution of the feed organic/solids loading
- A gas flare should be provided to flare off any excess biogas production
- Withdrawal of digested sludge or supernatant
- pH level to be kept within a range of 6.6 to 7.4
- Sufficient free board between sludge and gas withdrawal system to reduce gas contamination particularly if foaming occurs.

Operational parameters to be monitored for healthy digesters are (these should be considered with design parameters):

- Digester contents alkalinity should range between 1 500 to 2 500 mg/l
- Volatile acid concentration should range between 50 to 300 mg/l
- The volatile acid/alkalinity ratio should be in the range 0.1 to 0.2.

However, the simplest and most effective method of measuring the operational performance of the digesters is by measuring the gas production of the digesters. It is therefore strongly recommended that individual gas flow meters are installed and monitored on each individual digester and individual flow metering on the sludge feed.

Due to the presence of combustible gas being produced in the digestion process, a hazardous classification of the area needs to be undertaken. The following points should be considered when selecting the type of digesters and equipment:

- Ease of operation and reliability of digesters and equipment
- Maintenance, cleaning and interchangeability of equipment (digesters cannot easily be emptied and maintained if there is an equipment fault)
- Acceptable life expectation
- Compliance with the legal requirements in respect of safety and pollution
- Satisfy any specific requirement contained in the statutory codes and legislation
- Operation 365 days per year, 24 hours per day under specified design conditions
- Hazardous Area Classification for the equipment to be supplied.

Johannesburg has a variety of anaerobic digesters within the WWTW, all of which operate mesophylically between 37 and 40°C and all are mixed and heated.

The heating system of the digesters is the same on all sites namely a sludge-water heat exchanger. However the mixing of the digesters vary from Nozzle mixing (NWWTW and Goudkoppies) to Plunger type mixing (Driefontein and Bushkoppies) and draft-tube mixing (Olifantsvlei).

Mixing are done by applying Computational Fluid Diagram (CFD) and newer technologies (plunger and draft-tube mixing), due to their lower energy requirements, ease of maintenance and accessibility.

3.4.4 Biogas to Electrical Energy

The use of the biogas produced in the digesters to generate electricity and power through combined heat and power (CHP) plant should strongly be considered in any application where a suitable sludge infrastructure is in place.

The CHP facilities are advantageous because the heat produced from the generators can be used to heat the digesters (in place of methane gas boilers) and all the gas produced can be used for power production.

The reason for implementation of a CHP plant is to reduce energy costs of the plant and it is therefore important that the business case model and 'payback' period of the plant be considered. A typical CHP plant in South Africa with good existing sludge infrastructure should have a pay back of 6-8 years.

Use of the CHP Dashboard to determine the viability of a potential CHP project should be considered as a high level assessment of gas and power production. Refer to the discussions pertaining to Figure 16.

A project was awarded on tender for the 'design and build' of two CHP complete plants;

- 1.1 MWe at Northern WWTW and
- 0.72 kWe at Driefontein WWTW

The project included full design and implementation of both works. The first plant, NWWTW, was to be successfully commissioned before commencement of the second plant.

The full performance and operational responsibility of the works was placed on the contractor and a seven year operations and maintenance responsibility was included in the project (note: the 7 year period was intentionally done to include a full engine service before hand-over).

A high importance was placed on technical ability and reference of the contractor and a technical presentation was given by all bidders as part of the evaluation process.

The fundamental components and consideration for the NWWTW CHP plant included:

- Gas cleaning/conditioning system for:
    - Particle removal (particulate or mesh filters)
    - Hydrogen Sulphide removal (H_2S) the 2 most common methods include:
        - Iron sponge/impingement (lower CAPEX but higher OPEX/consumable costs)
        - Biological scrubber (higher CAPEX but much lower OPEX)
    - Moisture removal (via condensation)
    - Compression
    - Removal of non-methane Volatile Organic Contaminants (VOC's)
    - Siloxane Removal $C_{10}Si_5H_{30}O_5$ (D5) using SAG filters.

- Gas engines (or turbines):
    - Reliability, lifespan and reference
    - Size and configuration (number on duty/standby)
    - Operational and Maintenance costs
    - Efficiency (must be >37% for electrical recovery)
    - Control and Integration
    - Access, serviceability, spares, service intervals and service support
    - Injection system
    - Main engine type, number of cylinders and components
    - Alternator and power system integration
    - Number of cylinders, cycle, RPM and turbo
    - Noise and acoustic attenuation
    - Heat recovery system (water jacket and exhaust)
    - Safety aspects (shut-off values, alarms, flame arrestors, etc.)
    - Control and automation
    - Electrical voltage (400V) and output
    - Engine control (pre-lube, monitoring, pre-detonation, etc.).

- Heat recovery:
    - Piping and thermal insulation (losses)
    - Substance, Pumps and distance
    - Control, recycling and heat-dump for over temperature

- Electrical system:
    - Transformers (ring main voltage)
    - Cabling and security thereof
    - Switchgear and integration into grid
    - Synchronisation
    - Motor control centre
    - Field panels and Distribution boards
    - Lighting protection and earthing.

- Control, Instrumentation and Automation:
    - Gas quality (H_2S, methane, O_2, CO_2, etc.)
    - Gas analysers
    - PLC's (field and central)
    - SCADA and Remote monitoring

    - Reporting and Metering.

- Site services and other:
    - Civil infrastructure (roads, buildings, fencing, gates, stores, cable trenches)
    - Black start (start-up) generators
    - Oil store and spare storage
    - Pumps, chillers, heaters, water softeners and dosing equipment
    - Acid handling and/or re-use (H_2S scrubbing)
    - All piping, ducting, valves, components, supports and structures
    - Admin and ablutions.

Several factors are vital to be considered in the specification and design of such a system, these include:

- The quality, volume and composition of the biogas produced
- Site conditions (altitude, temperature, environment, location from digesters, etc.)
- Battery limits and measurement
- Gas storage sizing for buffering
- Plant layout and accessibility (for servicing, access, etc.)
- Containerised generator sets or engine room (including sound suppression consideration)
- Number of units and configuration for continuous operation
- Automatic operation of the plant (and precautions when unmanned)
- Integration and synchronisation with the grid (and how plant power outages are considered)
- Operating voltages and transformation
- Heat recovery, circulation and heat dumps/radiators
- Oil storage and disposal
- Hazardous area classification
- Safety and security (restricted access to site, inductions and limitation of theft, etc.)
- Fire and explosion shut-off and procedure.

The CHP plant was designed to operate continuously (365 days a year and 24 hours a day) supported by a >95% availability and a reliable automated operational philosophy. Minimum down-time and suitable redundancy were allowed for, as the cost of full 'stand-by' always need to be weighed against the utility costs.

Engine efficiency is 38% and thermal recovery is approximately 50%, thereby making the 'combined heat and power' plant around 88% recovery of efficiency on the biogas used.

It is imperative that a good operating philosophy of the engines be abided, this should include continuous operation of the engines (avoid stop/start), peaking power, buffering.

It is imperative to establish clear battery limits and responsibilities of supply. Does the limit of supply include the operation of digesters and responsibility for sludge stabilisation and production of gas or is it limited to the take-off of gas from the gas-holder. This may strongly be determined by the existing infrastructure and how it is being operated.

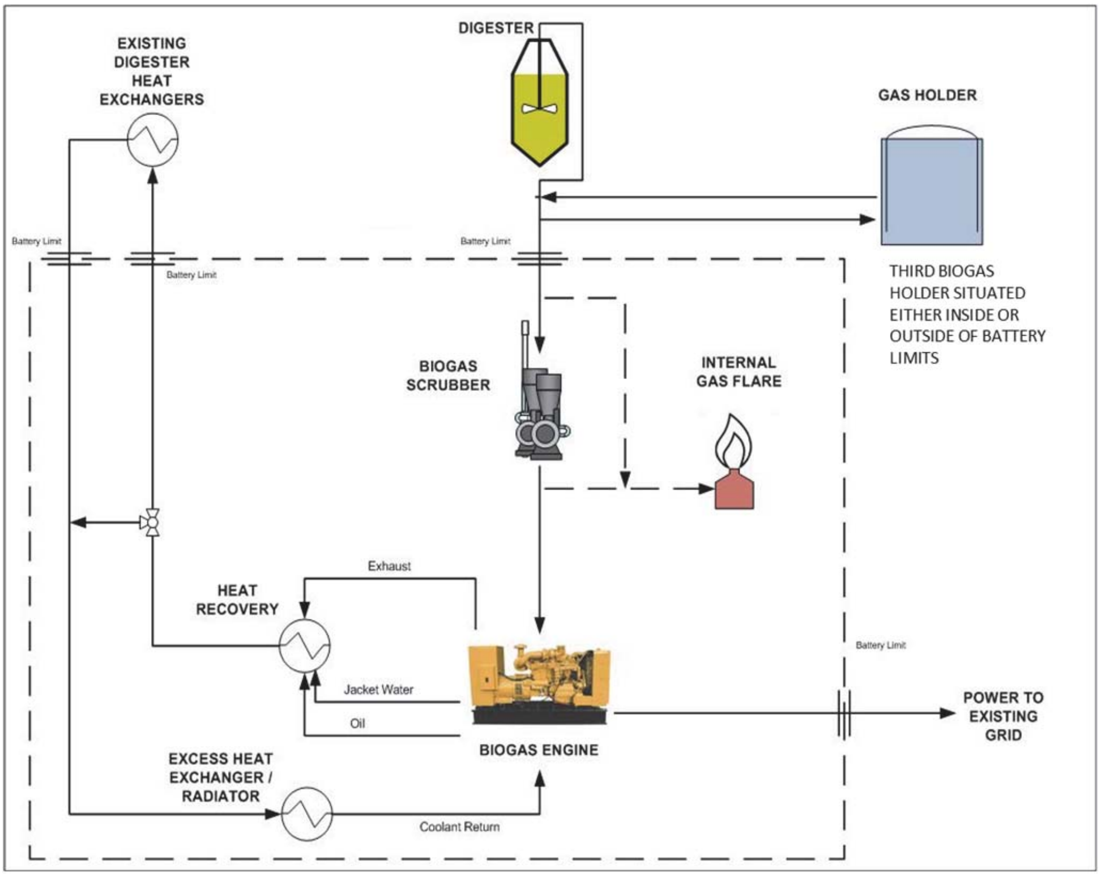

Figure 19: The battery limits applicable to a supply where the WSP is responsible for gas supply to the CHP plant (ring-fenced CHP supply only)

The following points also need to be identified:

- Who is responsible for the tying into existing infrastructure
- Who monitors and maintains specified monitoring equipment located outside the battery limits
- Where are the readings taken and how is power produced and performance monitored
- What are the operational limits and who has access to site and for what reasons

CHP is a sophisticated technology and require specialist staff who may not always be readily available within municipalities. In the case of the NWWTW, the operation and maintenance services was contracted to a specialist supplier in order to reduce the operational risk of the utility.

The remuneration for the operation was carefully considered and these considerations should include:

- Fixed cost [Rand/month] – based on availability and related to staff, security, insurance, overheads, etc.
- Variable cost [R/kWh] – based on running hours and related to maintenance and running costs
- How and where to measure the power generated and how to monitor fixed costs
- Penalties for poor performance and incentive for good performance.

NWWTW CHP plant was commissioned in November 2012 and has since been in operation with a >95% availability.

Installation of the Driefontein WWTW CHP plant was completed at the end of 2014 and is awaiting provision of biogas for commissioning.

The two Johannesburg wastewater treatment plants have a very high level of control and automation and have the option to operate in both 'island' and 'parallel' mode, however, these functions add to the capital costs of the plant.

A typical CHP plant should cost in the order of R25-R30 million per Megawatt installed for a base-level installation, provided the basic digestion and gas holding infrastructure is in place. There is also a limit to the viable recovery costs dependent on the size of works. Johannesburg Water calculated that works of <15 Ml/d may not be economically viable for a CHP installation and should only be considered in cases where power is scarce or where there are alternative drivers for such projects.

Johannesburg Water intends rolling out CHP installations to all its works in future with the below table providing the anticipated power generation ability of each works.

Table 16: Anticipated energy generation for each of the Johannesburg WWTW

Works	Capacity ML / d	Required MWe	Generated MWe
Northern	450	6.75	3.75
Olifantsvlei	250	3.75	2.10
Bushkoppie	250	3.75	2.10
Goudkoppies	135	2.03	1.13
Driefontein	60	0.90	0.50
Total	1145	17.18	9.58

Recommendation:
Consideration should be given to the implementation of CHP plants in all works around South Africa with functional anaerobic digestion comprising of a viable size.
Action:
The mapping of CHP at existing AD sites in South Africa is done in Chapter 5 of this Report.

3.4.5 Struvite recovery plant

Relatively high concentrations of orthophosphate are present in sludge wasted from a BNR treatment process that incorporates biological phosphorous removal. The digested sludge currently goes for sludge dewatering on belt filter presses and then to the sludge drying beds. The wash water and filtrate from the dewatering process which has a high phosphate concentration is dosed with lime to chemically precipitate the phosphate before being recycled back to the head of works.

Johannesburg Water has considered a Struvite Removal plant at Driefontein WWTW, still to be implemented, with the main objectives being:

- to remove orthophosphate from digested sludge and from the mass balance of the entire wastewater treatment works
- to reduce the ammonia from digested sludge and from the mass balance of the entire wastewater treatment works
- to prevent struvite crystal formation in pipes and equipment causing blockages and failures
- improvement of dewaterability of the sludge and reduction in polymer consumption

Johannesburg Water therefore selected a process for removal of struvite from the digested sludge (as opposed to from the filtrate) in order to have the benefit of the last three (3) objectives listed above.

