Energy benchmarking of South Australian WWTPs

J. Krampe

South Australian Water Corporation, 250 Victoria Square, Adelaide SA 5000, Australia (E-mail: joerg.krampe@sawater.com.au)

Abstract Optimising the energy consumption and energy generation of wastewater treatment plants (WWTPs) is a topic with increasing importance for water utilities in times of rising energy costs and pressures to reduce greenhouse gas (GHG) emissions. Assessing the energy efficiency and energy optimisation of a WWTP are difficult tasks as most plants vary greatly in size, process layout and other influencing factors. To overcome these limits it is necessary to compare energy efficiency with a statistically relevant base to identify shortfalls and optimisation potential. Such energy benchmarks have been successfully developed and used in central Europe over the last two decades.
This paper demonstrates how the latest available energy benchmarks from Germany have been applied to 25 WWTPs in South Australia. It shows how energy benchmarking can be used to identify shortfalls in current performance, prioritise detailed energy assessments and to help inform decisions on capital investment.

Keywords Energy benchmarking, specific energy consumption, energy optimisation

INTRODUCTION

With the steadily rising cost of energy and the need to reduce greenhouse gas emissions there is an increasing need to intensify efforts to reduce energy consumption from wastewater treatment plants (WWTPs). Even though the specific energy consumption of WWTPs is only low (comparable to boiling 750 mL water per PE and day), total WWTP energy consumption is significant. In South Australia, the WWTPs owned by the state's water utility, SA Water, have a total annual energy consumption of 139 GWh/year (excluding wastewater network consumption), which represents 27% of the total energy consumption of SA Water. In 2010 SA Water signed a Climate Change Sector Agreement which sets clear greenhouse gas reduction targets for SA Water to reduce greenhouse gas (GHG) emissions to 40% of 1990 levels by 2050. Energy efficiency measures in the wastewater area play an important role in achieving these targets. To identify opportunities for improved energy efficiency, SA Water began an evaluation process for the energy efficiency of its WWTPs.

Sewage contains energy which equates to 155 kWh/PE/y (Svardal and Kroiss, 2011) from the internal chemical energy of the organic content. This is based on a calorific value of 14 kJ/g COD and a specific load of 110 g COD/PE/y. According to Heidrich et al. (2011) 13 – 14 kJ/g COD represents the minimum content found in wastewater and under certain circumstances this value can reach up to 28.7 kJ/g COD. Depending on the treatment technology, some of this energy can be recovered from wastewater and utilised to power treatment processes up to the point of energy self-sufficiency under optimal conditions. Achieving self-sufficiency also involves efficient energy use and energy generation on site as clearly demonstrated by the Strass and Wolfgangsee-Ischl WWTPs (Nowak et al., 2011).

An excellent tool to assess the performance and determine the efficiency of individual treatment plants and processes is the benchmarking of performance against other plants and current industry standards. This allows for the identification of inefficiencies and helps in prioritising optimisation efforts. Balmér (2000) compared the operation costs and consumption of resources at Nordic nutrient

The definitive peer-reviewed and edited version of this article is published in Water Science & Technology, Volume 67, Issue 9, 2059-2066, 2013, doi:10.2166/wst.2013.090 and is available at www.iwapublishing.com. This is the accepted version.

removal plants and came to the conclusion that a non-monetary comparison is favourable over a monetary comparison for international studies. It was also concluded that a comparison based on connected people or load has advantages over relating consumption to the flow. The specific energy consumption of the five WWTPs in the study were compared as kWh/PE_{TKN12}/y and varied from 31.0 to 47.2 kWh/PE_{TKN12}/y. Lindtner et al. (2008) describe a benchmarking approach of large municipal WWTPs based on pollution load expressed in PE_{COD110}, which is focused on operation costs. This benchmarking was described as an excellent tool to find and realise cost reduction potentials, but also to prove excellence in performance of treatment plant operation. Mizuta and Shimada (2010) benchmarked the energy consumption of municipal WWTPs in Japan with specific power consumption specified in kWh/m^3. They showed that there is a large variety in the specific energy consumption of different plants and that the main influencing factor is treatment plant capacity, rather than process type. The authors found energy benchmarking to be a useful tool in demonstrating the advantages of implementing low energy consumption and energy recovery schemes.

