Energy From Wastewater – A Feasibility Study

ESSENCE REPORT

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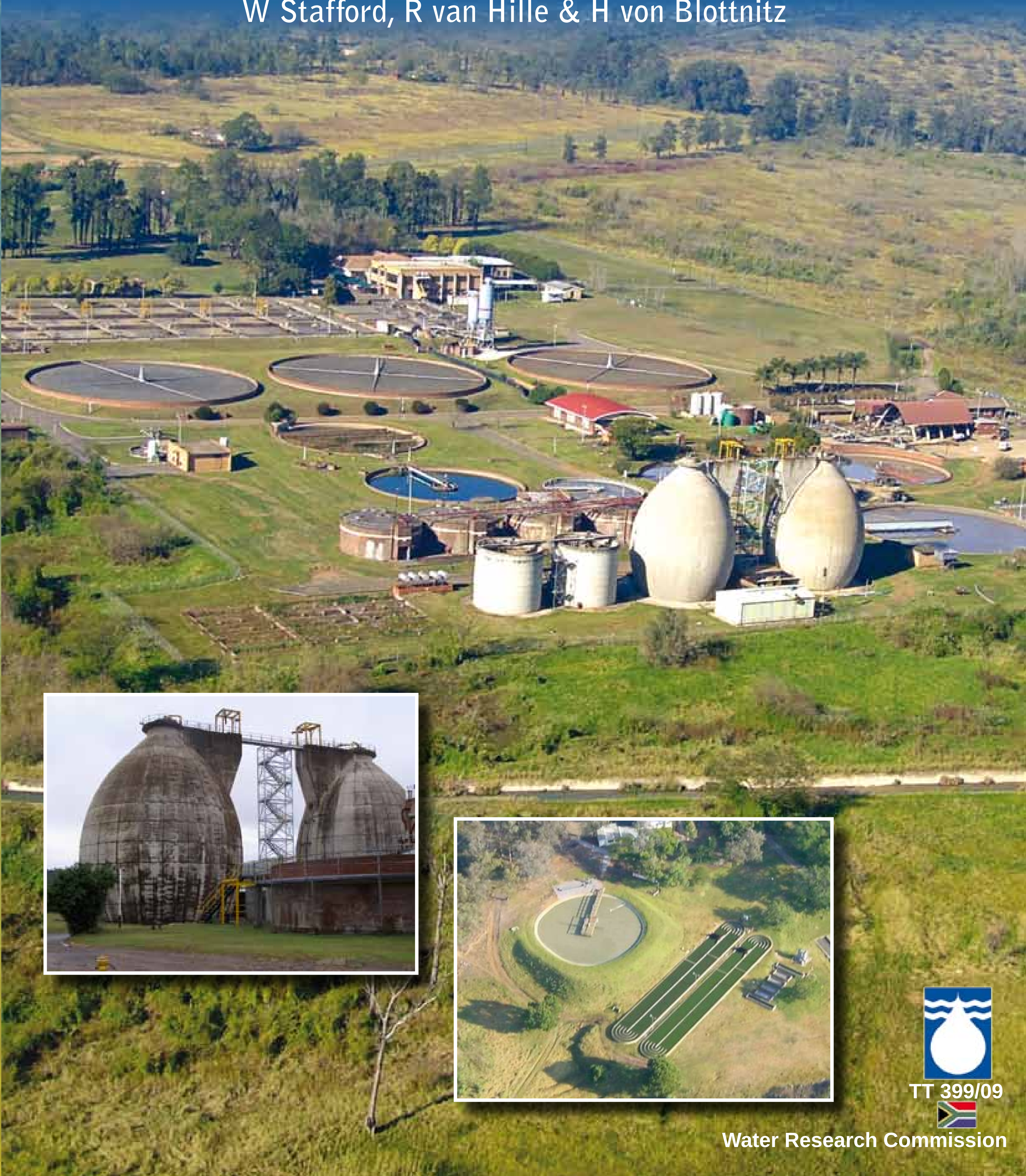

TT 399/09

Water Research Commission

ENERGY FROM WASTEWATER – A FEASIBILITY STUDY

ESSENCE REPORT

Report to the
Water Research Commission

by

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ABSTRACT

The opportunity exists to improve the current wastewater treatment processes by applying new solutions and technologies that can also reduce energy inputs and/or generate energy for other processes. Little information is presented in the existing literature on the application of energy from wastewaters and there is no overall view of the potential or experience in South Africa. This study explored the various waste streams and assessed the feasibility of appropriate technologies that could be used to generate energy. The assessment considered the net energy generated from wastewater foremost while the conservation or reclamation of water, reduction in disposal of wastes (solid, liquid and gas) and the generation of by-products were considered as added benefits. The technical approaches to recovering energy from wastewater were outlined and the feasibility of applying various technologies and solutions explored. Local and international case studies were used to demonstrate working examples and frame their potential in the South African context. Specific case studies considered particular processes or waste streams and determined the practical and large scale application of energy recovery from these wastewaters. Lastly, community and industrial surveys were conducted to assist in formulating recommendations for industry (wastewater generators), researchers (industrial and academic research) and policy makers (government).

The ultimate vision of this project is the integrated management of water, waste and energy within a model of sustainable development.

EXECUTIVE SUMMARY

The current view of wastewaters is that they generally represent a burden and necessarily incur energy costs in processing before they can safely be released into the environment. The opportunity exists to improve the current wastewater treatment processes by applying new solutions and technologies that can also reduce energy inputs and/or generate energy for other processes. This study explored the various waste streams and the appropriate technologies that could be used to generate energy.

A survey of the quality and quantity of wastewaters in South Africa identified the top three sectors having the greatest potential energy recovery as the formal and informal animal husbandry sector (cows, pigs and chickens), fruit and beverage industries (distillery, brewery, winery, fruit juicing and canning) and domestic blackwater (sewage). An estimated 10 000 MWth can be recovered from the wastewaters in the whole of South Africa, representing 7% of the current Eskom electrical power supply*. However, since most of the waste streams are widely distributed, the energy from wastewater is best viewed as on-site power.

The most appropriate technologies and their limitations are partly determined by the value of the required energy product (heat, electricity, combined heat and power or fuel) and the driving market forces that determine how this energy product can be used with our current technology. Furthermore, the ease of separation of the energy product from water can be key to the feasibility of the process (e.g. biogas separates easy from wastewater by natural partitioning whereas bioethanol requires energy intensive distillation). Anaerobic digestion (AD) is the most commonly recognised technology and has been applied to wastewaters of different characteristics at both small and large scales. AD is suitable for use with domestic sewage (particularly since 40% of South Africans are not currently serviced with waterborne sewage), as well as in the industrial and agricultural sectors. Bioethanol production by fermentation is suited to concentrated, high carbohydrate wastewaters and has potential in the fruit industry where sugar-rich wastewaters are generated in large volumes. Similarly, combustion and gasification are restricted to applications with concentrated waste streams (containing <40% water) due to the energy expended in de-watering and are most appropriate in the treatment of dewatered and solar-dried (or previously stockpiled) wastes. In contrast to these technologies, the growth of plant biomass for combustion/gasification and algal biomass for biodiesel production is suited to dilute waste streams. The sequestration of carbon dioxide and facilitated wastewater-treatment by photosynthetic oxygenation are added benefits. However, there are no large scale algal biodiesel production processes operating at present, in spite of published claims that the technology is technically an economically feasible and the growing incentives due to the recent increase in diesel prices. Microbial fuel cells (MFC) are an emerging technology that can also operate with dilute waste streams while producing electricity directly. MFCs are suited to applications in remote/rural sites with no infrastructure, but the technology is still in early development. A single wastestream or technology may not be suitable for achieving efficient energy recovery and the integration of technologies and/or waste streams may be required to realise the maximum energy from wastewater potential. There are

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* Approximately 140 000 MWth or 42 000 MWe (Eskom data tables 2007). Where MWth and MWe refer the thermal and electrical power in megawats (10^6 W), respectively

also frequently missed opportunities for reducing energy needs by the recovery of waste heat. The greatest potentials are realised when an industrial ecology approach is used to integrate process or waste heat from several industries, with pre-planning and the formation of industrial parks.

The net energy generated, reduction in pollution (wastewater treatment) and water reclamation are the main costs and benefits considered in assessing the feasibility of an energy from wastewater project. However, additional benefits such as certified emission reductions (CERs), fertiliser production, or the production of other secondary products, could tip the balance of economic feasibility. For the implementation of energy from wastewater technologies, essential services (WWTP operation, schools, and hospitals) and the needs of communities not serviced by sewage and electrical infrastructure should preferentially be targeted.

Several risks, barriers and drivers to developing an energy from wastewater project were identified. There is a general lack of research capacity and skills, and a greater need for research collaboration and information-sharing between research groups, government agencies and municipal practitioners. There is also no incentive for the generation of clean, renewable energy such as feed-in tariffs, green energy tariffs or peak tariffs.