The installation of a Struvite Removal Plant from Sludge system was proposed at Driefontein WWTW. The process is a facilitated struvite ($MgNH_4PO_4{\cdot}6H_2O$) precipitation process, where the ideal conditions for struvite formation are created in a proprietary reactor by means of the following process steps:

- Increasing of pH to between 7.8 and 8.2 by means of CO_2 stripping using aeration
- Introduction of $MgCl_2$ or MgO
- Mixing and retention for struvite crystal formation
- Sedimentation of struvite crystals
- Struvite crystals extraction and washing

Some specifications of the process include:

- Over 85% reduction of orthophosphates in the sludge
- Reduction of struvite build-up in pipes and equipment downstream of the AIRPREX plant, thereby eliminating struvite build-up in pipes which cause blockages and costly maintenance
- Improved dewatering of the digested sludge containing a lower residual phosphate content.

The Struvite Removal system for Driefontein WWTW will comprises of the following main components:

Struvite Removal-Reactor:

The reactor consists of a conical steel tank for struvite precipitation approximately 200 m^3 in volume and 15 meters high. The tank has a struvite discharge and a struvite washing system at the bottom.

The tank is coated with a special coating to minimise scaling and the precipitation and adhesion of struvite inside the tank.

The tank is equipped with an aeration system and is supported by a steel structure.

Aeration System:

The sludge inside the reactor is aerated to remove CO_2 from the sludge.

A rotary lobe type blower is provided for aeration. The blower has an acoustic enclosure to reduce noise levels.

Struvite Sludge discharge and Struvite Washer:

The struvite sludge discharge and struvite washer are connected to the *AirPrex®* struvite reactor. The discharge unit consists of an electric actuated valve, a discharge pump and a struvite washer.

The struvite washer is a classifier, which allows sedimentation to occur. It has a screw conveyor for removal of solids. Air and water flushing is connected to the struvite washer to wash the struvite crystals before discharge.

Magnesium Dosing Station:

The addition of magnesium salt to the digested sludge leads to the precipitation of struvite crystals.

A 30 m^3 polyethylene tank is supplied for the storage of dilute Magnesium chloride ($MgCl_2$).

Two membrane type dosing pumps are provided. Flow measurement will also be provided at the dosing station.

Electrical control panel:

The entire struvite system shall be controlled from a single motor control panel. The panel will be equipped with variable speed or frequency drives for the following units:

- The blowers
- The two magnesium dosing pumps and
- The struvite discharge pump.

The phosphate and ammonia reduction in the sludge can be determined from the AIRPREX® supplier as well as the amount of $MgCl_2$ to be dosed and the amount of struvite that will be produced.

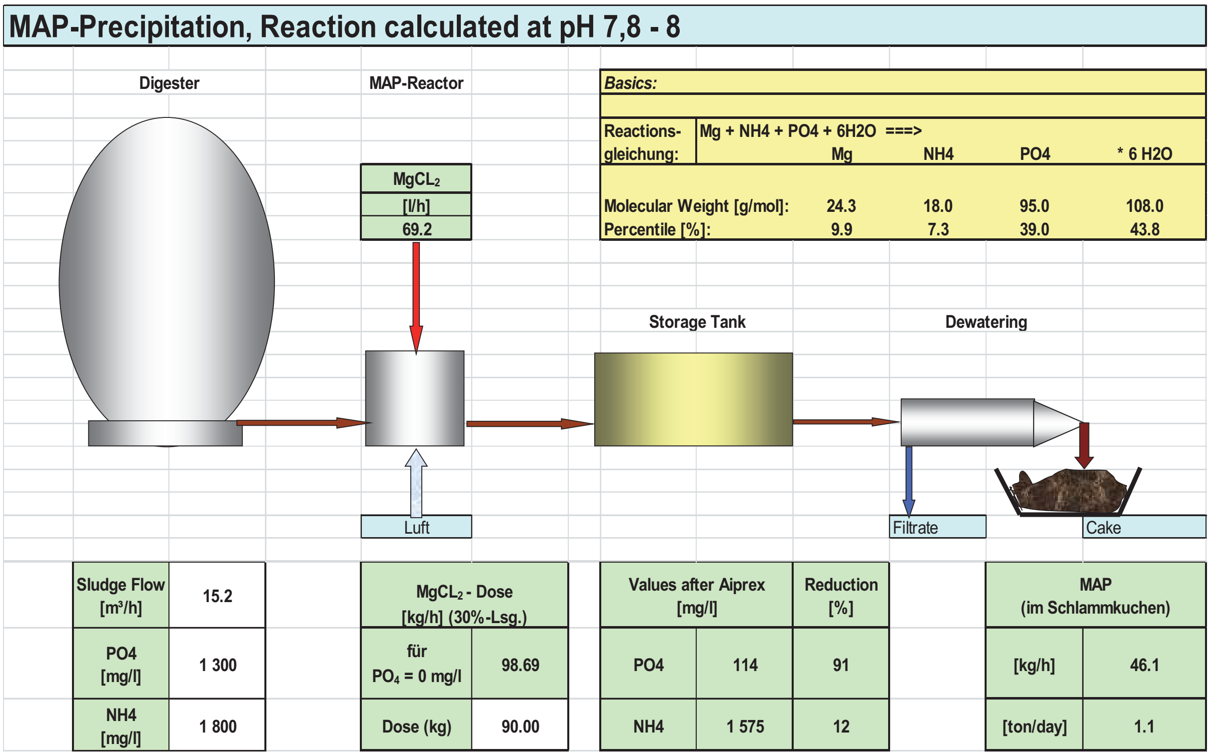

Figure 20: Flow process and sizing of the proposed Driefontein Struvite Removal Plant

The system is expected to produce over 1 ton of struvite a day, which could also be an income source for the fertiliser industry. Johannesburg Water's approach is not to sell struvite commercially, but to utilise it in-house for its nutrient (N and P) value.

3.4.6 Belt filter press

Sludge leaves the digesters at around 3% DS content and needs to be dewatered in order to make handling and disposal feasible. The following methods of sludge dewatering are most commonly used throughout the world:

- Belt Filter Presses
- Filter Plate Presses
- Centrifuges

Johannesburg Water has standardised on the use of Belt Presses for their sludge dewatering. Both other processes generally produce a drier sludge cake but are not preferred for the following reasons:

- The Filter Plate Presses work on a 'batch' process, which is not desirable as a continuous process is preferred;
- Centrifuges become problematic due to the high amount of grit present in Johannesburg Water's sludge, which creates a large amount of wear for the centrifuges;

- Belt presses have a lower cationic polymer dosage rate (4 kg/dry ton) and ease of operation and maintenance.

Johannesburg Water's design specifications for belt filter presses prescribe that the equipment shall be designed for continuous operation (365 days per year and 24 hours per day), a minimum of a 12 year life, minimum maintenance and operation costs and ease of maintenance and parts inter-changeability.

Specific performance requirement of the belt filter press equipment include:

- The sludge feed stream will have a solid content between 2 per cent and 6 per cent by mass. Sludge will be fed to the press at a rate of between 650 and 900 kg dry solids per hour.
- A minimum Dry solids content of 18 per cent for the digested sludge is required to be achieved by the presses.
- Flocculent dosing must not exceed 4.5 kg per ton of dry solids.
- The belt filter press unit shall have an effective belt width of 2.0 m.
- To operate without undue vibration and excessive noise. Maximum of 84dBA measured at 1 metre from operating equipment.
- Filtrate and wash water effluent quality shall be that the suspended solids (SS) content does not exceed 300 mg/l and 1 000 mg/l, respectively.
- The belt press design shall incorporate a large gravity dewatering section to pre-thicken the sludge prior to entering the press stages of the dewatering section.
- The pressure dewatering section shall comprise no less than 10 dewatering pressure rollers of adequate size (minimum diameter of the pressure rollers shall be 215 mm). The pressure rollers shall be designed using a minimum design load of 10 Newton per linear millimetre with a maximum deflection of 1 mm per metre of roller length.
- The press shall be a robust unit incorporating stainless steel rollers, filtrate collection trays and sump, as well as a sludge inlet distribution and flocculation system with a stainless steel sludge distribution chute.
- The press unit offered shall be totally enclosed on all sides (including the gravity filtration section), and suitable for operation under a negative pressure.

Johannesburg Water has placed significant value on the competency, reference and reliability of the equipment supplier.

3.4.7 Solar Drying Beds

Dewatered sludge cake which is properly digested and stabilised comes off the belt presses at around 18%DS content. This sludge needs to be further dried and managed in order to achieve a suitably disposable biosolids in terms of the Sludge Disposal Guidelines (WRC, 2006 & 2009).

Johannesburg Water further dries their sludge on open-air solar drying beds. All the Johannesburg Water works have solar drying beds which are large open-air concrete slabs on which the dewatered sludge is spread and allowed to dry in the wind and the sun.

Figure 21: Open air solar drying at the NWWTW

Johannesburg has a dry climate with low rainfall, which greatly benefits the solar drying process.

The sludge does need to be turned and aerated on a regular basis and this is done by sludge turners/aerators which are mechanically driven plant with a large rotating drum in front which lifts, aerates and spreads the sludge on the drying beds.

Solar sludge drying rate is dependent on the season and atmospheric conditions however a sludge dryness from 18% DS to >60% DS could be achieved in 3 to 4 weeks.

Figure 22: Sludge DS of 70% achieved at NWWTW

Figure 23: Recent acquisition of tractor-mounted sludge turners with lower capital costs, fuel consumption, local service backup and parts availability.

3.4.8 Sludge composting

Sludge dried to the required total solids concentration allows for the sludge to be heaped to approximately 3 m without the heap slumping or forming of anaerobic clods. Particle sizes range from 5-50 mm which provides adequate structure and balance between porosity (air space within the composting mass) and texture (available surface area for aerobic microbial activity). Passive air movement is achieved throughout the heap. At 60%DS, rapid uncontrolled heating of the heap to >60^{o}C is typically found which causes loss of moisture and slowing the microbial-based composting process.

Under the required conditions, temperature in the heaps rise rapidly to 40-50^{o}C. Upon reaching an average temperature of >60°C, the heaps are completely broken down and rebuilt using a front end loader. Anaerobic sludge clods are broken up using the mechanical turner. After rebuilding, temperatures rise to the required average temperature and the process is repeated. The composting period is complete once the heap has complied with the Option 5 stability requirements of the Sludge Guidelines, i.e. minimum temperature of 40^{0}C with a daily average of 45^{0}C or higher for 14 days. Samples are taken for laboratory analysis and heaps that comply with the Sludge Guideline requirements for microbiological class 1 are screened through a 15 mm mesh before curing. Satisfactory stabilisation of the final biosolids product is achieved when the %VS reached <0.45 kg/kg DS after curing.

Figure 24: Composting of sludge without a bulking agent.

The control of temperature and moisture content, at between 45% DS (start) and 65% DS (end), is essential for the success of the composting process. The final curing stage ensures that the final product does not cause either an odour or vector attraction problem. With C:N ratios below 20:1, the available carbon is fully utilised without stabilising all of the nitrogen. The excess nitrogen is then lost to the atmosphere as ammonia or nitrous oxide.

The windrows on the drying beds are formed parallel with the prevailing wind direction to ensure that the entire length of the windrow is exposed to the evaporative drying effect of the wind. The slope of the drying bed for drainage of surface water when it rains is in the same direction to limit ponding between windrows. The contaminated run off gravitates to emergency dams which recycles back to the inlet works.

3.4.9 Compost offset

The vast experience by Johannesburg Water in terms of sludge composting using a bulking agent, disposal of dewatered sludge cake on private farmland, and solar drying with composting, allows for a comparison of various operational costs of each operation. The following operational cost comparison, serve as indicative costing against which offsets can be derived:

Table 17: Cost to treat and transport sludge during 2009 (actual) and 2015 (calculated):

Sludge handling option	**R/ton sludge treated or transported: actual 2009 cost**	**R/ton sludge treated or transported: 2015 cost calculated***
Composting using a bulking agent	R560 (treated)	R988
Remote farm disposal	R360 (transported)	R634
Solar drying/composting + land disposal	R270 (treated)	R475

**escalated at 10% per year*

Compost produced at Northern Works is registered with the Department of Agriculture as a biosolids/fertilizer and sold to a private agent through the normal public tender procedure. This offsetting enables some of the production costs to be recovered. The operating costs for composting using a bulking agent, includes costs recovered by the sale of the compost to the private agent.

CHAPTER 4: FULL-SCALE PLANT PERFORMANCE ANALYSIS

Operational data from mainly the Johannesburg Northern plant, but also Olifantsvlei WWTW, were collected for each process step involved in producing, thickening, conditioning, treating and digesting sludge related to the biogas production for the Combined Heat and Power (CHP). Performance was analysed for each process unit by considering the sludge quality input to the process unit, the outflow from the unit and the expected design performance of each particular process unit (as described under Chapters 2 and 3).

The data was used to make conclusions in terms of the following study objectives:

- evaluate the performance of sludge digestion, biogas production and electrical power generation in a full-scale CHP plant;
- assess the recovery of struvite crystals formed after the digestion process for use as a slow release fertiliser and prevent potential blockages in downstream digested sludge treatment plant and equipment;
- share operational good practice to prevent high concentrations of Nitrogen and Phosphorus from dewatered sludge filtrate being recycled back to the bioreactors, causing effluent non-compliance;
- illustrate the value of thickening sludge prior to the digestion phase, where higher volatile solids loading rates are used to ensure sufficient digester capacity for sludge treatment; and
- illustrate how sludge stabilisation such as solar drying and composting, as well as final screening of digested sludge, produces an A1a class final biosolids product which complies with the 2006 WRC Sludge Guidelines.

