Modelling energy efficiency and generation potential in the South African wastewater services sector

John N. Zvimba and Eustina V. Musvoto

ABSTRACT

About 55% of energy used in the South African water cycle is for wastewater treatment, with the bulk of this energy associated with aeration in biological processes. However, up to 15% of wastewater energy demand can be offset by energy generation from sludge (power and/or combined heat and power), while best practices adoption can deliver energy efficiency gains of between 5% and 25% in the water cycle. Advanced process modelling and simulation has been applied in this study as a tool to evaluate optimal process and aeration control strategies. This study further applied advanced modelling to investigate and predict the potential energy consumption and consumption cost pattern by the South African wastewater sector resulting from implementation of optimal process and aeration energy use reduction strategies in support of sustainable municipal wastewater management. Aeration energy consumption and cost savings of 9–45% were demonstrated to be achievable through implementation of energy conservation measures without compromising final effluent regulatory compliance. The study further provided significant potential future energy savings as high as 50% and 78% through implementation of simple and complex aeration energy conservation measures respectively. Generally, the model-predicted energy savings suggest that adoption of energy efficiency should be coupled with electricity generation from sludge in order to achieve maximum energy consumption and cost savings within the South African wastewater services sector.

Key words | activated sludge, aeration, energy efficiency, modelling

John N. Zvimba (corresponding author)
Water Use and Waste Management, Water Research Commission,
Bloukrans Building, Lynnwood Bridge Office Park, 4 Daventry Street, Lynnwood Manor,
South Africa
E-mail: *johnz@wrc.org.za*

Eustina V. Musvoto
TruSense Consulting Services,
191 Hartley Street, Weavind Park, Pretoria,
South Africa

INTRODUCTION

The South African wastewater services sector currently operates a total of 824 municipal wastewater treatment plants (WWTPs), representing a total design capacity of 6,510 Ml/day, and receiving a total dry weather flow of about 5,130 Ml/day. Historically the design and operation of WWTPs focused on protecting the environment and safeguarding public health as required by regulations, with no special attention paid to energy use. However, with water and wastewater infrastructure having become huge consumers of energy, accounting for around 35% of municipalities' energy footprint, energy management is significantly becoming one of the most prominent issues facing water and wastewater utilities worldwide. Considering that the cost of energy consumption now represents a substantial cost to wastewater utilities globally (Rosso & Stenstrom 2005), it is essential to periodically conduct energy audits and introduce some changes in operations and infrastructure that can lead to energy savings (Daw *et al.* 2012).

The cost of energy at a WWTP can vary, ranging from 2% to 60% of total operating costs; thus, it can represent the main operating expenditure (Carlson & Walburger 2007). The specific electrical energy consumption varies depending on several operational and environmental characteristics, such as pollutant loads, plant size, age, and the type of treatment process units at the WWTP. International studies report specific electrical consumption per cubic metre (m^3) of wastewater treated in the range of approximately 0.26–0.84 kWh/m^3 (Pan *et al.* 2011; Venkatesh & Brattebø 2011). In this regard, the average maximum energy consumption for developed countries averages about 0.70 kWh/m^3 whereas the South African wastewater sector consumes on average more than twice at about 1.8 kWh/m^3 (Swartz *et al.* 2013). International

doi: 10.2166/wst.2020.157

total specific electrical energy consumption data based on pollutant load range from 0.5 to 1.3 kWh/kgCOD treated for large biological WWTPs (Jonasson 2007) and 0.7–2.25 kWh/kgCOD treated for medium biological WWTPs (Carlson & Walburger 2007). Specific aeration energy intensity values of 14.5–17 kWh/peCOD$_{100}$/yr have been reported at European WWTPs (Jonasson 2007). However, no benchmark specific energy intensity values based on pollutant load are available for South Africa.

Generally, in biological nutrient removal (BNR) wastewater treatment, aeration consumes the most energy, accounting for anything between 50% and 65% in nitrifying activated sludge plants (Rosso & Stenstrom 2005; Crawford & Sandino 2010). In South Africa, it is currently estimated that the six largest metropolitan municipalities operate around 103 WWTPs, discharging on average 3,600 Ml/d (average dry weather flow), and about 69% of these plants are energy-intensive BNR activated sludge processes. Moreover, 85% of these plants employ low-efficiency conventional surface aeration while the remainder use the more efficient fine-bubble diffused aeration (FBDA). In order to reduce both energy use and costs in the face of continued electricity cost increases and shortages while complying with strict final effluent standards, it is therefore imperative that municipalities focus on identifying and implementing optimal process and aeration energy use reduction strategies in support of sustainable municipal wastewater management.

As part of supporting the increased need to improve energy efficiency in South Africa and globally, several energy-related studies have been conducted (Burton *et al.* 2009; Frost & Sullivan 2011; Swartz *et al.* 2013; van Vuuren *et al.* 2014). The study by Burton *et al.* (2009) explored the various waste streams and corresponding appropriate technologies that could be used to generate energy within the South African wastewater sector. In this regard, formal and informal animal husbandry, fruit and beverage and domestic blackwater (sewage) were identified as the top three sectors with the greatest energy recovery potential. An estimated 10,000 MWh$_t$ was reported in the study as potentially recoverable from wastewaters generated in South Africa, representing 7% of the national power supply in 2009. Recent analysis of the status of anaerobic digestion in South Africa has further estimated the total biogas production potential from WWTPs to be 282,671 m^3/day, translating to 657,765 kWh/day electrical energy that may result in an estimated potential saving (at 60 cents per kWh electricity) of R144 million per annum in electricity costs (van der Merwe-Botha *et al.* 2016). A study by Swartz *et al.* (2013) recommended that demand-side management, particularly implementation of energy efficiency at both existing and new WWTPs, be adopted by wastewater utilities in South Africa. The study further recommended energy audits as well as development of technical solutions and tools for water and wastewater treatment plant supervisors and process controllers as ways of improving energy efficiency. In another related study, Frost & Sullivan (2011) identified supply and demand management, including regulatory interventions, as key to incentivising the sector to adopt energy efficiency measures.

In terms of technical innovations and tools that support a sector-wide adoption of energy efficiency, the last three decades have seen the introduction of very sophisticated and accurate biological models for activated sludge processes (Kappeler & Gujer 1994; Gujer *et al.* 1999; Henze *et al.* 1999) and commercial simulation programs that incorporate such models. These tools have been proven to be very useful for design, research and optimisation of WWTPs and their application has increased over the years (Corominas *et al.* 2010a, 2010b). At the same time, automated process control technologies have been developing rapidly and with the availability of more reliable and affordable sensors, automation is now extensively used at most WWTPs, resulting in the development of more efficient control strategies. To keep up with growing automated control, commercially available wastewater simulators have recently been incorporating modules that can simulate control strategies for processes such as aeration, pumping systems and chemical dosing. Use of these advanced process models and simulators has been proven to be an efficient engineering tool for the investigation of practical aeration energy conservation measures (ECMs) while maintaining or improving the required final effluent standards.

Corominas *et al.* (2009) applied modelling to optimise a biological nitrogen removal plant in Spain with a design capacity of 42,000 population equivalent (pe). The modelling enabled various aeration control strategies as well as the long-term impacts on final effluent quality to be evaluated. Energy cost savings of up to 30% were identified while maintaining the final effluent quality within the required standard. Musvoto *et al.* (2012) also applied modelling to investigate energy-saving operational measures at nitrifying activated sludge plants in the United Kingdom with design capacities of 158 Ml/d and 350 Ml/d. Measures identified included changes to aeration control strategies as well as implementing flow balancing using the catchment collection system and pump stations. It was identified that energy cost savings of up to 50% could be achieved depending on the measure implemented. The benefits of applying modelling to combine process operation optimisation and energy use were also identified by Rieger *et al.* (2012). They applied modelling to develop aeration control strategies as well as improve total nitrogen removal at three Swiss WWTPs of design capacities 13 Ml/d, 38 Ml/d and 190 Ml/d. The identified aeration control strategies resulted in annual energy cost savings of up to 30% for the three plants. Total nitrogen removal improved by up to 40% with the optimised aeration control strategies. More recently, Guerrini *et al.* (2017) developed a tool for measuring the energy costs at WWTPs and identifying how they could be reduced based on double-bootstrap data envelopment analysis.

