ENERGY RECOVERY FROM WASTEWATER SLUDGE – A REVIEW OF APPROPRIATE EMERGING AND ESTABLISHED TECHNOLOGIES FOR THE SOUTH AFRICAN INDUSTRY

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EXECUTIVE SUMMARY

The historical approach to sludge management in South Africa has been mostly to implement strategies and practices that fulfill legislative and regulatory requirements. Although Department of Water and Sanitation regulations recommend beneficial use, there are very few wastewater treatment plants (WWTPs) that recover energy (and/or other valuable resources) from wastewater sludge. However, the electricity shortages in 2008 exposed the risk to wastewater treatment operations posed by an unreliable power supply and continuous increases in electricity prices, stimulating interest in technologies for recovering energy from wastewater sludge. In response, the Water Research Commission (WRC) and its partners increased research funding into technologies to recover energy from wastewater, to provide detailed information on such technologies and decision support tools that can assist municipalities to evaluate these technologies.

This project was funded by the WRC as part of the ongoing research into recovering energy from wastewater sludge. The project evaluated one innovative/emerging and two established sludge-to-energy technologies that have not yet been implemented in South Africa. The selected technologies were:

(i) Emerging enhanced hydrothermal carbonisation polymeric carbon solid (PCS) technology
(ii) Established advanced anaerobic digestion using thermal hydrolysis (TH) as the sludge disintegration technology followed by mesophilic anaerobic digestion (MAD)
(iii) Gasification technology which is established for coal and woody biomass conversion.

The scope of the project included a technical and economic evaluation of implementing each technology at a typical South African WWTP, conducting a knowledge dissemination workshop, and preparation of a project report. Waterval WWTP, a 155 Ml/d biological nutrient removal activated sludge plant that produces about 50 tDS/d combined primary and waste activated sludge (WAS) was selected as the case study plant. The plant utilises conventional MAD for sludge stabilisation.

The emerging PCS technology was evaluated through laboratory- and pilot-scale studies. The pilot-scale study was carried out at Waterval WWTP. Primary sludge, WAS, combined primary sludge and WAS, and digested sludge were processed. Sludge combined with inlet works screenings was also processed. Data from the studies was applied in the preliminary design of a full-scale greenfield installation, processing 50 tDS/d combined primary sludge and WAS, on its own and in combination with screenings. The design assumed that the hydrochar from the process is utilised as a biofuel for combined heat and power (CHP) generation. A retrofit, processing 35 tDS/d digested sludge and screenings, was also evaluated.

Desktop modelling was applied to evaluate both advanced TH–MAD and gasification. Preliminary designs were also carried out for full-scale greenfield installations processing 50 tDS/d combined primary sludge and WAS and utilising biogas for CHP generation.

Cost benefit analysis (CBA) using net present value (NPV) as the evaluation criteria was applied to compare the whole life costs and benefits of each technology. The CBA was carried out for two residual sludge disposal scenarios:

- (iv) Beneficial utilisation of residual digested sludge or ash in agriculture
- (v) Disposal of the sludge or ash to landfill, assuming that the standards for agricultural use are not met

To provide a baseline comparison, the CBA was also carried out for a 50 DS/d greenfield installation of a conventional MAD plant, utilising biogas for CHP generation.

The key findings from the project were:

- Both the PCS technology and advanced TH–MAD are more economically attractive than conventional MAD
- The PCS technology is the most economically attractive technology with the highest positive NPV
- Apart from being the most economically attractive, the PCS technology offers other unique advantages to the South African water sector over established technologies, such as:
  - (i) ability to process a wide range of biomass, thus combining sludge and screenings management
  - (ii) ability to couple with existing technologies such as conventional MAD, advanced TH–MAD or gasification. A positive NPV was obtained for the 35 tDS/d retrofit to conventional MAD
  - (iii) potential to destroy contaminants of concern such as endocrine disrupting compounds (EDCs)
- Beneficial use of residual sludge or ash is more economically attractive than disposal to landfill.

In order to continue building the body of knowledge on the technologies reviewed in this project, the following is recommended:

- Installation of a full-scale demonstration plant for the emerging PCS technology, to gather more data on the technology
- Investigation of removal of EDCs from wastewater and wastewater sludge using the PCS technology
- Investigation of application of the PCS technology in low-cost sanitation systems
- Detailed modelling and economic evaluation of advanced TH–MAD, incorporating treatment of digested sludge centrate (which has high nutrient levels) and nutrient recovery technologies
- Evaluation of gasification technology through pilot/full-scale demonstration plants to better understand the economic and environmental impacts of the technology for the South African wastewater sector, particularly municipal installations
- Investigation of pathways to achieving a circular economy in the water and waste sectors utilising multi-biomass processing technology like the emerging PCS technology.

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NOTE

This document is written at a level that assumes a reasonable degree of technical understanding of wastewater treatment and sludge handling/management as well as biochemical and thermo-chemical conversion processes for converting biomass to energy.

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LIST OF ABBREVIATIONS

AD	anaerobic digestion
ADM1	anaerobic digestion model 1
ADM-3P	anaerobic digester model 3-phase
ADWF	average dry weather flow
As	arsenic
ASP	activated sludge plant/process
ASTM	American Society for Testing & Materials
BEAM	biosolids emission assessment model
BFP	belt filter press
BNR	biological nutrient removal
BOD	biochemical oxygen demand
BPO	biodegradable particulate organics
CBA	cost benefit analysis
CHP	combined heat and power
COD	chemical oxygen demand
DTGS	deuterated triglycine sulphate
DS	dry solids
DWE	dry weight equivalent
DWS	Department of Water and Sanitation (South Africa)
EBPR	enhanced biological phosphorus removal
EDC	endocrine disrupting compound
EEH	enhanced enzyme hydrolysis
EPS	extracellular polymeric substances
ERWAT	East Rand Water Care Company (South Africa)
FSA	free and saline ammonia
GHG	greenhouse gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GJ	gigajoule
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit
GWh	gigawatt hour
GWP	global warming potential
GWRC	Global Water Research Coalition
HHV	higher heating value
HRT	hydraulic retention time
HTC	hydrothermal carbonisation
HTP	hydrothermal polymerisation
MAD	mesophilic anaerobic digestion

MYPD	multi-year price determination
N	nitrogen
NACWA	National Association of Clean Water Agencies
ND	nitrification and denitrification system
NDEBPR	nitrification-denitrification enhanced biological phosphorus removal
NERSA	National Energy Regulator of South Africa
NPV	net present value
NWA	National Water Act
OHO	ordinary heterotrophic organism
Ortho P	ortho phosphate
P	phosphorus
PAO	phosphate-accumulating organism
PCS	polymeric carbon solid
PFD	process flow diagram
PS	primary sludge
PST	primary settling tank
RAS	return activated sludge
R&D	research and development
RHI	renewable heat incentive
RISE-AT	Regional Information Service Centre for South East Asia on Appropriate Technology
SAGEN	South African–German Energy Programme
SALGA	South Africa Local Government Association
SST	secondary settling tanks
SWG	supercritical water gasification
T	temperature
TBS	Tokyo Bureau of Sewage
TCOD	total chemical oxygen demand
TCLP	toxicity characteristics leaching procedure
TDS	total dissolved solids
TEQ	toxic equivalency
TGA/DSC1	thermal gravimetric analysis/differential screening calorimetry
TGA-FTIR	thermal gravimetric analysis – Fourier transform infrared spectrometer
TH	thermal hydrolysis
THP	thermal hydrolysis process
TKN	total Kjeldahl nitrogen
TOC	total organic carbon
TSS	total suspended solids
UK	United Kingdom
UPO	unbiodegradable particulate organics

US EPA	United States Environmental Protection Agency
USO	unbiodegradable soluble organics
VFA	volatile fatty acids
VS	volatile solids
VSS	volatile suspended solids
WAS	waste activated sludge, also surplus activated sludge (SAS)
WEF	Water Environment Federation
WISA	Water Institute of Southern Africa
W_2RAP	wastewater risk abatement plan
WRC	Water Research Commission (South Africa)
WRAPAI	Waste Refinery Australia Project Association Incorporated
WSAs	Water Services Authority (South Africa)
WSDP	water services development plans
WUA	water use authorisation
WWTP	wastewater treatment plant

UNIT ABBREVIATIONS

%	percent
°C	degree celsius
kg/s	kilogram per second
m^3/d	cubic metres per day
MJ	megajoule
Ml/d	megalitres per day
MJ/kg	megajoules per kilogram
mg/l	milligrams per litre
mg/dscm	milligrams per dry standard cubic metre
MPa	megapascal
MWe	megawatt electric
MW/d	megawatt per day
MWh/yr	megawatt hour per year
MWhe/yr	megawatt hour-electric per year
ng/dscm	nanograms per dry standard cubic metre
Nm^3/h	normal cubic metre per hour
ppmvd	parts per million by volume, dry basis
tDS/d	tonnes dry solids per day
t/ha/yr	tonnes per hectare per year

Chapter 1 Introduction

1.1 BACKGROUND

Sludge management forms a large part of wastewater operations. Whereas in the past a large section of the wastewater industry viewed sludge as nuisance waste to be disposed of, there is now general consensus that sludge is a potential source of valuable resources and alternative green energy. Data from research and analysis of sludge has shown that unprocessed sludge has the same energy content as low-grade coal, at approximately 19 MJ/kg (5.2 kWh/kg) on a dry weight basis. The energy content varies depending on the level of sludge treatment, with untreated primary sludge having the highest energy content (Table 1-1).

Table 1-1: Energy Available in Sludge Compared to Other Fuel Types (Various Sources)

Parameter	Units	Value
Raw primary sludge	MJ/kg DS	17–24
Waste activated sludge	MJ/kg DS	14–20
Anaerobically digested sludge	MJ/kg DS	11–13
Anthracite	MJ/kg	32–34
Bituminous coal	MJ/kg	17–23
Natural gas	MJ/kg	45–52
Biogas[1]	MJ/kg	21–24
Methane	MJ/kg	49–55
Firewood	MJ/kg DS	14–16

1. Biogas from anaerobic digestion with ~ 60–70% methane

Because of this potential, energy recovery from sludge has in recent years gained global importance and has become a key aspect in almost all sludge management strategies. In response, international research and technology development has focused on recovering resources such as electricity and/or heat, phosphorus, building material, etc. from sludge. Other key drivers for energy recovery are a combination of increases in fuel prices, more stringent regulation, concerns over climate change, advances in renewable energy technologies as well as growing public awareness. Also, since the capital costs of sludge management can be up to 50% of the overall investment at a wastewater treatment plant (WWTP) (Marx et al., 2004), energy recovery is essential for the long-term sustainability of wastewater operations.

The energy content of sludge is embedded in the volatile solids portion. While the composition of sludge may vary from treatment plant to treatment plant, sludge characteristics at individual plants have been found to be fairly consistent and predictable thus making the implementation of energy recovery technologies possible and sustainable. Therefore, to successfully extract potential energy from sludge, it is important to select a technology compatible with the characteristics of the sludge.

Energy recovery is achieved through two primary pathways: biochemical conversion and thermo-chemical conversion (US EPA, 2006; NACWA, 2010). There are currently proven and well-established technologies being utilised at WWTPs that fall into these two pathways. In addition, emerging technologies are also playing a major role in energy recovery from sludge. The two pathways produce different end products and the choice of technology is influenced by factors such as the quality of the sludge, the quality of, and markets for, the by-products, regulatory requirements and public perceptions.

A summary of established and emerging technologies that fall into the two pathways is given in Table 1-2. The table also shows the stage of development of each technology as well as the by-products and their possible uses.

The global interest in recovering energy from wastewater sludge has resulted in a substantial body of literature reviewing energy recovery technologies. The most widely applied established technology is anaerobic digestion. Recent technological advances that incorporate upstream pre-treatment of sludge (e.g. through thermal hydrolysis) prior to anaerobic digestion increases biogas generation and makes onsite electric (and thermal) power generation economically feasible at WWTPs (Panter and Kleiven, 205; Jolly & Gillard, 2009; Mills et al., 2013). Since 2007, thirty-four advanced anaerobic digestion plants, utilising thermal hydrolysis (TH) as sludge pre-treatment, have been installed internationally.

In one of the most significant studies commissioned by the Global Water Research Coalition (GWRC), Kasogo and Monteilth (2008) compared sludge energy recovery technologies and identified gaps gaps in information relating to the technologies on the market. The information gaps for all technologies evaluated (both established and emerging) were in terms of:

(a) classified life cycle analysis
(b) identification of carbon footprints and greenhouse gas (GHG) emissions
(c) social acceptance
(d) modelling energy and resource recovery technologies
(e) optimal pathways for sludge treatment.

The study concluded that these information gaps impact the ability of wastewater utilities to select appropriate sludge-to-energy technologies.

To close these gaps, Kasogo and Monteilth (2008) recommended that global research priorities be adjusted to provide much needed data on the carbon footprint and the relative sustainability of various sludge treatment processes. They found that this information is often difficult to acquire for many processes, especially for newer technologies, and suggested that the manufacturers of the various processes should be encouraged to provide an estimate of total life cycle costs and carbon footprint. They also recommended carrying out demonstration or benchmarking projects to supply the needed data to guide wastewater utilities in making prudent longer-term sludge management decisions.

Table 1-2: Summary of Wastewater Sludge Energy Pathways, Technologies and Products (NACWA,2010; various sources)

Treatment Process	Technology Stage	Energy Product	Energy Use	Biosolids Product	End Uses
Biochemical Conversion					
Anaerobic Digestion	Mature Proven	Biogas Fuel Gas	Process heat Power generation Vehicle use or Natural gas replacement	Class B cake (conventional) Class A cake (with thermal hydrolysis)	Land application Land reclamation
Bioethanol Production	Mature with efforts to reduce the carbon footprint	Ethanol	Vehicle use Power generation Process heat	Cake	Land application Land reclamation
Thermo-chemical Conversion					
Incineration Co-combustion	Mature Proven	Heat	Process heat Power generation	Ash	Landfill
Thermal Drying-Gasification	Mature/Proven for other biomass Emerging for wastewater sludge	Syngas Fuel Gas	Process heat Power generation Vehicle use or natural gas replacement	Ash	Landfill
Pyrolysis-Thermal Drying	Mature/Proven for other biomass Emerging for wastewater sludge	Bio-oil	Process heat Alternative fuel	Char	Land application Alternative fuel Land reclamation
Thermal Drying (alone or in combination with above)	Mature Proven	N/A	N/A	Dried Biosolids	Land application Land reclamation Distribution and marketing Alternative fuel
Hydrothermal Carbonisation	Emerging	Hydrochar/Solid Biofuel	Power generation Process heat	Class A Dried biosolids Solid biofuel Solid adsorption media Building material	Land application Distribution and marketing Alternative fuel Wastewater effluent tertiary treatment

1.2 STATUS OF ENERGY GENERATION FROM WASTEWATER SLUDGE IN SOUTH AFRICA

1.2.1 Overview

South Africa has lagged behind developed countries in adopting and implementing energy and resource recovery from wastewater sludge. However, the nationwide electricity shortages and the consequential tariff increases implemented by Eskom since 2008 have served as a stimulus for South African wastewater utilities to consider exploiting the energy potential of wastewater sludge. Other key factors that have also contributed to the increased interest by South African utilities include much stricter wastewater sludge disposal legislation, concerns about the long-term sustainability of wastewater operations and mitigating the impacts of climate change.

In response to the increased interest in this area, a number of research projects, mostly sponsored by the Water Research Commission (WRC) and the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), have been carried out since 2009 to provide the South African wastewater industry with resources to pursue energy recovery from wastewater sludge initiatives.

Burton et al. (2009) evaluated the feasibility of generating energy from industrial and municipal liquid and solid wastewater streams in South Africa. The study estimated that approximately 1 488 MW of power can potentially be recovered from industrial and domestic wastewater sludge generated by a population of 48.5 million people in South Africa. This was equivalent to about 7% of the Eskom national supply in 2009. The estimated power that could potentially be generated from existing municipal WWTPs only, and used onsite to offset local energy requirements, was 824 MW. The study, however, assumed that all the energy in the raw wastewater solids generated by the population was available for conversion, and thus overestimated the energy potential (van der Merwe-Botha et al., 2016).

Burton et al. (2009) identified technological, financial and implementation barriers and risks to energy from wastewater technology projects in South Africa. While certain technologies are established internationally, they have not been demonstrated at South African WWTPs, thus hampering large-scale implementation. The scalability and reliability of new technologies has not been proven. In addition, technology designs are not always suited to developing world conditions in South Africa, particularly in terms of operation and maintenance requirements. There is also a perception that technologies for generating energy from wastewater are complex to build and implement and South Africa lacks the human resources capacity for maintenance.

Certain technologies are expensive in terms of capital outlay and the skills/expertise required for maintenance, especially if these have to be imported. In addition, newer technologies require significant capital expenditure to get them established. This often deters small companies and municipalities who may not have enough resources to pursue energy from wastewater, especially if the economic benefits take a long time to be realised. There are also legislative barriers that prevent ease of involvement by the private sector as well as difficulty in accessing third party finance.

Implementation barriers such as inefficiency in government departments which results in a long wait for licences, and complex contractual requirements limit interest from the private sector. The considerable lack of skills at all levels (from design and implementation to operation) limits the ability to build and operate energy from wastewater facilities. The need to develop and retain skills in the sector was identified as a high priority throughout the Burton et al. (2009) study.

Burton et al. (2009) also identified that decision support tools that can assist municipalities to evaluate and compare energy from wastewater technologies were needed. The life cycle approach to evaluating the costs and benefit of implementing technologies was recommended as the most appropriate approach. Life cycle analysis would enable incorporation of the costs (CAPEX, operations and maintenance) and the inputs and outputs (chemicals, solid waste generation, water pollutants and gas pollutants) of the various technologies to be assessed and compared. Other benefits, such as recovery of secondary products (e.g. nutrients, valuable metals), can also be taken into consideration to allow the net benefit of the technology to be assessed.

Following the study by Burton et al. (2009), Swartz et al. published, in 2013, "Energy Efficiency in the South African Water Industry: A Compendium of Best Practices"[1] which also acknowledged the need to generate energy at WWTPs as part of achieving energy efficiency. The report recommended that:

(a) wastewater treatment facilities should be encouraged to implement biogas energy production projects, and incentives should be provided for this purpose
(b) feasibility of using alternative renewable energy technologies in relation to initial capital costs, site conditions, specific climate conditions and return-on-investment should be investigated. Financial incentives should be provided for such investigations and projects.

Based on the recommendations from Swartz et al. (2013), subsequent research in South Africa focused on biogas generation from anaerobic digestion of wastewater sludge. The partnership between the South African Local Government Association (SALGA) and the South African–German Energy Programme (SAGEN) implemented by the GIZ has carried out various studies into biogas generation from WWTPs as part of its mandate to promote renewable energy at the local government level in South Africa.

One such study, on the potential for the development of viable anaerobic digestion projects at nine selected municipal WWTPs (GIZ, 2015), concluded that:

- Although all the WWTPs investigated had anaerobic digesters, they were operated to optimise sludge management and not biogas production. Thus, refurbishment of the digesters would

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[1] The study by Swartz et al. (2013) was commissioned by the Global Water Research Coalition, a partnership represented by four continental co-ordinators; Australasia, Europe, South Africa and the USA.

be required in order to effectively collect the generated biogas and utilise it for electricity generation

- Implementing biogas to energy projects is financially viable at large WWTPs with influent flows greater than 15 Ml/d. In general, a long-term investment is required with viable returns only possible over a 7-to-10-year period
- Most of the municipalities that were part of the study shared great interest in biogas projects and viewed them as options to reduce energy costs and reliance on the electricity supplied by Eskom via the national grid, as well as to reduce their carbon footprint by implementing environmentally friendly waste disposal practices and using clean energy.

The study also developed a model "A Biogas to CHP Tool" (GIZ, 2015) that assists municipalities in assessing, at a high level, the technical and financial viability of implementing a sludge-to-biogas project at a particular WWTP.

The most recent study on energy recovery from wastewater sludge was carried out by van der Merwe et al. (2016). The study built on the findings of the GIZ (2015) study and evaluated the potential to implement combined heat and power (CHP) generation, utilising biogas from anaerobic digestion of sludge at municipal WWTPs. The study used Johannesburg Waters' Northern Works, the only WWTP in South Africa that has implemented advanced anaerobic digestion with CHP generation, as a case study. In addition, data on municipal WWTPs with conventional anaerobic digesters was collected and used to identify and quantify the opportunities to replicate the approach at Northern Works across the South African wastewater industry. The study's main objective was to provide a practical guideline for the design and operation of an advanced sludge anaerobic digestion plant, with CHP generation.

Some of the key findings from the study were:

- There are more than 950 public sector WWTPs treating approximately 6 550 Ml/d of wastewater. The estimated sludge yield is 1 200–1 800 tDS/d
- 217 plants employed anaerobic digestion. Of these, 108 plants confirmed that they use anaerobic digestion for stabilisation and treatment of sludge
- The total biogas production is 282 671 m^3/d, which is equivalent to electrical energy of 657 765 kWh/day. At a unit cost of 60 c/kWh electricity, this energy value represents a potential saving of R144 million per annum
- In terms of the feasibility of advanced anaerobic digestion with CHP generation uptake, 31 plants out of the 108 (29%) do not have sufficient generating capacity (irrespective of the type of financing model) while it is feasible for the other 77 plants (72%) to implement CHP generation (subject to the financing model applied).

Thus, since the electricity shortage crisis in 2008, there has been concerted effort in the South African wastewater sector to research technologies that generate energy from wastewater sludge. The research has mostly focused on the utilisation of biogas from anaerobic digestion of wastewater sludge.

1.2.2 Key Drivers for Energy Generation from Wastewater Sludge

1.2.2.1 Legislation and Regulation Compliance

The key legislation that drives the management and disposal of wastewater sludge in South Africa is the National Water Act (Act 36 of 1998), the National Environmental Management: Waste Act (Act 59 of 2008) and the Waste Amendment Act (Act 26 of 2014)[2].

The Department of Water and Sanitation (DWS) is responsible for the regulation of wastewater services, as mandated by Section 155(7) of the Constitution, Section 62 of the Water Services Act (No. 108 of 1997), and 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. Under this mandate, the DWS issues water use authorisations (WUA) to wastewater utilities, which permit them to treat and dispose of wastewater in a manner that complies with the National Water Act (NWA). The WUA specify that management activities must comply with "the requirements of Chapter 5 of the National Environmental Management: Waste Act, 2008 (Act 59 of 2008) and the Guidelines for the Utilisation and Disposal of Wastewater Sludge: Volumes 1-5" (WRC, 2006; 2009).

The Guidelines for the Utilisation and Disposal of Wastewater Sludge (WRC, 2006; 2009) were prepared, under sponsorship by the WRC, to assist municipalities in navigating the legislative requirements for sludge management and disposal. The guidelines consist of five volumes, each volume stipulating legislative and regulatory requirements for specific aspects of sludge management as follows:

- Volume 1: Report TT 261/06 Selection of Management Options
- Volume 2: Report TT 262/06 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.

The sludge guidelines, as a stand-alone, are not law. However, once they have been included in a WUA, they become enforceable, and water utilities can follow the guidelines as a basis for compliance with sludge regulations.

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[2] Only a summarised version of the legislative and regulatory requirements for sludge management are given in this report. For more details, readers should refer to the relevant acts as well as WRC (2006 & 2009) and van der Merwe et al. (2016).

Apart from complying with utilisation and disposal requirements, South African utilities are also required to comply with GHG emission requirements in sludge management activities. Compliance with GHG emissions is stipulated in the National Environmental Management: Air Quality Act (Act no 39 of 2004). Under this Act, the Draft National Greenhouse Gas Emission Reporting Regulations (June 2015) were published and circulated for public comment. The regulations stipulate the reporting requirements for five sectors. The two sectors in the regulations that impact sludge management activities are energy and waste. Activities under the energy sector that relate to sludge management and require GHG emissions reporting include fuel combustion, electricity and heat production as well as gas venting and flaring. Under the waste sector, wastewater treatment and discharge are listed as an activity that requires GHG emissions reporting (Government Gazette, 2015).

Wastewater activities and sludge treatment activities generate the two GHGs that contribute the most to global warming, i.e. methane (CH_4) and carbon dioxide (CO_2). Methane is generated mostly through anaerobic digestion of sludge. Methane has an estimated global warming potential (GWP) of 28–36 CO_2-equivalent over 100 years (US EPA, 2017). GHG emissions global data for the period 2000–2010 indicates that CO_2 and CH_4 contributed 76% and 16% respectively to total CO_2-equivalent emissions (Edenhofer et al., 2014). The South African data from the Department of Environmental Affairs for the same period, 2000–2010, indicates that CO_2 contributed 83.2%, and CH_4 contributed 11.4% of the total CO_2-equivalent emissions.

In addition to legislative requirements, the DWS introduced, in 2009, an incentive-and risk-based regulation through the Green Drop Certification programme. The process assesses the performance of WWTPs in terms of treatment technology, capacity, technical skills and compliance with legislative requirements. The initial Green Drop plan focused mainly on liquid treatment. However, the updated 10-year Green Drop plan (2015–2025) includes solids/sludge management as a stand-alone key performance indicator (DWS, 2015).

The four performance areas which will drive the industry towards compliant and resource-based sludge management strategies include (DWS, 2015; van der Merwe-Botha et al., 2016):

- 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 is not conceptualised or planned.

Both local and international studies have found that businesses often view compliance with regulations as a necessary burden to avoid consequential financial, reputational and performance repercussions (WEF, 2010; Sadiq & Governatori, 2014). In cases where the repercussions are not severe, businesses are tempted to ignore compliance requirements, which, in wastewater operations. would severely impact the environment and public health. The introduction of the incentive-driven

Green Drop process by the DWS is reported to have shifted South African municipalities' view of regulation from a "burden" to an opportunity to improve their wastewater business process and operations. The majority of municipalities report that they are reaping the benefits from improving their compliance regiments (WIN-SA, 2011; WIN-SA; 2012, van der Merwe-Botha et al., 2016).

1.2.2.2 Energy Cost and Availability

A study by Frost and Sullivan (2011) showed that wastewater treatment consumes about 55% of the energy utilised in the South African water sector. The bulk of this energy is consumed in the energy-intensive biological nutrient removal (BNR) activated sludge process for aeration. The process has been widely adopted by the wastewater sector in order to meet DWS high final effluent discharge standards that prevent pollution of surface water resources. A 2015 survey of municipal WWTPs showed that out, of the 950 public sector plants, 395 (~42%) employ the activated sludge process (van der Merwe-Botha et al., 2016). Depending on the type of aeration technology, aeration can consume 40–80% of the total energy consumption at a WWTP (Musvoto & Ikumi, 2016; Winter, 2011). Thus, any changes in energy availability and costs heavily impact both the efficiency and operating costs of wastewater treatment in a large number of municipalities.

Prior to 2008, South African wastewater utilities did not consider energy cost and availability to be a high risk to wastewater operations because electricity prices were historically low, and declining (in real terms) compared to other countries. This was due to a number of factors, the most dominant being Eskom's investment as well as accounting and pricing policies. Between 1978 and 2008 the real average price of electricity fell by more than 40% (Deloitte, 2014). However, from 2008, the trend in prices took a dramatic turn when demand outstripped supply, resulting in power shortages. In response, Eskom was forced to embark on a massive investment programme to increase South Africa's generation, transmission and distribution capacity. As a short-term measure, Eskom introduced both load shedding and electricity price increases.

Tariff increases were most drastic between 2008 and 2011, where the average annual increase over the four years was 27%, about four times above average annual inflation. Over the past eight years, between 2008 and 2016, the average tariff increase was 17%, about 2.7 times above average annual inflation. The tariff increases from 2016/2017 to 2017/2018 was moderate, at only 2.2%. However, in Eskom's 2018/2019 revenue application submitted to the National Energy Regulator of South Africa (NERSA), Eskom has requested a tariff increase of 19.9% for 2018/2019[3]. Thus, the increase in electricity prices is projected to rise further until Eskom's investment program is completed.

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[3] Media outlets e.g. fin24 and Business Day reported on 18th September 2017 that NERSA gave Eskom permission to hold hearings on the proposed 19.9% tariff increase in 2018/2019. If approved, such an increase could result in municipalities paying about 27.3% more for bulk electricity purchases.

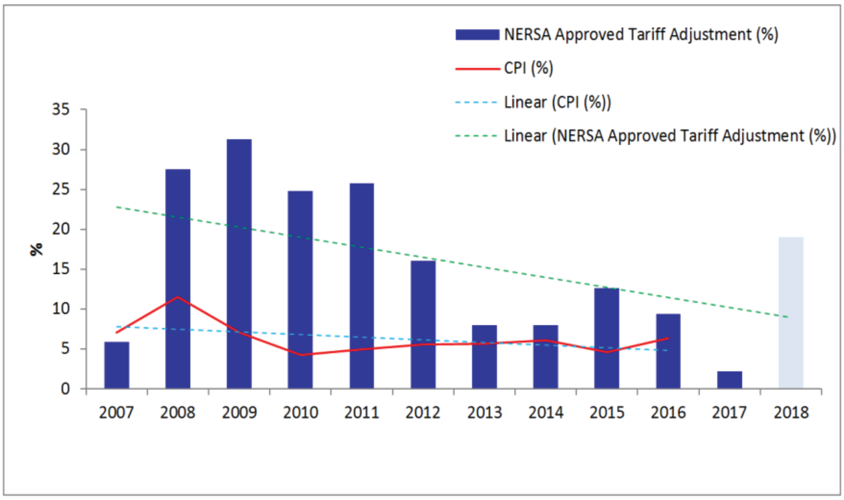

Figure 1-1: Historical (2007–2017) ESKOM NERSA Approved Tariff Increases, Including CPI (Based On Data From Eskom)

The combined effect of power supply disruptions and price increases had a significant impact on the South African wastewater sector, as it resulted in:

- Non-compliance with regulatory standards due to treatment process equipment not operating during power outages
- Additional investment required for repairs to damaged equipment as well as investment in back-up generators to supply electricity to critical treatment units during power outages
- Increase in operating costs due to high electricity prices which requires additional funding

While the increase in operating costs can be offset by increasing user rates, in South Africa, for social, economic and political reasons, it is not feasible for municipalities to indiscriminately increase user rates to finance the increase in energy costs. Thus, municipalities will be forced to use capital reserves to maintain fair municipal rates. This will reduce funding available for other critical areas such as maintenance and upgrade of treatment plants and process equipment. In addition, municipalities might be forced to base all purchases of services and equipment solely on lowest initial capital cost rather than considering the level of expertise as well as the life cycle cost of owning and operating the equipment. Such an approach is unsustainable in the long term.

In their research, Bhagwan et al. (2011) noted the risk of unsustainability posed by high electricity costs to an industry that relies heavily on energy-intensive technologies to meet regulatory requirements. They concluded that it is becoming increasingly difficult for South African municipalities to balance the regulatory requirement for higher effluent quality standards and sludge quality, which requires energy-intensive technologies, with the increased cost of energy to sustain these technologies.

The events of the past ten years have made South African municipalities conscious of the significant risk posed by the shortage and rising cost of electricity to the operation and treatment of wastewater.

The Wastewater Risk Abatement Plan (W_2RAP), a risk management tool to enhance municipal wastewater service delivery in the South African wastewater sector, confirms that electricity is universally identified as a risk at all municipalities. Wastewater treatment managers report that the most common approaches to mitigate risk are: (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 continuing with business as usual; (iii) exploring the scope for electricity efficiency gains; and (iv) exploring alternative energy sources to substitute for electricity (van der Merwe et al., 2011; 2016).

The energy crisis increased interest in energy efficiency in the country, encompassing both energy conservation in treatment processes and generation from wastewater sludge. The City of Johannesburg is the first municipality to take practical measures, by developing a strategy for power generation from anaerobic digester biogas at three of their seven WWTPs, namely Northern Works, Olifantsvlei and Goudkoppies. Northern Works was upgraded in 2016 by adding advanced anaerobic digestion through cell lysis and CHP generation; the first system in South Africa. Other municipalities have also explored energy efficiency initiatives through studies into energy generation and implementing more efficient aeration systems.