The studies utilised a variety of approaches to benchmark general plant performance and energy efficiency specifically, but all concluded that the benchmarking process was beneficial. Based on these positive experiences, SA Water decided to conduct an energy benchmarking study of its WWTPs in order to identify potential areas for optimisation and to target investments in order to maximise the benefit. The findings and experiences from this benchmarking are presented in this paper.

MATERIAL AND METHODS

SA Water owns 25 WWTPs, ranging from 250 to 1.2M PE_{BOD60} design capacity and covering a wide range of technologies, from Imhoff tank and lagoon plants, to trickling filters and different types of activated sludge plants. The key features of the plants presented in this paper are summarised in Table 1. Based on this variety of sizes and technologies it is difficult to benchmark the WWTPs against each other, as energy consumption and production potential depend heavily on plant size and technology. Therefore, benchmarking was done against industry standards.

Table 1: Overview of the WWTPs included in the benchmarking process

Plant	Connected PE_{BOD60}	Primary treatment	Secondary treatment	Disinfection and Reuse	Sludge Treatment
Aerated lagoon plants					
Whyalla WWTP	12,046	-	1 aerated, 2 facultative lagoons		Sludge lagoons
Pt Augusta West	3,030	-	1 aerated, 2 polishing lagoons	Chlorination, Reuse PS	Lagoons desludged on hardstands
Angaston	2,730	Imhoff tank	1 aerated, 2 facultative lagoons	Chlorination	Imhoff sludge tankered off site, lagoons periodically desludged
Murray Bridge	14,263	Imhoff tank	1 aerated, 1 polishing lagoon	Reuse PS	Imhoff sludge tankered off site, lagoons periodically desludged

Pt Augusta East	3,905	-	2 aerated, 2 polishing lagoons	-	Lagoons periodically desludged and stockpiled
Trickling filter plants					
Nangwarry	402	Imhoff tank	Trickling filter	-	Sludge scrapes
Naracoorte	2,337	Prim. sed.	Trickling filter	-	Anaerobic digestion (cold), drying beds
Gumeracha	431	Imhoff tank	Trickling filter	Pressure filters, chlorination, Reuse PS	Imhoff sludge tankered off site
Mt. Burr	212	Imhoff tank	Trickling filter	-	Sludge scrapes
Activated sludge plants					
Bolivar WWTP	1,000,660	Prim. sed.	Step-feed	Polishing lagoons	Mesophilic anaerobic digestion, CHP, sludge lagoons, hardstand
Bolivar HS	91,813	-	SBR	UV	Pumped to Bolivar
Pt Lincoln	15,798	-	SBR (IDEAL)	Polishing lagoons	Sludge lagoons
Glenelg	218,057	Prim. sed.	IFAS	Chlorination	Mesophilic anaerobic digestion, CHP, pumped to Bolivar
Christies Beach	113,755	Prim. sed.	IFAS	Chlorination	Mesophilic anaerobic digestion, trucked off site
Whyalla WRP	13,488	-	SBR	UV and Chlorination	Transferred to Whyalla WWTP
Hahndorf	3,888	-	Oxidation ditch	Chlorination	Transferred to Heathfield
Finger Point	16,892	-	SBR (IDEAL)	Chlorination	Sludge lagoons, hardstand
Aldinga	5,756	-	Oxidation ditch	Chlorination	Sludge lagoons
Pt Pirie	8,312	-	SBR	Polishing lagoons	Sludge lagoons
Heathfield	6,781	-	MLE	UV	Aerobic digestion, hardstand

Several countries in Europe have developed their own benchmarking systems. The first manual for energy benchmarking in Europe was developed in Switzerland (Müller et al., 1994). Crawford (2010) compared different benchmarking systems for energy efficiency and based on that study's findings it was decided to use the approach that is used in Switzerland, Germany and Austria to assess the energy efficiency of SA Water’s WWTPs. However, it was recognised that the benchmarks might not be fully applicable, for example due to higher nitrogen loads in Australian wastewater, as the N/C ratio has a significant impact on the overall energy efficiency of a WWTP (Nowak, 2003). Nevertheless, the described effluent targets between these countries and South Australia are comparable in broad terms.