In all the cited literature case studies, application of modelling to evaluate aeration ECMs has been identified as less risky and more cost-effective than directly implementing identified ECMs at full scale. Moreover, long-term effects on process performance and final effluent quality can also be predicted. It is therefore on this basis that the current study used advanced modelling and simulation to determine optimal process and aeration control strategies as well as providing potential future benefits in terms of both energy consumption and cost saving that can be realised within the South African wastewater sector through implementation of aeration ECMs.

MATERIALS AND METHODS

Case study plants

For the outputs of the project to be applicable on a broader scale, two BNR activated sludge plants were selected as case studies viz:

- Case study 1: The plant has a design capacity of 85 Ml/d average dry weather flow (ADWF) and uses a fine-bubble diffused aeration (FBDA) system.
- Case study 2: The plant has a design capacity of 15 Ml/d ADWF and uses surface aeration.

Case study plant 1

Description. Plant 1 is located in Pretoria, South Africa. The plant treats mainly domestic wastewater with a small industrial contribution. Screened and degritted raw wastewater is split between two modules which consist of primary settling tanks (PSTs), a balancing tank (BT), an enhanced biological phosphorus removal (EBPR) activated sludge bioreactor, secondary settling tanks (SSTs) and final effluent disinfection using chlorination. Module 1, commissioned in 1991, was further upgraded in 2013 with a design capacity of 45 Ml/d average dry weather flow (ADWF). A second module with a design capacity of 40 Ml/d ADWF was commissioned in June 2013. The plant total design flow and total chemical oxygen demand (TCOD) capacities are 85 Ml/d ADWF and 53,890 kg/d respectively. A new sludge-handling and treatment facility consisting of fermenter, anaerobic digesters, sludge dewatering and sludge liquor treatment facilities was commissioned in 2015.

Each bio-reactor consists of 14 cells. The first eight cells are unaerated and mixed anaerobic and anoxic cells. The following two cells can either be aerated or unaerated (swing cells). The last four cells are always aerated (aerobic cells). In order to allow maximum operational flexibility and to be able to meet low N and P final effluent limits, the bioreactors were designed to be operated in any of five process configurations, namely: three-stage Phoredox (A2O), Johannesburg, Modified Johannesburg, University of Cape Town (UCT) and Modified UCT. The process configurations are changed by manipulating where the influent, return activated sludge (RAS) as well as the internal mixed liquor recycles are discharged. During this study, the bioreactors were operated as a three-stage Phoredox process (Figure 1).

The general layout of the plant is shown in Figure 2 and the detailed EBPR activated sludge process in Figure 3.

The average influent flow and influent and effluent wastewater quality are summarised in Table 1.

The plant loading was still below its design capacity. Final effluent complied with the permit limits for all parameters except nitrate/nitrite. The plant was designed to be operated at a sludge age of 20–25 days. However, due to limitations in the capacity of the waste activated sludge thickening equipment, the plant was operated at longer sludge ages of 25–35 days during the study period. The internal mixed liquor recycle and return activated sludge recycle (RAS) rates were fixed at $2 \times$ ADWF and $1 \times$ ADWF respectively.

Aeration system and instrumentation. The aerobic compartments are aerated by a fine-bubble diffused aeration system. Air to Module 1 is supplied by single-stage centrifugal blowers and to Module 2 by turbo blowers. Each aerobic cell has a dedicated airflow control valve with actuator and feedback, an airflow meter and dissolved oxygen (DO) sensor. Fixed DO setpoint aeration control is applied. The operator uses a modified supplier-provided control algorithm that involves setting both the blowers' manifold pressure and DO for each aerobic cell. Blower speed and number of duty blowers and associated cell airflow control valves modulate to achieve the operator-set manifold pressure and DO. To

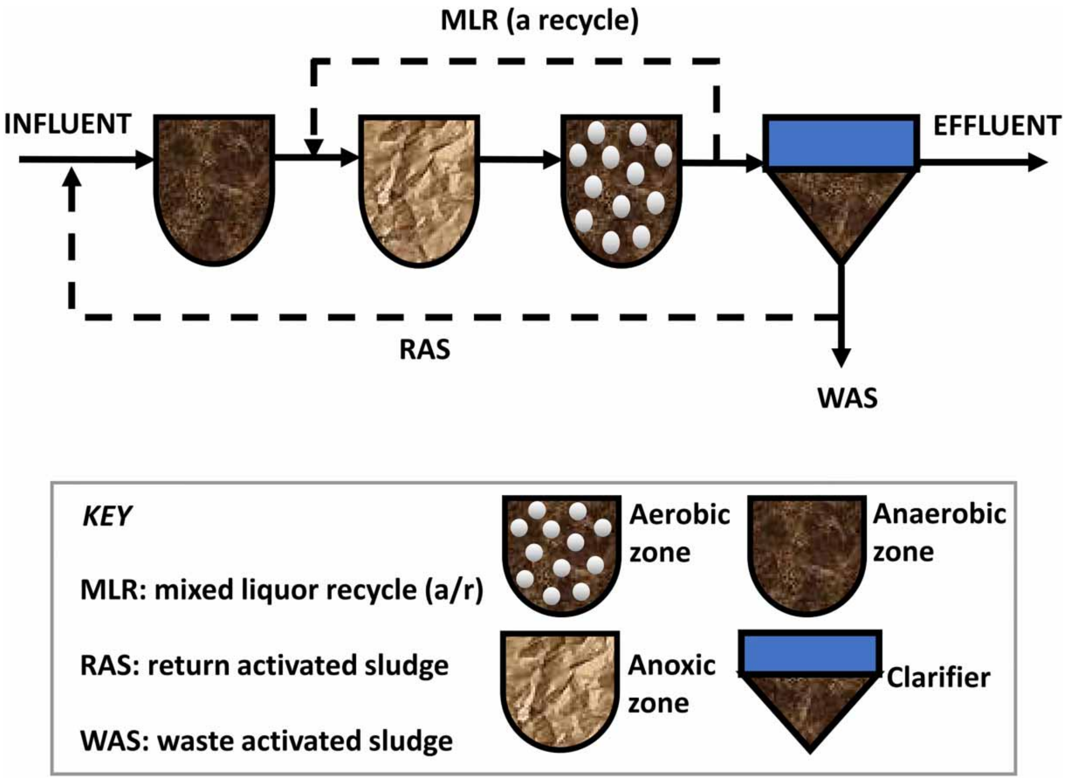

Figure 1 | Three-stage Phoredox process configuration.

