THE ROLE OF EMERGING INNOVATIVE WASTEWATER SLUDGE TO ENERGY TECHNOLOGIES IN TRANSITIONING TO A CIRCULAR ECONOMY IN THE WATER SECTOR: A SOUTH AFRICAN CASE STUDY

Eustina Musvoto and Nomvuselelo Mgwenya

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Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

Similar to other sectors, the benefits of transitioning to a circular economy (CE) in the water and wastewater (collectively water) sector have been demonstrated through both theoretical models and practical experience in those areas where partial circularity has been achieved. However, full transition still faces significant challenges and barriers. As in most countries, the current water and wastewater business cycle in South Africa is predominantly based on the linear economy approach. To address current and future water security challenges in a sustainable manner, there is a need to rethink the South African water and sanitation value chain and accelerate transitioning to a CE. Initiatives in South Africa have mostly been from the wastewater sector where research into some areas that support the CE (e.g. energy conservation and generation in wastewater management, wastewater effluent reuse) has been undertaken in recent years through the support of the Water Research Commission (WRC). Large metropolitan municipalities (Metros) have also recently started investigating and implementing treatment processes and technologies that support the CE. However, significant work is still required, not only to fill the technical knowledge gaps, but also to develop concrete national strategies and policies that can assist water services authorities (WSAs) accelerate and successfully transition to a CE.

This project was funded by the WRC as part of the research into innovative water and wastewater management solutions that can assist WSAs successfully transition to a CE. The project evaluated the role of sludge to energy technologies in accelerating the adoption of CE principles by converting wastewater treatment plants (WWTPs) into resource recovery facilities at the centre of that transition. Both desktop evaluation and field pilot studies were conducted. The emerging enhanced hydrothermal polymerisation (EHTP) technology that demonstrated, in previous research projects, effective treatment of sludge from conventional WWTPs, was selected as the case study technology. The main objectives of the project were to:

- Conduct a literature review to determine the global water sector CE status and the most appropriate frameworks and strategies that can be adapted for application by South African WSAs
- Assess the effectiveness of the EHTP technology to process wastewater sludge in combination with waste biomass from the community and evaluate beneficial use of the produced hydrochar within a CE
- Identify technologies at technology readiness level (TRL) 8 and above that can be coupled with the EHTP process to fully convert WWTPs into resource recovery centres and accelerate transition to a CE
- Identify local factors that impact transitioning to a CE as well as strategies that can be applied to develop a framework that can assist WSAs accelerate and successfully transition to a CE in wastewater management

A 60-litre EHTP pilot reactor was installed at Plant A and wastewater sludge (primary sludge, waste activated sludge and anaerobically digested sludge) was processed in combination with waste biomass from the community (food, paper, yard, wood and industrial waste) as well as faecal sludge from ventilated improved pit (VIP) latrines. Various analysis (microbiological, chemical, calorific value, proximate and elemental) were

conducted on the sludge feedstock and process products (hydrochar and process effluent as appropriate). The key findings from the project were:

- The International Water Association (IWA) recommended framework for transitioning to a CE in the water sector was found to cover all aspects of the water cycle and therefore the most appropriate to be adapted to South African conditions
- The EHTP technology successfully processed sludge in combination with faecal sludge from VIP latrines and waste biomass from the community to produce a sterile hydrochar. The hydrochar
    - had a higher calorific value than the feedstock and can be used as a biofuel for energy generation
    - had higher concentrations of organics and nutrients than the feedstock and met the Department of Water and Sanitation (DWS) criteria for Class A1a biosolids with unrestricted use in land application. Further investigations into viability of using the hydrochar in agriculture are currently being undertaken
    - can be converted to activated carbon that can be used as adsorption media for tertiary treatment of wastewater effluent. Further investigations are being undertaken to determine efficiency of the hydrochar derived activated carbon in removing micropollutants from wastewater effluent
    - can be used (as well as ash from combusting the hydrochar as a biofuel) in the building industry for cement and brick making. Further investigations are required to assess the quality of the produced cement and bricks
- The EHTP process can be successfully incorporated into WWTPs and coupled with other emerging and established technologies to fully convert WWTPs into resource recovery centres and produce by-products that can be used within the IWA framework interrelated pathways (water, energy and materials) that accelerate transition to a CE
- Key factors that need to change to ensure that WSAs can accelerate and successfully transition to a CE are governance, policy, regulations, consumer perceptions on wastewater by-products, infrastructure and technology. Strong leadership within central and local government was also identified as a key requirement to successful shift from a linear to a CE in wastewater management

The results from this project demonstrated that multi-biomass processing technologies like the EHTP process can be successfully incorporated into WWTPS and process wastewater sludge combined with low-cost sanitation systems faecal sludge and other waste biomass from the community to produce hydrochar that can be beneficially used within the IWA framework interrelated pathways for successful transition to a CE. The technology can also be coupled with other technologies to convert WWTPs into resource recovery centres at the centre of the transition. To ensure accelerated and successful transition to a CE by WSAs, governance, policy and regulations need to be changed through strong leadership at central and local government level. Other key factors that also need to be shifted from the linear to CE approach are technology, infrastructure, consumer behaviour and economics.

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Operators and Support staff at Plant A wastewater treatment plant.

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LIST OF ABBREVIATIONS

AD	Anaerobic Digester
ADWF	Average Dry Weather Flow
AOP	Advanced Oxidation Process
ASP	Activated Sludge Plant
BAC	Biochar Activated Carbon
BNR	Biological Nutrient Removal
BSO	Biodegradable Soluble Organics
CAP	Criteria Air Pollutant
CARA	Conservation of Agricultural Resources Act
CCME	Canadian Council of Ministers for the Environment
CE	Circular Economy
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
CO	Carbon Monoxide
COD	Chemical Oxygen Demand
CoU	City of Umhlathuze
DAF	Dissolved Air Flotation
DEAT	Department of Environmental Affairs and Tourism
DFA	Development facilitation act
DO	Dissolved Oxygen
DoA	Department of Agriculture
DoH	Department of Health
DRDLR	Department of Rural Development and Land Reform
DS	Digested Sludge also Dry Solids when in units (South Africa)
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry (South Africa)
DWS	Department of Water and Sanitation (South Africa)
EADP	Environmental Affairs and Developmental Planning
EBMUD	East Bay Municipal Utility District
EBPR	Enhanced Biological Phosphorus Removal
ECA	Environment Conservation Act
ECM	Energy Conservation Measure
EDC	Endocrine Disrupting Compounds
EEA	European Economic Area
EFSI	European Fund for Strategic Investments
EHTP	Enhanced Hydrothermal Polymerisation
EPA	Environment Protection Agency (USA)
ERWAT	Ekurhuleni Water Care Company
EU	European Union
EWS	eThekwini Water Services
FS	Faecal Sludge
FSA	Free and Saline Ammonia
GAC	Granular Activated Carbon
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HHV	Higher Heating Values

HiPRO	Hirecovery precipitating reverse osmosis
HTL	Hydrothermal Liquefaction
ICLEI	International Council for Local Environmental Initiatives
IDPs	Integrated Development Plans
IPR	Intellectual Property Rights
IWA	International Water Association
KPI	Key Performance Indicator
LED	Local Economic Development
LGTA	Local Government Transition Act
LMICs	Low- and Middle-Income Countries
MDA	Municipal Demarcation Act
MEC	Microbial Electrolysis Cells
MFC	Microbial Fuel Cells
MFMA	Municipal Finance Management Act
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
MMWWE	Mechanisms for Municipal Wastewater Effluent
MRF	Material Recover Facility
MSA	Municipal Structures Act
MSW	Municipal Solid Waste
N	Nitrogen
NEMA	National Environmental Management Act
NERSA	National Energy Regulator of South Africa
NF	Nanofiltration
NGOs	Non-governmental Organizations
NWA	National Water Act
O&M	Operation & Maintenance
OFMSW	Organic Fraction of Municipal Solid Waste
Ortho P	Ortho phosphate
p	Person; also depicted as capita (c) or head (hd)
PAA	Peracetic Acid
PAC	Powered Activated Carbon
PACE	Platform for Accelerating the Circular Economy
PCS	Polymeric Carbon Solid
pe	Population Equivalent
PFD	Process Flow Diagram
PLC	Programmable Logical Controller
PPP	Public-Private Partnership
PPPFA	Preferential Procurement Policy Framework Act
PS	Primary Sludge
PST	Primary Settling Tank
RAS	Return Activated Sludge
RDP	Reconstruction Development Programme
RO	Reverse Osmosis
ROI	Return on Investment
SABS	South African Bureau of Standards
SAC	Specific Absorbance Coefficient
SADC	Southern African Development Community
SALGA	South African Local Government Association

SANS	South African National Standard
SAPREF	South African Petroleum Refineries
SARS	South African Revenue Services
SCA	Supreme Court of Appeal
SCADA	Supervisory Control and Data Acquisition
SDF	Spatial Development Frameworks
SDG	Sustainable Development Goals
SPLUMA	Spatial Planning and Land Use Management Act
SST	Secondary Settling Tank
SWTW	Southern Wastewater Treatment Works
TCOD	Total Chemical Oxygen Demand: also represented as COD unless specified otherwise
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TOC	Total Organic Carbon
Total P	Total Phosphorus
TRL	Technology Readiness Level
TS	Total Solids
TSS	Total Suspended Solids
UCT	University of Cape Town
UN	United Nations
UV	Ultraviolet
VFA	Volatile Fatty Acids
VFD	Variable Frequency Drive
VIP	Ventilated Improved Pit
VOC	Volatile Organic Compounds
VS	Volatile Solids
VSS	Volatile Suspended Solids
WAS	Waste Activated Sludge, also surplus activated sludge (SAS)
WERF	Water Environment Research Foundation
WHO	World Health Organisation
WRC	Water Research Commission (South Africa)
WRP	Water Reclamation Plant
WSA	Water Services Authority
WSDP	Water Services Development Plans
WUA	Water Use Authority
WWTF	Wastewater Treatment Facility
WWTP	Wastewater Treatment Plant
WWTW	Wastewater Treatment Works

CHAPTER 1. INTRODUCTION

1.1 Background

In recent years, the concept of a circular economy (CE) has received prominence in political, business and research agendas. Research has identified that numerous potential benefits (e.g. improved resource security, a reduced environmental impact such as the drastic reduction in greenhouse gas emissions, economic and social benefits) are derived from transitioning from a traditional linear economy to a circular economy. Despite these significant benefits, it is acknowledged that transforming the linear economic model that has been dominant since the Industrial Revolution is a big challenge which entails the transformation of current production and consumption patterns. Innovative transformational technologies such as digital and engineering technologies, in combination with creative thinking have been identified as factors that will drive fundamental changes across entire value chains that are not restricted to specific sectors or materials. Such a major transformation would in turn result in significant impacts on the economy, environment and society. Understanding these impacts is crucial for researchers as well as policymakers in designing future policies in the field (Vanner et al., 2014; Rizos et al., 2017; European Commission, 2017).

Although the water sector has not yet fully transitioned to a circular economy, water utilities have been early adopters of technologies and business practices that support the circular economy. This has been in response to various threats and challenges that the sector has faced in recent years (i.e. water scarcity, increasing energy prices, more stringent regulations, rapid urbanisation and climate change impacts). Impeding regulatory environments and opaque market conditions have been identified as the main obstacles for the water sector transitioning fully to a circular economy (IWA, 2016). Thus, to define a clear role for water utilities in transitioning to a circular economy, the IWA developed a framework targeted at decision makers in water utilities as well as key stakeholders. The framework identified three key interrelated pathways to achieving circular economy principles in the water sector. These are water, material and energy pathways. In addition, consumers, industry, regulation, infrastructure and urban and basin economies have been identified as the main factors that drive and enable the transition of the water sector to a circular economy (IWA, 2016). Water utilities need to anticipate, respond to and influence these factors to accelerate the pathways to achieving a circular economy. In transitioning to a circular economy, water utilities also need to change their current way of operation and seek new management approaches, partnerships and business opportunities.

The IWA framework has identified WWTPs as one of the key junctions in the three pathways to transitioning to a CE in the water sector. This is mainly because within the man-made water cycle, wastewater is a carrier of 50% to 100% of waste resources that are lost mostly in the form of unrecovered water, energy and materials. The wastewater treatment sector is also responsible for 3% of electricity consumption globally and accounts for about 56% of the operational carbon footprint of urban water systems (Batstone et. al, 2015). Recently an increasing number of studies have focused on WWTPs and their potential for recovering valuable resources. These studies have shown that energy efficiency in WWTPs, combined with more efficient utilization of wastewater energy potential can lead to energy positive WWTPs. For example, energy self-sufficient WWTPs or even net energy producing WWTPs have been reported recently in cases applying co-digestion of wastewater with organic wastes from urban, agricultural, agronomic or industrial sources. Implementation of energy conservation measures and the use of renewable energy sources also improve a WWTP's energy efficiency. Due to its calorific value, dry sludge from WWTPs can also be used as an alternative fuel in industrial plants. Additionally, the carbon in wastewater can be utilized to produce high value by-products (e.g. biopolymers, chemicals, etc.). Nutrients such as phosphorus and nitrogen recovered from wastewater are used in agriculture, thus reducing the global environmental impact of their industrial production.

Technology plays a key role in resource recovery from WWTPs. Innovative technologies that can process multiple waste streams with wastewater sludge, generate energy and other high value products have minimal waste products and contribute to all the three circular economy pathways. This will have a significant impact in implementing a circular economy. Coupled with innovative waste to energy technologies, wastewater treatment plants – acting as wastewater bio-refineries – can be a key technological platform for circular economy systems that introduce innovative technological solutions and move towards resource recovery approaches in wastewater management.

1.2 Project Contextualization and Objectives

While the global community has taken some steps in promoting a circular economy, the South African water sector has not laid out concrete strategies or policies to transition to a full circular economy. A lot of research has, however, been carried out on processes and technologies that contribute to the interrelated pathways for transitioning to a circular economy in the water sector. Recent research sponsored by the WRC includes research on beneficial use of sludge through energy and resource recovery, reuse of reclaimed wastewater and energy conservation through aeration energy use reduction, all of which is related to some aspects of the principle of the circular economy. In addition, most of the large wastewater treatment plants already implement some technologies that, with planning and strategies in place, can accelerate transitioning to a circular economy (e.g. 26% of municipal wastewater treatments plants implement anaerobic digestion of sewage sludge – van der Merwe et al., 2016). However, none of the research and technology implementation strategies have yet focused on a full transition to circular economy principles and making WWTPs the centre of the transition.

The objective of this project was therefore to address this gap in knowledge. The project built on the research carried out under project K5/2475 "Energy and Resource Recovery from Wastewater Sludge – A Review of Appropriate Emerging and Established Technologies for the South African Industry" (Musvoto et al., 2018) that reviewed two established technologies (advanced anaerobic digestion and gasification) and one emerging technology (enhanced hydrothermal polymerisation). Of the three technologies, the enhanced hydrothermal polymerisation (EHTP) technology has the following main advantages:

- treats a wide range of biomass enabling waste from communities to be processed at centralised locations
- can be coupled with other waste to energy and wastewater sludge treatment technologies, thus maximising efficiency of existing and new infrastructure investment
- The product from the EHTP technology has multiple beneficial uses that include:
    - As a biofuel for energy generation with the resultant energy used at the WWTP as well as distributed to the community
    - Further processing of the product into adsorption media that can be used for tertiary treatment of effluent from the WWTP. The reclaimed effluent can then be re-used in agriculture and industry as well as for direct potable use
    - Used as an industrial material, e.g. cement and brick making
    - Used as a soil conditioner for agricultural and non-agricultural use
    - Extraction of valuable metals from the ash after burning the product as a biofuel

The versatility of the EHTP technology thus encompasses the three interrelated pathways for transitioning to a circular economy in the water sector by using WWTPs as the core to that transition. This technology was therefore selected as the central technology in evaluating the implementation of circular economy principles in the South African wastewater sector under this project.

A conceptual layout for the application proposed in this project is given in Figure 1-1.

Implementing circular economy principles at WWTPs using technologies such as the EHTP technology on its own or coupled with other technologies has the following benefits and advantages:

- Converts wastewater treatment facilities into integrated water, waste and resource recovery systems
- Fosters innovation and mutually beneficial partnerships with communities
- Creates new business models and jobs, develops new skills and invests in communities
- Reduced carbon footprint which mitigates the impacts of climate change

The outputs from this project will assist municipalities and water utilities in South Africa initiate planning and development of strategies as well as adoption of technologies that stimulate transitioning to a circular economy.

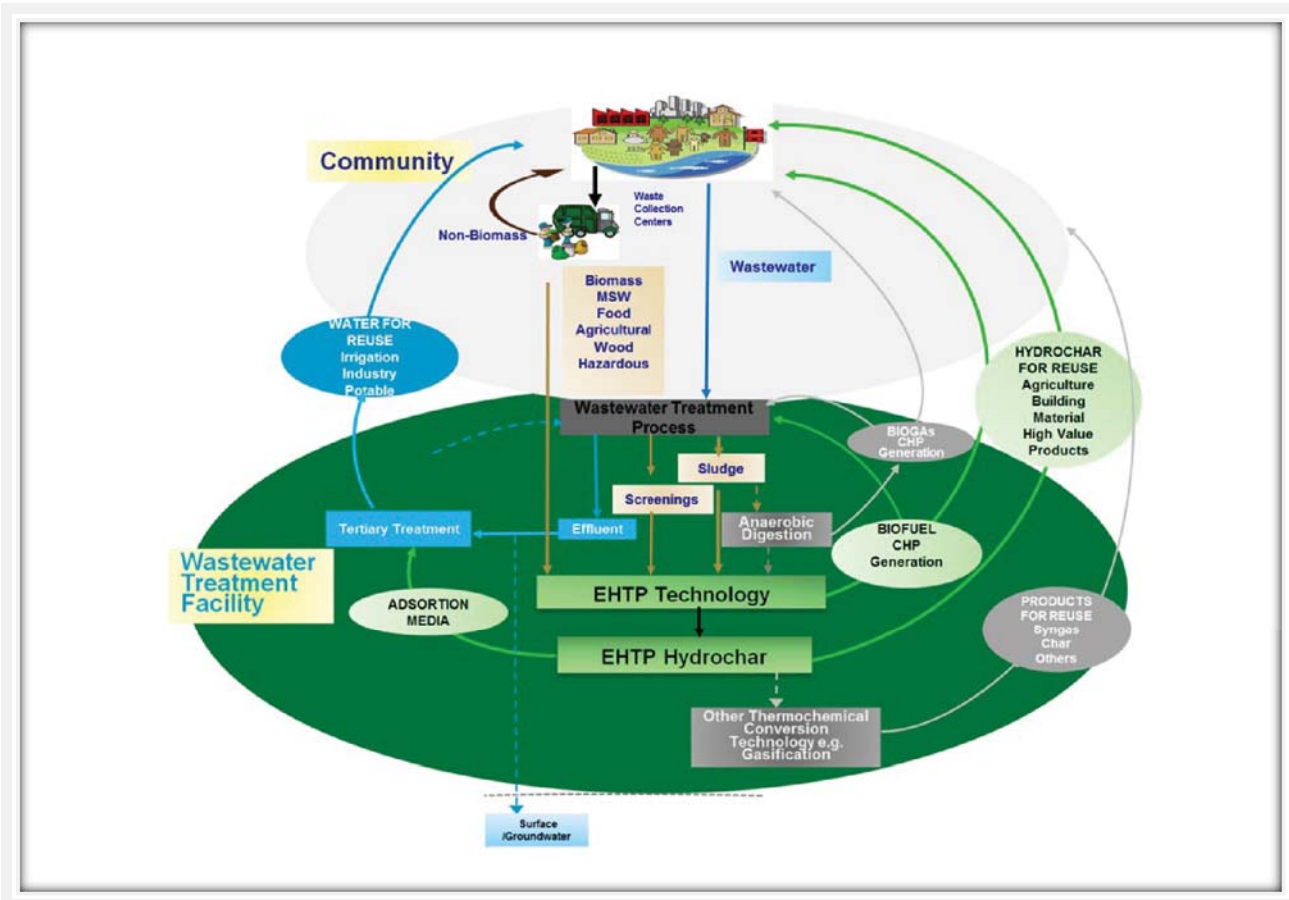


Figure 1-1: Proposed Conceptual Layout for Application of Innovative Waste to Energy Technologies as Accelerators for CE Transition in the Water Sector Using WWTPs as the Core of the Transition

The main objectives of this project were to:

- Conduct a literature review on the status of CE adaptation in the wastewater sector globally and in South Africa
- Combine pilot scale and desktop studies co-processing wastewater sludge with external biomass from the community in the EHTP technology and assess the product produced and its potential use within the three circular economy pathways
- Identify appropriate wastewater and sludge management technologies at technology readiness level (TRL) 8 and above that can be coupled with the EHTP technology to accelerate CE adaptation within the three pathways
- Evaluate factors that need to shift from the conventional linear economy model to a model that enables and boosts a CE within the South African wastewater sector to assist municipalities formulate strategies to adopt CE (e.g. regulation, consumer behaviour and demands, industry,

urban and catchment area planning and economies, infrastructure and technology) to assist municipalities formulate strategies to adopt CE regulation, consumer behaviour and demands, industry, urban and catchment area planning and economies, infrastructure and technology).

The pilot investigations were conducted using a 60 litre EHTP reactor. The reactor was located at Municipality 1's wastewater treatment Plant A in Gauteng. Sludge from Plant A and waste biomass from the local community were processed in the EHTP reactor. Laboratory analysis was conducted on the feedstock and produced hydrochar to assess potential use within the three circular economy pathways.

CHAPTER 2. LITERATURE REVIEW

2.1 Concept of Circular Economy

2.1.1 Overview

In recent years the concept of circular economy (CE) has received increasing attention worldwide. The shift is driven by the recognition that the assumptions of infinite resources and the cheap disposal of waste that underlies the conventional linear "take-make-consume-dispose" economic model is no longer sustainable in the face of increasing global population and demand. In contrast, the CE concept is a development strategy that enables economic growth while aiming to optimise the chain of consumption of biological and technical materials (Vanner et al., 2014; Rizos et al., 2017; European Commission, 2015)[1]. The Ellen MacArthur Foundation (2013) describes a CE as "restorative or regenerative by intention and design" and considers the potential across entire value chains and cross value chains and closing resource loops in all economic activities. Significant transformation of production chains and consumption patterns is required to keep materials circulating in the economy for longer, re-designing industrial systems and encouraging cascading use of materials and waste. Simplified illustrations of the linear and circular economies based on the European Commission definition are shown in Figure 2-1 and Figure 2-2 respectively.

It should be noted that while there are some elements of circularity such as recycling and composting in the linear economy, a CE goes beyond the pursuit of waste prevention and waste reduction to inspire technological, organisational and social innovation across and within value chains (Vanner et al., 2014). The figures indicate that a CE can be progressed through different approaches such as product design, cascading components, materials and resources, materials recycling, biochemical extraction and other biological processes for value/energy generation, circular/regenerative forms of consumption and industrial symbiosis. A distinction in approaches can be made for technical materials (non-biodegradable based on finite resources) and biological materials of biological origin and generally non-toxic and renewable materials (European Commission, 2014). The transition towards a CE affects different policy areas, ranging from mobility, agriculture, land use and waste management to business development and consumer education concerning actors across all sectors and levels of governance. Thus, a CE cannot be undertaken by a single institution or company and fosters connections across individual stakeholders and sectors. To reach its maximum potential, it needs coordinated efforts at different levels of governance, from local and regional to national and global.

[1] It should be noted that in addition to the definition presented here there are also numerous definitions and interpretations applied to describe the concept of CE (e.g. MacArthur Foundation; 2013, 2015). Reference should be made to Rizos et al., (2017); Kirchherr et al., (2017) for a history of the concept as well as more definitions

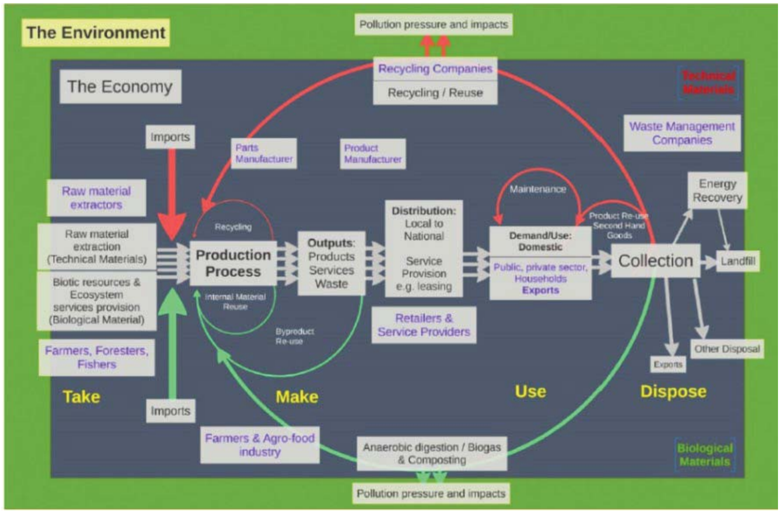
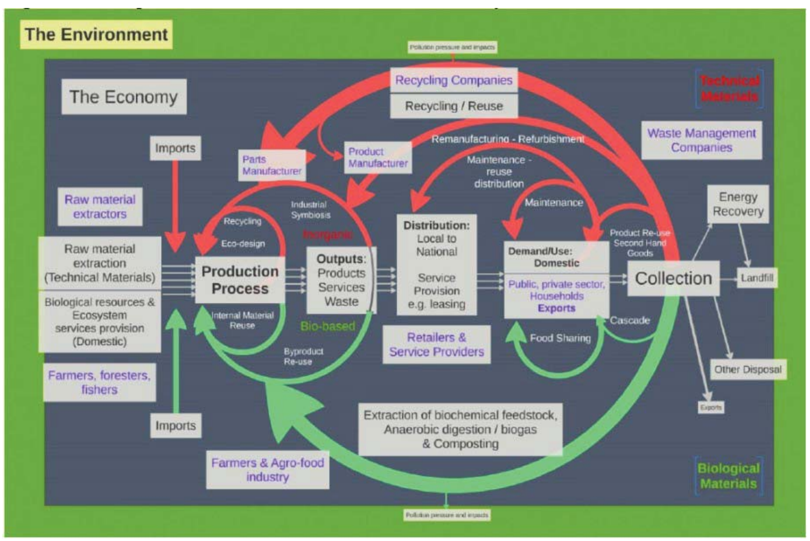


Figure 2-1: Simplified Illustration of the Conventional Linear Economy (Adapted from European Commission, 2014)



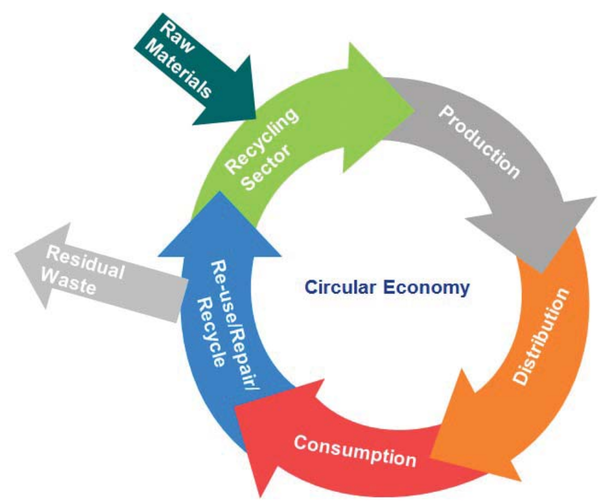


Figure 2-2: (a) Simplified Illustration of the Circular Economy (b) New Circular Economy Key steps of the Product Life Cycle (Adapted from European Commission 2014; Bačová et al., 2016)

2.1.2 Circular Economy Adaptation Progress

Regions that have made significant progress in promotion of the CE are the European Union (EU), China, Japan, South Korea and parts of the USA.

The European Union

The CE concept emerged in Europe in the 1980s and 1990s and is reported to have been formally used in an economic model for the first time by Pearce & Turner (1990). However, prior to this, early policies of EU member states – drawing on ideas that can be traced to the 1960s and 1970s – had promoted elements of circularity in certain parts of the economy. For example, driven by a desire to divert waste from landfill, the Netherlands and Germany pioneered concepts of waste prevention and reduction, with the waste hierarchy introduced to the Dutch Parliament in 1979 (Mcdowall et al., 2017). In the past decade, the concept has become more and more prominent and is now adopted as part of the EU economic policy and strategy.

Research has shown that numerous potential benefits are derived from the transition to a CE. A 2016 European Economic Area (EEA) study “Circular economy in Europe” identified that the benefits of implementing CE principles to EU countries include:

a) improved resource security and decreased import dependency
b) reduced environmental impact including a drastic reduction in greenhouse gas (GHG) emissions
c) economic benefits that include new opportunities for growth and innovation, as well as savings related to improved resource efficiency and
d) social benefits ranging from new job creation across all skill levels to changes in consumer behaviour, leading to better health and safety outcomes.

Through transitioning to a CE, the EU predicts a doubling of economic benefits, 11% growth in average disposable incomes and a halving of carbon dioxide emissions by 2030 (Ellen MacArthur Foundation, 2015). Specific benefits to countries and sectors within the EU have at been qualified in subsequent studies (EEA, 2016; Bacova et al., 2016).

While the benefits of the CE are being increasingly acknowledged, there still remain a range of barriers that need to be overcome. Among the barriers identified, technological, policy and regulatory, financial and economic, consumer and social, managerial as well as performance indicators are the most frequently cited as being the major challenges for the implementation of a CE (European Commission, 2014; Rizos et al., 2017; Galvao et al., 2018). The EU’s (2014) paper cited the barriers in these categories, including the following):

- Insufficient skills and investment in circular product design and production

- Resource pricing that does not encourage efficient resource use, pollution mitigation or innovation
- Lack of sufficient incentives due *inter alia* to the insufficient internalisation of externalities through policy or other measures
- Non-alignment of power and incentives between actors (within and across value chains) to improve cross-cycle and cross-sector performance
- Still limited consumer and business acceptance of potentially more efficient service-oriented business models
- Limited information, know-how and economic incentives for key elements in the supply and maintenance chain
- Insufficient waste separation at source
- Limited sustainable public procurement incentives in most public agencies
- Insufficient investment in recycling and recovery infrastructure, innovation and technologies
- Challenges in obtaining suitable finance for such investment
- Weaknesses in policy coherence at different levels
- Widespread planned obsolescence in products.

The significance of these barriers differs for particular materials, products and sectors. Different types of actions are required at the EU, national, regional and local levels to drive transformation depending on the nature of the barrier faced. Various drivers are often required in a sector or value chain to overcome these barriers and take into account the multiple factors that often influence each other[2]. Due to its complexity of transition to a CE is a multi-level governance challenge, requiring actions in the public and private sectors as well as at an individual level. Thus, identification and detailed understanding of specific barriers is very important so that appropriate mitigation measures can be put in place.