4.1 JOHANNESBURG NORTH WASTEWATER TREATMENT PLANT

Each of the operational units 3, 4 and 5 on the Johannesburg Northern plant are served by a central head of works for screening and degritting. The main treatment stream for each of the units consist of the following basic process configuration:

- Primary settling tanks.
  - Primary sludge to fermenters.
  - Elutriate/supernatant to activated sludge reactors.
  - Elutriated primary sludge thickened before transfer to anaerobic digesters.
- Balancing tanks.
- Biological nutrient removal activated sludge reactors.
- Activated sludge reactor; controlled on mixed liquor suspended solids (MLSS) concentration.
  - Waste activated sludge (WAS) is routed to the waste sludge gravity thickeners.
  - WAS is thickened to a target thickness of 3% solids.
  - Thickened WAS from unit 3 is routed to a central WAS sludge sump, while unit 4 and 5 WAS is routed to the RAW sludge sump where it is mixed with fermented primary sludge before it is pumped directly to the anaerobic digesters.
- Clarifiers with return activated sludge to the reactor.
- Disinfection with chlorine and retention in a chlorine contact tank.

Figure 25: Layout of the Johannesburg Northern Works

WAS collected in the WAS sump is pumped through two electro-kinetic disintegrator units at a combined rate of 30 l/s in order to improve biodegradability and biogas production. Disintegrated WAS is transferred to the raw sludge sump from where it is mixed with fermented primary sludge as well as other WAS streams that bypass the disintegration step. From this sump, sludge is pumped to four heated and mixed anaerobic digesters. Digested sludge is returned to the dewatering sludge sump from where it is routed to the belt filter presses.

During the investigated period the average load on Northern Works was estimated as:

- Average flow 395 Ml/d
- Average COD 450 mg/l
- Average Suspended Solids 200 mg/l

This loading is theoretically capable of producing sufficient biogas to generate electrical power in the order of 1 200 kWe and thermal power in the order of 1 325 kWt if all process steps are optimised. The average electrical power generated over this period was however only 201 kWe (electrical) and thermal power was 222 kWt. It is estimated that heating power of approximately 400 to 900 kWt is required to keep the anaerobic digester heat maintained in the mesophilic range, depending on operating conditions. This resulted in the anaerobic digesters operating at temperatures below the mesophilic range with reduced efficiency.

4.1.1 Performance Analysis of Sludge Thickening

Northern Works units 3 to 5 make extensive use of fermenters for the dual purpose of VFA generation and primary sludge thickening. The fermenters receive primary sludge from the primary settling tanks and wash water for the elutriation of VFA's from the fermenting sludge. The VFA rich wastewater is returned to the biological nutrient removal reactor (BNR) while the thickened sludge is transferred to the anaerobic digesters for stabilisation.

WAS is discharged directly from the BNR at reactor MLSS concentration in order to achieve and maintain the required reactor operating MLSS level. This WAS stream, typically with suspended solids concentrations in the range 3 000 to 4 500 mg/l, is then thickened in gravity thickeners before anaerobic digestion or dewatering.

Data with regard to flow, suspended solids, solids content, etc. in the feed, supernatant or the thickened underflow of the fermenters and WAS gravity thickeners were not available for analysis. However, because there are no process steps between the fermenters, the WAS gravity thickeners and the anaerobic digesters that impact the solids content, it can be concluded that the combined thickened sludge 50%-tile solid content is 3.4% (as per digester feed sludge in paragraph 4.2.3 below), ranging from 2.2% to 5.1% for 80% of the time while ranging between the extremes of 1.2% up to 7.5%. It would be expected that thickened WAS sludge would be responsible for the solids concentrations at the bottom end of this range while the thickened primary sludge would fit into the upper side of the range.

Design guidelines for gravity thickeners predict a thickened solids concentration range of 4% to 10% with a typical value of 6% for primary sludge and a thickened solids concentration range of 2% to 6% with a typical value of 4% for combined primary and waste activated sludge.

Olifantsvlei also utilise gravity thickeners for thickening WAS before digestion. A recent ten day evaluation of the Olifantsvlei gravity thickener performance confirmed that an average of 2.3% TS with a 50%-tile of 2.5% TS could be achieved with regard to the thickened underflow solids concentration.

The performance of sludge thickeners and the maintenance of high solids concentration in the thickened sludge underflow is to a large extent related to the effective management of the underflow extraction and as such deserves effort to optimise sludge solids concentration. A low frequency, ad hoc, manual extraction approach will give poorer results than a closely monitored more frequent automated underflow extraction approach.

4.1.2 Performance Analysis of Sludge Pre-Conditioning

One of the first cell lysis units used in South Africa was installed at Northern WWTW in order to evaluate the technology and assess the impact on sludge biodegradability and claimed improved biogas production during anaerobic digestion. Two parallel disintegrator units, based on electro-kinetic technology, were installed with a combined capacity of approximately 1 300 m^3/d, consuming a total input power of only 280 Watt. With this installed capacity the two units should be capable to handle all WAS sludge produced on Northern Works. At the time of the assessment only unit 3 WAS could be passed through the two units due to the configuration of existing infrastructure. It is estimated that unit 3 WAS comprises approximately 23% of the primary and secondary solids that are anaerobically digested. With an expected 10%-20% increase in gas production as per equipment supplier, the effect on the total gas production from the final sludge mixture would be quite diluted, making it very unlikely that any improvement in gas production could be confirmed by monitoring due to the insignificant and diluted impact. The cell lysis units were not operating at the time and no historical monitoring of the disintegration efficiency was done to date.

No information regarding actual experienced efficiency for the Northern Works could therefore be obtained for this report. However, laboratory scale digestion of ultrasound and electro-kinetic disintegrated sludge over ten-day digestion periods indicate 13.6% and 18.1% higher specific biogas yield respectively (*Jerke, 2013*). Full-scale testing at the Leipzig Rosental plant in Germany does not conclusively substantiate a 12% increase in gas production after conditioning of the feed sludge (68% primary sludge and 32% WAS mixture) with an electro-kinetic cell lysis unit (*Jerke, 2013*).

Marketing brochures of the EPS Group quote an improvement of 20% in biogas production to enhance their CHP plant output following electro-kinetic disintegration of feed sludge at their Dundalk and Drogheda STW's.

4.1.3 Performance Analysis of Anaerobic Digestion

Northern Works have four 2 000 m^3 heated and mixed anaerobic digesters for the digestion of sludge generated by the plant. Fermented primary sludge is thickened and collected in a central sludge sump from where it is pumped to the digesters. Unit 4 and 5 thickened WAS sludge bypasses these two sumps and is routed directly to the dewatering feed sump. Unit 3 WAS is collected in a WAS sump with a facility to pass sludge through the electro-kinetic sludge disintegrator before discharging conditioned sludge into the raw sludge sump, from where it is pumped to the digesters together with fermented primary sludge from units 3, 4 and 5.

It is reported that during the twelve month period 2014 to 2015, the average daily volume of sludge transferred to the digesters is 503 m^3/d. The composition of the composite feed sludge into the anaerobic digesters and the composition of the output sludge from three respective digesters are summarised in Tables 18 and 19.

Table 18: Composition of feed sludge to anaerobic digesters taken over period 2014-2015:

Constituent	Min	Max	Ave	Standard Deviation (STDEV.S)
Ammonia as N (mg/l)	43	1 000	252	144.6
COD (mg/l)	5 000	71 000	30 740	14 508
pH (mg/l)	4.8	7.0	5.9	0.67
Phosphate as P (mg/l)	39	310	134	85.4
Moisture (as %)	92	98	96	1.67
Volatile Solids (as %)	72	85	79.3	0.02
Total Solids (as %)	1.7	7.3	3.66	0.03

Table 19: Composition of sludge outflow from the anaerobic digesters taken over period 2014-2015:

	AD-3				AD-4				AD-5			
Constituent	Min	Max	Ave	STDEV	Min	Max	Ave	STDEV	Min	Max	Ave	STDEV
Ammonia as N (mg/l)	280	1 900	649	279	190	1 800	643	251	290	1 300	725	334
COD (mg/l)	1 400	35 000	10 166	9 925	1 200	34 000	16 493	7 888	3 300	37 000	17 990	7 292
pH (mg/l)	6.8	7.8	7.0	0.3	6.4	7.8	7.3	0.3	5.8	7.8	7.0	0.3
Phosphate as P (mg/l)	76	390	148	27	50	420	151	75	33	380	181	103
Moisture (as %)	98	99	98	0.6	97	99	98	0.4	97	99	98	0.4

The percentage solids in the digester feed and digestate is reflected in the cumulative probability graph below.

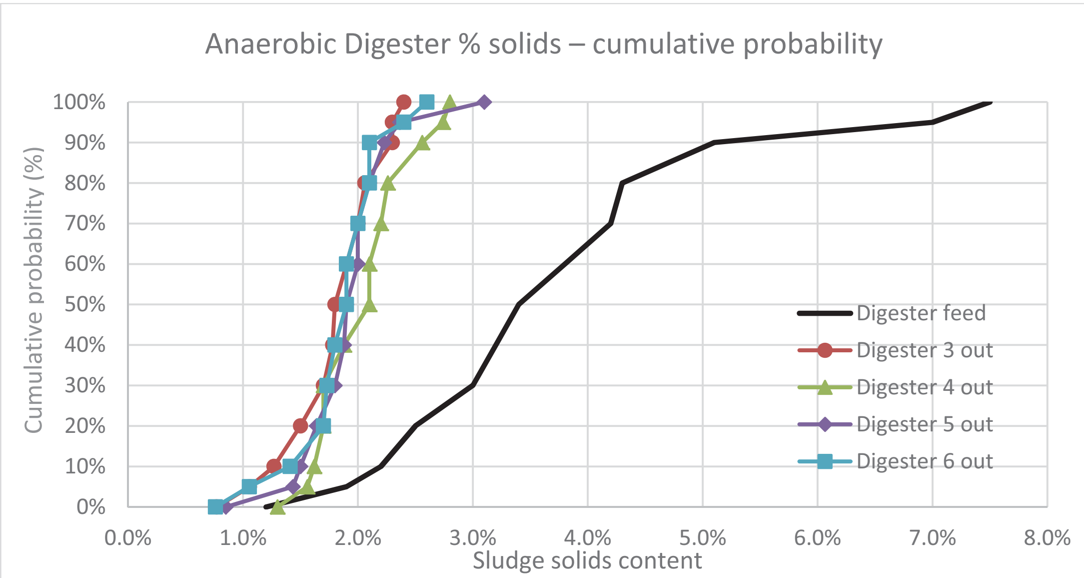

Figure 26: Cumulative probability graph for the anaerobic digester's sludge solids content

From the probability plot given in Figure 26 above, it is clear that the 50%-tile feed suspended solids is 3.4% while the 50%-tile digested solids content varies between 1.8% and 2.1% for the four digesters. At the reported sludge volume of 503 m^3/d this translates into 17.1 tDS/d into the digesters and approximately 10.1 tDS/d digested sludge, which is on the low side for a plant of this size. This observation could possibly be due to the fact that an unknown volume of sludge bypasses digestion and is routed directly to dewatering.

Using the 50%-tile values for suspended solids feed to the anaerobic digester of 3.4% as well as the digestate suspended solids of 1.8% to 2.1%, the solids reduction calculated ranges from 48% to 52%, which translates into a volatile solids reduction of 49% to 56%. These figures contradict the volatile solids reduction estimated at between 28% to 33% when based on volatile solids in (average of 79%) and volatile solids out (averaging between 71% and 73%) as reflected in figure 27. Considering the energy produced by the CHP units, the lower volatile destruction estimates seem to be the more accurate estimate.