The use of wastewater as a renewable energy resource can improve energy security while reducing the environmental burdens of waste disposal. Energy from wastewater therefore facilitates the integration of water, waste and energy management within a model of sustainable development.

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1. Wastewater in South Africa

Wastewaters are generally considered to be a burden to society, and incur energy costs in processing (typically of unrecognised magnitude) before they can be safely released into the environment. In the absence of adequate treatment, water contaminated by human, chemical or industrial wastes can cause a number of diseases through ingestion or physical contact. On this basis, it has been suggested that no other type of intervention has a greater impact upon a country's development and public health than the provision of clean drinking water and the appropriate disposal of human waste [1]. Approximately 40% of South Africans are not fully serviced with water and sanitation [2]. Furthermore, the sanitation sector is performing poorly (SAICE scorecard of C- in urban areas and E in all other areas) and present municipal wastewater treatment plants (WWTP) are suffering from poor operation, servicing and maintenance. Only 4% of the WWTP are fully compliant with the legislation for discharge into the environment and the majority of the plants require interventions [3, 4, 5, 6].

2. Energy in South Africa

South Africa is primarily dependent on fossil fuels (74% coal and 15% oil) for its energy[1] requirements and most (93%) of South Africa's electricity is supplied by coal-fired power stations (Figure 1 [7[).

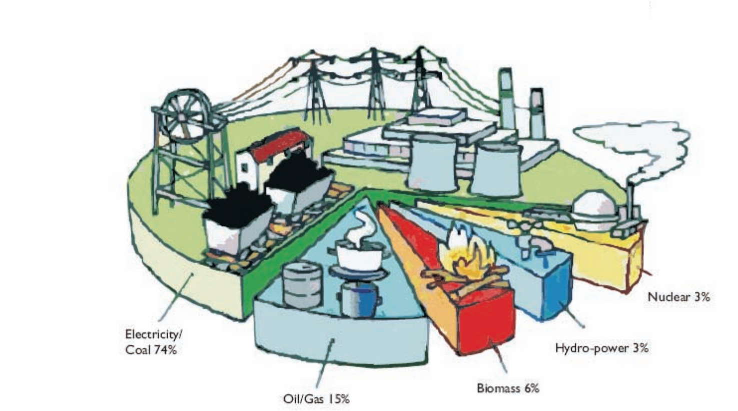

Figure 1. Energy resources in South Africa

Electricity generated by coal-fired power stations has a number of negative environmental impacts including: the consumption of a non-renewable fossil fuel resource; the consumption of vast quantities of water, mining of coal and the disposal of mining residues; and the generation of greenhouse gases, sulphur dioxides and solid fly ash residues.

The demand for this energy is also increasing rapidly due to urbanisation and industrial development. Although South Africa has large resources of coal, the need for new generation capacity has already reached crisis proportions. In the longer term this need has been estimated at 25 to 40 GW by 2025. Additionally, approximately 20% of the population still lack access to electricity [2].

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[1] **Energy** has the SI unit Joule (J). The Lower Heating value (LHV) is used for the energy value of fuels in this report. In contrast to the Higher Heating Value, it ignores the latent heat of vaporisation of water in the combustion products. **Power** is the energy in a given time and measured in Watts (W). 1W=1 Joule per second. The megawatt (MW) is equal to one million (10^6) Watts. MWth and MW are used in the text refer to thermal and electrical power respectively.

3. Objectives and conceptual framework

This project was initiated based on the need to explore the potential for energy from wastewaters that could contribute to the national energy demand. In addition to potentially contributing to the energy demand, there are opportunities to generate energy from wastewaters in a manner that is aligned with the sustainable development imperative. Thus, the adoption of appropriate wastewater treatment processes can be an essential part of the reduction in greenhouse gases (GHG) by reducing intrinsic energy needs, reducing the emission of gaseous pollutants and the direct sequestration of carbon dioxide (CO_2).

The objectives of this project were to:

- Present a review of established and emerging technologies for generating energy from wastewater.
- Provide a first order estimate of the quantity and quality of domestic and industrial wastewaters in South Africa, estimate the potential energy recovery and the potential contribution to the national energy demand.
- Document national and international practice of energy from wastewater using examples and case studies.
- Identify obstacles and areas of concern (including technical, commercial, social, environmental and regulatory aspects), and make recommendations for policy, Research and Development and industry.

The various options for energy recovery from wastewater can be distinguished according to input streams, process intermediates and energy outputs as follows:

- **Inputs:** The chemical potential energy that is carried in wastewaters in the form of carbonaceous material (suspended or dissolved, and mostly in diluted form). Exceptions are energy in the form of heat (for wastewaters above ambient temperature) and the use of wastewaters as growth media for organisms to fix carbon dioxide using the energy of sunlight (photosynthesis).
- **Intermediates:** Typically, the energy produced will be in an intermediate fuel such as gas (hydrogen or methane), liquid (ethanol or biodiesel) or solid (dry biomass).
- **Outputs:** The intermediate fuels might themselves be sold as energy products or they can be used on site for generation of heat and/or electricity. The conversion of thermal to electrical energy usually involves large losses, with typical efficiencies of 25 to 35% with current technology.

Given the variety of inputs, intermediates and outputs, there are several technologies that can potentially be used to harness energy from wastewaters (discussed below and summarised in Table 2). The characteristics and loads of the different wastewater streams determine the technologies appropriate for energy recovery. The costs and benefits of each technology can then be compared on a life cycle basis. The mindmap presented in Figure 2 outlines the overall approach taken in the project.

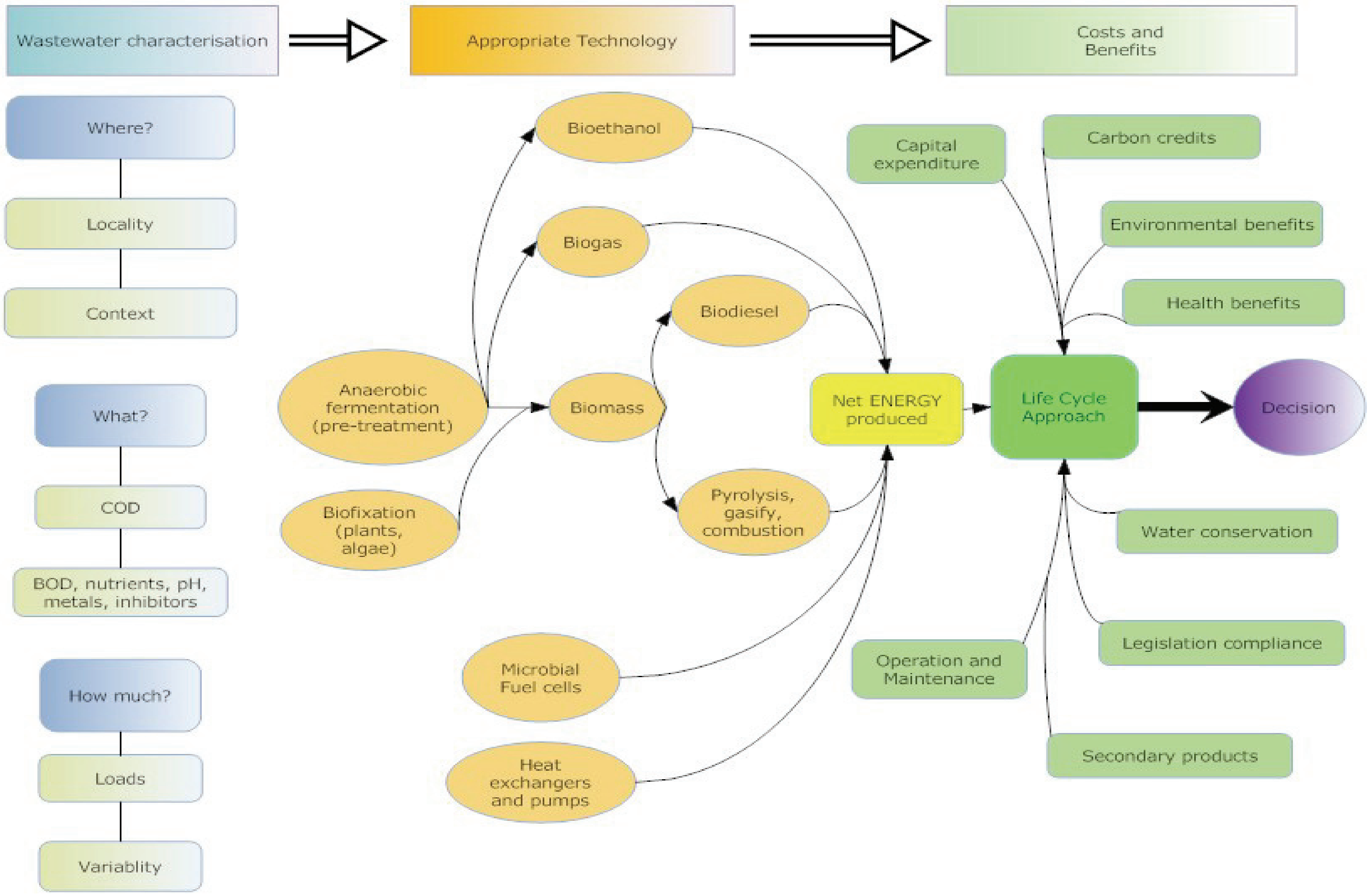

Figure 2. Mindmap of the energy from wastewater project

4. Technologies for energy from wastewater

The technologies for harnessing energy from wastewaters considered in this report are: (1) reducing energy needs through utilisation of waste heat and process heat integration, (2) generating biomass, (3) combustion and gasification, (4) anaerobic digestion for biogas, (5) fermentations for bioethanol and (7) the direct production of electricity using microbial fuel cells. These are summarised individually below and described in full detail in the technical report (WRC report no. 1732/1/09).