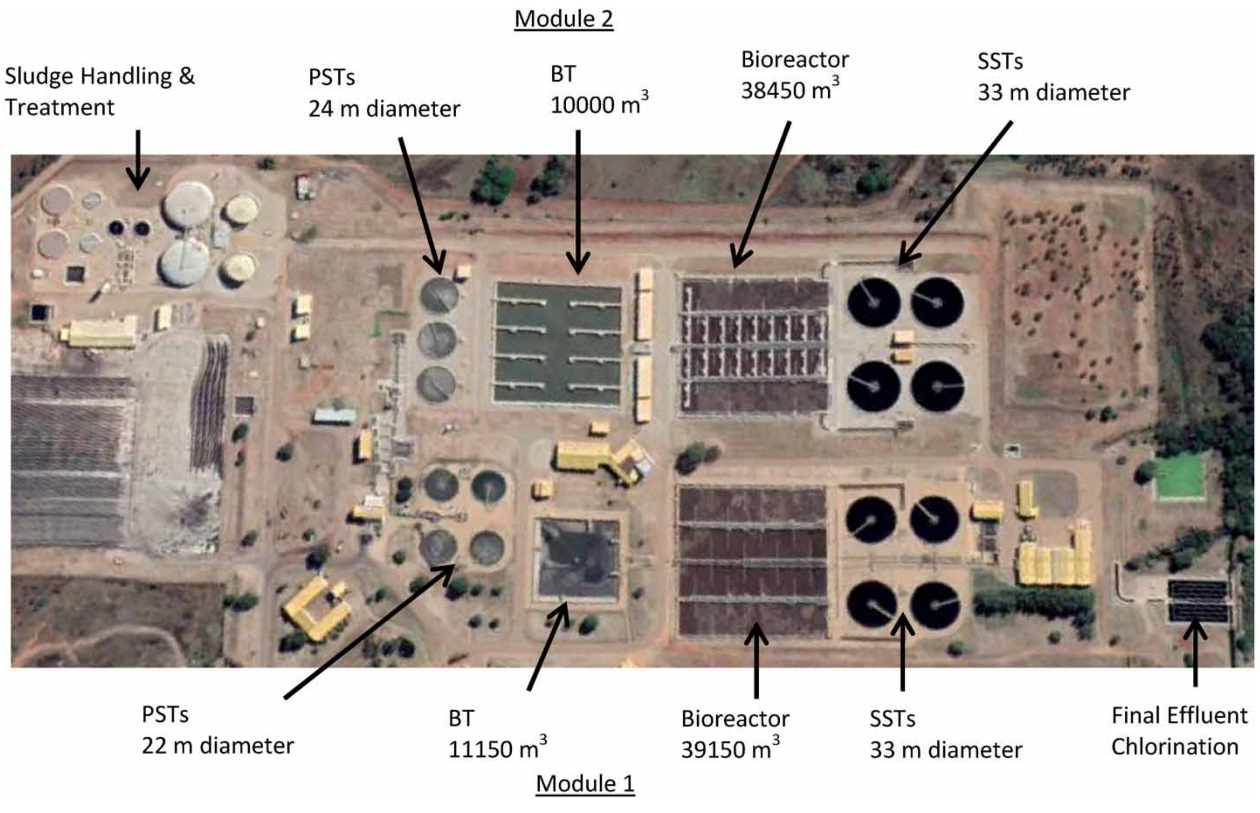

Figure 2 | General layout of case study plant 1.

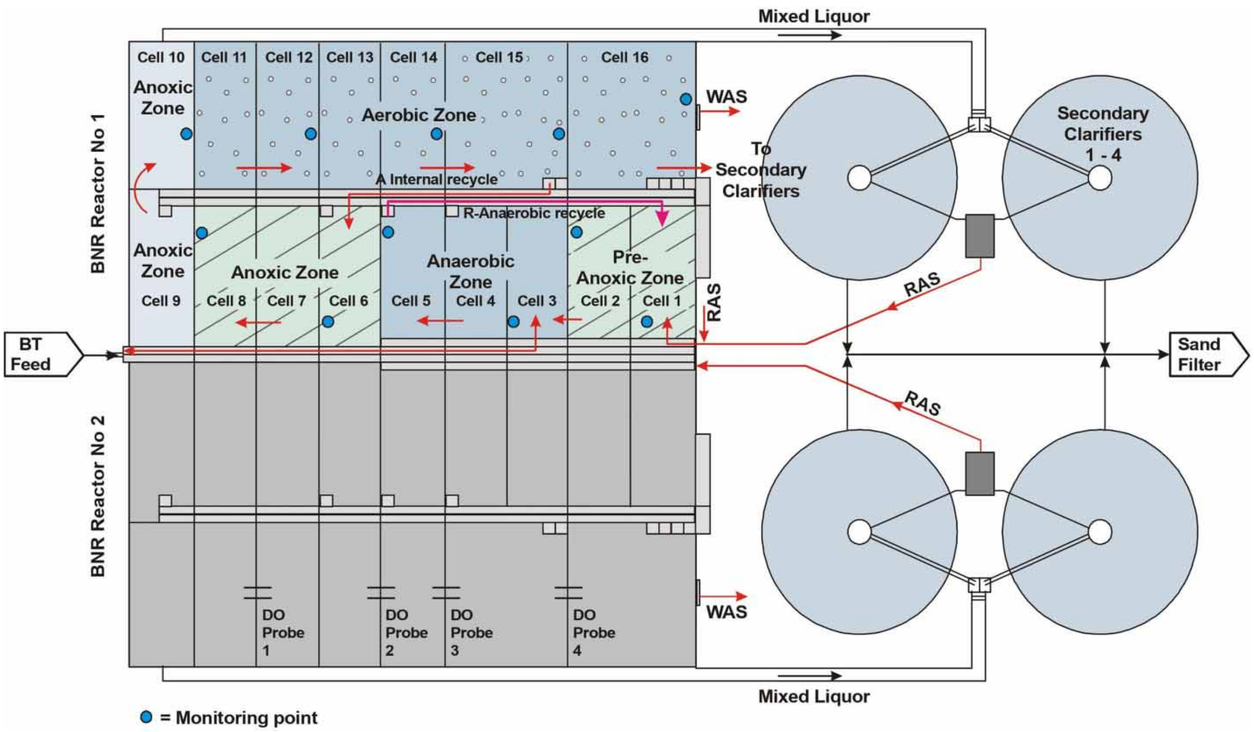

Figure 3 | EBPR activated sludge process layout.

prevent blower tripping, the operator also sets minimum valve opening positions that ensure minimum airflow. In addition, cell airflow measurements are used to override DO controlled valve open position to ensure diffuser minimum and maximum airflows are maintained.

The plant has various localised programmable logic controllers (PLCs) and a centralised supervisory control and data acquisition (SCADA) system. Major plant processes are monitored and controlled by local PLCs providing full automation to some of the processes. In addition the plant has an online auto-analyser that automatically measures ortho P, nitrate, nitrite and ammonia and specific absorbance coefficient (SAC) on the combined final effluent stream.

Case study plant 2

Description. Plant 2 is located in Johannesburg, South Africa, and treats mainly domestic wastewater. The plant was commissioned in 1990 with a design capacity of 15 Ml/d ADWF, and TCOD load of 15,000 kg/d. The treatment process consists of inlet works, primary sedimentation, an EBPR activated sludge bioreactor, two SSTs, a tertiary clarifier and final effluent chlorination. The bioreactor is configured as a three-stage Phoredox process as given in Figure 1 with the general layout of the plant shown in Figure 4.

The average influent flow and influent and effluent wastewater quality are summarised in Table 2.

The plant was operated at an average sludge age of 20–25 days. The mixed liquor recycle and RAS recycle rates were $2 \times$ ADWF and $1.7 \times$ ADWF respectively.

Aeration system and instrumentation. The aeration system consists of 10×55 kW low single-speed surface aerators arranged in rows of two along the aerobic zone. Two DO sensors are located in the last aerobic cell: one approximately in the centre and the other near the bioreactor outlet. An adjustable weir at the bioreactor outlet varies the immersion depth of the aerators. A fixed DO control strategy is applied. The average measurement from the DO sensors is used to automatically control the height of the overflow weir until the operator-set DO setpoint is achieved, thereby varying the immersion depth of the aerators. The aerators can also be automatically controlled by timers (to switch them ON or OFF) in case of malfunction of the DO sensors and/or weir control mechanism.

Collection and analysis of WWTP data

A baseline period for the study was selected. Data to enable capture of diurnal and seasonal variation of influent flow

Table 1 | Plant 1 average influent flow and influent and effluent wastewater quality during study period

Parameter	Units	Value	Final effluent permit limits
Flows			
AAF	ML/d	67.6	
ADWF	ML/d	57.4	
Influent loads			
TCOD	kg/d	28.3	
TKN	kgN/d	2.6	
FSA	kgN/d	1.5	
Total P	kgP/d	296	
Ortho P	kgP/d	131	
TSS	kg/d	15.1	
Influent concentration			
TCOD	mg/l	418	
TKN	mgN/l	39	
Ammonia	mgN/l	23	
Total P	mgP/l	4	
Ortho P	mgP/l	2	
TSS	mg/l	223	
Alkalinity	mg/l as $CaCO_3$	244	
Effluent concentration			
TCOD	mg/l	39	50
FSA	mgN/l	0.7	1
Ortho P	mgP/l	0.3	0.5
Nitrate & nitrite	mgN/l	6.4	6
TSS	mg/l	6.8	10

AAF, Average Annual Flow; ADWF, Average Dry Weather Flow.

and loading, model calibration and validation as well as establishing baseline energy use were collected through the following:

- Analysis of historically measured/recorded data at the plant, i.e.
  - o influent raw and settled wastewater flows and loads as well as final effluent quality
  - o operating parameters for the activated sludge process and other treatment units
  - o power usage by different treatment units
  - o energy tariff structure and energy costs.
- An additional special sampling program was conducted. Twenty-four-hour composite and hourly sampling and analysis on the influent and effluent under both dry (winter) and wet (summer) weather conditions were conducted. Samples to determine operating parameters were also collected along the treatment process. Online instrument measurements were also recorded at the same time to determine process operating parameters as well as aeration power consumption

The wastewater characteristics derived from the data analysis for the case study plants are summarised in Table 3.