The incentive for South African municipalities is that both international and local studies have shown that when energy efficiency initiatives are effectively implemented, it is possible for a WWTP to be energy sufficient or even energy positive. In addition, although not yet implemented in South Africa, there are a number of established and emerging sludge-to-energy technologies that have been proven internationally that can be implemented in South Africa at minimal risk.

1.2.2.3 Materials Recovery

In addition to energy, other valuable materials that can be recovered from wastewater include:

- Phosphorus (P) through precipitation of struvite (magnesium ammonium phosphate) and calcium phosphate for use as a fertiliser
- Ammonia in the form of aqueous ammonia or ammonia salts (sulphate or nitrate)
- Polymers (extracellular polymeric substances, EPS) for use in biotechnology
- Bioplastics
- Proteins
- Building material
- Metals

A thorough review of technologies for recovering other valuable materials is beyond the scope of this project. Readers can refer to numerous publications for details on technologies for recovering materials from wastewater sludge, and their stages of development[4]. Phosphorus (P) recovery,

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[4] Examples of literature on materials recovery from wastewater sludge include:

through crystallisation of struvite, is among the most established and proven technologies, which, if economically viable, can be implemented at minimal risk at South African WWTPs.

Implementing energy recovery creates opportunities for recovery of other materials; thus, these opportunities are not mutually exclusive. For example:

- Advanced anaerobic digestion produces sludge centrate that has high concentrations of phosphorus and ammonia, making struvite crystallisation and ammonia recovery viable
- Thermo-chemical conversion processes like gasification and incineration produce bio-ash that can be used in the production of construction materials
- Catalytic thermo-chemical conversion processes produce biochar that can be used as an adsorption material for treatment of wastewater effluent.

(i) Larsen et al. (2009) on technologies and processes that successfully extract phosphate as fertiliser
(ii) Kleerebezem and van Loosdrecht (2007) on manufacture of bioplastics
(iii) Pincince et al. (1998) on metal recovery metals from sludge
(iv) Stamatelatou and Tsagarakis, (2015) on volatile fatty acids (VFAs), polymer and extracellular polymeric substances (EPS) production for use in the food, cosmetics, construction, pharmaceutical and paint industry

Chapter 2 Project Overview

2.1 CONTEXT AND OBJECTIVES

2.1.1 Project Contextualisation

The historical approach to sludge management in South Africa has been mostly to implement strategies and practices that fulfill legislative and regulatory requirements enforced by the DWS. Although the new regulations stipulated in the DWS "Guidelines for the Utilisation and Disposal of Wastewater Sludge" (WRC, 2006; 2009) recommend beneficial use, there are very few WWTPs that recover energy (and/or other valuable resources) from sludge or even have the traditional cradle-to-grave approach to sludge management[1]. However, the electricity shortages in 2008 exposed the risk posed by unreliable power supply and continued increase in electricity prices to wastewater treatment operations in South Africa, stimulating interest in energy recovery from wastewater sludge technologies. As a result, research, mostly sponsored by the WRC, into energy efficiency (generation from sludge and conservation) in wastewater treatment increased from 2009. In addition, large municipalities like the City of Johannesburg developed strategies to mitigate the risk of high electricity prices which culminated in the first municipal advanced anaerobic digestion and CHP generation plant in South Africa being commissioned at Northern Works in 2014.

The most significant research that focused on energy generation from wastewater since the electricity price increases in 2008 were by Burton et al. (2009), GIZ (2015) and van der Merwe et al. (2016). Burton et al. (2009) identified the lack of detailed information relating to technologies that generate energy from wastewater sludge as one of the key barriers to implementing sludge-to-energy projects in the country. The study also identified anaerobic digestion (due to it being established, well understood and widely used locally and internationally) as the easiest and most suitable technology to apply to generate energy from sludge at South African WWTPs. Since the technology is well established, research investment needs are more towards applied research into technology and skills development rather than fundamental research. The study also identified fermentation to produce ethanol and gasification and advanced thermal technologies as areas that require further research and that South Africa lacks skills in.

Subsequent research by the GIZ (2015) assessed the potential to develop viable energy generation projects utilising biogas from anaerobic digestion of sludge. The research selected nine WWTPs as case studies and developed a modelling tool to assist municipalities in carrying out a high-level assessment of the financial viability of implementing a biogas to energy project at a WWTP, prior to carrying out a detailed feasibility study. Following the same theme, van der Merwe et al. (2016) focused on CHP generation at WWTPs, utilising biogas produced from anaerobic digestion of sludge.

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[1] It should be noted that the new approach to waste management advocates a "cradle-to-cradle" approach through implementing principles of the circular economy (World Economic Forum et al., 2014; European Commission 2015a)

Using data from the Northern Works WWTP, the research produced a guideline for municipalities to assess the feasibility of implementing anaerobic digestion and CHP generation at WWTPs.

The above analysis shows that while significant applied research has been carried out in South Africa on sludge-to-energy technologies, the focus has mostly been on anaerobic digestion and biogas generation. Therefore, to give municipalities more options, additional research is still required to evaluate a wider range of sludge-to-energy technologies that can be feasibly applied in South Africa.

To address some of the gaps identified in previous studies, the WRC continued its investment into research on energy efficiency in the wastewater sector by financing this project. The project evaluated the feasibility of implementing three sludge-to-energy technologies (two established and one emerging) at a typical South African WWTP.

Based on the literature review and the needs of the South African industry, the following technologies (from both biochemical and thermo-chemical conversion categories) were selected for evaluation, as follows:

a) Established

Advanced anaerobic digestion using thermal hydrolysis for sludge pre-treatment

Thermal hydrolysis (TH) is the most widely applied sludge pre-treatment method in advanced anaerobic digestion systems, with over 60 plants installed worldwide. The process involves injecting steam at high temperature and pressure to rupture cells and improve the conversion of organic matter to biogas in the digestion process. Performance data comparing seven sludge pre-treatment methods indicates that sludge pretreated using TH achieves the highest destruction of volatile solids (and hence biogas yield) during anaerobic digestion. The process also produces the least digested solids, thus reducing disposal costs (Jolly & Gillard, 2013).

Northern Works WWTP, which was evaluated by van der Merwe et al. (2016), uses electro-kinetic disintegration as the waste activated sludge pre-treatment method. Thus, evaluating advanced anaerobic digestion using TH as the sludge pre-treatment method improves the knowledge available to the South African wastewater sector.

Gasification

Gasification is a thermo-chemical conversion process (similar to combustion) that converts carbon-based material to synthetic gas (syngas) in a reactor after the addition of heat, steam, oxygen and/or nitrogen. Both heat and a combustible gaseous product are produced. Syngas can be used as fuel to generate electricity and heat. The process is well established and has been applied mostly for gasification of coal and woody biomass since the 1900s. The process has been applied for processing other biomass, including sewage sludge, with mixed results. A literature review for this project identified four commercial, full-scale gasification plants processing municipal wastewater sludge internationally. While there are no gasification plants processing wastewater sludge in South Africa, Burton et al. (2009) identified gasification as a feasible technology for South Africa to treat fresh dewatered and dried (or previously stockpiled) sludge. On this basis, gasification was selected for evaluation.

b) Emerging

Enhanced hydrothermal carbonisation

Hydrothermal carbonisation (HTC) is a thermo-chemical conversion process that converts wet organic matter, under moderate temperature and pressure, into a high-energy-value hydrochar that can be used as a biofuel. In some cases, the reaction is aided by a catalyst which reduces the temperature and processing time. A wide variety of waste biomass, without regard to moisture content, can be processed using HTC. Recent technology developments by companies like PCS Biofuels™ have advanced the HTC process through the development of patented catalysts and proprietary processing methods. Labelled as hydrothermal polymerisation (HTP), this enhanced process allows any type of low-value waste biomass to be efficiently and effectively processed in an anaerobic chemical environment at temperatures of around 200–240°C and autogenous pressure of 3–3.5 MPa for one hour. The process emits no methane and very little CO_2. This reduces the amount of GHGs released into the atmosphere. The resulting CO_2-neutral solid hydrochar can be burnt in a boiler to produce electricity and heat. The polymeric hydrochar can also be used in agriculture, the building industry and as an adsorption media. The enhanced HTC technology developed by PCS Biofuels™ is still emerging and has only been applied at full-scale for processing wood chips mixed with bagasse and palm oil. However, laboratory-scale tests in Canada have shown that the technology can process wastewater sludge, on its own and mixed with other biomass, to produce hydrochar with an energy content varying from 17–25 MJ/kg.

Catalyst-aided hydrothermal polymerisation PCS technology was selected for evaluation of its capacity to generate energy from wastewater sludge for the following reasons:

(i) destroys all microbial life (including prions and other micro-pollutants) to produce a sterile, odourless by-product that can be used as a biofuel and in industrial applications
(ii) any cellulose-based biomass can be used, which creates room for co-treatment of sludge with wastewater screenings and other waste from local communities (e.g. municipal solid waste, food industry waste, agricultural waste, etc.)
(iii) carbon dioxide neutral process with no methane generation
(iv) can be integrated with other existing sludge treatment and sludge-to-energy processes, like anaerobic digestion, thus maximising usage of existing infrastructure
(v) small footprint, and low maintenance and skills requirements.

2.1.2 Project Objectives

The main objectives of the project were to:

- Carry out a technical evaluation of each of the three technologies, to determine what capacity, at a case study greenfield plant, would be required to process the sludge currently being produced at the plant, determine the quantity of energy that would be generated and the quality and quantity of the processed sludge/by-products and determine the disposal/beneficial use options, in line with DWS regulations. Waterval WWTP was selected as the case study plant (see Section 2.2.1).
- Evaluate the financial and economic impacts of implementing each technology, compared to implementing the conventional mesophilic anaerobic digestion (MAD) that is currently being employed at Waterval WWTP.
- Conduct a knowledge dissemination workshop on the project results.
- Produce a report detailing the findings of the project.

The technical analysis involved preliminary design and modelling for the established technologies, to determine the capacity of the process required. Laboratory-scale and pilot-scale studies were initially carried out for the emerging PCS technology to collect data for full-scale preliminary design and modelling. In addition, a brief literature review, giving the technical overview and performance of each technology based on literature data, was conducted.

By adopting this approach, the project addressed the gaps in knowledge of sludge-to-energy technologies identified in previous research. In addition, valuable information on both established and innovative emerging technologies that South African municipalities can use to formulate long-term sludge management strategies was produced.

2.2 APPROACH AND METHODOLOGY.

2.2.1 Case Study Plant

Waterval WWTP was selected as the case study plant to provide baseline sludge data for evaluating the selected technologies. The PCS pilot-scale plant was also installed at the site and processed the various sludge types generated at the plant.

The design capacity of Waterval WWTP is 155 Ml/d average dry weather flow (ADWF). In 2015/2016, the influent ADWF to the plant was 120 Ml/d and annual average daily flow was 180 Ml/d. The works consists of four modules, each with its own set of primary settling tanks (PSTs), activated sludge bioreactors, and secondary settling tanks (SSTs). Waste activated sludge (WAS) is thickened in dissolved air flotation (DAF) thickeners and then combined with primary sludge (PS) from the PSTs prior to anaerobic digestion. The quantity of sludge (model predicted at design flow) and quality of sludge produced at the plant, based on the plant performance in 2015/2016, is shown in Table 2-1. Figure 2-1 shows a simplified process flow diagram (PFD) for the sludge treatment process.

Table 2-1: Quantity and Quality of Sludge Generated at Waterval WWTP (Based on 2015/2016 Site Measured Data). The Data Was Applied in the Technical Evaluation of the Selected Technologies

Parameter	Units	PS	WAS	Blend to Anaerobic Digesters
Sludge mass[1]	tDS/d	28	22	50
Concentration[2]	%	4.0	5.0	4.4
Volatile solids content	%	67	74	70
Ash content	%	33	26	30

Notes:

1. Sludge mass model predicted at design flow based on 2015/2016 wastewater characteristics, and treatment units performance
2. PS and WAS concentration based on site measurements for PST underflow and DAF thickeners overflow respectively

Fourteen primary anaerobic digesters operated in the mesophilic temperature range (35 ± 2°C) have been provided, viz:

- Digesters 1–4 process sludge from Module 1. The digesters are unheated and were designed to be operated at 33 days' retention time. The volume of each digester is 2 425 m^3
- Digesters 5–10 process sludge from Modules 2 and 3. The digesters were designed to be operated at 20 days' retention time. The volume of each digester is 3 600 m^3
- Digesters 11–14 process sludge from Module 4. The digesters were designed to be operated at 20 days' retention time. The volume of each digester is 1 140 m^3

The total primary anaerobic digester volume is therefore 35 860 m^3. Digested sludge from the primary digesters is discharged to four secondary, open, unheated anaerobic digesters. Sludge from the secondary digesters is dewatered on four belt filter presses (BFP). Due to the limited capacity of the BFPs, some of the digested sludge is diverted to sludge drying paddies for dewatering. The dried sludge is composted onsite and the compost is collected by local farmers at no charge. Dewatered sludge from the BFPs is stockpiled onsite and is also collected by farmers, on its own or sometimes when mixed with the compost.

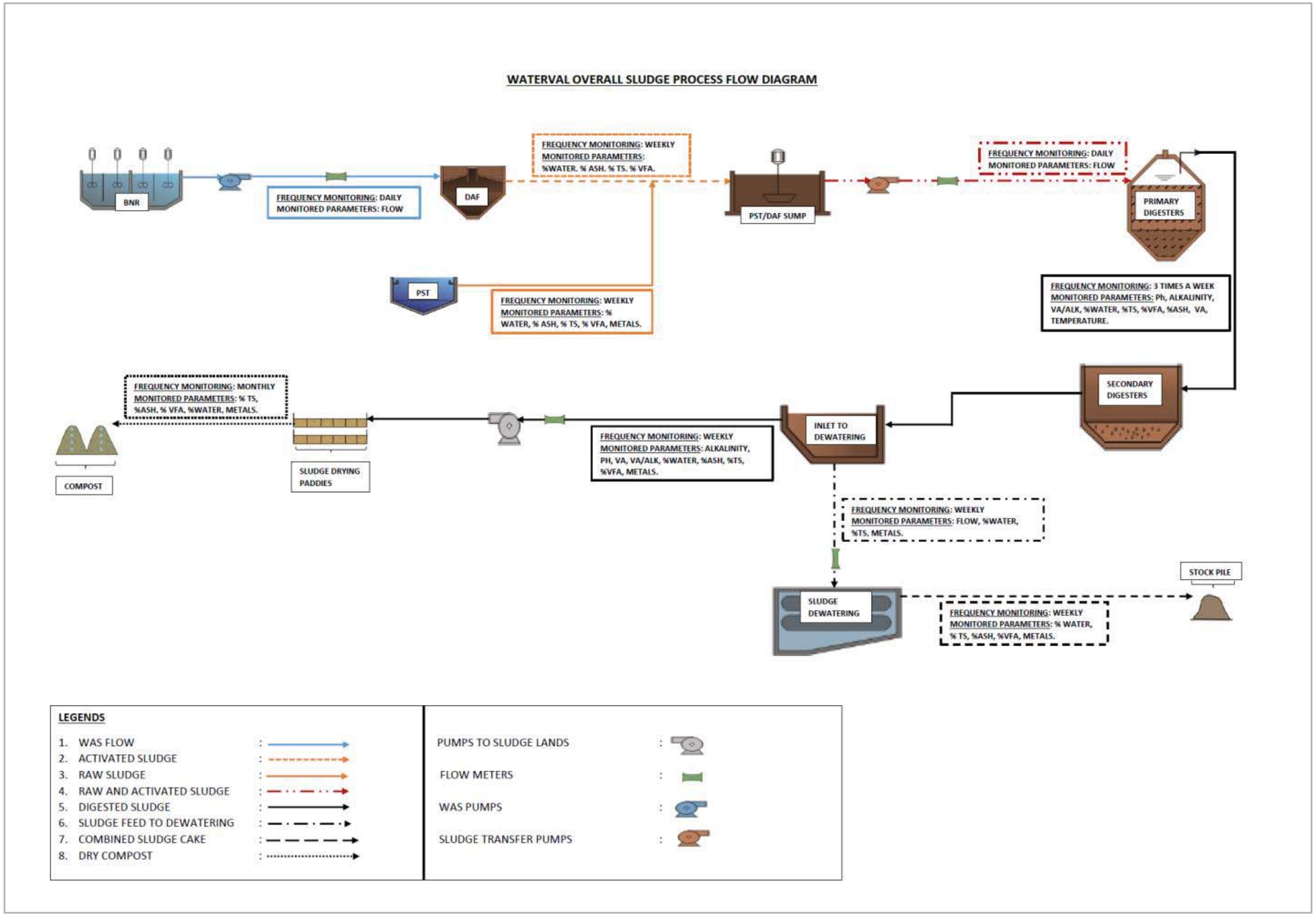

Figure 2-1: Simplified Process Flow Diagram For Sludge Handling and Treatment at Waterval WWTP (Courtesy of ERWAT)

The sludge at the site is analysed for microbiological parameters, metals and other physical parameters. However, the following parameters which would enable full classification of the sludge in terms of the sludge guidelines (WRC, 2006; 2009), are not routinely analysed:

- Faecal coliform
- Helminth ova (only total ova is analysed)
- Arsenic [6]
- Nutrients (TKN, Total P and potassium) that are required for classification of sludge for agricultural use
- Metal content in terms of the toxicity characteristics leaching procedure (TCP) for sludge disposal

Based on the available historical data, the classification for digested sludge and compost is provisionally as follows:

- Based on the total ova count, both the digested sludge and compost fall into “Class B” – General use quality
- The BFP dewatered digested sludge falls into stability “Class 2” and the compost into “Class 1”
- The pollutant class for both digested sludge and compost is “Class A” since all the metals achieve at least 90% compliance with the limits

Thus, provisionally, the digested BFP dewatered sludge is classified as B2a and the compost as B1a.

Additional analysis of the sludge is required to determine the optimal beneficial use/disposal route for sludge from the plant. Such analysis was beyond the scope of this project.

The biogas produced is stored in the gas holding tank and used for heating the boiler that produces hot water for heating the sludge. Excess gas is flared into the atmosphere. Historical analysis records showed that the biogas consisted of 65% methane. No records of the amount of biogas produced were available.

2.2.1.1 Technology Technical Evaluation Scenarios

Two scenarios for evaluating the technologies were adopted:

- Greenfield installation of the technology to treat 50 tDS/d combined PS and WAS, with the characteristics given in Table 2-1. Energy recovery was incorporated in the technologies as appropriate. The technologies were compared with a greenfield conventional anaerobic digestion plant similar in operation to the one at Waterval but with energy recovery

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[6] Analysis for arsenic carried out during the PCS pilot studies showed a concentration of ~20 mg/kg in digested sludge

- Retrofitting as appropriate the technology at an existing conventional MAD plant similar to Waterval
- The following routes to disposal were adopted in the evaluations
    - Current practice at Waterval of utilising processed sludge/by-products (if they comply with the DWS regulations) in the agricultural sector. Although currently ERWAT gives digested sludge and compost away to farmers for free, a market-related charge for compost was applied in the economic evaluation for this project
    - Dispose the processed sludge/by-products to the nearest landfill and pay a tipping fee. This is based on the assumption that the processed sludge/by-products do not meet the standard for beneficial use or site disposal.

2.2.2 Financial and Economic Evaluation Approach

Cost benefit analysis (CBA) was applied to present and compare the whole life costs and benefits of each technology. Net present value (NPV) was adopted as the CBA evaluation criteria. During the project proposal, it was intended to apply life cycle analysis (LCA) to holistically quantify the environmental impacts of each technology. However, the assessment could not be carried out under this project due to a lack of high-quality data as well as resource barriers (access to simplified LCA methodologies, finance and expertise). It is therefore recommended that future research on these technologies include adequate resources to carry out LCA. To take into account the long-term environmental impacts of the projects, hyperbolic discounting was applied in the CBA (Mullins et al., 2014).

The key parameters applied in the CBA are given in Table 2-2.

Table 2-2: Key Parameters Applied in the Cost Benefit Analysis

Parameter	Value	Comments
Discount rate	8%	Recommended rate for South African projects (Mullins et al., 2014)
Inflation rate	6%	Based on historical 2006–2016, and assumed to remain constant through the amortisation period
Period	20 years	Expected useful life of technology
Tax Rate	28%	South African corporate tax rate
Interest rate (cost of borrowing)	9%	LIBOR + 2.5%
Loan term	20 years	Assumed the same as discount period
Electricity tariff increase	13% pa	Mullins et al. (2014). Projected tariff increase based on Eskom MYPD

The sensitivity of the CBA to the project financing model was also evaluated. The scenarios that were evaluated were financing through:

- 100% equity
- 100% loan

- 45% grant and 55% equity (Department of National Treasury)
- 45% grant and 55% loan with bullet repayment

It should be noted that a detailed evaluation of project finance models is beyond the scope of this research. The finance models selected were based on publications from the Development Bank of Southern Africa (DBSA) and Department of National Treasury and only serve to illustrate the sensitivity of NPV to financing models.

2.2.3 Project Tasks

The project was carried out in six major tasks as outlined below.

2.2.3.1 Task 1: Evaluation of the PCS Technology

Laboratory-scale investigation

A laboratory-scale PCS reactor was set up at the University of Stellenbosch. To test the impact of the quality of sludge on treatment efficiency and quality of biofuel produced, different sludge types were processed in the reactor at varying temperature.

Proximate and ultimate analyses were carried out on both the feed sludge and the hydrochar produced to determine the physical and chemical compositions listed in the DWS "Guidelines for the Utilization and Disposal of Wastewater Sludge". The centrate (supernatant) from the treatment process was analysed for COD, TKN, free and saline ammonia (FSA), total P, E coli and trace elements. In addition, the feedstock and hydrochar were tested for selected endocrine disrupting compounds (EDCs).

The data from the laboratory-scale investigations was analysed and applied in the design of the procedure for pilot-scale investigations.

Pilot-scale investigation

This task involved the design and installation of a pilot-scale PCS reactor at ERWAT's Waterval WWTP. The investigation involved processing all the sludge types (i.e. PS, WAS, combined WAS and PS, and digested sludge) generated at the plant, on their own and in combination with screenings from the inlet works. Oxygen bomb calorimetric tests (to determine calorific value), proximate and ultimate analyses, were carried out on the feedstock and hydrochar. In addition, the supernatant was analysed for the same parameters as in the laboratory-scale tests.

Evaluation of implementation of the PCS technology at full scale

Data from the laboratory, pilot-scale investigations and the international full-scale demonstration plant was applied in the preliminary design of a full-scale plant, processing sludge of similar characteristics as that generated at Waterval WWTP. An economic evaluation, using the criteria outlined above, was then carried out.

2.2.3.2 Task 2: Evaluation of Advanced Anaerobic Digestion with Thermal Hydrolysis

A desktop preliminary design of an advanced THP–MAD digestion plant, processing combined PS and WAS of the same quality as that produced at Waterval WWTP, was carried out. An economic evaluation using the criteria outlined above was also carried out.

2.2.3.3 Task 3: Evaluation of Gasification Technology

A desktop preliminary design, using models and data from international pilot and full-scale sludge gasification plants, was carried out to determine the size of a full-scale plant treating combined PS and WAS of the same quality as that generated at Waterval WWTP. A high-level economic evaluation was carried out.

2.2.3.4 Task 4: Comparison of Technologies

The three sludge-to-energy technologies were compared based on the economic evaluation results. Gaps in technology knowledge and understanding were identified during this comparison. The advantages and disadvantages of implementing the technologies on South African plants were also presented.

2.2.3.5 Task 5: Knowledge Dissemination Workshop

A workshop was held to disseminate the outputs of the project to the general South African wastewater sector.

2.2.3.6 Task 6: Project Report

A project report was produced in line with the requirements of the WRC.

Chapter 3 Hydrothermal Carbonisation

3.1 CONVENTIONAL HYDROTHERMAL CARBONISATION

3.1.1 Process Fundamentals – A Brief Review

Hydrothermal carbonisation (HTC) is a thermo-chemical conversion process that converts organic matter to yield a solid, coal-like product referred to as hydrochar. The process, which was introduced by Bergius in 2013, has been in use as a method for simulating natural coalification in coal petrology for nearly a century (Funke and Ziegler, 2010).

HTC, unlike other thermo-chemical conversion processes (like dry pyrolysis and gasification), involves the conversion of wet biomass under moderate to high temperature and pressure and, in some cases, in the presence of homogeneous or heterogeneous catalysts. The conversion is through complex pathways that include hydrolysis, dehydration, decarboxylation, aromatisation and re-condensation. As temperatures increase, the physical and chemical properties of water change significantly, and water acts as a reactant, solvent and catalyst for organic compounds and facilitates these reactions (Prado & de Klerk, 2014; Berge et al., 2011). Fundamentally, the process involves lowering both the oxygen and hydrogen content of the feed (measured in terms of the O/C and H/C ratio) and increasing the carbon content of the subsequent hydrochar. Unlike dry thermo-chemical conversion processes, hydrolysis is the critical and initial step in HTC. Because hydrolysis exhibits lower activation energy, lower temperature HTC reactions have been shown to achieve the same level of conversion efficiency as higher temperature processes. Figure 3.1 shows the simplified reaction mechanisms for HTC and products classes, compared to dry pyrolysis.

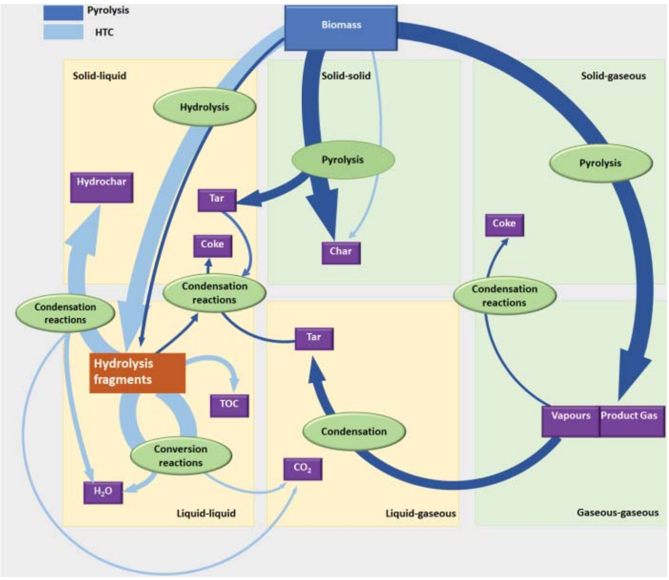


Figure 3-1: Simplified Reaction Mechanisms for HTC and Product Classes Compared to Dry Pyrolysis (Adapted from Libra et al., 2011)

Based on experimental results using pure cellulose ($C_6H_{10}O_5$) as a model substrate, the approximate stoichiometric equation for HTC can be represented as follows (Libra et al., 2011):

$$C_6H_{12}O_6 \rightarrow C_{5.25.}H_4O_{0.5} + 0.75CO_2 + 3H_2O + \text{energy} \qquad (3\text{-}1)$$

It should be noted that the approximate equation is based on processing of a pure substrate. Biomass is however not heterogeneous and, as mentioned above, complex reaction mechanisms are involved that are highly dependent on reaction conditions, and these mechanisms are still not well understood. For example, while the heat of enthalpy for processing cellulose shows that the reaction is exothermic, the initial phases are endothermic. It should also be expected that incomplete HTC is endothermic owing to the endothermic nature of the hydrolysis of cellulose (Libra et al., 2011). This impacts on HTC process design and control.

The process is classified as *subcritical* or *supercritical* water depending on the temperature and pressure ranges. Subcritical water conditions occur at temperatures between 100°C and 374°C and autogenous pressure (1–6 MPa), sufficient to keep the water at liquid state. Supercritical water conditions occur at temperatures above 374°C and pressure above 22 MPa, where water becomes compressible and its properties depend on the pressure.

For process temperatures below 400°C, most organics remain as they are or are converted to solids. The amount of gas produced is relatively small and is low in carbon and, consequently, GHG effects. Thus, the product of subcritical water HTC is mostly solid (50–80%) with smaller amounts of liquid (10–20%) and gas (2–10%). However, at higher temperatures, particularly when using a catalyst, more liquid hydrocarbons are formed and more gas is produced resulting in what is called "hydrothermal liquefaction". An increase of temperatures to supercritical levels results in hydrothermal gasification, and the primary products are gaseous (either methane or hydrogen), depending on process conditions (Libra et al., 2011).

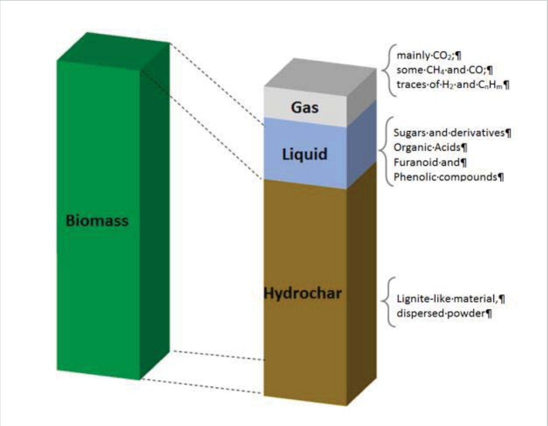


Figure 3-2: Products of Hydrothermal Carbonisation, Separated According to Their State of Aggregation (Adapted from Funke & Ziegler, 2010)

3.1.2 Factors that Affect HTC

Based on published data, the main factors that affect HTC are:

a) Hydrous conditions

HTC is a wet process, and it has been shown that solids above the liquid surface do not carbonise. Although it is possible to carbonise biomass in oil, water has been proven to accelerate the process and promote the reaction mechanisms. Water is therefore a necessary and key ingredient in HTC (Funke and Ziegler, 2011), for the following reasons:

- it is a good heat transfer and storage medium
- it suppresses pyrolysis
- it acts as a reactant, solvent and catalyst for organic compounds, and facilitates reactions like hydrolysis, ionic condensation and cleavage.

b) Temperature

Temperature to a large extent governs the reactions of HTC. Two simple kinetic models, based on empirical data, have been reported in the literature to describe the impact of temperature on reaction rate (Funke and Ziegler, 2011). Apart from the reaction rate, temperature also influences the number of biomass compounds that can be hydrolysed, e.g. hemicellulose is almost completely hydrolysed at 180°C to 212°C, major parts of lignin at around 200°C and cellulose at around 220°C to 256°C (Funke and Ziegler, 2011; Liu et al., 2013; Prado & de Klerk, 2014). Significant pyrolytic reactions might also occur at higher temperatures, even under *subcritical* water conditions, depending on biomass type. Temperature also indirectly affects HTC by changing the characteristics of water (solvent properties and viscosity) at high temperature which enhances the decomposition of biomass.

c) Pressure

The impact of pressure is less substantial than temperature, provided that the pressure is sufficient to maintain a liquid water phase. The pressure in a sealed HTC reactor rises isotropically due to increase in temperature or adding fluid. Under these circumstances, when no external additional pressure is added, experimental data has shown that although elevated pressure can depress dehydration and decarboxylation, this did not significantly impact the HTC process. Dissolution of enclosed gases was found to increase at higher pressure (Funke and Ziegler, 2010; Libra et al., 2011).

d) Retention time

Reported retention times for HTC range from some hours to several days, depending on biomass type as well as temperature and presence of catalysts. Research data indicates that the correlation between retention time and reaction rate has not been extensively investigated. A longer retention time has, however, been shown to generally increase reaction severity. Rather than reducing hydrochar yield, observations have indicated that longer retention times may significantly increase the yield of hydrochar, most likely due to ongoing polymerisation which eventually leads to precipitation of insoluble solids (Sevilla & Fuertes, 2009).

e) Solid loads

Based on the theoretical and experimental data, the ratio of biomass to water should be kept as high as possible to enhance polymerisation. Although HTC can process thinner biomass, moisture contents of 70–85% have been found to be ideal for efficient HTC (PCS Biofuels, 2014;

Afolabi et al., 2014). In general, less use of water is desirable for hydrothermal processes to keep both energetic losses and investment costs for pumps and heat exchangers low.

f) Catalysis

Catalysts enhance the rate of reaction and reduce reaction temperature and time. In addition, they also impact hydrochar properties. The presence of catalysts has been shown to produce hydrochar that has potential for technical application as functionalised carbonaceous material (Sevilla and Fuertes, 2009; PCS Biofuels, 2004; Tran et al., 2017). HTC technologies that use proprietary catalysts have proven to be efficient and economically competitive at pilot and full-scale demonstration.