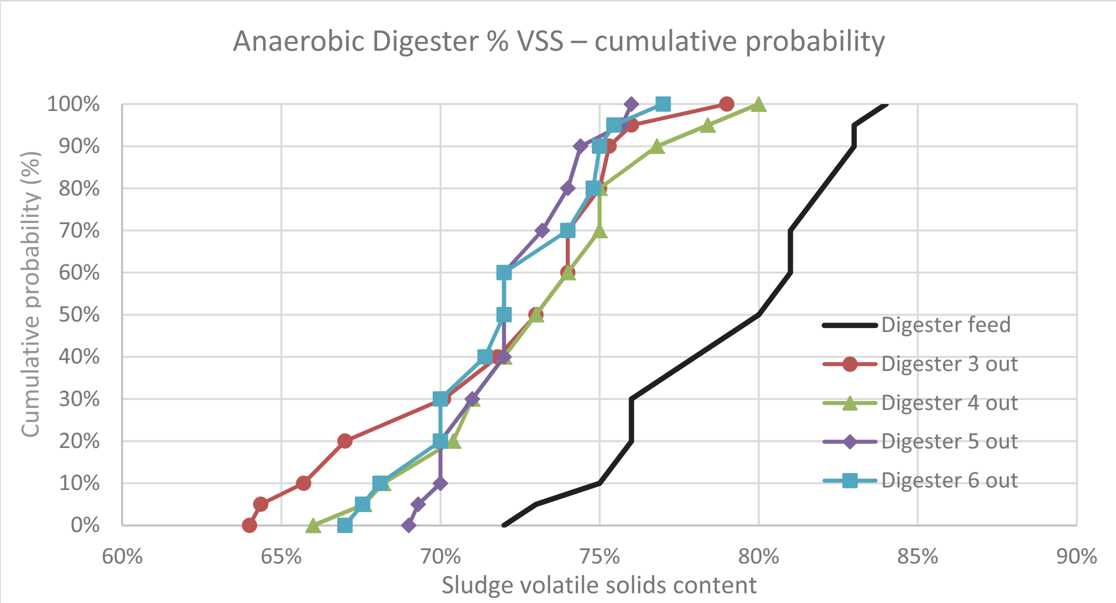

Figure 27: Cumulative probability graph for the anaerobic digester's %VSS

In order to improve performance and fully utilise this renewable energy source, the following design and operational aspects should be closely controlled:

- Increasing the feed sludge solids content by improved upstream sludge thickener control and desludging procedures. Feeding low solids sludge to the digester and thereby reducing the hydraulic retention time, could result in precipitous reduction in biogas production due to the impact of shorter retention. Feeding higher solids sludge also reduces the heating energy requirement and enhances digester temperature control.
- Managing the feeding cycle to ensure feed is as close to uniform/constant as possible.
- Optimise mixing intervals to ensure maximum biogas production.
- Digester temperature control should ensure minimal short term temperature variation. Allowing the digester temperature to fluctuate by more than one degree Celsius over a day could result in significant reduction in biogas production, as will operating the digester below the mesophilic temperature range. However, maintaining a lower digester temperature in order to keep the temperature constant is preferable to operating the digester at a higher temperature with more temperature fluctuation.

The improvement in biogas production because of diligent management of any of the aspects listed above has greater potential for improved biogas production than the expected improvement from cell lysis. It would therefore make sense to concentrate on optimisation of digester operation before embarking on new and expensive cell disintegration technology.

4.1.4 Performance Analysis of Struvite Control and Precipitation

The ammonia (as N) and phosphate (as P) concentrations into and out of the Northern Works anaerobic digesters are monitored and recorded. The ammonia nitrogen and phosphate phosphorus concentrations are reflected in the cumulative probability distribution plots below for a twelve month period 2014/2015:

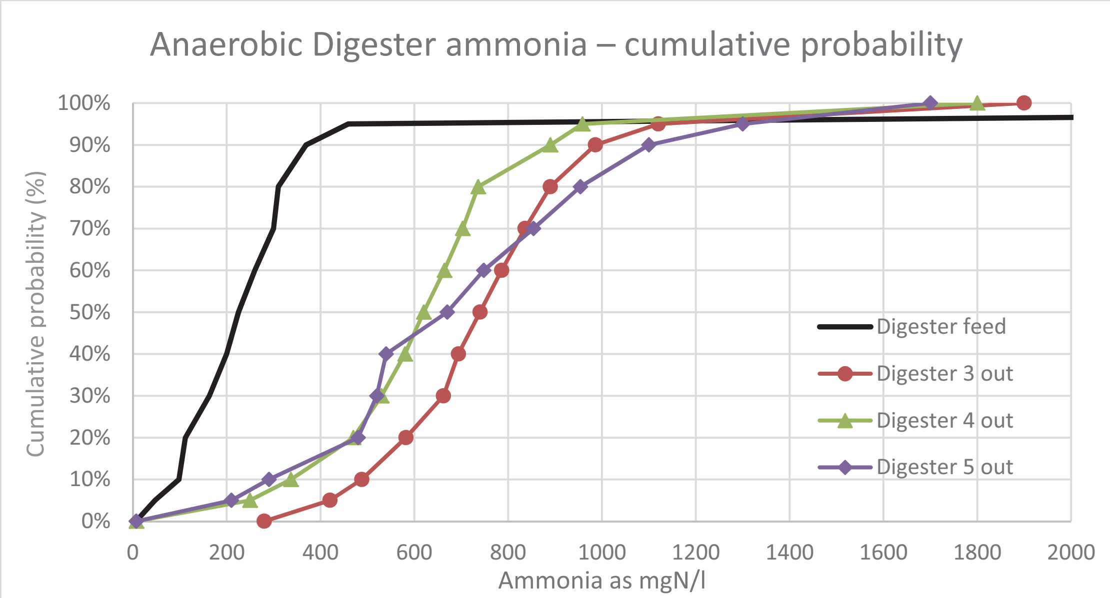

Figure 28: Cumulative probability graph for the anaerobic digester's ammonia concentration

The ammonia concentration enters the digesters at a 50%-tile value of 225 mgN/l while the digester discharge varies between 7 and 1 900 mgN/l with a 50%-tile value from 620 to 740 mgN/l among the three digesters reflected in Figure 28. This represents a nitrogen mass of between 312 to 372 kgN/d (could increase by a factor of three at peak values) which is effectively returned to the main treatment stream for treatment. This nitrogen load implies an estimated increase of 1 mgN/l mixed into the influent raw flow, which is insignificant.

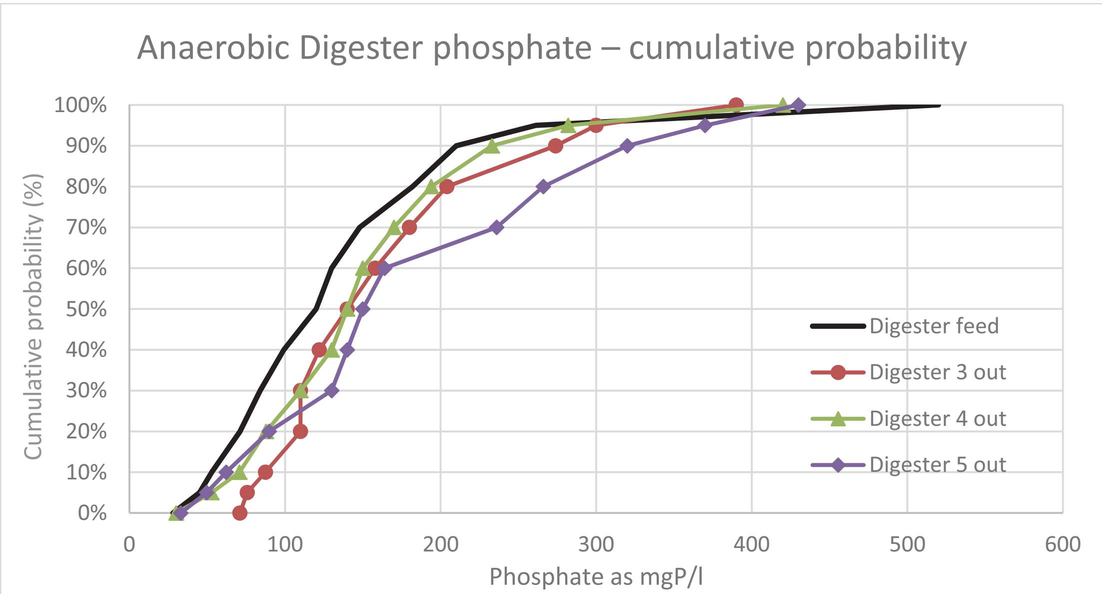

Figure 29: Cumulative probability graph for the anaerobic digester's phosphate concentration

The phosphate concentrations in the feed is only slightly less than the phosphate concentrations in the digester discharge. The 50%-tile phosphate concentration in the digester feed is 120 mgP/l while the 50%-tile digester discharge concentration increases slightly to between 140 and 150 mgP/l among the different digesters reflected in Figure 29.

In order to explain this low phosphate value, it may be concluded that most of the phosphorus release took place before the sludge enters the anaerobic digesters. Due to the waste activated sludge retention in the gravity thickeners and the mixing of primary and waste activated sludge prior to pumping the combined sludge to the anaerobic digesters, it is expected that most of the phosphorus accumulated in the sludge wasted from the enhanced biological phosphorus removal (EBPR) process, is released before the sludge is pumped to the anaerobic digesters. The WAS gravity thickeners are considered the most likely step where released phosphates are lost, but requires more data to confirm.

Alternatively phosphorus could be bound in insoluble chemical species typically resulting from ferric chloride precipitation from the treated effluent. This is reportedly not the case and the majority of phosphorus is biologically removed. More detailed process sampling and analysis data is required to explain the observed discrepancies.

The above observation also means that any additional pre-thickening steps such as a gravity belt thickener, would remove an additional proportional fraction (estimated at approximately 60% for this case study) of the phosphates from the thickened sludge via the filtrate stream before introduction to the digesters. The total ortho-phosphate mass in the recorded sludge stream is estimated at 73 kgP/d (but could increase by a factor of up to four at peak values). This observed ortho-phosphate concentration/mass is considered to be extremely low for a plant of this size with EBPR. Although it does not explain the low phosphate content, it should however be noted that this phosphorus mass relates to EBPR sludge of unit 3 only (because unit 4 and 5 WAS bypasses the anaerobic digesters and is routed directly to dewatering). It is estimated that unit 3 WAS represents approximately 32% of the EBPR sludge produced at this plant.

Risk: Effective nutrient recovery could be negatively impacted due to unexpected premature nutrient release and/or side-stream losses. Risk mitigation: Install nutrient recovery system at process position ensuring maximum available concentrations of relevant nutrients.

Based on the digestate quality reported above, the phosphate concentration would be limiting with regard to struvite precipitation (Mg dose is adjusted to suit) leaving a residual ammonia concentration estimated at 580 mgN/l while removing all the phosphate. Theoretically, approximately 590 kg of MAP can be produced based on the reported phosphate and ammonia concentrations in the digestate.

4.1.5 Performance Analysis of Sludge Dewatering

Digested sludge from the anaerobic digesters is collected in the dewatering sump together with waste activated sludge from units 4 and 5 that bypass the anaerobic digesters. From this sump, sludge is pumped to the belt filter press (BFP) dewatering facility. Combined wash water and filtrate from the BFPs are passed through gravity thickeners for the separation of remaining solids which is returned to the dewatering sump. Supernatant from the gravity thickeners is returned to the unit 4 main treatment stream. Dewatered cake is either removed and beneficially disposed on land or dried and composted on site before disposed. Performance of the belt filter presses in terms of feed solids and cake solids are reflected on the cumulative probability given in Figure 30:

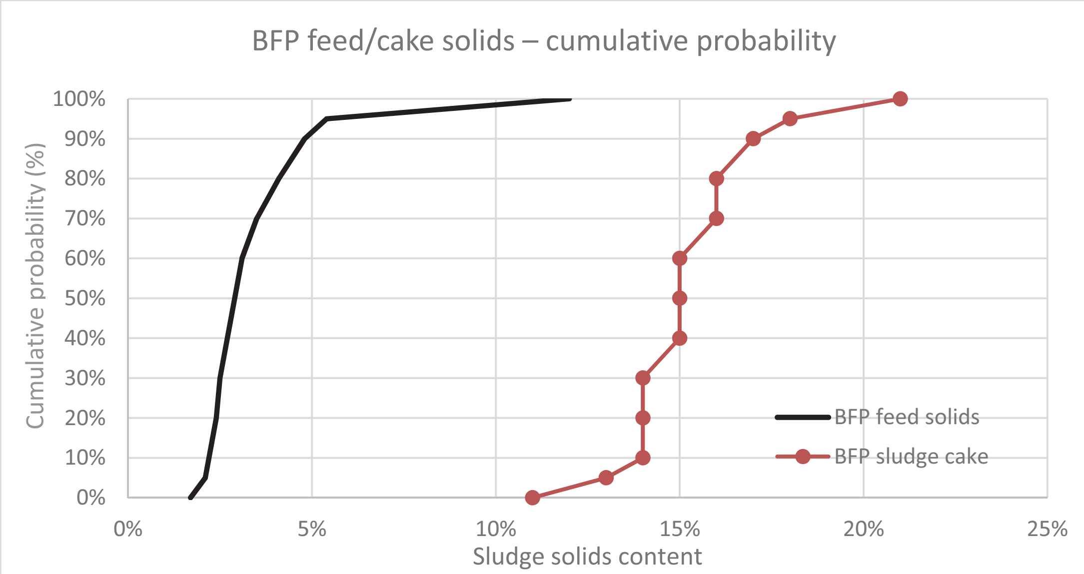

Figure 30: Cumulative probability graph for the BFC solids content

The combined digested primary and WAS sludge mixed with undigested WAS sludge is fed to the Belt Filter Presses at a solids content of between 2% and 12% with a 50%-tile solids content value of 3% dry solids. The solids content of the cake varies between 11% and 21% with a 50%-tile value of 15% dry solids. Polymer consumption and solids capture data are unfortunately not available. However, industry norms is in the order of 1-25 g polymer dosed per kg sludge and ≥95% solids capture (refer to Table 13).

At the Olifantsvlei plant digested sludge is dewatered to approximately 17% dry solids by belt filter press using an average cationic polymer dose of 3.7 kg per dry ton of sludge dewatered.

Northern Works dewatered cake is either dried on solar drying beds or trucked off site for beneficial land application. Because information on this solar drying and composting has been well evaluated and documented at the Olifantsvlei Plant and limited information is available with regard to Northern Works, the drying and composting of sludge cake at Olifantsvlei is presented as a case study.