Studies in the EU have shown that the transition to a CE requires systemic change and a more holistic, integrated approach which considers the multiple connections and influences within and between sectors, value chains and stakeholders (European Commission, 2014; 2016). With this approach important factors such as different incentives, distribution of economic rewards and impacts of specific measures along a value chain, across different sectors and policy areas are considered. Complementary tools and approaches which that can easily be advanced by the private and public sectors, as well as individuals at all levels from local to the EU. Policy intervention beyond private initiatives has been identified as a key driver to overcoming some of the barriers to transitioning to a CE. Identified potential policy actions

[2] For example, in the EU, the infrastructure to support the efficient collection of products after use, i.e. "reverse cycles" (Ellen MacArthur Foundation, 2013) or "reverse logistics" (Hawks, 2006), which is an essential component for a circular economy, can be heavily influenced by various levers: policy instruments (such as landfill tax), extended producer responsibility, new business models and take-back schemes.

include regulatory measures, economic incentives, targeted and increased funding, efforts to engage and link actors along the value chain and initiatives to raise awareness of the benefits of the circular economy and available solutions.

In 2015 the European Commission adopted an action to help accelerate the EU's transition towards a circular economy, boost global competitiveness, promote sustainable economic growth and generate new jobs. The action plan sets out measures to "close the loop" of product lifecycles: from production and consumption to waste management and the market for secondary raw materials. It also identifies five priority sectors to speed up the transition along their value chain (plastics, food waste, critical raw materials, construction and demolition, biomass and bio-based materials). The transition is supported financially through the European Structural and Investment Funds, Horizon 2020, the European Fund for Strategic Investments (EFSI), and the LIFE programme thereby building a strong foundation on which investments and innovation can thrive. Close cooperation with member states, regions and municipalities, businesses, research bodies, citizens and other stakeholders involved in the circular economy is promoted in the action plan (European Commission, 2019).

Other Regions

Apart from the EU, other regions that have made significant progress in promotion of a CE are China, Japan, South Korea and part of the USA.

The concept of CE is not new in China. It dates back to the 1990s, with origins in cleaner production, industrial ecology and ecological modernization. The thinking was inspired by examples of implementation in Europe, the United States and Japan (Shi et al., 2006). In 2003 the concept was formally accepted by the central government as a new development strategy which culminated in the 2009 Circular Economy Promotion Law, the natural framework for advancing CE. Subsequently, various action plans that provide further details for specific sectors as well as clarity on the implementation of the provisions of the CE promotion law have been put in place (MacDowall et al., 2017). Since implementation, the Promotion Law has evolved to include concern for eco-design, potential product regulations and restrictions on some classes of disposable goods, green consumption as well as extended producer responsibility.

In addition, the Promotion Law requires the establishment of target responsibility systems in support of the CE as well as measuring and evaluating progress against indicators. To promote CE, the Chinese government has invested significantly in demonstration projects, deployed tax incentives and allowed reuse/recycling activities that were previously banned (e.g. selling relatively clean wastewater). It is estimated that extending such practices would save Chinese businesses and households 32 trillion yuan (US$4.6 trillion) in 2030, equivalent to 14% of its projected gross domestic product that year (Geng et al., 2019). Although the Chinese CE agenda is framed on the same principles as the EU (waste minimisation, raw materials, resource efficiency), there are differences in policy focus areas. EU policies focus on consumption and product design more than China where the focus is on specific manufacturing sectors (MacDowall et al., 2017) and measures to increase efficiency and reduce waste pollution in manufacturing.

Japan and South Korea also have national strategies for enabling the CE. Japan has legislated on eco-design, made producers responsible for the after-use of their products and boosted markets for secondary materials. Most of these circular-economy initiatives have saved materials, waste, energy and emissions. In Kawasaki, Japan, reusing industrial and municipal wastes in cement manufacturing has reduced greenhouse-gas emissions by about 15% (41,300 tonnes per year) since 2009 and saves 272,000 tonnes of virgin materials annually. Similar to China, South Korea has operated industrial parks that use the principles of a circular economy to link the supply chains of companies and reuse or recycle common materials.

The United States has hundreds of corporate recycling as well as a handful of regional programmes such as the Zero Waste scheme in San Francisco, California. However, beyond this, there have been few broad federal initiatives comparable to those being pursued by China and the EU (GreenBiz, 2018). To develop new circular economy opportunities and realise their ambitions faster in the USA, the Ellen MacArthur Foundation launched a US chapter of its Circular Economy 100 (CE100) program in 2016.

The Circular Economy 100 is a pre-competitive innovation programme established to enable organisations to develop new opportunities and realise their CE ambitions faster. It brings together corporates, governments and cities, academic institutions, emerging innovators and affiliates in a unique multi-stakeholder platform. Specially developed programme elements help members learn, build capacity, network, and collaborate with key organisations around the circular economy (Ellen MacArthur Foundation, 2013).

The launch followed a study by the US Chamber of Commerce Foundation that showed that the 5,589 largest publicly traded companies in the US sent 342 million metric tons of waste to landfills and incinerators in 2014. On average, companies generate 7.81 metric tons of waste for every million dollars in revenue. The reduction of paper waste by a mere 1 percent would save these companies nearly $1 billion in total. To date, the members of the CE 100 program include large corporations like Walmart, Microsoft, Coca Cola, Google, Nike and other institutions.

South Africa

South Africa does not yet have a unified national policy and strategy for transitioning to a CE. However, lessons learnt from other regions as well as increased awareness of the potential opportunities are stimulating serious discussions and initiatives on a CE, both in the public and private sectors. Despite the lack of a national policy on CE, legislation like the National Environmental Management Act (Republic of South Africa, 2009) is driving progress in some areas of CE aspects such as waste recycling and converting waste to energy. Efforts are also being made on a government and sector level to co-operate with other regions that have gained traction in the transition to a CE. Examples of these efforts include the following:

- The Circular Economy Mission with the EU whose main objectives are to increase cooperation between the EU and developing countries in the field of environmental policy achieve a better understanding of the environmental challenges faced by developing countries and promote green solutions through business partnerships abroad (European Commission, 2018). The Terms of Reference for the Forum on Environment, Climate Change, Sustainable Development and Water between the EU and South Africa include an agreement to further cooperate in areas which include biodiversity, circular economy and water resources management issues among others. The cooperation also involves private sector operators
- Membership of the Platform for Accelerating the Circular Economy (PACE), a public-private collaboration platform and project accelerator. PACE aims to shape global public-private leadership and accelerate action towards the circular economy. Project focus areas include plastics, electronics, food & bioeconomy as well as business model and market transformation across China, ASEAN, Europe and Africa.

In addition to policy and industry initiatives, research is also required into specific aspects of application of the CE to South Africa. Some questions that need addressing at a policy and strategic level include the identification of drivers for CE in South Africa that would bring the most benefit to the country. The drivers need to be relevant to South Africa as a developing, resource rich country so that opportunities that exist in the economy can be identified and applied in shaping the CE agenda in the country[3]. In addition, risks to South Africa from other countries adopting CE also need to be understood, for example, the EU (Godfrey 2017, de Jong et al., 2016).

South Africa exported 6.1 billion worth of critical raw materials (72.1% GDP) to the EU, which would be substantially reduced if the EU moved fully to a CE. In addition, € 8.4 billion in mineral exports (22.7% of GDP) could be threatened.

2.1.3 Summary

Research to date has shown that the prospective economical, societal and environmental benefits of moving towards a CE and away from the linear economic model are compelling. At the same time, changing the linear economic model that has remained dominant since the onset of the Industrial

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[3] For example, the EU's CE agenda is mainly driven by resource scarcity, while India a developing economy has focused instead of focusing its CE strategy on waste has focused it on where the greatest demand for materials is within the Indian economy (i.e. Cities and construction, food and agriculture and mobility and vehicle manufacturing (MacArthur Foundation, 2016)

Revolution is not an easy task and would entail a transformation of our current production and consumption patterns. Innovative transformational technologies such as digital and engineering technologies, in combination with creative thinking about the CE will drive fundamental changes across entire value chains that are not restricted to specific sectors or materials (Vanner et al., 2014; Acsinte & Verbeek, 2015; Accenture, 2014). Such a major transformation would in turn entail significant impacts for the economy, the environment and the society. Understanding those impacts is crucial for researchers and policymakers for designing future policies in the field. This requires developing a good knowledge of the concept, the different circular economy processes and their expected effects on sectors and value chains. However, although a lot of research has been and is being conducted, research on the circular economy appears to be fragmented across various disciplines and there are often different perspectives about the interpretation of the concept and the related aspects that need to be assessed.

Furthermore, while there is progress in individual countries, regions and certain sectors on the adoption of CE, there is no international policy effort to integrate CE approaches. Such co-operation would contribute to many of the UN Sustainable Development Goals (SDGs), including those on water, energy, economic growth and climate change (SDGs 6, 7, 8 and 13). Without a global initiative, the sum of individual efforts remains inadequate and the opportunities and benefits of the CE are not fully realised.

2.2 Circular Economy Solutions in the Water Sector

2.2.1 Overview

For the water and wastewater (collectively water) sector, transitioning to a circular economy is in line with the United Nations Sustainable Development Goals (SDGs). Water has a dedicated goal in SDG6 (ensure availability and sustainable management of water and sanitation for all) and its attainment will be reliant upon contributing to and benefiting from the attainment of other SDGs, most notably in the context of the circular economy (SDG12, ensure sustainable consumption and production patterns).

This interdependence across goals manifests at a national level in highlighting the need for greater cooperation amongst sectors, incentivised innovation and enabling meaningful engagement with citizens (IWA, 2016).

Although the water sector has not yet fully transitioned to a circular economy, the need to respond to various challenges has placed the sector on the road to a circular economy. Water utilities have been early adopters of technologies and business practices that support the circular economy. This has been in response to various threats and challenges that the sector has faced in recent years, i.e. water scarcity, increasing energy prices, more stringent regulations, rapid urbanisation and climate change impacts. Impeding regulatory environments and opaque market conditions have been identified as the main obstacles for the water sector transitioning to fully to a circular economy (IWA, 2016).

To define a clear role for water utilities in transitioning to a circular economy, the IWA developed a framework targeted at decision makers in water utilities as well as key stakeholders.

The main purpose of the framework is to

- Identify opportunities and maximise these opportunities within the three interrelated pathways
- Identify regulatory and market levers that if addressed would contribute to acceleration of pathways to transitioning to circular economy
- Provide a basis for initiating and developing national or regional dialogue on the water utility pathways based on local context

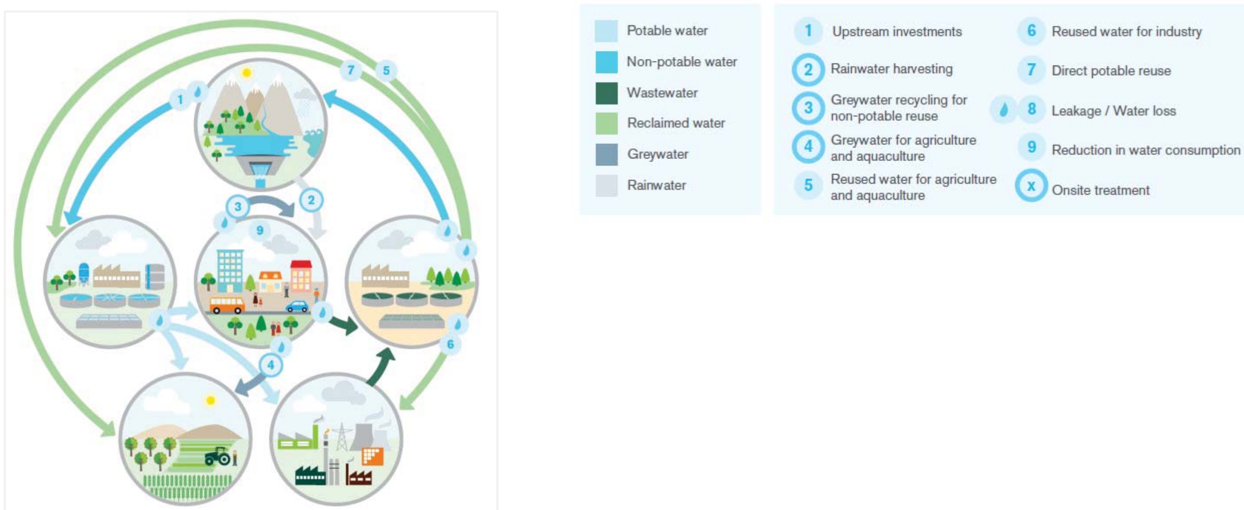
The framework identified three key interrelated pathways to achieving circular economy principles in the water sector, namely water, material and energy pathways. Graphical illustrations of these pathways are given in Figure 2-3. A brief description is given below.

Water Pathway

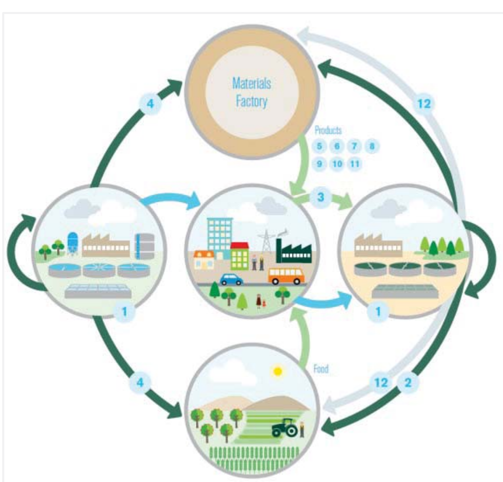
To reduce the inefficiency in existing water systems that worsen the gap between supply and demand, the IWA framework recommends that the water pathway needs to be developed as a closed loop. Three factors to achieving this are to have diversified resource options, efficient conveyance systems and optimal reuse. Options to be considered include upstream investment to ensure optimal conservation measures and pollution control to minimise treatment costs, rainwater harvesting, greywater recycling, wastewater reuse, reduction of water loss/leakage in potable water distribution systems and reduction in water consumption.

Materials Pathway

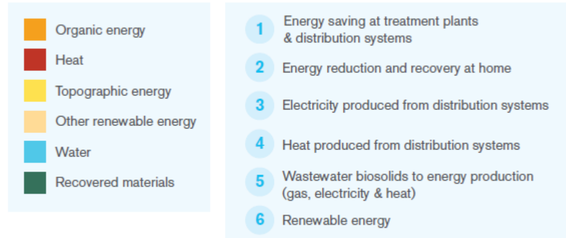
In the materials pathway resource recovery from wastewater operations must be able to compete with other products in the market for successful incorporation into the circular economy. Key issues to be considered include efficiency of resource recovery, scale of production, pricing, quality and consumer acceptance. It is therefore important for Water Utilities to collaborate with industry to understand and address these issues. Options that can be considered for successful materials recovery include resource efficiency, drinking water sludge reuse in agriculture and/or industry, wastewater sludge and products reuse for agriculture, co-processing of external biomass (e.g. municipal solid waste, agricultural waste, woody biomass, industrial waste, etc.) with wastewater sludge and recovery of high value niche products from wastewater operations (e.g. bioplastics, non-agricultural fertiliser, paper and cellulose, building materials, etc.).



(a) Water Pathway



(b) Materials Pathway



(c) Energy Pathway

Figure 2-3: Illustration of the IWA Framework Pathways to a Circular Economy in the Water Sector (Adapted from IWA, 2016)

Energy Pathway

Water and wastewater operations consume a lot of energy. A lot of energy is also consumed in the home for heating water. Untreated wastewater as well as certain treatment processes contribute to greenhouse emissions. The IWA framework recommends that the objective of the energy pathway should be to reduce carbon-based energy consumption, increase renewable energy production and consumption and contribute to the zero-carbon emissions initiative. Options to be considered in the energy pathway include energy saving at treatment plants and in conveyance systems, energy reduction and recovery in the home, electricity production from water conveyance systems, heat production from wastewater conveyance systems, energy generation from wastewater sludge and use of renewable energy for water and wastewater operations.

Throughout the pathways, there are critical junctions where water, energy, or materials intersect and opportunities arise to transition to a CE. By analysing these junctions, utilities can gain insights and take actions to and create partnerships for transitioning to the CE. These junctions include (IWA, 2016):

- **Water-Wise Communities**: Engaging citizens as consumers and professionals so that they can realise their instrumental role in supporting the integration of water across sectors through their personal and professional choices and decisions
- **Industry:** As large water users, water polluters and potential customers for materials, industry can help bring CE solutions to scale
- **Wastewater Treatment Plants:** Shifting the traditional paradigm and viewing, designing and operating wastewater treatment plants as resource factories, energy generators and used water refineries

- **Drinking Water Treatment Plants:** Promoting circularity through designing plants to operate more efficiently, treating water from multiple sources to produce different water quality for different purposes and keeping production costs low
- **Agriculture:** Being the largest water user and a significant water polluter, the agricultural sector is a vital partner to support a CE through creating business opportunities as well as improved efficiencies and value-added, competitive products and services
- **Natural Environment:** Increased understanding of the natural environment's value as a provider of water services and unlocking its significant potential in providing treatment, storage, buffer and recreational solutions will give rise to multiple benefits and cost-savings
- **Energy Generation:** Co-operating with the energy sector to create energy independence using less carbon-based energy and contributing renewable energy to the grid

The main factors that drive and enable the transition of the water sector to a circular economy are consumers, industry, regulation, infrastructure and urban and basin economies (IWA, 2016). Water utilities need to anticipate, respond to and influence these factors to accelerate the pathways to achieving a circular economy. The challenge for utilities is to shift these factors from traditionally enabling a conventional linear economy model to a circular economy model. In transitioning to a circular economy, water utilities also need to change their current way of operation and seek new management approaches, partnerships and business opportunities.

2.2.2 Challenges and Barriers in the Water Sector

Similar to other sectors, the benefits of transitioning to a CE in the water sector have been shown both through theoretical models and practical experience in those areas where partial circularity has been achieved (e.g. energy generation, wastewater effluent reuse). However, full transition still faces significant challenges and barriers, particularly in the application of WWTPs as bio-refineries at the centre of that transition and subsequent recovery and reuse of associated by-products. The most significant barriers that have been identified include:

- **Regulation**: Lack of laws and regulation to facilitate transition to a CE such as setting appropriate environmental standards for the use of recycled products, specifying health regulations related to the reuse and recycling of products, regulation on recovered product categorisation (as 'waste' or a 'resource') and certification, limiting disposal of wastewater solids to landfills and encouraging investment and innovation in reuse and recycle industry. Absence of integrated policies and existing legislative barriers have been identified as significant barriers to the development of wastewater biorefineries
- **Economics:** The cost of reuse of wastewater is not economically competitive due to water pricing policy (Hislop and Hill, 2011; Greyson, 2007). In most jurisdictions, water is priced very cheaply for political reasons to induce sustainable use in the long run (European Commission, 2014). The water market price or value should reflect not only internal costs, but also external costs

(externalities), including those of an economic, social, or environmental nature (Abu-Ghunmi et al., 2016). In the absence of supportive policies and if prices do not reflect the true economic costs of products, barriers to implementing a circular economy will persist (European Commission, 2014). Thus, it is recommended that with the emphasis on the importance of investment by the private sector, the wastewater treatment sector needs to also adopt a full-cost recovery model that charges users of the reclaimed water a price that covers the full cost incurred in wastewater treatment (CCME, 2006).

- **Public Perception:** Public Perception (or contaminated interaction) regarding resources recovered from wastewater and wastewater re-use is a significant barrier that needs to be thoroughly investigated and understood to enhance market value of recovered water and materials.
- **Technology:** The full-scale implementation of innovative recovery technologies is still limited. The impacts of emerging technologies for most wastewater products recovery have not yet been completely assessed in terms of sustainability and economics and in many cases, the technology readiness level (TRL) is still below 5 (Puyol et al., 2016).

Research and studies indicate that to overcome these barriers, widespread full-scale implementation of circular solutions for wastewater requires a standardized approach to evaluate fit-for-purpose developing technologies addressing environmental, cost, social (i.e. contaminated interaction), market and political aspects (e.g. policy favouring GHG reduction over resource recovery), as well as legislative barriers. Financial instruments, incentives and adequate regulatory mechanisms are also required to support public and private engagement in CE pathways.

2.3 South African Progress in Circular Economy in the Water Sector

While the global community has taken some steps in promoting a CE, the South African water sector has not laid out concrete strategies or policies to transition to a full CE. However, projects that promote some aspects of CE have been implemented, particularly in the areas of generation of biogas from sludge, use of sludge for agricultural purposes and on a small-scale reuse of wastewater effluent. In addition, research on processes and technologies that contribute to the interrelated pathways for transitioning to the CE as well as associated barriers and challenges is being promoted, mostly by the WRC. Research into the challenges and barriers has mostly been around the reuse of wastewater by-products. A summary of this research is discussed below.

2.3.1 Public Perceptions towards Wastewater Reuse

Direct Potable Reuse

The reuse of wastewater for potable use is an effective solution to water scarcity and is a key aspect of the water pathway to a CE. This concept has been effectively implemented within recent years in countries such as Namibia and Singapore. Public perceptions of the reuse of wastewater for potable use are a significant obstacle to the implementation of this strategy. It is thus important to understand the factors that influence these perceptions to successfully introduce and implement the potable reuse of wastewater.

The most comprehensive study on public perceptions on direct potable reuse of reclaimed water in South Africa was conducted by Muanda et al. (2017). The study focused on the social and institutional factors that could influence the public's perspectives on the reuse of wastewater for direct potable use in South Africa. Regulations governing the use of reclaimed water were also reviewed. Economic issues were incorporated in the social and institutional issues and were limited to the costs associated with water reclamation and the impact of tariffs.

Overstrand, Beaufort West and eThekwini municipalities were used as case studies areas for the research. The municipalities were at various stages of the implementation of potable use of reclaimed water projects. eThekwini was just before implementation stage, Overstrand was at an advanced planning stage and Beaufort West Municipality had already implemented water reclamation and was monitoring water quality and supplying to the public. Drought, decreasing rainfall, unavailability of other water sources as well as population and economic growth were the main drivers for the reclaimed water projects. The municipalities were seeking alternative viable and cost-effective options to ensure a continuous water supply to the public.

The study found common factors that influenced the public's perception of direct potable use of reclaimed water. The factors were disgust (or "yuck" factor), safety, water use, choice, trust in municipal services, equity, cost, socio-demographic/cultural, benefits/necessity, public consultation and the media. The impact of these factors was categorised as negative or positive according to how they influenced public perception of direct potable use of reclaimed water (Table 2-2). The study revealed that these factors were linked to three overarching themes: knowledge, emotions and social capital. Based on these themes, it was concluded that public resistance is largely the result of knowledge deficit pertaining to the introduction of water reclamation. The knowledge deficit is due to inadequate engagement between the public and the municipalities.

Muanda et al., (2017) also found that different factors would be increasingly relevant at different stages of the institutional process. Different emotions at different stages in the institutional process would also influence the public's perception of direct potable reuse of reclaimed water. The processes and associated emotions are as follows:

- **Planning:** The public felt as though they had no choice but to accept reclaimed water given the water scarcity they were experiencing. This was seen in Overstrand and Beaufort West municipalities where the water scarcity was highly visible. However, rejection is also possible in cases such as eThekwini, where water scarcity was not being experienced.

- **Reconciliation Study:** The municipalities' failure to adequately engage with the public created an information deficit. This led to indifference from the public as well as doubt and mistrust in the water service providers since the public did not know or understand the purpose of the reconciliation study. The public also did not have access to the results of the study.
- **Feasibility Study:** Fear and doubt were emotions that could be triggered by a lack of knowledge during the feasibility study. A lack of awareness about the treatment of the wastewater and the safety of the water could lead to rejection.
- **Reuse Decision:** The main factors that could impact public perception were equity, disgust, media, culture/religion and choice. Lack of public engagement could contribute to the public's rejection of reclaimed wastewater as they would feel ignored.
- **Implementation:** Emotions such as doubt and fear were due to concerns over the water quality. Some respondents were also worried that lower income people would be forced to accept reclaimed water while wealthier people would be able to purchase bottled water.
- **Post-implementation:** Safety was a significant concern. The public did not trust the water as there was inadequate engagement with them, creating a knowledge deficit around the topic.

Based on the data, Muanda et al., (2017) concluded that the public's decision to reject, resist or accept water reclamation was directly related to their knowledge at different stages of the institutional process. A lack of knowledge and poor public engagement would lead to negative public perceptions while trust increased with more information. The collated data was summarised and placed on an acceptance continuum to provide ways for municipalities to address negative perceptions.
(Table 2-1 and Figure 2-4).

Table 2-1: Summary of Prevalent Emotions Accompanying the Institutional Process Across the Case Studies (Muanda et al., 2017)

Stage of Institutional Process	Emotions Prevalent at Different Stages
1. Planning (water Scarcity)	**Denial or doubt** Lack of choice, fear, stress, confusion
2. Risk Management	**Mistrust, doubts** Stress, confusion
3. Reconciliation Study	**Doubt** Not being considered, mistrust
4. Feasibility Study	**Mistrust** Neglect, doubt, fear
5. Reuse decision	**Fear** Anger, unfairness, disgust, imposition
6. Implementation	**Safety concerns** Fear, lack of consideration
7. Post-implementation	**Trust** Doubt, fear and worry

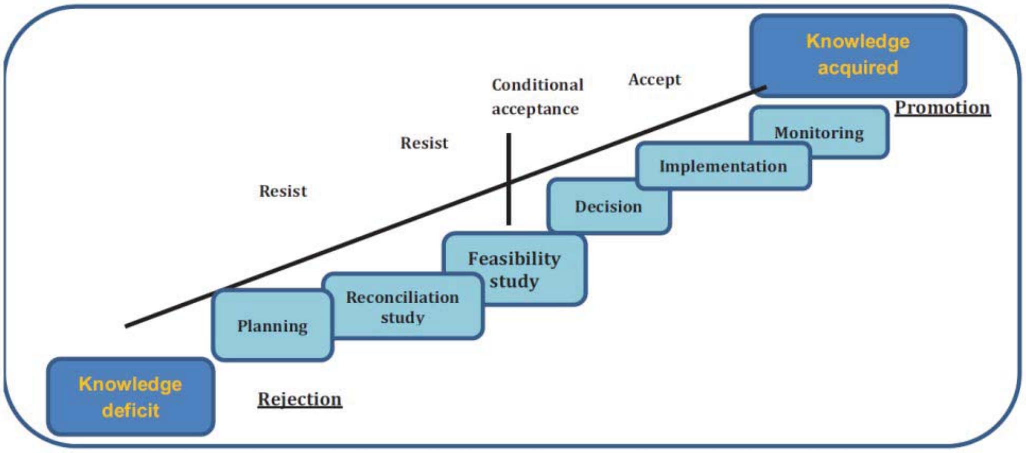


Figure 2-4: A Continuum of Acceptance Aligned with the Institutional Process (Muanda et al., 2017)

Table 2-2: Overview of Factors Influencing Public Perceptions and Related Indicators (Muanda et al., 2017)

Level	Public Perception Factors	Positive Indicators	Negative Indicators
Institutional	Media sensation	Information sharing and transparency Use of appropriate language/terms Educating media professionals	Lack of access to or delaying information Unbalanced information (media report/use of inappropriate language)
	Public consultation	Public consultation at an early stage Consensual decision making Seeking public and political buy-in	Lack of or inadequate consultation Public concerns not adequately addressed Lack of or inefficient communication Equity issues not adequately addressed
	Political halt	Political support	Lack of knowledge by political representative (lack of support) False promises (to find feasible alternative)
Economic	Cost	Lower tariffs No change in tariffs Balancing water tariffs (treatment technology)	Cost associated with health issues may be higher than actual cost of recycled water Increasing water tariffs Lack of communication (about cost)
Social	Disgust		Water quality (reference to wastewater effluent-smell) Health concerns from drinking reclaimed water Fear of drinking water of substandard quality
	Equity	Equitable service provision coverage	Disparity in service provision coverage
	Safety	Knowledge of water treatment Proven evidence of safety (no risks associated) Knowledge & assurance of water quality Communication & awareness Assurance of plant monitoring	Fear of risks over time Long-term health risks Poor water quality Lack of safety awareness
	Trust in municipal services	Confidence in municipal services There is adequate planning	Lack of consultation Low involvement in municipal affairs Unknown capacity of municipal staff
	Choice	Visible signs of scarcity Minimizing cost Water conservation	Unilateral decision at municipal level Lack of knowledge of optional water sources Unable to afford to buy water Lack of information sharing
	Benefits	Water security (continuous water supply) No water restrictions Access to water Reduced water tariffs (costs and safety benefits) Employment	Poor water quality No exhaustion of other options
	Socio-demographic/cultural	Conservationist attitude on the part of the youth	Unsuitability of water for infant (age) Poor water quality for spiritual purposes

The research by Muanda et al. (2017) suggests that water users in South Africa are not comfortable with drinking water from wastewater reclamation. The main reasons provided were repugnance, characterised in terms of the disgust (“yuck”) factor and suspicion of health risks. Other contributing factors included a lack of trust in the municipality’s capacity to produce drinking water that met quality standards from treated effluent as well as ignorance of the water cycle, water scarcity issues, water treatment technologies and scientifically proven processes and the significance of water quality standards. Public resistance that appeared to be caused mainly by lack of knowledge was apparent, indicating that social issues pertaining to water reclamation are due to institutional failures in knowledge sharing. The study concluded that identifying and addressing these social issues may improve the level of confidence in, and hence acceptance of direct potable use of reclaimed wastewater.

The findings by Muanda et al. (2017) are not unique to South Africa and are supported by findings from other countries where reclaimed wastewater schemes have been considered or have been successfully implemented for a long time (e.g. Australia, Singapore, Namibia, New Mexico).

Reuse in Agriculture

The agricultural sector, being the largest water user – is also the main potential user of reclaimed wastewater and has been identified as one of the key junctions in the water pathway to achieving CE. This means that understanding public perceptions on reusing reclaimed wastewater for agricultural purposes is important as it impacts the decision-making process by municipalities in water reuse projects as well as CE policies and strategies. The most recent study in this area in South Africa was conducted by Saldías et al. (2016).

Saldías et al. (2016) explored the response of farmers to wastewater reuse for agriculture in South Africa. The research was focused on the Western Cape’s hinterlands where the farmers irrigated grapes, fruit and vegetables. The main findings of the study were the following:

- Farmers had a positive perception of water reuse for irrigation, mainly because they are aware of the problem of water scarcity in the area. Thus, water reuse might not be a choice but the only option they have
- This positive perception, despite water scarcity, was based on the condition that the water supplied was of good quality. The data also indicated that the concern for good quality water was not because the farmers considered irrigation with treated effluent a threat to the health of farmers and workers or consumers but was apparently because agriculture in the area is export oriented.
- Farmers who already used reclaimed wastewater preferred a privately managed scheme over a public scheme due to lack of trust in the public authorities to provide safely treated effluent. In addition, the farmers also preferred options with low levels of regulatory restrictions on usage practices provided that high quality water was guaranteed

The findings by Saldías et al. (2016) regarding trust in the authorities to provide safely treated effluent has already been identified as a fundamental issue in determining public acceptance of water reuse in previous studies in South Africa of Adewumi et al. (2010) and studies conducted in other regions (Po et al., 2005). One of the key findings from Saldías et al. (2016) was that in addition to their primary function of protecting public health and allowing for safe reuse of water, regulations and guidelines should also consider the local cultural and socioeconomic conditions in order to enable the adoption of wastewater reuse for agricultural purposes.