3.1.3 HTC Products

The products from HTC are solids, liquids and gases. Compared with other thermo-chemical conversion processes, HTC produces higher solid yields, more water-soluble organic compounds and fewer gases. Results from HTC experiments (temperature 180–250˚C, and retention time 1–12 hours) with various feedstocks indicate hydrochar compositions of 50–80%; liquid dissolved in process water of 5–20% and gas 2–5% (Libra et al., 2011; Berge et al., 2011).

3.1.3.1 Hydrochar

Although HTC hydrochar properties are mainly influenced by the nature of the feedstock, process temperature, retention time and catalysis, the following general properties have been observed for subcritical water conditions processing woodchips and municipal waste (food, paper, municipal solid waste and wastewater sludge) as feedstocks:

- hydrochar yield (mass ratio of hydrochar to feedstock on dry weight basis) generally decreases with increased temperature, especially at values higher than subcritical water temperature. The retention time also has an influence, with maximum attainable yield achieved at higher retention time. The yield is also lower for high moisture content feedstock.
- The chemical structure more closely resembles natural coal than charcoal, with respect to the type of chemical bonds and their relative quantity, as well as its elemental composition, indicating that the carbon bridge bonding in the HTC process is similar to that of natural coalification. However, the sulphur and nitrogen content are less than that of coal. Depending on the type of feedstock, the ash content can also be less than that of some types of coal.
- H/C and O/C ratios are lower than in the initial product due to the release of H_2O and CO_2 during dehydration and decarboxylation. Control of decarboxylation can be an important process design and control parameter as it impacts the calorific value of the hydrochar as well as carbon sequestration. For hydrochar which is to be used primarily as a biofuel, decarboxylation is favourable in order to produce hydrochar with a higher heating value. On

the other hand, keeping decarboxylation as low as possible allows for a high carbon conversion from feedstock to hydrochar (high mass and energy yield) resulting in more efficient carbon sequestration (Titrici et al., 2007). In general, about 60–84% of the biomass carbon was observed to be retained in the hydrochar for municipal waste.

- Due to the elimination of mainly hydroxyl and carboxyl groups during HTC, the resulting hydrochar has a lower hydrophilicity than the original feedstock, making it easier to dewater.
- Hydrochar from waste feedstocks (e.g. food waste, anaerobically digested waste) has comparatively lower carbon content than from virgin feedstocks (e.g. woodchips).
- While the hydrochar from various feedstocks has more or less similar volatile fractions, the ash content is highly variable, e.g. the ash content for hydrochar from anaerobically digested waste and mixed municipal solid waste (MSW) is much higher than from paper waste and food waste.
- Hydrochar retains high levels of calcium, potassium and phosphorous. This was observed in animal manure and sewage sludge feedstocks, making it possible to use hydrochar as fertiliser/soil conditioner. It was also observed that, unlike phosphorus, nitrogen is volatilised at high temperature.
- While research on the fate of heavy metals is limited, available data indicates that heavy metals with low boiling points (e.g. Hg, Cd, and Se) were eluted from the reactor, while those with high boiling points (e.g. Pb, Ni, Cu, Zn, Mn, and Sr) were incorporated in the hydrochar.
- The hydrochar is sterile. HTC has been shown to destroy microbial life as well as some harmful organics. Experimental data on processing sewage sludge during this project has indicated a destruction rate of over 75% for polychlorinated biphenyls (PCBs), hexachlorobenzenes (HCBs) and other endocrine disruptors.
- Observations on the nanostructure of HTC hydrochar has revealed potential for technical applications as functionalised carbonaceous material. The material can be produced by varying the process parameters and/or further processing of the hydrochar. Some of the possible uses of the material are (Sevilla and Fuertes, 2009; PCS Biofuels, 2014):
    - Adsorption media for water purification
    - Generation of nano-structured material
    - Catalysis
    - CO_2 sorption
    - Energy production and storage in the field of fuel cells.

3.1.3.2 Liquid

Published data on analysis of process wastewater produced from HTC indicates a high load of inorganics and organics typical of the reported pathways during hydrothermal carbonisation of the feedstock. When processing mainly municipal waste streams (paper, MSW, food waste), acetic acid, several aromatics, aldehydes and alkenes were detected. Furanic and phenolic compounds were also identified. Process wastewater indicated high COD, BOD, and TOC concentrations, in the range equivalent to those typically found in landfill leachate. The pH was found to be acidic, ranging between 4.5 and 5 (Berge et al., 2011). Studies have also shown that HTC process wastewater is amenable to treatment using anaerobic or aerobic treatment processes. Opportunities also exist to recover high-value materials from the process wastewater. In full-scale installations, comprehensive evaluation of the process wastewater is required in order to select the most appropriate beneficial use, treatment process and disposal route.

3.1.3.3 Gases

The gas produced as a result of HTC is small. For process temperatures of up to 220°C and pressure of up to 2 MPa, very little gas is generated (1–5%) and most organics remain in solid form. More gas is produced at higher temperatures (Libra et al., 2011). The gas consists of CO_2 with traces of CO, CH_4 and H_2. Traces of C_mH_n-type components were also detected, most likely due to the thermal decomposition of the cellulosic materials, condensation of aromatic compounds, and/or the thermal oxidation of lipids. Data also suggests that gas composition does not vary significantly with feedstock. It should be noted, however, that analysis of gas composition from HTC is an area of ongoing research to improve both the accuracy of procedures and to determine the composition of trace gases produced.

3.1.4 Role of HTC in Biomass Conversion and Renewable Energy

Renewable energy is one of the most efficient ways to achieve sustainable development. Cellulosic and lignocellulosic biomass is most abundant in nature and therefore has enormous potential as a renewable source of energy and other valuable materials. In general, biomass is composed of 34–50% cellulose, 16–34% hemicellulose, and 11–29% lignin. The traditional approach to biomass conversion has mostly been through two pathways: (i) drying and thermal conversion into energy by direct burning in boilers and gasifiers and (ii) biochemical conversion (of mostly high moisture content biodegradable biomass like manure, food and wastewater sludge) through fermentation and anaerobic digestion. The traditional technologies, however, have limitations that prevent wide application and production of renewable energy that can economically compete with energy from non-renewable sources. These limitations include:

- Other thermo-chemical conversion technologies require drying which increases energy input. In addition, properties of biomass feedstock result in harmful emissions as well as serious fouling of equipment. The non-homogenous nature of different biomasses (in terms of physical shape, composition and energy density) also presents serious challenges in the design and operation of these technologies.
- Biochemical conversion technologies cannot process a wide range of biomass, require long retention times and are sensitive to biological reactions. In addition, high levels of CH_4 are

produced, which, if not utilised effectively and released into the atmosphere, increase GHG effects.

Due to the above limitations, research and development into application of HTC for processing biomass has increased in recent years. The increase is due to the significant advantages that HTC offers over traditional technologies, namely (Gupta et al., 2010; Cantero et al., 2013):

- utilises water, a non-toxic, environmentally benign, and inexpensive media for chemical reactions
- can process wet biomass and does not require an energy-intensive drying process like other thermo-chemical conversion processes
- converts a wide range of biomass which, in addition to energy generation, makes a sustainable waste management technology
- achieves a high conversion efficiency at relatively low operating temperature compared to other biomass conversion processes (e.g. combustion 0%, anaerobic digestion 50%, HTC 100%)
- has shorter reaction times compared to biochemical conversion processes and produces a completely sterile product with no microbial activity
- very low GHG emissions compared to other processes
- produces from a wide range of biomass a hydrochar that is homogenous and has combustion behaviour similar to coal without the emissions. This makes it suitable for onsite combustion to generate energy as well as combustion or co-combustion with lignite in existing coal-fuelled boilers. Thus, HTC hydrochar presents an opportunity to substitute for coal burning and limit environmental impacts associated with this practice.

Research and technology development has been on both *subcritical* and *supercritical* water HTC. Published data, however, indicates that *subcritical* water HTC (temperature 180–375°C) is more efficient and economical for producing high-calorific hydrochar. Studies have shown that when processing biowastes (municipal solid waste, wastewater sludge, food waste and animal manure), cellulose and hemicellulose were almost totally decomposed at temperatures lower than 250°C, prior to lignin decomposition at around 300°C. Addition of catalysts has been shown to reduce both retention time and optimal temperatures required (PCS Biofuel, 2014; Berge et al., 2011; Liu et al., 2013).

3.1.5 Comparison of HTC With Other Thermo-chemical Conversion Processes

Research over the years has indicated that HTC offers significant advantages over established thermo-chemical and biochemical conversion processes. As a result, a number of technology companies have, in the past five years, developed the process (under subcritical and supercritical water conditions) for demonstration and full-scale implementation (e.g. PCS Biofuels™ – Canada, Pacific Northwest Laboratory – USA, Ingelia SL – Spain and SunCoal Industries – Germany). Of these emerging technologies, the one developed by PCS Biofuels™ which utilises catalysts at subcritical water conditions was selected as the most efficient and economically feasible to process a wide range of biomass including wastewater sludge. The technology was therefore evaluated for implementation in South Africa for processing wastewater sludge.

Table 3-1: Comparison of *Subcritical* Water HTC With Other Thermo-chemical Treatments and Typical Product Yields

Process	Process conditions						Approximate product yield (weight %)		
	Temperature range (°C)	Heating rate	Residence time	Pressure	Surrounding medium	Cooling rate	Char	Liquid	Gas
Slow pyrolysis	~400	Slow[b]	Hours to weeks	Low[c]	Little or no O$_2$	Slow	35	30	35
Fast pyrolysis	~500	Fast[b]	Seconds	Variable[c]	Little or no O$_2$	Rapid	12	75	13
Gasification	> 800[a]	Fast[c]	10–20s	Variable[c]	Lightly reducing atmosphere	-	< 10	5	> 85
Torrefaction	200–300[a]	Moderate[a]	Several hours[a]	Atmospheric[a]	Little or no O$_2$[a]	None[a]	70[a]	0[a]	30[a]

All values are approximations provided by Libra et al. (2011), unless denoted otherwise.
a (Van der Stelt et al., 2011)
b (Demirbas & Arin, 2002)
c Values are highly variable and depend on desired distribution of product yield (Child, 2014)

3.2 ENHANCED HYDROTHERMAL CARBONISATION

The latest technology developments by companies like PCS Biofuels™ have advanced the HTC process through the development of patented catalysts and proprietary processing methods. Labelled as hydrothermal polymerisation (HTP), this enhanced process allows any type of low-value waste biomass with moisture content from near 0% to 60% or more to be efficiently and effectively utilised. HTP also improves the speed, safety, quality and control of solid fuel production compared to pre-existing methods. The result is a tailored polycarbon solid fuel suitable as a drop in-replacement for coal in power plants, cement plants and iron smelters. Having an energy content of up to 29 GJ per tonne (if produced from, for example, woodchips), polycarbon solid fuel can be mixed with coal to lower the overall carbon intensity of existing coal-burning facilities or completely replace the use of coal altogether.

A detailed review of the PCS technology and its application to processing wastewater sludge, based on laboratory- and pilot-scale studies under this project, is given in the following sections.

3.2.1 Polymeric Carbon Solid (PCS) Technology

3.3 OVERVIEW

3.3.1 General

The PCS technology is a catalytic, thermo-chemical, enhanced hydrothermal carbonisation (hydrothermal polymerisation) process that occurs within an optimal temperature range of 180–240°C (autogenous pressure < 3.5 MPa). While other technologies have used sub- and supercritical water conditions to produce a biofuel, the proprietary reagent used by PCS significantly reduces the operating temperature required and consequently the pressure generated. The reduced temperature and pressure decreases both capital requirements and operating expenses. Similar to other HTC processes, the technology is tolerant to impurities and accepts a wide range of feedstock, including MSW, sewage sludge, animal manure, agricultural waste, wood products including sawdust, lumber, bark, branches, forestry and construction waste (Figure 3-3).

Diverse Global Supply of Feedstock Sources

Wood & Wood Waste
- √ Lumber, chips, sawdust, bark
- √ Leaves, branches & yard waste
- √ Brush, trees including diseased
- √ Land Clearing Waste

Agricultural Waste
- √ Animal Manure, Human Sludge
- √ Straw, hay, grass, shrubs
- √ Water hyacinth, bamboo
- √ Bagasse, Poplar Trees
- √ Palm Oil husks, trunks
- √ Rice husks, Grain husks
- √ Cassava root, undergrowth
- √ Purpose Grown Crops
- √ Agricultural Surplus

Municipal / Organic Waste
- ✓ Wet Food Waste
- ✓ Spoiled Food
- ✓ Coffee Cups
- ✓ Paper, Plastic
- ✓ Newsprint
- ✓ Cardboard
- ✓ Wood construction / demolition

Other Potential PCS Feedstock
- √ Algae, Municipal Sewage Sludge
- √ Peat Moss, Mulch
- √ Diseased Animals
- √ Hospital Waste
- √ Biological Waste
- √ Hazardous Organic Waste

Figure 3-3: Range of Feedstock that can be processed by the PCS Technology

The simplicity of operation in PCS technology plants makes them suitable for installation in any setting where a significant amount of biomass is accumulated. A typical plant consists of a mixing tank, pressure vessels where the chemical reaction occurs, and buffer tanks for storage of the end product. The pressure vessels are designed as a self-contained process to transfer maximum energy into the next tank with minimal start-up energy and minimal odour or noise emissions. The exothermic energy is recycled so that PCS plants will have a positive energy balance.

3.3.2 Net Energy Gain

Results from the PCS process have shown that the technology converts cellulose with an energy density of approximately 15 GJ/tonne (dry weight equivalent - DWE) to a hydrochar with an energy density of ~27 GJ/tonne (PCS Biofuels, 2014). Therefore, approximately 1.5 tonnes of DWE cellulose are converted to 1 tonne of PCS Biofuel, so, in effect, 22–24 GJ/tonne of cellulose is converted to 27 GJ/tonne, for a net energy gain of 3–5 GJ, using the PCS technology.

The proprietary catalyst lowers the temperature at which the reaction occurs, thus lowering the temperature and pressure and, ultimately, the net energy necessary for the PCS conversion process. As a result, for every tonne of PCS biofuel produced, an extra 3–5 GJ of energy is unlocked.

3.3.3 Heat Management

Heat management is a material operating expense and a central part of the net energy gain. The initial start-up energy requirements depend on the optimal operating temperature for the feedstock as well as the design of the reactors. To reduce heat requirements, various designs can be applied. The adopted design will depend on the biomass being processed as well as the economics of the project.

3.3.4 Advantages of the PCS Technology

The PCS technology has several advantages over the mature and emerging waste-to-energy technologies that are most used currently. Some of the advantages are common to all HTC processes, while others are unique to the PCS technology as an enhanced HTC (hydrothermal polymerisation) process.

- CO_2-neutral process with no methane production
- Wet process – biomass can be used without expensive pre-drying as required in gasification
- Accepts a very wide range of biomass types and is thus an effective waste management technology
- Can safely process problematic wastes that currently require expensive disposal, e.g. hospital and biological waste
- Highest carbon efficiency value of all biomass conversion technology options (PCS = 100% / anaerobic digestion = 50%)
- Can be easily scaled up in continuous batch process
- Intensive exothermic process converts biomass at molecular level with net energy gain
- Self-contained process with little odour or noise emissions
- Low investment and operating costs due to moderate temperature and pressure
- Straightforward technical operation – no specialist skills needed in the production process
- Environmentally friendly; residual water is sterile and can be treated using a simple process and re-used
- Resulting hydrochar is hydrophobic, and easily dewatered and processed into high-value products, e.g. biofuel, fertiliser/soil conditioner, functionalised carbon microspheres, building material, energy storage.

3.4 CURRENT APPLICATIONS

The PCS technology has been proven through laboratory- and full-scale installations. A full-scale demonstration plant processing wood chips, bagasse and palm oil was commissioned in South Korea in 2015. The plant consists of two 1 000 litre batch reactors processing 3.2 t/d feedstock and yielding about 2.4 t/d of hydrochar.

Figure 3-4: PCS Technology Full-scale Installation in South Korea (October, 2015)

In South Africa, laboratory- and pilot-scale studies processing municipal wastewater sludge have been carried out under this project using sludge from the case study plant, Waterval WWTP. The results of the studies are discussed below.

3.5 APPLICATION OF PCS TECHNOLOGY IN PROCESSING WASTEWATER SLUDGE

3.5.1 Overview

Given that it has the flexibility to utilise a wide range of biomass, the PCS technology can be applied to processing wastewater sludge on its own as well as in combination with another biomass. Results from laboratory-scale plants and full-scale demonstration plant processing other biomass have demonstrated that the process will offer the following potential benefits when applied to the treatment of wastewater sludge:

- The process treats all sludge generated at the plant, i.e. primary and secondary sludge, individually or in combination with each other.
- Screenings from fine screens can be combined with sludge and treated in the process. The presence of grit and sand will not affect the efficiency of the process other than to add a significant amount of ash to the final biofuel.
- If there is insufficient cellulosic material in the feed sludge, then additional cellulosic material from other sources (e.g. MSW, food and agricultural waste, paper) can be added. The addition of cellulosic materials will increase the energy density of the solid hydrochar and will aid in the dewatering and pelletising processes.
- Odour from the sludge will be reduced or eliminated upon processing.
- Sludge quantities will be significantly reduced, thus reducing disposal costs.

- The product (PCS hydrochar) is sterile. The process has demonstrated the ability to destroy all microbial life including some EDCs, which are problematic contaminants in wastewater.
- PCS hydrochar is hydrophobic, hence it is easy to dewater and will not attract moisture on storage.
- PCS hydrochar has multiple uses. It can be used as a biofuel to generate electricity (and heat) at the WWTP that can be used to offset energy use in other processes, e.g. aeration. The hydrochar can also be sold for agricultural and industrial use, generating revenue for the wastewater utility.

Based on these potential benefits, the PCS technology was therefore tested at both laboratory and pilot scale to determine its efficiency when processing wastewater sludge from a typical South African WWTP.

3.5.2 Laboratory Studies

3.5.2.1 Approach and Methodology

A 200 ml reactor was used for the laboratory-scale tests. A heating jacket was installed to heat the reactor. Temperature and pressure gauges were also installed to record these parameters. Catalyst was added to the feedstock prior to processing. The following feedstocks were processed:

- Synthetic sewage sludge to calibrate the experimental procedure
- BFP dewatered WAS and composted sludge (BFP WAS mixed with wood chips in a 1:4 w/w ratio) from Stellenbosch WWTP.

The following analysis was carried out on both the sludge feedstock and the hydrochar:

- Elemental analysis that determined the carbon, oxygen and nitrogen content. More detailed analysis to determine calorific value, etc. was carried out during the pilot-scale tests
- Analysis of selected EDCs.

The reaction temperatures were 180°C (minimum temperature to achieve HTC activation energy) and 240°C (maximum temperature observed during PCS laboratory studies using other biomass) at a reaction time of 1 hour. WAS samples were processed at 14% DS and the compost samples at 80% DS.

3.5.2.2 Results

Physical appearance

Images depicting the physical appearance of WAS, composted sludge and hydrochar, after freeze-drying, are shown in Figure 3-5. Both the raw sludge and char has a typical brown colour. Differences in texture can be observed between the samples treated at 180°C and that treated at 240°C. The higher reaction temperature yielded a finer product while the lower temperature results in a product with a texture just slightly different from that of the initial feedstock.

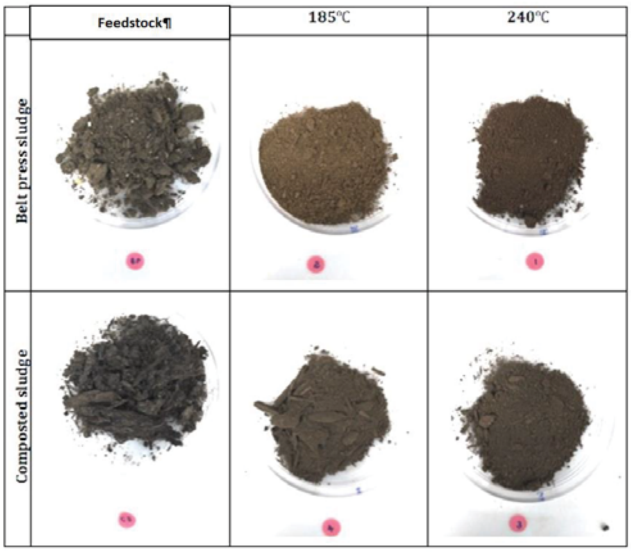


Figure 3-5: Physical Appearance of Dried Sludge Feedstock and Hydrochar (Temperature 185°C and 240°C; Processing Time 1 Hour)

Elemental analysis

Table 3-2 shows the results of the elemental analysis for sludge feedstock and hydrochar.

Table 3-2: Laboratory-scale Elemental Analysis Results for Sludge Feedstock and Hydrochar (1 Hour Processing Time)

Parameter	Feedstock		Hydrochar			
			Processing Temperature 180°C		Processing Temperature 240°C	
	BFP WAS	Composted Sludge	BFP WAS	Composted Sludge	BFP WAS	Composted Sludge
Fixed Carbon (%)	31.0	24.4	40.4	24.5	41.9	34.2
Oxygen (%)	40.7	50.3	36.3	60.1	34.0	49.4
Nitrogen (%)	12.	14.4	15.0	15.4	13.0	16.4

The following is noted:

a) When processing WAS

- Fixed carbon in the hydrochar was higher than in the feedstock, showing a carbon enrichment of about 30%. There is no significant difference between the hydrochar fixed carbon content at processing temperatures of 180°C and 240°C, indicating that for WAS, maximum carbon enrichment can be achieved at the minimum temperature of 180°C.
- Oxygen content in the hydrochar was lower by 4% and 6% at processing temperatures of 180°C and 240°C respectively. Thus, the O/C ratio of the feedstock was reduced, indicating that the hydrochar has a higher calorific value than the feedstock, confirming findings from literature data.
- Nitrogen content in the hydrochar increased indicating that within the optimal PCS process temperature range, the nitrogen is trapped in the hydrochar and does not solubilise into the process effluent or escape as gas.

b) When processing composted sludge

- Apart from the oxygen content, the fixed carbon and nitrogen results follow the same trend as for WAS. However, the change in elemental composition only occurs at 240°C, with very little change at 180°C. This is due to the presence of woodchips in the compost which have not been previously processed. WAS has been previously processed in the activated sludge process and is hydrolysed and thus is hydrothermally carbonised at a lower temperature. The oxygen content of the hydrochar is higher than the feedstock at 180°C, and marginally lower at 240°C.
- The carbon enrichment of 41% for the composted sludge is higher than that for WAS which would indicate a higher calorific value hydrochar from the composted sludge, due to the presence of woodchips.

Analysis for endocrine disrupting compounds

Four compounds (bisphenol A, chloramphenicol, carbamazepine and methylparaben) were analysed to determine the micro-pollutant load. Ultrasound assisted extraction was employed on previously lyophilised samples. Samples were then cleaned up using solid phase extraction and finally analysed using liquid chromatography- mass spectrometry. Table 3-3 shows the initial micro-pollutant load in BFP WAS samples.

Table 3-3: Micro-pollutant Load in BFP WAS Samples

Compound	**Load in sludge samples (ppb)**
Chloramphenicol	0.115
Bisphenol A	0.148
Methylparaben	0.745
Carbamazepine	0.487

Table 3-4 and Table 3.5 show the micro-pollutant removal percentage from process water (difference between the liquid before and after the PCS process) and sludge feedstock (difference between the solid feedstock and hydrochar after the PCS process) respectively.

Table 3-4: Micro-pollutant Percentage Removal from Process Water at Processing Temperatures of 180°C and 240°C

Product (Hydrochar)	Processing temperature (°C)	Micro-pollutant percentage removal during HTC			
		Methylparaben	Carbamazepine	Chloramphenicol	BIsphenol A
BFP WAS	240	99.6	99.9	100	82.4
BFP WAS	180	99.7	99.9	100	
Composted sludge	240	99.7	99.7	100	
Composted sludge	180	99.8	99.9	100	81.7

Table 3-5: Micro-pollutant Percentage Removal from Sludge at Processing Temperatures of 180°C and 240°C

Product (Hydrochar)	Processing temperature (°C)	Micro-pollutant percentage removal during HTC			
		Methylparaben	Carbamazepine	Chloramphenicol	BIsphenol A
BFP WAS	240	96.7	100	100	87.4
BFP WAS	180	99.5	99.5	100	
Composted sludge	240	99.7	99.3	99.8	66.4
Composted sludge	180	99.5	99.8	100	76.3

The following is noted from the preliminary laboratory-scale analysis of EDC destruction in the PCS process:

- EDCs were removed from both the solid feedstock and the liquid formed from the process. The percentage removal of the selected group of EDCs was as follows:
    - 99–100% average removal was achieved for methylparaben, carbamazepine and chloramphenicol
    - Bisphenol A average removal was 78%
    - Maximum removal was achieved at the lower temperature of 180°C with no significant difference between the removal at 180°C and 240°C

3.5.3 Pilot-Scale Studies

3.5.3.1 Approach and Methodology

Pilot-scale investigations were carried out at ERWAT's Waterval WWTP using a 60-litre PCS pilot-scale reactor. The following sludge was processed during the pilot-scale studies:

a) Primary sludge collected from the underflow of Module 4 PSTs
b) WAS from Module 4 DAF thickeners
c) Digested sludge collected from the sampling point prior to the belt press
d) Combined primary and thickened WAS

The sludge was processed on its own and in combination with screenings collected from the inlet works screenings compactor. Based on the results of the laboratory analysis, the optimal temperature for the pilot-scale tests was determined to be 205–210°C with a processing time of 1 hour. The autogenous pressure generated ranged from 2.5–3.5 MPa.

3.5.3.2 Gross Calorific Value

The gross calorific values (higher heating value – HHV) were determined using the oxygen bomb calorimetry test (as per ASTM D5865). The results for the various sludge feedstocks, sludge and screenings feedstocks, and product (hydrochar) are summarised in Table 3-6. A graphical representation of the results is given in Figure 3.6.

Table 3-6: Gross Calorific Values for Feedstock and PCS Technology Processed Product

Feedstock	Feedstock HHV (MJ/kgDS)	Hydrochar HHV (MJ/kg DS)
Primary Sludge	13.6	16.5
Primary Sludge and Screenings	19.9	20.5
Digested Sludge	14.9	10.6
Digested Sludge and Screenings	18	19.5
WAS	14.5	15.5
WAS and Screenings	18.3	24
Primary Sludge and WAS	19.3	24.7
Primary Sludge, WAS and Screenings	17.9	26.4

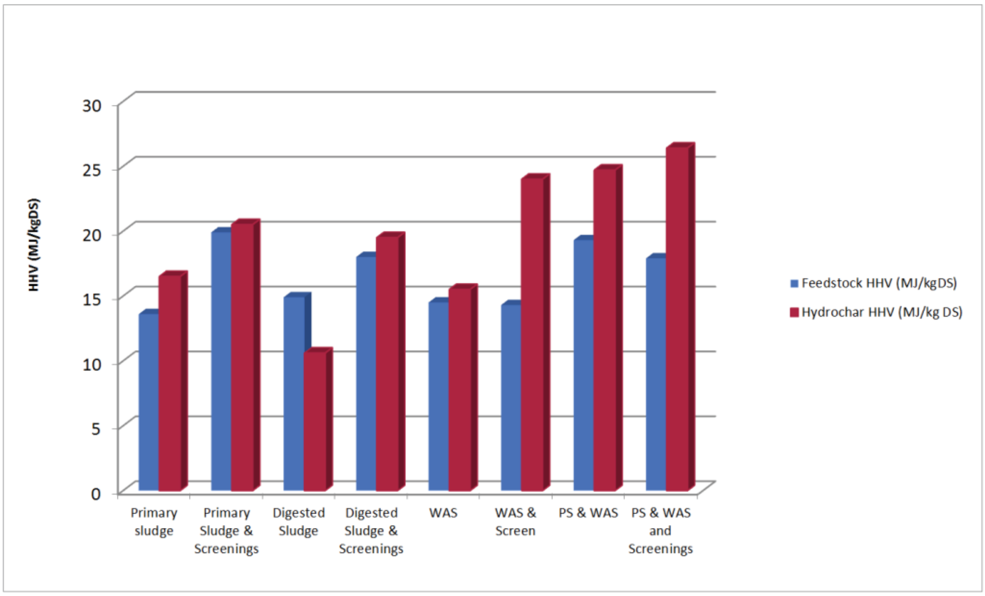


Figure 3-6: Gross Calorific Values (HHV) for Feedstock and PCS Technology Processed Product

The following is noted:

- Processing sludge with PCS technology increased the gross calorific values of primary sludge, WAS and combined primary sludge and WAS. The increases were as follows:

Primary sludge	21%
WAS	7%
Combined WAS and Primary Sludge	27%
Digested sludge	29%

  Combined primary sludge and WAS had the highest increase while digested sludge showed a decrease in calorific value of about 29%.
- The most likely hypothesis for the decrease in calorific value for the digested sludge and modest increase for WAS is the previous processing of digested sludge in the anaerobic digesters, and the activated sludge process, respectively, which results in different kinetic pathways for the produced hydrochar, as discussed in Section 3.1. The lower calorific values are reflected in the higher loss of volatile content and fixed carbon in the digested sludge and WAS (see proximate analysis results in Section 3.5.3.3 below).
- Adding screenings to the sludge feedstock increased the gross calorific values of the hydrochar, for all combinations of sludge and screenings, including digested sludge. The highest percentage increase was for combined primary sludge, WAS and screenings, while primary sludge and screenings had the lowest increase. It should be noted that (i) sludge batches were collected on different days, hence the quality of the sludge varied and was impacted by the performance of the existing liquid and sludge treatment processes; (ii) the consistency and quality of screenings varied from batch to batch and thus influenced the characteristics of the combined feedstock. In full-scale installations, screenings will be cut or shredded prior to being combined with sludge, thus improving consistency.

3.5.3.3 Proximate Analysis Results

Proximate analysis, using a Mettler TGA/DSC1, was carried out to determine the moisture, volatiles, fixed carbon and ash contents. The method used was a modified ASTM E1131 proximate analysis for coal. The proximate analysis results for sludge-only feedstock and product are summarised in Table 3-7. A graphical representation of the results is given in Figure 3.7.