Two different sets of benchmarks were used in this study. The first was prepared by Haberkern et al. (2008) for the German UBA (Federal Environment Agency) and is partly summarised in Table 2. This dataset focused on activated sludge plants with a design capacity above 5,000 $\mathrm{PE}_{\mathrm{BOD60}}$, as these plants consume the majority of the energy used in wastewater treatment in Germany. The targets specified there were mainly used for the benchmarking of WWTPs with anaerobic digestion and onsite energy generation, as there were specific benchmarks specified for this group. The other set of benchmarks were developed by Baumann and Roth (2008) with a specific focus on the state of Baden-Württemberg and the treatment technologies and sizes of WWTPs applied there (Table 3 and 4). Therefore, the benchmarks cover a wider variety of treatment processes and treatment plant sizes. This dataset was used to benchmark all treatment plants by their total energy consumption for consistency. The two benchmarks generally align very well, with only marginal differences where size and technologies overlap. Both datasets differentiate between guide and target numbers, where the guide number represents average observed performance, whereas the target number refers to top performance.

Table 2: Target and guide numbers for the specific energy consumption (extract from Haberkern et al., 2008)

Process	**Parameter**	**Unit**	**Target number**	**Guide number**	
			> 5,000 PE	**5,000 - 10,000 PE**	**> 10,000 PE**
Total WWTP	energy consumption	kWh/$\mathrm{PE}_{\mathrm{BOD60}}$/y	18	35	30
WWTP with digester	electricity self supply	%	100	-	60
	external heat supply	kWh/$\mathrm{PE}_{\mathrm{BOD60}}$/y	0	-	3
Digester	quantity of bio gas	L/PE/d	30	-	20
Aeration	energy consumption	kWh/$\mathrm{PE}_{\mathrm{BOD60}}$/y	10	18	16
Pumps	energy consumption	Wh/m^3/m	4	-	6

The benchmarks from Haberkern et al. (2008) also address the additional energy consumption that has to be considered for additional treatment steps such as UV disinfection and odour control, but this was not covered in this initial benchmarking study.

Table 3: Guide numbers in kWh/$\mathrm{PE}_{\mathrm{BOD60}}$/y for specific energy consumption (Baumann and Roth, 2008)

	< 1,000 PE	**1,000 - 5,000 PE**	**5,001 - 10,000 PE**	**10,001 - 100,000 PE**	**> 100,000 PE**
Aerated lagoons	**50**	**40**	**35**	-	-
Rotating biological contactor	**34**	**23**	**18**	-	-
Trickling filter	**32**	**25**	**20**	25	25
Extended aeration	70	45	38	34	-
Activated sludge (AS)*	60	40	34	30	27
AS and trickling filter	-	-	-	30	26

* With separate sludge stabilisation e.g. anaerobic digestion
Bold numbers are usually nitrification only

The benchmarks also take into account treatment performance, as smaller plants and certain technologies are usually only designed for nitrification. These values are highlighted in Tables 3 and 4.

Table 4: Target number in kWh/PE_{BOD60}/y for specific energy consumption (Baumann and Roth, 2008)

	< 1,000 PE	1,000 - 5,000 PE	5,001 - 10,000 PE	10,001 - 100,000 PE	> 100,000 PE
Aerated lagoons	**32**	**30**	**25**	-	-
Rotating biological contactor	**23**	**18**	**15**	-	-
Trickling filter	**20**	**17**	**15**	18	18
Extended aeration	38	28	23	20	-
Activated sludge (AS)*	32	24	20	18	18
AS and trickling filter	-	-	-	18	18

* With separate sludge stabilisation e.g. anaerobic digestion
Bold numbers are usually nitrification only

The values in Table 2 to 4 are only valid for plants with the following conditions:

- Total maximum sewage volume: 91 m^3/PE_{BOD60}/y or 250 L/PE_{BOD60}/d
- Pumping head of influent to plant ≤ 3 m
- N/BOD_5 ratio of < 0.2 in the plant influent

However, high level benchmarking was conducted even for plants slightly outside these conditions, as the intention was to prioritise plants for the need for detailed energy assessments.