2.3.2 Frameworks to Improve Public Acceptance of Wastewater Reuse

Following on their findings on public perceptions on direct potable water reuse, Muanda et al. (2017) evaluated factors that could influence public perceptions regarding wastewater and to identify sustainable solutions which could be used to foster a positive attitude towards wastewater reclamation. The study showed that the public was more likely to reject the direct potable use of reclaimed wastewater if there was a greater knowledge deficit and poorer public engagement. The more knowledge the public had and the better the public engagement, the greater the possibility of acceptance. The authors intended for the continuum of acceptance to show that the effects of the factors were moving between promotion and rejection as opposed to being static. After analysing the data, the authors suggested the following procedures for addressing negative public perceptions at each stage of the institutional process:

- Identify prevailing negative perceptions and related emotions
- Identify the knowledge required, according to the key issues pertaining to the stage in the institutional processes
- Identify or develop a medium for knowledge sharing
- Identify public engagement methods suited to the knowledge requirements of the stage in the institutional process
- Identify or develop a medium for public engagement appropriate to the stage.

A summary of a generic guidance on what actions municipalities in South Africa, facing similar context as the case study municipalities, can take and use to shift public perceptions is given in Appendix A.

2.3.3 Public Perceptions towards Wastewater and Biosolids Reuse

No significant research has been undertaken to gauge public perception towards biosolids reuse in South Africa. Research that was carried out in other countries that could inform perceptions in South Africa is summarised below.

Research by Muanda in 2003 which focused on public perceptions of the reuse of reclaimed wastewater and biosolids in Knoxville, Tennessee indicated that public perceptions were influenced by previous ill management of wastewater and biosolids as well as the source of the biosolids and wastewater.

Demographics, trust, cost, knowledge, environmental concerns and health concerns also had an impact on public perceptions. Respondents were also intensely opposed to the reuse of wastewater for drinking purposes and it was observed that with an increase in contact or ingestion, acceptance of reclaimed wastewater decreased. On the other hand, towards the reuse of biosolids was very positive. Ma (2003) also found that the correlation between knowledge and perceptions surrounding wastewater and biosolids reuse was a positive one. This meant that more knowledge of the topic would likely lead to an increase in support for reuse schemes.

A WERF study (Beecher et al., 2004) explored public attitudes towards the reuse of biosolids. The study looked at different case studies in which attempts to implement biosolids recycling had either failed or succeeded and tried to identify the factors contributing to each outcome. B Beecher et al.'s report focused on metropolitan areas within the United States of America (2004). Some of the metropolitan areas explored and the factors leading to an outcome were as follows:

- King County, WA: Biosolids from the county were used in forestry and agriculture projects. The public was concerned and uncomfortable with the thought that urban residents were dumping their waste in rural areas. Concerns over whether wind would blow the biosolids from the fields as well as concerns surrounding toxicity afflicted the respondents within the area where biosolids were being reused. The recycling of biosolids was ultimately successful in King County because of the county adjusting its public engagement strategy and collaborating with farmers and spokespeople in order to improve the relationship between the public and the county (Beecher et al., 2004).
- Milwaukee, WI: The biosolids from Milwaukee after heat treatment are used as an organic fertiliser and marketed as "Milorganite". Public acceptance was not a hindrance in this case study due to effective marketing of the product. The effectiveness of this marketing was rooted in a consumer-oriented model; the goal is to make the consumer comfortable with the product.
- Montgomery County, MD: Sludge from Washington was being sent to the Montgomery County Regional Facility. The public was resistant to this project. Odour control at the facility was poorly managed and public concern was exacerbated by the fungus Aspergillus Fumigatus. After fifteen years the site was shut down as residents had managed to garner enough political influence within the county. The closure of the site was attributed to poor public engagement throughout the development and implementation process, a shifting community and an inappropriate location of the composting facility.
- Everett, WA: A site where biosolids application for forestry could take place was identified by Seattle Metro and The City of Everett. This property was owned by the Tulalip tribe. The government understood the importance of public engagement and organised a door-to-door campaign designed to inform residents. However, too little time was allocated for this task and many neighbourhoods went uninformed. As a result, there was organised opposition to the

project. City staff were not willing to communicate with the residents as they were poorly informed on the processes involved in the biosolids project. The tribe also viewed this intended use of biosolids as a social issue with the white man unloading his waste on the Native Americans. Although the site was ideal for the recycling facility, poor staff training, failure to timely address public concerns as well as disregard for some political and social factors ultimately led to the rejection and failure of the project.

2.3.4 Summary

Since wastewater products reuse is at the canter of transitioning to a CE using the model proposed in this project based on the IWA framework, additional research is required on key barriers to wastewater products reuse in South Africa. While significant research has been undertaken on use of reclaimed wastewater, more research is still required on the use of biosolids and biosolids related by-products.

CHAPTER 3. CO-PROCESSING OF SLUDGE AND OTHER BIOMASS IN THE EHTP TECHNOLOGY

3.1 Technology Fundamentals

The EHTP process is a catalysed, wet, sub-critical water thermo-chemical conversion process that processes biomass to produce a solid hydrochar. The process is similar to hydrothermal carbonization (HTC) except catalysts are selected to reduce decarboxylation reactions and reduce carbon dioxide (CO_2) evolution. Thus, the process has been coined enhanced hydrothermal polymerization (EHTP). The process takes place in a sealed anaerobic tank that is heated to temperatures between 180-240°C for a reaction time of 1-2 hours, depending on feedstock type and required product quality. At this temperature range, the generated autogenous pressure is less than 4 MPa. Under these conditions, most organics remain as they are or are converted to liquid (~15% of solid feedstock). The amount of gas produced is relatively small (~5% of solid feedstock) and low in CO_2 with no methane (CH_4) generated. Thus, the process has minimal greenhouse gas (GHG) effects. A schematic representation of the process is given in Figure 3-1.

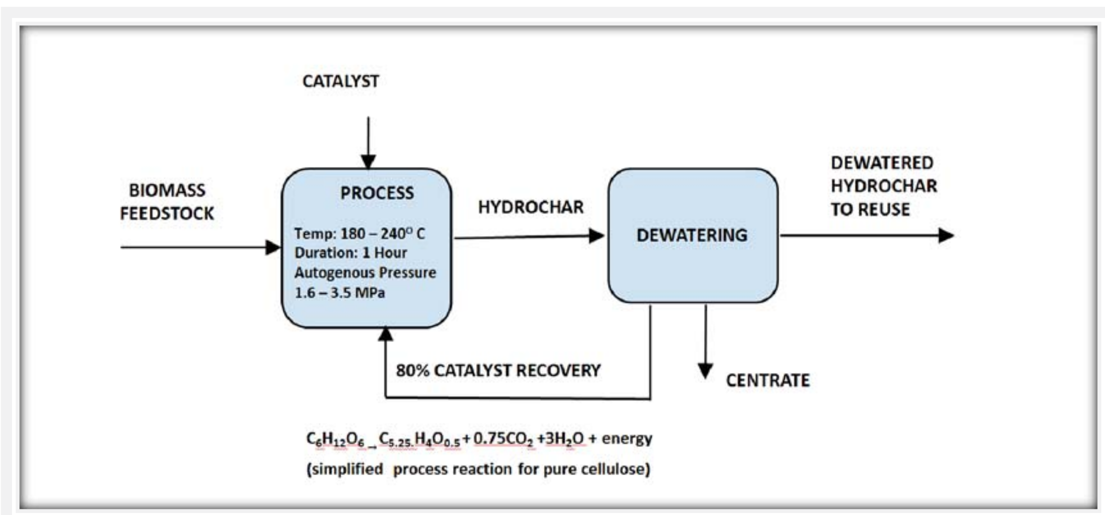


Figure 3-1: Schematic Representation of the EHTP Process

The EHTP technology has previously been tested at laboratory and pilot scale in South Africa when processing wastewater solids only as well as wastewater solids in combination with other external biomass. The testing was carried out under various WRC supported projects namely:

- *Project K5/2475//3: Energy Recovery from Wastewater Sludge – A Review of Appropriate Emerging and Established Technologies for the South African Industry.* The project tested the EHTP technology at laboratory and pilot scale when processing various sludge types, i.e. primary sludge (PS), waste activated sludge (WAS), combined PS & WAS and anaerobically digested sludge (DS) from a biological nutrient removal (BNR) activated sludge plant. The sludge was also processed in combination with inlet works screenings. The project compared full-scale designs and performances of the EHTP technology with anaerobic digestion (conventional and advanced) and gasification.

- *Project K5/2776//3: Application of an Emerging Low Energy Technology for the Removal of Endocrine Disrupting Compounds (EDCs) from Wastewater Sludge.* The project investigated the efficiency of the EHTP technology at pilot scale, in removing selected EDCs from various sludge types generated at a BNR activated sludge plant (PS, WAS, combined PS&WAS and DS). The efficiency was compared with established sludge treatment technologies (aerobic and anaerobic digestion, composting, alkali treatment and advanced oxidation).
- *Project K5/2895//3: Evaluation & Field Testing of an Emerging Hydrothermal Polymerisation Process for Treatment of Faecal Sludge.* The project investigated application of the EHTP technology to treat faecal sludge (FS) from ventilated improved pit (VIP) toilets in KwaZulu-Natal and Gauteng. FS was processed on its own and in combination with wastewater sludge.

The results from these previous studies showed that the EHTP process treated both wastewater sludge and FS to produce a completely sterile hydrochar with no microbial life. The hydrochar had a higher calorific value than the original sludge feedstock except for pre-processed feedstock like DS. Furthermore, the EHTP process destroyed selected EDCs. Analysis of the hydrochar also showed that it has potential multiple uses such as:

- Biofuel that can be used for combined heat and power (CHP) generation at WWTPs, co-combustion with coal or other green biofuel in power stations, as a substitute for coal in pulverised coal injection (PCI) processes and domestic use as a replacement for polluting fuels like firewood, coal and kerosene
- In agriculture as a fertilizer/soil conditioner
- Building material in cement and brick making
- Adsorption media for tertiary treatment of water/wastewater effluent instead of conventional coal derived granular activated carbon (GAC).

Previous studies, therefore, demonstrated that the EHTP process is a feasible sludge treatment technology that can be applied as a substitute to conventional sludge treatment processes like anaerobic digestion. The technology not only produces a higher quality sterile multi-use hydrochar, but also destroys some emerging contaminants of concern. In this project, the EHTP technology was tested to determine if it can be applied to co-treat sludge and waste biomass at WWTPs thereby converting them to resource recovery centres within a CE. Various waste biomass normally found in municipal communities (food waste, organic municipal solid waste, wood and yard waste, paper waste) were co-processed with wastewater sludge. Sludge in combination with FS from ventilated improved pit (VIP) toilets was also processed. The various applications for the hydrochar were investigated. The 60-litre EHTP pilot scale batch reactor that was used in previous studies was also used for this project.

3.2 Approach and Methodology

3.2.1 Pilot Plant Location

The EHTP pilot scale reactor was located at the Municipality 1's wastewater treatment Plant A, a biological nutrient removal (BNR) activated sludge plant. Combined PS and WAS from the plant was processed on its own and co-processed with FS from VIP toilets and waste biomass from the community. Other industrial waste was.

3.3 Feedstock Sources

The feedstock that was processed in the EHTP reactor is given in Table 3-1. The proportion of biomass in each feedstock was chosen on a theoretical basis and does not reflect the available biomass in the community relative to the sludge.

Table 3-1: Feedstock Processed in EHTP Pilot Reactor

Biomass Type		Volumetric Proportions	Comments
Sludge Only			
a)	PS & WAS	50%: 50%	Thickened PS and WAS and dewatered DS from Plant A
b)	Digested Sludge (DS)		
Sludge with Screenings			
a)	PS&WAS + screenings	70%:30%	Thickened PS and WAS and dewatered DS from and screenings from Plant A
b)	DS and screenings	60%:30%	
Household and Food Waste			
a)	Food waste on its own		Food Waste from local households and restaurants. Paper waste from local offices
b)	PS&WAS + Screenings + Food waste	50%:25%: 25%	
c)	DS + Screenings + Food waste	50%:25%: 25%	
d)	PS&WAS + Screenings + Paper	50%:25%: 25%	
a)	DS + Screenings + Paper	50%:25%: 25%	
b)	PS&WAS/Screenings + Food waste + Paper	50%:25%: 25%	
c)	DS + Screenings + Food waste + Paper	45%:15%: 20%:20%	
Woody Waste			
a)	Woodchips		Woodchips from a local timber company Yard waste from a local gardening service.
b)	Yard waste only		
c)	DS/Screenings + yard waste	50%:25%: 25%	
Low-Cost Sanitation Faecal Sludge			
a)	Area (A) FS		VIP toilets in Municipality 1, (Area (A) informal settlement) and Municipality 2 (stockpile at Area B).
b)	Area (A) FS + PS&WAS	50% :50%	
c)	Area B Fine and Coarse Screened FS		
d)	Area B Fine and Coarse Screened FS + PS&WAS	50% :50%	

3.3.1 EHTP Pilot Plant Experimental Procedure

The reactor is designed to be heated by an inbuilt electrical element and is equipped with a feedstock input valve, product output valve as well as various pressure relief and safety valves. Two temperature sensors monitor the temperature of the heating element as well as the contents inside the reactor. Reactor pressure was monitored by a pressure gauge. An energy meter was also connected to the reactor to monitor the energy used per batch experiment.

Prior to adding the sludge feedstock to the reactor, the sample volume, mass, total suspended solids (TSS) and pH were measured. A portion of the feedstock sample was retained and about 5 ml of dilute hydrochloric acid was added to the sample to stop biological activity. The retained sample was stored in the refrigerator at 3^{o}C prior to laboratory analysis. A catalyst solution was then added to the feedstock sample and the volume of catalyst as well as mass and volume of the feedstock sample (including catalyst) were recorded. The feedstock sample was fed into the reactor which was then sealed and purged with nitrogen gas prior to heating the contents to the selected reaction temperature.

The reaction temperature was held constant for 1 hour, after which the heating was turned off and the reactor was cooled to room temperature. The product (hydrochar and supernatant) was discharged into a container and allowed to settle. The mass, volume, TSS and pH of the product were recorded. After settling, a portion of the supernatant was stored in a container in the refrigerator at 3^{o}C prior to laboratory analysis. The remainder of the supernatant was decanted and discarded leaving wet hydrochar. A portion of the wet hydrochar was stored in a container in the refrigerator prior to laboratory analysis. The remainder of the hydrochar was sun-dried. A portion of the sundried feedstock and hydrochar were also sent to the laboratory for analysis. It should be noted that the product settled quickly thus it was not necessary to use the manual sieves that were available for dewatering. In a full-scale plant, the product can therefore be easily dewatered using screens without any polyelectrolyte requirements as is required in dewatering anaerobically digested sludge.

The volume of the feedstock was 40 litres in the proportions indicated in Table 3-1 and the average operating temperature for all batches was 195 ± 3^{o}C, generating an autogenous pressure of 3.4±2 MPa.

The following analysis was conducted on the feedstock and hydrochar samples:

- Proximate analysis using a Mettler TGA/DSCI following the modified ASTM E1131 method for coal.
- Elemental analysis for metals using Microwave Plasma-Atomic Emission Spectrometer (MP-AES). Elemental carbon (C), nitrogen (N), oxygen (O), sulphur (S) were also determined for some samples
- Gross calorific value measured in an oxygen bomb calorimeter as per ASTM D5865
- Microbiological (E. coli and helminth ova) analysis using standard methods for the examination of water and wastewater (APHA, 2017) was also conducted on Area (A) FS feedstock, hydrochar and process supernatant. Of all the feedstock, Area (A) FS was fresh and contained the highest concentration of pathogens and was therefore selected for microbiological analysis.

3.4 Results and Discussion

3.4.1 Proximate Analysis

Baseline Sludge Only and Sludge with Screenings Feedstock

Table 3-2 gives the proximate analysis results for sludge feedstock, sludge with screenings feedstock and produced hydrochar. Graphical representation of the results is given in Figure 3-2.

Table 3-2: Proximate Analysis Results for Sludge only, Sludge with Screenings and Hydrochar

Parameter (% Dry Basis)	PS & WAS		PS & WAS + Screenings		DS		DS + Screenings	
	Feedstock	Hydrochar	Feedstock	Hydrochar	Feedstock	Hydrochar	Feedstock	Hydrochar
Volatile solids	73.0	58.2	81.8	68.5	60.7	44.4	75.4	70.2
Fixed Carbon	8.7	11.7	7.2	22.5	9.7	11.7	13.5	16.5
Ash	18.3	30.2	8.8	11.1	29.6	44.1	11.1	13.4
% TS reduction		39.3		20.5		32.9		17.2
% VS Reduction		51.7		33.4		51.0		23.0

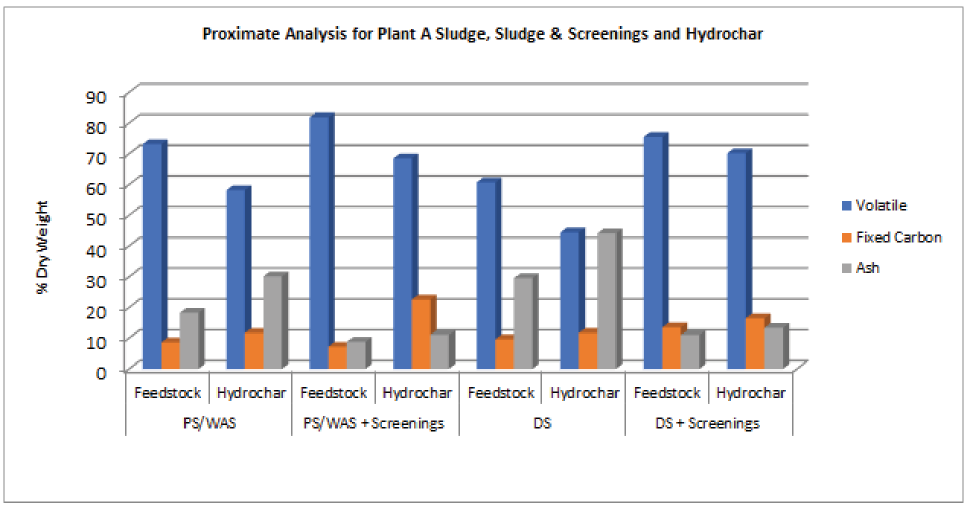


Figure 3-2: Proximate Analysis Results for Baseline Sludge only, Sludge with Screenings and Hydrochar

Hydrochar from all feedstocks had lower volatile content than the feedstock. The volatile solids (VS) reduction when processing sludge only was closely similar for both PS&WAS and DS. The total solids (TS) reduction was slightly higher for PS&WAS (39%) than for DS (33%). The VS and TS reduction decreased with the addition of screenings to the sludge feedstock. The ash content for the hydrochar was higher than the feedstock with the highest in hydrochar from DS (44%). The fixed carbon (FC) content was also higher in the hydrochar than the feedstock for all feedstocks.

The results are similar to the findings in the previous study under Project K5/2475//3.

Wastewater Sludge Combined with Faecal Sludge

Detailed results of the proximate analysis for combined PS&WAS and FS feedstock and hydrochar are given in Appendix A. The graphical representation is given in Figure 3-3. Similar to sludge only, the EHTP process reduced the VS and TS. Thus, hydrochar from all feedstocks had lower volatile content. The VS and TS reduction was highest for Area (A) FS, which was slightly higher than pre-processed DS hydrochar (51%). Area (A) FS had a higher volatile content because it was fresher due to biweekly desludging of VIP toilets whereas the FS from Area B had previously been stockpiled and undergone significant biodegradation. The ash and FC contents were also higher in the hydrochar. Combining FS with sludge results in feedstock with higher volatile and FC contents and lower ash content than the original FS. The TS reduction is also generally higher for combined sludge and FS feedstock.

Sludge Combined with Other Waste Biomass

Proximate analysis results for sludge in combination with other waste biomass are given in Appendix A. Graphical representation is in Figure 3-4. Similar to sludge only, the EHTP process reduced the VS and TS. The results are similar to previous results when processing sludge only and sludge combined with FS indicating (i) VS and TS destruction during processing and (ii) increase in FC and ash content in the produced hydrochar.

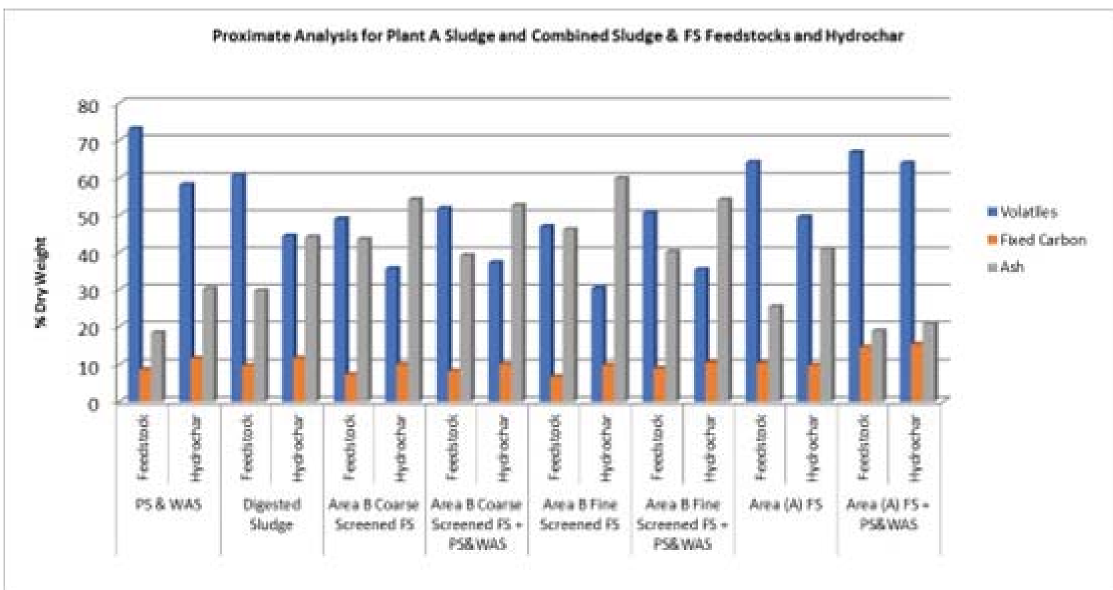


Figure 3-3: Proximate Analysis Results for Sludge, Combined Sludge & FS Feedstocks and Hydrochar

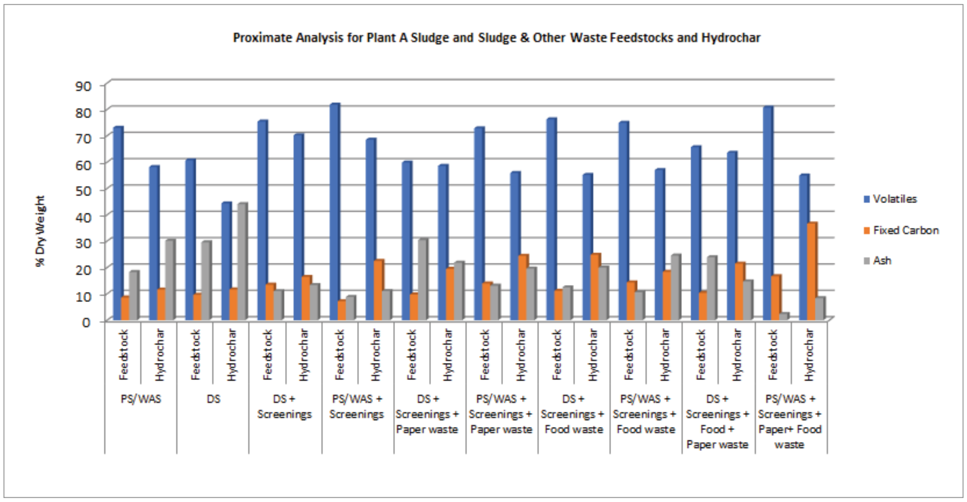


Figure 3-4: Proximate Analysis Results for Sludge and Sludge & Other Waste Feedstock and Hydrochar

3.4.2 Calorific Values

Baseline Sludge Only and Sludge with Screenings Feedstock

The calorific value analysis results for sludge only and sludge combined with screenings are given in Table 3-3 and illustrated graphically in Figure 3-5.

Table 3-3: Calorific Value (HHV) for Sludge Only and Sludge Combined with Screenings Feedstocks and Hydrochar

Sample	Feedstock (MJ/kgDS)	Hydrochar (MJ/kgDS)	% Increase/ Decrease
PS & WAS	20.3	25.4	25.1
PS/WAS + Screenings	22.3	27.6	23.9
Digested sludge	18.6	16.4	-12.0
DS + Screenings	22.0	25.0	13.7

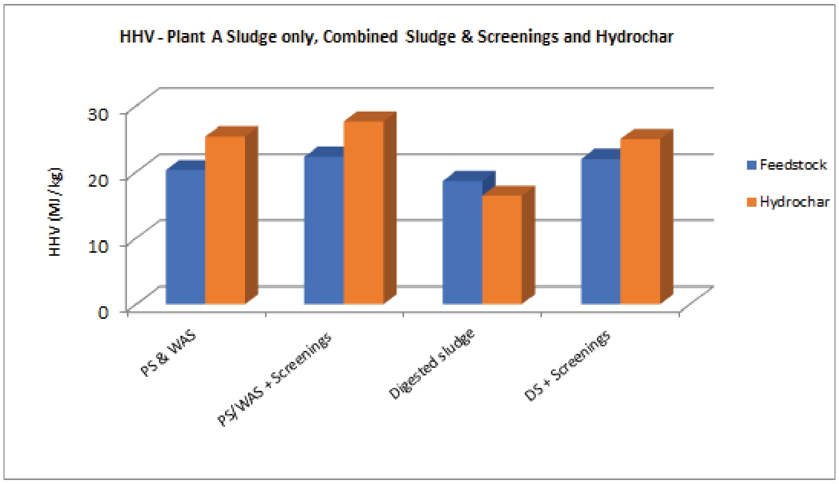


Figure 3-5: Calorific Value (HHV) for Sludge Only, Sludge Combined with Screenings Feedstocks and Hydrochar

The results confirm findings from previous studies that show that the hydrochar from the EHTP process has higher calorific value than the feedstock. However, for feedstock that has been pre-processed like DS, the hydrochar calorific value is lower. Combining sludge with screenings increases the calorific value of the feedstock due to the presence of more organics which consequently results in hydrochar with a higher calorific value. The impact of screenings is more significant for DS where, instead of a reduction in calorific value that was observed when processing DS on its own combining DS with screenings results in hydrochar with a higher calorific value.

Sludge Combined with Faecal Sludge

Calorific value results for sludge combined with FS are summarised in Table 3-4 and illustrated graphically in Figure 3-6.

Table 3-4: Calorific Value (HHV) for Sludge, FS, Combined Sludge & FS Feedstocks and Hydrochar

Sample	Feedstock (MJ/kgDS)	Hydrochar (MJ/kgDS)	%Increase/Decrease
PS & WAS	20.3	25.4	25.1
Digested sludge	18.6	16.4	-11.8
Area B Fine Screened FS	10.4	12.2	17.3
Area B Fine Screened FS + PS&WAS	11.2	12.4	10.7
Area B Coarse Screened FS	11	11.8	7.3
Area B Coarse Screened FS + PS&WAS	12.4	13.2	6.5
Area (A) FS	17.6	20.8	18.9
Area (A) FS + PS & WAS	20.4	23.4	14.7

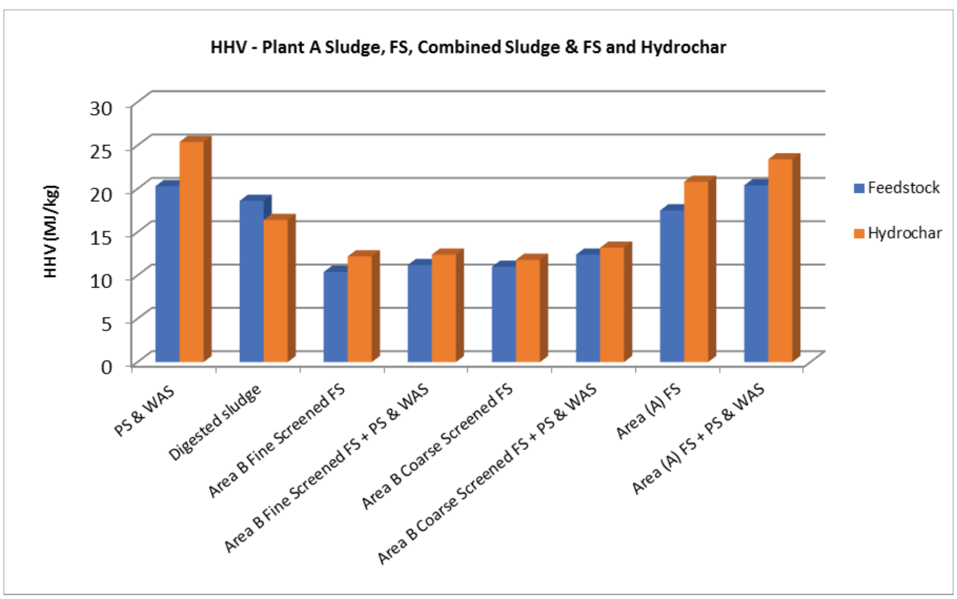


Figure 3-6: HHV Results for Plant A Sludge, Area B and Area (A) FS, Combined Sludge & FS and Hydrochar

The calorific value of the feedstock from combining PS&WAS with FS was higher than that for FS only. Consequently, the caloric value of the hydrochar was higher. This confirms results from previous studies where combining feedstock with lower calorific value (or pre-processed feedstock) with higher calorific value feedstock increases the calorific value of the produced hydrochar. It should be noted that the increase in calorific value depends on the mixing proportions of the feedstocks.

Sludge Combined with Other Waste Biomass

The calorific values for sludge combined with other waste biomass are given in Table 3-5. The graphical representation of the results is given in Figure 3-7.

Table 3-5: Calorific Value (HHV) for Sludge Combined with Other Biomass and Hydrochar

Sample	Feedstock (MJ/kgDS)	Hydrochar (MJ/kgDS)	% Increase/ Decrease
PS and WAS			
PS &WAS	20.3	25.4	25.1
PS/WAS + Screenings	22.3	27.6	23.9
PS/WAS + Screenings + Paper waste	21.4	23.2	8.3
PS/WAS + Screenings + Food waste	21.1	21.0	-0.5
PS/WAS + Screenings + Paper+ Food waste	21.2	23.6	11.3
DS	18.6	16.4	-11.8
DS + Screenings	22.0	25.0	13.7
DS + Screenings + Paper waste	14.7	21.5	46.3
DS + Screenings + Food waste	20.9	24.5	17.0
DS + Screenings + Food + Paper waste	21.2	19.8	-6.5
DS + Screenings + Yard waste	21.3	25.6	20.0

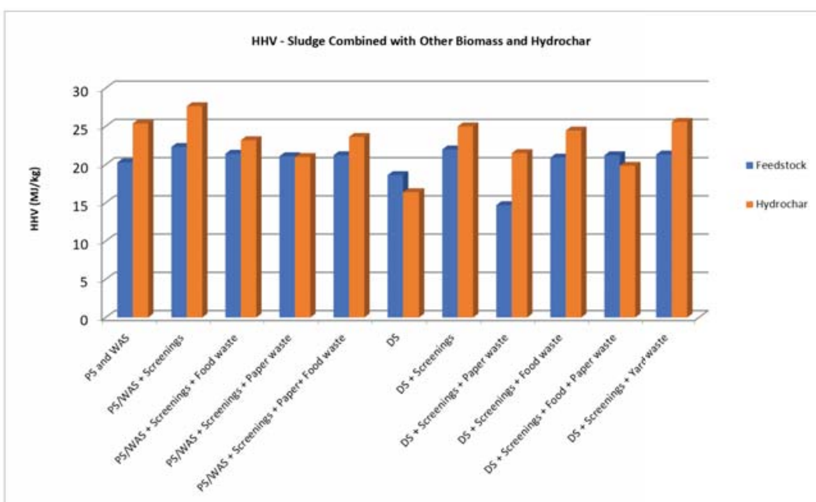


Figure 3-7: HHV Analysis Results for Sludge Combined with Other Biomass and Hydrochar

The following is noted:

- Combining sludge with other community waste biomass resulted in hydrochar with higher calorific value except for a few samples with food waste. The quality of food waste varied per batch which could have resulted in the lower calorific value in some of the samples.
- The increase in hydrochar calorific value was more significant for DS where addition of other waste increased the calorific value of the feedstock. Consequently, the hydrochar had a higher calorific value compared to hydrochar produced from processing DS on its own. Adding yard waste had the most significant impact resulting in hydrochar with a calorific value of 26 MJ/kgDS.