4.1 Utilisation of waste heat

The use of heat contained in wastewaters which are to be discharged from industrial processes represents one element of process heat integration. Thermodynamic theory suggests that the recovery of waste heat can be implemented at any scale, provided there is a heat gradient between the two streams, and that they are separated by a good heat conductor. The heat capacity[2] and flow rate of the wastewater affect their suitability for heat exchange. Planned integrated applications for waste heat utilisation through application of Pinch analysis allow for the greatest opportunities for energy recovery to be achieved [8].

4.2 Production of biomass for energy generation and carbon sequestration

Various forms of biomass have potential for energy generation. These can be processed via thermal (gasification or combustion) routes, anaerobic digestion or via fermentation routes. The energy products generated include steam and/or electric power, or liquid and/or gaseous fuel for use in a distributed energy network. In assessing the potential for energy generation from wastewater biomass, one considers both the wastewater sludges (a form of biomass) and the growth of organisms (fungi, plant and algae biomass) on these wastewaters for use in fuel generation. Use of such waste material for energy generation may however compete with its potential use in agriculture.

Plant biomass

Wastewater has been shown to be an effective fertiliser. The average person's annual production of faeces (containing 0.4 kg total nitrogen and 0.2 kg total phosphorus) and urine (containing 3.0 kg total nitrogen and 0.3 kg total phosphorus) is capable of fertilising up to 600 m^2 of land area for plant biomass (agricultural crop) [9]. Concerns for the safety of the environment and human-health, and the accordant governmental regulations, prevent primary sewage from being directly disposed of to land, water or sea [4]. However, both the sludge from anaerobic digesters and algal biomass have been shown to be effective fertilisers contributing to soil fertility and soil carbon sequestration [10]. Further, the treated wastewaters from industry (containing no pathogens) that do not meet standards for disposal to rivers are recognised for use in irrigation; subject to meeting certain requirements [11]. The use of these wastewaters for the growth of terrestrial plants can result in a valuable fuel source (wood for combustion, gasification or other appropriate energy from wastewater technologies) while also mitigating GHG emissions by sequestering carbon dioxide (CO_2).

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[2] Specific heat capacity (expressed in J/g/K) measures the number of joules of energy required to change the temperature of one gram of the substance by one Kelvin.

Microbial biomass

Microbial systems which include bacteria, yeast and fungi, utilise a broad spectrum of organic compounds over a range of concentrations for the production of biomass. Typically, these systems are characterised by having a high affinity for substrates that enables them to metabolise soluble organic pollutants at low residual concentrations. Such biomass can be removed from the wastewater through phase separation (e.g. settling) and thereby provide a concentrated resource for energy generation through a variety of technologies.

Algal biomass for biodiesel production and other energy products

Due to their simple cellular structure, microalgae have higher rates of growth and photosynthesis, thereby a higher productivity than conventional crops. Certain species of algae can produce large quantities of oil as a storage product (up to 80% dry weight) and are potentially up to 23 times more productive with respect to oil per unit area than the best oil-seed crop [10]. Using a conservative estimate of an algal productivity of 1 $g/m^{2.}.day^{-1}$, containing 30% oil, algal lipid productivity exceeds palm oil by 10 fold and jatropha, canola and sunflower crops by more than 30 fold (based on agricultural productivity data of [12, 13]). The type of lipid varies with algal species, but typically the hydrocarbon chain is in the C_{16}-C_{20} range. This leads to the potential to use the oil for transesterification to produce biodiesel. Harvesting involves concentrating the algae from their dilute suspension. Oil extraction is followed by transesterification to convert triglycerides (oil) to alkyl esters of the fatty acids (biodiesel) by the addition of an alcohol such as methanol. Glycerol is a by-product with potential for conversion by fermentation to ethanol and hydrogen (H_2) as energy products [14] Fig. 1. In addition to the use of the oil accumulated in algae for biodiesel production, algal biomass has potential to be processed in the same manner as other biomass to a variety of energy products, including heat, steam, electricity, liquid fuels, biogas and H_2. The system has other advantages since many algae can tolerate brackish or saline waters and can be grown on a variety of wastewaters [15]. The need for external aeration (and hence energy input) during wastewater treatment is often reduced since photosynthetic oxygen generated by the algae helps degrade recalcitrant pollutants aerobically [16].

Consider an open algal pond of 5 km^2 with a depth of 0.15 m. An algal productivity of 0.1g algae per litre per day can be achieved. Since the algae typically contains 30 % oil and the conversion efficiency into biodiesel is >95% efficient, the biodiesel production potential is 8.21×10^6 kg per annum [12, 15, 17]. Biodiesel has a net energy value of 41 MJ/kg, therefore 3.37×10^8 MJ of energy could be generated per year. When combusted this can generate 11 MWth.

Figure 3: Growth of algae for the production of biodiesel

Production of biodiesel from algae is technically feasible but has not yet been demonstrated economically [17]. However, the economic feasibility is being driven by the recent rapid increase in diesel prices [18]. Algal ponds and photobioreactors are currently used to produce algal biomass for high value products, while algal polishing ponds are used in the treatment of wastewaters at WWTP. Compared to photobioreactors, pond systems are favoured for their low cost, natural illumination and limited oxygen build-up, but disadvantages include contamination, evaporation of water, diffusion of CO_2 to the atmosphere and susceptibility to environmental conditions such as temperature and dilution by rain [19, 20, 21]. The constraints to algal biodiesel production centre on attaining high algal concentrations and lipid yields, thereby minimising land area and ‘reactor’ requirements, the efficient provision of light and CO_2, control of evaporation and ensuring efficient oil recovery. The financial feasibility of algal biodiesel production can be enhanced by simultaneous wastewater treatment, production of animal feeds or production of valuable secondary products [15, 18, 22, 23].

4.3 Combustion and gasification

The heating of biomass in the presence of a limiting oxygen supply results in gasification and the production of syngas. Syngas consists primarily of a mixture of carbon monoxide, carbon dioxide and hydrogen that may be used as a combustion fuel (heat energy value of 8-14 MJ/kg or 10-20 MJ/Nm^3), or may be converted to liquid fuels using a biological or chemical process. Syngas can be used to produce synthetic petroleum via the Fischer-Tropsch synthesis or via the Mobil methanol to gasoline process. Alternatively the carbon monoxide of the syngas can be transformed into ethanol by the anaerobic bacteria, with typical yields of 340 litres ethanol per tonne (municipal solid waste, biomass waste, animal wastes etc.) [24].

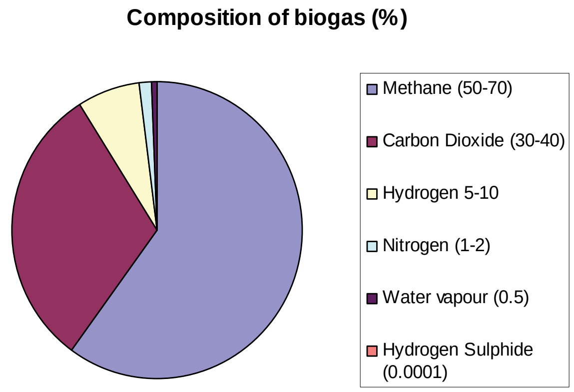
The combustion of biomass (or syngas) in the presence of an excess oxygen supply results in complete oxidation and the formation of hot flue gases that are typically used to produce steam to drive electric turbines for electricity production, with an efficiency of approximately 30%. If the heat energy is also captured, providing combined heat and power (CHP), the efficiency can be increased to 80%.

When assessing the feasibility of combustion or gasification, it is essential to consider the potential operational problems of this approach. These include moisture content, tar formation, mineral content, over-bed burning and bed agglomeration. The feedstock has to be relatively dry, with a maximum moisture content of 40 to 50%. Dryers may be included in the design, but there is a clear trade off between the amount of energy available in the feedstock and the amount of energy expended on drying. There are several potential negative environmental effects as a result of the gaseous and solid phase pollutants (heavy metals, dioxins, furans and NO_x gases), which are dependent on the nature of the feedstock.