Table 3-7: Sludge-only Feedstock and PCS Hydrochar - Proximate Analysis Results

Parameter (% dry basis)	Primary Sludge		WAS		Digested Sludge		Primary Sludge and WAS	
	Feed-stock	Hydrochar	Feed-stock	Hydrochar	Feed-stock	Hydrochar	Feed-stock	Hydrochar
Volatiles	55.3	42.7	61.6	40.7	55	34.1	67	61
Fixed carbon	6.7	8.6	9.5	9.2	7.9	6.5	7.0	11
Ash	37.9	48.8	28.9	50.1	37.4	59.7	76	28
Volatile		22.8		42.3		37.4		12
Total solids		40.1		61.9		61		7.0
Fixed carbon		0.5		-43.8		-48.5		46

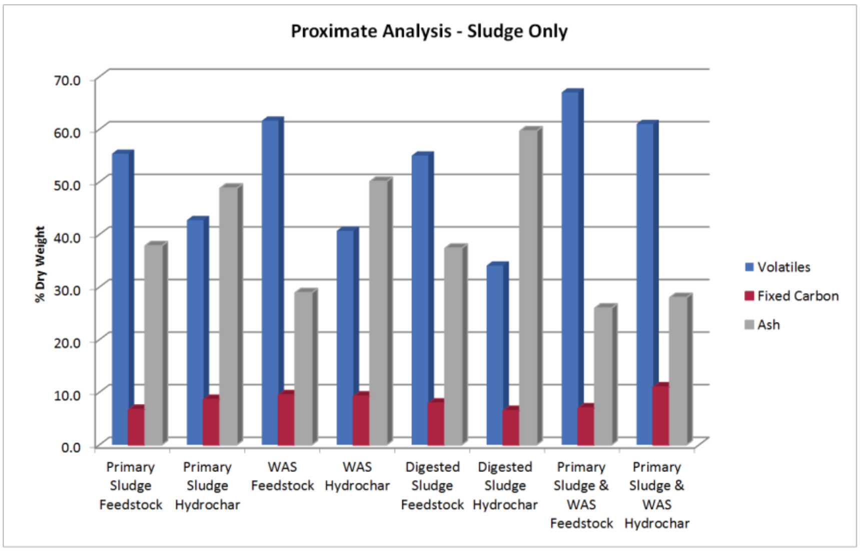


Figure 3-7: Sludge-only Feedstock and PCS Technology Hydrochar – Proximate Analysis Results

Table 3-8: Sludge and Screenings Feedstock and PCS Technology Hydrochar – Proximate Analysis Results

Parameter (% dry basis)	Primary Sludge and Screenings		WAS and Screenings		Digested Sludge and Screenings		Primary Sludge, WAS and Screenings	
	Feed-stock	Hydrochar	Feed-stock	Hydrochar	Feed-stock	Hydrochar	Feed-stock	Hydrochar
Volatiles	60.5	55.3	62.0	54.3	58.7	49.0	64	14
Fixed carbon	8.4	11.0	9.3	12.8	7.8	11.0	9.0	19
Ash	31.3	33.9	28.5	32.9	33.8	39.8	25	5.3
Volatile content		15.5		24.3		29.3		14
Total solids reduction		7.6		13.5		15.2		19
Fixed carbon increase		22.0		19.0		20.0		5.3

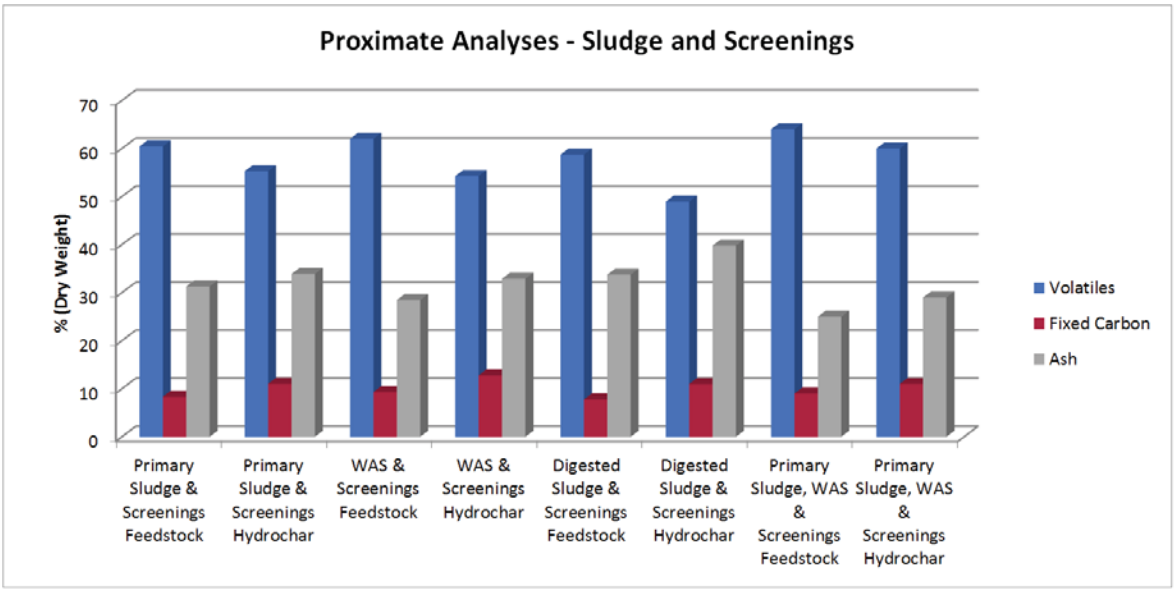


Figure 3-8: Sludge and Screenings Feedstock and Hydrochar – Proximate Analysis Results

The following is noted:

- The PCS process reduced the volatile content and, consequently, the total solids of the feedstock, as follows:
    - when sludge was processed alone, WAS and digested sludge had much higher volatile and total solids reduction than primary sludge and combined primary sludge and WAS. The reduction for combined primary sludge and WAS was the lowest;
    - a similar pattern was displayed when processing sludge and screenings.
- The hydrochar from processing WAS and digested sludge had a lower carbon content than the feedstock, hence the lower calorific value (as discussed in Section 3.5.3.2 above). However, when sludge with screenings was processed, the product had a higher fixed carbon content, showing an average carbon enrichment of about 20%.

3.5.3.4 Ultimate Analysis Results

Ultimate analysis was carried out to determine the carbon, hydrogen, nitrogen and sulphur content of the feedstock and product. The metal content, for metals stipulated in the DWS Guidelines for the Utilisation and Disposal of Wastewater Sludge, was also analysed (i.e. arsenic, cadmium, chromium, copper, lead, mercury, nickel and zinc). Since X-ray fluorescence spectrometry was applied, other elements that are not necessarily stipulated in the DWS guidelines were also analysed. The following was noted:

- The product from all samples had less hydrogen, nitrogen and sulphur than feedstock. The percentage reduction varied from 10–50%

- High boiling point (Pb, Ni, Cu, Zn, Mn and Sr) metal content increased in the hydrochar samples showing that heavy metals were retained in the solid product and not transferred into the liquid
- Results from the bomb calorimetry tests to determine gross calorific values showed that about 30–40% of the metals were retained in the bomb calorimeter. indicating that some of the metals can be recovered after combustion of the product.

3.5.3.5 Evolved Gas Analysis

The evolved gases for both the combined primary sludge, WAS and screenings feedstock and hydrochar were analysed using a Thermo Nicolette 6700 mid infrared Fourier transform infrared spectrometer with KBr optics, a DTGS detector and a ThermoTGA-FTIR 10 cm gas cell. A comparison of the results for the feedstock and hydrochar showed that the hydrochar emits about 50% less NO_x and SO_x. This can be ascribed to the stripping of nitrogen and sulphur compounds into the solution phase during processing. Thus, the PCS process produces a hydrochar that is a better, cleaner biofuel.

3.5.3.6 Quality of Hydrochar Dewatering Supernatant

The supernatant from the PCS reactor was analysed for the parameters shown in Table 3-9.

Table 3-9: Quality of PCS Process Supernatant

Parameter	Units	Primary Sludge and WAS Supernatant	Primary Sludge, WAS and Screenings Supernatant	% of Raw Influent Load at Waterval WWTP
Flow	m^3/d	145		
pH		4.28	3.89	
Concentration				
Ammonia	mgN/L	0.31	0.20	
Ortho P	mgP/L	32	31	
TCOD	mg/L	26 125	22 413	
cBO_5	mg/L	3 500	490	
Loads				
Ammonia	kgN/d	0.04	0.03	0.00
Ortho P	kgP/d	4.61	4.50	0.98
TCOD	kg/d	3 788	3 250	5.34
$cBOD_5$	kg/d	508	71	

The supernatant has a high concentration of TCOD. The TCOD load is, however, low compared to the total load coming into the plant. The biodegradability of the supernatant was not checked, though the low $cBOD_5$ indicates that the biodegradability of the supernatant is low. The ortho P and ammonia loads are negligible, showing that the process retains N and P in the solid phase, thus confirming that the hydrochar can be used as a fertiliser.

3.5.3.7 Results of Microbiological and Micro-pollutant Analysis

Both feedstock and hydrochar samples, as well as the liquid effluent, were analysed for E coli and ova. The results indicated that the process eliminated all microbial life forms, resulting in zero counts of E. coli, ova and other spores. Sterile microbiological/stability Class A1 biosolid product was thus produced. In addition, preliminary laboratory-scale tests indicate that the process can destroy EDCs in both the solid feedstock and the liquid formed from the process (Section 3.5.2.2).

3.5.3.8 Summary and Conclusions on PCS Technology Laboratory and Pilot-Scale Studies

The following conclusions were drawn, based on the results of the PCS technology pilot-scale studies processing municipal wastewater sludge or a combination of municipal wastewater sludge and screenings in South Africa:

- The PCS process treats both sludge and sludge with screenings at a short processing time of 1 hour, and temperatures from 180°C to 240°C. Pilot-scale studies showed that an optimal temperature of 210^{o}C can be applied to give a high-quality product.
- The process increased the calorific value of primary sludge, WAS and combined primary sludge and WAS to the level of low-grade coal (lignite/sub-bituminous), which makes the product a clean, useful biofuel with very low emissions compared to coal, as indicated by the results of the gas analysis. Due to previous processing during anaerobic digestion, the calorific value of digested sludge decreased after being processed in the PCS reactor.
- Processing combined sludge and screenings increased the calorific value of the hydrochar by up to 35%. Thus, the process not only provides a single solution for sludge and screenings handling at WWTPs but also presents an opportunity for co-processing wastewater sludge with other biomass (e.g. MSW, food waste, agricultural waste, etc.) from the community.
- The process reduced volatile and total solids by 40–62% and 22–37%, respectively, when processing sludge only. The high solids reduction for digested sludge has shown that despite the hydrochar produced from digested sludge having a lower calorific value, PCS technology can be applied to further process digested sludge and further reduce the quantity of biosolids for final disposal, thus saving on disposal costs.
- The process produces a sterile, inert product without any microbial activity, of a quality that is above DWS requirements for microbiological/stability Class A1 biosolids. This gives a wide range of options for beneficial use, e.g. agricultural use (depending on metal content and pollutant class), and commercial products (e.g. solid biofuel with metal recovery, adsorption media, brick making, cement making).

The pilot-scale studies have demonstrated that PCS technology treats wastewater sludge to a higher quality than that achieved with the commonly applied biochemical conversion aerobic and anaerobic digestion processes widely applied in South Africa. The PCS process also converts the sludge to a useful biofuel and commercial product. In addition, the studies have demonstrated that the technology can be applied to post-treat digested sludge, further reducing sludge quantity and producing a higher quality product. This enables technology coupling at treatment plants that already have sludge digestion processes, thus avoiding making the existing technology redundant. The ability to co-process sludge with other biomass offers a unique opportunity to produce a high-value biofuel (and other useful commercial products) and the vison of converting wastewater treatment facilities into resource recovery centres a reality.

Thus, the PCS technology can be applied to process raw primary sludge, WAS, combined primary and WAS and digested sludge. Sludge can also be co-processed with screenings and other external biomass. Based on the pilot-scale studies, Figure 3-9 shows a schematic layout of how the PCS technology can be incorporated into a typical South African wastewater treatment plant.

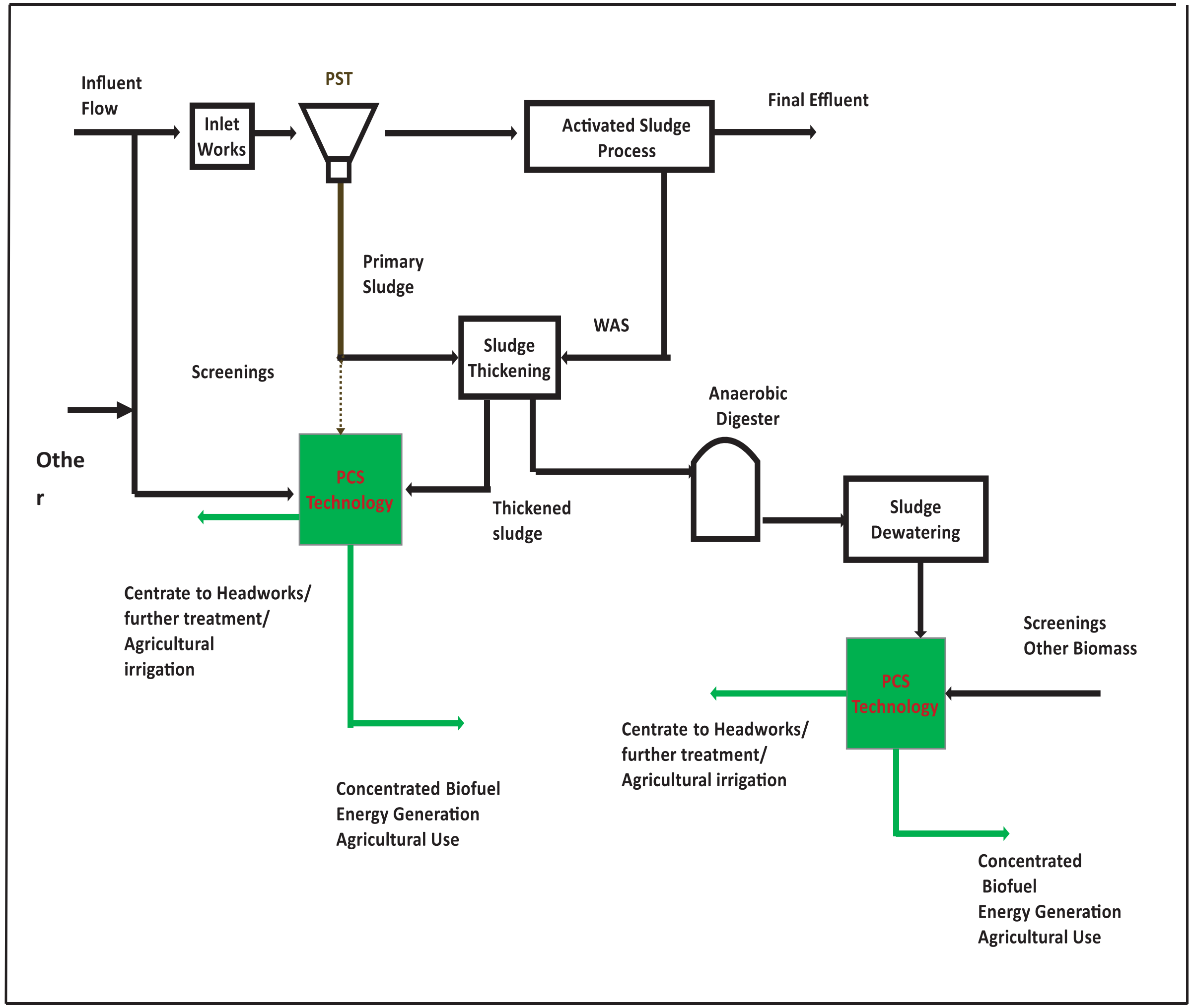


Figure 3-9: Schematic Layout of Incorporation of PCS Technology at a Typical Wastewater Treatment Plant

3.6 PRELIMINARY DESIGN OF FULL-SCALE IMPLEMENTATION OF PCS TECHNOLOGY FOR SLUDGE TREATMENT

Data from the laboratory- and pilot-scale studies at Waterval WWTP (as well as data from the full-scale demonstration plant treating other biomass) were applied to design a full-scale plant treating wastewater sludge similar in quality to the sludge produced at Waterval WWTP.

The preliminary design was carried out for the following scenarios:

a) Greenfield installation processing indigenous primary sludge and WAS, alone and with screenings
b) Retrofitting the PCS technology to process indigenous anaerobically digested sludge with indigenous screenings, and also with screenings imported from other sites.

3.6.1 Greenfield Installation for Primary and Waste Activated Sludge Alone and Sludge with Screenings

The following unit treatment processes are required under this scenario:

- Sludge pre-thickening and dewatering to at least 20% DS. It was assumed that WAS is thickened and dewatered on combined linear screen/BFP units. Primary sludge is dewatered on BFP
- Screenings handling and preparation consisting of a building with macerators, conveyers, odour control and associated equipment
- PCS process reactors, catalyst makeup and dosing system and associated equipment
- Hydrochar dewatering on BFP
- Hydrochar drying in a "greenhouse"-type solar dryer. The hydrochar needs to be dried to at least 70% DS if it is to be used as biofuel for a boiler to generate heat and power
- CHP generation unit consisting of a biomass boiler, extraction condensing turbine and generator. The CHP unit gross electrical, thermal and overall efficiencies were assumed to be 30%, 65% and 80% based on data from existing biomass power plants
- Metal recovery
- Ash beneficial use in agriculture as a soil conditioner, assuming that it meets the standard for agricultural use, and disposal to landfill if it does not.

Figure 3-10 gives a simplified PFD, including mass and energy balances, for the installation. A summary of the treatment unit sizes as well as mass and energy balances is given in Table 3-10.

Table 3-10: Summary of Treatment Units for PCS Process Installation at a Greenfield Plant Treating 50 tDS/d Primary and Waste Activated Sludge

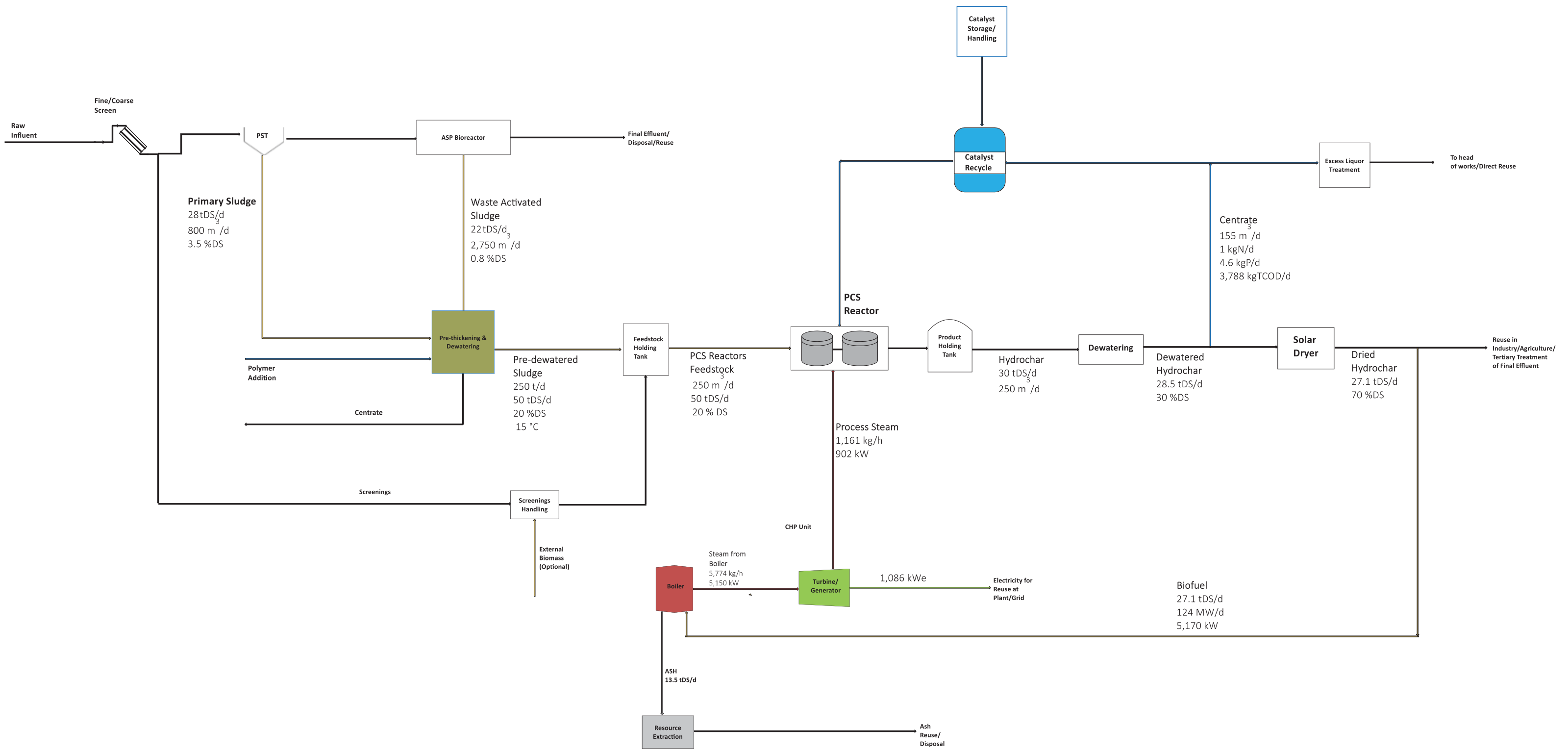
Parameter	Units	Value
PCS Process Capacity		
Sludge to process, dry mass	tDS/d ay	50
Feed dry solids	%	20
Sludge flow to reactors	m^3/day	250
Reactor volume (each)	m^3	23
No. of reactors		3
Volatile solids reduction[1]	%	60
Total solids reduction[1]	%	40
Hydrochar dry mass	tDS/d	30
Hydrochar dry solids	%	12
Hydrochar Dewatering and Drying		
Dewatered hydrochar dry mass	tDS/d	28.5
Dewatered hydrochar dry solids	%	30
Hydrochar wet mass to drying	t/d	95
Dried biofuel dry mass	tDS/d	27.1
Dried biofuel dry solids	%	70
Hydrochar unit energy content	MJ/kg	16.5
Energy content[1]	MWh/yr	45 300
Energy Production		
Steam from boiler	kg/h	5 774
Steam extracted to PCS process	kg/h	1 616
Electricity production	MWhe/yr	9 513
Electrical power	kWe	1 086
Ash		
Ash mass [1]	tDS/d	13.5
Dewatering Centrate		
Flow	m/d^3	155
Ammonia load	kgN/d	1
Ortho P load	kgP/d	5
Soluble COD load	kg/d	3 788
$cBOD_5$ load	Kg/d	508

Note:

1. A conservative approach was applied by using the lowest HHV, highest ash content and highest TS destruction (i.e. lowest biofuel yield) from the results of the pilot-scale studies.

The mass and energy balances indicate that the hydrochar, when used as a biofuel for a CHP generation system, generates excess electrical energy (after process heating) that can be re-used in other parts of the treatment plant, e.g. to offset aeration energy in the activated sludge process. The excess heat can be used in other parts of the plant or in nearby communities/industries.

PCS Technology - Indicative Mass and Energy Balance: 50 tDS/d Combined Primary and Waste Activated Sludge



Summary of Design Data

Sludge Production	
Primary	28 tDS/d
WAS	22 tDS/d
Screenings	0 tDS/d
Imports	0 tDS/d
Total	50 tDS/yr
	18,250 tDS/yr

Feedstock to PCS Reactors	
Sludge	50 tDS/d
Screenings	0 tDS/d
External Biomass	0 tDS/d
Feedstock DS	20 %DS

PCS Reactors	
Feedstock dry mass	50 tDS/d
Feedstock flow	250 m^3/d
Feedstock wet mass	250 t/d
Reactor volume each	23 m^3
No. of reactors	3
Total solids reduction	40%

Product Dewatering	
Hydrochar to dewatering	30 tDS/d
Solids capture	95%
Dewatered hydrochar	28.5 tDS/d
Dewatered dry Solids	30 %DS
Centrate flow	155 m^3/d
Ammonia load	1 kgN/d
Ortho P load	4.6 kgP/d
TCOD load	3,788 kg/d
BOD load	508 kg/d

Hydrochar Drying	
Product to drying	28.5 tDS/d
Solids Capture	95%
Dried product	27.1 tDS/d
Dried solids	70 %DS

Energy Production	
Biofuel	27.1 tDS/d
Biofuel HHV	16.5 MJ/kg
Total energy produced	45,300 MWh/yr
Process energy	7,902 MWh/yr
Electricity for reuse	9,513 MWheur
Electrical power	1,086 kWe
Ash to disposal	13.5 tDS/d

Figure 3-10: Simplified PFD (With Mass and Energy Balances) for a Greenfield Installation Treating 50 tDS/d Combined Primary and Waste Activated Sludge

3.6.2 Retrofit to Treat Digested Sludge and Screenings

Under this scenario, digested sludge from existing anaerobic digesters is mixed with screenings (both indigenous and imported from other sites) to achieve a feed concentrate of 20% dry solids. Adding screenings will increase the HHV of the biofuel produced to 20 MJ/kg compared to 11 MJ/kg if digested sludge only were processed. The same treatment units as indicated in the greenfield installation are required, except for pre-dewatering. Figure 3-11 shows a simplified PFD for the installation and Table 3-11 gives a summary of the treatment unit sizes as well as mass and energy balances.

Table 3-11: Summary of Treatment Units for PCS Process Installation as a Retrofit to Treat Digested Sludge and Screenings

Parameter	Units	Value
PCS Process Capacity		
Sludge to process, dry mass	tDS/d ay	35
Feed dry solids	%	20
Sludge flow to reactors	m^3/day	170
Reactor volume (each)	m^3	23
No. of reactors		2
Volatile solids reduction	%	30
Total solids reduction	%	20
Hydrochar dry mass	tDS/d	28
Hydrochar dry solids	%	12
Hydrochar Dewatering and Drying		
Dewatered hydrochar dry mass	tDS/d	26.6
Dewatered hydrochar dry solids	%	30
Hydrochar wet mass to drying	t/d	89
Dried biofuel dry mass	tDS/d	25.2
Dried biofuel dry solids	%	70
Unit energy content	MJ/kg	16.5
Energy content[1]	MWh/yr	42 520
Energy Production		
Steam from boiler	kg/h	5 420
Steam extracted to PCS process	kg/h	817
Electricity production	MWhe/yr	8 392
Electrical power	kWe	958
Ash		
Ash mass	tDS/d	12.7
Dewatering Centrate		
Flow	m/d^3	67
Ammonia load	kgN/d	< 1
Ortho P load	kgP/d	< 1
Soluble COD load	kg/d	1 750
$cBOD_5$ load	Kg/d	234

Similarly, to the greenfield installation, excess electrical energy is generated that can be used in other parts of the plant. Retrofits of this nature at a plant with existing anaerobic digesters offer the opportunity to recover energy from both the biogas generated in anaerobic digesters and the biofuel from post-processing digested sludge with screenings (or other external biomass) in the PCS technology.

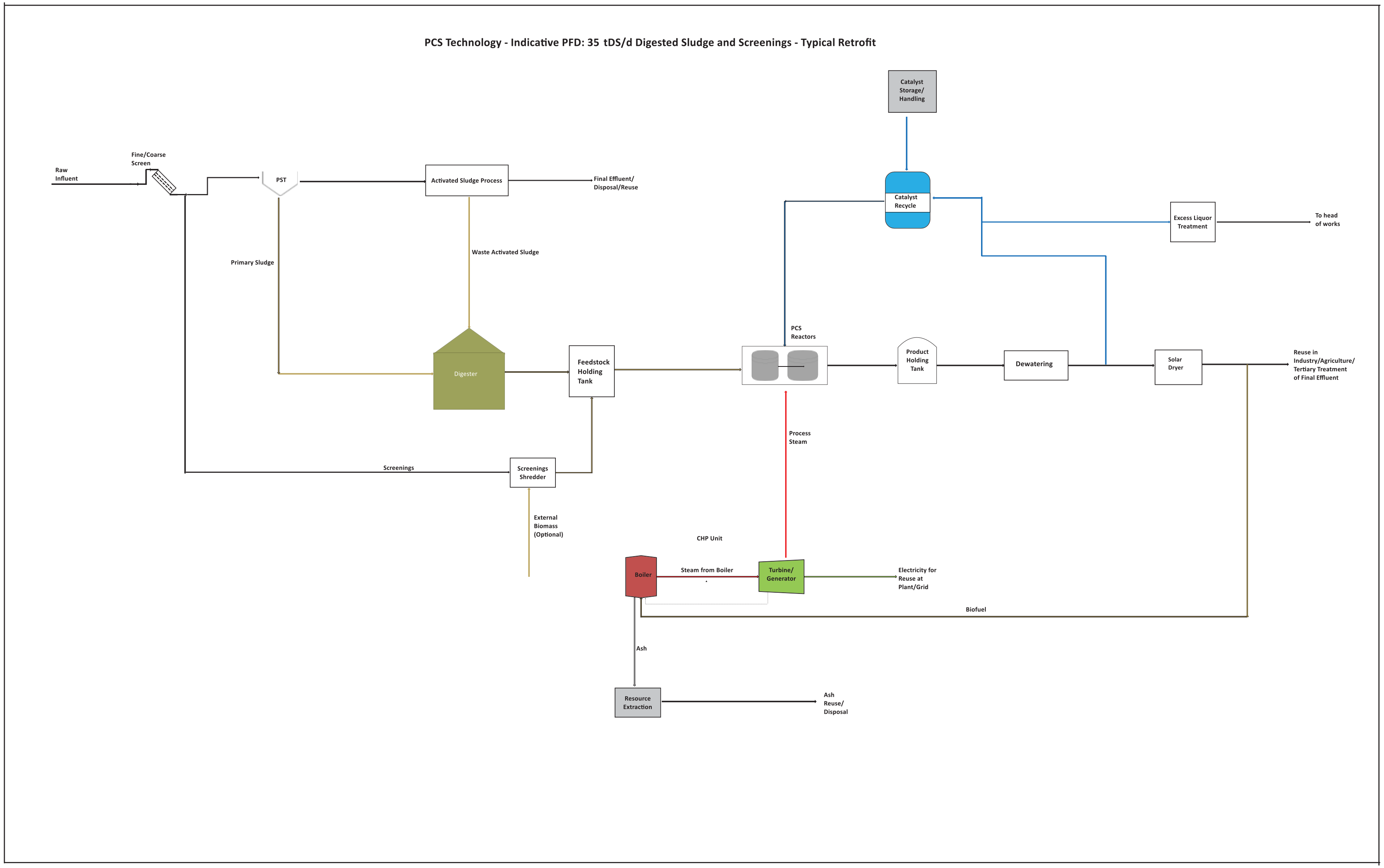


Figure 3-11: Simplified PFD for Retrofit Installation Treating Digested Sludge and Screenings

3.7 ECONOMIC EVALUATION OF INSTALLATION OF PCS PROCESS

3.7.1 Primary and Waste Activated Sludge Only

Two scenarios were evaluated, namely:

- Beneficial use of ash from combustion of biofuel in the boiler
- Disposal of ash to landfill, in the event that it does not meet the DWS standards for agricultural use and there is no market for any other beneficial use.

The criteria outlined in Section 2.2.2 were applied for the economic evaluation.

Table 3-12 gives a summary of the economic evaluation using CBA (cost benefit analysis) with NPV (net present value) as the decision criteria.

Table 3-12: Summary of PCS Process Economic Evaluation- Primary Sludge and WAS Only – 50 tDS/d Greenfield Site

Parameter	PS and WAS Only 50 tDS/d		PS and WAS and Screenings 57 tDS/d	
	Beneficial Use of Ash	Ash to Landfill	Beneficial Use of Ash	Ash to Landfill
CAPITAL COST				
Annual Capital Cost (R million)	363.3	363.3	407.8	407.8
Unit Capital cost (R million/tDS)	7.3	7.3	7.1	7.1
OPERATING COST				
Annual Operating Cost (R million/yr)	12.7	16.0	17.3	22.2
Unit Operating Cost (R/tDS)	694	879	833	1 069
INCOME/BENEFITS				
Annual Income/Benefits (R million)	13.0	18.6	18.5	20.5
NPV (R million)				
100% Equity	-247	-409	-212	-257
100% Debt	-163	-324	-118	-162
45% Subsidy, 55% Equity	-84	-245	-28	-74
45% Subsidy, 55% Debt	163	2.4	248	203

The following is noted:

- Beneficial use of ash gives a higher NPV than disposal of ash to landfill
- The financing model of 45% subsidy and 55% loan gives the only positive NPV and is hence the most favourable for financing the project
- Co-processing of sludge and screenings gives a higher NPV than processing sludge only. This is due to the increase in calorific value of the hydrochar with the addition of screenings
- The benefit of a reduced carbon footprint was not taken into account in the CBA.

3.7.2 Digested Sludge with Screenings

A similar economic evaluation was carried out for retrofitting existing anaerobic digesters with PCS technology at a WWTP with existing anaerobic digesters and processing digested sludge and screenings. A summary of the economic evaluation is given in Table 3-13.