Calorific value Summary

The results indicate that wastewater sludge can be successfully processed in the EHTP reactor in combination with other community waste biomass to produce hydrochar with higher calorific value than the feedstock. The mix proportions impact the calorific value of the hydrochar. Waste that has undergone pre-processing and/or hydrolysis (e.g. digested sludge, some food waste, chicken manure, etc.), has been found to produce hydrochar with a lower calorific value than the feedstock. It is assumed the lower calorific value is due to changes in the kinetic pathways during the enhanced hydrothermal polymerisation process. This results in a higher loss of volatile content as well as fixed carbon. Mixing high proportions of pre-processed waste with untreated PS and WAS produced hydrochar with a lower calorific value than hydrochar from sludge only. On the other hand, mixing sludge with high proportions of unprocessed waste (e.g. wood chips, yard waste) produced hydrochar with a higher calorific value than hydrochar from sludge only. The impact of other waste is more significant on digested sludge where processing digested sludge combined with other waste results in an increase in calorific value compared to a decrease when processing digested sludge on its own. For full-scale implementation, the proportions of waste biomass will need to be optimally selected to ensure that the hydrochar produced has the highest calorific value, if the hydrochar is to be used as a biofuel.

3.4.3 CHNOS Analysis

Sludge and sludge in combination with FS and other waste biomass feedstocks and hydrochar CHONS analysis results (as well as CHNOS values found from the literature for selected solid biofuels are given in Appendix A). Hydrochar had lower O/C and H/C ratios than the feedstock. The results indicate that the EHTP process improves the fuel characteristics by reducing the O/C and H/C ratios and consequently increasing the calorific value as indicated in the calorific value results. The ratios are higher than that for coal which is considered a more efficient biofuel. CO_2 emissions from fuels depend primarily on their carbon content and their H/C ratio. The higher the H/C ratio, the higher the energy efficiency of the fuel and the lower the CO_2 emissions from its combustion. Therefore, the EHTP hydrochar when combusted as a biofuel will have less carbon emissions than coal. Further discussion on using EHTP hydrochar as a biofuel is given in Section 4.2.2.

3.4.4 Chemical and Microbiological Analysis

Microbiological Analysis

Since fresh Area (A) FS had the most pathogens, microbiological analysis was conducted only on Area (A) FS and the produced hydrochar. The pathogen content of the solid hydrochar is compared to the pathogen limits in ISO 30500:2018 (non-sewered sanitation systems – Prefabricated integrated treatment units – General safety and performance requirements for design and testing) as shown in Table 3-6.

Table 3-6: Microbiological Analysis Results for Area (A) FS and Hydrochar Compared to the ISO 31800:2018 Limits

Parameter	Area B Coarse Screened FS		Area (A) FS		ISO 30500: 2018 Limits
	Feedstock	Hydrochar	Feedstock	Hydrochar	
Helminth Ova (count/dry gram)	151	0			<1
Human enteric Helminths (eggs/ml)					
Ascaris infertile			1	0	<1
Ascaris dead			5.5	0	<1
Ascaris with immotile larva			1.5	0	<1
Ascaris eggs undeveloped			8.5	0	<1
Taenia: potentially viable			0.5	0	<1

The impact of process temperature on coliform bacteria was also investigated and the results are given in Table 3-7.

Table 3-7: Microbiological Analysis Results Area (A) FS and Hydrochar

Parameter	Units	Area (A) FS 160°C		Area (A) FS 180°C		Area (A) FS 195°C	
		Feedstock	Hydrochar	Feedstock	Hydrochar	Feedstock	Hydrochar
E. coli	colonies/100ml	1,125	0	2,420	0	62,000	0
Total Coliform	colonies/100ml	2,420	0	2,420	0		

The results indicate the following:

- The hydrochar does not contain any E. Coli or Helminth Ova confirming that the EHTP process destroys all microbial life in fresh FS that has not undergone any significant previous biodegradation
- The destruction is achieved even at the lowest applied process temperature of 160°C
- The hydrochar complies with the bacteriological limits specified in ISO 30500
- The hydrochar also meets the criteria for microbial Class A in terms of the DWS Sludge Guidelines.

Chemical Analysis

Table 3-8 gives the chemical analysis results for Area (A) and Area B feedstock and hydrochar samples.

Table 3-8: Chemical Analysis Results for Area (A) and Area B FS and Hydrochar at (195°C)

Parameter	Area (A) FS		Area B Coarse Screened FS	
	Feedstock	Hydrochar	Feedstock	Hydrochar
Chemical Oxygen Demand (Total) (mg O_2/kg)	21,467	80,000	7,951	12,692
Ammonium (mg N/kg)	2,564	6,841	598	862
Nitrate (mg N/kg)	<0.4	1.1	4.0	3.3
Nitrite (mg N/kg)	<0.1	<0.1	6.3	<0.1
Total Kjeldahl Nitrogen (% m/m)	1.9	3.4	2.3	10.0

The following is noted from the results:

- The fresher Area (A) FS had higher TCOD and ammonia than Area B FS. Area (A) FS had no nitrates/nitrites. The TKN concentration was closely similar
- The hydrochar had higher TCOD and ammonia and TKN than the feedstock for both sets of FS indicating that processing FS in the EHTP process results in carbon and nitrogen enrichment of the hydrochar.

CHAPTER 4. TECHNICAL EVALUATION OF THE EHTP TECHNOLOGY

4.1 Applications

The field tests have indicated that the EHTP technology can be applied to process sludge on its own and in combination with other waste biomass to produce a sterile hydrochar with various potential uses.

Based on the results from the field testing the EHTP technology can be applied for wastewater solids and other community waste biomass management, within a CE as follows:

- process untreated wastewater sludge or further treat pre-digested sludge at centralized WWTPs in combination with other waste biomass from the community. FS from low-cost sanitation systems can also be co-processed.
- FS from low-cost sanitation systems at a centralized facility or a facility for a few households. Application for individual households at a small scale is also feasible.

These applications are graphically illustrated in Figure 4-1 and Figure 4-2.

4.2 Technology Performance

The performance of the technology was evaluated based on compliance with regulations as well as potential disposal and beneficial use routes for wastewater solids in South Africa.

4.2.1 Compliance with Sludge Management Regulations

The original sludge feedstock and generated hydrochar were classified according to the classification given in the Department of Water and Sanitation (DWS) Guidelines for the Utilisation and Disposal of Wastewater Sludge (Snyman and Herselman, 2006 & 2009). Sludge is classified based on 3 categories:

- Microbiological content
- Stability
- Organic and inorganic pollutants

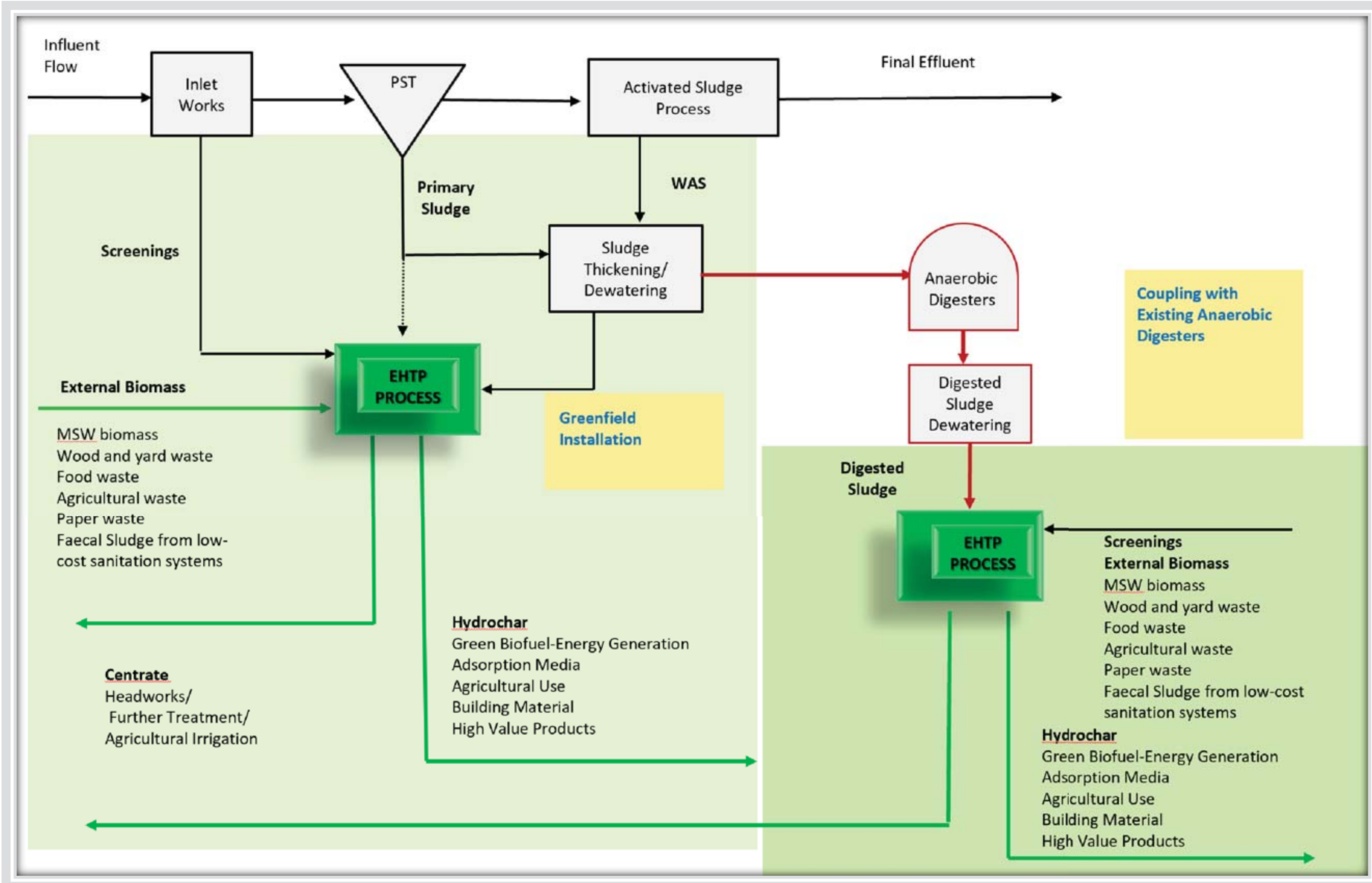


Figure 4-1: Schematic Illustration for Incorporation of the EHTP Technology at a typical Centralised WWTP to Process (a) Un-treated Primary and Waste Activated Sludge combined with External Waste Biomass and FS from Low-Cost Sanitation Systems (b) Pre-digested Sludge combined with External Waste Biomass and FS from Low-Cost Sanitation Systems

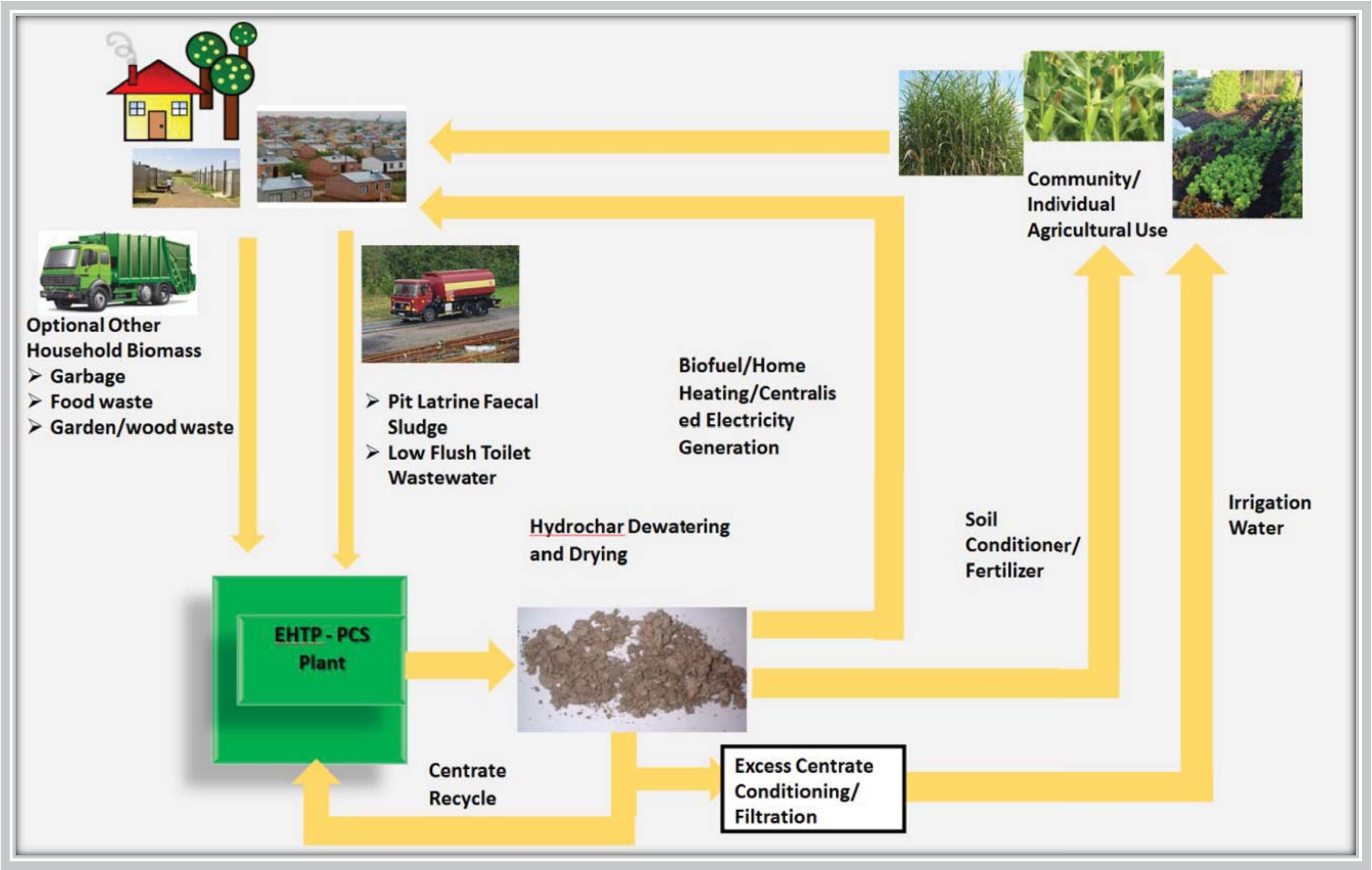


Figure 4-2: Detailed Schematic Illustration for Application of the EHTP Technology to process Faecal Sludge from low-cost sanitation system at a Centralised Facility

Microbiological Class

A summary of the microbiological content of wastewater sludge and FS feedstock and the hydrochar produced from the EHTP process are given in Table 4-1.

Table 4-1: Microbiological Content of Feedstock and EHTP Hydrochar

Parameter	E. coli (colonies/g)		Helminth Ova (count/dry gram)	
	Feedstock	Hydrochar	Feedstock	Hydrochar
Sludge from Waterval WWTP				
PS & WAS	5×10^7	0	60	0
DS	5.1×10^5	0	5	0
Faecal Sludge from VIP Latrines				
Area (A) FS[a]	6.2×10^4	0.0	0	0
Area B FS[b]	1.5×10^4	10	151	0.0

a. Samples from pit latrines emptied frequently (once a week or less)
b. Samples from stockpiled FS that has undergone significant biological degradation

A comparison of the concentrations in the feedstock and produced hydrochar with the limits in the DWS Guidelines shows that both the wastewater sludge and FS feedstock, including anaerobically digested sludge fall into Class C. The EHTP process removed all microbial life and produced a Class A hydrochar.

Stability Class

Being a thermal process, the EHTP process is designed to produce hydrochar that satisfies the stability Class 1 of the DWS Guideline.

Pollutant Class

Ultimate analysis was carried out on both feedstock and hydrochar to determine the concentration of metals stipulated in the DWS Guidelines. The ultimate analysis results generally showed an increase in the content of heavy metals in the hydrochar for all feedstock samples (i.e. wastewater sludge, FS and combined feedstock). Thus, heavy metals are generally retained in the solid product and not transferred into the liquid during the EHTP. Classification of the hydrochar in terms of the DWS Guidelines depends on the metal content of the original feedstock. For example, sludge tested from a WWTP in Gauteng under a previous project had very low metal content and is in pollutant Class a (see Table 4-2). Although the EHTP process increased the heavy metal content of the hydrochar, the metal content was still low enough for the hydrochar to be classified as Class a. This was also detected for faecal sludge where the heavy metal content is very low and the increase through the EHTP process did not result change the hydrochar pollutant class.

Inorganic pollutants specified in the DWS Guidelines were not tested because the sludge that was processed was from WWTP that processed mostly domestic wastewater.

Table 4-2: Concentration for Regulated Metals in Sludge from a WWTP in Gauteng (Musvoto et al., 2018)

	Primary Sludge			WAS			Digested Sludge		
	Feed	Product	% Increase	Feed	Product	% Increase	Feed	Product	% Increase
Compulsory Metals (mg/kg)									
Arsenic (As)	12	11	-6.7	0	20	100.0	20	0	-100.0
Cadmium (Cd)	0	0		0	0		0	0	
Chromium (Cr)	202	289	43.1	152	371	143.9	277	290	4.6
Copper (Cu)	266	427	60.5	184	495	169.2	326	398	22.1
Lead (Pb)	82	152	83.9	143	384	168.6	301	245	-18.8
Mercury (Hg)	0	0		0	0		0	0	
Nickel (Ni)	48	87	81.8	0	0		73	0	-100.0
Zinc (Zn)	2,053	2,886	40.6	1,324	3,262	146.4	2,318	3,039	31.1
Some of the Recommended Benchmark Metals (mg/kg)									
Manganese (Mn)	541	384	-29.1	898	1,445	61.0	1,069	1,225	14.6
Molybdenum (Mo)	16	23	45.6	7	17	131.0	10	19	84.8
Selenium (Se)	19	22	15.1	9	14	53.7	20	27	31.4
Strontium (Sr)	103	104	1.2	90	142	57.3	123	153	24.0
Thallium (Ti)	2,254	3,780	67.7	1,384	3,679	165.9	2,489	3,632	45.9
Vanadium (V)	84	151	80.8	44	113	154.6	87	97	12.5

Other Micropollutants

The efficiency of the EHTP process in removing endocrine disrupting compounds (EDCs) was also evaluated at both laboratory and pilot scale (WRC Project K5/2776//3). Sludge feedstock was processed in the EHTP reactor and both the feedstock and produced hydrochar and process supernatant were analysed for selected pharmaceuticals, estrogens and Per-polyfluoroalkyl substances (PFAS). The results

Process Water

The EHTP process produces a very low volume of process water. About 10-20% of the initial solids is converted to liquid. The process effluent will therefore consist of the initial water content and the liquid generated from the small portion of liquified solids. Analysis of process water has shown that it is completely sterile with no microbial life. It however contains high concentration of TCOD, TKN and P and has a low pH. At centralised WWTPs, the process water can be returned to the inlet works after pH adjustment and co-treated with the incoming wastewater.

Summary

EHTP therefore, produces hydrochar that falls in the highest microbial and stability classes. The pollutant class will depend on the quality of the original feedstock. In cases where the feedstock has low content of heavy metals, then the hydrochar from the EHTP process falls into the Class A1a; the highest class that the sludge can achieve under the DWS regulations. Thus, the hydrochar has no microbiological, stability and pollutant restrictions and therefore has a wide range of beneficial uses provided it meets the specific requirements for that use. If the process water has to be discharged into the environment or used for irrigation, then further treatment can involve pH adjustment followed by aeration to remove COD and TKN.

4.2.2 Beneficial Uses

Biofuel

The EHTP process produces hydrochar with a higher calorific value than the feedstock except in cases where the feedstock has been previously pre-processed (e.g. digested sludge, old faecal sludge). Combining pre-processed sludge with untreated sludge and/or other waste biomass (e.g. inlet works screenings, waste biomass from the community) increases the calorific value of the hydrochar. The characteristics calculated necessary to describe the energy content of both the feedstock and hydrochar are higher heating value (HHV), fuel ratio, hydrochar yield (H_y), energy densification (Ed) and energy yield (E_y). These characteristics for selected feedstock and produced hydrochar are summarised in Table 4-3.

Table 4-3: Proximate Analysis Results and Biofuel Characteristics (Processing Temperature 190-200^oC)

	Volatile (%)	Ash (%)	Fixed C (%)	HHV (MJ/kgDS)	Fuel Ratio	H_y (%)	Ed	E_y (%)
Sludge Feedstock								
PS/WAS Feedstock	68.5	17	11.6	20.3	0.17			
PS/WAS Hydrochar	68.1	19.9	14.8	25.4	0.22	62.7	1.25	78.4
PS/WAS + Screenings Feedstock	73.0	6.7	13.1	22.3	0.18			
PS/WAS + Screenings Hydrochar	78.9	14	14.5	27.6	0.18	47.9	1.24	59.3
DS Feedstock	60.7	29.6	9.7	18.6	0.16			
DS Hydrochar	44.4	44.1	11.7	16.4	0.26	64.7	0.88	57.0
DS/Screenings Feedstock	75.4	11.1	13.5	22.0	0.18			
DS/Screenings Hydrochar	70.2	13.4	16.5	25.0	0.24	60.1	1.14	68.3
Faecal Sludge Feedstock								
Area B Coarse Screened FS Feedstock	49.0	43.5	7.3	12.6	0.15			
Area B Coarse Screened FS Hydrochar	35.6	54.2	10.0	10.6	0.28	45.4	0.84	38.3
Area B Fine Screened FS Feedstock	46.9	46.1	6.7	10.8	0.14			
Area B Fine Screened FS Feedstock Hydrochar	30.3	59.9	9.8	9.2	0.32	53.9	0.86	46.2
Area B Coarse Screened FS/ PS&WAS	51.8	39.1	8.2	12.4	0.16			
Area B Coarse Screened FS/PS&WAS Hydrochar	37.2	52.6	10.1	13.2	0.27	63.1	1.07	67.3
Area B Fine Screened FS/ PS&WAS	50.6	40.1	9.0	11.2	0.18			
Area B Fine Screened FS/ PS&WAS Hydrochar	35.3	54.1	10.5	12.4	0.30	51.8	1.11	57.5
Area (A) FS	64.2	25.3	10.3	17.6	0.16			
Area (A) FS Hydrochar	49.5	40.8	9.8	13.5	0.20	72.0	0.77	55.5
Area (A) FS / PS &WAS	66.7	18.8	14.4	20.4	0.22			
Area (A) FS / PS &WAS Hydrochar	64.0	20.8	15.2	23.4	0.24	60.0	1.15	68.9

Sludge that was not pre-processed and combined sludge feedstock produced hydrochar that had higher calorific values and energy densification above 1 showing that the EHTP improves energy densification in feedstock. The fuel ratio (Fixed Carbon/Volatile Content) for hydrochar is higher than the feedstock. The ash content of the hydrochar is higher than the feedstock. However, sludge feedstock and hydrochar had lower ash content (in the range of some coals) than FS feedstocks ad hydrochar. Low ash content indicates better quality as a biofuel.

Table 4-4 summarises the elemental composition and calculated H/C and O/C ratios of the feedstock and hydrochar. The ratios decrease during the EHTP process due to dehydration and decarboxylation reactions. O/C and H/C ratios were plotted as a Van Krevelen diagram (Figure 4-3), a widely accepted method for comparing the fuel properties of coals and recently other biofuels. The highest ranked coals have the lowest H/C and O/C ratios and plot in the bottom left corner of the diagram.

Table 4-4: Elemental Analysis and H/C and O/C Ratios

Sample	Elemental Analysis (% DS)					H/C	O/C
	C	N	H	S	O		
Sludge and Faecal Sludge							
Primary Sludge Hydrochar	36.9	2.0	5.1	1.3	12.0	0.14	0.33
Primary Sludge + Screenings Hydrochar	36.2	1.7	6.6	0.7	20.9	0.18	0.58
WAS Feedstock	31.0	12.8	3.0	1.3	40.7	0.10	1.31
WAS Hydrochar	41.9	13.0	2.8	0.9	34.0	0.07	0.81
Digested sludge Feedstock	28.0	3.6	4.6	1.3	14.7	0.16	0.52
Digested Sludge Hydrochar	26.8	2.3	4.0	0.9	11.6	0.15	0.43
Composted Sludge feedstock	24.4	14.4	3.3	1.3	50.3	0.14	2.06
Composted Sludge Hydrochar	34.2	16.4	2.6	0.9	49.4	0.08	1.44
Area B Coarse Screened FS Feedstock	27.3	2.0	3.7	0.9	17.9	0.13	0.66
Area B Coarse Screened FS Hydrochar	24.9	1.7	3.0	0.7	10.3	0.12	0.41
Area B Fine Screened FS Feedstock	25.7	2.1	3.8	0.9	21.5	0.15	0.84
Area B Fine Screened FS Hydrochar	15.4	1.3	1.9	0.5	21.0	0.12	1.36
Area B Fine Screened FS + PS & WAS Feedstock	30.0	2.3	4.6	0.9	23.1	0.15	0.77
Area B Fine Screened FS + PS & WAS Hydrochar	32.4	2.0	3.9	0.7	8.3	0.12	0.26
Area B Coarse Screened FS PS & WAS Feedstock	19.2	1.6	2.9	0.6	35.6	0.15	1.85
Area B Coarse Screened FS+P & WAS Hydrochar	22.5	1.7	3.0	0.5	18.2	0.13	0.81
Area (A) FS Feedstock	39.9	3.5	5.7	0.8	18.0	0.15	0.45
Area (A) FS Hydrochar	39.6	2.3	5.6	0.5	9.7	0.14	0.24
Area (A) FS + PS & WAS Feedstock	38.5	4.9	6.0	0.7	31.1	0.16	0.81
Area (A) FS + PS & WAS Hydrochar	52.3	2.5	7.1	0.5	16.8	0.14	0.32
Other Fuels							
Wood	50.0		6.0		44	0.12	0.88
Peat	54.8	0.9	5.4	0.1	35.8	0.10	0.65
Lignite	70.0	25.0	5.0		25	0.07	0.36
Coal (Pittsburgh Seam)	75.5	1.2	5.0	3.1	4.9	0.07	0.06
Bituminous Coal	83.0	2.0	5.0		11	0.06	0.13
Anthracite	83.0	2.0	3.5		2	0.04	0.02

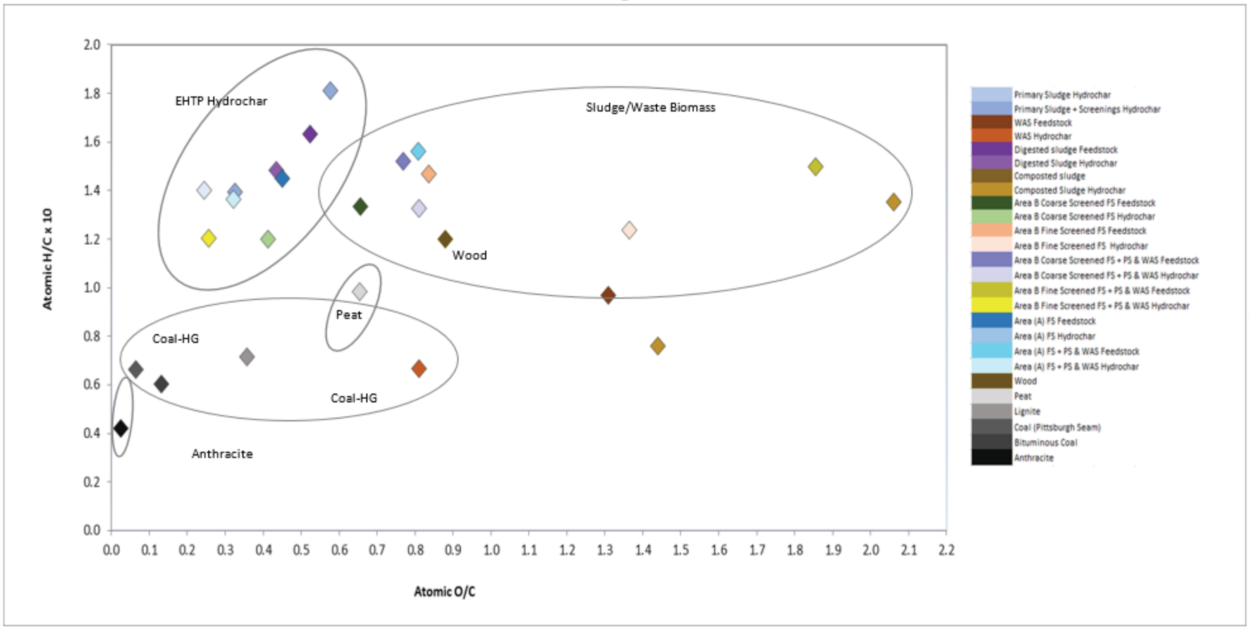


Figure 4-3: Van Krevelen Diagram for Sludge Feedstocks and Hydrochars from the EHTP Process as well as Coals and other Fuels

The EHTP process enhances the fuel properties of biomass by removing hydrogen and oxygen resulting in carbon densification in the hydrochar. The sludge feedstocks as well as combined sludge and other biomass had oxygen and hydrogen content higher than low-grade brown coal. After EHTP, hydrochar oxygen and hydrogen contents were reduced and the hydrochar O/C ratio values were between low bituminous coal and brown coal while the H/C ratios were higher than coal.

CO_2 emissions from fuels depend primarily on their carbon content and their hydrogen-carbon ratio. Over the years, the trend of fossil fuel usage tends toward a higher hydrogen to carbon (H/C) ratio. The higher the H/C ratio, the higher the energy efficiency of the fuel and the lower the CO_2 emissions from its combustion. Primitive fuel, such as wood, had twice the carbon content as compared to its successor, coal. However, coal, with a lower H/C ratio, was twice as energy efficient compared to wood. Later, coal was succeeded by oil, which had a still higher H/C ratio and thus benefited over wood and coal in having higher energy efficiency and lower CO_2 emissions. Natural gas has still lower carbon content as compared to oil. However, the ratio of carbon to hydrogen is still lower in biofuels. In fact, biofuels such as hydrogen have zero carbon to hydrogen ratios.