4.4 Anaerobic digestion (AD) to produce biogas

Biogas is a fuel that is produced by the anaerobic digestion of organic matter using microorganisms in an oxygen-free environment. Biogas production involves several stages carried out by a variety of microorganisms. There is an initial hydrolysis where saprophytic microorganisms convert complex organic compounds into less complex organic compounds which are then converted to organic acids by acetogenic microorganisms. Methane forming microorganisms utilise these acids to form methane, the main component of biogas. Biogas is a mixture of gases, typically containing of 50-70% methane.

Additionally, hydrogen can be produced by anaerobic digestion, either as a component of the biogas or as the major product. The latter requires the microbial population to be dominated by specific organisms, such as *Rhodobacter* or *Enterobacter* species. However, current models indicate significantly greater energy recovery with methane from biomass digestion, although developing fuel cell technology may result in hydrogen fermentation becoming more attractive [25].



Biogas has an energy value of 6 kWh/m^3.

1 m^3 of biogas supplies 6 kWh of thermal energy to cook three meals for a family, or power a 1hp internal combustion motor for 2 hours to generate 1.25 kWh of electricity.

Household anaerobic digesters daily produce 0.38 m^3 biogas per m^3 digester.

A small household anaerobic digester (5-10 m^3) produces 2-4 m^3 biogas per day. This is sufficient to cook all daily meals for 6-12 people.

Figure 4: Biogas production and usage

Biogas can be used in many applications (stoves, boilers) with little modification. For applications in combustion engines (generators, motor car engines), the gas requires considerable upgrading to remove non-methane components. The gaseous components which need to be removed in order to upgrade biogas for particular applications are shown in Table 1. Several established technologies exist for the upgrading of biogas.

Table 1. Gaseous components requiring removal prior to application of biogas

Application	H_2S	CO_2	H_2O
Gas heater (boiler)	< 1000 ppm	No	No
Kitchen stove	Yes	No	No
Stationary engine (CHP)	< 1000 ppm	No	no condensation
Vehicle fuel	Yes	recommended	Yes
Natural gas grid	Yes	Yes	Yes

4.5 Fermentation to bioethanol

The production of bioethanol as a renewable liquid fuel is well established. Bioethanol can either be used on its own or blended with conventional liquid fuels to form either Gasohol or Diesohol [26]. Typically, bioethanol is formed by fermentation of simple sugars such as glucose and fructose under anaerobic conditions. Many yeasts, such as *Saccharomyces sp*. and some bacteria such as *Zymomonas sp.*, carry out this fermentation [27]. The current challenges are to use waste streams in which the organic carbon is not present as simple sugars by using a chemical/biological pre-treatment or using novel microorganisms that utilise a broader range of organic substrates. There is currently significant research focus on these cellulolytic pre-treatment methods. The low ethanol yields (typically

10% (v/v)) obtained in fermentation means that the subsequent energy intensive distillation is necessary. Conventional ethanol plants may expend more than 30% of the heat energy of the bioethanol fuel in the distillation process.

4.6 Microbial fuel cells

Fuel cells are devices that can convert chemical energy into electrical energy. Microbial fuel cells (MFC) operate by using bacteria that oxidise organic matter in the wastewater to transfer electrons to an anode and then via a circuit to the cathode where they combine with protons and oxygen to form water. The difference in the potential coupled to electron flow produces electricity.

MFCs are an emerging technology and a number of MFCs have been successfully operated with both pure cultures and mixed cultures that were enriched either from sediment or activated sludge from wastewater treatment plants. Wastewaters of very different characteristics from various sources including sanitary wastes, food processing wastewater, dairy manure, swine wastewater and corn stover can be used [28, 29, 30]. Essentially, this technology can use bacteria already present in wastewater as catalysts to generate electricity while simultaneously treating wastewater, but its development is hampered by low power output and high material costs [31]. To date, MFCs have not been developed in large scale applications, but are being used to generate energy for BOD (biological oxygen demand) sensors, the EcoBot-II robot and small telemetry systems [32, 33].

A summary of the appropriate energy from wastewater technologies, together with main requirements, outputs, advantages and disadvantages are shown in Table 2.

Table 2. Summary of energy from waste water technologies

Technology	Wastewater characteristics	Advantages	Disadvantages	Comments
Fermentations for biomass and secondary products	• Nutrients (C, N) • Non-toxic effluent for microbial growth • Dissolved or suspended organic	• Can produce high value secondary metabolites as by-products • Can remove toxic and recalcitrant chemicals	• Chemicals such as phenol are inhibitory. • pH, salinity, aeration need to be adjusted for growth of the microbe.	• More biomass produced from aerobic compared to anaerobic fermentations. • Biomass production for use as a feedstock for bioethanol production and for gasification.
Anaerobic Digestion	• Works best at warmer temperatures (30 to 60°C) • pH: 5.5-8.5 • Good design to control digestion and collection of gas • Dissolved or suspended organic	• Suitable with most substrates • Can achieve 90% conversion • Help contain odour • Produces biogas for heating, electricity generation and steam • Produces less biomass than aerobic fermentation	• H_2S oxidised to $SO_{2.}$ and when combined with water vapour can form sulphuric acid which is corrosive • High capital investment	• Produces biogas fuel rich in methane/hydrogen (60%) and carbon dioxide (40%) • The bio-liquid and sludge can be used as fertiliser and compost for soils, as feed for biodiesel production or can be gasified
Combustion Gasification	• Biomass • Low water content and Suspended organic matter	• Heat energy • Destruction/conversion of all hazardous material • Mature technology available • 95% fuel-to-feed efficiency	• Electricity costs are higher than for a coal-fired power station. • Could produce hazardous off-gases	• Organic compounds are converted to syngas for use as power, chemicals, Fischer-Tropsch liquids and gaseous fuels, fertiliser and steam. • Metals can be recovered • Ash and tar wastes
Algal growth for biodiesel production	• Carbon and nitrogen sources, oxygen • Non-toxic effluent for growth • Dissolved organic – limited COD	• Low energy requirements- use energy of sunlight for algal growth. • Can result in carbon dioxide sequestration • Can utilise dilute wastewater streams	• Algal ponding area can represent considerable land area. • Photobioreactors have large capital costs. • No suspended solids • Evaporation, dilution, contamination	• Algal oils that are converted to Biodiesel fuel by transesterification • By-product filter cake rich in proteins and carbohydrates from algae • Valuable secondary products
Bioethanol production	• Carbon and nitrogen sources • Non-toxic effluent for microbial growth • Carbohydrate (sugar) rich • Dissolved organics (or suspended with emerging technology)	• Established technology producing fuel suitable for a variety of combustion engines	• Cost of carbohydrate rich raw materials • Large volumes of bioreactors needed • Non-dilute wastewaters required	• Ethanol fuel, carbon dioxide and biodunder
Microbial Fuel Cells	• Non-variable wastewater sources • Non-toxic effluent for microbial growth • Dissolved organics	• Can be used at less than 20°C • Suitable for use with low concentration of organics in wastewaters • Efficient (direct conversion to electricity)	• Capital intensive • Still in development • Variable COD reduction depending on wastewater	• Direct conversion of waste to electricity. • Off-gas mainly carbon dioxide. Some microbial sludge formed.
Heat recovery	• Wastewaters with temperature above ambient	• Direct heat recovery	• Heat above ambient and the need for heat energy.	• Heat for household heating, steam generation, reduces electricity requirements

5. Energy from wastewater: international and national practice

5.1 Applications of appropriate technology

There are examples worldwide where energy is recovered from wastewaters to yield a variety of energy products at varying scales (from small rural to large industrial operations). Examples include:

Heat integration. At the Bruce Energy Centre in Canada, forward-planning to integrate energy usage was applied. The Centre was situated adjacent to the nuclear Ontario Power station for the supply of steam heat for several industries - alcohol distillation, food and feed manufacture, a plastic manufacture, and for heating a greenhouse. At the Kalundborg power station (Denmark) there was no forward planning, but the plant was adapted to supply excess heat for a local refinery, pharmaceutical and enzyme manufacturing factories, and for supplying heating to households in the town; thereby replacing approximately 3 500 household oil-fired units and supplying 15% of the refinery’s energy needs. Low grade waste heat can also be utilised in the heating of water in aquaculture applications such as the Asnæs trout fish farm in Denmark. Alternatively, heat pumps have been used to recover and upgrade the low grade heat for a city’s hot water distribution system [34], or to maintain the optimal temperature of an on-site industrial process.

Domestic biogas. The Chinese government began a mass household biogas implementation program in 1975, and within a few years units were being constructed at a rate of 1.6 million per year. However, the units were often poorly designed and of low quality and by the 1980s many of these were no longer in use. The technology has continued to be developed and implemented and in 2005 China had 17 million digesters with annual production of 6.5 billion m^3 biogas. Importantly, biogas provides energy to one quarter of households in rural areas. This pattern of rapid introduction of biogas units was repeated in India, Nepal, Vietnam and Sri Lanka. There are currently over 2 million family sized units in operation in India, and over 200 000 families a year are switching from the traditional fireplace to biogas for cooking and heating [35]. By contrast, in South Africa (and Africa as a whole) the implementation has been generally minimal, despite the high costs of alternatives in rural settings such as the construction and servicing of ventilation improved toilets. The initial capital costs and the maintenance levels required have been higher than expected and household-level operational experience has been lacking [36].