Determination of baseline-period energy use

The data collected above were used to determine actual total energy use and costs as well as the split by different functional areas/treatment units for the selected baseline period.

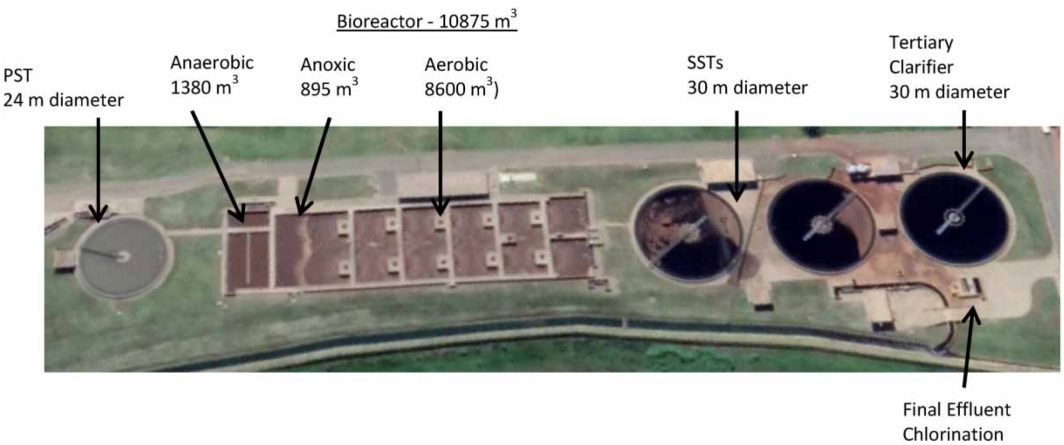

Figure 4 | General layout of case study plant 2.

Table 2 | Plant 2 average influent flow and influent and effluent wastewater quality during the study period

Parameter	Units	Value	Final effluent permit limits
Flows			
AAF	m^3/d	18,693	
ADWF	m^3/d	19,243	
Influent loads			
TCOD	kg/d	8.6	
TKN	kgN/d	665	
FSA	kgN/d	432	
Total P	kgP/d	84	
Ortho P	kgP/d	48	
TSS	kg/d	2,933	
Influent concentration			
TCOD	mg/l	461	
TKN	mgN/l	36	
Ammonia	mgN/l	23	
Total P	mgP/l	4.5	
Ortho P	mgP/l	2.5	
TSS	mg/l	157	
Alkalinity	mg/l as $CaCO_3$		
Effluent concentration			
TCOD	mg/l	35	55
FSA	mgN/l	2.3	4
Ortho P	mgP/l	0.4	0.6
Nitrate & nitrite	mgN/l	0.9	6
TSS	mg/l	12	15

Evaluation of aeration energy use reduction strategies through modelling and simulation

BioWin^{TM} (coupled with BioWin Controller) simulator (www.envirosim.com) was used for modelling and simulation following the Good Modelling Practice unified protocol (Water Environment Federation, 2013). BioWin^{TM} is a wastewater treatment process simulator that ties together biological, chemical, and physical process models. BioWin^{TM} is used worldwide to design, upgrade, and optimise wastewater treatment plants of all types. The core of BioWin^{TM} is a proprietary biological model which is supplemented with other process models such as water chemistry models for calculation of pH and precipitation reactions, and mass transfer models for oxygen modeling and other gas–liquid interactions.

Table 3 | Wastewater characteristics for the case study plants

		Plant 1		Plant 2	
Parameter	Symbol	Raw	Settled	Raw	Settled
Organics/COD fractions					
BO (SB)/Total (St)	FSbi	0.81	0.84	0.79	0.82
BPO (Sbp)/Total (St)	FSbpi	0.60	0.49	0.53	0.44
BSO (Sbs)/Total (St)	FSbsi	0.21	0.35	0.26	0.38
VFA (Sa/Total (St)	FSai	0.03	0.07	0.03	0.07
USO (Sus)/Total (St)	FSusi	0.06	0.08	0.08	0.11
UPO (Sup)/Total (St)	FSupi	0.13	0.08	0.13	0.07
Nitrogen fractions					
FSA/TKN	Fnai	0.67	0.77	0.65	0.01
Phosphorus fractions					
Ortho P/Total P		0.49	0.66	0.57	0.60
Other fractions					
TKN/COD		0.09	0.12	0.09	0.71
Total P/COD		0.011	0.12	0.12	0.12
VSS/TSS		0.93	0.94	0.10	

The historical wastewater data as well as additional data collected for summer and winter was used to calibrate and validate the models following the protocol outlined in the Water Environment Research Foundation's *Methods for Wastewater Characterization in Activated Sludge Modeling* (WERF 2003). Simulations were then carried out using the calibrated models to evaluate feasible aeration energy conservation measures (ECMs) and corresponding process operational and control parameters that would ensure final effluent compliance at minimum energy use. The identified ECMs were classified by ease of implementation (without major interference with the existing process at the plants) as well as capital investment requirements. Current modes of operation were also simulated to serve as a reference.

Case study plant 1

The following feasible ECMs were evaluated for Plant 1:

1. Simple Low Capital Investment
   - Operating at optimal sludge age and maximising denitrification using the current fixed DO setpoint aeration control strategy
2. Low to Medium Capital Investment
   - Ammonia-based advanced process control strategies (feedback cascaded ammonia/DO control and feed-forward feedback ammonia on DO control)

3. Complex High Capital Investment
   - Replacing Module 1 single-stage centrifugal blowers with the same high-speed turbo blowers installed in Module 2 and implementing advanced process control (APC).

The basic BioWin model configuration for Plant 1 is depicted in Figure 5.

Case study plant 2

Feasible ECMs that were evaluated for Plant 2 were:

1. Simple Low Capital Investment
   - Operating at optimal sludge age and maximising denitrification using the current fixed DO setpoint aeration control strategy
2. Low to Medium Capital Investment
   - Installation of variable speed drives on the surface aerators and implementing ammonia-based APC strategies (feedback cascaded ammonia/DO control and feedforward feedback ammonia on DO control)
3. Complex High Capital Investment
   - Replacing surface aerators with fine-bubble diffused aeration and implementing ammonia-based APC
   - Implementing influent flow balancing.

The basic BioWin model configuration for Plant 2 is given in Figure 6.