The results indicate that EHTP improves the fuel characteristics of sludge and other waste biomass by producing a hydrochar with lower H/C and O/C ratios and higher calorific value. The hydrochar also has a higher H/C ratio than traditional fuels such as coal and will thus have less carbon emissions when combusted as a biofuel.

It must be noted that the ash content of the hydrochar is higher than that for high grade coal and will therefore impact the combustion efficiency of the hydrochar.

Agriculture

The hydrochar produced from the EHTP process has higher concentrations of nutrients and carbon than the feedstock. Thus, the hydrochar can be used as a soil conditioner/fertiliser provided that the heavy metal concentrations do not exceed the limits in the Sludge Guidelines. A detailed investigation on the application of hydrochars generated from sludge for agricultural purposes is currently being undertaken.

Adsorption Media

Preliminary laboratory tests have shown that hydrochar produced from processing woody biomass in the EHTP process can be applied as adsorption media and has characteristics like some commercial grade activated carbon. Studies are currently being undertaken to investigate the efficacy of using hydrochar from processing sludge as adsorption media.

Other Applications

The hydrochar also has potential to be used as building material (cement and brick making), as a cathode in microbial fuel cells and as energy storage devices due to the presence of nitrogen functional groups. Further investigations on these applications will be undertaken.

4.3 Technology Design, Operation and Usability

4.3.1 Design and Operation

EHTP plants are simple to design and operate. A typical plant consists of a mixing tank, pressure reactors (designed to ASME standards or equivalent for pressure vessels) where the chemical reaction occurs and buffer tanks for storage of the end product. Heat management is a material operating expense hence the reactors are designed and operated to minimize heat wastage and ensure that the plants have a positive energy balance. Currently the reactors are designed to operate as binary batch reactors with heat transfer between the reactors thus reducing the energy requirements for processing a feedstock batch after start-up. For large operations, heating for the reactors is provided by direct steam generated from combustion of the biofuel in a boiler. Excess steam is directed to a turbine for power or combined heat and power (CHP) generation which can be used at the WWTP or in the community. Reactors for small low-cost sanitation systems can be heated by an electrical element powered by a renewable energy source (e.g. solar panel).

4.3.2 Adaptability and Scalability

The simplicity of operation of EHTP technology plants makes them adaptable and suitable for installation at existing WWTPs or Greenfields sites for processing FS and/or sludge. The actual plant design will depend on several factors such as:

- The type of feedstock to be processed (i.e. sludge, FS or combinations)
- Final use of generated hydrochar (onsite energy generation, offsite use in agriculture, building industry, etc.)
- Existing infrastructure (O&M staff and capability, heat recycling, safety, quality control)

- Degree of automation vs manual labour, particularly with respect to preparation and handling of external biomass in cases of combined processing
- External biomass preparation requirements in cases of combined processing
- Future growth capacity requirements
- Availability and cost of land.

Due to the compartmentalised nature of the binary reactor design of the plants, the plants can easily be scaled up. A plant could also be disassembled and transported to another site if required

4.3.3 Infrastructure Requirements

EHTP plants do not require any special infrastructure and can be located on any site. The site preparation is like that for WWTPs. The small footprint means that the plants do not demand large land requirements. For treatment of wastewater solids, typical upstream and downstream infrastructure is required for feedstock and hydrochar handling as follows:

- Feedstock transportation for FS and/or external biomass
- Feedstock handling building with macerators if required and odour control if necessary
- screening (coarse and fine screens) for plants treating FS from pit latrines that contain large quantities of large objects
- Pre-thickening and dewatering equipment for plants treating wastewater sludge (e.g. linear screen/belt filter press, centrifuge, screw press). Thickening is required to at least 20% dry solids (DS) to minimize the volume of the reactors and process energy requirements. Alternatively, solid external biomass can be added to thicken the sludge
- Hydrochar dewatering equipment (e.g. linear screen, drum screen)
- Hydrochar pelletisation (depending on use) and drying equipment (e.g. solar dryer, electric/waste heat dryer, drying beds)
- Power or combined heat and power generation if hydrochar is used for onsite energy generation
- Transportation for offsite hydrochar use
- Hydrochar dewatering centrate treatment for standalone plants where there is no liquid wastewater treatment infrastructure. Very little centrate is discharged since most of the centrate is recycled for catalyst recovery and simple treatment consisting of pH adjust and aeration might be required depending on end use of the centrate.

4.3.4 Technology Robustness

The process efficiency is not affected by the presence of impurities in the feedstock (e.g. sand, rags, etc.). The reactors are made of steel and durable. The technology is therefore robust and can be applied to process biomass with impurities depending on the use of hydrochar.

4.4 End User Technology Testing

The efficiency of the technology and the quality of hydrochar when processing wastewater sludge/FS can be predicted from sludge quality and then applying results from studies undertaken during technology development. Costs associated with the plant can also be estimated using results from technology development and if required, with the assistance of TruSense. It is planned that models be developed during upscaling of the technology so that they can be applied by end users to predict full-scale requirements.

4.4.1 Platform for other Initiatives

One of the main advantages of the technology is the versatility to process a wide range of waste biomass and produce a hydrochar with multiple uses. This versatility makes it a disruptive technology in both wastewater solids and general waste management creating a platform to launch the following initiatives:

- Introduce radical strategy and policy changes in both wastewater solids and general waste management through using this technology (and similar technologies) to transition to a circular economy in the water and waste sectors using wastewater treatment facilities as the loop closing bio-refineries at the core of that transition.
- Promote and stimulate employment and small business opportunities in communities particularly low-income communities through
  - sorting of municipal solid waste separating organics and cellulose-based waste that will be diverted from landfills and processed in the EHTP technology plants
  - Downstream hydrochar utilization and marketing through exploitation of the multiple potential uses

CHAPTER 5. APPROPRIATE TRL8/9 TECHNOLOGIES FOR COUPLING WITH EHTP TO PROMOTE CIRCULAR ECONOMY

5.1 Overview

To fully implement the CE framework proposed in Section 1 with WWTPs as resource recovery centres, coupling of various technologies with the EHTP technology is required to exploit opportunities within the 3 interrelated pathways (water, energy, materials). These key technologies fall into the following categories:

- Tertiary treatment of final effluent for both non-potable and potable reuse
- Alternative sludge treatment technologies with treated sludge fed to the EHTP technology
- Biomass processing technologies for further processing of hydrochar from the EHTP into high value products
- CHP generation technology

A brief review of available technologies (both established and emerging) in each pathway and how they can be coupled with the EHTP technology is given below.

5.2 Water Pathway

The contribution to the water pathway by wastewater treatment in the IWA framework is through wastewater reclamation and reuse (WRR). The reclaimed water can be reused in agriculture and industry and direct potable reuse. Tertiary treatment of final effluent is required to achieve the required quality for the intended reuse purpose and involves suspended and colloidal solids removal, removal of dissolved solids and other micro-pollutants of concern and disinfection. Non-potable reuse often requires suspended and dissolved solids removal and disinfection. Potable reuse requires advanced treatment methods. Technologies are usually applied in series to achieve the desired reused water quality.

The EHTP technology produces hydrochar that can be converted to activated carbon and used as adsorption media within the treatment processes. Figure 5-1 illustrates the potential coupling of the EHTP hydrochar activated carbon (HAC) with other tertiary treatment processes in WRR schemes within a CE. A summary of the established and emerging technologies that can be coupled with the EHTP technology for wastewater reclamation and reuse as part of the water pathway appears in Table 5-1.

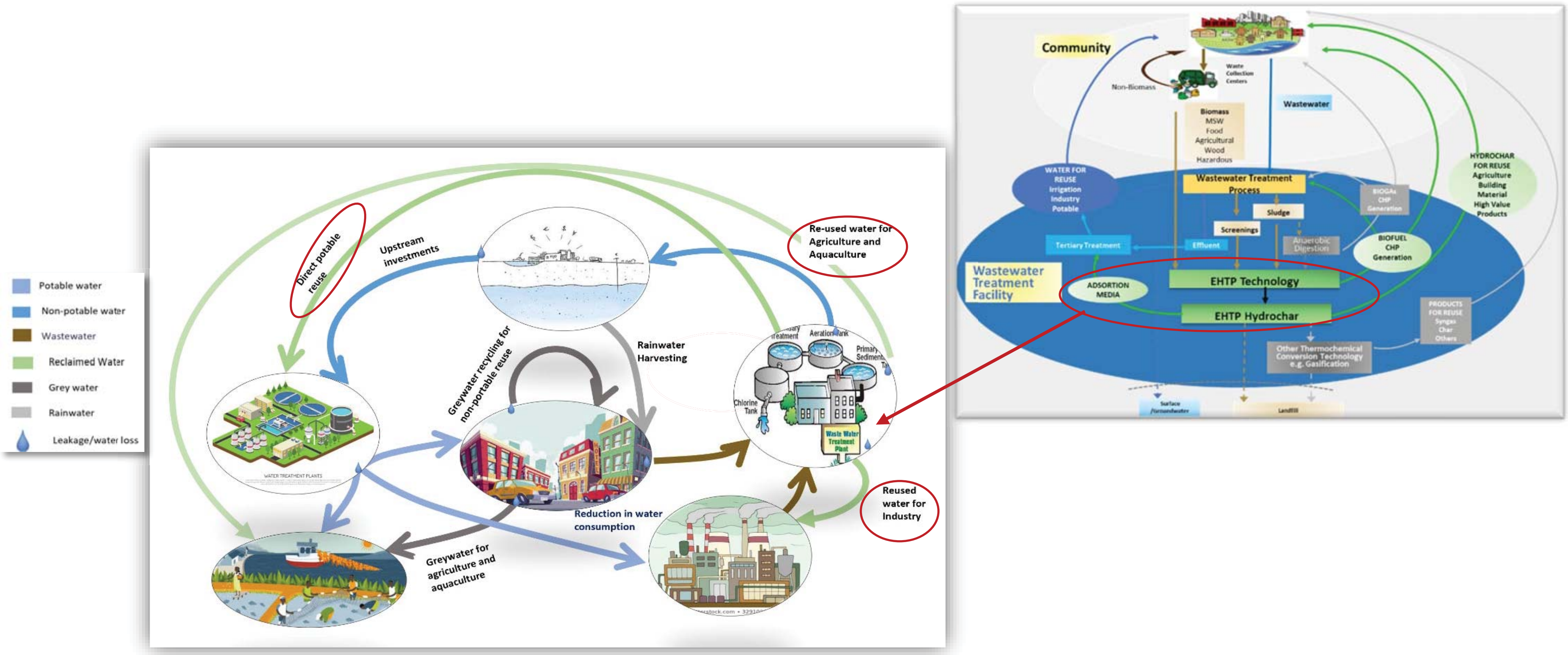


Figure 5-1: Illustration of Potential Coupling of EHTP With Other Technologies Within the Water Pathway

Table 5-1: Water Treatment Technologies that can be Coupled with the EHTP Technology for Wastewater Reclamation and Reuse as part of the Water Pathway

Technology	State of Development	Brief Description and Application
Disinfection Technologies		
Chlorination	Established	Chlorine based disinfection for the removal of wastewater constituents and pathogenic microorganisms such as faecal coliforms, streptococci, Salmonella sp. And enteric viruses that are not removed by previous secondary treatments
Ozonation	Established	Ozone applications involve oxidative reactions, where ozone can be used for disinfection or oxidation of specific contaminants. Organic compounds which are difficult to oxidize include many solvents, most pesticides, and compounds that cause tastes and odours
Ultraviolet (UV) Radiation	Established	UV disinfection transfers electromagnetic energy from a mercury arc lamp to an organism's genetic material (DNA and RNA) by penetrating through the cell wall destroying the cell's ability to reproduce. UV disinfection destroys virtually all harmful pathogen, bacteria, viruses, spores and cysts. UV can also inactivate protozoa notably Cryptosporidium and Giardia that cannot be destroyed through chlorine-based disinfection.
Per*a*cetic acid (PAA)	Emerging	PAA is an oxidizing agent used as a routine wastewater disinfectant. It is a stronger oxidant than hypochlorite or chlorine dioxide but not as strong as ozone. PAA does not affect effluent toxicity, so need not be removed as with chlorine. PAA does not explode. The solution is acidic (pH 2) and requires care in handling, transport, and storage.
Adsorption Technologies		
Granular and powdered activated carbon (GAC and PAC)	Established	Adsorption media for organic and inorganic pollutants removal. When a solution containing absorbable solute comes into contact with a solid with a highly porous surface structure, liquid-solid intermolecular forces of attraction cause some of the solute molecules from the solution to be concentrated or deposited at the solid surface. Removes heavy metals, colour and some micropollutants of concern like EDCs.
Ion exchange resins	Emerging	Ion exchange (IX) resin technology has been used extensively as a practical and effective form of water treatment. The process removes soluble ionized contaminants such as hardness and alkalinity from water via a reversible ionic interchange between a solid phase (resin beads) and liquid phase (water). Selective resins have also been developed to remove heavy metals, nitrate, perchlorate and some other contaminants
Novel green activated carbons	Emerging	Green activated carbons are made from renewable non-fossil fuel sources such as. e.g., sawdust, waste tyres, prawn shell, mango seed kernel, wood chips, wheat straws, lemon peel, orange peel, tree barks, rice husks, maize cobs, hazelnut husks, etc.). Activated carbon from EHTP hydrochar also falls into this category. Green activated carbons remove heavy metals, colour, and micropollutants of concern like EDCs. Some also remove other contaminants like nitrate, phosphorus and ammonia.
Membrane Liquid Separation Technologies		

Technology	State of Development	Brief Description and Application
Ultrafiltration (UF)	Established	Pressure driven ultrafine membrane media for solids removal. Removes particles 0.02 to 0.05 microns, including bacteria, viruses, and colloids. Usually applied in WRR to produce water for specific industrial reuse or as pre-treatment for reverse osmosis (RO) in direct and indirect potable reuse
Nanofiltration (NF)	Established	Pressure driven speciality membrane process that operates between UF and reverse osmosis (RO) and rejects dissolved solutes in the range of 1 nanometre. These include organic molecules (molecular weight 200-400), metals and multivalent ions such as calcium chloride, sodium chloride, bacteria and viruses. Application in WRR is usually for, and low rejection of monovalent ions, such as chloride
Reverse Osmosis (RO)	Established	Pressure-driven separation process that employs a semipermeable membrane and the principles of crossflow filtration. Most effective separation process for all salts and inorganic molecules as well as organic molecules with molecular weight greater than 100. Removes contaminants such as endotoxins/pyrogens, insecticides/pesticides, herbicides, antibiotics, nitrates, sugars, soluble salts, metal ions, bacteria and viruses. Used as a polishing/further treatment stage in WRR for potable reuse or high-quality industrial reuse
Advanced Oxidation Processes (AOP)		
Hydroxyl Radical and Ozone based AOPs	Established	Removal of recalcitrant organics that include non-biodegradable COD, TOC, VOC, dyes, surfactants, pesticides, herbicides, disinfection by-products, endocrine disrupting chemicals, etc.
Other novel AOPs (Catalytic ozonation, photocatalysis)	Emerging	

5.3 Energy Pathway

The contribution to the energy pathway by wastewater treatment in the IWA framework is through generation of energy from biosolids. The EHTP process produces hydrochar that is used as a biofuel that can be used for combined heat and power (CHP) generation. The EHTP technology can be coupled with the following technologies within the energy pathway (see Figure 5-2 and Table 5-2).

- Anaerobic digesters to further treat digested sludge combined with community biomass. CHP will be generated from both biogas during anaerobic digestion and EHTP hydrochar. Associated CHP technologies are listed in Table 5-2. The residual ash from hydrochar combustion can be beneficially used through the materials pathway in agriculture and the building industry for cement making. Metals can also be extracted from the ash
- Gasification to process EHTP hydrochar to generate liquid and gaseous fuels, e.g. synoil and syngas. Similar to above, the residual ash can be beneficially used through the materials pathway
- EHTP hydrochar can be used for fabrication of low-cost and high-performance air-cathodes for microbial fuel cells. This will enable coupling with microbial fuel cell technology

Depending on the available waste biomass from the community, other thermochemical conversion processes like hydrothermal liquefaction and pyrolysis can be incorporated at the WWTPs to process waste that cannot be processed in the EHTP reactor to increase the by-products for beneficial use.

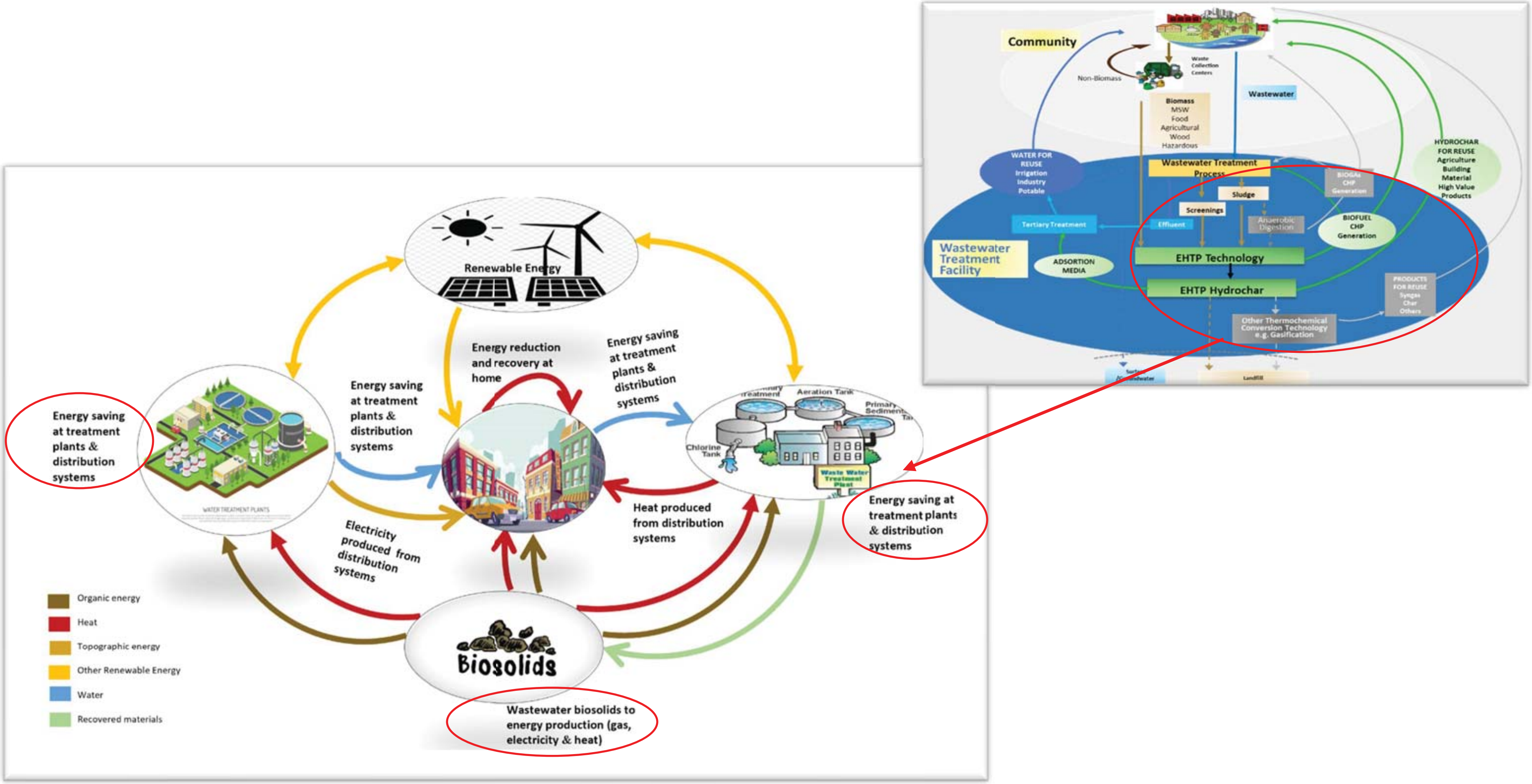


Figure 5-2: Illustration of Potential Coupling of EHTP With Other Technologies Within the Energy Pathway

Table 5-2: Technologies that can be Coupled with the EHTP as part of the Energy Pathway

Technology	State of Development	Brief Description and Application
Bio-chemical Conversion Processes		
Anaerobic digestion (AD) and aerobic digestion	Established	The AD process consisting of several sequential and parallel biochemical reactions that break down organic waste material to methane and carbon dioxide in the absence of oxygen to produce biogas containing mostly methane and carbon dioxide. Biogas can be burned directly for heat or steam or used in CHP generation. Aerobic digestion is the degradation of the organic sludge solids in the presence of oxygen. The micro-organisms in the sludge convert the organic material to carbon dioxide and water, and the ammonia and amino species to nitrate. Sludge from both technologies is processed in the EHTP technology with other waste biomass to generate hydrochar for CHP generation
Microbial fuel cells (MFCs)	Emerging	MFC technology utilises microbes in the oxidation of organic substances to produce electricity. MFCs enable energy recovery from municipal wastewater, while limiting both the energy input and excess sludge production. Good effluent quality and low environmental footprint can be achieved from the process because of effective combination of biological and electrochemical processes and the process is inherently amenable to real-time monitoring and control which benefits good operating stability. EHTP hydrochar can be used for fabrication of low-cost and high-performance air-cathodes for microbial fuel cells
Thermochemical Conversion Processes		
Gasification	Established	Thermochemical conversion process that converts biomass into gases, which are then synthesized into the desired chemicals or used directly. Production of thermal energy is the main driver for this conversion route that has five broad pathways: combustion; carbonization; pyrolysis; gasification and liquefaction. Hydrochar from EHTP can be further gasified with other waste biomass to produce synoil and syngas for CHP generation
Combined Heat and Power Generation Technologies		
Various technologies	Established and Emerging	Include boilers, turbines and novel technologies like fuel microgrids that convert the hydrochar that is generated from the EHTP technology to heat and electric power.

5.4 Materials Pathway

EHTP hydrochar and other by-products can be used within the materials pathway as follows:

- As a soil conditioner/fertilizer in agriculture
- Building material for brick making. Ash from combusted biofuel can be used in cement making
- Extraction of metals
- Energy storage in hydrogen fuels cells

Further research is required to develop some of the beneficial uses of EHTP hydrochar within the materials pathway.

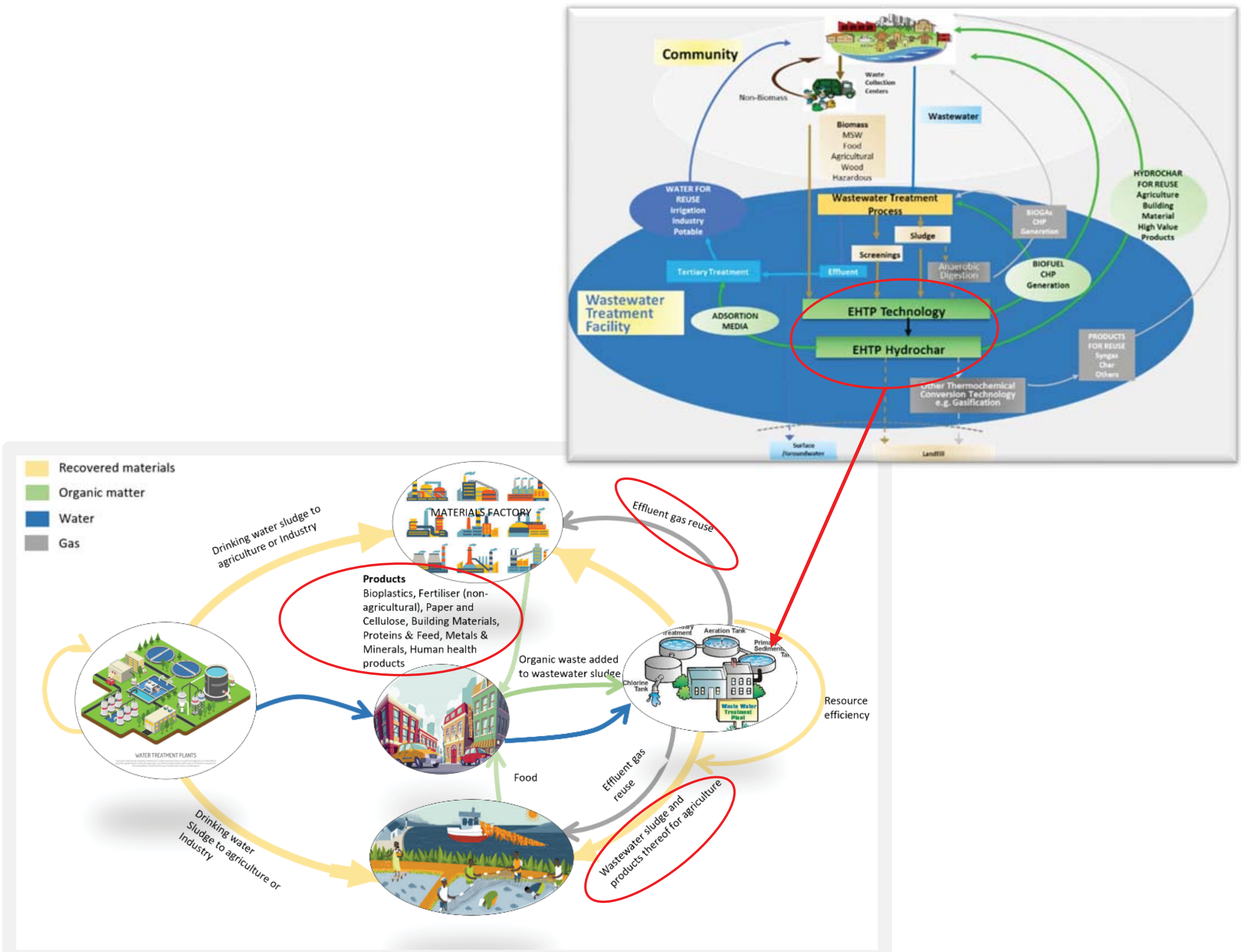


Figure 5-3: Illustration of Potential Coupling of EHTP With Other Technologies Within the Water Pathway

CHAPTER 6. TOWARDS A FRAMEWORK FOR IMPLEMENTING CIRCULAR ECONOMY PRINCIPLES IN THE SOUTH AFRICAN WASTEWATER SECTOR

6.1 Factors that Impact Transitioning to a Circular Economy – Overview

Similar to other sectors, the benefits of transitioning to a CE in the water sector have been shown both through theoretical models and practical experience in those areas where partial circularity has been achieved (e.g. energy generation, wastewater effluent reuse). However, full transition still faces significant challenges and barriers particularly in the application of WWTPs as biorefineries at the centre of that transition and subsequent recovery and reuse of associated by-products. Key factors that impact transitioning from the conventional linear economy to a CE in the South African wastewater sector identified from the IWA framework include:

- Legislation and Regulations
- Consumer behaviour and demands
- Infrastructure and technology
- Industry
- Urban and catchment area planning and economies.

These factors are classified as pathway drivers and enablers as they need to be shifted from a conventional linear economy to support a CE. It is therefore important for the South Africa wastewater sector to fully understand, anticipate, respond to and influence these factors to prevent them from being barriers and/or remove any existing barriers to a CE. Further to understanding CE drivers, the wastewater sector also needs to understand and proactively create new management approaches, partnerships and business opportunities that boost a CE. These include:

- Integrated urban resource management
- Intersectoral regulation, policies, and incentives
- Innovation
- Broad-based stakeholder connection
- New business models.

Research and studies indicate that to overcome barriers created by systems that favour the linear economy, widespread full-scale implementation of circular solutions for wastewater requires a standardized approach to evaluate fit-for-purpose developing technologies addressing environmental, cost, social (i.e. contaminated interaction), market and political aspects (e.g. policy favouring GHG reduction over resource recovery), as well as legislative barriers. Financial instruments, incentives and adequate regulatory mechanisms are also required to support public and private engagement in CE pathways.

Similar to other countries, in South Africa, transitioning to a CE in the South African wastewater sector will be challenging and also requires a multi-pronged and collaborative approach. Although the responsibility of implementing CE in the wastewater sector lies at the municipal level, for systemic change, transition requires several elements of the system to change simultaneously requiring all governments levels, businesses, innovators, investors and consumers to participate in the transition process. Strong and innovative leadership is therefore required at all government levels.

Key factors and their impact within the CE pathways are briefly discussed and evaluated in the following sections.

6.2 Legislation and Regulations

6.2.1 Implications of Planning Legislation and Policies on Transition to Circular Wastewater and Waste Organics Economies

Circular economy development initiatives are recent in South Africa. However, since the turn of the century most municipalities have acknowledged the role of solid waste recycling as a way of waste management and promoting economic development. The evolution of planning policies and legislation [4]shows that the circular economy in wastewater and solid organics has a potential to spur spatial and local government transformation, also playing a central role in poverty alleviation in the process. During the apartheid era, planning was largely a top-down state sanctioned activity that was used for the creation of one racial group privilege over others through spatial fragmentation. In post-apartheid South Africa, planning and planning legislation is used as a tool for revitalisation and poverty alleviation. It is in this context that planners need to be sensitized about innovative and cutting-edge initiatives such as the CE model in wastewater and waste organics that can be used to spur environmental sensitive economic growth and job creation at a local level.

The current post-apartheid South Africa planning legislation has a potential to support sustainable CE catchments in several ways. First and foremost, local government legislations such as the Municipal Structures Act (MSA) and Municipal Demarcation Act (MDA) have, since 2000, largely demarcated local government boundaries based on functionality and settlement typologies (Republic of South Africa, 1998a; 1998b). Therefore, if the current stated criteria for the demarcation of local municipal boundaries suffices, local municipalities are likely to have inbuilt sustainable CE catchments within them. Secondly, the promulgation of SPLUMA heralded the dawn of Master Plans/Schemes covering the entire local municipal boundaries in South Africa. SPLUMA compels all municipalities to formulate 'wall to wall' schemes that are used as tools for land use management within their areas of jurisdiction. It should also

[4] A detailed overview of the evolution of the planning legislation and policies in South Africa from the colonial to the past apartheid era is given in Appendix C.

be emphasized that all spatial and development planning at a local level in South Africa occurs in terms of Integrated Development Plans (IDPs) and spatial development framework (SDFs). Central of IDPs and SDFs is Local Economic Development (LED) which must be treated as a compulsory cross sectoral component of municipal development plans. Transition from the linear to CE has huge potential in promoting environmental conservation, economic growth and job creation. Local municipalities must therefore mainstream CE models and initiatives in IDPs and must also make them integral components of their LED strategies. Likewise, there is need for national government departments such as the DWS to support the transition to local CE development strategies.

Based on the analysis of the evolution of planning policy and legislation in South Africa, one can argue that the current policy and legislative context is responsive to the sustainable transition to a CE in water, wastewater and waste organics management. It has the potential to support sustainable catchment basins for this transition to happen. During the apartheid era, local government planning jurisdictions were fragmented along racial lines. Their demarcation by and large disregarded functional synergies among settlements as well as natural geographic catchments in some instances. In addition, master plans and land use schemes were also restricted to local authorities that were domiciled by white population groups. The post-apartheid planning legislative framework focuses on integrated development planning and therefor supports CE principles.

6.2.2 Key Legislation and Regulations that Impact All Circular Economy Pathways

Laws and regulations that directly impact CE pathways have been identified as key barriers and enablers for successful transitioning to a CE in the water sector. Lack of (or existing inhibiting) laws and regulations can hinder development of suitable infrastructure and technologies, wastewater biorefineries, sustainable economies, investment and consumer and private sector participation.