RESULTS AND DISCUSSION

Based on the available benchmarks it is possible to compare the energy consumption of WWTPs based on their size or treatment technology. For the purpose of this paper only the comparison for some treatment technologies will be presented. Figure 1 shows the results for the aerated lagoon systems which cover a capacity up to 15,000 PE_{BOD60}. The benchmarks vary for the different plants based on their relative sizes.

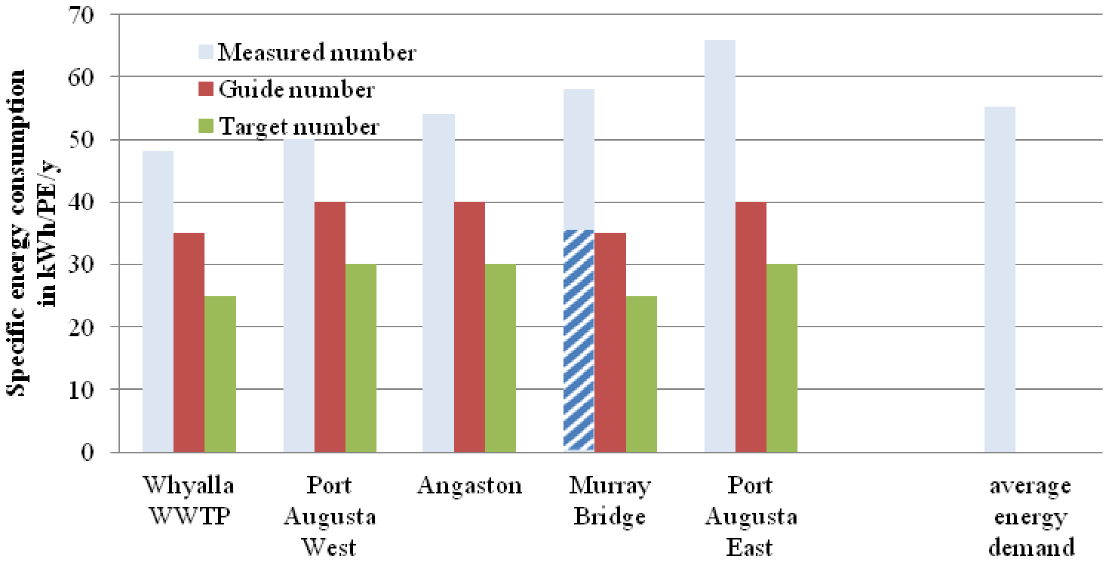

Figure 1: Specific energy consumption of SA Water's aerated lagoon plants (dashed column for Murray Bridge excludes the reuse pump station)

The measured energy consumptions exceed the guide numbers by 10 to 20 kWh/PE/y for two main reasons. Firstly, some of the plants (Murray Bridge, Pt Augusta West) include infrastructure effluent reuse, which is not considered in the benchmarks and therefore has to be excluded for the purpose of benchmarking. The exclusion of the reuse infrastructure was only possible for Murray Bridge WWTP and resulted in the specific consumption getting close to the guide number. Secondly, some of the plants are only partly loaded to their design capacity (e.g. Pt. Augusta East utilisation ratio = 28%), but their surface aeration systems has not been adjusted, as they also provide a mixing function and must be operated to ensure sufficient mixing and avoid short circuiting. Timer-based operation of the aerators (accepting settling at night time with low flows entering the plant) or taking individual lagoons off line are currently being explored as options to further reduce energy consumption.

In Figure 2 the specific energy consumption for four trickling filter plants is compared with benchmarks. The plant in Nangwarry showed extremely good performance, while the Gumeracha and Mt Burr trickling filter plants have a far higher specific energy consumption. This is surprising as the Mt Burr and Nangwarry plants share the same design and are similarly loaded. Currently a detailed energy assessment is underway to identify the reasons for the high specific energy consumption. The plant at Gumeracha was designed for a significant industrial waste stream which is no longer received; therefore the plant is significantly underloaded. One option that is currently being considered to increase the energy efficiency of the plant is taking one of the two trickling filters off line. This will allow a significant reduction in pumping.