Financial analysis and energy use benchmarking

Estimated equipment and services costs for implementing feasible aeration ECMs identified using modelling and

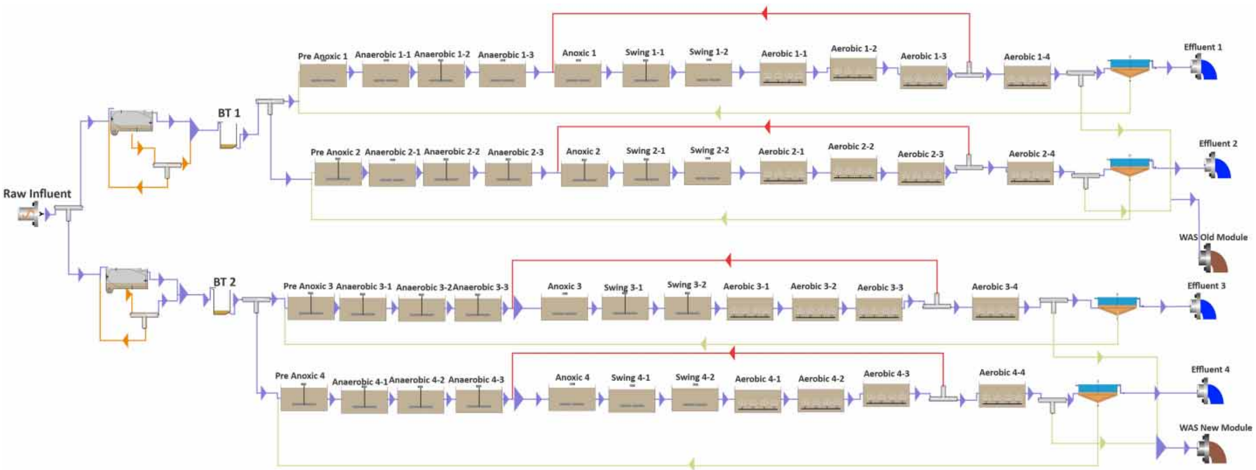

Figure 5 | Basic BioWin model configuration for Plant 1.

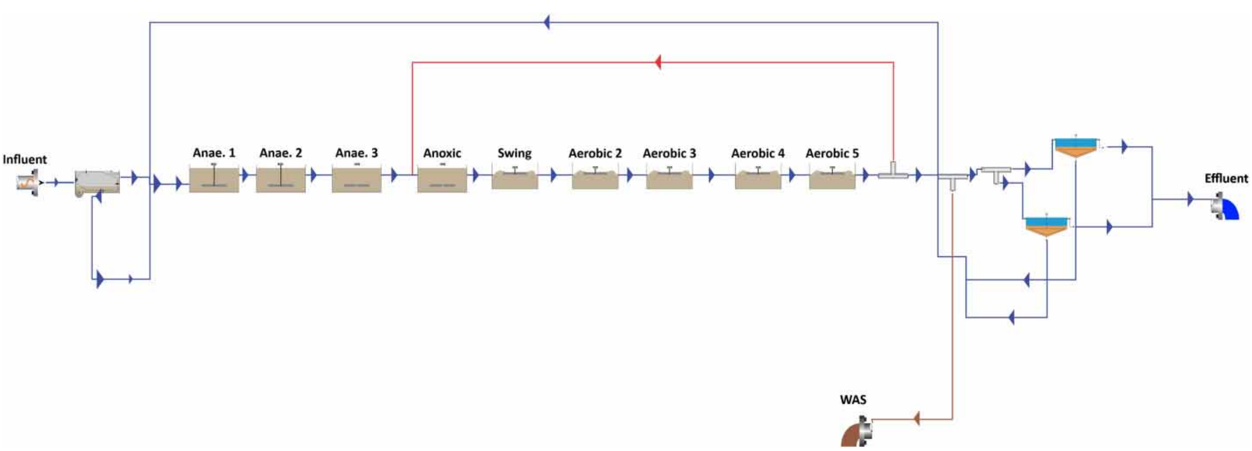

Figure 6 | Basic BioWin model configuration for Plant 2.

simulation were obtained from local suppliers. Simple payback was applied as a financial evaluation technique. Process-driven benchmark aeration energy consumption intensities based on COD load treated and population equivalent served were also calculated for the baseline period as well as for the recommended ECMs. These were compared with available international and national benchmarks and can be used as a starting point for evaluating the national energy benchmarking criteria applicable to South Africa.

RESULTS AND DISCUSSION

Energy profile

The energy profiles for the two case studies are given in Figure 7. The energy splits for both plants indicate that aeration consumes the most energy, confirming previous findings from other studies on activated sludge processes (Rosso & Stenstrom 2005; Crawford & Sandino 2010). In this regard, aeration for Plant 2 with surface aeration accounted for 74% of total energy consumption compared with 42% for Plant 1 with a more efficient fine-bubble diffused aeration (FBDA) system.

Energy use benchmark

Benchmarking is critical to the success of any energy management initiative. By benchmarking energy use, municipalities can compare themselves with the rest of the industry and then set realistic energy use reduction goals that can bring them in line with the best practice in the industry. The benchmark aeration energy use intensity for the case study plants as well as international benchmark values based on studies in Europe are summarised in Table 4.

The aeration energy consumption intensities for both plants are higher than the values observed in Europe. The value for Plant 1 with FBDA is 29–52% higher than the international values. Plant 2 with the less efficient surface aeration system has aeration energy intensity values 41% higher compared with Plant 1 and 82–114% higher than international values. This is attributed to lack of optimisation and use of inefficient aeration systems at the case study plants. In this regard, there is scope to reduce aeration energy use at both South African case study plants to values observed internationally, with more opportunity existing in case study 2.

Aeration energy conservation measures and potential energy savings

The aeration ECMs that were considered feasible for implementation in the two case studies were selected and further analysed using advanced dynamic process modelling and simulation. The aeration ECMs were then classified by ease of implementation without major interference with the existing process as well as limiting capital investment requirements as follows:

- Simple Low Capital Investment
  - Optimised process control by operating at optimal sludge age and maximising denitrification

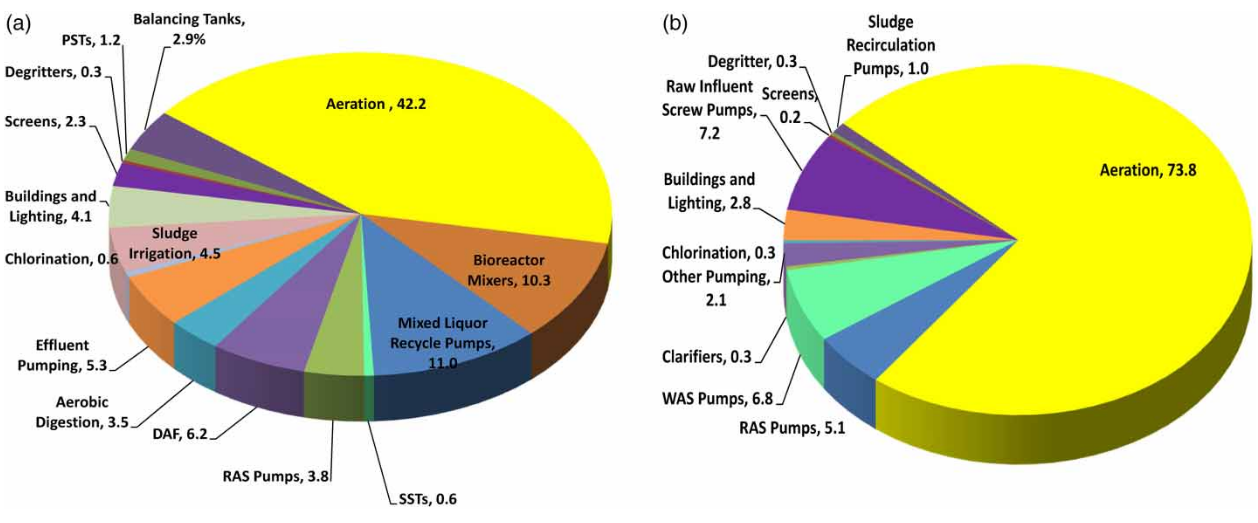

Figure 7 | Energy profiles for (a) case study 1 and (b) case study 2.

Table 4 | Comparison of aeration energy use intensity for the case studies including internationally observed values

Aeration energy use intensity parameter	Value		
	Plant 1	Plant 2	International
Per population equivalent served COD (kWh/pe COD_{100}/yr)	22	31	14.5–17[a]

[a]Case studies in Europe (Austria, Germany and Sweden).

- Low to Medium Capital Investment
  - Ammonia-based advanced process control strategies
- Complex High Capital Investment
  - Replacement of inefficient aeration systems and significant treatment process modifications.

The model-predicted aeration energy consumption and cost savings as well as final effluent quality including the baseline values for comparison are given in Table 5.