Agricultural biogas. Meili village (Zhejiang Province, China) slaughters 28 000 pigs, 10 000 ducks, 1 million ducklings and 100 000 chickens each year and the wastewaters are fed to an AD that produces enough biogas for more than 300 households plus 7 200 tonnes of organic fertiliser each year [37]. A similar process is used in Linköping (Sweden), but the biogas is upgraded to vehicle fuel quality and since 2005 all public transport vehicles in the city (> 60 buses) have been converted to run on biogas [38]. In Ireland, wastewater from farms in Ballytobin and food processing industries generate electrical and heat energy for the small farming community by means of anaerobic digesters. This plant generates an estimated 150 000 kWh of electricity and 500 000 kWh of heat energy per year using gas turbines and combined heat and power [39].

Green electricity from biogas. In the agricultural town of Hamlar, Germany, biogas is used to generate 680 kW of heat and electricity by combined heat and power [40]. The operation supplies 80% of Germanys' herb market and the waste herb stalks as well as other wastes (potato skins, blood from chicken slaughter-houses) are fed into anaerobic digesters at a loading of 100 tonnes per day. There is an initial pre-treatment step followed by two anaerobic digesters of 885 m^3. The heat from biogas combustion is used for herb drying and pretreatment (pasteurisation and heating the fermenter to 35-40°C). Economic incentives for green (clean, renewable) energy result in the plant selling all of its electricity to the grid at a very favourable rate and then buying back the electricity it requires.

Bioethanol. A few examples of the use of wastewater and wastewater sludges for the production of bioethanol have been reported. The VTT Technical Research Centre of Finland has developed technology for the distributed production of ethanol by fermentation of food processing wastewaters. This technology enables production even at a small scale and is estimated to have potential to meet 2% of the total volume of petrol sold in Finland and is currently being commercialised by St1 Biofuels Oy [41].

Algal biodiesel. To date, it has been proposed that algal biodiesel is financially feasible only with concomitant wastewater treatment or production of animal feed, valuable secondary products or additional energy products. Recent analysis estimates that algal biodiesel from wastewaters can be profitable with a reasonable breakeven after 2-4 years [22, 23]. Fuelled by the increased diesel price, there is currently much speculative interest in algal biodiesel. Several companies have been formed, who are proposing to use algae for producing biofuels and acquiring certified emission reductions (CERs) through CO_2 mitigation [42, 43]. An example is Aquaflow Bionomic (New Zealand) who claim that they are starting biodiesel production from wild algae grown in wastewater treatment plants maturation ponds with the aim of "… one million litres of the fuel each year from Blenheim by April 2008." [44]. Further developments will reveal if such projects are financially feasible and will be implemented for production rather than demonstration purposes.

5.2 Integrating energy from wastewater technologies

Although streams and technologies can be suitably matched in isolation, the integration of technologies and waste streams holds the greatest promise in attaining long-term energy security while maximising wastewater treatment. There are several examples where this has been successful:

- The FlexFuel project (Southern Denmark) integrates several technologies and wastes. There is a biogas plant with a pre-treatment plant for household waste, a pre-treatment plant for steam explosion for treating solid waste to release monomeric units, and a unit for fermentation to ethanol and its subsequent distillation. The overall process uses a combination of a wide range of waste materials. The process allows recovery of both bioethanol and biogas for processing to combined heat and power (electricity), as well as the production of a valuable secondary product- fertiliser for use in agriculture The project is being implemented on the Danish island of Ærø (population 6863) [45].
- An AD biogas and bioethanol system was shown to be a flexible system capable of utilising different wastes. In 1996, grain production reached 504 million tonnes in China and the over-

production meant that it was difficult to sell the grain. Tianguan Alcohol Factory in Nanyang therefore expanded its operation to consume 1.75 million tonnes of shop worn grains/year to produce ethanol as fuel for automobiles, and used the sludge of the distiller to produce biogas in a 30 000 m^3 digester and supply more than 20 000 households with biogas [37].

- The Advanced Integrated Wastewater Pond Systems (AIWPS) [46] have been shown to be effective in treating municipal wastewaters in South Africa [47, 48, 49]. They consist of an AD and high rate algal pond (HRAP). A system in Grahamstown has been monitored for wastewater treatment efficacy over nine years:- levels of nutrient and organic removal comparable with conventional wastewater treatment works and negligible *E. coli* counts were achieved [50]. There is energy available from biogas and the algae produced can be used as a fertiliser or fuel (e.g. biodiesel).

5.3 Energy from wastewater practice in South Africa

Despite these and many other international examples of an energy from wastewater experience, there are only a few examples of recovery of energy from wastewater in South Africa, and there exists no overall view of the potential or a strategy for harnessing this renewable energy source. Experiences include:

- Several wastewater treatment plants use anaerobic digesters as part of the wastewater treatment process. However, many vent or flare the gas while some use the heat internally to maintain digester temperatures and to heat building space. This demonstrates that energy use has been poorly integrated into WWTP and the opportunities for mitigating greenhouse gas (GHG) emissions have not been realised. The Cape Flats WWTP uses biogas to help dry and pellet the wastewater sludge, thereby reducing the on-site disposal costs and environmental burdens (i.e. eutrophication of the nearby freshwater lake, Zeekoevlei) [51]. The pellets produced have an energy content ~16.6 MJ/kg and have been used by Pretoria Portland Cement Company Ltd. (PPC) factory as additional fuel in their cement combustion kilns. Recently, there have been problems with the production of biogas and diesel replacement fuel has been used at great expense. Analysis has indicated that the Cape Flats WWTP could generate enough AD biogas to be self-sufficient in its basic energy requirements, but this is not being actualised (see Cape Flats- best practice case study, WRC Report 1732/1/09, Appendix).
- Recently, a combined heat and power plant has been commissioned at PetroSA's gas-to-liquids refinery to utilise the biogas produced from wastewater treatment. The electrical output replaces 4.2 MW of grid-based electricity and the plant is expected to produce approximately 33 000 tonnes per year of certified emissions reductions (CERs). Along with receiving debt financing from the South African Development Bank, the sale of emissions credits has helped make the PetroSA project economically feasible [52].
- A few isolated installations of household or community scale anaerobic digesters are identified around the country [53] (AGAMA systems are assessed as part of a case study, see WRC report 1732/1/09, Appendix).

6. Wastewater energy potentials in South Africa

A series of surveys and calculations were performed to determine the potential for energy recovery from wastewaters in South Africa. These are discussed on a sector-by-sector basis and summarised in Table 3 (more details available in the Technical report, WRC report no. 1732/1/09).

6.1 Wastewater energy potentials at wastewater treatment plants (WWTP)

Wastewater arriving at wastewater treatment plants may include both domestic and industrial wastewaters. Domestic wastewater includes both the blackwater (faeces and urine from toilets) and greywater (washing and food preparation). Industrial loads will have characteristics depending upon their source and will contribute differently to the individual municipal WWTP. Many industries also have on-site wastewater treatment before discharging to the municipal WWTP or to land, rivers or sea. The characteristics of wastewater discharges will further vary from location to location depending upon the population and industrial sector served, land usage, groundwater levels, and degree of separation between storm water and domestic wastes.

The potential for energy generation at wastewater treatment works was calculated based on existing municipal WWTP infrastructure, and on domestic blackwater (faeces generated by entire population as well as that currently serviced by flush toilets).

Potential from current municipal WWTP: South Africa has 968 municipal WWTP with a total maximum capacity of 7 600 ML/day. Taking an average COD of 0.860 g/L, this amounts to 6540 tonnes COD per day or 75.6 kg/s. Since the energy content is 15 MJ/kg COD, this equates to an energy potential of 1134 MJ/s or 1134 MWth. If the WWTPs are operating at 75% of their capacity, the energy potential is 850 MWth. The municipal WWTP load consists of captured domestic backwater, domestic greywater and industrial wastewaters.

Total domestic blackwater load (human faeces): There are 48.5 million people in South Africa (48 502 063 people [2]) and each person generates 100 g (dry weight) of faeces per day. This represents 56.1 kg/s for the total population. Since the thermal energy value is 15 MJ/kg dry mass, this represents 842 MJ/s or 842 MWth. However, currently only 509 MW can be attained, because 60% of the population have flush toilets that feed the sewage system of the municipal WWTPs [2] Therefore, the energy potential from the human faeces component of the existing domestic blackwater treatment is estimated to be between 509 and 842 MWth.

This calculation is in approximate agreement with the method for determining methane emissions from anaerobic digestion (Intergovernmental Panel on Climate Change, IPCC):
CH_4 emissions (kg/day) = Total COD removed (kg/day) x B_o (kg CH_4/kg COD) x MCF
Where: COD: Chemical Oxygen Demand of the wastewater to be treated
B_o: maximum methane producing capacity (default value: 0.25 kg CH_4/kg COD)
MCF: methane conversion factor (for anaerobic conditions, MCF = 1)
Therefore, CH_4 emissions (kg/day) = Total COD removed (kg/day) x 0.25.
Based on a daily COD removal of 56.1 kg/s or 4 847 040 kg/day; 1 211 760 kg methane/day is generated. As the energy content of methane is 55.6 MJ/kg, this amounts to 67 373 856 MJ per day or 780 MW.