Table 3-13: Summary of PCS Process Economic Evaluation – Primary Sludge & WAS Only – 50 tDS/d Greenfield Site

Parameter	Digested Sludge and Screenings 35 tDS/d	
	Beneficial Use of Ash	Ash Disposal to Landfill
CAPITAL COST		
Capital Cost (R million)	167.3	167.3
Unit Capital Cost (R/tDS)	4.8	4.8
OPERATING COSTS		
Annual Operating Cost (R million/yr)	10.7	13.7
Unit Operating Cost (R/tDS)	835	1 070
INCOME/BENEFITS		
Annual Income/Benefits (R million/yr)	12.3	17.7
NPV (R million)		
100% Equity	-33	4
100% Debt	6	43
45% Subsidy, 55% Equity	43	79
45% Subsidy, 55% Debt	156	193

The following is noted:

- Due to the significant reduction in total solids after combustion of the biofuel, disposal of the ash to landfill is more economically viable than beneficial use of the ash
- The NPVs for the different finance models are positive except for one (100% equity for beneficial use of ash). Thus, retrofitting with PCS technology to further process digested sludge combined with screenings is an economically viable option
- Reduction in carbon footprint was not taken into account in the CBA

3.8 SUMMARY AND DISCUSSION

HTC offers significant advantages over traditional thermo-chemical and biochemical biomass conversion processes like gasification, incineration and anaerobic digestion. Unlike these processes, HTC converts a wide range of biomass, in a relatively short period of time, to a biofuel that burns like coal but with much lower emissions. Thus, the process offers a sustainable option for waste management and renewable energy generation. In the past ten years, research and development has focused on converting the HTC process into a commercially viable technology that can produce renewable energy that can economically compete with energy from non-renewable sources, utilising the abundant wide range of cellulosic and lignocellulosic biomass. The latest technology developments, that include proprietary processing methods and patented catalysts, have resulted in enhanced hydrothermal carbonisation technologies, coined hydrothermal polymerisation (HTP). These enhanced processes allow any type of low-value waste biomass, with moisture content from near 0% to 60% or more, to be efficiently and effectively utilised. HTP also improves the speed, safety, quality and control of solid fuel production over conventional HTC methods.

Under this project, PCS technology, an emerging HTP technology, was evaluated for its efficacy in converting wastewater sludge to a solid biofuel. The technology has already been demonstrated at laboratory-scale and full-scale, processing other biomass (wood waste, paper, agricultural and food waste). Laboratory- and pilot-scale studies were carried out using the PCS technology to process sludge on its own and sludge with screenings. The results of the studies indicated that the PCS technology offers the following advantages when processing wastewater sludge compared to established thermo-chemical and biochemical conversion processes:

- Moderate optimal operating temperature (205–210°C) and autogenous pressure (2.5–3.5 MPa), and short processing time of 1 hour, requiring lower capital and operating costs.
- Converts primary sludge, WAS and combined primary sludge and WAS (with and without screenings) into a hydrochar with a higher calorific value than coal (lignite/sub-bituminous) that can be used as a biofuel. Gas analysis showed that the hydochar, on combustion, emits about 50% less NOx and SOx making the hydrochar a cleaner biofuel.
- Processing combined sludge and screenings increased the calorific value of the sludge by up to 35%. Thus, the process not only provides a single solution for sludge and screenings handling at WWTPs but also presents an opportunity for co-processing wastewater sludge with other biomass (e.g. municipal solid waste, food waste, agricultural waste, etc.) from the community to increase the calorific value of the biofuel produced.
- Can also process anaerobically digested sludge to further reduce the quantity of sludge for disposal or to convert the anaerobically digested sludge to a high-calorific biofuel by co-processing with screenings or other external biomass from the community.
- The process produces a sterile, inert product, without any microbial activity, of a quality that is above the DWS requirements for microbiological/stability Class A1 biosolids. This gives a wide range of options for beneficial use in, for example, agriculture (depending on metal content and pollutant class), or commercial products (e.g. adsorption media, solid biofuel with metal recovery, brick making, cement making).
- Centrate produced after dewatering of the hydrochar is sterile. The centrate also has low ammonia and Ortho P concentrations.
- The process has shown potential, at laboratory scale, to destroy EDCs which are contaminants of concern in the water sector.

Following the pilot-scale studies, a preliminary design and economic evaluation of the PCS technology was carried out. The preliminary design and economic evaluation was for two scenarios:

a) Greenfield installation processing 50 tDS/d of combined primary and waste activated sludge based on sludge quality from Waterval. The evaluation was also carried out for processing sludge with screenings.
b) Retrofitting with PCS technology to process 35 tDS of anaerobically digested sludge (with the same quality as digested sludge from the existing anaerobic digesters at Waterval WWTP) mixed with screenings.

The evaluation assumed that the hydrochar from the process is used as a biofuel for CHP generation, using a CHP unit consisting of a biomass boiler, steam turbine and generator. Two disposal scenarios for the produced biofuel combustion ash were economically evaluated, namely:

a) Ash meeting DWS standards for agricultural use
b) Ash not complying with the DWS pollutant classification and disposed to landfill.

The results showed that:

a) For the 50 tDS/d greenfield installation processing primary sludge and WAS (alone, and with screenings):
    - Beneficial use of the ash from biofuel combustion is more economical than disposal of the ash to landfill.
    - The preliminary design NPV is sensitive to the financing model adopted. Thus, it is important for water utilities to carry out detailed financial modelling before selecting a specific technology or sludge disposal/beneficial use scenario.
    - Centrate from dewatering the hydrochar has a very low ammonia and ortho P load but higher soluble COD load. The COD to BOD ratio is about 7.5 which indicates that most of the soluble COD is unbiodegradable. The soluble COD load is, however, only equivalent to about 5% of the raw influent load (for a plant the size of Waterval). Therefore, the centrate does not need specialised pre-treatment and can, after pH adjustment, be returned to the head of the liquid treatment process without impacting final effluent compliance with the special N, P and COD standards that are typically applied at South African NDEBPR plants.

b) For the 35 tDS/d retrofit processing digested sludge with screenings:
    - The preliminary design NPV is also sensitive to the financing model adopted. However, all, except one, of the financing models evaluated yielded positive NPV. Thus, retrofitting the anaerobic digesters at WWTPs with PCS economically viable to both reduce the amount of sludge for disposal and also generate additional energy from the PCS hydrochar.
    - The retrofit scenario offers opportunities for coupling the technology with existing anaerobic digestion technology, thus preventing redundancy of existing infrastructure. It also offers an opportunity to generate energy from two sources – utilising biogas from

anaerobic digestion and biofuel generated from processing digested sludge and screenings (and if required other external biomass from the community).

3.8.1 Discussion and Recommendations

This project's evaluation of emerging enhanced hydrothermal carbonisation PCS technology provides the South African water sector with other options to consider for sludge management outside traditional thermo-chemical and biochemical conversion technologies. Of particular interest to the sector should be the ability of innovative emerging technologies like the PCS technology to convert a wide range of biomass, other than just wastewater sludge, into a sterile hydrochar that can be used as a biofuel to generate energy for use at the WWTP and offset energy that is purchased from the grid. The hydrochar also has multiple other uses that can open up other revenue streams for the water sector.

The findings in this study have indicated that the PCS technology is an economically viable option for sludge management and energy recovery, with CBA calculations showing positive NPV (depending on the financing model). It is recommended that further evaluation of these innovative alternative sludge management technologies be carried out to provide additional tools to the South African water sector and increase the chances of uptake. Areas to be considered include:

a) Installation of a full-scale demonstration PCS plant processing wastewater sludge from centralised WWTPs (similar to the one analysed in this study) on its own and in combination with screenings and other external biomass from the community. It is recommended that such a study provide the following information:
    - A full-scale economic evaluation of the technology when operating at full scale including the different finance models available to South African municipalities.
    - The carbon footprint, compared to established technologies like anaerobic digestion.
    - Potential use of the hydrochar in other industries and sectors. Of particular importance would be re-using the hydrochar as (i) a fertiliser/soil conditioner – the bio-availability of the nutrients in the hydrochar needs further investigation; and (ii) as functionalised carbon microspheres for removal of contaminants from water and wastewater effluent. This will create the opportunity to use the hydrochar generated from wastewater sludge for tertiary treatment of final effluent for re-use in agriculture or other industries.
    - Hydrochar dewatering technology options and post-treatment and re-use of centrate.

b) Investigation into application of the technology for removal of EDCs of concern in South Africa from both sludge and liquid wastewater.

c) Evaluation of application of the technology at activated sludge plants of different sizes. This needs to include an energy efficiency evaluation for the whole plant, including energy conservation in the liquid treatment process (particularly aeration), to assess how much the generated energy offsets the energy requirements for other processes.

d) Installation of a full-scale demonstration plant for application in low-cost sanitation. The plant will demonstrate processing wastewater/faecal matter from low-cost sanitation systems such as low-flush toilets or dry sanitation systems, in combination with biomass from communities.

e) Evaluation of implementing circular economy principles in the water sector through application of technologies like the PCS technology that can process a wide range of biomass from the community.

Chapter 4 Advanced Anaerobic Digestion

4.1 INTRODUCTION

Anaerobic digestion of municipal wastewater sludge is well established and is the most implemented in South Africa. Historically, mesophilic, single-stage anaerobic digestion has been implemented at most WWTPs not necessarily as a way of recovering energy but as a sludge treatment method to achieve sludge quality that is in line with the requirements of the DWS "Guidelines for the Utilisation and Disposal of Wastewater Sludge". Most WWTPs with anaerobic digesters vent or flare the generated biogas, while the rest use it for reheating boilers which generate steam for heating the digesters (Van der Merwe-Botha et al., 2016).

However, over the past five years, there has been a change in approach by South African water services authorities (WSAs), following the international trend to optimally generate and utilise biogas from anaerobic digestion of sewage sludge. In 2013, Johannesburg Water commissioned the first advanced anaerobic digestion plant in the country (with upstream sludge disintegration waste activated sludge prior to anaerobic digestion, followed by biogas conversion to electricity), at its Northern Works WWTP. Other WSAs are likely to follow suit and implement similar advanced anaerobic digestion with energy recovery schemes. Other large WSAs like ERWAT, City of Cape Town and eThekwini Municipality are reportedly investigating implementing advanced anaerobic digestion at their large WWTPs.

Even though anaerobic digestion is a proven biological process with a long history and worldwide application in treating sewage sludge, optimisation of the technology is still being continued. Optimisation efforts range from improving the quality of feed sludge (through improved control of liquid treatment processes), improved operation and control, application of pre-treatment technologies, and the development of models, modelling software and advanced control system.

4.2 CONVENTIONAL MESOPHILIC ANAEROBIC DIGESTION

4.2.1 Process Fundamentals

Anaerobic digestion (AD) is a complex process, consisting of a number of sequential and parallel biochemical reactions that break down organic waste material to methane and carbon dioxide in the absence of oxygen. A number of models that describe anaerobic digestion processes for sewage sludge have been developed over the years. However, the International Water Association (IWA)'s Anaerobic Digestion Model 1 (ADM1) (Batstone et al., 2002) is the one most applied in research, design and operation of anaerobic digesters. Improved models based on ADM1 have been developed since the publication of ADM1, e.g. the 2-phase steady state anaerobic digestion model by Soteman et al. (2005 a, b) and the 3-phase anaerobic digester model (ADM-3P) by Ikumi et al. (2014).

The reactions that take place in an anaerobic digester can be divided into two main types (Botstone et al., 2002):

a) Biochemical reactions:
These are biologically mediated, catalysed (by intracellular or extracellular enzymes) reactions that utilise biodegradable organics (substrate);

b) Physico-chemical reactions:
These reactions are not biologically mediated and include physio-chemical processes such as ion association/dissociation, gas-liquid transfer and precipitation.

The biochemical reactions involve four different phases, namely: hydrolysis, acidogenesis (fermentation), acetogenesis, and methanogenesis, as depicted in Figure 4.1.

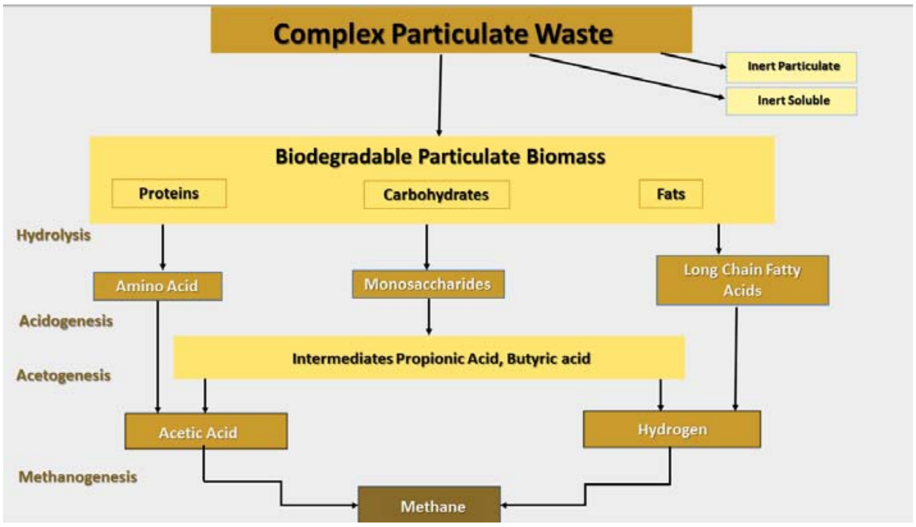


Figure 4-1: Simplified Basic Phases in Anaerobic Digestion

Only brief descriptions of the biochemical reactions are outlined below; readers should refer to the references for detailed discussions of the various anaerobic digester models.

a) Hydrolysis

Hydrolysis is considered to be the first biologically mediated step in the anaerobic digestion process. Microorganisms utilise extracellular enzymes to transform biodegradable particulate organics – mostly proteins, fats and carbohydrates – into soluble simple monomers (i.e. compounds suitable for use as sources of energy and cell carbon) such as monosaccharides, amino acids and long chain acids. Hydrolysis is the rate-limiting step in anaerobic sludge digestion because of the potential for substrate inhibition of the production of extracellular enzymes by microorganisms. It has been established that different sludges have different hydrolysis rates and require different retention times to fully hydrolyse the available biodegradable particulate organics (BPO). As an example, Ikumi et al. (2014) concluded that hydrolysis of 85% of BPO in primary sludge only requires a retention time of 10–15 days, while blended primary sludge and

WAS requires 25–30 days and WAS from nitrification-denitrification enhanced biological phosphorous removal (NDEBPR) systems requires 40–50 days. pH levels below 6.5 have been found to completely inhibit the process (Henze et al., 1995).

Various models (e.g. ADM1) allow for a non-biologically mediated first step, prior to hydrolysis. The step involves disintegration of complex particulate feed through a number of processes such as lysis, non-enzymatic decay, phase separation and shearing (Pavlostathis and Gosset, 1986). The disintegration yields biodegradable organics (95% of which is BPO), unbiodegradable particulate organics (UPO) and unbiodegradable soluble organics (USO).

b) Acidogenesis

The simple monomers produced in the hydrolytic phase are adsorbed by two separate groups of acidogens and are degraded further into mixed organic acids (consisting mostly of butyric and propionic acids), hydrogen and carbon dioxide (Batstone et al., 2002).

c) Acetogenesis

Two groups of acetogenic bacteria utilise the intermediate products from previous steps and convert them to acetic acid, hydrogen and carbon dioxide. While the conversion of sugars and amino acids to acetic acid is a fast reaction which is not inhibited by pH, the conversion of long chain fatty acids to acetic acid and hydrogen is a slower reaction due to the slower growing bacterial culture which is sensitive to pH.

d) Methanogenesis

In the final phase, methane is produced by highly specialised species of methanogens (methane formers) that use a selected group of compounds from acetogenesis via three pathways, i.e. (i) splitting acetic acid by aceticlastic methanogens, (ii) assimilating lower alcohols and carbon dioxide and (iii) reduction of carbon dioxide with hydrogen by hydrogen utilising methanogens.

4.2.1.1 Biogas Production and Utilisation

Anaerobic digestion of organic matter yields a mixture of gases (known as biogas) and biomass. Biogas is composed mainly of methane (60–70% CH_4), some carbon dioxide (30–40% CO_2) and trace amounts of other gases like hydrogen (H_2) and hydrogen sulphate (H_2S).

Based on a theoretical mass balance for an anaerobic digester operating under steady state conditions and assuming that all biodegradable organic matter is converted to methane, the theoretically calculated gas yield at standard conditions is as follows (Metcalf & Eddy, 2013):

- 0.5–0.6 m^3 biogas/kg COD removed
- 0.7–0.8 m^3 biogas/kg VS removed

The biogas produced in anaerobic digestion can be utilised as a fuel for heat for an engine which powers a generator to produce electricity. Alternatively, the biogas can be cleaned (stripped) of CO_2 and injected into the gas network or used for other purposes as a substitute for natural gas.

The most common heat engines used for biogas conversion are gas turbines and combustion engines (internal e.g. reciprocating engine, or external, e.g. Stirling engine). For small-scale operations, combustion engines have been found to be more efficient. Gas turbines are generally more efficient when applied in a co-generation or combined heat and power (CHP) mode where both electricity and useful heat are simultaneously generated.

Traditionally, a scrubbing technology (water, organic, chemical) has been applied to purify biogas. However, new technology such as membrane permeation and cryogenic separation is also being implemented (Yang and Li, 2014). Selection of the appropriate technology depends on the cost and the purity of methane required.

Studies in South Africa have indicated that most of the biogas generated through anaerobic digestion of wastewater sludge is flared and not beneficially utilised (van der Merwe-Botha et al., 2016). This is in contrast to international trends where utilisation of biogas from anaerobically digested wastewater sludge has been incorporated into policy and schemes have been put in place to incentivise renewable energy generation from waste. For example:

- In 2013, it was estimated that the UK water industry generated ~800 GWh per year of electrical energy from sewage sludge (Mills et al., 2013). Subsidy schemes such as the renewable heat incentive have been implemented to drive development of biomethane to grid technology as complementary to, or a substitute for, CHP.
- Energy efficiency generation is recognised in the European Union's (EU) co-generation directive 2004/08/EC. EU countries like Denmark, the Netherlands and Finland have the world's most intensive co-generation economies (WRAPAI, 2009).
- Germany has set targets to increase electricity from co-generation to 25% of the country's electricity needs by 2050 (WRAPAI, 2009).

4.2.1.2 Factors that Impact Anaerobic Digester Performance

The rate at which the microorganisms grow is of paramount importance in the AD process. The operating parameters of the digester must be controlled so as to enhance the microbial activity and thus increase the anaerobic degradation efficiency of the system. The main parameters that impact digester performance are briefly discussed below.

Sludge composition

The composition of sludge affects biogas yield. Sludge with high BPO and low unbiodegradable content is best suited to anaerobic digestion. Thus, primary sludge and WAS from short sludge age plants yield more biogas than WAS from long sludge age plants. Experimental investigations and plant-wide modelling by Ikumi et al. (2014) confirmed that material in WAS that is unbiodegradable (i.e. influent unbiodegradable particulate organics and endogenous residue) is not further degraded during anaerobic digestion even with digesters operating at very long hydraulic retention times (HRT > 60 days). Also, WAS from NDEBPR systems, which have a higher fraction of unbiodegradable particulate organics, would yield less biogas than WAS from a fully aerobic or a nitrification-denitrification (ND) system only, operated at the same sludge age.

pH

Anaerobic bacteria, especially methanogens, are sensitive to pH, and acidic conditions can inhibit the growth of methanogens. Optimum pH for AD has been determined to be between 6 and 8.

In the three-phase anaerobic digestion model, Ikumi et al. (2014) demonstrated that anaerobic digester pH is a result of the alkalinity in the influent organics (intrinsic or measurable), which, when degraded, transfers to the aqueous phase through the release of ammonia (N), polyphosphate (P) and utilisation of dissociated volatile fatty acids (VFA). Thus, the three bio processes (hydrolysis, acetogenesis and methanogenesis), that generate alkalinity, together with the influent H_2 CO_3 alkalinity establish the total alkalinity and hence the pH of the anaerobic digester.

Digester retention time affects the pH value. At higher retention times, more hydrolysis of BPO occurs, releasing organically bound N and P into the liquid. It has been shown that in batch anaerobic digester systems, acetogenesis occurs at a rapid pace and can lead to accumulation of large amounts of organic acids resulting in low pH which can inhibit methanogens. Reduction in pH can be controlled by the addition of an alkaline, usually lime.

Temperature

Two temperature ranges have been found to provide optimum digestion conditions for the production of methane, namely:

(i) the mesophilic (20–65°C) range
(ii) thermophilic (50–65°C) range

The optimum temperature for the mesophilic range has been established to be 32–35°C.

Carbon to nitrogen ratio (C/N)

The optimum C/N ratio in anaerobic digesters is in the range 20 – 30. A high C/N ratio indicates rapid consumption of nitrogen by methanogens and results in lower gas production. On the other hand, a lower C/N ratio causes ammonia accumulation and pH values exceeding 8.5, which is toxic to methanogenic bacteria.

Total solids content/organic loading rate

Organic loading rate (OLR), measured as volatile solids rating rate, is a measure of the biological conversion capacity of the AD system. It is a very important process control parameter as excessive feeding is the most frequent cause of digester failure. In addition, digester capacity, particularly in continuous systems, depends on the solids content of the feed sludge, hence it is important to maintain proper control of the feed sludge concentration. Digesters are classified as high, medium and low rate based on the feed total solids concentration. Excessive feeding results in excessive amounts of VFA being produced which could reduce alkalinity and pH and inhibit methanogenesis. In such cases, the feeding rate to the system must be reduced. OLR is therefore a particularly important control parameter in continuous systems. Some typical operating parameters for anaerobic digesters processing sewage sludge are given in Table 4-1.

Table 4-1: Typical Solids Operating Parameters for Anaerobic Digesters Processing Sewage Sludge (Metcalf & Eddy, 2003)

Digester Type	Total Solids Content %	Volatile Solids Loading Rate (kg VSS/m^3/d)
High Rate	5–10	1.5–3.0
Standard Rate	3–5	0.5–1.4

Retention time

The required retention time for completion of the AD reactions varies depending on the type of feed sludge, process temperature, and process type. Experience of full-scale mesophilic AD and laboratory-scale studies indicates that digester retention times of 10–15 days are required to remove ~85% of BPO when digesting primary sludge only. The required retention time increases to 20–30 days when digesting blended primary and WAS and to 40–50 days when digesting WAS from NDEBPR only (Ristow et al., 2004; Ikumi et al., 2014; WISA, 2002).

Mixing

Mixing is essential for optimal performance of the digester and improves process stability and biogas yield. Benefits of good mixing include (WISA 2002):

- uniform blending of feed sludge with digester contents, promoting contact with micro-organisms
- prevents grit settlement and scum formation, thus effectively using available digester capacity
- promotes an even temperature profile within the digester
- enables even distribution of added chemicals, e.g. for pH correction
- promotes rapid dispersion and dilution of toxic substances, thus minimising their negative impact on the process
- improves biogas release from the lower levels of the digester tank.

It is, however, essential to control the mixing intensity to avoid excessive CO_2 stripping which could increase alkalinity (and hence pH) thus negatively impacting process performance (Ikumi et al., 2014).

The kind of mixing equipment and amount of mixing varies with the type of reactor and the solids content in the digester.

4.2.1.3 Handling and Treatment of Anaerobic Digester Supernatant

Anaerobic digester supernatant and centrate from digested sludge thickening and dewatering can contain high concentrations of ammonia and ortho P. Ammonia and ortho P concentrations are higher for digested WAS from NDEBPR systems due to release of organically bound N and P as the biomass (OHOs and PAOs) dies off and converts to BPO. The amount of ammonia and ortho P released increases with sludge retention time as more time is available for hydrolysis of the BPO (Ikumi et al., 2014).

Generally, centrate is returned to the head of the works so that it can be treated in the secondary treatment process. However, for WWTPs that have to comply with stringent final effluent N and P standards, returning nutrient-rich centrate can result in non-compliance with these standards. Under these circumstances, it is necessary to separately treat and remove the N and P from the centrate. With the recent drive towards resource recovery from wastewater treatment facilities, technologies that recover struvite are now being applied in separate treatment of centrate from AD processes. Vendors that supply commercially proven, specialised struvite recovery technologies include Ostara (Canada), Multiform Harvest (USA) and RHDHV (Netherlands).

4.3 ADVANCED ANAEROBIC DIGESTION

In the past five to ten years, energy production has emerged as a key driver for implementing anaerobic digestion of sewage sludge. Anaerobic digestion technology development has therefore focused on improving biogas generation. Since hydrolysis is the rate-limiting step in the overall anaerobic digestion process, technology development has focused on sludge disintegration methods prior to digestion that will stimulate higher hydrolysis rates, increase VFA production and consequently methane production. Higher utilisation of BPO also results in less digested solids which increases the sustainability of the process.

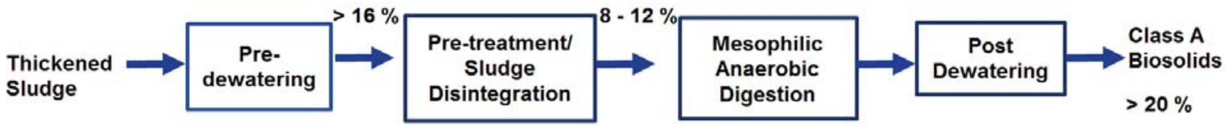


Figure 4-2: Schematic Representation of Application of Sludge Disintegration Prior to Mesophilic Anaerobic Digestion (MAD)

Implementing sludge disintegration technologies prior to digestion is termed advanced anaerobic digestion. Several sludge disintegration technologies, including biological, thermal, mechanical, chemical, electrical and combined technologies, have been developed and implemented at full scale since the late 1990s. A brief description of some of these methods is given below. A detailed discussion of thermal hydrolysis, which has been selected for this study, is given in Section 4.3.1. Readers should refer to the references for details on the other methods described here.

a) Biological pre-treatment

Biological pre-treatment utilises microbial enzymes to enhance degradation of complex organic waste and improve AD. Enhanced enzyme hydrolysis (EEH) is one of the processes that has been tested both at laboratory and demonstration scale for the pre-treatment of WAS. The process was originally proposed by Mayhen et al. (2002) and is based on the concept of optimising AD by separating the hydrolysis and acidogenesis phases from the methanogenesis phase. The original process is designed to operate in two stages:

- a mesophilic (~42°C) first stage, operated at about 1.5–2 days HRT, followed by
- a thermophilic pasteurisation stage (55–65°C), also with a HRT of about 1.5–2 days.

Sludge from the EEH process is fed to the MAD. Reported increases in biogas after EEH pre-treatment range from 10 to 35% (Salihu et al., 2016)

b) Thermal pre-treatment

Thermal pre-treatment involves the addition of heat to improve hydrolysis of the sludge prior to AD. The heat applied ruptures the chemical bonds of the cell wall and makes the proteins accessible to biological degradation in the anaerobic digestion process. Optimal operating conditions have been found to be 160–180°C temperature, 30–60 minutes processing time and 0.6–2.5 MPa pressure (Jolly & Gillard, 2009; Zhang, 2010; Salihu et al., 2016). Thermal hydrolysis of sludge is the most successfully commercialised pre-treatment method, with a number of proprietary technologies installed at full scale. A detailed discussion of thermal hydrolysis is given in Section 4.3.1. Reported biogas increases after thermal pre-treatment of WAS range from 10 to 120%.

c) Mechanical pre-treatment

In mechanical pre-treatment, the biodegradability of the sludge is increased by disrupting the floc and/or lysing the cells. Techniques most applied are ultrasonication (ultrasound), grinding and high-pressure homogenisation (Jolly & Gillard, 2009; Zhang et al., 2012). Ultrasonication is reported to be the most efficient mechanical pre-treatment method, with 10 to 60% enhancement in biogas production during AD (Pilli et al., 2011).

d) Chemical pre-treatment

Acids, alkalis and oxidants are added in the hydrolysis of sludge. The methods that have been found to be effective for sludge pre-treatment are oxidation (ozonation and peroxidation) methods. Peracetic acid has also been found to have good potential for sludge pre-treatment (Salihu et al., 2016). Acid and alkaline pre-treatment is often coupled with other pre-treatment methods, e.g. thermal, mechanical and electrical.

e) Combined pre-treatment

Studies have also shown that combining pre-treatment methods can result in better sludge hydrolysis and biogas production than a single method on its own. Most of the combined pre-treatment methods are based on laboratory-scale proof of concept with mixed results in terms of enhanced biogas production, and their operational and economic effectiveness has not yet been proven at demonstration scale. Combined methods that are reported to have potential for sludge pre-treatment are thermo-chemical pre-treatment of WAS at temperatures ranging from 50 to 121°C and alkaline (N_aOH) additions (Zhang, 2010; Salihu, 2016). Other combined methods being investigated include electrochemical pre-treatment, and mechanical (high homogenised pressure) with alkaline addition.

f) Electrical pre-treatment

This method, often referred to as pulsed electric fields, involves subjecting the sludge to focused high-voltage electric pulses to break down cellular membranes and cell walls, complex organics and macromolecules (Rittman et al., 2008).

4.3.1 Thermal Hydrolysis Process

The thermal hydrolysis process (THP) involves using high temperature (165°C) and pressure (0.6–0.7 MPa) to disrupt and solubilise sludge before it is fed to a conventional, usually mesophilic, anaerobic digester. The process also homogenises the sludge so that it is more digestible, resulting in increased methane production as well as reduced quantity and higher quality of digested sludge. The process is the most implemented disintegration technique with more than 60 full-scale THP sites worldwide, either in operation or under construction. However, the increase in biogas does not necessarily result in an overall net increase in energy yield. The process demands an input of high-grade heat and additional electrical energy, when compared with conventional MAD. The high-grade heat demand typically outweighs the heat available from a CHP unit burning the biogas produced. Most THP installations in the UK were reported to currently require a support fuel (typically natural gas) to maintain the process (Mills et al., 2011). Thus, the economics of the process need to be carefully analysed on a case-by-case basis.

Cambi and Veolia are the two main vendors that supply THP. A brief description of their systems is given below.

4.3.1.1 Cambi Thermal Hydrolysis Process

Cambi can be considered to be the most established provider of THP for advanced anaerobic digestion of wastewater sludge. According to their website, they have installed over 55 full-scale thermal hydrolysis plants globally.Figure 4-3 shows a schematic layout of the Cambi THP.

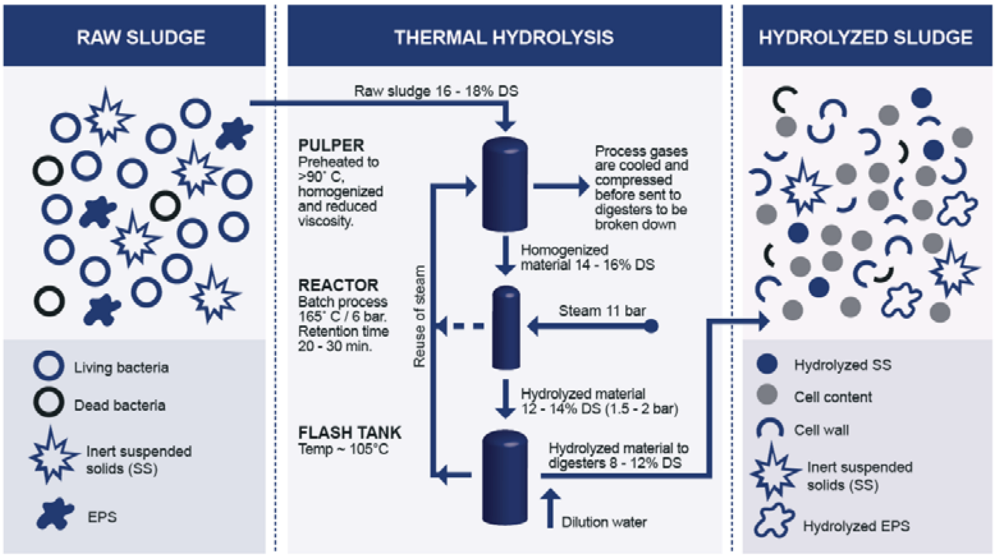


Figure 4-3: Schematic Representation of the Thermal Hydrolysis Process (adapted from Cambi, 2016)

The main features of the Cambi THP are as follows (Cambi, 2016):

- Feed sludge is pre-dewatered to 16–18% dry solids and stored in a silo.
- The dewatered sludge is fed into the pulper to be mixed and heated by recycled steam from the reactor(s) and the flash tank. Process gases are compressed and broken down biologically in the digesters.
- Thermal hydrolysis takes place in reactor(s) operated in a batch mode at 165°C for 20–30 minutes. The steam is gradually released and sent back to the pulper.
- The sterilised sludge is then passed rapidly into the flash tank, resulting in cell destruction from the pressure drop. The sludge temperature is decreased to approximately 102°C by flashing steam back to the pulper.
- The sludge is then cooled to the required digestion temperature, partly by adding dilution water and partly in the heat exchangers.