Good Practice Note: Monitoring of Belt Pressed Cake (BPC)

- Monthly analysis of heavy metals on belt press cake, to include As, Cd, Cr, Cu, Pb, Hg, Ni and Zn
- N, P and K is monitored monthly on belt pressed cake (BPC)

Table 20: Heavy metal concentrations of the final biosolids product, as compared to the Sludge Guideline limits for Class A1a sludge:

Heavy metal constituent analysed	Pollutant Class a	Annual average in mg/kg (2013)	Annual average as % of limit (2013)	Annual average in mg/kg (2014)	Annual average as % of limit (2014)
Arsenic (As)	<40	6.9	17	7.4	18
Cadmium (Cd)	<40	<4.9	<12	<10	<25
Chromium (Cr)	<1 200	154	13	333	28
Copper (Cu)	<1 500	281	19	309	21
Lead (Pb)	<300	34	11	33	11
Mercury (Hg)	<15	0.8	5	0.6	4
Nickel (Ni)	<420	94	22	63	15
Zink (Zn)	<2 800	866	31	840	30
		in g/kg		**in g/kg**	
Nitrogen (N)		-	-	62	-
Phosphorus (P)		-	-	22	-
Potassium (K)		3.0	-	2.7	-

4.1.6 Performance Analysis of Sludge Drying and Composting

The Johannesburg Water sludge plan for the disposal of sludge, as implemented at Olifantsvlei, is based on solar drying and composting of biosolids. Anaerobically digested sludge is dewatered to approximately 17% solids before passing through the following process steps:

1. **Solar drying of the dewatered sludge to 45% to 55% solids on concrete beds:** The composting of dewatered sludge cake require that the cake is solar dried to a solids content of 45-55% in order to ensure the required porosity of the sludge is maintained during the composting process. Solar drying is achieved by:
   - Spreading dewatered cake on an uncovered concrete paved area to a maximum depth of approximately 400 mm. The application rate varies between 0.14 to 0.31 m^3/m^2 (25 to 71 $kgDS/m^2$) to achieve a drying time of between 19 and 34 days.
   - Daily turning of sludge cake, preferably by mechanical sludge turner, is essential in order to prevent crusting and achieve the reported drying cycle times.
   - Drier sludge cake from the BFP, i.e. solids content of >17% significantly reduces the required solar drying time to achieve the target solids content of 45% to 55%. Once this solid content is achieved, composting can proceed.

Good Practice Note: Monitoring of Biosolids

- 8 temperatures taken from each heap daily
- Averaging of 5 data points as per Options 5 stability requirements
- Monthly analysis of heavy metals on composted biosolids
- Composite sample of each heap upon 14 day temperature requirement
- Reporting of faecal coliforms in cfu/1 g
- N, P and K is monitored monthly on

2. **Composting and curing of the solar dried sludge without the addition of a bulking agent:** The Guidelines for the Utilisation and Disposal of Wastewater Sludge, Volume 5, state one of the options for the stability class 1 and vector attraction reduction as being "Option 5: Use aerobic processes at a temperature greater than 40°C (average temperatures 45°C) for 14 days or longer (e.g. during sludge composting)". Once the sludge is solar dried to 45-55% dry solids, the composting process can proceed as follows:

   - The achieved dry solids content allows sludge to be heaped into rows of approximately 3 m high without slumping, thus allowing natural air flow through the heap to maintain an aerobic process.
   - Dry solids content of more than 60% result in rapid uncontrolled heating to more than 60°C, rapid drying and inhibition of the composting process.
   - During the composting process the temperature rapidly increases to the required temperature of between 40°C and 50°C.
   - If the sludge reaches temperatures of 60°C the windrows should be restacked in order to prevent excessive temperatures.
   - It is essential that the dry solids content during the composting period is maintained between 45% (start) and 65% dry solids (end).
   - Once the required temperatures are maintained for the required fourteen day period, the composting process is complete and biosolids can be removed for curing.

Compost produced by following the procedure described above has been demonstrated to comply with the requirements of a class A1a product in terms of the 2006 Sludge Guidelines. Although the microbial class A and the stability class 1 as reflected above are the result of a controlled composting process, the pollutant class a is determined by industrial pollutants from industries in the plant catchment. The pollutant classification for each treatment plant should therefore be confirmed as part of the sludge classification exercise before selecting a sludge disposal route.

Final Biosolids Product Composition:

Table 21: A comparative table depicting the composition of the final biosolids product vs the standards contained in the Sludge Guidelines, specific to Class A1a biosolids

Microbiological compliance:

Constituent	Unit	Class A sludge	Final Product
F. coliforms	CFU/1 g dry	< 1 000 MPV 10 000	0 (80%) <1 000 (97%)
Helminth ova	Viable ova/1 g dry	< 0.25 MPV 1	0 (100%)

Stability compliance

Constituent	Unit	Class 1 sludge	Final Product
Total Kjeldahl Nitrogen as N	g/kg DS	-	38
Total Phosphorus as P	g/kg DS	-	45
Potassium as K	g/kg DS	-	4.3
Moisture	%	-	35
Total Solids	%	-	65
Volatile Solids	VS kg/TS kg	38% reduction in VS	0.44 (41% reduction)
pH		-	6.0

Pollutant compliance

Constituent analysed	Pollutant Class a Limits	Annual average as mg/kg (2013)	Annual average as % of limit (2013)	Annual average as mg/kg (2014)	Annual average as % of limit (2014)
Arsenic (As)*	<40	7.0	17	11.7	29
Cadmium (Cd)	<40	<4.8	<12	<10	<25
Chromium (Cr)	<1 200	172	14	293	24
Copper (Cu)	<1 500	317	21	378	25
Lead (Pb)	<300	36	12	43	14
Mercury (Hg)	<15	0.6	4	0.61	4
Nickel (Ni)	<420	122	29	89	21
Zink (Zn)	<2 800	1099	39	968	35
		in g/kg		**in g/kg**	
Nitrogen (N)		-		50	
Phosphorus (P)		-		20	
Potassium (K)		5.2		3.3	

** non-metal*

Figure 31: Layout of the windrows and composted sludge at Johannesburg sludge drying and composting plant

Towards the end of 2012, a 1 128 kWe CHP plant consisting of three 376 kWe containerised biogas fuelled generators were commissioned at Northern Works. The biogas produced by the four refurbished anaerobic digesters is supplied to the CHP plant via a 350 m^3 storage tank. Hydrogen sulphide is removed from the biogas by biological desulphurisation, the gas is dehumidified and is then passed through a carbon filter for the removal of siloxanes before it is utilised as fuel to drive the generators. Each of the CHP units consume approximately 170 m^3 of biogas per hour. A biogas production rate in the order of 12 240 m^3/d is therefore required to run the three CHP units at full generating power.

The average biogas production since CHP commissioning is in the order of 2 900 kl/d or 120 m^3/hr, only allowing one generator to run part of a day, resulting in an average power of 250 kWe. Biogas production during the last twelve months has dropped to 2 200 m^3/d or 92 m^3/hr, resulting in an average power of 201 kWe. This trend is depicted on the time-series graph given in Figure 31. Hydraulic retention in the anaerobic digesters is an important operating parameter with regard to biogas production as identified earlier. Based on recorded flows to the digesters for the data received, the hydraulic retention in the digesters for the applied volumes is plotted on the same graph. The correlation between the reduced hydraulic retention and the reduced electrical power is obvious.

From the graph it can be seen that:

- The solids concentration in the feed generally remains at the same level.
- The volume of sludge pumped to the digesters increase resulting in a reduced hydraulic retention.

This situation results in:

- ➢ The lower hydraulic retention leads to a poorer digester efficiency, lower solids destruction and lower biogas production.
- ➢ In turn the lower biogas production leads to less generated electrical and thermal power, which in this case results in a thermal supply that is unable to maintain the required mesophilic temperature range in the digester.
- ➢ The lower temperature has a negative knock-on effect on digester efficiency and biogas production.

➢ Such a situation as described above will have a significant impact on overall energy recovery efficiency.

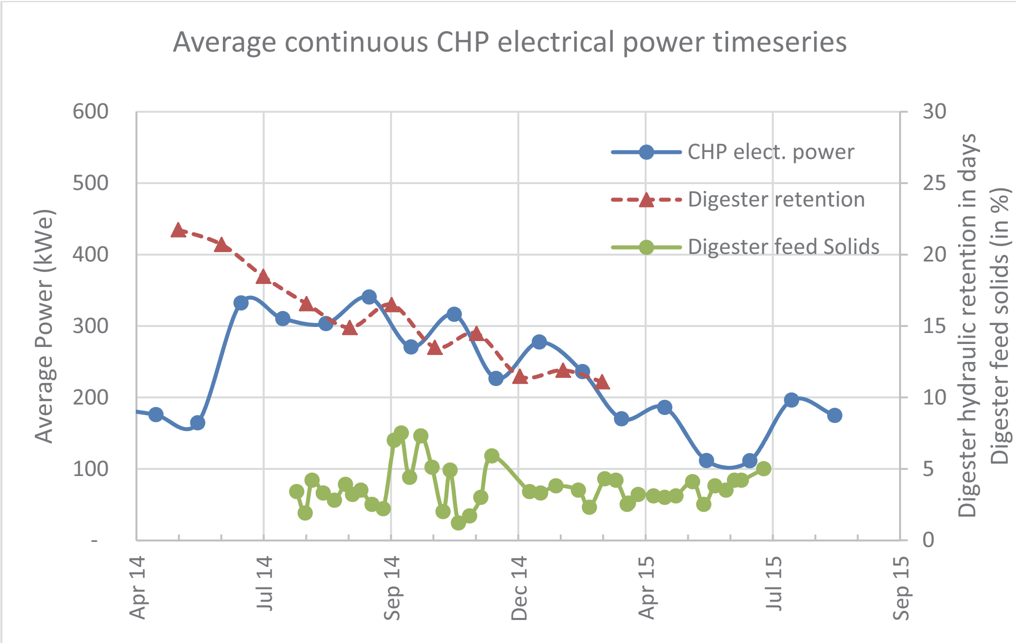

Figure 32: CHP electrical power over time as a function of HRT and % solids in digester feed

It is unfortunate that the digester performance or digestate quality does not have a compliance standard or guideline, as in the requirement for treated effluent. Diligent anaerobic digester process control is therefore rare. Furthermore, anaerobic digester operating skills are not at the required level, mainly due to the fact that anaerobic digestion fell into disfavour when energy costs where relatively low. It is only in recent years that anaerobic digestion has regained popularity, due to excessive electrical energy cost hikes in South Africa.

Risk: The lack of a 'compliance standard' or 'operational limit' for the digestate result in sub-optimal process control of anaerobic digesters
Risk mitigation: Establish operational limits and best practice for the operation of anaerobic digesters, and monitor performance on a continuous basis.

Management should promote and encourage effective anaerobic digestion process control by:

- Providing the infrastructure to enable and maintain effective process control with regard to pH, VFAs, alkalinity and temperature. Good process control should be a priority;
- Providing facilities to thicken feed sludge to optimal solids concentration is considered one of the most important sludge conditioning steps for effective anaerobic digestion and CHP systems;
- Providing feed sludge flow monitoring per digester to ensure appropriate feed distribution among digesters; and
- Biogas flow monitoring per digester to ensure a healthy process as well as to optimise digester feeding and mixing strategies while maximising biogas production. Deviation from a predetermined biogas flow target range should initiate process evaluation/correction.

The effective operation of the anaerobic process as described above will ensure the biggest return in terms of biogas and renewable energy production. Once all of the above is in place and maintained, it would then make sense to improve biogas production though the investigation and implementation of newer technologies such as cell lysis for enhanced biogas production.

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CHAPTER 5: THE POTENTIAL FOR BIOGAS-TO-ENERGY TECHNOLOGY UPTAKE IN SOUTH AFRICAN MUNICIPALITIES

Anaerobic digestion is widely applied in the South African wastewater industry for the treatment of wastewater solids. Anaerobic digestion converts sludge from the primary settling, waste activated sludge and thickening processes, to a substance that is sufficiently stable and odour-free. Although anaerobic digestion is a well-recognised and widely implemented treatment technology in South Africa, the technology has not been exploited for its energy recovery potential.

In order to establish the current use, status and perceptions on anaerobic digestion at municipal treatment plants, a survey was done to map the current status of anaerobic digestion and CHP feasibility and uptake potential in South Africa. The following key aspects were explore in this part of the study:

- The application of anaerobic digesters to treat wastewater sludge;
- Biosolids (sludge) classification at plants which employ anaerobic digestion;
- The potential for biogas-to-energy from existing anaerobic digesters;
- The minimum requirements to recover energy from biogas.

5.1 STATUS OF MUNICIPAL WASTEWATER AND SLUDGE TREATMENT IN SOUTH AFRICA

The most recent Green Drop Report results (2013 and 2014) indicate that wastewater services delivery is performed by 152 Water Services Authorities in South Africa via 824 wastewater treatment systems.