The Constitution of the Republic of South Africa (1996) enshrines the basic human right to have access to sufficient water and a healthy environment. The DWS fulfils these rights through specific legislation such as:

- National Water Act (Act 36 of 1998)
- Water Services (Act 108 of 1997)
- National Environmental Management Act (Act 36 of 1998)
- Provincial legislation, municipal by-laws and other government policies are also applied.

Sanitation provision is governed by the strategy framework on Water Services (2003) and the Water Services Act of 1997. The legislation and regulations are structured to acknowledge that water is a scarce national resource that should be protected, used, developed, conserved, managed and controlled in a sustainable and equitable manner for the benefit of all people and in accordance with the constitution.

Other key legislation that impacts implementation of CE initiatives include the following:

Municipal Systems Act 2000 (Act 32 of 2000)

The Municipal Systems Act stipulates that all spatial development initiatives within municipalities must occur within the ambit of integrated development plans (IDPs) (Republic of South Africa, 2000). The Act defines an IDP as a super plan for an area that provides an overall framework for development through coordinating the work of all spheres of government, namely local, district, and central as well as all stakeholders such as the private sector, civil society and NGOs in efforts to enhance development (Musvoto, 2011:235). Incorporation of CE principles in IDPs will ensure successful implementation of CE in all sectors including the water sector.

Procurement Legislation

The procurement system in South Africa has been reformed over the years and there are numerous legislative frameworks that guide procurement practices in South Africa. These include the:

- Constitution
- Public Finance Management (PMFA) Act 1 of 1999
- Municipal Finance Management Act (MFMA) No. 56 of 2003
- Preferential Procurement Policy Framework Act (PPPFA) No. 5 of 2000
- Broad-based Black Economic Empowerment (B-BBEE) Act 53 of 2003
- Promotion of Administrative Justice Act (PAJA) No 3 of 2000
- Promotion of Equality and the Prevention of Unfair Discrimination Act (PEPUDA) No 4 of 2000
- Construction Industry Development Board Act No. 38 of 2000
- Prevention and Combating of Corrupt Activities Act (PRECCA) No. 12 of 2004.

The primary objective of the reforms was to have a procurement system that is fair, equitable, transparent, competitive and cost effective. The reforms also have a secondary objective that focuses on addressing certain socio-economic factors. In this regard procurement policy makes provision for (i) categories of preference in the allocation of contracts and (ii) the protection or advancement of persons, or categories of persons disadvantaged by unfair discrimination in the past. To support the legislation and eliminate the deficiencies and fragmentations in governance, interpretation and implementation of specifically PPPFA, supply chain management (SCM) was introduced as a policy tool for the management of public procurement practices (National Treasury, 2005). SCM is therefore an integral part of procurement in the South African public sector.

Despite well-meaning reforms and application of SCM as a strategic tool, the procurement system still faces many challenges and is viewed as a barrier to innovation in the public sector including implementation of CE at municipal level where wastewater management and other services are provided.

The system prevents supply chain managers from being innovative in procuring goods, services and systems. Key issues that supply managers face include:

- Lack of flexibility to allow for any real innovation
- Innovation is branded “irregular” and often subjected to political stigmatisation then stigmatised by politicians
- Budgetary planning timelines make it impossible to introduce new projects or programmes during a budgetary year.
- Price is the main determining factor in procurement

Further to barriers that prevent innovation to promote CE, general systemic challenges such as lack of training and capacity, lack of transparency and non-compliance with SCM policy and regulations make it difficult for municipalities to achieve their procurement objectives.

Changes to the current public procurement system and adoption of innovative and sustainable procurement systems such as the Circular Public Procurement (CPP) is required to promote CE in all sectors including the wastewater sector. CPP is an integrated approach to public procurement that acknowledges the need to enable innovation through circular economy principles[5]. CPP can play a significant role in the transition towards a CE and can bridge innovation and sustainability, thus leading to a more holistic approach, where innovation incorporates all aspects of sustainability. CPP offers the following advantages to municipalities and other public entities:

- ability to influence market development by ensuring a steady demand of products and services designed for a CE especially in joint venture/cross border procurement
- improved savings and overall environmental performance
- potential to become a driver of new business models used to deliver goods and services

Implementing CPP would require public entities to define more complicated and exhaustive criteria in public contracts than the current criteria based on the lowest price and make use of the most economically advantageous tender (MEAT) approach. The MEAT approach considers other aspects that have indirect costs such as the amount of GHG emissions generated during a product’s lifetime or production methods that create unnecessary pollution or environmental damage. In most countries including South Africa procurement through the MEAT is not standard practice and is estimated to be as little as 3% of the total tenders published.

[5] CPP can be defined as the process by which public authorities purchase work, goods or services that seek to achieve closed energy and material loops whilst minimising, and in the best case avoiding negative environmental impacts and waste creation across their whole lifecycle. This can be achieved through the promotion of products designed to last longer, with materials that can be upcycled, and by focussing on the use of the products and associated services rather than on their ownership (ICLEI, 2016)

In view of the shortcomings of the current public procurement system, South Africa has started initiatives that in future will eliminate rigidities in the current system and promote a CE. Finalisation of the Draft Public Procurement Bill (2020) which will eventually be enacted into law is underway (SALGA, 2020a). The bill seeks to create a single regulatory framework for public procurement, thereby eliminating the fragmentation that has brought about confusion in this area of the law since the advent of constitutional democracy.

Apart from legislative initiatives, progress in other sectors in implementing CE by national and municipal entities in the country will eventually result in CPP being commonly applied. Some initiatives that have successfully promoted CE and in some cases achieved partially circularity include:

- the Recycling and Economic Development Initiative of South Africa (REDISA) tyre waste management initiative that was created to deal with the national tyre waste problem. The initiative has reduced tyre dumping and also promoted research into different uses for rubber recycling, as well as into eco-design of more recyclable tyres
- the Western Cape Industrial Symbiosis Programme (WISP) a free facilitation service which develops mutually beneficial links between companies from all industrial sectors, so that underutilised or residual resources (materials, expertise, logistics, capacity, energy and water) from one company can be recovered, reprocessed and re-used by others. WISP is supported by the City of Cape Town through Green Cape
- Membership of metros and other cities in global organisations that promote sustainable development such as the Global Lead City Network on Sustainable Procurement (GLCN) that most large metros (e.g. City of Tshwane, City of Cape Town, eThekwini Municipality) are members of

Carbon Tax Legislation

The Carbon Tax (Act 15 of 2019) was gazetted on 23 May 2019 and came into effect on 1 June 2019. The objective of the carbon tax legislation is to reduce the impacts of climate change through facilitating a viable and fair transition to a low-carbon economy which is essential to ensure an environmentally sustainable economic growth path for South Africa. It was set to be implemented in phases (the first phase from 1 June 2019 to 31 December 2022), to minimise the impact on businesses prices of key resources like electricity (National Treasury, 2019). The Act sets out the activities in respect of which the tax is levied and provides thresholds in respect of these activities. Where the GHG emissions of a taxpayer exceed the thresholds, the taxpayer is liable to pay tax (levied per ton of carbon dioxide equivalent of GHG emissions of a taxpayer). This liability may be reduced through using the various allowances available and in some instances the tax is only payable where the allowances are exceeded. The tax is levied in terms of Section 54 A of the Customs and Excise Act 91 of 1964 (Customs and Excise Act) as an environmental levy and is paid to and administered by the South African Revenue Service (SARS) (Republic of South Africa, 2015).

Implementing CE in the wastewater sector within the three interrelated pathways will reduce GHG from wastewater operations and reduce or eliminate the carbon tax liability. The carbon tax encourages implementation of CE within the country.

6.2.3 Consumer Behaviour and Demands

Consumer behaviour and demands have always played a key role in service delivery. However, the relationship between consumers and utilities will become more interdependent as consumers become more increasingly prosumers, i.e. a consumer who becomes involved with the production of the goods and services that they use. An increase in environmental awareness coupled with technologies that enable efficient water and energy management and production in the home mean that the decisions and actions of consumers will have implications on service choice and business models. For example, consumer perceptions on wastewater by-products and cost of these products impact their acceptance and eventual use in the market. This is significant in WRR schemes which are a key to successful implementation of the CE water pathway. Other factors like water and energy efficient devices in the home will reduce household consumption and impact on traditional revenue streams for municipalities.

Details of the impact of consumer behaviour and demand on the water, energy and materials pathways are discussed in the relevant sections below.

6.2.4 Infrastructure and Technology

To fully transition to a CE, new wastewater and related sector infrastructure needs to be built to promote CE. Existing infrastructure also needs to be modified from serving the traditional linear economy to a CE. The South African wastewater sector is already facing challenges in terms of maintaining and operating existing wastewater infrastructure with most WWTPs currently dysfunctional resulting in excessive energy and materials consumption, non-compliance with discharge regulations and environmental pollution. These inherent problems need to be solved before CE can be implemented.

The sector is also facing challenges in adopting new technologies that are required to support a CE. Previous studies identified technological, financial and implementation barriers and risks to adopting technologies that support partial circularity through energy generation from wastewater. While certain technologies are established internationally, they have not been locally demonstrated, thus hampering large scale implementation. The reliability of new technologies has also not been proven. Furthermore, 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 are complex to build and implement and South Africa lacks the human resources capacity for maintenance. Decision support tools that can assist municipalities to evaluate the costs and benefit of implementing technologies are also needed (e.g. life cycle analysis).

Apart from the above challenges, there are also legislative and regulatory barriers to building new and upgrading existing infrastructure to promote a CE. Municipalities therefore have to consider requirements of key legislation like the Municipal Systems Act (Act 32 of 2000) and legislation governing public procurement and where necessary make changes (or influence for changes to be made) in order to ensure that CE can be successfully implemented.

6.2.5 Industry

Industry plays a significant role in ensuring the success of CE initiatives as they are the eventual consumers of the products. In the wastewater sector industry participation is critical in supporting all the three pathways. Municipalities therefore need to communicate with industry to ensure that there is a need for CE by-products and that the quality, quantity, as well as chemical and physical properties of these products are acceptable. Key areas that municipalities need to engage industry to ensure a successful CE include

- Reuse of reclaimed wastewater
- Use of various materials generated through the materials pathway
- Use of excess energy generated at WWTPs

6.2.6 Urban and Catchment Area Planning and Economies

Local economies in cities and in the wider basin area are critical to the success of wastewater management circular economy initiatives and they evolve to create greater balance between resource demand and supply. New markets, industries and supply chains will emerge in cities and savings in water use and nutrient materials recovery will benefit basin economies (e.g. agriculture).

Basin planning has been proven to be an important aspect of implementing CE as it creates ways to integrate the benefits and impacts of implementing CE in multiple sectors, incorporating factors such as climate, socioeconomic environmental and other key impacts. Experience in LMICs have shown that recent basin planning methodologies now include participatory mechanisms to reduce conflicts among users. This comprehensive approach promotes resource optimization and efficiency and maximize economic and social well-being without undermining the sustainability of the ecosystems (Rodriguez, 2018).

6.3 Pathway Specific Circular Economy Barriers, Drivers and Opportunities

6.3.1 Water Pathway

Wastewater reclamation and reuse (WRR) is at the core of the water pathway in achieving CE in the wastewater sector. Reuse has long been recognised as an alternative source of water in water-scarce countries, especially for agriculture, which is the largest user and has differentiated water quality requirements. For water-scarce countries like South Africa, wastewater reuse is the only affordable alternative. Reuse can be direct or indirect and the main reuse options are:

a) non-potable reuse for irrigation
b) non-potable reuse for industry
c) potable reuse

The DWS has developed a water reuse strategy to assist municipalities make informed decisions relating to WRR. Reuse is becoming increasingly acceptable and feasible owing to more frequent and severe droughts, increasing shortages, improved purification technology and decreasing treatment costs.

Regulations and Guidelines for Wastewater Reuse

Reuse for Agriculture

The National Water Act (Act 36 of 1998[6] in Government Gazette of 6 September 2013) gives the general authorisation for irrigation of land using wastewater. The authorisation specifies the wastewater quality standards at different quantities of irrigation and other regulatory requirements (registration, location, monitoring, protective measures, etc.) to comply with the general authorisation. The general authorisation applies if the water quality parameters fall within the general limits otherwise the user must apply for a Water Use Licence. In terms of the NWA, irrigation with wastewater is not allowed within 100 m of the edge of a water resource (stream, river, dam, borehole) that is used for human consumption or animal watering, or within the 100-year flood-line, or on land that overlies a major aquifer. The National Environmental Management Act (1998) outlines the conditions that require an environmental impact assessment (EIA) or a basic assessment. Municipal bylaws and guidelines might also be applicable for onsite reuse for irrigation.

Direct potable reuse

Potable water standards are given in SANS 241-1:2015. Currently, SANS 241 gives limits for pollutants that are commonly found in surface water and does not include limits and specifications for contaminants of emerging concern (CECs) that are present in wastewater and are not removed by conventional wastewater treatment and remain in final effluent that is reused. Increased implementation of effluent reuse calls for new policy initiatives and broadening of environmental legislation, including the modification of the current SANS 241 to include the currently non-regulated CECs. Expansion of SANS 241 will alleviate public safety concerns and improve acceptance of wastewater reuse schemes thus enabling adoption of a CE.

6

Revision of General Authorisations in Terms of Section 39 of the National Water Act, 1998 (ACT NO. 36 OF 1998) (THE ACT) Published under Government Notice 665 in Government Gazette 36820, dated 6 September 2013. Commencement date: 6 September 2013.

Reuse for Industry

There are no specific guidelines for reclaimed wastewater for use in industry. The general guidelines given in the South African Water Quality Guidelines Volume 3: Industrial Water Use (DWAF, 1996) are essentially a user needs specification of the quality of water required for different industrial uses. They provide the information needed to make judgements as to the fitness of water to be used for different industrial uses. The guidelines are applicable to any water that is used for industrial purposes, irrespective of its source (municipal supply, borehole, river, etc.) or whether or not it has been treated.

Consumer Perceptions on Wastewater Effluent Reuse

The reuse of wastewater for potable use is an effective solution to water scarcity and is a key aspect of the water pathway to CE. Public perceptions on the reuse of wastewater for potable use are a significant obstacle to the implementation of this strategy. It is thus important to understand the factors that influence these perceptions to successfully introduce and implement the potable reuse of wastewater.

As discussed in Section 2.3.1 few studies were conducted on consumer perceptions on reclaimed wastewater in South Africa. The few studies that focused on non-potable reuse identified the following key factors that impacted consumer perceptions of reclaimed wastewater:

1. Economic efficiency
   Non-potable water tariffs significantly influenced consumer willingness to embrace water reuse.
2. Social acceptance
   Although many of the institutional respondents were generally enthusiastic about treated effluent use, there was caution in expressing general satisfaction about the treated effluent service. Trust in the service providers and in the scientific investigations, technologies and knowledge dissemination during project implementation on water quality and safety played a crucial role in determining the social acceptability of water reuse.
3. Technical feasibility
   Colour coding and clear identification/labelling of the non-potable pipes played a significant part in encouraging respondents' acceptance of dual systems conveying different water qualities.
   The closer recycled water is to human contact or ingestion, the more people opposed to using the water. Hence, there exists more favour for minimal human contact uses. Toilet flushing, landscape irrigation and car washing were the most widely accepted options for reclaimed mine water amongst domestic respondents.

The studies concluded that the public's decision to reject, resist or accept water reclamation related directly to their knowledge at different stages of the institutional process. A lack of knowledge and poor public engagement would lead to negative public perceptions. Municipalities could improve consumer acceptance by implementing strategies that address these perceptions. The studies found that increase in non-potable water reuse can be facilitated with adequate attention given to the following strategic issues:

1. For non-potable water reuse to become viable, non-potable water tariffs must be cheaper than potable water tariffs
2. Non-potable reuse makes economic sense when the source is situated close (within a radius of 500 metres) to the consumers
3. For effective administrative and operational processes, budgets for non-potable water reuse may need to be administered separately from the municipal sanitation budget
4. Numerous water reuse projects have failed in the past despite receiving favourable support initially from the potential consumers. This may be because consumers often saw the logic in the move towards water reuse but felt that they themselves could not use the water. Hence, adequate attention to social acceptance of non-potable reuse for domestic applications is necessary
5. Due to the deteriorating wastewater treatment works infrastructure and the increasing release of low-quality treated effluents into natural water bodies, any publicized negative incidents in non-potable reuse may easily discourage the public from embracing reuse. The onus is therefore on service providers to prove that they can be trusted. Municipalities have an obligation towards a consistent supply of the quality expected that would be positive for the embracing of non-potable water use
6. Non-potable reuse within a domestic community will require service providers to assure and promote general safety for consumers

Some of the approaches for addressing consumer resistance to wastewater to reuse based on these studies have been discussed in Section 2.3.2 (see Table).

Financing of Wastewater Reuse Schemes

In low- and middle-income countries (LMICs) the water sector is customarily inefficient and under-funded. In this regard, public-private partnerships (PPPs) are playing a significant role in assisting governments fund much needed investment and bring technology and efficiency that can improve the performance and financial sustainability of the water sector. PPPs are increasingly being used in the water and sanitation sector to finance and operate bulks water supply and wastewater treatment, introduce new technology and innovation where traditional sources are being scarce, such as in desalination and water reuse. Utilities are drawing on specific expertise, such as non-revenue water reduction and pressure management, to bring efficiencies and service improvements. Private investors and providers are increasingly local and regional, increasing competition and bringing down prices.

In South Africa, PPPs are now being viewed as a key financing vehicle for water reuse schemes. However, there are barriers that need to be overcome for PPPs to be viable.

Regulatory Barriers

Complex regulation legislation governing PPPs and municipal services in South Africa make implementing PPPs onerous, time consuming (with timeframes of three to six years to complete) and ultimately too costly. High project size threshold figure of R300 million also means that only large projects are viable. Rigid and complex procurement regulations also provide challenges for municipal PPPs. Further regulatory risks to PPPs are also caused by lack of clarity in the following areas (Graham, 2019):

- the National Water Act and the Waste Act do not clarify whether treated wastewater is either considered 'waste' or 'water resource', creating uncertainty about the licencing requirements
- rights of downstream water users to wastewater effluent flows in rivers, which may affect the ability to divert wastewater treatment works outflows to industrial users

Initiatives are being made to address these barriers and create opportunities for successful PPP implementation in water reuse schemes. The national Treasury is currently reviewing PPPs regulations that will include some of the following key issues:

- development of different processes for large and small PPPs
- a model PPP contract to assist municipalities in streamlining the process, as well as sector-specific guidelines to clarify the regulatory requirements in each

To support these initiatives, regulatory clarification is also required from the DWS regarding downstream water rights and water allocations in each catchment (Graham, 2019).

Financial Barriers

Three major financial barriers to municipal reuse PPPs have been identified (Graham, 2019):

1. Cross-subsidisation

   Cross-subsidisation of water services results in certain users, including large industrial water users, paying more than the cost of water supply. Use of PPPs would provide an alternative water supply to these high paying users and divert this revenue stream through the private sector which municipalities might be reluctant to do.
2. Low water tariffs

   Low municipal industrial water tariffs and even lower raw water tariffs (from the DWS) increases the risk of a project being financial unviable since any treated effluent reuse tariffs need to be competitively priced compared to existing tariffs.
3. Recovery of revenue from municipalities/customers

There are concerns from private parties about the ability to recover revenue from customers of municipalities. While offtake agreements mitigate this concern, the ability of industrial customers to pay will always be impacted by the economic environment.

Some of the steps being taken to address the financial barriers include:

- Setting up of the Infrastructure Investment Programme for South Africa (IIPSA) by the National Treasury and the European Union and managed by the DBSA. The objectives of the programme, are to provide grant funding to leverage or crowd-in long-term loan finance via financial instruments such as technical assistance and studies, interest rate subsidies, direct capital grants or other credit enhancement measures for a range of infrastructure projects, including water reuse
- Several initiatives by the national and provincial governments to address, in the long-term, the issue of low water tariffs. In the short-term it is recommended that PPPs efforts focus on water stressed municipalities with relatively high industrial water tariffs to increase the attractiveness of reuse (Graham, 2019).

Capacity Barriers

Capacity barriers have been identified at national and municipal government levels as well as the private sector. The barriers include:

- Insufficient staff and expertise at the National Treasury municipal PPP unit
- Critical technical staff shortages in municipalities which impact their ability to operate treatment plants, and to scope, plan, and specify infrastructure projects. A lack of long-term infrastructure planning to adequately plan and scope large-scale projects as well as poor contract management is also a concern
- Gap on transaction advice in the private sector due to little experience in water and sanitation PPPs
- To address these barriers, the DBSA and the DWS are in the process of trying to set up a municipal water reuse project office, which is to be housed within the national government. The International Finance Corporation (IFC) has a programme that provides free transaction advice and support for PPPs to municipalities through a reimbursable grant model. It is also recommended that should this initiative not materialise, alternative capacity building programmes should be undertaken by municipalities to support the packaging of projects and PPP contract management (SALGA, 2020b).

Environmental Risks

Environmental factors, such as the seasonal variation of the effluent and composition, could limit reuse if appropriate technologies are not applied. Nutrient imbalance in the effluent is also a concern to water reuse in agriculture. High levels of salinity, heavy metals and CECs are also a concern since they could accumulate in soil or crops necessitating advanced treatment even for reuse in agriculture. This could result increase in costs making reuse schemes unaffordable.

Case Studies for Wastewater Effluent Reuse in South Africa

Due to critical water shortages wastewater reclamation and reuse, although not part of full CE initiatives, has gathered momentum in South Africa in recent years. Some of the successful projects implemented and being planned include:

- Durban water recycling project
- Beaufort West Wastewater Reuse
- City of uMhlathuze non-potable water reuse project for industries
- Water reuse in Olifants River catchment
- Indirect potable reuse at Zandvliet WWTP.

A summary of some of these projects is given in Appendix B.

6.4 Materials Pathway

The benefits of materials recovery from wastewater and the need to achieve this within a CE (rather than the traditional linear economy approach of managing sanitation waste) are now well understood and appreciated globally and in South Africa. The challenge for the South African wastewater sector is how to successfully shift the entrenched linear economy model to a CE. Employing sludge management strategies that are focused on recovering valuable materials from sludge is one of the key ways to convert WWTPs into resource recovery facilities within a CE. Therefore, municipalities need to understand the legislation and regulations that impact sludge valorisation as well as other key factors such as technologies for valorisation and market levers (pricing, quality, consumer demands and perceptions).

Global studies and experiences have demonstrated that established and emerging technologies can be applied to successfully recover not only nutrients but higher value products such as bioplastics, biopolymers, heavy metals, protein and other chemicals. Coupled with enabling legal, regulatory and financial environments, sector partnerships and an understanding of the market, materials recovery can successfully achieved. Although the DWS regulations recommend beneficial use, most of the sludge from WWTPs is currently disposed of into landfills or stockpiled in ponds and drying beds. It is estimated that only about 20-30% of sludge generated at South African WWTPs is used in agriculture (EADP, 2020). Recovery of nutrients and other high value products still lags and is in its infancy. Efforts to implement comprehensive materials recovery are sporadic and currently limited to the large metros. Opportunities therefore exist for municipalities to develop strategies that lead to successful materials recovery within a CE.

6.4.1 Legal Requirements for Sludge Management

Key legislations that drive the management and disposal of wastewater sludge in South Africa are the National Water Act (Act 36 of 1998) and the National Environmental Management: Waste Act (Act 59 of 2008) including the Waste Amendment Act (Act 26 of 2014)[7].

The 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 permits them to treat and dispose 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: Volume 1-5 (Snyman and Herselman, 2006 & 2009)".

The Guidelines for the Utilisation and Disposal of Wastewater Sludge (Snyman and Herselman, 2006 & 2009) were prepared under sponsorship by the WRC to assist municipalities navigate the legislative requirements for sludge management and disposal. The guidelines consist of 5 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 standalone, 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.

Apart from complying with utilisation and disposal requirements, South African utilities are also required to comply with greenhouse gas (GHG) emission requirements in sludge management activities. Compliance with GHG emissions is stipulated in the National Environmental Management: Air Quality Act,

[7] 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 Snyman and Herselman (2006 & 2009) and van der Merwe et al., (2016).

2004 (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 is listed as an activity that requires GHG emission reporting (Dept. of Environmental Affairs, 2015).

In addition to legislative requirements, the DWS introduced in 2009, an incentive-and risk-based regulation through the Green Drop Certification program. 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).

6.4.2 Wastewater Sludge Valorisation within a Circular Economy: Barriers and Opportunities

Nutrient Recovery

Sewage sludge is composed of significant amounts of nutrients, such as phosphorus which can be extracted to produce fertilisers. Several technologies are now available that can be successfully applied to recover nutrients from wastewater sludge. Most of these technologies focus on crystallisation of phosphorus from streams generated in sludge thickening and dewatering in the form of mainly struvite. Other products that can be recovered from sludge treatment side streams are ammonium sulphate, nitrate and calcium phosphate. Physical processes such as ion exchange, adsorption and membrane processes can also been applied for nutrient recovery.

The City of Cape Town has started implementing nutrient recovery from sludge. The new regional sludge handling facility at Cape Flats WWTP will include advanced anaerobic digestion with struvite crystallisation from dewatered sludge liquor. The pasteurised Class A1a sludge and struvite will be used in agriculture (Jones and Elston, 2021).

Construction Materials

The main oxides (Al_2O_3, CaO, SiO_2, and Fe2O_3) present in wastewater sludge and/or incinerated sludge ash are like that of cement or clay. Therefore, sludge has been (and can potentially be used) as raw material for construction materials and other related products. This includes, but is not limited to:

- bricks
- eco cement

- ceramic materials and lightweight aggregates

Due to the high level of organic matter in sludge, which can cause decrease mechanical strength and delay the hydration process, pre-treatment of sludge is required. Most of the manufacturing processes therefore include a heating process where potential hazardous microbiological constituents and organic material present in the sludge are destroyed, leaving the product sterile and harmless. In most instances the inorganic pollutants (metals) are also converted to an insoluble form preventing secondary environmental pollution (Herselman et al., 2009a, 2009b).

Various studies and full-scale implementation have demonstrated that municipal dewatered sludge as well as incinerated sludge ash can be applied as raw material for brick manufacturing. The sludge brick is superior to traditional bricks in compression strength, water absorption rate, abrasion strength and bending strength. It has also been demonstrated that making bricks from wastewater sludge uses less energy and the bricks are cheaper than conventional clay bricks. In South Africa utilisation of wastewater sludge in brick production has been successfully demonstrated, producing good bricks that complied with the relevant standards regarding strength and accepted by the building industry[8].

Of the other applications cement making has also been found to be feasible. However, depending on the characteristics and origin of the sludge, various conditioning steps may be needed. The manufacturing of ceramic materials and lightweight aggregates holds potential but requires further treatment processes such as pelletisation, thermal treatment and even mixing with other materials such as waste glass.

The use of sludge in the manufacture of construction materials therefore provides South African municipalities with an efficient and cost-effective method of sludge management within a CE.

Heavy Metals and Minerals

Opportunities exist to recover various heavy metals from sludge (Cu, Zn, Ni, Cr, Pb, Mn) because of the growing concern due to possible soil and groundwater contamination since most of the sludge is disposed on land and landfills. Various studies have demonstrated feasible processes for metal recovery such as extraction, supported liquid membranes and calcination.

Higher Value Products

Other higher value products that can be recovered from wastewater sludge include:

Adsorbents

Wastewater sludge has the potential to be used as a precursor for the synthesis of adsorbents due to its high content in carbonaceous matter. The most widely employed methods for adsorbent preparation, are

[8] Coega Bricks were the pioneers for utilising wastewater sludge for the manufacture of bricks in South Africa

carbonisation, physical activation, chemical activation and a combination of physical and chemical activation (Smith and Tibbett, 2004).

Bioplastics

Polyhydroxyalkanoates (PHAs) can potentially be produced during wastewater and sludge treatment. The biodegradable PHAs can be used as a sustainable alternative to petroleum-based plastics.

Proteins

Recovery of proteins from sludge has great potential due to the high proportion of proteins (up to 61%) in activated sludge and that around 50% of the dry weight of bacteria cells are due to protein content (More et al., 2014). Various processes (physical, chemical, chemical, physico-chemical, biochemical and hydrothermal) have been investigated for recovery of protein from sludge.

Hydrolytic Enzymes

Waste activated sludge contains hydrolytic enzymes (amylase, phosphatase, lipase, protease glucosidase, aminopeptidase, etc.). These enzymes are widely used in various industries (agriculture, detergents, pulp and paper, cosmetics, dairy, etc.) thus creating an opportunity for their recovery from wastewater sludge. Different physical and chemical methods such as stirring or ultrasonication with additives and disrupting chamber have been found to be successful in extracting some of the enzymes like protease lipase and amylase (Guerra-Rodríguez, 2020).

6.4.3 Legislation for Commercial Products Containing Sludge

Volume 5 of the sludge guidelines (Requirements for Thermal Sludge Management Practices and for Commercial Products containing Sludge) gives the regulatory requirements for fertilizer and construction products (Table 6-1). The legislation is not well defined or prescriptive and several pieces of legislation may therefore need to be considered and more than one Government Department or sphere of government may have a regulatory role to play. Furthermore, high value products are not included in the current legal requirements. Although no specific authorisation is required per se, it is important that the regulations relating to the various statutes are adhered to, where applicable. While not specified in the Table 6-1, the DWS and/or DEAT, need to be consulted in terms of any water use authorisation that may be required for a WWTP or a waste permit that may apply for an off-site management option, should the sludge be destined for use in a commercial product.

Table 6-1: Regulatory Requirements Applicable to Commercial Products Containing Sludge (Herselman et al., 2009c)

	Fertilizer Products	Commercial Products: Construction
Applicable Act Governing Practice	Fertilizer, Farm Feed, Agricultural Remedies and Stock Remedies Act (Act 36 of 1974) Hazardous Substances Act (Act No 15 of 1973) National Health Act (Act 61 of 2003	Hazardous Substances Act (Act No 15 of 1973) National Health Act (Act 61 of 2003)
Authorisation Required	Registration as a fertilizer with Department of Agriculture	None specified
Lead Authority	Department of Agriculture	Department of Health
Regulatory Instrument	Certificate of registration Applicable health and pollution control regulations, provincial and local bylaws	Applicable health and pollution control regulations, provincial and local bylaws
Regulatory Guidelines	Sludge Guidelines (Volume 5) and/or Minimum Requirements (latest applicable versions)	

Further to the requirements in Table 6-1 the standard and quality of construction and building material is also regulated by the South African Bureau of Standards (SABS). These standards are published documents which list specifications and procedures established to ensure that a material or product is fit for its purpose and perform in the manner it was intended for. Standards for building and construction material are included in the South African National Standards (SANS): Materials and Mechanical Standards. Where an applicable SANS for a specific product exists, the final product must conform to this standard before it can be used.

The existing legislation and guidelines do not cover all the materials that can be recovered from wastewater. Therefore, they need to be updated to avoid grey areas that can act as barriers to fully utilising the materials pathway within a CE.