The THP process is followed by MAD. Steam for thermal hydrolysis is mainly produced in a co-generation waste-heat boiler using exhaust gas and cooling water from the gas engine. Alternatively, biogas or other fuel sources can be used.

Some of the advantages cited for the Cambi process are (Arbu-Orf and Goss, 2012; Cambi, 2016):

- Increased sludge biodegradability and therefore more biogas production

- A significant reduction in sludge cake volume
- A higher digestion rate, and 8–12% dry solids feed to digestion increases digester capacity two to three times when compared to conventional MAD
- Stable and reliable digester operation
- Highly energy-efficient process
- Eliminates foaming problems caused by filamentous bacteria (Nocardia, etc.)
- Sludge dewaterability improved up to 40% dry solids
- Pasteurised EPA Class A biosolids cake with no regrowth or reactivation of bacteria.

4.3.1.2 Veolia Anaerobic Digestion with THP

Two THP technologies are supplied by Veolia Water Technologies, i.e. the continuous mode Exelys™ (applied for small plants of 8.1–35.7 tDS/d) and batch mode Bio Thelys™ systems. The process pre-treats dewatered sludge (~15% DS) at a temperature of 165°C and pressure of 0.6–0.8 MPa for about 30 minutes.

Figure 4-4 shows a schematic layout of the Veolia THP when utilising the batch mode Bio Thelys™ system. The process can be operated in three configurations, which is reported to offer greater flexibility and meet client needs (Veolia, 2017):

- *Lysis/Digestion*
  Thermal hydrolysis is applied to the whole or part of the sludge stream prior to MAD. This is applied mostly on plants with digester capacity limitations.
- *Partial Lysis/Digestion*
  Thermal hydrolysis is applied only to secondary sludge from the biological treatment process (e.g. WAS). Hydrolysed secondary sludge can then be anaerobically digested on its own or mixed with primary sludge, where available prior to MAD. The configuration is mostly applied to save costs on the THP.
- *Digestion/Lysis/Digestion*
  Thickened sludge is digested first in primary MAD. The digested sludge is then thermally hydrolysed and digested further in secondary MAD. This is reported to achieve optimal energy savings and sludge reduction. There are reportedly seven full-scale installations of the Veolia THP in Europe. The reported advantages are similar to the ones outlined for Cambi.

4.3.1.3 Treatment of Centrate from Thermal Hydrolysis Processes

Due to enhanced hydrolysis of the disintegrated sludge, centrate from dewatered advanced TH–MAD sludge is high in ammonia, ortho P and unbiodegradable soluble organics, compared to centrate from conventional MAD. Observation data from pilot and full-scale advanced TH–MAD plants in the United Kingdom (processing sludge from nitrifying activated sludge plants), as well as modelling results, show that the ammonia and ortho P load in the centrate can be as high as 75% and 120%, respectively, of the raw influent loads. For NDEBPR plants with stringent final effluent N and P limits, specialised treatment processes (e.g. combined annamox and chemical P precipitation, or struvite crystallisation, ammonia stripping and chemical P precipitation) are required to ensure compliance with N and P limits. The high N and P content in the centrate creates opportunities for nutrient recovery using the innovative technologies that are on the market. The cost of centrate treatment needs to be taken into account when evaluating sludge P.

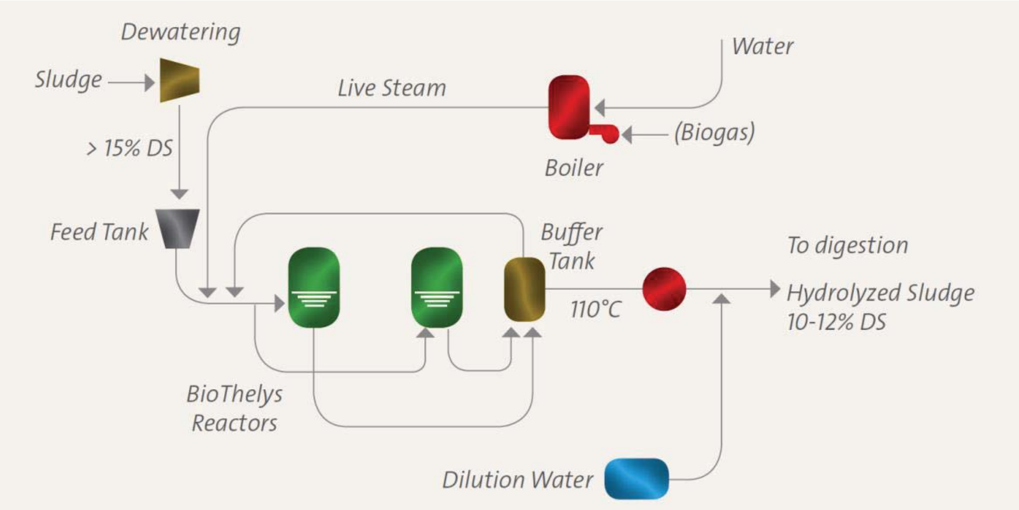


Figure 4-4: Flow Diagram of Veolia Bio Thelys THP Process

4.4 APPLICATION OF ADVANCED ANAEROBIC DIGESTION IN SOUTH AFRICA

4.4.1 Overview

Johannesburg Water's Northern Works is the only municipal plant in South Africa that has implemented advanced anaerobic digestion. The plant, which has a design capacity of 450 Ml/d ADWF, is Johannesburg Water's biggest WWTP and the site of its first biogas to energy project. NDEBPR activated sludge process is employed for secondary treatment of liquid wastewater. During 2014/2015 the works produced about 94 tDS/d of sludge (both primary and WAS) and utilised about 8 MW/d of electricity (Juncker et al., 2016). Sludge is stabilised in four anaerobic digesters.

Motivated by a steep increase in energy costs, Johannesburg Water initiated a feasibility study into biogas to energy generation at their wastewater treatment works in 2009. The study objectives were as follows (Deacon and Louw, 2012; van der Merwe-Botha, 2016):

- determine the risks associated with CHP operations in wastewater treatment and identify the most common causes of CHP failure
- identify contaminants to be removed from biogas before its use as fuel in CHP generation, as well as the most efficient, cost-effective and sustainable technologies for biogas cleaning
- identify the most appropriate and cost-effective prime mover for CHP systems
- determine the volume and quality of the biogas produced at Northern Works
- identify appropriate upstream sludge disintegration technologies to increase biogas production in the anaerobic digesters. Investigations focused on three technologies which were deemed feasible – mechanical disintegration, ultrasonic and electro-kinetic disintegration.

After the study was completed, the following were installed at the plant in 2012 (Juncker et al., 2016):

- electro-kinetic disintegration of gravity thickened WAS, prior to anaerobic digestion
- a gas cleaning and conditioning system
- three CHP engines, each with an installed capacity of 376 kWe, i.e. a total ~1.1 MWe (~10% of the WWTP's requirements), and associated heat recovery equipment.

To increase the amount of biogas produced, refurbishment of two additional existing digesters was being undertaken in 2015. The design estimated that once the balance of the existing digesters was available, all of the sludge could be treated anaerobically and the CHP plant would be able to produce up to 4.5 MWe, covering approximately 56% of the power requirements at the plant.

The initial feasibility study conducted by Johannesburg Water estimated that approximately 300 Nm^3/h of biogas would be produced in the digesters, and the CHP plant was sized on this basis. In the first phase of the project, the plant was expected to achieve an average output of 600–700 kWe a day (roughly 5 000 MWh/year at 95% mechanical availability), running two engines at 80% and leaving a third engine as standby. At this output, the project payback period was six to eight years.

However, at a WISA workshop in 2016, it was reported that after three-and-a-half years of operation, the CHP plant had been online for 29 432 hours out of a possible 29 904 hours (~98.5 % runtime) and produced about 7 000 MWh (~2 000 MWh/yr) of electric power to date (Juncker et al., 2016). Thus, the plant could only generate an average of 238 kWe which is 37% of the expected design daily average output of 650 kWe when running two engines and 21% of installed capacity.

The reduced power output was due to low biogas production in the anaerobic digesters which averaged about 100–150 Nm^3/h. Some of the remedial actions recommended to increase biogas production were:

- Increase sludge feed thickness from the then current 2% TDS

- Constant feeding to digesters
- Optimisation of digester mixing and heating
- Improve digester maintenance
- Measure gas quality and quantity
- Optimise upstream WAS disintegration technology.

4.5 PRELIMINARY DESIGN OF FULL-SCALE IMPLEMENTATION OF ADVANCED THERMAL HYDROLYSIS – MESOPHILIC ANAEROBIC DIGESTION

Since the THP is the most widely employed upstream sludge disintegration process in advanced anaerobic digestion, its implementation at a typical South African WWTP was evaluated as part of this project. Waterval WWTP was selected as the case study plant. The preliminary plant was assumed to be a greenfield installation sludge processing 50 tDS/d of combined primary and WAS, of the quality discussed in Section 2.2.1.

The following treatment units are required:

- Sludge pre-thickening and dewatering units to increase sludge feed concentration to 16%. It was assumed that WAS is thickened and dewatered on combined linear screen BFP units, while primary sludge is dewatered on BFP.
- A storage tank for the thickened sludge.
- A THP unit, followed by pre-digester cooler/buffer tank to reduce sludge temperature prior to feeding to the MAD.
- Belt filter presses for dewatering digested sludge.
- A solar drying system for digested sludge.
- CHP generation unit and boiler.

It was assumed that the generated biogas is used primarily to heat a boiler and the steam is used to heat the THP. The remainder of the steam generates electricity via a CHP unit. Some of the electricity from the CHP unit is used in supplementary heating for the boiler and the remainder is used in other parts of the plant.

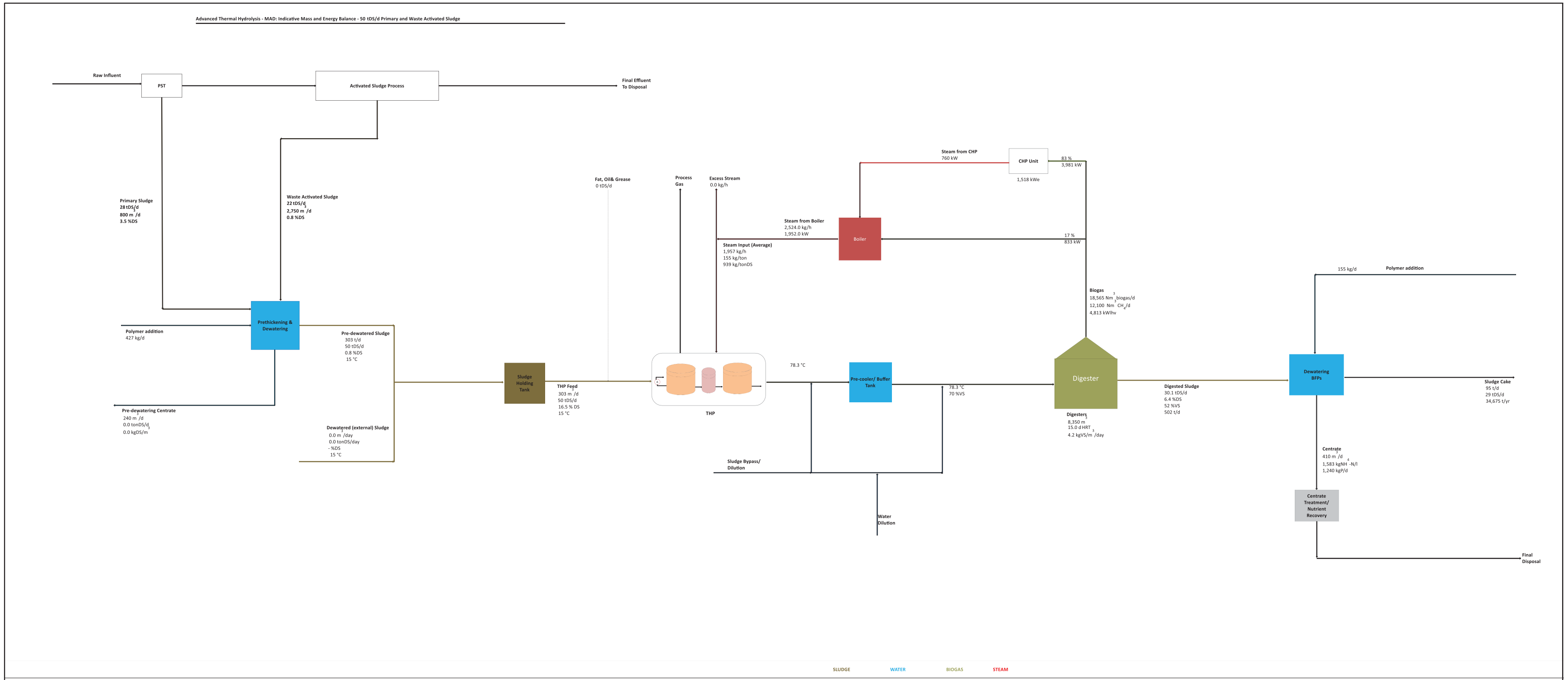
Table 4-2 gives a mass and energy balance comparison of a greenfield installation of a conventional MAD plant and an advanced TH–MAD plant. The mass and energy balance diagram for the advanced TH–MAD plant is shown in Figure 4-5.

Table 4-2: Summary of Mass and Energy Balance for Conventional MAD and Advanced Thermal Hydrolysis–MAD for a Plant Treating 50 tDS/d Combined PS and WAS

		Conventional MAD	Advanced THP–MAD
Digester Capacity			
Total undigested sludge to digester	tDS/d ay	50	50
VS to digester	tDS/d ay	35.8	45.7
Feed concentration	%	7	10
Sludge flow to digester	m³/day	714	500
Hydraulic retention time	days	20	15
Required digester volume	m³	15 873	11 115
VS loading rate	kgVS/m³/d	1.8	
VS reduction	%	40[1]	55
Digested sludge dry solids	tDS/year	12 940	11 000
Biogas Production			
Annual biogas production	m³/yr	4 965 551	6 776 015
Daily biogas production	m³/day	13 604	18 564
Methane production[2]	m³/day	8 843	12 067
Biogas energy content	MWh/yr	30 899	42 165
Energy Production			
Biogas energy bypass to boiler for sludge heating/THP	%	0.0	17
Biogas energy to CHP generation	MWh/yr	30 899	35 000
Electricity produced[3]	MWhe/yr	11 742	13 300
Electrical power	kW	1 340	1 518
Dewatering			
Dewatered sludge dry solids	%	20	30
Dewatered sludge wet mass	t/yr	61 461	35 021
Dewatering Centrate			
Flow	m/d³	422	410
Ammonia load	kgN/d	1 151	1 583
Ortho P load	kgP/d	773	1 240

Notes:

1. Based on measured performance of existing digesters at Waterval WWTP
2. Methane content in biogas = 65%
3. CHP engine efficiency 38% and thermal recovery 50% (van der Merwe-Botha et al., 2016)



Summary of design data

Sludge Production	
Primary	28 tDS/d
Secondary	22 tDS/d
Other	0 tDS/d
Total	50 tDS/d
	18,250 tDS/yr

Thermal Hydrolisis	
Sludge to hydrolysis	50 tDS/d
Sludge bypassed	0 tDS/d
Hydrolysis feed DS	16.5 %DS
Wet flow to hydrolysis	303 t/d

Mesophilic Anaerobic Digestion	
Total DS to digester	50 tDS/d
Total VS to digester	35.5 tVS/d
Digester feed DS	10 %DS
Digester feed flow	500 t/d
Digester volume	8,350 m^3
Digester loading	4.2 kgVS/m^3/d
HRT	15 d
VSR	55 %

Energy Production	
Biogas production	18,564 Nm^3/year
Biogas produced	6,699,210 Nm^3/year
Energy content	42,165 MWhlhv/yea
Electrical power	1,518 kWe
Electricity produced	13,300 MWh/year
Biogas bypassed to boiler	17.3 % of total flowrate
External fuel need	0 kW
External fuel	0 MWhlhv/year

Dewatering	
Dry solids to dewatering	30.1 tDS/d
Capture rate	95 %
Dry solids after dewatering	30 %DS
Sludge cake produced	0.5 t/d
Sludge cake	34,675 t/d
Reject water flow	410 m^3/d
Ammonia load	1,583 kgNH_4-N/d

Figure 4-5: Mass and Energy Balance for Greenfields Installation of Thermal Hydrolysis Advanced Anaerobic Digestion for Treating 50 tDS/d of Primary Sludge and WAS (adapted from Cambi)

4.5.1 Economic Evaluation

Two scenarios were evaluated, namely:

- Beneficial use of digested sludge as compost for agriculture
- Disposal of solar-dried digested sludge to landfill in the event that it does not meet the standards or there is no market for beneficial use.

Table 4-3 gives a summary of the economic evaluation for a greenfield advanced TH–MAD plant processing 50 tDS/d of combined PS and WAS similar in quality to that produced at Waterval WWTP. Included as a comparison is an evaluation for a similar-sized conventional MAD plant. The costs in Table 4-3 are for an upgraded greenfield conventional MAD plant that includes sludge pre-thickening to 7–10% and biogas utilisation for CHP generation. It should be noted that the impact of GHG emissions was not taken into account in the economic evaluation.

Table 4-3: Economic Evaluation Summary – Thermal Hydrolysis Advanced Anaerobic Digestion of Primary Sludge and WAS

Parameter	Conventional MAD		Advanced TH–MAD	
	Beneficial Use of Digested Sludge as Compost	Digested Sludge Disposal to Landfill	Beneficial Use of Digested Sludge as Compost	Digested Sludge Disposal to Landfill
CAPITAL COST				
Total Capital Cost (R million)	420.4	408.5	520.8	520.8
Unit Capital Cost (R/kgDs)	8.4	8.2	10.4	10.4
OPERATING COSTS				
Total Annual Operating Cost (R million)	21.9	29.8	22.3	30.1
Unit Operating Cost (R/kgDs)	438	596	446	602
INCOME/BENEFITS:				
Annual Income/Benefits (R million)	14.3	7.5	15.1	12.9
NPV (R million)				
100% Equity	-508	-708	-489	-663
100% Debt	-413	-613	-369	-542
45% Subsidy, 55% Equity	-314	-502	-248	-416
45% Subsidy, 55% Debt	-37	-225	-104	-63

The following is noted:

- All NPVs under the different financing models are negative which indicates that neither technology would be considered economically attractive.
- Beneficial use of sludge as compost gives higher NPV values than disposal of sludge to landfill.
- Implementing advanced TH–MAD is more economically beneficial than conventional MAD. The advantages of advanced TH–MAD over conventional MAD are discussed in more detail in Section 4.6.
- Neither the cost of specialised treatment processes for the high-nutrient, low-carbon centrate, nor the benefits of nutrient recovery, were taken into account for the advanced TH–MAD plant.
- The high-level financial modelling indicates that the financing model of 45% subsidy and 55% loan gives the highest NPV (albeit negative) and is hence the most favourable.

4.6 SUMMARY AND DISCUSSION

4.6.1 Summary

Thermal hydrolysis, with over 60 plants either installed or in the planning stage, is the most established sludge pre-treatment method for advanced anaerobic digestion. Reports based on data from laboratory and full-scale plants indicate increased biogas yields 10 to 120% above conventional MAD gas yields. Apart from increased gas yields, thermal hydrolysis also offers the following advantages over conventional MAD:

a) *Reduced reactor digester capacity*
   The required retention time for anaerobic digesters following thermal hydrolysis is lower (10–15 days) than that required for conventional MAD (> 15 days). This saves on the capital costs of new installations and also increases the capacity of existing digesters if a THP is retrofitted upstream of the digester.
b) *Pathogen-free and stabilised digested sludge*
   Digested sludge after thermal hydrolysis has been found to be pathogen free and classified as EPA Class A biosolids. In South Africa, the sludge would be classified as microbiological/stability Class AI. Thus, the sludge, if it passes the metal and other pollutant criteria standards, can be used for agricultural purposes without additional treatment.
c) *Thermal hydrolysis significantly improves sludge dewaterability*
   After anaerobic digestion, data from pilot and full-scale plants indicates BFP dewatered sludge concentrations of around 30% DS compared to ~20% achieved for sludge from conventional MAD.
d) *Significant reduction in carbon footprint*
   Application of thermal hydrolysis reduces GHG emissions more than conventional MAD because of the advantages cited above. Increased biogas production reduces the use of non-renewable sources of energy at WWTPs. GHG emissions are also reduced by avoiding practices such as sludge disposal to landfill, applying untreated sludge to land, use of chemical fertilisers, lime stabilisation and incineration.

As part of this project, preliminary design, modelling and economic evaluation of an advanced TH–MAD plant was carried out. The evaluation was for a greenfield installation treating 50 tDS/d of combined primary sludge and WAS, based on the sludge quality at Waterval, a NDEBPR WWTP with conventional MAD. It was assumed that the biogas would be used for CHP generation. Two sludge disposal scenarios were economically evaluated, namely:

- digested sludge meeting DWS standards for agricultural use as compost
- digested sludge not complying with the DWS pollutant classification and disposed to landfill

An equivalent greenfield installation of a conventional MAD plant with biogas utilisation for CHP generation was also evaluated to serve as a baseline comparison. The results showed that for the 50 tDS/d plant:

- Implementing advanced TH–MAD is more economically beneficial than conventional MAD.
- Beneficial use of sludge is more economical than disposal of sludge to landfill, even with the additional cost of thermal hydrolysis.
- All NPVs for the preliminary design are negative and the NPV is sensitive to the financing model adopted. Thus, it is important for water utilities to carry out detailed financial modelling before selecting a specific technology or sludge disposal/beneficial use scenario.
- Dewatered, digested centrate from advanced TH–MAD is high in ammonia (free and saline ammonia), ortho P and unbiodegradable soluble organics. Since most WWTPs in South Africa have to comply with stringent ammonia, nitrate and ortho P standards, the centrate cannot just be returned to the head of the plant as is common practice for most plants with conventional MAD. Specialised sidestream treatment and/or nutrient recovery technologies therefore need to be evaluated when considering installation of advanced TH–MAD plants.

4.6.2 Discussion and Recommendations

In order to provide the South African water sector with additional tools to evaluate advanced anaerobic digestion technologies, it is recommended that further evaluation and research be carried out in the following areas that were not covered in this report:

a) Detailed whole plant modelling and preliminary design combining liquid treatment processes and advanced THP–MAD, including:
    - evaluation of the impact of dewatered digested sludge centrate on final effluent compliance, as well as sidestream treatment and nutrient recovery technologies
    - economic evaluation, including financial modelling, taking into account different finance models and sludge utilisation/disposal routes
    - carbon footprint evaluation

b) Investigation of technology coupling with other waste-to-energy technologies, e.g. the enhanced HTC PCS technology discussed in Chapter 3

c) Economics of implementing advanced TH–MAD at plants of different sizes to determine the optimal plant size for the technology. Modelling of regional sludge handling facilities, taking into account sludge transportation needs.

Chapter 5 Gasification Technology

5.1 INTRODUCTION

5.1.1 Process Fundamentals

Sludge gasification to produce syngas (synthetic gas) is an established technology. Most full-scale installations are in Europe, mainly in Germany. The process has been applied to coal and wood since the 1900s. Although the technology is established for processing other biomass, it is still considered emerging when applied to processing wastewater sludge.

Gasification is a thermo-chemical conversion process (similar to combustion) that converts carbon-based material to synthetic gas in a reactor after the addition of heat, steam, oxygen and/or nitrogen. Both heat and a combustible gaseous product are produced. Generally, two methods of gasification have been employed (Ross, 2010):

a) partial oxidation which is similar to combustion but occurs under insufficient oxygen or air for complete combustion to take place
b) indirect heating of biomass using steam in the absence of oxygen or air

The process takes place at temperatures greater than 800°C. Produced syngas consists mainly of hydrogen (H_2), carbon monoxide (CO), nitrogen (N_2), traces of methane (CH_4) and other hydrocarbons, as well as tar, particulates and carbon dioxide (CO_2). Theoretically, any form of biomass can be processed through thermal gasification. However, the efficiency of the gasifier is limited by factors such as a high moisture content in the feedstock, ash fusion temperature, the design of the feeding system and the mixing and separation of feedstock (US EPA, 2012).

The generic steps in gasification start with the preparation and drying of feedstock (usually to 10–20% moisture) which is then fed into a gasifier where a two-stage process takes place. In the first stage, the volatile fraction of the solids is transformed, in the absence of air (pyrolysis), into a carbon-rich substance called “char”. This transformation occurs at a temperature of around 600°C or less. In the second step, the char is gasified in the presence of oxygen or air at temperatures greater than 800^{o}C and is converted to syngas.

The quality and composition of syngas varies depending on the type of gasifier and feedstock. The syngas produced can be cleaned through methods such as:

- ash-capturing cyclones
- solvent-based tar scrubbers
- water, acid or caustic scrubbers

Cleaned syngas can be used as a fuel to generate electricity and heat. It can also be converted to a liquid fuel or for chemical production. The non-homogeneous character of most biomass (e.g. cornhusks, switchgrass, straw) poses difficulties in maintaining constant feed rates to gasification units. The high oxygen and moisture contents result in a low heating value for the produced syngas, typically less than 2.5 MJ/m^3.

Some processes can recover heat in the form of steam which can be re-used to supplement drying the feed stock. If the syngas is fed into a CHP engine, then additional heat can be recovered from the exhaust and used to supplement other heat forms.

A schematic layout of a generic gasification process is shown in Figure 5-1.

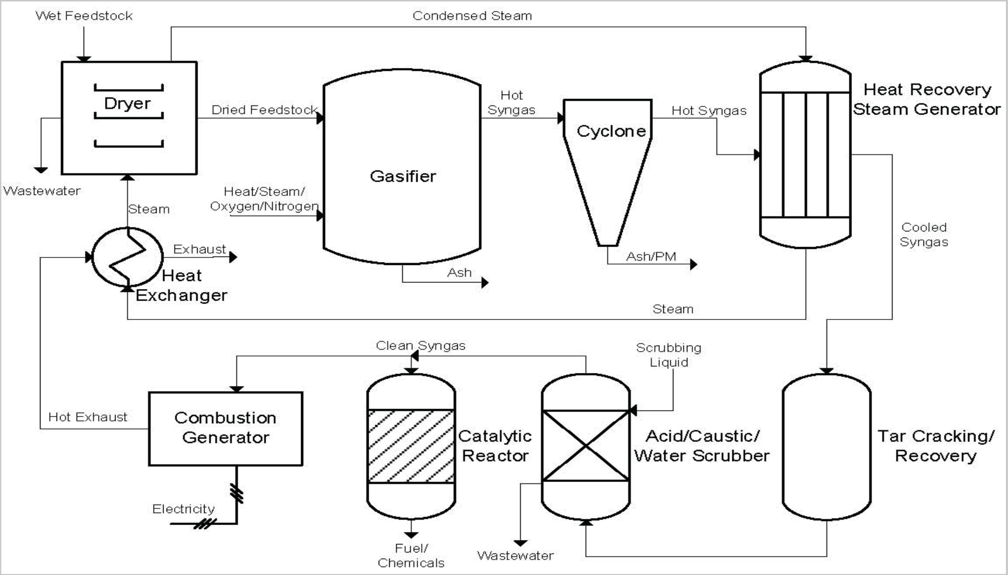


Figure 5-1: Process Flow Diagram of a Typical Gasification Process (US EPA, 2012)

5.1.2 Comparison of Gasification with Other Combustion Processes

Gasification, combustion and pyrolysis are the three most applied thermal conversion processes for converting biomass to energy. While gasification and combustion are mature and established, pyrolysis is still considered an emerging technology[7].

Combustion occurs with sufficient oxygen to completely oxidise the feedstock, producing gaseous by-products (e.g. carbon dioxide and sulphur dioxide) and water. Gasification occurs with insufficient oxygen or with steam, thus complete oxidation does not occur. Pyrolysis occurs in the absence of an oxidising agent (air, oxygen, or steam). Thus, gasification is viewed as an intermediate process

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[7] It should be noted that gasification is mature and proven for processing of other biomass, but is still at demonstration stage and considered emerging for wastewater sludge applications

between combustion and pyrolysis and is sometimes referred to as partial oxidisation‖ or partial pyrolysis.

A summary of the three processes is given in Table 5-1. Gasification, combustion and pyrolysis each have advantages and disadvantages. In any particular project, it is important to evaluate the goal of the project, the biomass resources available, and the particular needs of the facility in choosing a thermal conversion process.

Table 5-1: Comparison of Combustion, Gasification and Pyrolysis (Ross, 2010)

	Combustion	**Gasification**	**Pyrolysis**
Process Characteristics			
Oxidising Agent	Greater than stoichiometric supply of oxygen*	Less than stoichiometric oxygen* or steam as the oxidising agent	Absence of oxygen or steam
Typical Temperature Range (with biomass fuels)	800°C to 1 200°C	800°C to 1 200°C	350°C to 600°C
Main Products	Heat	Heat Combustible gas	Heat Combustible liquid and combustible gas
Main Components of Gas	CO_2 and H_2O	CO and H_2	CO and H_2
Composition of By-products[1]			
Tars, Water (Liquid)		Up to 20%	60% to 70%
Char (Solid)		Up to 20%	10% to 15%
Product Gas		~85%	10% to 25%

Notes:

1. The by-product composition is for fast pyrolysis at medium temperature (T = ~500°C) and gasification at higher temperature (T > 800°C)

The main advantages of gasification over combustion and for biomass processing include:

- occurs at lower temperatures than combustion
- produces a variety of by-products (syngas, char)
- by-products can be utilised through existing fossil fuel infrastructure, facilitating easier transition to renewable energy
- produces gaseous fuel which is easier to transport
- gaseous fuel increases efficiency of electricity generation compared to solid biofuel
- facilitates CHP generation, as both heat and electricity can be recovered

5.1.3 Gasifier Types

A variety of biomass gasifier designs have been developed that are currently being applied for commercial purposes. Three types have been applied to sewage sludge gasification, namely:

- fixed bed (updraft, downdraft, bubbling and circulating)
- fluidised bed
- plasma

Differentiation is based on the means of supporting the biomass in the reactor vessel, the direction of flow of both the biomass and oxidant, and the way heat is supplied to the reactor. Table 5-2 lists the most commonly used configurations. These types are reviewed separately below.

5.1.3.1 Downdraft and Updraft Gasifiers

Overview

Fixed-bed gasifiers are the most suitable for small-scale operations and thus have a wide range of applications. The most common types of fixed-bed gasifiers are downdraft (co-current type) and updraft (counter-current type). Recent developments in designs have combined characteristics from both types of gasifiers. The main difference between updraft and downdraft gasifiers is the direction of gas flow through the unit. In downdraft gasifiers, the oxidising agent (air or pure oxygen, with or without steam) enters at the top of the gasifier and the produced gas exits at the bottom. Gas flow is the reverse in updraft gasifiers. Updraft gasifiers can have capacities of about 10 MW or less. Downdraft gasifiers can have capacities of about 2 MW or less (Ross, 2010).

Updraft gasifiers

The updraft gasifier is the oldest technology and has been applied in coal gasification for almost 150 years. Updraft gasifiers have high thermal efficiency, are easy to control, and are more tolerant of fuel switching than downdraft gasifiers. Updraft gasifiers have outlet temperatures of 250°C and operating temperatures of 800–1 200°C. An advantage is that they can handle moisture contents as high as 55%. A disadvantage is that they have high tar production and so require more extensive cleaning of the syngas. Tar removal from the product gas has been a major problem in updraft gasifiers (Roos, 2010).