6.2 Wastewater energy potentials from animal manures and abattoirs

Animal rearing and processing operations give rise to high organic load liquid and solid wastes. The use of organic wastes from this sector for energy recovery is commonplace around the world, both on a rural or single household scale (such as in China) and for large scale animal processing operations (such as in the United States). In the whole of South Africa the energy potential for animal husbandry (formal and informal sectors) and associated abattoirs is approximately 7500 MWth.

The combination of organic solid and liquid wastes are typically managed together for energy recovery, and the combined waste stream available at a single location will likely allow for the full potential for energy generation from this sector to be realised. Anaerobic digestion is typically used for the combined waste stream.

Factors which influence energy recovery potential include the type of operation and animals processed differences in farming/processing approaches, animal densities, location, washing practices, wastewater management etc. Differences between waste management at various sites give order of magnitude differences in composition. A number of observations were made on the basis of the case study results (Table 3). Firstly, in the context of this current study, energy recovery from wastewater in isolation from that recovered from solid waste is not likely to make a significant contribution to national or even local energy demand in dairies and poultry abattoirs. Solid and liquid waste is likely to be managed together in most technologies. Potential for energy recovery exists in centralised operations, including feedlots, dairies, piggeries and abattoirs. On-site energy recovery systems on small to medium feedlots, dairies and piggeries are likely to provide sufficient energy for onsite needs, and larger operations will have the potential to export energy. Although solid waste collected from corralled rural cattle is suggested to represent the most significant potential for energy recovery in this sector, the practicalities of energy recovery from this source are significant. This is both in terms of collection (manual collection of the solid wastes from the kraals would be required in the mornings), and in terms of requirement for a rollout of small scale digesters close to the source of the wastes. Hence the proportion of this energy potential which could realistically be recovered would be significantly lower than that shown in the table.

6.3 Wastewater Energy potentials at fruit factories

The typical wastewater volume generated by the canning and juicing of fruit is 7 m^3 to 11 m^3 of wastewater per tonne of raw produce processed. These wastewaters usually contain suspended solids, particulate organics, as well as various cleaning solutions, and typical CODs are 4400 to 15000 mg/L for the canning and juicing processes, respectively. The fruit juicing process yields solid residues of approximately 50 % by weight of fruit used. This fruit pomace contains about 70% moisture and is rich in sugars (5 to 6 wt% sugars). Obviously, this can be mixed with wastewaters for energy recovery purposes, but this has not been considered here since it is considered solid waste.

The annual energy potential from fruit juice and canning in South Africa can therefore be calculated as from the annual production (http://www.nda.agric.za/docs/Trends2003/Horticulture.pdf) of the various fruit sectors as follows:

- Production of citrus fruit (oranges, lemons, grapefruit and naartjies) in 2002/2003 was 1.9 million tonnes of which approximately 26% (0.5 million tonnes) was processed (juiced and canned). Since 10 m^3 wastewater per tonne is generated with a COD of 10 000 mg/L, this amounts to a load of 5×10^{7} kg per annum. Assuming a heat energy value of 15 MJ/kg, this could produce to 7.5×10^{8} MJ per year or 24 MWth.
- Production of deciduous fruits (apple, pear, table grapes, peaches, nectarines, plums, apricots) in 2002/2003 was 1.7 million tonnes with 39 % (0.7 million tonnes) processed (juiced and canned). With a COD of 10 000 mg/L, the load is 7×10^{7} kg per annum. Assuming a heat energy value of 15 MJ/kg this could produce 10×10^{8} MJ per year or 34 MWth.
- Similarly, the production of subtropical fruits (avocados, bananas, pineapples, mangoes, papayas, granadillas, litchis, guavas) was 0.3 million tonnes in 2002/2003, with approximately 66 % processed for juicing and canning. Using the same method calculation, the energy potential is approximately 10 MWth.

The total energy potential from fruit processing wastewaters, (excluding the solid fruit pulp) is therefore approximately 68 MW. Fruit juicing and canning operations are mostly seasonal, operating for about a third of the year (March to June), so the energy recovered would be seasonal unless additional alternative wastes were sourced.

6.4 Wastewater energy potentials at breweries

SA Breweries wastewaters are fairly consistent in volume and uniform in characteristics. Approximately 3.2 L of combined wastewater with a COD of about 3 g/L is produced per 1 L of beer. A total beer production of 2.61×10^{7} HL (SAB 2006) allows the calculation of the brewery wastewater load and the potential power of 17 MWth. Five of the SAB breweries operate their own wastewater treatment plants, where the majority of the COD is removed prior to disposal to the municipal WWTP. The energy is not currently harnessed since the methane-rich biogas captured from the anaerobic digesters at SAB is currently flared; however, investigations are underway to utilise the energy potential for steam generation.

The energy potentials from several other industrial sectors were similarly surveyed to obtain first order estimates of energy from various wastewaters in South Africa. This information is summarised below in Table 3, below.

Table 3 .Energy potentials from various wastewaters in South Africa

Wastewater	Comment	Energy potential: Thermal power (MWth)
Domestic blackwater (human faeces)	Municipal WWTP service only 60% of the population and therefore only 60% of human faeces is currently captured. The municipal \WWTP are distributed with approximately 968 WWTP. The majority of WWTP are small < 0.5 ML/day, larger plants 2.5 ML/day. WWTP also receive domestic urine, greywater and industrial loads (not considered here).	509- 842
Animal husbandry	**Cattle in Feedlots** Mixed solid and liquid waste slurries. Represent point sources which could be accessed through on site energy recovery. 9 feedlots represent more than half the total cattle in feedlots	79 – 215
	Rural cattle Considers solid waste only, collected at night in kraals. Only a small percentage of this energy is realistically recoverable	1 271 - 3 445
	Dairies Mixed solid and liquid waste slurries collected, include washing and milk spills. Represent point sources which could be accessed through on site energy recovery	117 – 121
	Piggeries Mixed solid and liquid waste slurries. Represent point sources which could be accessed through on site energy recovery	18 – 715
	Poultry farms Considers solid wastes only	940 - 2976
	Red meat and poultry abattoirs Considers liquid wastes only	1 – 55
Olive production	Distributed and seasonal	4
Fruit processing	Distributed and seasonal. Only the wastewaters from canning and juicing are considered (pulp and pomace excluded)	68
Winery	Distributed and seasonal.	3
Distillery	Distributed. Grain, grape and sugar-cane (molasses) considered. Compared to grain and grape, molasses has the greatest energy potential, is not seasonal and is less distributed (3 major plants, all in KZN).	70
Brewery	Distributed. 7 breweries	17
Textile Industry	Distributed	22
Pulp and Paper	17 mills	45-100
Petrochemical waste	4 refineries. One gas to liquid fuel refinery	48

7. Barriers and risks to energy from wastewater projects

In order to determine why the above potentials are not being realised, an analysis was conducted on the barriers and risks associated with energy from wastewater in the South African context. The analysis was achieved through a thorough review of academic literature, through site visits to existing small-scale AD installations and through a stakeholder workshop run with industry and local government input. Detailed outputs of the review, as well as the full workshop report and details of the site visits can be found in WRC report 1732/1/09 Appendix.

From an institutional perspective, it was observed that wastewater management in the urban context is the domain of civil engineers, and constitutionally, is a function of local government (which sometimes relies on the water boards to execute). Energy technology sits between mechanical, electrical and process engineers, and constitutionally, is a function of national government. It is very challenging to work across these disciplines that have different mandates and objectives. On the one hand, we have to enable various engineering disciplines to jointly design something that both treats wastewater to acceptable standard and generates energy cost effectively. Furthermore, we need to challenge the division of powers between spheres of government.

7.1 Technology and wastewater considerations

The principal consideration which arose when exploring the barriers to energy from wastewater implementation, were the characteristics of the wastewater streams and the appropriate technologies. The wastewater issues were identified as:

- Water content: Depending on the water content, different technologies will be appropriate. For dilute wastewaters, de-watering may be impractical due to the energy cost associated with it. These wastewaters will be amenable to growing biomass.
- Effluent composition: Many industrial wastes may contain components that are inhibitory to microbial growth or recalcitrant to degradation and may therefore require prior separation or pre-treatment. Such extraction may also yield economically valuable by-products.
- Volume and seasonality: These are important factors to consider especially since most of the wastewaters suitable for energy from wastewater are from the agricultural sector.

The technology barriers were identified as:

- Certain technologies are well established internationally but have not been demonstrated on South Africa wastewater, thus hampering large scale implementation.
- Scalability and reliability of new technologies (such as microbial fuel cells) is not proven
- Technology designs are not always suited to the local context of a developing country like South Africa, for example in terms of maintenance and operational requirements for distributed systems
- There are perceptions that energy from wastewater technologies are complex to build and implement. In addition, South Africa lacks the human resource capacity for maintenance.