6.5 Energy Pathway

To fully convert WWTPs into biorefineries within a CE, the energy pathway needs to involve implementation of comprehensive energy efficiency measures that include both energy recovery and energy conservation in the treatment process. It has now been demonstrated at a global scale that with well-implemented energy efficiency measures, WWTPs can become energy neutral thereby eliminating the need to get energy from the grid[9]. There are also full-scale plants that now generate excess energy and feeding back into the grid[10]. Within a CE that proposes co-processing of sludge with external biomass

[9] Examples of WWTPs that have achieved energy through can be found in the USA, Germany, Switzerland, Austria and Denmark (Gu et al., 2017).
[10]Some recent key examples include (i) Ejby Mølle WWTP (Denmark) the largest publicly owned water resource recovery facility (WRRF) that transformed from a large electricity power consumer into a net producer of energy (electricity and heat) and achieved carbon neutrality in just 5

as in this project, the chances of converting WWTPs into net produces of renewable energy are much higher.

The electricity shortages and the resulting increase in electricity cost over the past 10 years have made South African municipalities conscious of the significant risk posed by the shortage and rising cost of electricity to wastewater management. The energy crisis therefore increased WSA's interest in energy efficiency. The City of Johannesburg is the first municipality to take practical measures by developing a strategy for power generation from anaerobic digester biogas at 3 of their 7 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. The City of Cape Town is also implementing advanced anaerobic digestion (using thermal hydrolysis) and CHP generation at the new regional sludge handling facility at Cape Flats WWTP. Other large metropolitan municipalities are also actively exploring 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. By incorporating innovative technologies and co-processing sludge with waste biomass, municipalities can generate excess renewable energy that they can distribute back into the grid while reducing GHG emissions and generation income within a CE.

6.5.1 Key Legislation and Regulations

To successfully implement energy efficiency at WWTPs within a CE, the following key legislation and regulations that govern energy as well as wastewater and sludge management need to be considered:

- Electricity Regulation Act, 2006 (Act No. 4 of 2006)
- National Gas Act (Act No. 48 of 2001)
- National Environmental Management Act (Act No. 36 of 1998)
- National Environmental Waste Act (No. 59 of 2008)
- National Environmental Air Quality Act (Act No. 39 of 2004)
- National Water Act (Act 36 of 1998
- Carbon Tax Act (Act 15 of 2019)
- Spatial Planning and Land Use Management Act (2013)

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years. (ii) Billund WWTP(Denmark) which was upgraded to Biorefinery in 2016 by co-digesting sludge, municipal solid waste organics and biogas to increase biogas production, minimising energy consumption, enhancing process control and improving effluent quality. The plant transformed from a large electrical power consumer into a producer of electricity and heat (180% of its demand) to achieve carbon neutrality (Jazbec, 2020).

Other key regulations and guidelines that impact municipalities when implementing energy efficiency and generating renewable energy at WWTPs within a CE are as follows:

White Paper on the Renewable Energy Policy of the Republic of South Africa

The White Paper on Renewable Energy Policy's objective is to give much needed thrust to renewable energy. The policy envisages a range of measures to bring about integration of renewable energies into the mainstream energy economy. The policy set a target of 10,000 GWh renewable energy contribution to final energy consumption by 2013, to be produced mainly from biomass, wind, solar and small-scale hydro. The renewable energy is to be utilised for power generation and non-electric technologies such as solar water heating and biofuels. (DME, 2003).

National Energy Efficiency Strategy

The Energy Efficiency Strategy (EES) which came into effect in 2005 (revised in 2008 and 2011) aims to assist in providing energy for all residents of South Africa and to minimise the negative effects of energy usage on human health and the environment, by reducing energy consumption through efficient practices and sustainable energy development. The recently updated strategy prioritises energy efficiency programmes and has an overall target of 12% of energy efficiency for the country, 10% for residential and 15% for other sectors by 2015. (DME, 2005, 2008).

The Integrated Resource Plan (IRP)

The IRP (2010-2030) was developed from the Electricity Regulation Act of 2006 and is an electricity infrastructure development plan based on least-cost electricity supply and demand balance, considering security of supply and the environment (minimize negative emissions and water usage). The plan makes provision for efficiency and renewable energy development and yet also calls for new coal-fired power stations and nuclear. Priority has been given to the deployment of renewable energy technologies and provision has been made for distributed generation which is intended to allow for power generation embedded within municipal distribution networks and therefore diversify their supply base (DME, 2007).

Biofuels Industrial Strategy

The strategy was adopted in 2006 (and revised in 2007). The strategy stipulates a 2% (400 million litres per year) level of penetration into the national liquid supply to be achieved within a 5-year pilot period. The 2% level can be achieved without jeopardising food security. The strategy targets new and additional land and proposes that basic food crops be excluded in the initial stages. A fuel levy exemption of 50% on biodiesel and 100% fuel tax exemption for bioethanol are proposed. The strategy therefore provides opportunities for the wastewater sector to participate in biofuels generation from sludge by incorporating appropriate technologies (DME, 2007).

Local Government Energy Efficiency and Renewable Energy Strategy

The strategy was developed through a consultative process with municipalities and provides guidance on developing energy efficiency and renewable energy strategies. The document also provides an indication/outline of key energy efficiency and renewable energy areas for local government to address as well as an outline of key areas of support work to be taken forward by SALGA, in partnership with relevant national departments and key stakeholders (SALGA, 2014).

The White Paper on National Climate Change Response

The White Paper presents the country's vision for an effective climate change response and the long-term transition to a climate-resilient low carbon economy and society. Although the document does not clearly argue for the benefits of renewable energy and energy efficiency the identified interventions to mitigate emissions, the main opportunities given in the document consist of energy efficiency measures, demand-side management and moving to a less emissions-intensive generation mix (SALGA, 2014).

Other Legislation and Regulations

Local municipal bylaws and strategic planning documents also need to be considered. Relevant authorisations and licences will need to be obtained to undertake activities that generate energy within a CE. These include environmental authorisations for sourcing and use of external biomass for co-processing with sludge as well as construction and upgrading of any facilities, atmospheric emission licences, facility registration for energy generation and supply to the grid, storage of biofuel, etc.

6.5.2 Barriers to Energy Efficiency at WWTPs

Energy generated from wastewater sludge falls into the category of biomass renewable energy. Any excess energy that is generated and has to be used in the community will be under this classification. Some of the key issues that impact implementation of energy efficiency and renewable energy projects in SA include:

Complex Legislation and Regulation

The national legislative environment imposes numerous challenges for municipalities to implement energy efficiency and renewable energy initiatives. The role/mandates of municipalities in implementing these measures are also not clearly defined. Furthermore, as discussed in the water pathway, complex procurement legislation and regulations are also a barrier to municipalities to procure technologies and services to implement energy efficiency projects at WWTPs.

Shifting Renewable Energy Strategies

The successful Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) has been marred by uncertainty in the past when it was suspended after Eskom announced that it would no longer sign Power Purchase Agreements (PPA) with Independent Power Producers (Odendaal, 2017). Although the programme is now back on track, it has created uncertainty on the commitment of government and its agencies to renewable energy. Furthermore, although the IRP makes provisions for renewable energy development, it also calls for new coal-fired power stations which is creates uncertainty.

Institutional Barriers

Institutional barriers that exist at the municipal level include (IEA, 2016; Feng et al., 2012):

- Lack of incentives or conflicting incentives to staff regarding energy efficiency
- Energy efficiency measures require upfront investment, which can deter action if financing is associated with an increase in water tariffs
- While energy efficiency projects save electricity their adoption can interrupt processes or increase operational and maintenance requirements and cost
- Due to differences in process configurations, wastewater quality and effluent discharge standards, energy conservation measures are not easily replicated from one plant to another making energy conservation onerous and costly
- Subsidising electricity cost resulting in low tariffs

Lack of Skills and Capacity

There is a shortage of knowledge and skills regarding energy efficiency opportunities, solutions, costs, benefits, etc. at municipal level. Municipalities often do not have energy management programs and therefore do not have the capacity and data to determine the potential for energy efficiency improvements. There is also limited experience regarding appropriate procurement models for renewable energy and energy efficiency projects. More energy efficiency and renewable energy skills are also required at government level to ensure strong partnerships with municipalities and the private sector.

Finance Access and Availability

Key financial barriers include low credit rating of municipalities, unattractiveness of energy efficiency projects to lenders and an underdeveloped financing market. Furthermore, as with many developing countries, South Africa is no exception to political volatility. This political volatility results in shifting strategies and regulation making it difficult to attract private sector investment. Although PPPs are also a solution, the same barriers identified for WRR schemes apply and need to be addressed.

High Risk of Energy Efficiency Projects

The market for energy efficiency technologies is still in its infancy stage in South Africa and the lack of maturity leads to higher volatility and thus to greater risk. In the case where excess energy is generated at a WWTP, selling electric power to the private sector would only be attractive if the buyer was willing to buy electricity at a premium price, for example if the buyer wanted to promote its green profile. Such an option is complicated and costly as long-term commitments must be negotiated between the Municipality and the buyer as part of a Power Purchase Agreement and wheeling arrangements to transport electricity to the buyer must be concluded with the owner of the grid. Experience indicates that, given the complexity in ensuring a constant supply of sludge (e.g. if the municipal WWTP breaks down or operates inefficiently), such arrangements would entail high levels of risk.

Energy Efficiency Incentives

To promote energy efficiency and fully exploit the energy pathway potential within a CE, both regulation and incentives are required. The revised DWS incentive-based regulatory Green Drop 2021 program (which is due in 2022) will contain an energy component as recommended from previous studies and consultations with stakeholders. Energy audits and GHG emissions monitoring are expected to eventually be part of Drop audits.

In preparation for the new Drop certification program, municipalities should already start using the existing guidelines for energy conservation and energy generation in their strategic planning processes and include specific targets for energy efficiency in their operations in the Water Services Development Plans (WSDPs). Frequent energy audits should also be undertaken. Furthermore, municipalities need to be aware of and pursue energy efficiency incentives and rebate programs.

6.6 Summary

This section has evaluated the key factors that impact transitioning to a CE in the South African wastewater sector focusing on the three interrelated pathways (water, materials and energy). While large metros have taken significant steps to implement WRR and energy recovery to alleviate water and electricity shortages, shifting from the traditional linear approach of wastewater management is challenging and requires a multi-pronged approach and collaboration between all levels of government and private sector and community participation. Appropriate institutional and governance structures need to be in place for the CE approach to be accepted and integrated into municipal water services planning. These include the planning decisions made by various institutions that affect the management of resources at different governance scales. Municipalities should also endeavour to strongly influence factors that are not directly in their control such as in the regulatory environment. Successful transition also requires that all levels of government analyse and understand these factors and then develop national and local government frameworks and strategies to achieve CE in the water sector.

Countries and water utilities that have taken significant steps in transitioning to a CE have addressed the challenges at a systemic level, driven by government agencies, policies and programs. Some of the recommended specific targeted actions that government departments such as the DWS can take to support municipalities' transition to a CE are given in Table 6-2.

Table 6-2: Suggested Specific Targeted Actions that Government Departments can Take to Support Municipalities to Transition to a Circular Economy (adapted from Jazbec et al., 2020)

Action	Description
Level Playing Field	• Putting in place circular economy frameworks and policy actions that include metrics and indicators and set targets • Enabling market opportunities to decrease investment risk in circular economy projects and businesses • Enabling equitable competitive conditions for circular businesses and development of circularity standards • Removing legislative and regulatory barriers to circular economy
Value Chain Collaboration	• Facilitating the collaboration and alignment of partners within the value chain to optimise the circularity of resources • Enabling and rewarding value-chain collaboration
Long Term Value Creation	• Disclosing environmental and social benefits through credible, standardise valuation methods • Setting up actions to incorporate and reward product longevity, thereby ensuring their longer use
Market Participation	• Facilitating better participation of consumers or end-users in the market to optimise for the circularity of resources
Integration of the Public Good	• Considering both the cost and benefits of externalities in consumption and production to achieve positive community outcomes
Circular Economy Finance Knowledge	• Creating tools to value circular business models correctly (credit risk, solvency, time, customer loyalty, breakeven and initial capital investment will be different to linear models) and use circular economy definitions and tools to measure "circularity" • Increasing awareness and knowledge of circular economy within the financial departments and institutions
Incentives for First Mover Action	• Removing policies that subsidise linear models, and replacing them with financial or fiscal incentives for circular economy • Creating markets via public procurement policies based on circular economy

The water sector also needs to take actions to embed circular economy principles and practices within their organisations. Some of the suggested targeted actions that municipalities can take are given in Table 6-3.

Table 6-3: Suggested Specific Targeted Actions that Municipalities can Take to Support Municipalities to Transition to a Circular Economy (adapted from Jazbec et al., 2020)

Action	Description
Leadership	• Facilitating a sector-wide visioning process for the circular economy approach • Showcasing leadership within the water industry on circular economy innovation and initiative
Partnerships and Planning	• Facilitating collaboration between urban, water and other planning professionals • Developing and sharing best practice information with other sectors • Develop collaborative policy and research opportunities with government agencies and initiatives that support circular economy across related sectors (e.g. waste management, agriculture)
Knowledge and capacity	• Establishing a circular economy special interest group incorporating members from Municipalities/SALGA and other institutions like the WRC • Developing circular economy materials that provide guidance for WSAs transitioning to a circular economy approach • Investigating opportunities for finance • Working with WSA's supply chains to better understand material flows, and to support the recycling of products used and produced • Funding and commissioning collaborative research on current circular economy knowledge gaps, opportunities and challenges including ways to assist in circular economy decision making evaluation and measurement at multiple scales • Capturing and publishing case studies and lessons learnt that illustrate broad circular economy innovations, including technological advances, governance approaches, and institutional and financial models • Building capacity in the urban water industry on the circular economy.
Measuring Benefits	• Developing a comprehensive set of circular economy indicators for water utilities that include natural and social capitals • Liaising with regulators to recognise the opportunity cost, capital offsets, and triple bottom line benefits associated with circular economy • Continuing to engage with customers to understand their preferences and willingness to pay for circular economy outcomes.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The project evaluated the role of sludge to energy technologies in accelerating the adoption of circular economy principles in the wastewater sector using wastewater treatment plants (WWTPs) as the centre of that transition by converting them into resource recovery centres. The emerging enhanced hydrothermal polymerisation (EHTP) polymeric carbon solid process that had shown, in previous research projects, to be effective in treating sludge from conventional WWTPs as well as a wide range of biomass was selected as the case study technology. The main objectives of the projects were to:
The main objectives of the project were to:

- Conduct a literature review to determine the global water sector CE status and the most appropriate frameworks and strategies that can be adapted for application by South African WSAs
- Assess the effectiveness of the EHTP technology to process wastewater sludge in combination with waste biomass from the community and evaluate beneficial use of the produced hydrochar within a CE
- Identify technologies at technology readiness level (TRL) 8 and above that can be coupled with the EHTP process to fully convert WWTPs into resource recovery centres and accelerate transition to a CE
- Identify local factors that impact transitioning to a CE as well as strategies that can be applied to develop a framework that can assist WSAs accelerate and successfully transition to a CE in wastewater management

A 60-litre EHTP pilot reactor was installed at Plant A and wastewater sludge (primary sludge, waste activated sludge and anaerobically digested sludge) was processed in combination with waste biomass (food, paper, yard, wood and industrial waste) from the community as well as faecal sludge from ventilated improved pit (VIP) latrines. Various analysis (microbiological, chemical, calorific value, proximate and elemental) were conducted on the sludge feedstock and process products (hydrochar and process effluent as appropriate). The key findings from the project were:

- The International Water Association (IWA) recommended framework for transitioning to a CE in the water sector was found to cover all aspects of the water cycle and therefore the most appropriate to be adapted to South African conditions
- The EHTP technology successfully processed sludge in combination with faecal sludge from VIP latrines and waste biomass from the community to produce a sterile hydrochar. The hydrochar
  - had a higher calorific value than the feedstock and can be used as a biofuel for energy generation

    - had higher concentrations of organics and nutrients than the feedstock and met the Department of Water and Sanitation (DWS) criteria for Class A1a biosolids with unrestricted use in land application. Further investigations into viability of using the hydrochar in agriculture are currently being undertaken
    - can be converted to activated carbon that can be used as adsorption media for tertiary treatment of wastewater effluent. Further investigations are being undertaken to determine efficiency of the hydrochar derived activated carbon in removing micropollutants from wastewater effluent
    - can be used (as well as ash from combusting the hydrochar as a biofuel) in the building industry for cement and brick making. Further investigations are required to assess the quality of the produced cement and bricks
- The EHTP process can be successfully incorporated into WWTPs and coupled with other emerging and established technologies to fully convert WWTPs into resource recovery centres and produce by-products that can be used within the IWA framework interrelated pathways (water, energy and materials) that accelerate transition to a CE
- Key factors that need to change to ensure that WSAs can accelerate and successfully transition to a CE are governance, policy, regulations, consumer perceptions on wastewater by-products, infrastructure and technology. Strong leadership within central and local government was also identified as a key requirement to successful shift from a linear to a CE in wastewater management

The results from this project demonstrated that multi-biomass processing technologies like the EHTP process can be successfully incorporated into WWTPS and process wastewater sludge combined with low-cost sanitation systems faecal sludge and other waste biomass from the community to produce hydrochar that can be beneficially used within the IWA framework interrelated pathways for successful transition to a CE. The technology can also be coupled with other technologies to convert WWTPs into resource recovery centres at the centre of the transition. To ensure accelerated and successful transition to a CE by WSAs, governance, policy and regulations need to be changed through strong leadership at central and local government level. Other key factors that also need to be shifted from the linear to CE approach are technology, infrastructure, consumer behaviour and economics

7.2 Recommendations

Since CE is a nascent field to the South African water sector it is recommended that additional research be conducted to continue building knowledge that can be used by the water sector to successfully transition and implement CE. The following is recommended:

- Study that demonstrates a CE project using various municipal WWTPs as case studies. The study will include an assessment of key factors that impact the case study municipalities transitioning to a CE, development of CE solutions within the three interrelated pathways as well as costing and financing options. The study will assist the wastewater sector develop concrete strategies for transitioning to a CE
- Further research into the impact of current legislation and regulations and how they can be improved to support a CE in the water sector. The research will also include development of a national framework for CE in the water sector.

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APPENDIX A CHAPTER 2 & 3 TABLES

Table A-1: Approaches for Addressing Public Resistance to the Potable Use of Reclaimed Water (Muanda et al., 2017)

Stages	Emotions/ Perceptions	Approach			
		Knowledge Required	Medium	Engagement/Involvement	Medium
Planning **Water Scarcity and risk management**	**Doubts** **Denial** Fear Stress Confused Mistrust Imposition	Inform about water scarcity Provide tangible evidence of water scarcity Communicate risk management plans	Information management system Use of signs and boards Use flyers and pamphlets Use media Water bill Brochures	Public awareness Participate in meetings Address issues and concerns Public advisory board	Public relation campaign Presentation (using facts) Posters (with facts) Media Flyers, advert, boards School programme
Reconciliation Study	**Doubt** Neglected Unconsidered	Inform public about purposes, outcomes and impacts (before and after)	Information centre Leaflet Use of water bill Use of media	Discussion forums Public meetings/dialogue	Presentations Posters Use of media Use of water bill
Feasibility Study	**Mistrust** Neglected Unconsidered Doubtful Fear/Worry	Inform public about purposes, outcomes and impacts (before and after)	Information centre Leaflet Use of water bill Use of media	Discussion forums Public meetings/dialogue Public advisory board	Presentations Posters Use of media Use of water bill
Reuse decision	**Fear/worry** Anger Unfairness Disgust Imposition Unconsidered Despair/Shame Mistrust	Basis for decision Decision making process Technology selection criteria and effectiveness Treatment process	Information centre Use of media Use municipal notice board and website Use of water bill Demonstration (lab scale model) Use high profile people/celebrity Share previous experiences	Public advisory board Public meetings Discussion forums with public representatives Schools visit	Political marketing Use of councillors to inform Presentations Agenda and themes for discussions
Implementation	**Safety** Fear/worry Unconsidered Confused Shame/Sadness Imposition	Implementation process Safety measures Timeline for implementation Technical information Qualifications of plant working and management staffs	Information centre Use of media Refresher course for plant staffs	Public advisory board Public meetings Public guided plant visits	Presentations Posters
Post-implementation	**Trust** Unsafe Unconsidered Anger Doubtful Fear/Worry	Monitoring programme/schedule Water quality monitoring parameters and frequency/process Water quality results (BD and GD) Safety measures Risk management plan	Information centre Use of media Use of municipal notice board and website Periodic check up by health officials Use of water bill	Guided plant visits Information campaign School visits Road show Information sharing sessions	Plant visit programme Posters & leaflets Banners Booklets Themes for discussion Use of medical experts

Table A-2: Proximate Analysis for Sludge, FS, Combined Sludge and FS Feedstocks and Hydrochar

Parameter (% dry basis)	PS & WAS		Digested Sludge		Area B Coarse Screened FS		Area B Coarse Screened FS + PS&WAS		Area B Fine Screened FS		Area B Fine Screened FS + PS&WAS		Area (A) FS		Area (A) FS + PS&WAS	
	Feed stock	Hydrochar	Feed stock	Hydrochar	Feed stock	Hydrochar	Feed stock	Hydrochar	Feed stock	Hydrochar	Feed stock	Hydrochar	Feed stock	Hydrochar	Feed stock	Hydrochar
Volatiles	73.0	58.2	60.7	44.4	49	35.6	51.8	37.2	46.9	30.3	50.6	35.3	64.2	49.5	66.7	64
Fixed Carbon	8.7	11.7	9.7	11.7	7.3	10	8.2	10.1	6.7	9.8	9	10.5	10.3	9.8	14.4	15.2
Ash	18.3	30.2	29.6	44.1	43.5	54.2	39.1	52.6	46.1	59.9	40.1	54.1	25.3	40.8	18.8	20.8
% TS reduction		39.3		32.9		19.8		25.7		23.1		25.9		38		9.8
% VS Reduction		51.7		51		41.7		46.7		50.4		48.2		52.2		13.4

Table A-3: Proximate Analysis for Sludge and Sludge & Other Waste Biomass Feedstocks and Hydrochar

Parameter (% dry basis)	PS/WAS		DS		DS + Screenings		PS/WAS + Screenings		DS + Screenings + Paper waste		PS/WAS + Screenings + Paper waste		DS + Screenings + Food waste		PS/WAS + Screenings + Food waste		DS + Screenings + Food + Paper waste		PS/WAS + Screenings + Paper+ Food waste	
	Feed stock	Hydro char	Feed stock	Hydro char	Feed stock	Hydro char	Feed stock	Hydro char	Feed stock	Hydro char	Feed stock	Hydro char	Feed stock	Hydro char	Feed stock	Hydro char	Feed stock	Hydro char	Feed stock	Hydro char
Volatiles	73.0	58.2	60.7	44.4	75.4	70.2	81.8	68.5	59.9	58.6	72.9	55.9	76.3	55.1	75.0	57.0	65.7	63.6	80.7	54.9
Fixed Carbon	8.7	11.7	9.7	11.7	13.5	16.5	7.2	22.5	9.8	19.5	14.0	24.5	11.2	24.9	14.4	18.4	10.4	21.5	16.7	36.7
Ash	18.3	30.2	29.6	44.1	11.1	13.4	8.8	11.1	30.4	21.8	13.1	19.6	12.5	20.0	10.6	24.6	23.9	14.8	2.4	8.4
% TSS reduction		39.3		32.9		17.2		20.2				33.0		37.6		56.7				71.4
% VSS Reduction		51.7		51.0		23.0		33.2				48.6		54.9		67.1				80.6

Table A-4: CHONS Analysis Results for Area B and Area (A) FS and Hydrochar

Sample	C	N	H	S	Ash	O	H/C	O/C
	%	%	%	%	%	%		
Sludge Feedstock and EHTP Hydrochar								
Primary Sludge Hydrochar	36.9	2.0	5.1	1.3	42.6	12.0	0.139	0.326
Primary Sludge + Screenings Hydrochar	36.2	1.7	6.6	0.7	33.9	20.9	0.181	0.577
WAS Feedstock	31.0	12.8	3.0	1.3	28.9	40.7	0.097	1.313
WAS Hydrochar	41.9	13.0	2.8	0.9		34.0	0.067	0.811
Digested sludge Feedstock	28.0	3.6	4.6	1.3	47.9	14.7	0.163	0.524
Digested Sludge Hydrochar	28.5	2.2	4.2	1.2	51.9	11.9	0.148	0.435
Composted Sludge feedstock	24.4	14.4	3.3	1.3	37.0	50.3	0.135	2.061
Composted Sludge Hydrochar	34.2	16.4	2.6	0.9		49.4	0.076	1.444
FS Feedstock and EHTP Hydrochar								
Area B Coarse Screened FS Feedstock	27.3	2.0	3.7	0.9	43.5	17.9	0.133	0.656
Area B Coarse Screened FS Hydrochar	24.9	1.7	3.0	0.7	54.2	10.3	0.120	0.414
Area B Fine Screened FS Feedstock	25.7	2.1	3.8	0.9	46.1	21.5	0.147	0.837
Area B Fine Screened FS Hydrochar	15.4	1.3	1.9	0.5	59.9	21.0	0.124	1.364
Area B Fine Screened FS + PS & WAS Feedstock	30.0	2.3	4.6	0.9	39.1	23.1	0.152	0.769
Area B Fine Screened FS + PS & WAS Hydrochar	32.4	2.0	3.9	0.7	52.6	8.3	0.121	0.256
Area B Coarse Screened FS + PS & WAS Feedstock	19.2	1.6	2.9	0.6	40.1	35.6	0.150	1.854
Area B Coarse Screened FS + PS & WAS Hydrochar	22.5	1.7	3.0	0.5	54.1	18.2	0.133	0.810
Area (A) FS Feedstock	39.9	3.5	5.7	0.8	25.3	18.0	0.145	0.450
Area (A) FS Hydrochar	39.6	2.3	5.6	0.5	40.8	9.7	0.140	0.245
Area (A) FS + PS & WAS Feedstock	38.5	4.9	6.0	0.7	18.8	31.1	0.156	0.809
Area (A) FS + PS & WAS Hydrochar	52.3	2.5	7.1	0.5	20.8	16.8	0.136	0.321
Other Fuels								
Wood	50.0		6.0			44.0	0.120	0.880
Peat	54.8	0.9	5.4	0.1	3.0	35.8	0.099	0.653
Lignite	70.0	25.0	5.0			25.0	0.071	0.357
Coal (Pittsburgh Seam)	75.5	1.2	5.0	3.1	10.3	4.9	0.066	0.065
Bituminous Coal	83.0	2.0	5.0			11.0	0.060	0.133
Anthracite	83.0	2.0	3.5			2.0	0.042	0.024

APPENDIX B THE PLANNING LEGISLATIVE AND POLICY CONTEXT AND TRANSITION TO WASTEWATER AND SOLID ORGANICS CIRCULAR ECONOMY IN SOUTH AFRICA

B1 Overview

Globally, there is increasing policy thrust towards transition from linear to circular economies. The linear economy which has been dominant since the industrial revolution regards waste from production and consumption activities as an end with no reuse value. Likewise, waste disposal through dumping into the environment has been a key feature of industrial and modern economies. The post-modern turn in the world economy heralded transition from linear to circular economies. In circular economies, unlike in the linear economic mode of production, waste is not an end, but rather a means to creating a new economy through recycling and purification of waste.

In South Africa, transition to a CE in wastewater management is still in its infancy. This project is the first initiative to explore strategies that accelerate this transition focusing on using technology and WWTPs as resource recovery facilities. The spatial planning policy and legislative context plays a central role in enabling the transition from linear to circular economies. All spatial and development planning initiatives in South Africa must be guided by Municipal Integrated Development Plans (IDPs). However, the question that requires interrogation is what changes need to be made to the current planning policies around wastewater management in municipalities to support transition from the current linear economy to a CE in the water sector. Linked to this is also the question of what catchment/basin economies can be promoted through changing to CE. These questions cannot be fully answered without looking at the history of planning, planning policies and legislation in South Africa. Planning evolved from being an autocratic and top-down state activity during the apartheid era to being relatively more democratic and inclusive in post-apartheid South Africa. Three historical periods can be identified in the South African planning legislative and policy context. These are the colonial period to the peak apartheid era, late apartheid era and the current post-apartheid era.

B2 Planning policy and legislation during Colonial and Peak Apartheid Period

The annexation and subsequent colonisation of South Africa by Europeans was significant in the development planning policies and legislations. According to van Wyk (1999) during the colonial period planning policies and legislations followed the British example as shown using restrictive covenants in the regulation of land use. However, this trend was fused with racial and segregationist agendas of the colonial government. Van Wyk points to the fact that restrictive covenants made up of race, use and density were used to regulate land use. As urban growth and urbanisation became more pronounced restrictive covenants became less and less relevant in the regulation of land use at a city-wide scale. This led to the introduction of the following planning legislations:

- The Gold Law 8 of 1885 (T) provided for orderly settlement of mining population, and for the setting aside of sites for residential, recreational, afforestation and mining uses
- Crown Land Disposal Ordinance 57 of 1903 (T) land could be reserved for specific purposes including churches, education, cemeteries, recreation, etc.
- The Public Health Act of 1919 provided for the subdivision and layout of land for building, the width of streets, the limitation of dwellings on sites and zones within which different land use limitations would apply. Influenced by health problems resulting from WW1
- Building Laws regulated the structure and soundness of buildings, density, height, and coverage
- To coordinate and control town planning, the Proclamation of Townships Ordinance 19 of 1905 (T) made provision for a Townships Board to process the applications for township establishment. This was followed by amendments – the Townships Act of 1907 (T)

A significant milestone in the development of Town Planning Legislation in South Africa was the passing of the Transvaal Townships and Town Planning Ordinance 11 of 1931. This called for the use of Town Planning Schemes by local authorities and is widely regarded as one of the earliest town planning legislations in South Africa. However, it should be noted that this planning legislation was differentially applied along racial lines. The Transvaal Townships and Town Planning Ordinance 11 of 1931 only applied to areas that were domiciled by the White population group. Areas where the Black population group resided (mostly rural areas) were not compelled to use schemes as mechanisms for land use management and regulation.

Racial segregation in Spatial Planning in South Africa intensified when Apartheid was introduced in 1948. The Group Areas Act, the Amendments to the Urban Areas Act of 1952, 1957, 1964 and 1971 required racial segregation within discrete areas of the four racial groups recognized by the Population Registration Act in South African cities (McCarthy, 1992). As such regardless of the functional interdependence in and around South African cities during the apartheid era, there was fragmented spatial planning based on racial geography.

B3 Late Apartheid Period

From the late apartheid period that loosely spans from the mid-80s to the 1994, there was realisation that exclusive and fragmented spatial planning in and around South African cities was unsustainable. This led to reforms to the apartheid spatial planning policies and practices. Key spatial planning legislations that were introduced in this regard include the Identification Act of 1986; the Abolition of Influx Control Act of 1986; Regional Services Council Act of 1985 and the Development of Housing Act of 1985. According to McCarthy (1992) the main focus of these legislations was removal of apartheid racial restrictions on the movement of people in urban areas and they also committed to equitable service provision. The other important planning legislations that were introduced during late apartheid include the Abolition of

Racially Based Land Measures Act of 1991, the Upgrading of Land Tenure Rights Act of 1991 and the Less Formal Township Establishment Act. According to Mabin and Smit (1997) the focus of these legislations was to speed up land development in cities in the face of rapid urban growth and urbanisation.