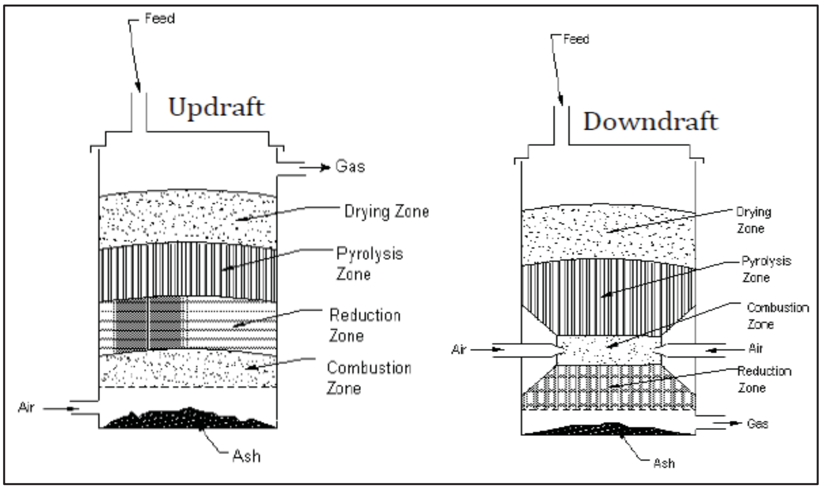

Figure 5-2: Schematic Layout of Updraft and Downdraft Fixed-Bed Gasifiers (US EPA, 2012)

Downdraft gasifiers

The downdraft gasifier has the same mechanical configuration as the updraft gasifier except that the oxidant and product gases flow down the reactor, in the same direction as the biomass. A major difference is that this process can combust up to 99.9% of the tars formed. Low moisture biomass (< 20%) and air or oxygen are ignited in the reaction zone at the top of the reactor. The flame generates pyrolysis gas/vapour, which burns intensely leaving 5 to 15% char and hot combustion gas. These gases flow downward and react with the char at 800 to 1 200°C, generating more CO and H_2 while being cooled to below 800°C. Finally, unconverted char and ash pass through the bottom of the grate and are sent for disposal (Bridgwater & Evans, 1993; Reed and Siddhartha, 2001; Paisley et al., 2001).

The advantages of downdraft gasification are that up to 99.9% of the tar formed is consumed, requiring minimal or no tar clean-up, minerals remain with the char/ash, reducing the need for a cyclone, and it is a proven, simple and low-cost process. The main disadvantages of downdraft gasifiers are that they require feed drying to a low moisture content (< 20%), the syngas exiting the reactor is at high temperature, requiring a secondary heat recovery system, and about 4–7% of the carbon remains unconverted (Roos, 2010).

Table 5-2: Summary of Gasifier Types (Roos, 2010)

Gasifier Type	Development Stage	Scale	Fuel Requirements		Efficiency	Gas Characteristics	Other Notes
			Moisture	Flexibility			
Downdraft Fixed Bed	Mature/Oldest	5 kW_{th} to 2 MW_{th}	< 20%	Less tolerant of fuel switching Requires uniform particle size Large particles	Very Good	Very low tar Moderate particulates	Small scale Easy to control Produces biochar at low temperatures Low throughput Higher maintenance costs
Updraft Fixed Bed		< 10 MW_{th}	Up to 50–55%	More tolerant of fuel switching than downdraft	Excellent	Very high tar (10% to 20%) Low particulates High methane	Small and medium scale Easy to control Can handle high moisture content Low throughput
Bubbling Fluidised Bed	Mature/Old	< 25 MW_{th}	< 15%	Very fuel flexible Can tolerate high ash feedstocks Requires small particle size	Good	Moderate tar Very high in particulates	Medium scale Higher throughput Reduced char Ash does not melt Simpler than circulating bed
Circulating Fluidised Bed		A few MW_{th} up to 100 MW_{th}	<15%	Very fuel flexible Can tolerate high ash feedstocks Requires small particle size	Very good	Low tar Very high in particulates	Medium-to-large scale Higher throughput Reduced char Ash does not melt Excellent fuel flexibility Smaller size than bubbling fluidised bed
Plasma	Relatively New	< 30 MW	any	Greater feed flexibility, without the need for extensive pre-treatment Solid waste capability	Very good	Lowest in trace contaminants, no tar, char, residual carbon, only producing a glassy slag	Large scale Easy control Process is costly High temperature (2 700–4 500°C)

Gasifier Type	Development Stage	Scale	Fuel Requirements		Efficiency	Gas Characteristics	Other Notes
			Moisture	Flexibility			
Liquid Metal	Embryonic/Pilot Scale	< 7 MW	< 5%	Generally requires low moisture due to the possibility of steam explosion	Very good	Low trace contaminants, virtually no tar, char, residual carbon	High syngas quality
Supercritical Water	Novel/R&D	Unknown	70–95%	Suitable for conversion of wet organic materials	Good	Suppressed formation of tar and char	Short reaction time High energy conversion efficiency by avoiding the drying step Selectivity of syngas with temperature control and catalysts

5.1.3.2 Bubbling Fluidised Bed

Most biomass gasifiers under development employ one of two types of fluidised bed configurations, namely bubbling fluidised bed and circulating fluidised bed. A bubbling fluidised bed consists of fine, inert particles of sand or alumina, which have been selected for size, density, and thermal characteristics. As gas (oxygen, air or steam) is forced through the inert particles, a point is reached when the frictional force between the particles and the gas counterbalances the weight of the solids. At this gas velocity (minimum fluidisation), bubbling and channelling of gas through the media occurs, such that the particles remain in the reactor and appear to be in a “boiling state” (Craig et al., 1996). The fluidised particles tend to break up the biomass fed to the bed and ensure good heat transfer throughout the reactor.

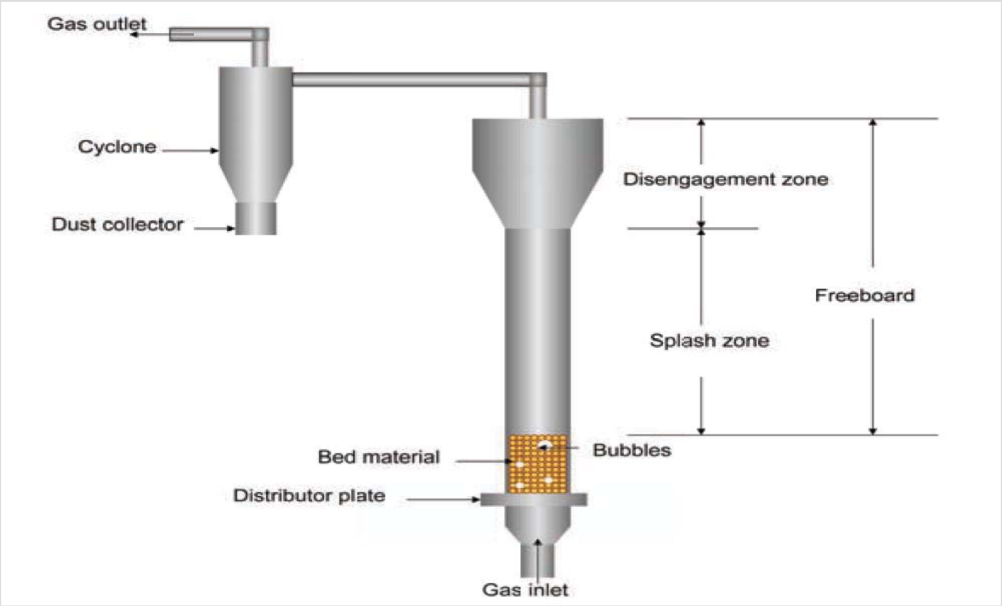

Figure 5-3: Bubbling Fluidised Bed (Geldart D, 1986)

The main advantages of bubbling fluidised-bed gasification are (Bridgwater & Evans, 1993; Paisley et al., 2001):

- Yields a uniform product gas
- Exhibits a nearly uniform temperature distribution throughout the reactor
- Able to accept a wide range of fuel particle sizes, including fines
- Provides high rates of heat transfer between inert material, fuel and gas
- High conversion possible with low tar and unconverted carbon

The main disadvantage is that the large bubble size may result in gas bypass through the bed.

5.1.3.3 Circulating Fluidised Bed

Circulating fluidised bed gasifiers operate at gas velocities higher than the minimum fluidisation point, resulting in entrainment of the particles in the gas stream. The entrained particles in the gas exit the top of the reactor, are separated in a cyclone and returned to the reactor.

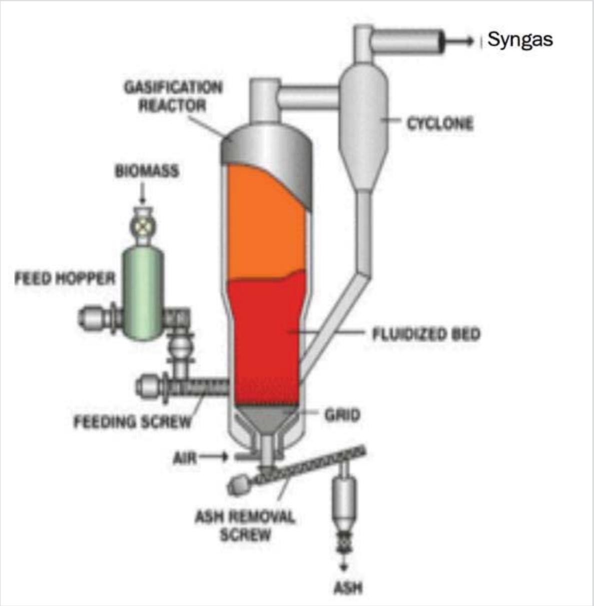

Figure 5-4: Circulating Fluidised Bed Gasifier (Brown & Cauldwell, 2012)

The main advantages of circulating fluidised-bed gasification are (Bridgwater, 1993; Paisley et al., 2001):

- Suitable for rapid reactions
- High heat transport rates are possible due to high heat capacity of bed material
- High conversion rates possible with low tar and unconverted carbon

The disadvantages of circulating fluidised-bed gasification are:

- Temperature gradients occur in the direction of solid flow
- Size of fuel particles determines minimum transport velocity; high velocities may result in equipment erosion
- Heat exchange less efficient than bubbling fluidised-bed.

5.1.3.4 Other Gasifiers

The new gasification technologies that are under research and development (R&D) and considered still embryonic are plasma, liquid metal and supercritical water gasification.

In plasma gasification, the primary heat source is a plasma torch, where gas is passed through an electric arc and dissociated into ions and electrons creating extremely high temperatures (> 5 000°C). The high temperatures enable very large carbon conversion percentages and good control of the hazardous materials captured in the slag. Due to the high temperatures, plasma gasifiers are generally more costly than traditional gasifiers.

Liquid metal gasification is still under R&D and some suppliers have carried out pilot-scale studies. Feedstock is introduced into a crucible filled with molten metal, usually iron, at around 1 300°C. Water in the feedstock is split into H_2 and O_2. Theoretically, the iron is then oxidised to FeO and then reduced back to iron after the O_2 reacts with carbon in the feedstock to make CO gas (US EPA, 2012). The main components of the syngas are H_2 and CO. Oxygen gas can also be added to the process to improve process efficiency. The iron is also reported to assist in capturing unwanted waste, such as chlorine and sulphur, producing a glass-like material (slag).

Another process which is receiving R&D attention is supercritical water gasification (SWG). The process utilises supercritical water (pressure > 22 MPa, temperature > 374°C) to convert organics into a hydrogen-rich syngas. SWG requires feedstocks with moisture contents ranging from 70 to 95%. The novelty of the process lies in the reforming of biomass and biological residues in supercritical water.

5.2 SEWAGE SLUDGE GASIFICATION

5.2.1 Overview

Gasification of sewage sludge follows similar physical and chemical changes as gasification of another biomass. However, because of the high moisture content in sludge which can vary from 79 to 99% depending on the type of sludge, there is a need for some form of drying or dewatering prior to the sludge being fed to the gasification reactor[8].

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[8] Newer technologies like plasma gasification that operate at high temperature are reported to be able to handle wet sludges without the requirement for pre-drying (US EPA, 2012)

The ideal solids content prior to feeding the reactor should be about 60–70%. The requirement for sludge to be dried prior to gasification affects the economics of sewage sludge gasification because of the high energy demand associated with the drying process.

Apart from the requirement for drying, sludge pretreated in certain processes is not economically viable for gasification, e.g. anaerobic digestion removes most of the energy from the sludge thus this energy will not be available to be recovered as syngas in gasification. Aerobically digested, composted and lime-stabilised sludge is generally also not economically viable for gasification.

5.2.2 Environmental Impacts

Literature reviews indicate that most of the research into gasification has been focused on gasifier performance with the generated syngas combusted and not on integrated systems where the syngas is cleaned and used for commercial purposes (US EPA, 2012). Research on integrated systems enables more accurate determination of the impact of gasification on the environment. Despite lack of research data on integrated systems for sewage sludge gasification, it is still necessary to remove the following wastes produced in all gasification processes to avoid release to the atmosphere:

- criteria air pollutants (CAPs)
- hazardous air pollutants (HAPs)
- GHGs
- wastewater side streams

5.2.2.1 Criteria Air Pollutants

Criteria air pollutants include sulphur compounds (SO_x), carbon monoxide (CO), nitrogen compounds (NOx) and particulate matter. The amounts of CAPs produced during gasification vary depending on the type of feedstock, the type of gasifier, the syngas cleaning system and the final use of the syngas. If the pollutants are not removed through a cleaning system, they are released during combustion of the syngas.

Most sulphur compounds will convert to sulphur dioxide (SO_2) and this is usually removed using an alkali absorption solution or a dry sorbent such as zinc oxide. Carbon monoxide is typically removed through combustion in an engine, turbine or oxidiser.

Sewage sludge has a high nitrogen content; thus, NOx is produced during combustion of syngas and these compounds are usually removed through liquid scrubbing or dry sorbents prior to combustion of the syngas.

Cyclones, water scrubbers and bag houses are applied for particulate matter removal.

5.2.2.2 Hazardous Pollutants

As with CAPs, the quantity of hazardous pollutants emitted from gasification depends on the process and can therefore only be accurately determined from empirical data. The main hazardous pollutants are hydrochloric acid (HCl), dioxins (chlorinated organics) and metals.

The quantities of hydrochloric acid and dioxins depend on both the type of feedstock and temperature. Dioxin production has been found to decrease at temperatures greater than 850°C as well as with increased oxygen content, low chloride content in the feedstock and low reactor retention times (US EPA, 2012). Removal of HCl from syngas is achieved through liquid scrubbing or using a dry absorbent such as sodium carbonate or calcium dioxide.

Metals in the feed sludge are released during the gasification process and end up in the char, the ash, the liquid stream from gas cleaning or in the combustion flue gas stream. Research has shown that wet scrubbing can remove most metals in the syngas stream, except mercury which might require adsorption techniques such as activated carbon. There is no data on the leachability of metals trapped in the char or ash when disposed to landfill (Reed et al., 2005).

5.2.2.3 Greenhouse Gases

GHGs trap heat in the atmosphere and contribute to the phenomenon known as global warming. Carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and fluorinated gases are classified as GHGs. The global warming potential of GHGs is usually expressed in terms of carbon dioxide equivalents (CO_2e). The United States Environmental Protection Agency (US EPA) has assigned the following CO_2e values for various GHGs (US EPA, 2010):

• N_2O	310
• CH_4	28–36
• Fluorinated gases	140–23 900

Because of the high values of global warming potential of GHGs, it is now an accepted practice to reduce the emissions from wastewater treatment activities including sludge handling, treatment and disposal. While models exist for estimating GHG emissions from sludge handling and treatment activities, e.g. the biosolids emission assessment tool, BEAM (CCME, 2009; Brown et al., 2010), the most accurate way of comparing the GHG emissions from sludge treatment processes is through a life cycle analysis structured to cater for specific conditions.

5.2.2.4 Sidestream Wastewater

Gasification produces wastewater from the drying and gas cleaning processes. The composition of the streams varies depending on the process. Sidestreams from the drying process can contain volatile organics due to the high temperatures that volatilise organics, while gas cleaning processes such as scrubbing produce sidestreams that require further treatment prior to disposal.

No information on the quality of wastewater produced in gasification of sewage sludge is available in the literature.

5.2.2.5 Emissions Data from Full-Scale Gasifiers

While there is limited data in the literature on emissions from full-scale plants, Maxwest Environmental Systems, prior to closing down, compiled emissions data from its gasification plant processing sewage sludge in Sanford, Florida. The emissions values from this plant are given in Table 5-3. Also included are the limits set by the South African Department of Environmental Affairs, where applicable. Maxwest filed for bankruptcy in 2013[9] and the Sanford plant has since closed down.

Table 5-3: Emissions Data Submitted by Maxwest to the Florida Environmental Agency (US EPA, 2012)

Pollutant	Unit ($7\%O_2$)	MaxWest Gasifier Value	Florida EA Allowable	South African National Standards (SANS 1929: 2005)[a]
Cadmium (Cd)	mg/dscm	7.23×10^{-5}	0.095	
Carbon Monoxide (CO)	ppmvd	7.87	3 800	10^{b}
Dioxin/Furan (TEQ)	mg/dscm	0.0285	0.32	
Hydrogen Chloride (HCl)	ppmvd	1.8	1.2	mg/m^3
Lead (Pb)	mg/dscm	8.19×10^{-4}	0.3	0.5×10^{-3}
Mercury (Hg)	mg/dscm	7.98×10^{-3}	0.28	
Oxides of Nitrogen (NOx)	ppmvd	432	220	0.04
Particulate Matter (PM)	mg/dscm	9.6	80	0.04
Sulphur Dioxide (SO_2)	ppmvd	4.17	26	0.05

Notes:

a. Government Gazette 9 June 2006. Limit is annual average

b. 8 hour maximum limit

The data indicates that HCl, mercury and nitrogen oxides exceeded the Florida allowable limits. If the gasifier were in South Africa, then particulate matter and SO_2 would most likely have exceeded the SANS limits.

5.3 COMMERCIAL STATUS OF WASTEWATER SLUDGE GASIFICATION

5.3.1 Overview

Although previous research (US EPA, 2012) indicated about four vendors that claimed to be capable of installing full-scale sewage sludge gasification plants, in this research, only three were identified as having commercially operating plants on a continuous basis, namely:

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[9] It was reported in the press in January 2015 that PHG Energy of Nashville acquired the gasification plant and patents from Maxwest. The Sanford plant is still reported to be closed.

- Sulzle Kopf with two gasification plants, at Balingen and Mannhein WWTPs, in Germany
- Tokyo Bureau of Sewerage with a plant at Kiyose WWTP
- Intervate that, in partnership with Yorkshire Water, installed a gasification plant at Yorkshire Water's Lower Brighouse WWTP[10]. It is, however, reported that the plant co-gasifies wastewater sludge with wood pellets.

Maxwest Environmental systems installed a full-scale gasification plant in Sanford, Florida. The company went bankrupt in 2013 and the plant closed down.

Other companies have set up trials and pilot-scale studies on sewage sludge gasification, as follows:

- Nexterra conducted trials at a research facility in Kamloops, British Columbia (Canada). The trials were completed in 2009 and the company was commissioned by the Stamford Water Pollution Control Agency (Connecticut, USA) to install a gasification plant processing about 25 tDS/d and estimated to generate 1–3 MW of electricity from syngas. The project was abandoned due to concerns about cost and technical feasibility.
- M2 Renewables (M2R) and Pyromex AG conducted pilot-scale trials using a 1 tDS/d gasification unit in Munich, Germany. Although the trials were reported to be successful, reports of any full-scale installations could not be found.
- Hybrid Energy carried out pilot-scale trials at the University of British Columbia which were completed in 2014. The company is seeking opportunities to install a full-scale plant.

The above review indicates that although gasification of other biomass like coal, wood, food waste etc. is a mature proven technology, it is still emerging (embryonic) when applied to wastewater sludge.

A review of the Sulzle Kopf and Tokyo Bureau of Sewerage full-scale installations, that are still operational, is given below. No information could be obtained for the Yorkshire Water plant.

5.3.2 Review of Full-scale Installations

5.3.2.1 Sulzle Kopf Gasification Plant, Balingen, Germany

Sulzle Kopf installed a demonstration gasification plant processing sewage sludge at Balingen WWTP in 2002. The plant had a capacity of about 2.5 tDS/d (935 tDS/yr). In 2010, the plant was rebuilt and the capacity increased to about 5.4 tDS/d (1 955 tDS/yr, serving a population equivalent of about 250 000).

Figure 5-5 shows the process flow diagram of the Kopf gasification process.

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[10] It is understood through email communications with Intervate that they are no longer operating the Yorkshire Water plant and EnertecGreen have taken over the operations.

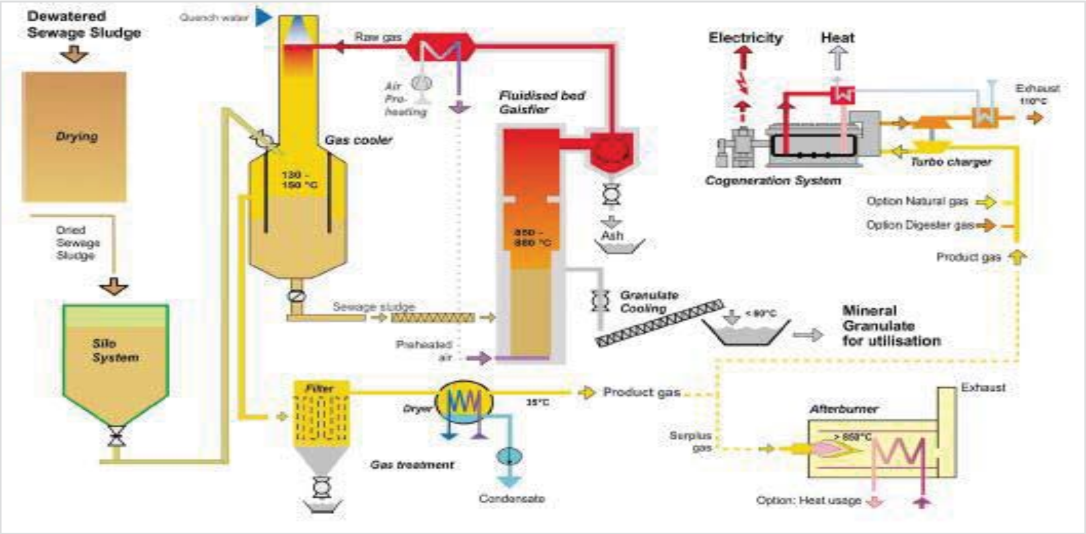

Figure 5-5: Flow Diagram of the Kopf Gasification System Process (from Sulzle Kopf, 2014)

The unique main components of the process are as follows (Judex et al., 2012):

- A sludge drying unit that dries sludge to 70–85% dry solids.
- An atmosphere bubbling fluidised-bed gasifier operated on air and steam. The carbon is converted into gas and inert ash. The ash is discharged into an ash silo and re-used as a fertiliser, for P recovery and as inert filler material.
- Gas treatment that consists of a cyclone, filtration, cooling, washing and acid scrubbing (removes H_2S and NO_x). This is followed by three activated carbon filters to remove mercury, any remaining H_2S and aromatic hydrocarbons.
- Energy generation using the syngas in a CHP engine. The electricity can be used at the WWTP and the heat for sludge drying and community heating.

In 2011, Kopf installed another full-scale gasification plant at Mannheim WWTP based on the same principles. Details of the two gasification plants are given in Table 5-4.

The mass and energy data reported from the Balingen plant in 2012 indicated the following (US EPA, 2012)

- 0.5 kwh/kg total solids treatment is produced
- Only 0.1 kwh/kg total solids treated is used for gasification and the remaining 0.4 kwh is used by the WWTP.

Table 5-4: Details of the Balingen and Mannheim Gasification Plants (Judex et al., 2012)

Parameter	Units	Original plant	Rebuilt plant	Gasification plant in Mannheim
Location		Balingen (Germany)	Balingen (Germany)	Mannheim (Germany)
Population equivalent		124 000	250 000	600 000
Average annual flow	Ml/d	14	28	108
Throughput	tDS/yr	935	1 955	5 000
Gasification agent		Air	Air	Air with steam injection
Gasification temperature	°C	850	850	850–900
Installed power	kW	230	720	2 200 (electrical)
Power to CHP	kW_{el}	75	75	-
Power to dryer	kW	-	250	1 500 (thermal)
Type of dryer		Solar dryer	Belt dryer	Rotary dryer
Footprint	m^2	80	120	500
Electrical consumption	kW	12	25	75 kW
Cold gas efficiency	%	66	66	70

5.3.2.2 Tokyo Bureau of Sewage

In September 2005, the Tokyo Bureau of Sewage (TBS) conducted sewage sludge gasification tests using a demonstration plant at the Kiyose Water Reclamation Centre. The plant had a capacity of 15 tDS/d and the demonstration tests were concluded in July, 2006, after running the plant for 3 400 hours (Takahashi, 2007). A schematic layout of the gasification process is shown in

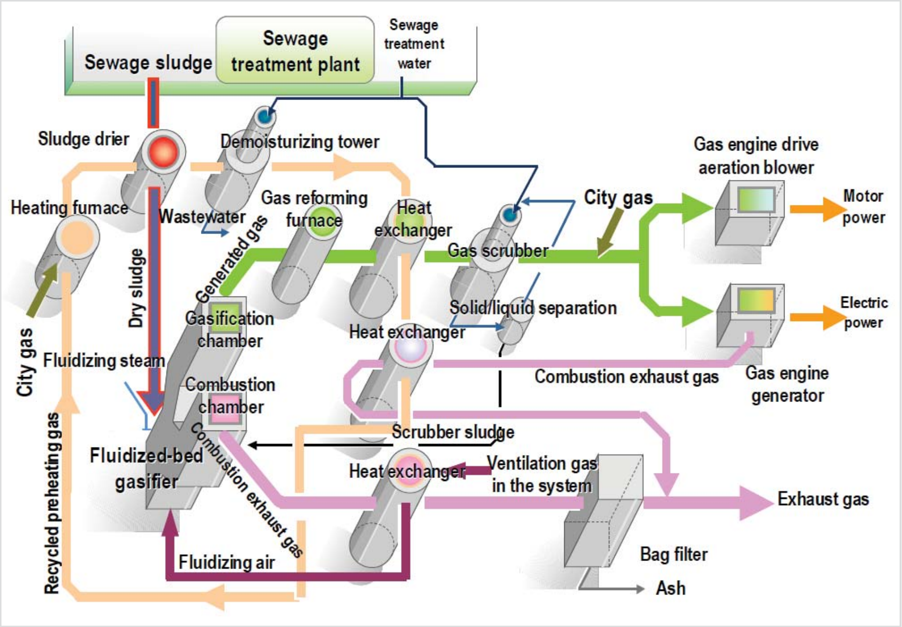

Figure 5-6: Schematic Layout of the Kiyose Water Reclamation Centre Gasification Plant (Takahashi, 2007)

The main components of the gasification process are as follows:

- Sludge dryer that dries sludge to a solids content of 70–80%.
- Internally circulating fluidised-bed gasifier operating at 650–750°C. At this temperature, the sludge undergoes pyrolysis in the oxygen-starved chamber and is converted to gas and char.
- Heat recovery furnace operating at 800–900°C where the gas is burnt at high temperatures and heat is recovered from the gas and used for sludge drying and heating the gasifier.
- Gas reforming unit with gas scrubbing where impurities such as ash, nitrogen and sulphur compounds are removed, and the clean gas is conveyed to the gas engine to generate electricity.

After successful operation of the demonstration plant, a full-scale plant processing about 100 tDS/d was commissioned at Kiyose Water Reclamation Centre in July 2010. Details of the full-scale plant are summarised inTable 5-5.

Table 5-5: Details of the Kiyose Water Reclamation Centre Gasification Plant (US EPA, 2012)

Parameter	**Value**
Location	Kiyose, Japan
Technology	Circulating Fluidized Bed
Feedstock Pre-treatment	Sewage sludge from the waste plant is fed into a high-pressure screw press to a moisture content of 70–80%, then fed into a dryer that decreases the moisture content to 20%. The dryer consumes 350 kW.
Gasification System Performance Maximum Capacity (dry) Internal Energy Consumption **Energy Output** Gross Electrical	 100 tDS/d 500 kW NA
Gross Thermal Net Electrical Net Thermal	NA 150 kW NA
Syngas Composition	8.5% H_2, 11% CO_2, 7.5% CH_4, balance N_2 small amounts of C2 and C3 hydrocarbons
Gas Clean-up	Liquid gas scrubber and bag house
By-products/Waste Streams	Wastewater from a de-moisturising tower, ash from the bag house and flue gas
Potential Emissions	Not yet published
Products/By-product End Use	The syngas is combusted in an internal combustion engine generator and aeration blower for electricity production
Economics	Estimated $100 million for operation of 20 years (includes construction, manpower, maintenance and operation costs)

5.3.2.3 Highbury Energy Indirect Gasifiers

Highbury Energy (Vancouver, British Columbia) developed an indirect gasifier which they have tested at pilot scale at the University of British Columbia when treating wastewater sludge as well as wood chips. Indirect gasification is a modification of the bubbling bed gasifier. A simplified layout of the Highbury Energy indirect gasification system is shown in Figure 5-7.

In the indirect gasifier system, sand particles are constantly re-circulating from the bubbling bed gasifier to the combustor and back to the gasifier. Partially dried sludge and steam are fed into the gasifier stage which is full of hot solids (T > 800°C). The sludge is heated and reacts with steam, releasing raw syngas which flows out through a cyclone for treatment. The char/sand mixture in the bed flows to the high velocity combustor, where the char is burnt with air, raising the sand temperature to over 900°C. The flue gas and sand are separated in the combustor primary cyclone and the hot sand (T ~ 900°C) returns to the fluid bed gasifier and provides the heat for the gasification process. The flue gas passes through a secondary cyclone, where the underflow solids containing the ash from the sludge become a waste stream. The flue gas is treated to meet emission limits for particulates.

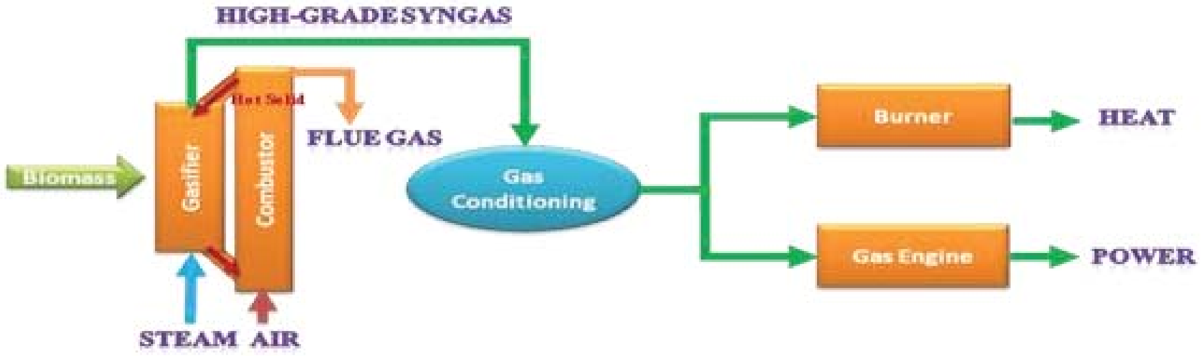

Figure 5-7: Simplified Schematic of Power Generation from Sewage Sludge via Indirect Gasification (Highbury Energy, 2016)

The raw syngas from indirect gasification has a lower heating value of about 12 MJ/m^3. However, it is approximately double that of a conventional air-blown gasifier. In the syngas conditioning stage, any solids in the raw syngas are removed by filtration, and the tars are removed by scrubbing the gas with a renewable solvent and returned to the combustor as auxiliary fuel. Water condensed from the raw syngas is re-used to form steam for the gasifier. Additional scrubbing may well be necessary to remove ammonia and heavy metal impurities from the syngas. The clean syngas at about 35°C can then be either fed to a burner or to a gas engine to produce electrical power.

Heat integration within the process is important, especially for gasification of wet sludge. Heat is needed for partial drying of the dewatered sludge, for producing steam from the condensed syngas water vapour, and for pre-heating the air to the char combustor. Most of this heat is recovered from the hot syngas and the hot flue gas. Some of the clean syngas is diverted to provide part of the heat for sludge drying. The lower the feed moisture content to the dryer, the greater the syngas that can be used to produce electrical power.

Although not yet implemented at full scale, Highbury Energy have developed a model that can be applied to determine the costs as well as mass and energy balance of a full-scale installation.