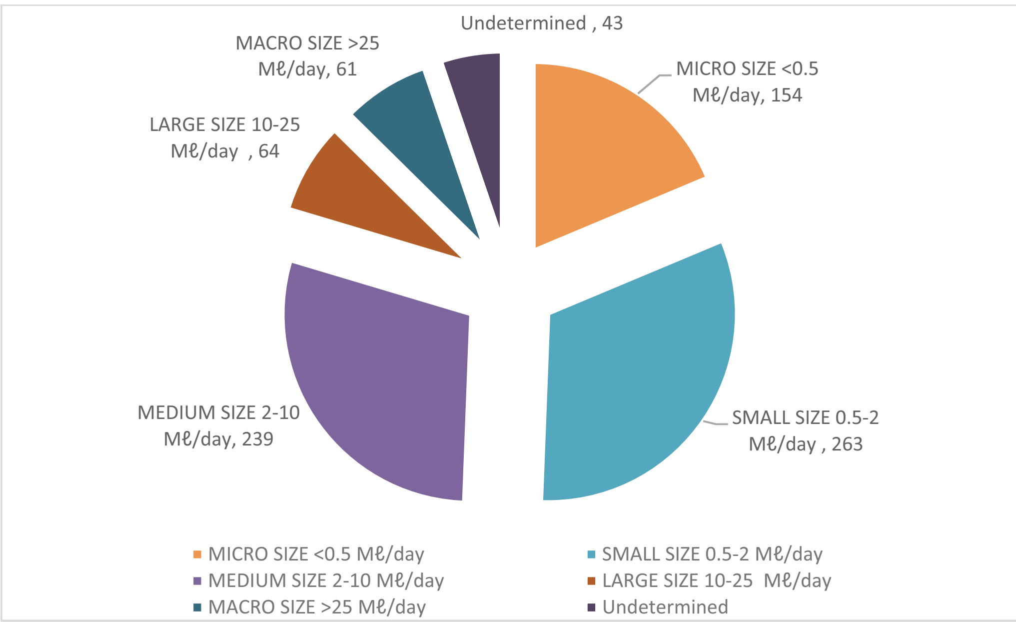

Figure 33: Graphic illustration of the distribution of design capacity and operational flows of municipal wastewater treatment plants in South Africa

A total operational flow of 5 129 Ml/day is received at the 824 treatment facilities, which has a collective hydraulic design capacity of 6 510 Ml/day (as ADWF). This means that 78.8% of the existing design capacity is taken up by the current operational flows, leaving a theoretical surplus of 22.2% as ‘available’ capacity for future demand.

Table 22: A summary of the spread of WWTW, design capacity and operational flow across the different Provinces in South Africa

Province	Total number of WWTW	Total Design Capacity (Ml/day)	Total Daily Inflow (Ml/day)
Mpumalanga	76	321.48	139.95
North West	37	289.5	181.7
Free State	93	400.70	259.87
Gauteng	58	2572.9	2452.0
Kwazulu-Natal	141	1084.7	714.7
Limpopo	58	187.18	126.25
Western Cape	158	1024.8	803.6
Northern Cape	79	139.3	87.4
Eastern Cape	124	489.1	363.4
National Totals	**824**	**6509.7**	**5128.8**

Analysis of the sludge treatment technologies that are used by WSAs indicates that various technologies are employed at municipalities (Green Drop Progress Report 2014). Table 23 indicate that the majority of sludge treatment technologies include solar drying beds, anaerobic digestion, sludge lagoons and belt presses.

Table 23: Summary of wastewater (sludge) treatment technologies reported at 152 WSAs across South Africa (Green Drop Progress Report 2014)

	Anaerobic Digestion	Belt Press Dewatering	Centrifugal Thickening	Centrifugal Dewatering	Screw Press Dewatering	Solar/Thermal Drying Beds	Dissolved Air Flotation Thickening	Gravity Thickening	Lime or Other Chemical Stabilisation	Plate Filter Press Dewatering	Rotary Drum Sludge Thickening	Sludge Lagoon/Pond	Composting	Incineration	Pelletisation	Thermo-Chemical Treatment	Other
EASTERN CAPE	13	1	0	2	0	29	0	4	0	0	1	30	0	0	0	2	2
FREE STATE	21	0	0	0	4	35	1	2	0	0	0	11	2	1	0	1	3
GAUTENG	40	9	0	0	0	25	7	10	0	0	0	3	1	0	0	0	2
KZN	24	5	1	1	6	55	4	2	0	1	0	19	2	0	0	0	4
LIMPOPO	9	0	0	0	0	24	0	0	0	0	0	9	6	0	0	1	0
MPUMALANGA	25	1	0	1	2	37	2	1	0	0	0	3	1	0	0	0	1
NORTH WEST	58	4	0	2	6	90	4	4	0	0	0	17	8	0	0	0	2
NORTHERN CAPE	11	0	0	0	0	17	1	1	0	0	0	3	3	0	0	0	0
WESTERN CAPE	16	23	1	2	3	41	4	3	0	0	0	30	2	0	0	0	14
TOTALS	**217**	**43**	**2**	**8**	**21**	**353**	**23**	**27**	**0**	**1**	**1**	**125**	**25**	**1**	**0**	**4**	**28**

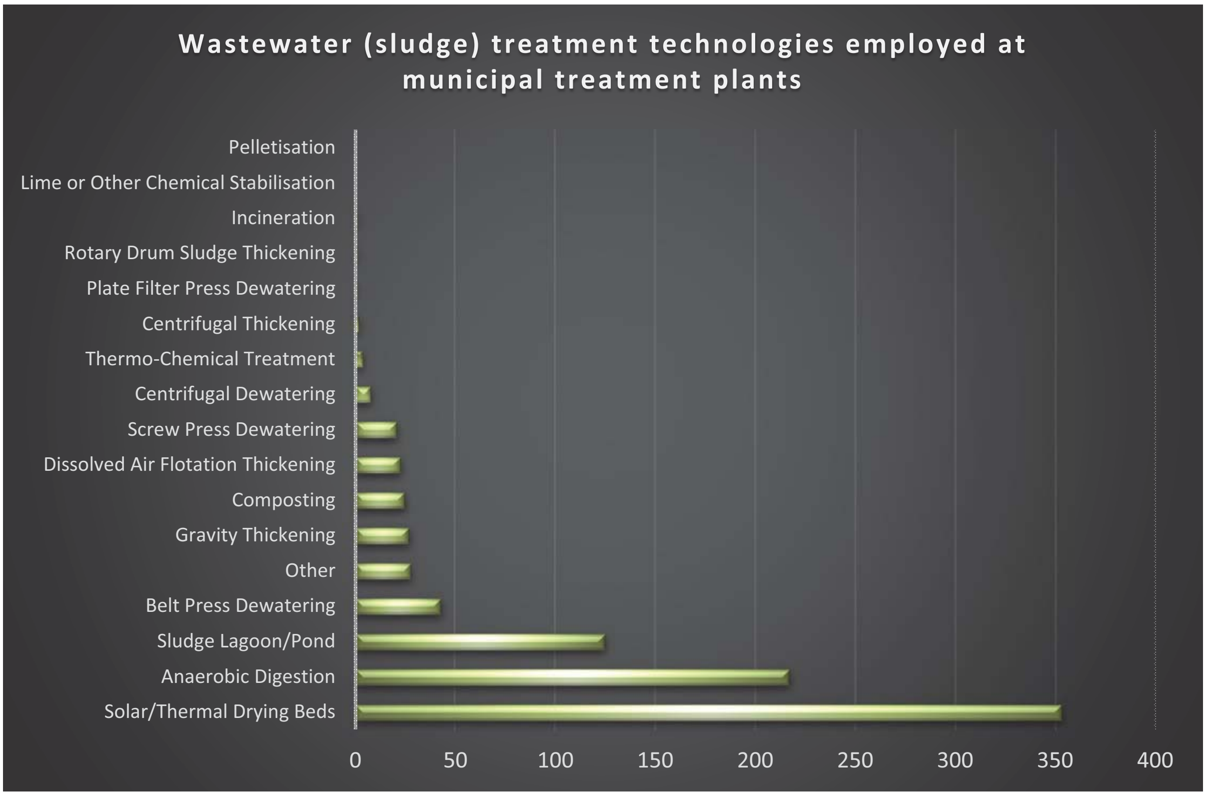

Figure 34: National spread of wastewater (liquid) treatment technologies at municipal treatment plants

5.2 ASSESSMENT OF ANAEROBIC DIGESTION IN SOUTH AFRICA

Based on information presented in Table 23, all municipalities currently using anaerobic digestion technology were approach as part of a dedicated research survey on the status of their anaerobic digesters. A research invitation and an Assessment Questionnaire were used to engage each municipality are attached as ***Annexure A***. This invite to participate included 217 WWTW.

The majority of the municipalities responded to the questionnaire, by way of the following responses:

- Confirmed that anaerobic digesters are in use and provided responding data;
- Confirmed that anaerobic digesters are no longer in use and have been decommissioned;
- No response to the questionnaire, but responded to telephonic enquiries;
- No response at all;
- Confirmed that the baseline information is incorrect and that the plants do not have ADs.

From the initial 217 WWTW identified, 108 plants verified the use of anaerobic digestion for the stabilisation and treatment of sludge. An example would be Mangaung Metro, whereby the reference or baseline information indicated that anaerobic digesters are in use at 5 WWTW, however, verification confirmed that only 1 WWTW have anaerobic digesters.

Furthermore, the study shows that 46 WSAs (out of 152) have approximately 420 anaerobic digesters, which are spread across 108 WWTW (out of 824) across 9 Provinces, as given in Table 24. This means that approximately 13.1% of all plants have had investment made in anaerobic digesters, with a corresponding total design volume of 1 367 Ml. It is observed that Gauteng's WWTW has substantially invested in anaerobic digestion, and therefore present a localised opportunity for energy recovery from sludge digestion. KwaZulu-Natal also represents a fair investment in anaerobic digesters.

Table 24: Summary of anaerobic digestion at municipal wastewater treatment plants in South Africa. Comparative data are indicated in yellow blocks.

Province	No. WWTW per Province	Design Capacity (Ml/d)	No. of WSAs with ADs	No. of WWTW with ADs	Total no. of ADs	Design capacity of WWTW with ADs (Ml/d)	Operational flow to WWTW with ADs (Ml/d)	Total AD volume (Ml)
MP	76	322	4	8	11	55	58	14.95
NW	37	290	4	6	12	144	114	20.7
FS	93	401	6	10	51	192	163	37.7
GP	58	2573	8	35	212	2479	2263	719.7
KZN	141	1085	8	21	56	692	532	89.4
LP	58	187	3	7	30	80	76	39.7
WC	158	1025	7	11	26	313	217	51.9
NC	79	139	3	4	10	80	48	18
EC	124	489	3	6	12	89	68	13.0
	824	**6511**	**46**	**108**	**420**	**4124**	**3539**	**1005**

All of the municipalities, with one exception in the Free State, confirmed that they would like feedback of the results of the study. This translate to a keen interest by WSAs and WSPs to confirm the potential of their WWTW for CHP. Each municipality who participated in the research, received their results back. An example of the feedback report is available as ***Annexure B***.

5.3 ASSESSMENT OF BIOGAS TO ENERGY POTENTIAL

Building on work done by GIZ and SALGA in the field of biogas-to-energy feasibility modelling and costing, an excel-based tool was used to calculate the potential for energy recovery from the wastewater treatment plants (108x) and anaerobic digesters (420x). The tool was sensitive towards digestion temperature and retention time, which again impact on VSS destruction. Typically, too small digesters or hydraulically overloaded digesters (low retention time) will have low VSS destruction, and reduced energy production.

In such cases where no data or information was received, alternative sources of information was used and best estimates were made. Such sources would include: technical reports, engineering drawings, Process Flow Diagrams, google images (and measurements), telephonic interviews, etc.

The tool was purposefully configured to calculate biogas conversion to electrical/thermal power based on actual (current) flow, sludge loading, and operational configuration of the treatment plant. The resultant output would therefore provide an estimate for the 'actual energy potential'. The full potential of the plant could be derived by applying the plant's design capacity and by making assumptions that all mixing, heating and biogas collection systems are operational and that all primary sludge and WAS feed to the anaerobic digesters. The model allowed for certain estimations, ratios, production/conversion rates and efficiency ratios to estimate biogas production and conversion to electrical power:

Refer: (balticbiogasbus.eu/eb//about-biogas/aspx; Metcalf & Eddy, 2014, energy pedia):

- Energy content of biogas = 22-24 MJ/m^3
  - 21-23.5 MJ/m^3
  - 1 m^3 biogas = 0.5-0.6 l diesel fuel = 6 kWh
- Biogas production from AD = 0.75-1.12 m^3/kg VS destroyed
- 1Nm^3 biogas (97% CH_4) = 9,67 kWh
- Calorific value of biogas from AD = >23 MJ/Nm^3
- Density = 1.2 kg/Nm^3
- CH_4 = 55-70% (65%).

- That anaerobic digesters are loaded to 2 kgVSS/m^3.d with primary sludge;
- That the mass of primary sludge would be available;
- Mass Humus produced, Trickling filter: 0.38 kgVSS/kgCOD;
- Mass WAS produced, extended aeration, 15 day sludge age: 0.30 kgVSS/kgCOD (varies with sludge age);
- Mass WAS produced activated sludge, 15 day sludge age: 0.24 kgVSS/kgCOD (varies with sludge age);
- COD remaining in PST effluent after settling in PST (input): 0.70 fraction or 30% COD settled (default);
- Fraction SS settled into PST underflow, primary sludge (input): 0.50 fraction or 50% SS settled (default);
- Primary sludge VSS fraction consumed by anaerobic digestion 0-0.66 fraction (function of AD retention and temperature)*;
- WAS volatile solids consumed by anaerobic digestion: 0.6 of primary sludge VSS destruction estimate above;
- Volatile solids content of mixed PS and WAS (input): 0.80 fraction (default);
- Biogas produced per mass of VSS consumed: 0.79-0.97 kl/kg (0.79 only secondary sludge up to 0.97 only primary sludge);
- Energy content of biogas: 24 MJ/kl;
- Thermal to electrical energy conversion efficiency: 0.36 fraction.