B4 The Post-Apartheid Period

A democratic dispensation started in South Africa in 1994 with a democratically elected government. As part of the democratic dispensation a suite of changes were made in the spatial planning and development planning legislation with the view of reversing the apartheid legacy of fragmented and exclusionary spatial planning. The post-apartheid government embarked on the Reconstruction and Development Programme (RDP) with the objective of poverty alleviation through addressing socio-economic and basic infrastructures services backlogs. It is in this context that a range of spatial planning and development planning legislations were introduced and these have implications for sustainable transition from linear to circular economic models in wastewater and waste organics. The legislations and policies are in the sphere of spatial planning, land use management, local government, and housing.
Spatial planning and land use management legislation in post-apartheid South Africa.

Development Facilitation Act (DFA)

The Development Facilitation Act (67 of 1995, DFA) was introduced as 'the only post-1994 national planning legislation that dealt with spatial development principles and land use management mechanisms. It was used alongside provincial and homeland legislation as well as Municipal Town Planning Schemes. In 2010, Chapters 5 and 6 of the DFA that dealt with land use management were ruled unconstitutional because they granted land use management powers to provincial tribunals. The Supreme Court of Appeal (SCA) argued that powers to approve land use applications were core municipal functions. This in turn led to the introduction of the Spatial Planning and Land Use Management Act (SPLUMA), (SACN, 2015).

SPLUMA

SPLUMA was developed to legislate for a single, integrated planning system for the entire country. It contains the following elements:

- Definitions, objectives, definition of planning system and categories of spatial planning (Chapter 1)
- Development principles; provision for the development of norms and standards (Chapter 2).
- Intergovernmental support (Chapter 3)
- Spatial development frameworks (Chapter 4)
- Land use management schemes (Chapter 5)
- Land development management, including tribunals (Chapter 6)
- General provisions (Chapter 7).

According to the Department of Rural Development and Land Reform (DRDLR), the custodian department of SPLUMA, the enactment of SPLUMA has brought seven fundamental changes to spatial planning and land use management. These changes are:

- Reiteration of the sole mandate of municipalities where municipal planning (land development, land use management) is concerned, placing municipalities as authorities of first instance invalidating inconsistent parallel mechanisms, parallel systems and measures or institutions that existed to deal with land development applications
- Establishment and composition of municipal planning tribunals and appeals structures by municipalities to determine, and decide on, land development applications.
- Providing municipalities with options for tribunals and appeals structures to be created based on capacity
- Development of a single and inclusive land use scheme for the entire municipality with special emphasis on a municipal differentiated approach
- Preparation of respective SDFs by all three spheres of government, based on norms and standards guided by development principles
- Preparation of Regional Spatial Development Frameworks as may be required
- Strengthened intergovernmental support through enforcement, compliance and monitoring processes
- Alignment of authorisation processes where necessary on policies and legislation impacting land development applications and decision-making processes.

Post-Apartheid Local Government Reform and Legislation

Since the last days of apartheid in South Africa, the need to transform fragmented local government was apparent. During the height of apartheid, local government mostly in and around the main cities was spatially segregated according to racial geography. The compelling need for comprehensive local government boundaries and municipal planning were spelt out in the Local Government Transition Act, Second Amendment of 1996 (LGTA). According to Musvoto (2011: 288) the LGTA, required local government to draft Integrated Development Plans (IDPs) based on the assessment of local realities, determination of local needs, vision, resources, skills, prioritisation, integrated development frameworks, implementable projects and monitoring and evaluation. The transformation of local government spelt out in the LGTA culminated into the 1998 White Paper on Local Government; Municipal Demarcation Act of 1998; Municipal Systems Act of 2000 and the Municipal Structures Act of 2000.

White Paper on Local Government

The White Paper on Local Government alludes to the fact that local government is the form of governance that is closest to the people. Likewise, it notes that it must play a central role in reversing the apartheid legacy of spatial fragmentation and unbalanced distribution of resources along racial lines. To play this role effectively the White Paper on Local Government argues that local government must be developmental. That is, it must play a leading role in integrating and coordinating development and must also lead and learn. Key instruments in integrating and aligning development highlighted by the local government white paper are IDPs, budgeting, performance management and working together with local citizens and partners.

The Municipal Demarcation Act of 1998

The Municipal Demarcation Act of 1998 gives power to the Municipal Demarcation Board to define and redefine local government boundaries in consultation with stakeholders.

Municipal Structures Act of 2000

The Municipal Structures Act outlines the types and criteria for the demarcation of the different types of municipalities in South Africa. Three categories of Municipalities namely A, B and C are identified. Category A municipalities are metropolitan municipalities and are defined according to the following criteria:

- A conurbation featuring areas of high population density; and an intense movement of people, goods and services; extensive development; and multiple business districts and industrial areas.
- A centre of economic activity with a complex and diverse economy.
- A single area for which integrated development planning is desirable.
- Having strong interdependent social and economic linkages between its constituent units.

Municipal Demarcation Board South Africa (2010: 1)

Category B Municipalities are based on settlement types, manageable size, and functionality. Category C Municipalities are District Municipalities, and these comprise of a defined group of local municipalities.

Municipal Systems Act of 2000

The Municipal Systems Act stipulates that all spatial development initiatives within Municipalities must occur within the ambit of IDPs. The Municipal System Act defines an IDP as a super plan for an area that provides an overall framework for development through coordinating the work of all spheres of government, namely local, district, and central as well as all stakeholders such as the private sector, civil society and NGOs in efforts to enhance development (Musvoto, 2011: 235).

Housing legislation and policies

The housing agenda of the democratic South African government was first mostly spelt out in the Housing White Paper of 1994. Focus was on a National Housing Scheme, stabilisation of the housing markets, and mobilisation of housing finance. The 1994 Housing White Paper was translated into the Housing Act of 1997. This act clearly notes that housing is a basic human right and it also commits to the creation of socially and economically integrated communities which provide social and economic opportunities in relatively favourable locations. With the turn of the millennium, it became apparent that housing interventions that were given effect by the White Paper on Housing and the Housing Act were limited in terms creating sustainable human settlements. This led to the introduction of the Breaking New Ground (BNG) in 2004 (Department of Human Settlements, 2004). The BNG spells out the need to create sustainable human settlements through housing interventions that take consideration of environmental, social and economic aspects of development.

APPENDIX C CASE STUDIES FOR NON-POTABLE WASTEWATER EFFLUENT REUSE IN SOUTH AFRICA

C1 Durban Water Recycling Project (eThekwini Municipality)

Through a public-private partnership (PPP), the municipality successfully implemented a wastewater recycling project for industrial purposes. This project is an example of sustainable wastewater management with multiple environmental, economic, and social benefits for the region. In addition, the project is the first of its type in South Africa and became an exemplar of a solution that considers wastewater as an asset rather than a liability to be disposed of. Instead of increasing the capacity of the existing marine outfall pipeline in the city's Southern Wastewater Treatment Works (SWTW) to discharge primary treated wastewater to the ocean, Durban explored the possibility to further treat it and reuse it for industrial purposes. Mondi, a paper industry, and SAPREF, an oil refinery, expressed interest in receiving the treated wastewater. The goal of the project was to treat around 48 million litres per day (approximately the 10 percent of the city's wastewater) and achieve an acceptable quality for industrial reuse: 85 percent of the treated water would go to Mondi, and the rest to SAPREF. To be able to supply recycled water to the two industrial users, the municipal water utility (eThekwini Water Services [EWS]) needed to upgrade the existing activated sludge process, build a new tertiary wastewater treatment plant, refurbish the high-level storage tank, and install a reclaimed water reticulation system. One complexity of the project was that Mondi required high-quality water, given that it is used to produce fine paper. (World Bank, 2018). Specifications of the Durban Water Recycling plant are listed in TableC-1.

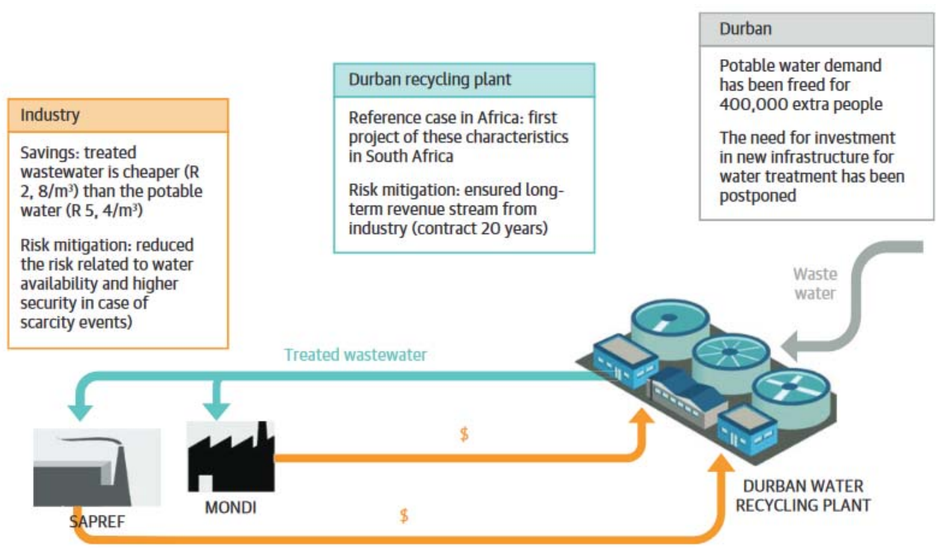


Figure C-1: Durban Wastewater Recycling Project and Benefits

Table C-1: Specifications of the Durban Water Recycling plant

Durban Water Recycling plant	
Size	47,500 m^3/day (capacity)
Main Innovations	Integrated wastewater management plan Multi-quality recycled water Innovative contract agreement and finance
Technology	**Secondary treatment:** conventional activated sludge and secondary sedimentation tanks **Tertiary treatment:** lamella settlers, addition of poly aluminium chloride (PAC), dual media filtration ozonation, Granular Activated Carbon (GAC) Adsorption, and chlorine disinfection
Water Consumption	
Mondi (paper Industry) Consumption	30, 000 to 39,000 m^3/day
SAPREF (Refinery) Consumption	3,300 to 8,900 m^3/day

C2 Beaufort West Wastewater Reuse

Beaufort West is a town in the Great Karoo region with a population of 34 000 people. Being in an arid region, Beaufort West has no perennial rivers and is therefore heavily reliant on groundwater for water supply. To diversify the municipality's water sources and increase water resilience, the municipality entered into a 20-year performance-based BOT PPP concession agreement with a private company for Direct Potable Reuse of wastewater effluent. The water reuse facility in Beaufort West produces 2.3 Ml/d of SANS Class 1 standard drinking water. The plant is configured with Memcor® ultrafiltration membranes to remove all total suspended solids, and a two-stage reverse osmosis plant to remove other smaller impurities and toxicants from the water. Finally, to ensure that the water is safe for human consumption, the water is treated with ultraviolet light and hydrogen peroxide – a step known as advanced oxidation. With this technology, this water-sparse Karoo town can augment its water supply for generations to come.

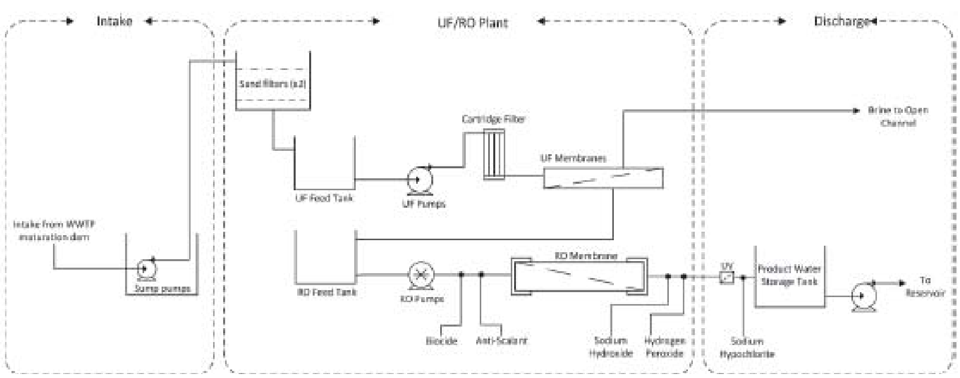


Figure C-2: Process Schematic of the Beaufort West Water Reclamation Plant

C3 City of uMhlathuze non-potable water reuse project for industries

The uMhlathuze Wastewater Project is key to ensure a sustainable water supply. The uMhlathuze Wastewater Project involves a feasibility study for a wastewater and associate by-products re-use facility for the City of Umhlathuze (CoU). The study will specifically explore the viability of procuring a public-private partnership (PPP) as the delivery mechanism for this re-use of treated wastewater facility. The project is currently awaiting views and recommendations from National Treasury (Genesis, 2017).

C4 Mossel Bay Municipality WWTW, Western Cape

The Mossel Bay plant involves water reclamation for industrial purposes only. Final effluent from the regional wastewater works is treated further to provide the high-quality water needed for the PetroSA refining process.

C5 Water reuse in Olifants River catchment

There is extensive water reuse in the Olifants River catchment, in Mpumalanga Province. Approximately 38 Ml/day from domestic sources and 205 Ml/d from industrial wastewater. This non-potable water is used for a variety of purposes including industrial process water, irrigation and mining usage. In addition to this, acid mine water is reclaimed and treated for potable and non-potable use.

There are three techniques that are used by businesses around the Olifants River:

i. Reuse of own water: The private partners reuse their own process water. This can either be through treatment and reuse for the same purpose, or through a cascading approach, whereby the quality of the water decreases as it progresses through different uses.
ii. Purchase of effluent from municipality: Some users in this catchment have effluent purchase agreements in place with eMalahleni Municipality, with a guaranteed volume to be purchased by the private party, with an allowance for deviations, and a volumetric rate for purchases above the agreed threshold. In these circumstances, the private partner put in the infrastructure, and transferred this to the municipality.
iii. Public-Private Partnership: The eMalahleni Water Reclamation Plant at eMalahleni is an initiative driven by Anglo Coal in partnership with BHP Billiton and dMalahleni Local Municipality. This plant reclaims acid mine drainage water and treats this to potable quality. The HiPRO (hi recovery precipitating reverse osmosis) plant produces 50 Ml/d at 99% efficiency. The water is sold to domestic customers, bottled, released to the environment for ecological reserve purposes, and used onsite (DWS, 2011).

C6 The Goreangab Water reclamation plant

Windhoek, Namibia was the first city to implement long term DPR without the use of an environmental buffer (USEPA, 2012). The Goreangab Water Reclamation Plant (WRP) Figure 2 3 with current capacity of

21 000 m^3/d has been practicing DPR since 1968, provides 35% of the potable water needs of Windhoek with a population of approximately 250 000 (Du Pisani, 2006).

Figure C-3: The Goreangab Water Reclamation Plant (Wingoc, 2014)

The Goreangab water reclamation plant (NGWRP), a 21,000 m^3/day facility built in 2002 incorporates the treatment process shown in Figure C-4 (Lahnsteiner et al., 2013). The reclaimed water, which is blended with treated surface water in a ratio of one-third to two thirds, accounted for 26% of the total amount of water produce in 2003 (Van der Merwe et. al., 2006). During the rainy season, the surplus potable water is injected into boreholes south of the city after an additional Granular Activated Carbon (GAC) filtration and disinfection treatment to prevent bacterial growth and clogging. By 1990, the alternative supply sources that were considered included pumping from the Tsumeb aquifer (located 490 km from the city), pumping from the Okavango River (750 km from the city), Managed Aquifer Recharge (MAR) in the southern part of Windhoek (offering storage possibilities of up to 11 Mm^3 per year). Table presents water treatment total capital cost.

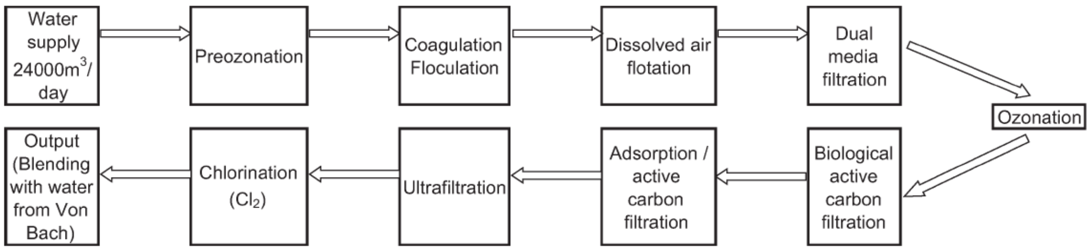
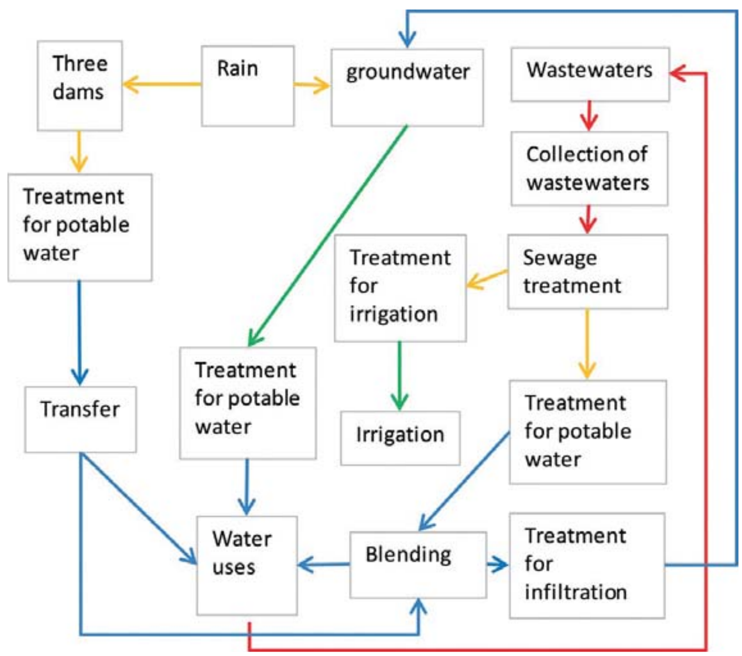


Figure C-4: Processes at the Goreangab water reclamation plant (Lafforgue and Lenouvel, 2015)



Notes: red: wastewater: yellow: raw water
green: treated water for non-potable uses
blue: drinking water

Figure C-5: The urban water cycle in Windhoek

Table C-2: New Goreangab water reclamation plant (21 Mℓ/d) capital costs (Turner et al., 2015)

NGWRP Capital Costs (breakdown estimated using typical rates)	Cost (Rand) (2001)	% of Project	Cost (Rand) (2014/15)	Unit Cost (Rm/Mℓ/d) (2014/15)
Direct Costs				
Intake	2 137 188	1.7	4 550 278	0.22
DAF	3 785 875	3.1	8 060 492	0.38
RG sand filters	4 885 000	4.0	10 400 635	0.50
Ozone	13 006 313	10.6	27 691 691	1.32
BAC	11 968 250	9.8	25 481 556	1.21
GAC	10 869 125	8.9	23 141 413	1.10
UF	13 128 438	10.7	27 951 707	1.33
Post-treatment	4 396 500	3.6	9 360 572	0.45
Waste treatment and disposal	1 221 250	1.0	2 600 159	0.12
Electrical, electronic and control	10 747 000	8.8	22 881 397	1.09
Civil building and structures	21 713 825	17.8	46 230 823	2.20
Bulk electrical supply	5 202 525	4.3	11 076 676	0.53
Product pumpstation & pipelines	5 495 625	4.5	11 700 715	0.56
Subtotal Direct Costs	**108 556 913**	**88.9**	**231 128 114**	**11.01**
Indirect Costs				
Professional fees, site monitoring, disbursements	13 569 444	11.1	28 890 653	1.38
Subtotal Indirect Costs	**13 569 444**	**11.1**	**28 890 653**	**1.38**
Total Cost (excluding VAT)	**122 126 357**	**100.0**	**260 018 768**	**12.38**

C7 Economics for Wastewater Reuse

The Water Services Sector in South Africa – An Overview

Water services refer to water supply and sanitation services and include regional water schemes, local water schemes, on-site sanitation and the collection and treatment of wastewater. Water and wastewater services are also essential for businesses and industries and efficient provision of these services can help to promote economic development and the eradication of poverty.

Municipalities either purchase untreated raw water from DWS, pumped from dams, rivers and boreholes, or purchase bulk water from Water Boards (e.g. Rand Water) treated to a potable standard.

The 2019/20 consumptive raw water charges ranged between R0.05/kl and R21.04/kl nationally (DWS, 2019). This charge includes:

- Water management
- Infrastructure charges, and
- A water research fund levy

The 2018/19 bulk water tariffs averaged R9.27/kl, varying from R5.04/kl to R17.52/kl. The tariff depends on various factors, such as the availability of water, water quality, distance of distribution, and cost of infrastructure finance (DWS, 2017). Table and

Table show the 2019/2020 residential & industrial water tariffs and sanitation tariffs (excluding fixed charges and surcharges). Industrial water tariffs across various metros are graphically illustrated in Figure C-6.

Table C-3: Water Tariffs for Selected Metros (Minimum Restriction Levels in Place) for FY 2019/20

		Cape Town		eThekwini		Tshwane		Ekurhuleni		Johannesburg	
		Monthly use (kl)	R/kl	Monthly use (kl)	R/kl	Monthly use (kl)	R/kl	Monthly use (kl)	R/kl	Monthly use (kl)	R/kl
Residential	Step 1	0-6	14.45	0-6	21.39	0-6	11.61	0-6	11.74	0-6	9.10
	Step 2	6-10.5	19.86	6-25	25.30	7-12	16.56	7-15	19.34	6-10	9.66
	Step 3	10.5-35	26.99	25-30	33.70	13-18	21.75	16-30	23.69	10-15	16.49
	Step 4	>35	49.80	30-45	51.98	19-24	25.16	31-45	29.47	15-20	23.99
	Step 5	–	–	>45	57.15	25-30	28.76	>45	36.35	20-30	32.96
	Step 6	–	–	–	–	31-42	31.08	–	–	30-40	36.51
	Step 7	–	–	–	–	43-72	33.26	–	–	40-50	46.62
	Step 8	–	–	–	–	>72	35.61	–	–	>50	49.66
Commercial & Industrial	Step 1					0 - 100 000	24.51	0-5 000	25.37	0-200	42.19
	Step 2	Not stepped	25.88	Not stepped	33.35	10 001-100 000	23.26	5 001 -25 000	25.77	>200	44.50
	Step 3					>100 000	21.68	>25 000	26.89	–	–

Table C-4: Sanitation Tariffs for Selected Metros (Minimum Restriction Levels in Place) FY 2019/20 (GreenCape, 2020)

		Cape Town L1		eThekwini		Tshwane		Ekurhuleni		Johannesburg	
		Monthly water use (kl)	R/kl of sewage	Monthly water use (kl)	R/kl of sewage	Monthly water use (kl)	R/kl of sewage	Monthly water use (kl)	R/kl of sewage	Property size (m^2)	R (Res) or R/kl (C&I)
Residential	Step 1	0-6	12.7	0-6	3.57	0-6	8.21	0-6	16.29	0-300	213.94
	Step 2	6-10.5	17.45	6-25	5.95	7-12	11.08	7-15	13.03	301-1000	416.47
	Step 3	10.5-35	24.51	25-30	11.37	13-18	14.27	16-30	5.54	1 001 -2 000	630.05
	Step 4	>35	38.55	30-45	17.67	19-24	14.27	31-45	5.09	>2 000	907.80
	Step 5	–	–	>45	19.72	25-30	14.27	>45	3.47	–	–
	Step 6	–	–	–	–	31-42	14.27	–	–	–	–
	Step 7	–	–	–	–	>42	14.27	–	–	–	–
Commercial & Industrial	Step 1							0-5 000	10.22		
	Step 2	Not stepped	23.25	Not stepped	9.02	Not stepped	9.14	5 001-25 000	5.45	Not stepped	31.54
	Step 3							>25 000	3.54		

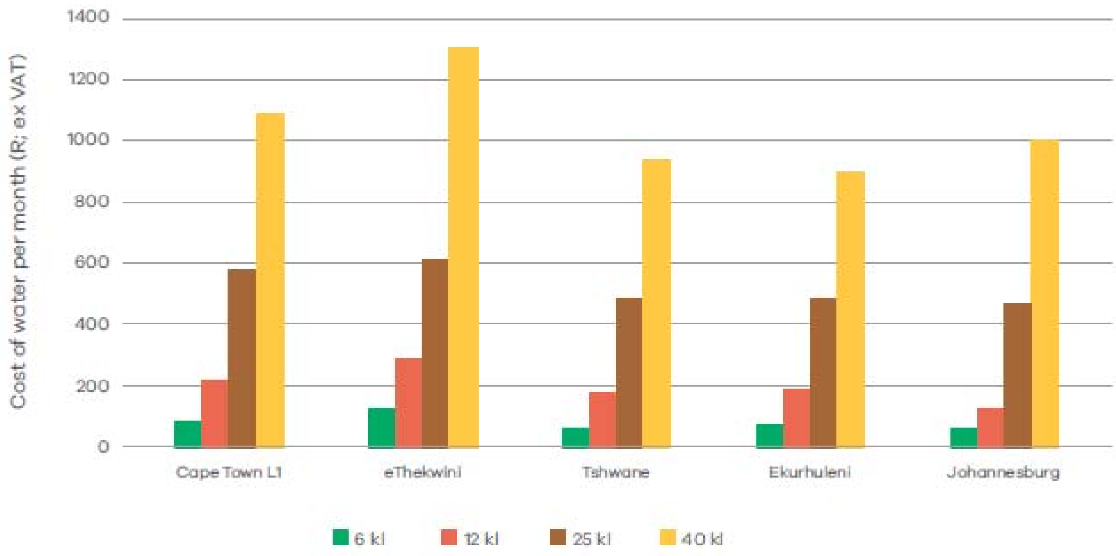
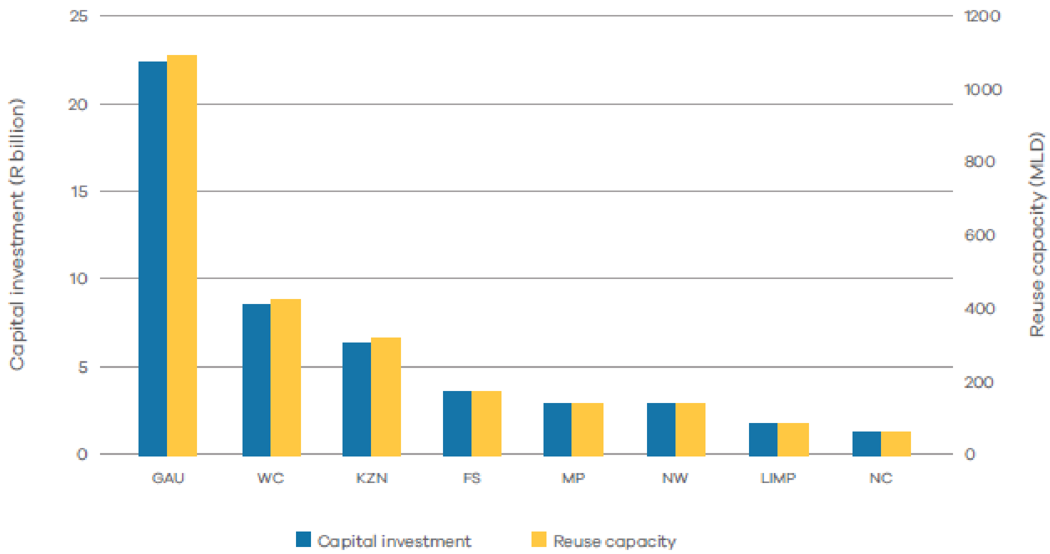


Figure C-6: Comparison of Water Tariffs for Commercial and Industrial Businesses Across Various Metros

Wastewater Reuse

The total theoretical potential market size for potable reuse projects at WWTWs larger than 1 MLD indicates capital investment opportunities of ~R50 billion at current costs as shown in Figure C-7 (GreenCape, 2020).



**Theoretical market potential based on available wastewater volume, projected water demand and maximum blending ratio of 20%. WWTWs smaller than 1 MLD were excluded as they are unlikely to be financially feasible. Based on design capacity of WWTWs according to 2014 Green Drop reports

Figure C-7: Theoretical Investment Potential for Water Reuse Projects (at 2019 Costs) Summed by Province

Economics of the water reclamation plants mentioned in table were reviewed in table
The George and Mossel Bay water reclamation plants were built during the 2010/2011 drought period. These projects were mostly undertaken under emergency conditions and considerable time pressure. Although constructed during the same drought period, the Beaufort West water reclamation plant had been in the planning phase since 2007, forming part of the municipality's medium-term plan to develop sustainable drinking water supplies. The New Goreangab water reclamation plant has historical significance as the first direct potable reuse plant in the world. The Old Goreangab reclamation plant (Old Plant) was constructed in 1969, while the 21 Mℓ/d New Goreangab water reclamation plant (NGWRP) for direct potable use was commissioned in 2002 and built alongside the Old Plant. The summary of O&M costs for each water reclamation and desalination plant is shown in Table .

Table C-5: List of Water Reclamation Plants (Turner et al., 2015)

Plant	Type of Plant
Beaufort West 2.1 Mℓ/d reclamation plant	Reuse – direct potable
Windhoek 21 Mℓ/d Goreangab reclamation plant	Reuse – direct potable
George 10 Mℓ/d UF plant (full capacity tested as 8.5 Mℓ)	Reuse – indirect potable
Mossel Bay 5 Mℓ/d UF/RO plant	Reuse – direct industrial

Table C-6: Summary of the O&M Costs for each of the Water Reclamation and Desalination Plants (Turner et al., 2015)

Water Reuse Plants				
Plant	**Beaufort West reclamation plant**	**Goreangab water reclamation plant**	**George UF plant**	**Mossel Bay UF/RO plant**
Type of Plant	Reuse: Direct potable	Reuse: Direct potable	Reuse: Indirect potable	Reuse: Direct industrial
Owner	Beaufort West Municipality	Windhoek Municipality	George Municipality	Mossel Bay Municipality
Operator	Water & Wastewater	Wingoc George	George Municipality	Veolia
Operational Status	1.2 Mℓ/day	17.5 Mℓ/day	Zero mode	Zero mode
Completed	2010	2001	2010	2010
Capital Cost - at time of construction - Adjusted for 2014/15 - Per unit capacity	R26.5 mill R34 mill R16.22 mill/Ml/day	R122 mill R260 mill R12.38 mill/Ml/day	R36 mill R46 mill R5.44 mill/Ml/day	R40mill R51 mill R10.19 mill/Ml/day
O&M Cost (2014/15)	R6.92/m³	R4.87/m³	R2.11/m³	R2.72/m³
Energy Use	2.07 kWh/m³	0.57 kWh/m³	0.23 kWh/m3	0.73 kWh/m³
Electricity Cost	R1.88/m³	R0.57/m³	R0.23/m³	R0.64/m³
Chemicals	R0.85/m³	R1.55/m³	R0.44/m³	R0.18/m³
Consumables	R0.50/m³	R1.00/m³	R0.50/m³	R0.50/m³
Maintenance	R1.01/m³	R0.78/m³	R0.23/m³	R0.49/m³
Staff	R1.96/m³	R0.88/m³	R0.49/m³	R0.79/m³
Laboratory cost	R0.47/m³	R0.06/m³	R0.15/m³	R0.07/m³
SHEQ	R0.23/m³	R0.03/m³	R0.08/m³	R0.05/m³