7.2 Financial risks and barriers

A number of financial risks and barriers were identified through the study. These may be grouped into those related to the technologies, and those relating to access to finance. Certain technologies are expensive both in terms of capital outlay and the skills/expertise required for maintenance – particularly where both parts and expertise are required to be imported. In addition, newer technologies require significant capital expenditure to get them established. Small companies/ municipalities in particular may not have enough resources to pursue energy from wastewater, especially if long payback periods are encountered. However, with the increase in electricity tariffs as well as the energy shortage in South Africa, this will become more feasible.

With respect to access to finance, energy from wastewater is often very low on budget allocations, and there is the perception that funding opportunities are poor. Although public private partnerships were identified to be necessary for the realisation of opportunities, legislation surrounding the nature of such partnership contracts limits the interest from private sector parties in pursuing such projects. A further note was made on the expense and difficulty in accessing third party funding sources such as those from DME, Eskom Demand Side Management and the Clean Development Mechanism (CDM). Not having a feed-in and /or peak tariff in South Africa further limits the potential profitability.

7.3 Implementation barriers

A third consideration was in the institutional and human resource constraints on projects. With respect to the former, it was identified that inefficiency in government departments was a significant barrier to realisation of projects for example the time it takes to do an Environmental Impact Assessment is quite substantial, as is the time to obtain other licences during start-up. As mentioned above, the need for going to tender and contractual considerations limit the interest in public private partnerships. A further consideration was that the primary focus of wastewater treatment is on effluent quality and not energy generation.

With respect to human resource constraints, it is identified that there is a considerable lack of skills at all levels (from designing and implementation to operation) which limits the ability to build and operate energy from wastewater operations. The need to develop and retain skills in the sector was identified as a high priority throughout the study.

7.4 Need for decision support tools

Harnessing the potential of energy from wastewater requires use of decision support frameworks and tools such as those which are offered in the context of a life cycle approach. Using such approaches, the costs (CAPEX, operations and maintenance) and inputs and outputs (chemicals, solid waste generation, water pollution, and gas pollutants) of the various technologies appropriate to a given wastewater can be assessed and compared. Other benefits such as secondary products can also be taken into consideration. The net benefit of the energy from wastewater process includes the replacement of conventionally derived energy (i.e. coal-powered electricity), the generation of energy or fuel products and useful by-products as well as the reduction of polluting wastes and water usage.

8. Harnessing energy from wastewater possibilities in South Africa

As reported in Section 6 above, a significant potential has been identified for recovering energy from wastewater streams in South Africa, both on a larger ‘industrial’ scale, and on a decentralised household scale. The earlier review of technologies identified a number of available and reasonably mature to mature technologies that can realise this potential. Matching wastewater streams with energy potential to the appropriate technologies requires simultaneous consideration of stream characteristics and the operational parameters for the efficient functioning of an appropriate technology. An attempt to match stream and technology considerations is presented in the table below (Table 4).

Table 4. Appropriate technologies for energy from wastewater. Wastewater is characterised into those rich in organic dissolved solids, suspended solids and sludges. The appropriate technologies with key operating parameters and energy efficiency are shown.

Wastewater	Technology	Notes	Key parameter and range	Efficiency Energy/COD
Dissolved solids	Combustion and gasification	Not applicable	-	-
	Biogas	Mature technology, applicable to majority of effluent types. Optimum pH range of 6.5-8.0 and can be inhibited by ammonia, sulphide and aromatic organics. Incomplete COD reduction so polishing is normally needed. Hydrogen production also possible, but associated COD reduction minimal (< 15%)	COD	0.2-0.45 g CH_4 per g COD for 10-23 MJ/kg COD or 0.05-0.1 g H_2 per g COD for 6-24 MJ/kg COD
	Bioethanol	Current technology limited to fermentable sugar substrates. Significant research into microbes that can ferment cellulose is needed. Requires energy intensive distillation to obtain pure product and generates high COD distillate effluent, often containing recalcitrant organics.	COD as fermentable sugars > 25 g/L* Total COD < 250 g/L to avoid osmotic stress	13 MJ/kg glucose
	Algae for biodiesel	Requires N and P as nutrients. Insignificant reduction in COD. Valuable filter cake as by-product.	COD < discharge specification	Not applicable per COD, but conservatively up to 80 kJ/m^3/day**
	Microbial fuel cells	Can reduce the COD from 40-80% of the input material with conversion to electricity typically 90% efficient.	COD from various sources	200-300 mW/g COD removed. Loading rate of 0.6 kg COD/m^3 per day.
Suspended solids	Combustion and gasification	Not applicable – must be dewatered first to give a sludge	-	-
	Biogas	Optimum pH range of 6.5-8.0 and can be inhibited by ammonia, sulphide and aromatic organics. Incomplete COD reduction so polishing is normally needed. Residence time can be increased to facilitate acetogenesis.	TSS – wide range	0.2-0.45 g CH_4 per g COD 10-23 MJ/kg COD
	Bioethanol	Current commercial technology not applicable unless prior hydrolysis to fermentable sugars is performed.	-	-
	Algae for biodiesel	Possible for algal cultivation, but no reduction in COD	-	-
	Microbial fuel cells	Not applicable	-	-
Sludge	Combustion and gasification	Depends on water content and the need for de-watering	% water: < 75%	15-20 MJ/kg dry
	Biogas	Optimum pH range of 6.5-8.0 and can be inhibited by ammonia, sulphide and aromatic organics. Incomplete COD reduction so polishing is normally needed. Increased solids loading increases residence time. New pre-hydrolysis processes can greatly improve yields.	% solids 3-10%***	0.2-0.45 g CH_4 per g COD 10-23 MJ/kg COD
	Bioethanol	Not applicable	-	-
	Algae for biodiesel	Not applicable	-	-
	Microbial fuel cells	Not applicable	-	-

* Based on an energy efficiency value of 8 (Brazilian cane sugar) and relative to feed concentrations in SA molasses based plants. Assumes no energy input to pre-treat the effluent. ** Based on algal productivity of 1 g/m^2/day, a pond depth of 15cm and a lipid content of 30%. *** Typical value for sludge digestion, although “dry” AD technologies have been developed which can accommodate 25% solids

It was observed that the only readily available and mature technology that can be applied to all types of wastewaters with energy potential is anaerobic digestion to produce biogas. An added attractive feature of this technology is that the separation of the energy product (methane rich biogas) from the wastewater occurs naturally, with no need for energy inputs to drive this separation. These features of biogas technology help to explain its dominance in international energy from wastewater practice, though care should be taken not to construe from this the conclusion that anaerobic digestion is the only technology that should ever be considered. An important industrial scale example in the South African scenario is the fruit sector, which produces wastewaters rich in simple dissolved carbohydrates that are particularly amenable to ethanol fermentation as an alternative to methane production.

Where more than one technology may potentially be applicable to a particular wastewater, a pre-feasibility study needs to be done to compare the obtainable types and yields of energy products. This is illustrated by the example in the box below, where three technology options for energy recovery from sewage sludges are compared, firstly theoretically and then by reference to figures obtained from three plants operated by Thames Water in the UK. This firstly serves to illustrate the approach to be taken in comparing the energetic yields of competing energy from wastewater technologies. Secondly, it shows that treating sewage sludge by AD to yield biogas is energetically slightly preferred over incineration for energy. Thirdly, and importantly, it illustrates that advanced anaerobic digestion technologies can serve to significantly increase biogas (and hence energy) yields, whilst simultaneously reducing the amount of sludge requiring disposal (both in quantity and in pathogenic risk).

Table 5. Combustion versus anaerobic digestion of sewage sludge

		Energy recovery option		
		Combustion	***AD***	***Enhanced AD***
Theoretical data				
Solids mass flow	**kg/day**	**1,000**	**1,000**	**1,000**
Solids content	% w/v	29%	10%	10%
Liquid mass flow	kg/day	2,448	9,000	9,000
Ash content *	%	30%	20%	20%
VS destruction	%		45%	65%
Gas yield/VS destruction	m^3/kg		1	1
CH_4 content in biogas			65%	65%
LHV biogas **	MJ/m^3		22.1	22.1
LHV fuel ***	MJ/kg	13	-	-
$\Delta Hvap_{water}$	kJ/kg	2260		
Gas production	m3/day		360	520
Gross thermal power out	**MJ/day**		**7,956**	**11,492**
Gross thermal power out	**kW**	**86**	**92**	**133**
Residues	per day	300 kg ash	3.2 m^3 20% sludge	2.4 m^3 20% sludge
Energy conversion unit		Steam turbine	CHP engine ****	CHP engine****
Conversion to electricity	%	30%	40%	40%
	kW	**26**	**37**	**53**
Compared to real data for 2007		***Beckton/Crossness***	***Reading***	***Chertsey***
Gross electricity produced/tds processed	kWh/tds	619	737	1057
Nett electricity produced/tds processed	kWh/tds	226	371	823
Parasitic load	kWh/tds	393	366	234
Gross power produced	**kW**	**25.8**	**30.7**	**44.0**
Surplus power produced *****	**kW**	**9.4**	**15.5**	**34.3**

* For combustion calculation the dried sludge ash content was used. This value was taken from the average dry sludge composition from Phyllis database. For AD calculations the wet ash content refers to (1-volatile matter) and was obtained from values used at Thames Water

** LHVbiogas = methane content•LHVmethane where LHVmethane = 34 MJ/m3

*** LHVfuel taken as sewerage sludge average composition from Phyllis database

**** Only the electricity produced is considered here

***** This is the net power of the WWTP process since some of the power is used on-site.

A similar study performed on a theoretical sugar rich effluent, comparing the energy recoveries from ethanol fermentation and AD for biogas generation suggests that more energy (16.05 MJ/kg) could be recovered by AD than fermentation (13.00 MJ/kg). These figures are based on a 45% conversion of glucose to ethanol and experimentally derived data for the anaerobic digestion of glucose and exclude the considerable energy cost of distillation. This suggests that in most cases AD may be the more attractive option, even for readily fermentable wastewaters.