**Adapted VSS destruction as a function of retention and temperature from "Sludge stabilisation, Manual of practice FD-9, Water Environment Federation, 1993, p14"*

The results for biogas to energy potential is summarised in Table 25. The **national overview** indicate that a total of 46 WSAs have anaerobic digesters on-site spread across 108 WWTW. The raw COD and SS values indicate that a fairly high COD is received on average (725 mg/l COD; 350 mg/l SS). Typically, plants with industrial contributions receive high COD/SS influent (up to 2 240 mg/l COD and 984 mg/l SS). On the contrary, some plants receive very low COD and SS contributions (minimum of 214 and 130 mg/l, for COD and SS respectively). One explanation would be the infiltration of ground water and loss of drinking water to the municipal sewers.

Table 25: National overview of biogas to energy potential at municipal WWTW

	Min	Max	Ave	SD	Total
Design Flow, Ml/d	2	405	25	25	4 123
Actual present flow, Ml/d	1	394	21	24	3 539
Raw COD, mg/l	214	2 240	725	424	79 344
Raw Suspended solids, mg/l	130	984	350	225	37 623
Number of digester structures	1	6	3	2	420
Total volume of digesters, m^3	100	179 200	6 178	18 596	1 005 017
VSS loading, VSS/m^3.d	0.1	3	1.0	1.0	119.8
VSS destruction	2%	63%	51%	3%	-
Biogas produced, m^3/d	**98**	**22 288**	**1 970**	**1 977**	**282 671**
Thermal power at 23 MJ/m^3, kWt	**26**	**6 003**	**535**	**513**	**77 099**
Electrical power at 36% eff, kWe	**10**	**2 161**	**193**	**185**	**27 757**
Electrical energy per day, kWh/d	**229**	**51 865**	**4 584**	**223 334**	**657 765**
Elec. energy cost per year at R0.60/kWh, R/a	**2 130**	**3 539 321**	**1 002 864**	**1 097 649**	**143,942,502**
Primary sludge produced, kg/d	140	48 620	3 594	3 790	548 302
Secondary sludge produced, kg/d	29	35 370	2 289	2 713	368 917
Primary sludge produced, kl/d	4	11 640	89	90	13 548
Secondary produced, kl/d	1	4 348	90	653	14 531

Total biogas production is estimated at 282 671 m^3/day, based on status quo conditions and process configurations. This biogas production translates to electrical energy of 657 765 kWh/day with an estimated saving (at 60 cents per kWh electricity) of R144 million per annum.

On average, 3 594 kg primary sludge and 2 289 kg secondary sludge is produced per plant on a daily basis, resulting in a total sludge production of 548 302 Kg/d primary sludge and 368 917 Kg/d secondary sludge.

The energy recovery and monetary savings potential can be adjusted upward when considering the following improvement and adjustments:

- Full use of each plant's design capacity;
- Upgrading or refurbishing all anaerobic digesters with heating and mixing equipment;
- Structural refurbishment of anaerobic digesters;

- Improved operations of various sludge handling processes responsible for the volume and quality of sludge input to the digesters, especially the primary settling tanks and waste sludge handling from activated sludge plants.

Overall, Gauteng WWTW are in the most favourable position in terms of biogas production and electrical energy conversion, followed by KwaZulu-Natal and Western Cape. Mpumalanga, North West, Limpopo and Eastern Cape indicate a low potential for biogas recovery on a provincial level, although some individual municipalities such as Polokwane, Rustenburg, Mbombela, Tlokwe, etc. indicate good potential for energy recovery.

5.4 SLUDGE MONITORING PRACTICES

Resource recovery philosophies include aspects of sludge/biosolids as a valuable resource, especially given the nutrient value of the nitrogen and phosphorus content of sludge. Part of the study was to establish the current biosolids classification and re-use of sludge or biosolids by WWTW which employ anaerobic digestion technology. Only 25 of the 108 plants confirmed that their final sludge is classified (=23%), whereas 77% of the plants either did not classify their sludge or did not provide this information. The majority of classified biosolids falls in the Class A category (microbial) and in the Class 1a and 2a categories (stability and pollution).

Table 24: Sludge classification of the final biosolids produced from the WWTW that formed part of the AD research study

Sludge Classification Type A	No of Plants with this class type	Sludge Classification Type B	No of Plants with this class type	Sludge Classification Type C	No of Plants with this class type	#
A1a	4	B1a	3	C1a	1	***8***
A1b	2	B1b	0	C1b	0	***2***
A1c	1	B1c	0	C1c	0	***1***
A2a	6	B2a	2	C2a	0	***8***
A2b	0	B2b	2	C2b	0	***2***
A2c	0	B2c	0	C2c	0	***0***
A3a	1	B3a	0	C3a	2	***3***
A3b	0	B3b	0	C3b	0	***0***
A3c	0	B3c	0	C3c	1	***1***
#	***14***	**-**	***7***	**-**	***4***	**-**

FOOTNOTE:

Microbial Class	*A*	*B*	*C*
Stability Class	*1*	*2*	*3*
Pollution Class	*a*	*b*	*c*

In addition, given the pertinence and importance of the management of the overall management of all process units involved in the treatment of sewage sludge, the study also included a survey of the monitoring of process streams and specific constituents which are usually monitored to optimise sludge treatment and benchmark each units' performance.

The operation and monitoring of the anaerobic digestion process is of particular importance, given the various factors that impact on the content of biogas. Typically, the design of the plant, process operation and the raw substrate (e.g. industrial and domestic influent mix) will impact on the biogas yield and methane concentration, and therefore, on the energy recovery.

5.5 COMPARATIVE ANALYSIS OF WRC 2009 AND 2016 ENERGY RECOVERY STUDIES

Previous research conducted by WRC (Burton et al., 2009) estimated that up to 1 134 MW energy could potentially be produced when taking the total sewage available for energy conversion. The following assumptions given in Table 25 were made to support this high level estimation.

Table 25: Energy potential estimates from the WRC study in 2009

Wastewater source of energy	Energy potential	Assumptions
Population of SA, incl. domestic black and grey water	1 488 MJ/s or 1488 MW	200 l/d sewage per person, population of 48.5 million, COD of 860 mg/l, calculated 96.6 kg/s, energy content of 15 MJ/kg
Municipal WWTW	1 134 MJ/s or 1134 MW	7600 Ml/d total flows, COD of 860 mg/l, calculated 75.7 kg/s, energy content of 15 MJ/kg
Domestic blackwater load	824 MJ/s or 824 MW	48.5 million people generate 100 g dry weight faeces with energy value of 15 MJ/d, calculated as 56 kg/s, 842 MJ/s or 842 MW
Total captured domestic blackwater of serviced population	509 MJ/s or 509 MW	60.4% of population with flush toilets = 29.3 million people, 100 g dry weight per person, calculated as 33.9 kg/s, energy content of 15 MJ/s

The findings from the current study indicate that only 27 757 kWe and 77 099 kWt (electrical and thermal energy, respectively) can be generated based on current process configuration and plant loading rates. This is significantly lower compared to the estimates reported in 2009.

Table 26: Comparison between energy potential from municipal wastewater sources based on WRC research findings reported in 2009 and 2016

	2009 WRC research: Estimate of total potential								WRC research: Estimate of total potential		
	Capita	Flow	Tot flow	COD	COD	Energy	Energy	Power	Tot flow	TF/AD	2009/16 ratio
										Power	Ratio
	no.	l/c.d	Ml/d	mg/l	kg/d	MJ/kg	MJ/d	MWt	Ml/d	MWt*	%
Population SA	48.5 mill	200		860	8 342 000	15	125 130 000	1 448	9 700	350	24.2%
Municipal WWTW			7 600	860	6 536 000	15	98 040 000	1 135	7 600	276	24.4%

** "thermal power" of WRC feasibility model (kWe/0.36)*

The 2016 results indicate that approximately 24% of the Burton et al. 2009 estimates are realised based on the current status of anaerobic digestion. Some explanations can be offered to contextualise the 76% difference:

- The 2009 research was based on first order estimations and did not include a detailed survey of the current status and loading of anaerobic digesters;

- The 2016 research had the benefit of a detailed questionnaire with direct input from municipalities, which benefitted a more accurate estimation of biogas to energy;
- 70% of COD is typically oxidised aerobically in the activated sludge process and is therefore not available for recovery. The remainder of this sludge (WAS) is however available for further recovery;
- A treatment plant deliver a sludge/biosolids mass as end product which also present an energy value;
- Final effluent from a treatment plant typically contain COD which is lost for energy recovery;
- Current technology does not allow for a full energy recovery of 15 MJ/kg COD;
- The 2009 study assume that all plants are equipped (heated, mixed, gas collected) and fully operational with maximum potential to recover energy, whereas the 2016 studies confirm that most plants and anaerobic digesters are not optimally operated and/or functional and represent a margin of their potential for energy recovery.

5.6 MINIMUM FEASIBILITY REQUIREMENTS FOR CHP

One question that was consistently raised by technical managers pertained to the minimum requirements to **economically and sustainably** develop biogas to energy at a given plant. This section deals with this aspect in more detail.

The Anaerobic Digestion Survey and CHP feasibility assessment (***Annexure A***) assumed that that basic infrastructure is already in place to optimally utilise the available organic load to generate biogas. Therefore, the municipal treatment plant is assumed to have primary settling tanks, sludge thickeners (as required) and high rate anaerobic digesters which are optimally loaded with an operational heating and mixing system. The organic loading of a plant (as mass loading) is the main driver of biogas and CHP potential. It is therefore logical that the CHP feasibility will improve for a given flow when the raw sewage organic concentration increases. Although primary sludge has a higher biogas potential than secondary sludge, the CHP feasibility for a given plant will be reduced if secondary sludge is not anaerobically digested. Treatment plants based on extended aeration technology only (no primary settling tanks or associated anaerobic digesters) do normally not qualify as potential CHP candidates. It must noted that the load treated by extended aeration technology will have reduced CHP feasibility and should be considered in terms of the total plant loading scenario. The graph below reflects the organic load expressed in terms of flow and organic load as Chemical Oxygen Demand. For the purpose of this study, the COD/SS ratio was assumed to be 2, i.e. for a COD of 1000 mg/l the Suspended Solids is assumed as 500 mg/l.

From the equipment perspective, the feasibility of a CHP system is primarily driven by the capital investment required (GIZ-SALGA study, 2015). The cost of a CHP system is primarily driven by the generating capacity and secondly by the funding model. Funding by the municipality – assuming no financing cost – would represent the most favourable feasible extreme while funding with normal commercial financing cost would represent the upper extreme. These two extreme financing cases are reflected in Figure 35 to demonstrate the sensitivity with regard to the impact of financing over the project life cycle.

For the purposes of this study, the "minimum feasibility requirement" is defined as **a CHP project with an assumed lifespan of 15 years that will pay back the investment including financing cost over the project life cycle of 15 years.** Any loading or condition better than this will result in the generation of a positive cash flow over the project life cycle. With reference to Figure 35, any loading condition above and to the right of each of the four scenario curves has the potential to generate a positive cash flow over the project life cycle, indicating a feasible project. The graphs are based on the following assumptions:

- No financing cost for the scenario that is fully funded by municipality. The minimum generating capacity for this scenario is approximately 70 kWe.
- Commercial financing scenario at 7.5% per annum over a 10 year term. The minimum generating capacity for this scenario is approximately 230 kWe.
- Operating and maintenance cost over the CHP project life cycle is included, with allowance for escalation of 6% per annum. The operating cost includes a full time operator which has a progressively negative impact on feasibility the smaller the CHP capacity is. The operator contribution would typically be up to 30 cent/kWh for a CHP plant with a capacity of 70 kWe. This cost per kWh reduces dramatically as the CHP capacity increases.
- Utility power cost escalation is based on best estimate (10% per annum for first three years followed by 8% per annum over the project life cycle.

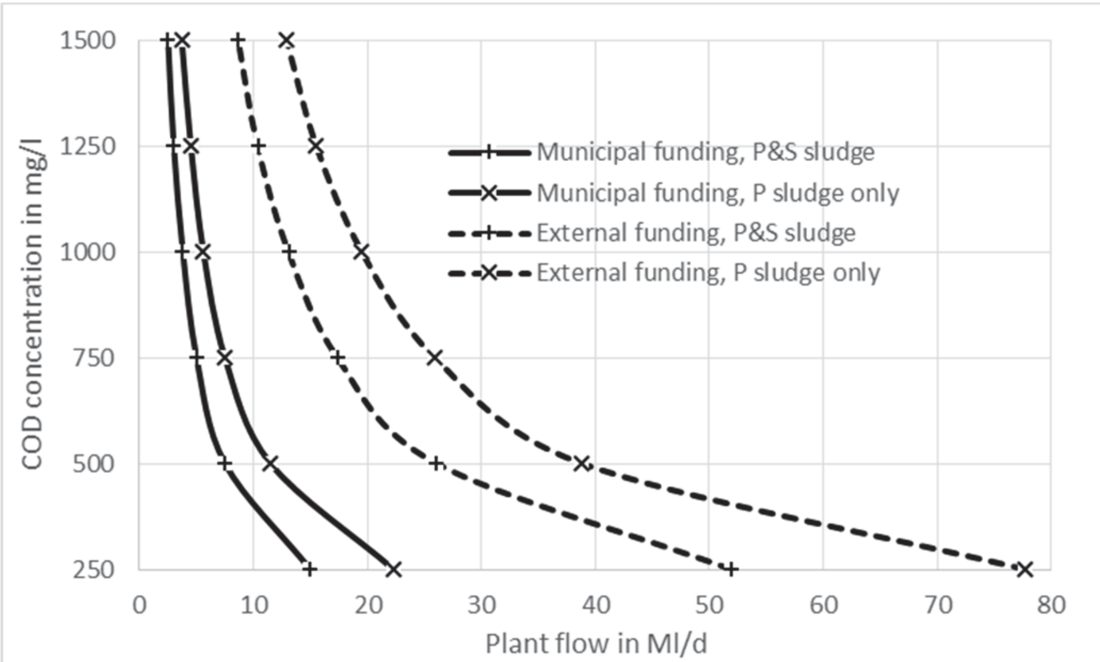

Figure 35: Minimum CHP feasibility requirement for a fifteen year payback period for various loading, sludge routing and financing scenarios

An example of interpreting funding in Figure 35 is given under 1 and 2:

1. For a plant with a flow of 5 Ml/d and a COD of 750 mg/l, funded by municipal funds, primary and secondary sludge are anaerobically digested, the estimated project payback period is 15 years, and i.e. the project is feasible and would pay for itself. Any loading condition more than this would result in a positive cash flow over the project life cycle.
2. For a scenario based on commercial funding, a flow of 26 Ml/d with a COD of 750 mg/l and only primary sludge routed to anaerobic digesters, the estimated project payback period is 15 years, i.e. the project is feasible and would pay for itself. Any loading condition more than this would result in a positive cash flow over the project life cycle.