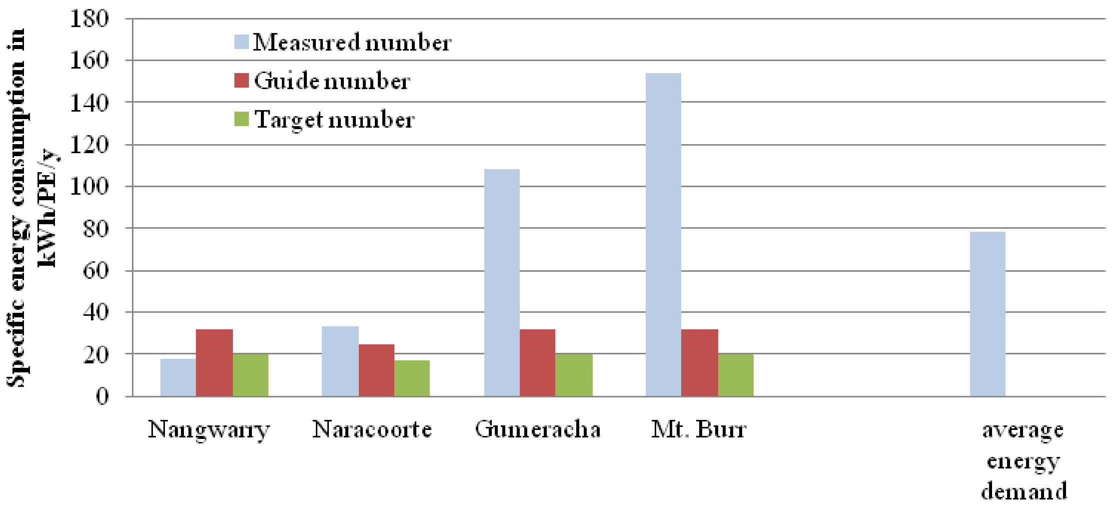

Figure 2: Specific energy consumption of SA Water's trickling filter plants

Figure 3 compares the specific energy consumption of all activated sludge plants, which covers continuous flow plants and SBR plants as well. The lowest specific energy consumption was recorded for Bolivar WWTP which is SA Water's largest WWTP with a design capacity of approximately 1.2M PE_{BOD60} which is discussed in more detail below. The plant with the highest energy consumption is Heathfield WWTP, which is operated with separate aerobic sludge stabilisation. This has been identified as the reason for the elevated energy consumption, but at the same time the plant uses UV disinfection before discharge, which isn't considered in the applied benchmarks. Pt Pirie WWTP, the second highest specific energy user, had issues with its aeration systems during the relevant period and these have since been optimised.