The results in Table 5 indicate that implementing the identified simple to complex aeration ECMs can potentially save 9–45% of aeration energy consumption and cost. Implementing simple measures would result in consumption and cost savings of 9% and 10% respectively for case study 1 with 16% and 23% respectively for case study 2. On the other hand, complex measures that involve replacing less efficient conventional surface aerators with more efficient technologies such as FBDA (and the associated latest blower technology) or combined aerator/mixer as well as implementing advanced process and aeration control strategies such as ammonia-based control, appear to significantly improve energy savings. These complex measures provided the highest consumption and consumption cost savings of 21% and 23% respectively for case study 1, and 37% and 41% respectively for case study 2. Corominas *et al.* (2009) have reported model-predicted energy cost savings of up to 30% while Musvoto *et al.* (2012) have reported energy cost savings as high as 50% without compromising final effluent quality within the required standard. Rieger *et al.* (2012) identified aeration control strategies resulting in annual energy savings of up to 30% for three plants.

It is also critical to note that implementation of the identified ECMs, which include optimal process and aeration control, results in improved biological nutrient removal and compliance with final effluent nitrogen and phosphorus limits. Model predictions indicate: (i) average final effluent nitrate/nitrite concentrations of 1–1.5 mgN/l, 75–83% below the average baseline value and permit limit of 6 mgN/l; and (ii) average ortho P concentrations of less than 0.1 mgP/l, showing that near-complete ortho P removal can be achieved. Moreover, the model-predicted effluent quality given in Table 5 shows a generally improved effluent wastewater quality compared with the compliance achieved during the study. In addition, the potential reduction in energy consumption also results in potential reduction of greenhouse gas emissions predicted at about 400 and 1,000 t/year carbon reduction for implementation of simple and complex measures respectively. Implementing energy efficiency programs is therefore a key contribution that the wastewater sector can make in further support of climate change mitigation strategies (IPCC 1996, 2007; Ziervogel *et al.* 2014; Moeletsi *et al.* 2017).

Table 5 | Model-predicted aeration energy consumption, cost savings and final effluent quality for case studies 1 and 2

	Case study 1			Case study 2		
Aeration energy parameter	Baseline	Simple measures	Complex measures	Baseline	Simple measures	Complex measures
Consumption (MWh/year)	4,678	4,265	3,674	2,518	2,109	1,596
Consumption savings (MWh/year)		413	1,004		409	922
Maximum demand savings (kW)		47	115		47	105
% Consumption saving		9	21		16	37
% Consumption cost saving		10	23		23	41
Carbon reduction (t/year)		409	992		405	913
Average final effluent concentrations						
Ammonia	0.4	0.3	0.8	10	1	3.5
Ortho P (mgP/l)	0.3	0.1	<0.1	0.5	0.2	<0.1
Nitrate/Nitrite (mgN/l)	6	3	1	5	4	3

Future predicted aeration energy consumption and cost

Implementing energy conservation only

Applying the energy use and cost benchmark data determined above, it has been estimated that the six largest South African metropolitan municipalities currently consume an estimated 445 GWh/year of electrical energy for aeration at a cost of about R376 million. Both the consumption and cost are expected to increase in the future, in line with increases in quantity of wastewater to be treated and projected electricity cost increase (Eskom 2012). Predicted future aeration energy consumption and cost were analysed for three scenarios, i.e. baseline – the current situation where nothing gets done, and the implementation of simple and complex aeration ECMs described above. It was assumed that energy consumption increases at the same rate as wastewater discharge and the latter increases at the same rate as population growth. A simple exponential growth model was accepted for predicting future population. Therefore future energy consumption was calculated based on exponential growth (Equation (1)):

$$EE_t = EE_0\,(1 + r)^t \tag{1}$$

where:

EE_0 (kWh/year) = current electrical energy consumption in year 0

EE_t (kWh/year) = future electrical energy consumption in year t

r = annual population growth rate assumed at 1.5%.

The electrical energy cost was therefore calculated using Equation (2):

$$\textit{Electrical Energy Cost in year t}\ (EC_t) = EE_t * R_t \tag{2}$$

where: R_t (c/kWh) = power utility tariff rate in year t.

It was assumed that the power utility tariff rates continue to increase at the current annual rate of 14% per year. Thus the future annual tariff rate was calculated from the current tariff rate using the exponential growth model as in Equation (1).

The predicted future aeration energy consumption and cost for the three scenarios are depicted in Figures 8 and 9 respectively.

Model-predicted results depicted in Figures 8 and 9 indicate that if nothing is done, future aeration annual energy consumption and cost will significantly increase above the baseline values. It is estimated that the consumption will increase to 480 GWh/year while consumption cost will increase to R780 million/year over a period of five years; a significant increase of 8% and 107% of consumption and consumption cost respectively. Over a period of ten years, energy consumption and consumption cost are predicted to increase

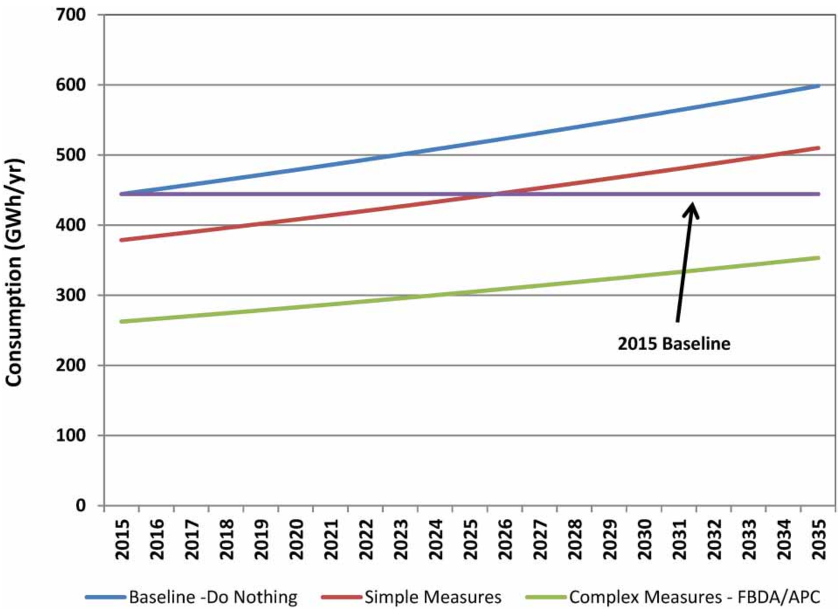

Figure 8 | Future predicted aeration energy consumption for the six largest South African metropolitan municipalities.

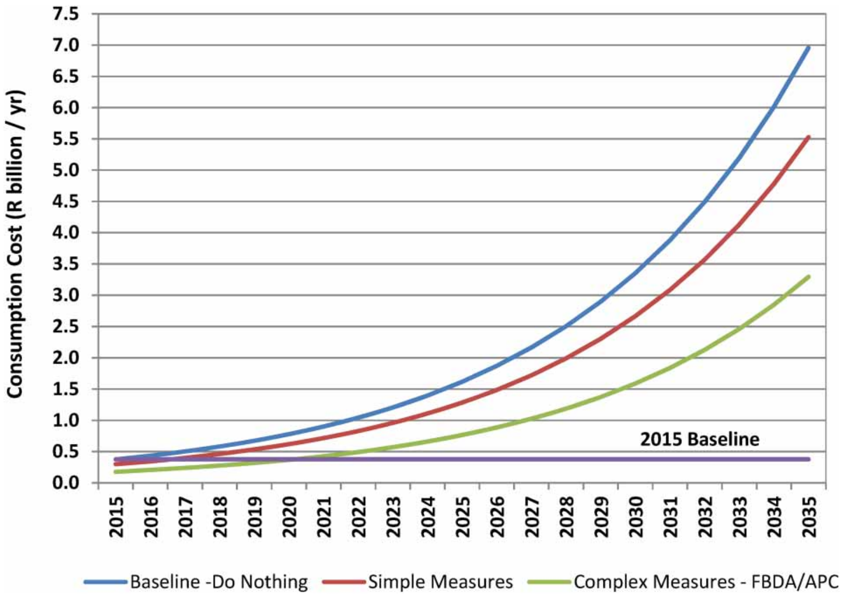

Figure 9 | Future predicted aeration energy consumption cost for the six largest South African metropolitan municipalities.

to 516 GWh/year and R1.6 billion/year; an increase of 16% and 330% respectively. Model predictions over a 20-year period indicate a significantly large consumption and consumption cost increase to 600 GWh/year and R7 billion; 35% and 1,750% increase respectively. The option of doing nothing is therefore costly and unsustainable for municipalities in the long term.