5.4 SUSTAINABILITY OF SEWAGE SLUDGE GASIFICATION

Although gasification using biomass such as coal and wood is a mature, proven technology and has been in use for the past 150 years, uptake of wastewater sludge gasification has been very poor with only three full-scale plants reported to be in operation on a sustainable basis. The poor uptake is also evident for gasification of other biomass, as indicated by the following research studies:

1. A 1995 report by the World Bank on a project to assess the status of biomass gasification technologies and their applicability in developing countries concluded that the short-term

commercial prospects of small-scale biomass gasifiers designed to generate power in developing countries appeared limited. Three major factors were cited, *viz*:

- Unfavourable economics compared with fossil fuels
- Low quality and reliability of equipment resulting in operational difficulties
- Inherent difficulties in training sufficiently qualified or experienced personnel, resulting in substandard operation of units

2. Fifteen years later, a similar survey of small-scale biomass gasifiers, commissioned by the German government, looked at experiences in Germany as well as in India, Sri Lanka, and various African countries. The study suggested that small-scale biomass gasification had become no more reliable or successful than it had been during the 1980s and similar difficulties were being experienced everywhere, not just in poor countries, but also in Germany. Out of the 50 biomass gasifiers installed between 2000 and 2010, many had been taken out of operation after some months of trial. Most of the developers suffered insolvency (GTZ and HERA, 2010).
3. A US EPA study in 2012 that assessed the viability of wastewater sludge gasification identified 44 vendors claiming to have sludge gasification capability. Only two were identified at the time as having plants running consistently at commercial level – Kofp and Maxwest. Maxwest filed for bankruptcy in 2013 and its plant in Florida was shut down. Two companies, Nexterra and M2 Renewables, which were judged at the time, based on pilot-scale studies, to be technologically ready to upgrade to commercial scale, had potential projects abandoned due to technical and cost concerns. The report concluded that the variability in technology and lack of information on commercial-scale systems made it difficult to comprehensively assess the viability of sludge gasification. The report recommended the following:
   - Independent assessment of the few existing commercial plants needs to be undertaken to verify performance and environmental data through direct measurements.
   - Due to the large number of components, and the variation in gasification systems, the technology cannot be considered as uniform and a single unit. Thus, continuous evaluation of the technology is required to accurately determine performance, capital and operating costs, environmental impacts and ability to comply with regulatory standards, particularly clean air regulations, before broad implementation.
4. In 2015, a study by Ernsting[11] on the success of power generation through biomass gasification identified that of the 40 biomass and pyrolysis plants with a capacity of at least 1 MW which have been proposed across the UK in recent years, at least nine have been built. Out of the nine, eight of these gasifiers have failed and been shut down.
5. The literature review in this research confirmed four commercial full-scale sewage sludge gasification plants; two in Germany, one in Japan and one in the UK. The plant in the UK processes a combination of wastewater sludge and wood pellets as it was deemed that it would not be

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[11] Ernsting, A (2015). *Biomass Gasification and Pyrolysis* Report. Biofuelwatch

economical to process wastewater sludge on its own. The vendors were not willing to disclose data on the performance of the plants.

The above research studies confirm that, despite significant interest in developing this technology to a sustainable commercial level, technical and economic challenges as well as environmental and social concerns have resulted in the technology not being commercially viable and still considered to be in the emerging phase for most biomass, including wastewater sludge. Each of the challenges cited for impending commercial uptake of the technology are briefly discussed below.

5.4.1 Unreliability of the Technology

Biomass gasification at temperatures below 1 300°C produces gas with a range of heavy hydrocarbons (tars). Build-up of tars causes fouling which eventually clogs up vital equipment and prevents it from functioning optimally. Avoiding and/or breaking down tars has been found to be a major challenge. Gasifiers using dry wood have been found to have fewer fouling problems. Higher combustion temperatures can also reduce problems and Plasma Arc gasification, if developed to a mature technology, might be a viable solution. The issue of unreliable technology is compounded by the high variability of gasification technologies and designs that depends on factors such as size and biomass type, leading to variable performance.

5.4.2 High Costs

High capital and operating costs have been cited as impending implementation of gasification. The combination of high capital costs and low net electrical efficiency often makes the technology not viable economically. Gasification is a complex technology and requires highly skilled operators which increases operating costs. The technology also requires constant monitoring, sophisticated control systems and frequent maintenance which contributes to high operating costs.

5.4.3 Higher Environmental and Health and Safety Concerns

Biomass gasification has been identified as carrying additional risks because producer gas and syngas are highly explosive. To prevent an explosion when pressure builds up inside a gasifier, operators may be forced to vent dirty producer gas straight into the atmosphere, bypassing the various mitigation systems designed to clean it. Research by Ernsting (2015) identified problems with biomass gasifiers (not necessarily processing wastewater sludge) in Europe where unlawfully high air emissions were discharged and explosions and fires occurred. Communities have also raised concerns about air quality and safety when objecting to installation of biomass gasifiers.

5.5 APPLICATION OF SEWAGE SLUDGE GASIFICATION IN SOUTH AFRICA

5.5.1 Overview

South Africa does not have any gasifiers processing wastewater sludge. Only one supplier, Ecorevert, was identified as having the potential to supply gasification technology to process wet biomass such as wastewater sludge. The company has installed a gasification plant processing abattoir waste in Kroonstad. The company has a trial facility in Boksburg where they plan to process a variety of wastes. Demonstrations using wastewater sludge have not been carried out.

Due to the paucity of data at full scale, both in South Africa and internationally, a model developed by the University of British Columbia (Watkinson, 2016) was applied in evaluating the potential for implementing gasification at Waterval WWTP.

5.5.2 South African Regulatory Requirements for Sewage Sludge Gasification

Currently, there are no DWS regulations relating specifically to sewage sludge gasification. The Guidelines for the Utilization and Disposal of Wastewater Sludge: Volume 5 (2009) give the regulations for thermal treatment of sewage sludge but focus on incineration. An air pollution licence is required to undertake thermal treatment. A general risk-based equation is given in the guideline to calculate the pollutant limit for sludge that is destined for complete combustion on its own or co-combustion with another biomass. The guideline emission limits for sludge combustion and co-combustion are given in

Table 5-6: Total Emission Limit Values Applicable to Co-combustion of Sludge with Other Waste (Herselman et al., 2009)

Pollutant	Emission Limits (mg/m^3)
Total dust	30
HCl	10
HF	1
NO_x	500–800
SO_2	50
TOC	10
Sum of Cd, Hg, TI	0.05
Sum of Sb, As, Pb, Cr, Co, Cu, Mn, NI, V	0.5
Measurement results to be standardised at: Temp 273K, pressure 101 3kPa, 10% oxygen, dry gas	
Dioxins and furans	
Dioxins and furans*	0.1 ng/m^3 TEQ
*for determination of total concentrations of dioxins and furans, the mass concentrations of individual elements should be multiplied by the toxic equivalence factors (TEQ) below before summation	

Table 5-7: Emission Limits for Sludge-only Incinerators (Herselman et al., 2009)

Pollutant	Emission Limits (mg/m^3)
Total dust	10
Total organic carbon	10
HCl	10
HF	1
SO_2	50
NO and NO_2 expressed as NO_2 for existing incineration plants with a nominal capacity exceeding 6 t/h, or new incineration plants	200
NO and NO_2 expressed as NO_2 for existing incineration plants with a normal capacity of 6 t/h or less	400
Cd, TI, Hg (each)	0.05
Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V, Be, Ba, Ag, Sn (each)	0.5

Additionally, the following requirements also apply:

- total particulate emissions should not exceed 180 mg/m^3 at 11% O_2, 0% moisture and 101.3 kPa
- opacity of the smoke should not exceed 20%
- all emissions to air other than steam or water vapour should be odourless and free from mist, fume and droplets
- any substance that the authorities may consider necessary, e.g. polycyclic hydrocarbons, benzene, etc. should also be monitored.

5.5.3 Evaluation of Implementing Gasification at Waterval WWTP

Given the lack of concrete design information and full-scale performance data for sewage sludge gasification, the model developed at the University of British Columbia, based on the Highbury Energy indirect gasification system, was used to evaluate implementing gasification at Waterval WWTP. The model was developed based on a pilot-scale study processing wastewater sludge. The limitations of the results from the model are as follows:

- Assumptions on the quality of syngas and energy-generating potential are not accurate as there is no verification from full-scale data. This is especially important for a technology like gasification which has demonstrated low net energy efficiencies
- Emissions levels could not be determined
- Quality of side stream wastewater could not be determined
- Cost estimates are based on data from the United States since there are no suppliers in South Africa who can supply this information
- The modelling is based on a model developed by one supplier. Due to paucity of full-scale plants and data, the modelling could therefore not be cross checked. Thus, there is a high likelihood of bias in the data produced.

Based on the above, there was not enough information to carry out a comprehensive economic evaluation in the same way as for other technologies discussed in and Chapter 4 Thus, only mass and energy balances and cost estimates were carried out, as discussed below.

5.5.3.1 Mass and Energy Balance

Table 5-8 gives the sludge characteristics used in the calculations. Calculations were based on processing 50 tDS/d.

Table 5-8: Data Applied in the Calculations Based on Raw Sludge Characteristics

Parameter	Units	Value
Total Solids	%	5
Ash	%, dry	26.8
High Heating Value	MJ/kg, dry	18
Lower Heating Value	MJ/kg, dry	16.7
Volatile Matter	%, dry	66.8
Fixed Carbon	%, dry	6.4
Ash	%, dry	26.8
C	%, dry	40.63
H	%, dry	6.00
O	%, dry	20.3
N	%, dry	5.42
S	%, dry	0.81
Ash	%, dry	26.8

Calculations were carried out to determine the level of dewatering needed to ensure that all the syngas produced in the gasifier could be utilised to produce power. Dewatering options, producing dewatered sludge of 60% and 80% water content were assumed, depending on the dewatering technology used. The dewatered sludge is then dried to a final solid content of about 27% in the feed to the gasification step. At this moisture content, no waste water is produced in the gasification process itself, as the condensed moisture from the syngas is re-used to produce the steam for gasification. It was assumed that all the syngas produced is used to produce power.

Table 5-9 shows the water to be evaporated in the drying step to reach 27% moisture content in the gasifier feed. The dryer heat load, at 80% water, is about 83% higher than at 70% water, which illustrates the importance of the dewatering step.

Table 5-9: Dryer Heat Load as Function of Extent of Dewatering

Dewatered Sludge % Water	Water to be Evaporated in Drying Step (t/d)	Dryer Heat Load (MW)
80	183	5.7
70	100	3.3
60	58	1.9

The complete energy balance was then carried around the system.

5.5.3.2 Discussion of Mass/Heat Balance Calculation

The energy and energy balance of the system is illustrated in Figure 5-8.

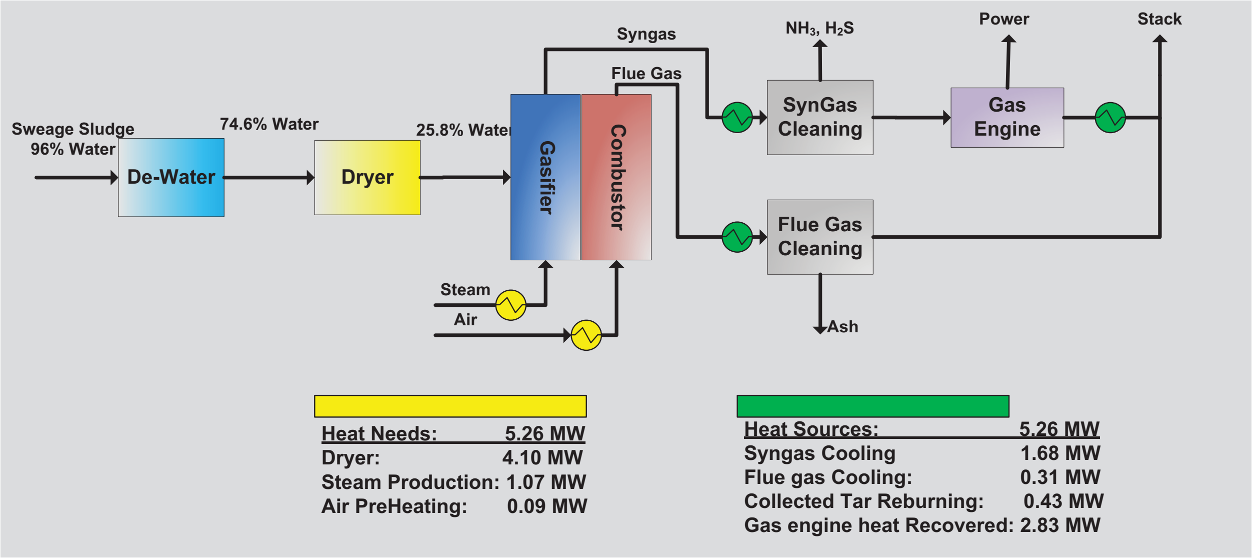

Figure 5-8: System Considered for Mass and Energy Balance

The heat loads in the system are drying of dewatered sludge, production of steam from syngas condensate, and pre-heating of the char combustor air. The heat sources are cooling of the syngas to a temperature that it can be used in the gas engine, cooling of flue gas from the char combustor, burning of the tar recovered in the syngas cleaning, which is recycled to the combustor (not shown on the flowsheet) and heat recovery from the gas engine. Heat recovery is generally taken to be 50% of available heat, except for the gas engine, where heat loss is 20%. The quantities of heat for this balance are shown in Figure 5-8.

The total thermal input to the plant is 9.66 MWt. Clean syngas production is 49 354 m^3/day (at 0°C) containing 33% H_2, 34% CO, 13% CH_4, 7% CO_2, and 3% N_2, on a dry basis. Syngas low heating value is 12.4 MJ/m^3. This syngas is all fed to the gas engine, which produces power of 2.83 MWe, or in excess of 20 000 000 kWh/y.

It should be noted that if the water content is above 75%, part of the syngas will have to be recycled and used as auxiliary fuel, e.g. in the dryer, and the power output would be reduced.

5.5.3.3 Cost Estimate

Costs of biomass gasification systems can be estimated using information from the US EPA publication "Biomass Combined Heat and Power Catalog of Technologies" (2007). The costs in this publication are based on gasifiers primarily treating feed materials such as woody or agricultural biomass. The publication also deals with small moving-bed gasifiers, or larger fluid-bed gasifiers, and includes costs of feed preparation and drying. These costs do not include the dewatering step required to reduce moisture content to 75%.

Using some assumptions to augment the extra costs of drying the wet sludge and adding additional allowances for scrubbing facilities to accommodate the impurities in the sewage sludge, the following costs were estimated for a plant with a capacity of 50 tDS/d treating combined PS and WAS similar in quality to that produced at Waterval WWTP.

Table 5-10: Cost Estimate for 50 tDS/d Gasification Plant Treating Combined PS and WAS

Parameter	Cost US$ (million)
Equipment and Installation Costs	
Pre-dewatering	9.8
Dryer, Gasification Plant, and Gas Cleaning	10.8
2.8 MWe Gas engine	3.0
Sub-total	22.8
Indirect Costs (at 40% of total installation costs)[1]	9.1
Total Capital Investment	US$ 31.9 million R480 million

*Notes:

1. Indirect costs include: engineering and supervision, construction expenses, legal expenses, contractor's fee, and contingency.

The 2.8 MWe gas engine power plant assumes that all the clean syngas produced is available for power generation, and none is diverted to assist the drying process. For gasification plants, operating and maintenance costs are about 4% of FCI/yr, or 0.76 million USD/yr. Annual power production depends on the time-on-stream. For 85% availability (310 days/year), power produced is 21 million kWh/yr.

5.6 SUMMARY AND DISCUSSION

The literature review of gasification has shown that while the technology is over 150 years old and has been successfully applied for coal and wood, the technology has not been successfully applied for processing other biomass and producing power. Despite increased international interest and input of resources through government grants and subsidies, there are very few sustainable full-scale operations. Only four full-scale plants were identified globally as processing wastewater sludge on a sustainable basis. The technology is therefore considered as emerging for this application and still requires further evaluation. The main challenges associated with biomass gasification were cited as unreliable technology, high costs and environmental and social concerns. These challenges are compounded by the variability in technology types and designs making uniform evaluation of the technology difficult. Also, since the technology is proprietary, there has been unwillingness on the part of suppliers to openly share information and performance data, inadvertently hindering development of the technology.

Due to the paucity of performance data and open design and modelling procedures, the model supplied by Highbury Energy, developed at the University of British Columbia, was applied in evaluating implementation of gasification at Waterval WWTP, the case study plant. The model was developed based on comprehensive pilot-scale studies processing wastewater sludge. The main drawbacks of this approach are as follows:

- The results of the model could not be verified against full-scale performance due to lack of data from the three identified full-scale plants
- The model does not predict the quantity of emissions
- Capital cost estimates were based on supply of equipment in US dollars due to lack of local suppliers for the technology. The only supplier in South Africa has not yet carried out trials processing wastewater sludge and therefore does not have enough data to enable comprehensive evaluation of full-scale implementation

Due to the above, a detailed CBA analysis as for the other technologies could not be undertaken.

Chapter 6 Comparative Analysis of Technologies

6.1 OVERVIEW

This project evaluated one emerging and two established sludge-to-energy technologies for application at a typical South African WWTP. The details and analysis of each technology have been given in previous chapters. Only a brief overview of each technology as well as the comparison between the technologies is given in this chapter.

6.1.1 PCS Technology

The PCS^{TM} Technology is an emerging enhanced HTC process that has the ability to convert a wide range of wet biomass into a sterile, higher calorific value hydrochar that can be used as a biofuel. The hydrochar also has potential multiples applications (e.g. in agriculture as a fertiliser/soil conditioner, specialised carbon microspheres that can be used as adsorption media, construction industry as a building material, energy storage). The technology has been demonstrated at laboratory and full-scale when processing another biomass but not wastewater sludge. In this project, the application for converting wastewater sludge into a biofuel was evaluated using laboratory and pilot-scale studies. The pilot-scale plant was installed at Waterval WWTP which was used as the case study plant for the project. Based on the findings from the pilot-scale studies, a preliminary design of a full-scale implementation of the PCS technology processing sludge of the same quality as that at Waterval WWTP was carried out for two scenarios:

- A greenfield installation processing 50 tDS of combined primary sludge and WAS only and with screenings
- A retrofit processing digested sludge (with screenings) from existing conventional anaerobic digesters similar to the ones at Waterval WWTP

In both cases, the hydrochar produced was used as a biofuel for CHP generation.

A cost benefit analysis using NPV as the decision criteria was then carried out for two disposal routes:

- Beneficial use of combusted biofuel ash for agricultural purposes
- Disposal of ash to landfill

The results of the economic evaluation are compared with the other technologies in Section 6.4.

6.2 ADVANCED THERMAL HYDROLYSIS – MESOPHILIC ANAEROBIC DIGESTION

Thermal hydrolysis as a sludge disintegration technology prior to anaerobic digestion is now considered an established technology. Over 60 plants have been installed worldwide. The majority are CambiTHP^{TM} with fewer than ten installed by Veolia Technologies. In this project, a desktop evaluation of implementing advanced thermal hydrolysis–mesophilic anaerobic digestion (TH–MAD) at a plant like Waterval WWTP was carried out. Full-scale plant design and performance data from vendors as well as mathematical modelling were applied to carry out a preliminary design for a greenfield installation treating 50 tDS/d of combined primary sludge and WAS (similar in quality to the Waterval case study plant). The biogas produced was used for CHP generation.

The case study plant Waterval WWTP currently utilises conventional MAD for sludge processing (with no biogas utilisation). To provide a baseline for technology comparison, preliminary design of a 50 tDS/d greenfield installation for a conventional MAD plant (but with biogas utilised for CHP generation) was also carried out.

A cost benefit analysis using NPV as the decision criteria was then carried out for both technologies as discussed in Section 6.4.

6.3 GASIFICATION

Although gasification technology is an old, established thermo-chemical conversion process that has been successfully implemented in processing coal and woody biomass, it was discovered during this project that the technology is still considered emerging/unproven when applied to processing wastewater sludge. Only four global full-scale plants were identified as operational on a sustainable basis. The main challenges associated with biomass gasification were cited as unreliability of technology, high costs as well as environmental and social concerns. Since no data was available from full-scale installations, a desktop model was applied to develop a preliminary design for the same case study full-scale plant processing 50 tDS/d combined primary sludge and WAS. A high-level cost estimate was carried out using international pricing models since no information was available on local prices for most of the equipment.

Because of this lack of robust design and financial data, a detailed cost benefit analysis similar to the other technologies was therefore not carried out.

6.4 TECHNOLOGY COMPARISON

Economic evaluation

Table 6-1 gives a summary of the cost benefit analysis for installing a 50 tDS/d plant processing combined primary sludge and WAS for the PCS technology (including processing sludge with screenings) and advanced TH–MAD. Also included in the table is the evaluation for installing a conventional mesophilic anaerobic digestion plant similar to the one currently existing at Waterval WWTP.

The following is noted from the economic evaluation results for a greenfield installation processing 50 tDS/d:

- For the financing model adopted, the PCS technology has the highest and positive NPV for all scenarios. It therefore appears that implementing the PCS technology at a greenfield site is the most economical attractive option. Conventional anaerobic digestion is the least economically attractive even with the generated biogas being utilised for CHP generation
- When comparing conventional MAD and advanced TH–MAD, the latter is more economically attractive. It should however be noted that the economic advantages of advanced TH–MAD over conventional MAD with CHP generation depends on the size of the plant. Previous research in South Africa has shown that plants with an influent flow less than 15 Ml/d do not produce sufficient sludge to warrant installation of advanced anaerobic digestion with CHP generation facilities
- Beneficial use of sludge is more economically attractive than disposing sludge to landfill for all three technologies

The results in Table 6-2 show the economic evaluation for a PCS technology retrofit treating 35 tDS/d of previously anaerobically digested sludge with screenings. The following is noted:

- The NPV is positive for both sludge disposal routes. Therefore, the technology is economically viable for further treatment of digested sludge (with screenings or external biomass) or for extensions of existing conventional anaerobic digestion facilities
- It should be noted that a thermal hydrolysis plant (THP) can also be retrofitted at a WWTP with existing conventional MAD. This was however not evaluated in this project.

Table 6-1: Economic Evaluation for Greenfields Installation Processing 50 tDS/d PS & WAS (and with Screenings for PCS Technology)

Parameter	PCS Technology				Advanced TH – MAD		Conventional MAD	
	PS & WAS Only		PS & WAS and Screenings					
	Beneficial Use of Ash	Ash Disposal to Landfill	Beneficial Use of Ash	Ash Disposal to Landfill	Sludge Beneficial Use	Sludge Disposal to Landfill	Sludge Composting & Beneficial Use	Sludge Disposal to Landfill
CAPITAL COST								
Capital Cost (R)	363.3	363.3	407.8	407.8	520.8	520.8	420.4	408.5
Unit Cost (R /kgDS)	7.3	7.3	7.1	7.1	10.4	10.4	8,410	8 170
OPERATING COST								
Annual Operating Cost (R million)	12.7	16.0	17.3	22.2	22.3	30.1	21.9	29.8
Unit Operating Cost (R/tDS)	694	879	833	1,069	446	602	438	596
INCOME/BENEFITS								
Annual Income/Benefits	13.0	18.6	18.5	20.5	15.1	12.9	14.3	7.5
NPV (R million)	**163**	**2.4**	**248**	**203**	**104**	**-63**	**-37**	**-225**

Table 6-2: PCS Process Economic Evaluation Summary for Digested Sludge and Screenings – 35 tDS/d Retrofit

Parameter	Digested Sludge and Screenings 35 tDS/d	
	Beneficial Use of Ash	Ash Disposal to Landfill
CAPITAL COST		
Capital Cost (R million)	167.3	167.3
Unit Capital Cost (R /tDS)	4.8	4.8
OPERATING COSTS		
Annual Operating Cost (R million/yr)	10.7	13.7
Unit Operating Cost (R/tDS)	835	1 070
INCOME/BENEFITS		
Annual Income/Benefits (R million/yr)	12.3	17.7
NPV (R million)	156	193

Advantages of advanced sludge-to-energy technologies

In general, advanced sludge-to-energy technologies like the established advanced TH–MAD (or any other advanced anaerobic digestion process) and the emerging PCS technology offer several advantages over conventional MAD:

- The technologies generate more energy than conventional MAD and hence combined with the advantages below, tend to be more economically attractive as illustrated by the cost benefit analysis undertaken in this project
- Significant reduction in the amount of sludge is achieved which reduces disposal costs for sludge that cannot meet the standards for beneficial use
- Processed sludge from the technologies is also easier to dewater achieving higher dry solids concentration which further reduces the quantity for disposal. Sludge from advanced TH–MAD plants achieves around 30% dry solids after dewatering. PCS technology hydrochar is hydrophobic and is dewatered to the same level without any polyelectrolyte addition
- Processed sludge is sterile. Sludge from TH–MAD plants has been classified as EPA Class A which is equivalent to the South African microbiological/stability Class A1. The PCS technology produces hydrochar that is completely sterile with quality that is above both these classes because the process destroys all forms of life in the sludge

Specific advantages of the PCS technology

The PCS technology is the latest generation of emerging biomass to energy technologies that can be applied for energy generation from wastewater sludge. Findings in this project have confirmed the following advantages over the established thermo-chemical and biochemical conversion processes like conventional and advanced anaerobic digestion processes that are currently widely applied for sludge management:

- Economically favourable than any of the technologies reviewed under this study (i.e. conventional and advanced anaerobic digestion or gasification)
- Co-processes sludge with screenings offering a single solution for sludge and screenings management at a WWTP
- Enables technology coupling with existing technologies e.g. anaerobic digesters providing opportunities for further energy recovery from digested sludge and screenings
- Produced hydrochar has multiple uses apart from as a biofuel, which creates opportunities for other revenue streams for the wastewater sector
- Low GHG emissions. Releases very little gas (1–5%) with only traces CH_4 and most organics remain in solid form
- Centrate from the process does not require complicated pre-treatment prior to discharge to the WWTP main liquid treatment process
- Potential to destroy EDCS which are of concern in the water sector. Legislation to limit these contaminants in wastewater effluent and sludge might be imposed in South Africa in future
- Because of the ability to

(i) process a wide range of biomass to produce a hydrochar with multiple uses and

(ii) be coupled with other technologies

the PCS technology creates feasible pathways to implementing circular economy principles in the water and waste sectors

Chapter 7 Conclusions and Recommendations

7.1 CONCLUSIONS

This project reviewed three sludge-to-energy technologies; the PCS technology which is an enhanced HTC process, advanced thermal hydrolysis–mesophilic anaerobic digestion (TH–MAD) and gasification. Conventional MAD which is the technology currently being used at Waterval WWTP, the case study plant, was also evaluated to serve as the baseline for the comparison of the technologies. The technologies were evaluated to determine their viability for implementation in the South African wastewater sector. Both technical and economic evaluations were carried out. The following conclusions were drawn from the study:

- The PCS technology is the most economically attractive technology, based on the financing models that were applied in the cost benefit analysis.
- Advanced TH–MAD is the second most economically attractive technology. The economics of the technology, however, depends on the size of the plant. Practical experience has shown that large plants are more economically attractive than smaller plants.
- Given the problems cited in the literature for gasification plants processing wastewater sludge, it was concluded that more evaluation of the technology is required in order to better understand the implications of applying the technology, particularly in South African municipalities.
- The PCS technology, as well as being the most economically attractive, being a multi-biomass processing technology, offers other advantages, apart from energy generation, over the current widely applied conventional anaerobic digestion processes. Thus, although still an emerging technology, it has potential to have a significant impact on sludge and waste management in future.

7.2 RECOMMENDATIONS

The main objective of the project was to build on previous research and provide the South African water sector with additional knowledge and tools to better select sludge-to-energy technologies. The project has reviewed three technologies that have not yet been implemented in South Africa. In order to continue adding to the body of knowledge available to the sector and increase the chance of uptake of new technologies, continued applied research in the following areas is recommended for each technology.

The PCS technology

The emerging PCS technology has demonstrated at laboratory and pilot scale that it offers unique advantages over established sludge processing technologies. The cost benefit analysis has also demonstrated that out of the three technologies that have been reviewed, it is the most economically attractive for the selected case study. In addition, the technology has the potential to play a huge role in waste management because of its ability to process a wide range of biomass. The following is therefore recommended in order to improve on the available knowledge:

a) Install a full-scale demonstration plant processing wastewater sludge from centralised WWTPs on its own and in combination with screenings and other external biomass from the community. This will provide additional information on the economics of full-scale installation, carbon footprint, hydrochar dewatering technologies, other potential use of hydrochar and materials recovery from both the hydrochar and centrate.

b) Investigate application of the technology to remove EDCs of concern in South Africa from both sludge and liquid wastewater.

c) Investigate the economics of implementing the technology at centralised plants of different sizes to determine optimal plant size for the technology. This needs to include an energy efficiency evaluation for the whole plant including energy conservation in the liquid treatment process (particularly aeration) to assess how much of the generated energy offsets the energy requirements for other processes. Modelling of regional sludge handling facilities, taking into account sludge transportation, can also be evaluated.

d) Install a full-scale demonstration plant for application in low-cost sanitation. The plant will demonstrate processing wastewater/faecal matter from low-cost sanitation systems such as low-flush toilets or dry sanitation systems, in combination with biomass from communities. This will demonstrate the economics of implementing the technology on a small scale.

e) Evaluate implementing circular economy principles in the South African water sector through utilisation of the technology to (i) process other biomass from the community in combination with wastewater sludge (ii) couple with existing technologies and new technologies and (iii) explore additional uses/markets for the hydrochar. This will provide alternative waste management planning strategies for South African municipalities and create employment opportunities for the wider community.

Advanced thermal hydrolysis-mesophilic anaerobic digestion

Although not yet implemented in South Africa, advanced TH–MAD is an established technology that has been demonstrated at full scale at over 60 installations internationally. Thus, the technology has sufficient full-scale demonstration data for successful implementation in South Africa. However, because of the significant financial and economic impact of implementing the technology, the following continued applied research is recommended:

a) Detailed whole plant modelling and preliminary design combining liquid treatment processes and advanced THP–MAD, including:
    - evaluation of the impact of dewatered digested sludge centrate on final effluent compliance and tertiary treatment processes such as disinfection

    - investigation of centrate treatment and nutrient recovery technologies and the overall economic impact of implementing the technologies
    - economic evaluation covering financial modelling taking into account different finance models and sludge utilisation/disposal routes
    - carbon footprint evaluation

b) A more detailed economic evaluation of implementing advanced TH–MAD at plants of different sizes to determine optimal plant size for the technology. Modelling of regional sludge handling facilities taking into account sludge transportation can also be included.

Gasification

Although an old, established process, wastewater sludge gasification has only a few full-scale plants globally that are operational on a sustainable basis. It is therefore recommended that the South African wastewater sector view this technology as unproven in this area. The following is therefore recommended:

a) Install pilot and/or full-scale demonstration plants processing various types of sludge, alone and in combination with other biomass from the community. Data from the demonstration plant can be used to assess:
    - the economic impact of full-scale installations, using life cycle cost analysis, as carried out for the other technologies in this project
    - operation and maintenance requirements, including skills requirements
    - environmental impacts, particularly gaseous emissions

b) Evaluate technology coupling with other technologies such as the PCS technology and anaerobic digestion.

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APPENDIX A: SUMMARY OF SLUDGE CLASSIFICATION BASED ON south african guidelines for permissible utilisation of sewage sludge

Table 7-1: Sludge Classification System

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

Details of each class are given in Table 7-2, Table 7-3 and 7.4 (WRC, 2006;2009)

Table 7-2: Preliminary Classification According to Microbiological Class

Microbial class	A	B	C
Microbial constituents	All three samples comply with the following standard	Two of the samples comply with the following standard	One or more of the samples exceed the following concentration
Faecal coliforms (CFU/g_{dry})	< 1,000	< $1x10^6$ to $1x10^7$	> $1x10^7$
Helminth ova (Total viable ova/g_{dry})	< 0.25 (or one viable ova/4g_{dry})	< 1 to 4	> 4

Table 7-3: Preliminary Sludge Classification According to Stability Class

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 70 percentile basis	No stabilisation or vector attraction options required
Option 1: Reduce the mass of volatile solids by 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 unit Option 4: Meet specific oxygen uptake rate for aerobically treated sludge Option 5: Use aerobic processes at a temperature greater than 40°C (average temperature 45°C) Option 6: Add alkaline material to raise the pH under specific conditions Option 7: Reduce moisture content of sludge that does not contain unstabilised solids (from treatment processes either 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 land.			

Table 7-4: Preliminary Sludge Classification According to Pollutant Class

Metal Limits for South African 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 - 800	> 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	1.1 - 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 - 1 225	> 1 225
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

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