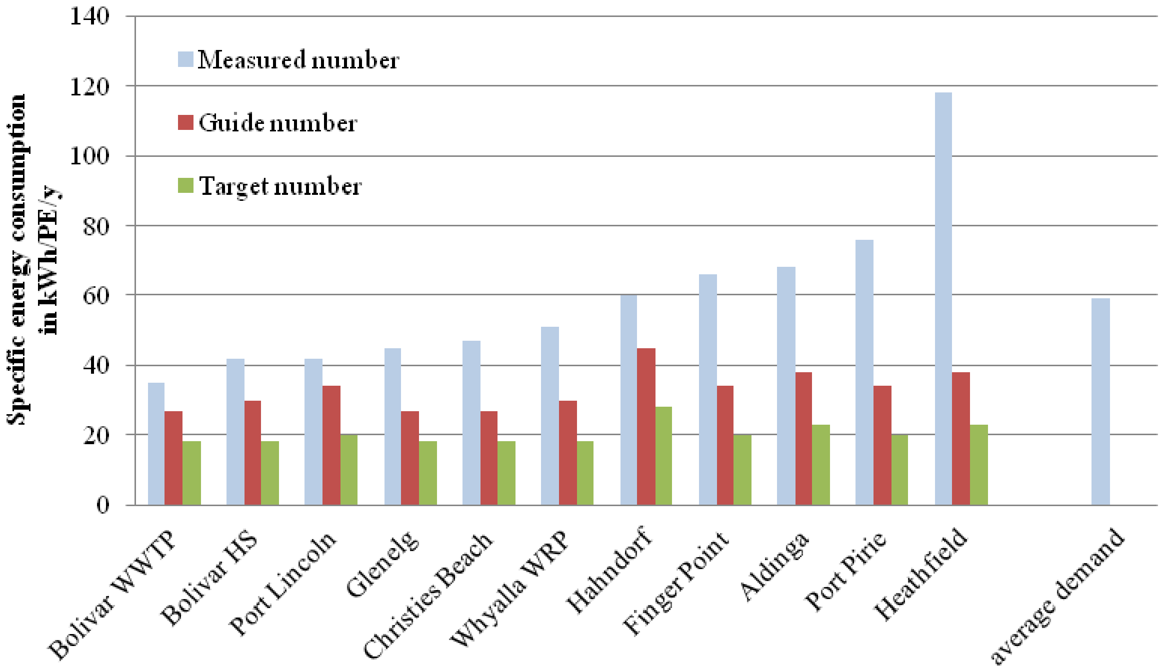

Figure 3: Specific energy consumption of SA Water's activated sludge plants

Based on the findings of the benchmarking and in depth knowledge of plant performance and processes it was possible to develop recommendations for improvements in energy efficiency for almost all plants. The options range from detailed energy assessments to operational changes and plant modifications that involve capital expenditure.

In Figure 4, a more detailed assessment of the two largest WWTPs of SA Water, which utilise anaerobic mesophilic digestion and onsite energy generation, is presented. For this assessment the benchmarks from Haberkern et al. (2008) have been used. The benchmark for specific energy consumption has been calculated using specific biogas production and assuming a calorific value of 6.5 kWh/m^3 for biogas and an electrical conversion efficiency for larger combined heat power units (CHPs) of 38%.

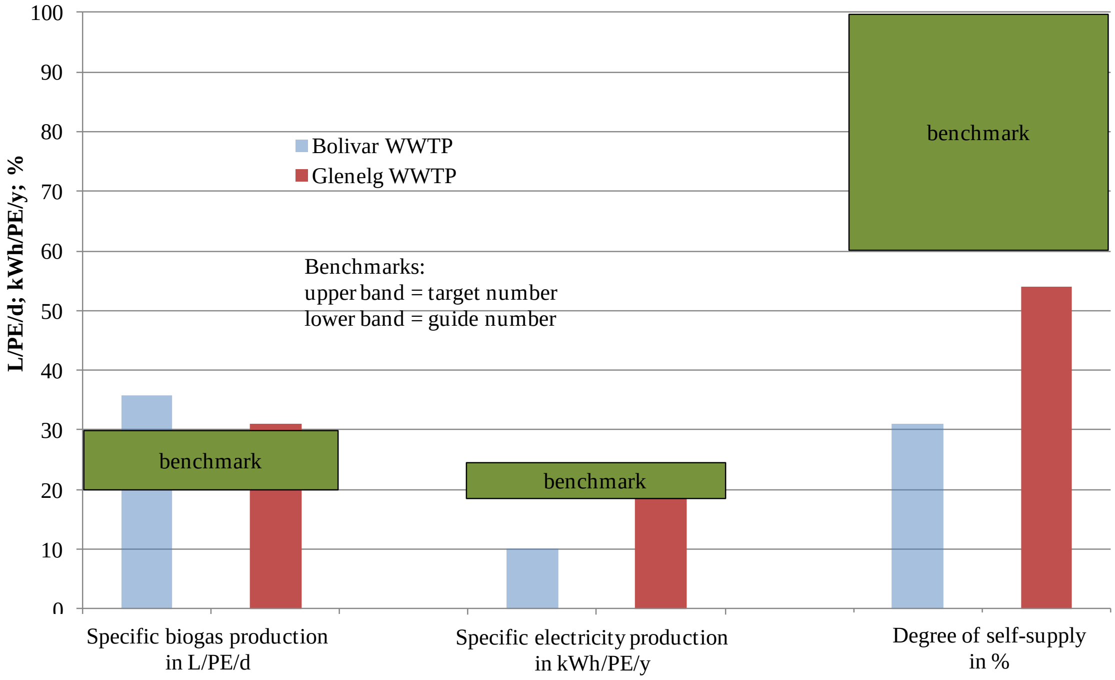

Figure 4: Key energy production benchmarks - Bolivar and Glenelg WWTPs (target and guide numbers from Haberkern et al. (2008))