On the contrary, modelling results show that the impact of the predicted high energy consumption and consumption cost within the South African wastewater sector can be mitigated through implementation of aeration ECMs. If the aeration ECMs identified in Table 5 were implemented and the corresponding savings achieved, the results indicate that:

(a) for simple measures the 2015 baseline energy consumption will be exceeded in about 11 years (by 2026);
(b) for complex measures, higher savings are achieved, thus the 2015 baseline energy consumption will be exceeded after 20 years (beyond 2035);
(c) due to the associated cost of implementing the ECMs, the consumption cost was predicted to exceed the baseline consumption cost earlier; in two years for simple measures and five years for complex measures. The cost will however still be lower than the 'do nothing' scenario.

Implementing energy conservation in combination with energy generation

The generation of biogas from anaerobic digestion of wastewater sludge is a well-established technology. With continued improved efficiency of anaerobic digestion and electricity from biogas generation technologies, it is feasible to generate substantial electricity that can be used to offset the demand at wastewater treatment plants, essentially moving the plants towards 'energy neutrality'. Currently it is estimated that the six largest South African metropolitan municipalities generate on average about 332,000 tDs/year of sludge from their activated sludge plants, which if anaerobically digested in conventional mesophilic digesters, can potentially yield an estimated 977,000 m^3/year of biogas. This biogas can conservatively generate about 142 GWh/year of electricity, based on a low value of electricity from biogas of 5.8 kWh/m^3 and 25% engine efficiency. The use of this electricity to offset aeration energy consumption can result in savings in consumption and cost (present value) of electricity that would be purchased from the power utility. Figures 10 and 11 show the model-predicted future aeration energy consumption and consumption cost that would be incurred from electricity purchased from the power utility with and without biogas generation.

Model-predicted results depicted in Figures 10 and 11 indicate that if energy generation from biogas were implemented, significant annual savings would be achieved in electricity purchased from the power utility and the corresponding cost. The savings for each scenario illustrated by electricity consumption and cost in the current year are as follows:

- For the baseline scenario, in the first year, the electricity purchased is estimated to drop by 143 GWh/year, from

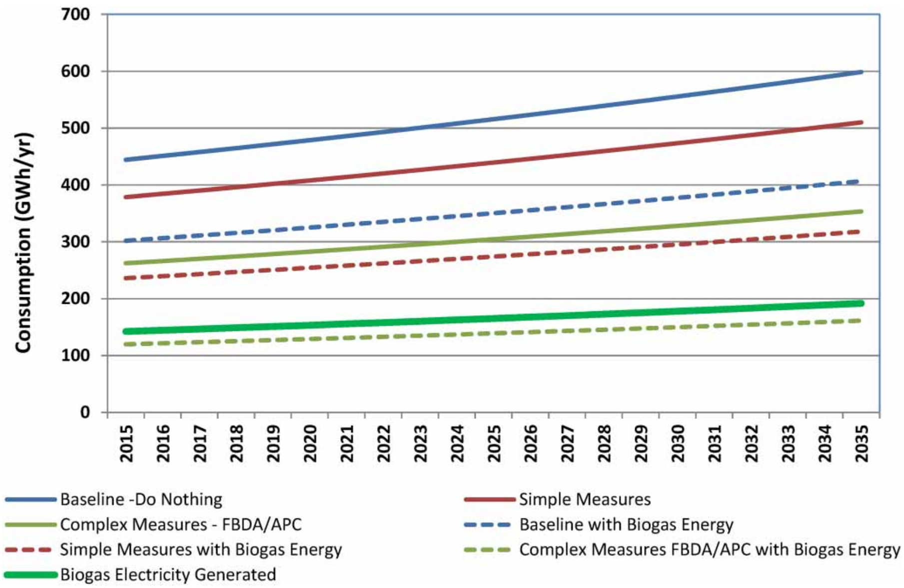

Figure 10 | Future predicted aeration energy consumption electricity with and without biogas electricity generation for the six largest South African metropolitan municipalities.

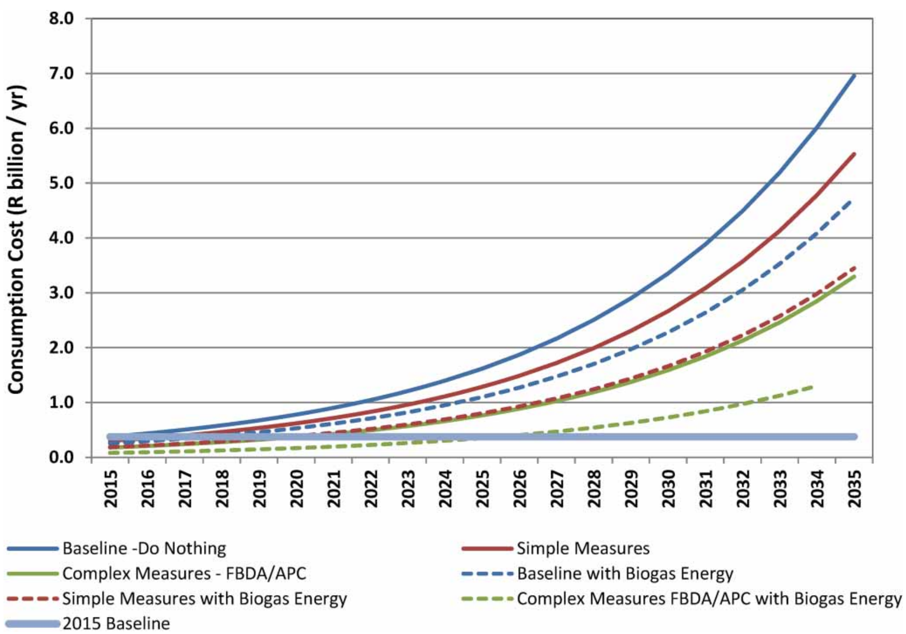

Figure 11 | Future predicted aeration energy consumption cost incurred from electricity with and without biogas electricity generation for the six largest South African metropolitan municipalities.

445 to 302 GWh/year and the cost from R376 to R225 million/year; a potential annual saving of 32% is achieved.

- Potential savings increase to 38% for the simple measures scenario with the current electricity purchased estimated to drop from 379 to 236 GWh/year and the cost from R299 to R186 million/year.
- A substantial increase in savings of about 54% is achieved for the complex measure scenario with electricity purchased estimated to drop from 262 to 120 GWh/year and cost from R178 to R81 million/year in the first year.
- The exponential nature of the consumption cost graph given in Figure 11 indicates significant long-term potential cost savings in the order of billions resulting from

implementation of energy efficiency coupled with biogas energy generation.

Thus, the results show that implementing energy efficiency in conjunction with energy generation achieves significant potential energy savings much higher than only implementing aeration ECMs.

Since this study was completed, the feasibility of energy generation within the South African wastewater sector has significantly progressed. In this regard a number of studies have been conducted showing that energy generation from biogas produced from anaerobic digestion of sludge is economically feasible for the South African municipalities (Burkard & van der Merwe 2018). In this regard, integrating implementation of energy efficiency with generation within the South African wastewater sector has a significant potential of reducing future energy consumption and cost for wastewater utilities, ultimately translating into significant greenhouse gas emission reduction in support of climate change mitigation.

CONCLUSIONS

The current study findings generally illustrate the significant potential energy savings available to the South African wastewater sector through focusing on and prioritising implementation of aeration energy conservation at BNR activated sludge plants. The use of technically superior tools such as advanced mathematical modelling and simulation that enable evaluation of both aeration conservation measures and process control strategies, as demonstrated in this study, yields additional benefits that would not be realised through just aeration equipment changes. The most significant benefit of this approach is that final effluent compliance with regulatory requirements is not compromised through implementation of aeration ECMs, thereby satisfying the primary wastewater treatment objective of protecting the environment. Other additional benefits include cost-efficiency through desktop evaluation of options before practical implementation and better understanding of process performance under various process and aeration control strategies.