9. Conclusions

9.1 Conclusions from reviews of literature and practice

- The review of the literature revealed that internationally, a number of technologies are being explored for obtaining energy from wastewaters. Some reports were found that provided detail of large scale operations.
- In South Africa, there are very few documented reports of technologies being used for effective energy recovery from wastewater.
- The review of established and emerging technologies provided information indicating that anaerobic digestion (AD) used for biogas production is the most commonly recognised technology. AD is a proven technology and is currently being operated at various scales. In developed countries, this has been implemented on large scale, whereas in developing countries it is generally operated at small scale for domestic applications.
- Utilisation of waste heat through heat integration is relatively common internationally, in some cases in very large scale plants.
- Combustion and gasification are restricted to application with concentrated waste streams (containing <40% water) due to the cost of removing water prior to combustion.
- Plant biomass production for combustion and algal biomass for biodiesel production is suited to dilute waste streams. Carbon dioxide sequestration and wastewater oxygenation by algal photosynthesis are obvious additional benefits. There are no large scale algal biodiesel production processes operating at present in spite of published claims that the technology is technically feasible, and economically attractive in the case of ponding.
- Bioethanol production by fermentation is suited to concentrated high carbohydrate/ sugar wastewaters. It suffers from the disadvantage that considerable energy is expended when using traditional distillation methods. Dunder is a by-product.
- Microbial fuel cells (MFC) can operate with dilute waste streams and can produce electricity directly. These may ultimately be suitable for application in remote/rural sites with no infrastructure, but the technology is still in early development.

9.2 Conclusions relating to energy from wastewater in South Africa

- From the first order estimate of the quality and quantity of wastewaters in the whole of South Africa and the estimation of the 10 000 MWth can be recovered. This is approximately 7% of the current Eskom power supply (approximately 140 000 MWth or 42 000 MWe).
- As an example, domestic blackwater (human faeces) could generate 842 MWth. The energy from wastewater that can be generated is best viewed as on-site power for essential services (WWTP, schools, hospitals and clinics) since it provides a mechanism for sustainable energy usage and a means to help fulfil national and international legislation and obligations for clean, renewable energy.
- The most appropriate technologies and their limitations are partly determined by the value of the required energy product (heat, electricity, combined heat and power or fuel) and the driving market forces that determine how this fuel can be used with our current technology.

The ease of separation of the energy fuel product from water is often the key to feasibility. For example, biogas separates easy from the wastewater by natural partitioning whereas bioethanol requires energy intensive distillation.

- AD is suitable for application with rural/household sewage, (particularly since 40% of South African communities are not serviced with waterborne sewage), as well as municipal WWTP and agricultural communities. However, skilled management and skills-training is required if AD is to be applied successfully in South Africa.
- Heat integration could be applied effectively in heavy industry in South Africa. Limitations to implementation include human resource capacity and the need for pre-planning.
- Combustion / gasification could be applied in limited cases such as treatment of dewatered and solar-dried (or previously stockpiled) sewage sludge.
- Fermentation for bioethanol has potential in the agricultural sector, but is currently limited to the availability of high COD, carbohydrate-containing wastewaters such as those in the fruit processing and sugar-cane processing industries.
- Production of algal biomass for use in combustion/gasification or for production of oils for biodiesel is not yet feasible in South Africa, but rapid progress is being made, incentivised by the recent increases in diesel prices.
- Additional benefits (such as certified emission reductions) and the production of other secondary products (such as fertiliser) could tip the balance of economic feasibility when implementing an energy from wastewater project.

10. Recommendations and areas of concern

In the synthesis and reflection of the underlying evidence of this energy from wastewater study, several recommendations emerged. Workshops were held with industrial stakeholders and community members (many of whom are implementing AD biogas technology) to obtain more information on the obstacles, risks and barriers that were then used to formulate recommendations (see Technical report Appendix, WRC report no 1732/1/09). The recommendations have been divided up into those relevant to different sectors: Industry (wastewater generators) research and technology development (Industrial and academic research) and policy (government). Further detail is available in the associated Guides (WRC report no TT 400/09).

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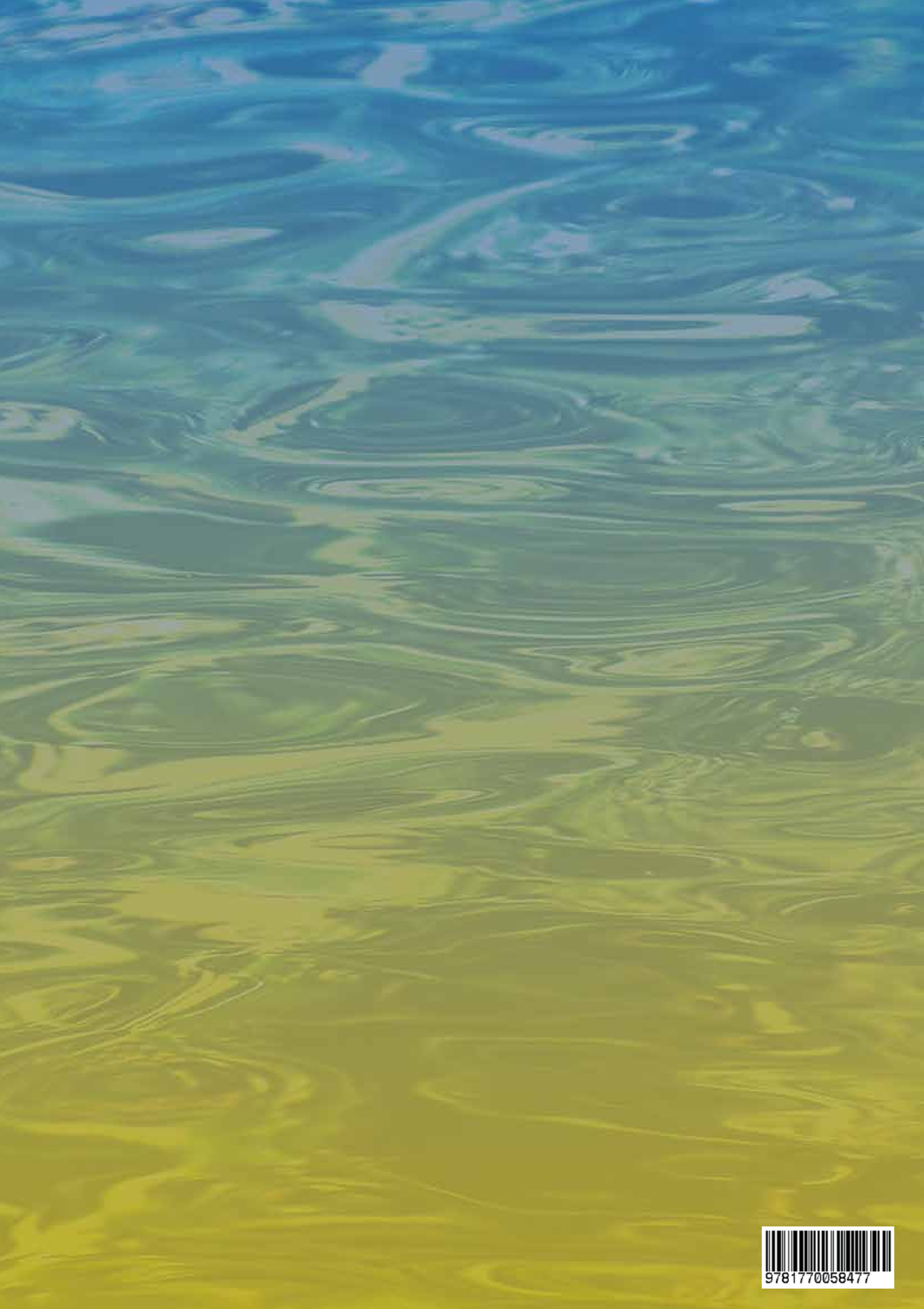

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