Both plants outperform the specific biogas production benchmark. In order to cross-check the accuracy of measured gas production, the theoretical gas production for both plants was calculated using the results of Kapp (1984), who found a specific biogas production of ~540 L/kg TS_{in} for primary sludge and ~275 L/kg TS_{in} for waste activated sludge at 20 days retention time in the digester. This cross check confirmed the measured gas production. The main reason for the very high biogas production is the high amount of primary sludge (60% of total sludge production), due to large primary sedimentation tanks (~4 h hydraulic retention time at annual average flow (AAF)). At Glenelg WWTP the high biogas production results in a high specific electricity production as well; however, at Bolivar the guide number is not achieved. This is a result of reliability issues with the installed single turbine and the generally low electrical efficiency of the installed system. This is currently being addressed in a capital project where three new gas engines are to be installed at Bolivar. This is expected to bring the specific energy production up to the target number. The low specific electricity production at Bolivar is also the reason why the plant is not achieving the benchmark in regard to the degree of electricity self-supply. However, at Glenelg, energy production cannot explain the shortfall in the degree of self-supply and so this must be related to energy consumption.

In Figure 5 the specific energy consumption for the whole plants and the aeration system for Bolivar and Glenelg WWTP are compared against the Haberkern et al. (2008) benchmarks.

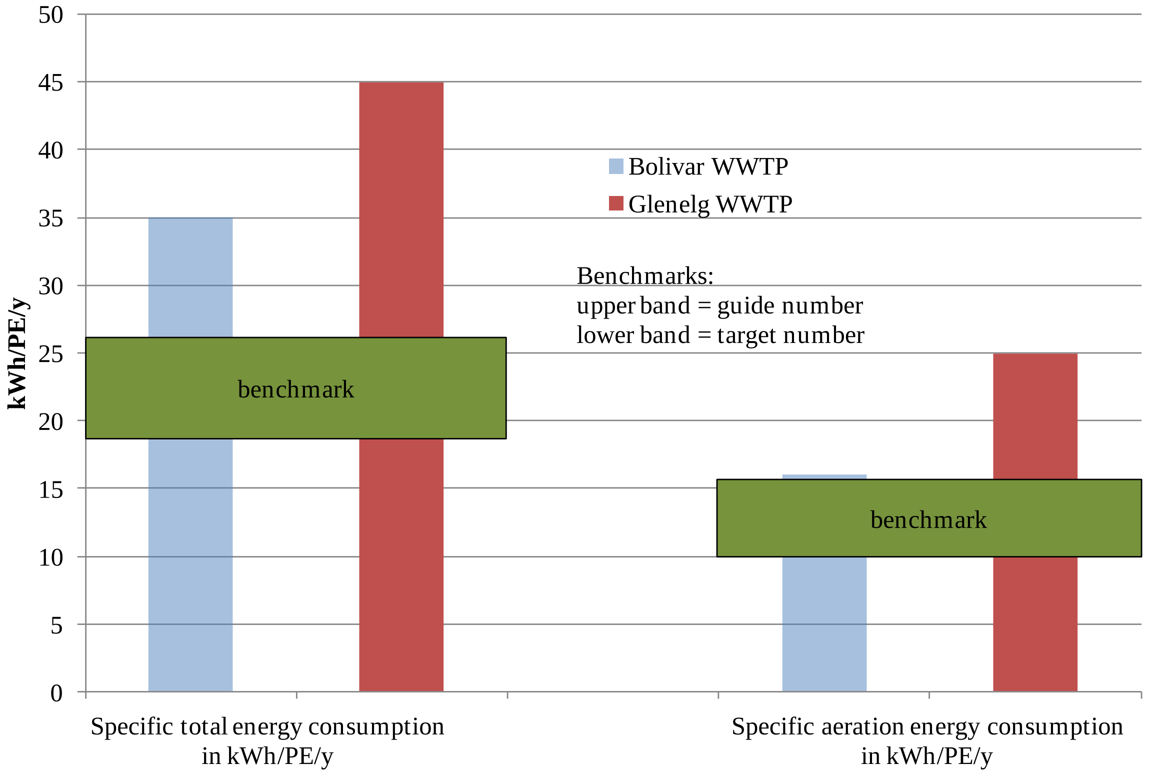

Figure 5: Key energy consumption benchmarks – Bolivar and Glenelg WWTPs (target and guide numbers from Haberkern et al. (2008))