It should, however, be noted that although the advanced process modelling approach predicts significant energy and cost savings, this might not be realised in practice due to both technological and human challenges normally identified as hindering the implementation of efficient process and aeration control systems in practice. Therefore, before practically implementing aeration conservation measures of this nature within the South African wastewater sector, the following is recommended:

- A more detailed investigation of market available options for aeration technologies as well as process and aeration control technologies. The quality and costs including maintenance requirements are of critical importance to the success of the aeration energy conservation measures.
- Application of superior economic evaluation techniques such as life-cycle cost analysis, which considers all the costs incurred during the project life, so that the most cost-effective measures can be selected for implementation.
- Detailed engineering design support for medium to high capital measures that require significant modifications to existing infrastructure as well as new treatment units and equipment.

Overall, the South African water sector is however encouraged to consider nation-wide aeration energy use benchmarking exercises for activated sludge plants to properly guide municipalities in planning for energy management initiatives.

ACKNOWLEDGEMENTS

We acknowledge the support of the Water Research Commission, South Africa, for funding the project, the City of Tshwane and Ekurhuleni Water Care Company for assisting with data collection and additional sampling.

REFERENCES

Burkard, T. & van der Merwe, M. 2018 *Biogas Feasibility Study: Kingstonvale Wastewater Treatment Works and Biogas Feasibility Study: Zeekoegat Wastewater Treatment Works*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH Reports, Berlin, Germany.

Burton, S., Cohen, B., Harrison, S., Pather-Elias, S., Stafford, W., van Hille, R. & von Blottnitz, H. 2009 *Energy from Wastewater – A Feasibility Study*. Research Report No. TT399/09, Water Research Commission, Pretoria, South Africa.

Carlson, S. & Walburger, A. 2007 *Energy Index Development for Benchmarking Water and Wastewater Utilities*. AWWA Research Foundation, Denver, CO, USA.

Corominas, L., Subiranas, J., Comas, J., Vanrolleghem, P. A., Rieger, L. & Poch, M. 2009 Using modeling to optimize a full-scale WWTP for energy reduction and increased biological nitrogen removal. In: *Proceedings WEF Nutrient Removal Conference 2011*, Washington, DC, USA.

Corominas, L., Flores-Alsina, X., Muschalla, D., Neumann, M. B. & Vanrolleghem, P. A. 2010a Verification of WWTP design guidelines with activated sludge process models. In: *Proceedings WEFTEC 2010,* New Orleans, LA, USA.

Corominas, L., Rieger, L., Takács, I., Ekama, G., Hauduc, H., Vanrolleghem, P. A., Oehmen, A., Gernaey, K. V., van Loosdrecht, M. C. M. & Comeau, Y. 2010b New framework for standardized notation in wastewater treatment modelling. *Water Science & Technology* **61** (4), 841–857.

Crawford, G. & Sandino, J. 2010 *Energy Efficiency in Wastewater Treatment in North America: A Compendium of Best Practices and Case Studies of Novel Approaches*. Water Environment Research Foundation, Alexandria, VA, USA.

Daw, J., Hallett, K., DeWolfe, J. & Venner, I. 2012 *Energy Efficiency Strategies for Municipal Wastewater Treatment Facilities*. Technical Report NREL/TP-7A30-53341, National Renewable Energy Laboratory, Golden, CO, USA.

Eskom 2012 *Part 1 Revenue Application: Multi-Year Price Determination 2013/14 to 2017/18 (MYPD 3)*. http://www.eskom.co.za/CustomerCare/MYPD3/Documents.

Frost & Sullivan 2011 *Power Outages and Their Impact on South Africa's Water and Wastewater Sectors*. Research Report No. KV267/11, Water Research Commission, Pretoria, South Africa.

Guerrini, A., Romano, G. & Indipendenza, A. 2017 Energy efficiency drivers in wastewater treatment plants: a double bootstrap DEA analysis. *Sustainability* **9** (7), 1126.

Gujer, W., Henze, M., Mino, T. & van Loosdrecht, M. 1999 Activated Sludge Model No. 3. *Water Science and Technology* **39** (1), 183–193.

Henze, M., Gujer, W., Van Loosdrecht, M., Mino, T. & Blackall, L. 1999 *Modelling and Microbiology of Activated Sludge Processes: Proceedings of the 4th IAWQ Seminar on Modelling and Microbiology of Activated Sludge Processes*. Published as *Water Science and Technology* **39** (1).

Intergovernmental Panel on Climate Change 1996 *Technologies, Policies and Measures for Mitigating Climate Change*. IPCC Technical Paper I – November 1996.

Intergovernmental Panel on Climate Change 2007 *Synthesis Report*. Contribution of Working Groups I, II and III to the Fourth Assessment.

Jonasson, M. 2007 *Energy Benchmark for Wastewater Treatment Process: A Comparison between Sweden and Austria*. Department of Industrial Electrical Engineering and Automation, Lund University, Sweden.

Kappeler, J. & Gujer, W. 1994 Verification and applications of a mathematical model for 'aerobic bulking'. *Water Research* **28** (2), 311–322.

Moeletsi, M. E., Tongwane, M. I. & Tsubo, M. 2017 Enteric methane emissions estimate for livestock in South Africa for 1990–2014. *Atmosphere* **8**, 69.

Musvoto, E. V., Kitson, J., Hartley, R. & Holmes, J. 2012 Application of mathematical modelling to find energy saving operational methods under a new variable energy tariff. In: *EcoSTP Conference*, 25–27 June, Santiago de Compostela, Spain.

Pan, T., Zhu, X. D. & Ye, Y. P. 2011 Estimate of life-cycle greenhouse gas emissions from a vertical subsurface flow constructed wetland and conventional wastewater treatment plants: a case study in China. *Ecological Engineering* **37** (2), 248–254.

Rieger, L., Takács, I. & Siegrist, H. 2012 Improving nutrient removal while reducing energy use at three Swiss WWTPs using advanced control. *Water Environment Research* **84** (2), 170–188.

Rosso, D. & Stenstrom, M. K. 2005 Comparative economic analysis of the impacts of mean cell retention time and denitrification on aeration systems. *Water Research* **39** (16), 3773–3780.

Swartz, C. D., van der Merwe-Botha, M. & Freese, S. D. 2013 *Energy Efficiency in the South African Water Industry: A Compendium of Best Practices and Case Studies*. Research Report No. TT 565/13, Water Research Commission, Pretoria, South Africa.

van der Merwe-Botha, M., Juncker, K., Visser, A. & Boyd, R. 2016 *Guiding Principles in the Design and Operation of a Wastewater Sludge Digestion Plant with Biogas and Power Generation*. Research Report No. TT 681/16, Water Research Commission, Pretoria, South Africa.

van Vuuren, S. J., van Dijk, M. & Loots, I. 2014 *Conduit Hydropower Pilot Plants*. Research Report No. TT 596/14, Water Research Commission, Pretoria, South Africa.

Venkatesh, G. & Brattebø, H. 2011 Energy consumption, costs and environmental impacts for urban water cycle services: case study of Oslo (Norway). *Energy* **36**, 792–800.

Water Environment Federation 2013 *Wastewater Treatment Process Modeling*, 2nd edn. Manual of Practice No. 31, Water Environment Federation, Alexandria, VA, USA.

Water Environment Research Foundation 2003 *Methods for Wastewater Characterization in Activated Sludge Modeling*. Water Environment Federation, Alexandria, VA, USA.

Ziervogel, G., New, M., Archer van Garderen, E., Midgley, G., Taylor, A., Hamann, R., Stuart-Hill, S., Myers, J. & Warburton, M. 2014 Climate change impacts and adaptation in South Africa. *WIRES Climate Change* **5**, 605–620.

First received 4 November 2019; accepted in revised form 25 March 2020. Available online 6 April 2020