By extrapolation of the kWe data of each of the 108 WWTW (plants with anaerobic digestion) to the above graph, the following indication of number of plants feasible for CHP can be provided:

- 31 plants (28.7) do not have sufficient generating capacity (produce < 70 kWe), irrespective of the type of financing of loading scenario;
- 77 plants (71.3%) have a generating capacity of >70 kWe and will potential be feasible for CHP uptake, subject to the financing model applied;
- From the 77 plants:

- 41 plants have a generating capacity of 71-230 kWe and will be feasible for CHP uptake providing that municipal funding is available;
- 36 plants have a generating capacity of >230 kWe and will be feasible for CHP uptake with commercial funding and highly feasible with municipal funding.

Borderline feasibility plants could be re-evaluated pending the following impacting factors:

- Low CHP utilisation due to low current flow and slow growth;
- Low CHP utilisation due to low organic load and slow growth;
- Upskilling of operating and maintenance capacity could influence project feasibility. The implementation of a performance based outsourcing could be one mechanism to effect improve CHP production;
- Inaccurate data submitted for assessment purposes, such as plant organic loading (COD and SS) has a significant impact on project feasibility;
- Different financing approach could swing feasibility (i.e. own funds, grants, etc.); and
- A poor fit of generator size could result in a non-feasible project, with smaller capacities being especially sensitive. The feasibility of a project is impacted by how well the size of the generator fit the biogas potential, particularly from 400 kWe upward where the generator sizing steps increase from 100 kWe to 200 kWe (SALGA-GIZ findings). In this case selecting a smaller generator may result in a feasible project.
- CHP units are sized for the ultimate capacity. If the plant loading at the time of assessment is low and a low growth is expected, the financial feasibility for this situation will tend to be negatively impacted. A lower initial CHP capacity may result a financially more feasible project.

Note: the GIZ-SALGA CHP Feasibility Tool is available and has the capability to calculate investment cost and payback period, using basic input data.

5.7 RECOMMENDATIONS

Based on the research findings, the following recommendations are provided:

Research focus:

- The study report be used as a Guideline by municipalities who are in the planning- or design stage of a biogas recovery project
- The Report serve as guide for best practice in the design, management and monitoring the individual processes responsible for sludge handling in South Africa
- The data collected during this study on the status of anaerobic digestion and sludge classification be expanded, further processed and documented as a separate WRC
- Development of a national business case on biogas to energy from WWTW
- Development of a detailed business case, including cost benefit analysis, for the Gauteng WWTW anaerobic digesters for full-scale biogas to energy/CHP implementation
- Further research include for an energy balance to illustrate the actual- and potential energy recovery from raw wastewater.

Regulation focus:

- The Regulator consider the introduction of a compliance standard or guideline for digester performance or digestate quality, and deserves equal attention to that of the requirement for treated effluent. This is imperative given the link between in efficient sludge treatment and the knock-on on final effluent quality
- Further research for setting of operational and critical limits and best practice for the operation of anaerobic digesters and the monitoring of performance on a continuous basis.

The inclusion of these as part of the Green Drop 10-year plan bodes well for a positive change in the industry

- Development of a Guideline to assist municipalities to compile a Sludge Management Plan that considers the various sludge handling process units, sludge monitoring and management, legal requirements, energy generation potential, greenhouse impacts, best practices, performance comparison and benchmarking.

Operational focus:

- Adoption of best practice and optimization of biogas production through optimisation of the various process units. The current study showed that the majority of municipalities do not operate or monitor sludge management according to best practice, which impact negatively on biogas yield and quality
- Upskilling of operating skills, especially focussing on:
  - infrastructure to enable and maintain effective process control with regard to pH, VFAs, alkalinity and temperature
  - facilities to thicken feed sludge to optimal solids concentration
  - feed sludge flow monitoring per digester and appropriate feed distribution
  - quantitative and qualitative biogas monitoring per digester to ensure a healthy process as well as to optimise digester feeding and mixing strategies while maximising biogas production.

Strategic focus:

- Raising awareness on the value proposition for biogas recovery at municipal plants in South Africa, as well as the constraints perceived by municipalities hampering the uptake of CHP technology in the municipal environment
- Quantifying the impact of unused biogas as a greenhouse gas and the potential contribution of SA wastewater treatment plants towards the climate change debate
- Communicating the CHP development minimum requirements at WWTW for biogas to energy potential
- Informing policy and strategy, as well as the regulation and legislation pertaining to energy recovery, sludge management, appropriate technology selection and licensing (water use and waste) in South Africa.

5.8 REFERENCES

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ANNEXURE A: Questionnaire issued to identified municipalities to investigate the use of anaerobic digestion as sludge treatment technology:

Name of Municipality: ____

Name of Wastewater Treatment Plant: ______________________________

Respondent name: ____

Contact number: ______________________ **E-mail:** ____________________________

WATER RESEARCH COMMISSION

- Thank you for your knowledge contribution to the WRC research study on Anaerobic Digestion of municipal sewage sludge.
- Please complete at your earliest convenience and return to Dr M vd Merwe-Botha at **marlene@watergroup.co.za** or phone 011-9540242 if uncertain.
- If the required information is not available, please enter NI (No Information).

TREATMENT PLANT	TOTAL	Module 1	Module 2	Module 3	Module 4	Module 5
Population served		-	-	-	-	-
Technology (e.g. Biofilter, Act Sludge-BNR, AS-Aerobic, AS-Denitrification, SBR, etc.)						
Design capacity (Ml/d)						
Current flow (Ml/d)						
Industrial (%)						
Domestic (%)						
Raw COD (mg/l)						
Settled COD (mg/l)						
Raw SS (mg/l)						
Settled SS (mg/l)						
Raw N as TKN (mg/l)						
Raw P as TP (mg/l)						

Electricity demand of plant (kWh/day)						
Electricity demand of plant (kWh/m^3 wastewater treated)						
SLUDGE PRODUCTION						
List which Modules feed sludge to the Anaerobic Digesters		***Total Dry Solids (TS) (%)***	***VS (% of TS)***	***Grease & Fat (% of TS)***	***pH***	***Alkalinity (mg/l)***
Primary settling tank	*yes/no*					
Humus tank	*yes/no*					
Waste from AS	*yes/no*					
Gravity thickener	*yes/no*					
DAF	*yes/no*					
Secondary clarifier return flow	*yes/no*					
ANAEROBIC DIGESTION (AD)	**TOTAL**	**AD-1**	**AD-2**	**AD-3**	**AD-4**	**AD-5**
Number of anaerobic digesters						
Operational status (use/not used/decommissioned)						
If not in use or decommissioned, state reason						
Volume per unit (m^3)						
Flow to unit (m^3/day)						
AD heated (yes/no)						
If yes, temperature (^oC)						
AD mixed (yes/no)						
If yes, mixing type (gas, mechanical stir, mechanical pump)						
HRT (d)*						
SRT (d)*						

COD in (mg/l)						
COD out (mg/l)						
Alkalinity out (mg/l)						
pH in						
pH out						
VS in (%)						
VS out (%)						
Methane (% CH_4)						
Biogas production (m^3/day)						

**HRT=Average time the liquid are held in AD; SRT=average time solids are held in AD; if AD without recycle, then HRT=SRT*

OTHER SLUDGE HANDLING		**Final sludge destination (irrigation, compost, etc.)**		
Aerobic digestion	*(yes/no)*			
Sludge lagoon	*(yes/no)*			
Sludge drying beds	*(yes/no)*			
Mechanical dewatering	*(yes/no)*			
Other				
SLUDGE CLASSIFICATION (WRC Sludge Guideline 2009)	e.g. A1a, B2a, etc.			

QUESTIONS
1. What projects or plans does the municipality have in place for biogas to energy?
2. Is the municipality under pressure to implement energy saving or recovery considering the rising electricity costs?
3. What do you perceive to be the technology barriers to greater uptake of energy from wastewater in SA?
4. What are the perception barriers to greater uptake energy from wastewater in SA?
5. What are the funding/financial barriers to greater uptake of energy from wastewater?
6. What are the institutional barriers to greater uptake of energy from wastewater?
7. Do you think a business case for uptake of energy can be made in your municipality?
8. Should the Regulator drive greater uptake?
9. Should energy recovery be a national focus area or are there other places where larger gains can be had?
10. What is required to remove the barriers?
WOULD YOU LIKE TO RECEIVE AN EVALUATION OF YOUR PLANT'S POTENTIAL FOR ENERGY RECOVERY WITHIN 4 WEEKS?
(yes/no)

ANNEXURE B:

Example of feedback and result of study to each participating municipality

ANAEROBIC DIGESTION AND ENERGY RECOVERY FROM MUNICIPAL WASTEWATER SLUDGE

15 March 2016

The Water Research Commission commissioned a study in 2015 to investigate and document the treatment of municipal sewage sludge and its application in biogas to energy from the anaerobic digestion process.

Your municipality has been approached to participate in this study, by providing data pertaining to the size and performance of your anaerobic digesters. The national profile and opportunities will be documented in **WRC Report K5/2478** and presented at the WISA May 2016 Conference.

We thank you for your kind cooperation and herewith provide feedback of the findings for your particular plant, based on your input data. In cases where no information or uncertain data was received, the research team reverted to best estimates or assumptions. The Biogas-to-Energy outputs hereunder are therefore considered as the *'indicative' potential*, and not as absolute values.

Please NOTE that the WRC Report will NOT show names of municipalities or treatment plants.

Tlokwe WWTW:

Parameters	Default	Plant	Mod 1
Design Flow, Ml/d		45	45
Actual present flow, Ml/d		33	33.0
Raw COD, mg/l	700		900.0
Raw Suspended solids, mg/l	350		150.0
Settled or unsettled			Settled
COD settled out in PST	30%		97%
SS settled out in PST	50%		95%
Primary sludge to Anaerobic digester			YES
Est. PS solids to digester %	4%		4.0%
VSS content of primary sludge	80%		80%
Technology (Trickling filter/Act sludge)			AS
Sludge age, days	12-20		20
Humus/WAS to digester			YES
Humus/WAS solids to digester %	2.5%		2.5%
VSS content of secondary sludge	75%		75%
Number of digesters, no.		3	3
Volume per digester, m^3		5490	1830
Digester operating temperature, ^{0}C	32-38		30
Hydraulic retention, days	>15	43.7	43.7
VSS loading, $VSS/m^3.d$	1.6-3.6	0.7	0.7
VSS destruction	35%-58%	61%	61%
Biogas produced, m^3/d		**2,292**	**2,292**
Thermal power at 23 MJ/m^3, kWt		**617**	**617**
Electrical power at 36% eff, kWe		**222**	**222**
Electrical energy per day, kWh/d		**5,333**	**5,333**
Elec. energy cost per year at R0.60/kWh, R/a		**1,167,874**	**1,167,874**
Primary sludge produced, kg/d		4,703	4,703
Secondary sludge produced, kg/d		202	202
Primary sludge produced, kl/d		118	118
Secondary produced, kl/d		8	8
Primary sludge to digester, kg/d		4,703	4,703
Secondary sludge to digester, kg/d		202	202
Primary sludge to digesters, kl/d		118	118
Secondary sludge to digester, kl/d		8	8
Digester mixed feed solids, %		3.9%	3.9%
Primary VSS to digester kg/d		3,762	3,762
Secondary VSS to digester kg/d		152	152
Primary VSS destroyed kg/d		2,317	2,317
Secondary VSS destroyed kg/d		56	56
Digestate solids content, %		2.0%	2.0%

\# The energy potential has been calculated based on 'existing operational flow', as opposed to 'plant design capacity'. The energy recovery potential is therefore likely to increase with increased flow to the treatment plant/s, subsequent to the increased loading rate to the anaerobic digester/s.

Please contact us should if you consider the above results output to be out of the expected range, and we will adjust the input data accordingly.

Thanking you for partaking in this research. The municipality and contributing individuals will be duly acknowledged, as a research participant and for your valued contribution, in the published Report.

Contact person: Dr Marlene vd Merwe-Botha (marlene@watergroup.co.za)

Acknowledgement: Biogas-to-Energy Tool by GIZ and SALGA

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