For both plants energy consumption exceeds the guide number, at Bolivar by approximately 10 kWh/PE/y and at Glenelg by 20 kWh/PE/y. This clearly explains why Glenelg WWTP cannot achieve the expected degree of electricity self-supply. Part of the high specific energy consumption at Bolivar WWTP is explained by the sewage pump station which lifts raw sewage 7 m and 9 m, respectively, from the main incoming sewers. This high lift is outside the typical range of pumping that has been considered for the benchmarks (< 3 m). However, currently additional energy sub-metering is being installed at Bolivar to allow a further breakdown of the energy consumption and allow regular detailed energy assessments in future.

The main reason for the high specific energy consumption at Glenelg is the aeration system, as the plant exceeds the guide number for aeration by approximately 10 kWh/PE/y. This high energy consumption for aeration is a result of the Integrated Fixed Film in Activated Sludge Systems (IFAS) process that is used in 2 of 3 trains at Glenelg WWTP. Due to local conditions it is required to operate the IFAS reactors at dissolved oxygen (DO) setpoints of 5 mg/L to keep the IFAS material suspended and mixed throughout the whole tank and to have a sufficient oxygen penetration depth in the biofilm. The high DO concentrations also have a negative effect on denitrification performance. To improve the energy efficiency and at the same time improve the effluent quality, Glenelg WWTP will be modified to increase the bioreactor volume and remove the IFAS material.

SUMMARY AND CONCLUSIONS

This paper demonstrates how energy benchmarking has been applied to South Australian WWTPs. The plants investigated cover a wide range of sizes and treatment technologies, necessitating the use of international benchmarks to provide enough plants for comparison. Based on an assessment of different benchmarks by Crawford (2010), it was decided to benchmark the plants using kWh/PE/y as the main parameter for comparison. The latest benchmarks published by Haberkern et al. (2008) and Baumann and Roth (2008) have been used to assess the efficiency of the considered plants.

In this paper the comparison based on treatment technology results have been presented for aerated lagoon systems, trickling filters and activated sludge plants. In all those categories a large variability in specific energy consumption was observed and only a few plants achieved the benchmarking values. It has been identified that the main reason for higher specific energy consumption of plants in Australia is related to reuse infrastructure (reuse pump stations, UV disinfection etc.) that is typically not considered in benchmarks from Haberkern et al. (2008) and Baumann and Roth (2008). To address this limitation, additional energy sub-metering of the reuse infrastructure for the relevant plants is currently being considered. In the longer term this data could be used to develop additional benchmarks for reuse infrastructure.

Despite the ‘uncertainty’ of some data this initial benchmarking was an extremely useful exercise as it helped to identify significant potential for optimisation, identified data shortfalls and helped prioritising optimisation efforts in regard to energy efficiency measures.

The benchmarking process undertaken appears robust. By excluding reuse infrastructure, a good match between boundary conditions for included infrastructure was provided between benchmarks and the largest WWTPs (Bolivar and Glenelg). Where large discrepancies between benchmarks and observed energy use were found, this was able to be clearly explained by infrastructure shortfalls or site specific conditions. This shows that energy benchmarking with the available benchmarks is a powerful tool to evaluate the efficiency of individual plants. It helps prioritising efforts for additional sub-metering and detailed assessments which will result in a better understanding of the energy flows in the assessed plants and ultimately improve their energy efficiency.

REFERENCES

Balmér, P. (2000) Operation costs and consumption of resources at Nordic nutrient removal plants, Water Science & Technology, Vol 41, No 9, pp 273 – 279, 2000

Baumann, P., Roth, M. (2008) Senkung des Stromverbrauchs auf Kläranlagen, Leitfaden für das Betriebspersonal (Reduction of the energy consumption of WWTPs – manual for operators), Heft 4, DWA Landesverband Baden-Württemberg, 2008

Crawford, G. V. (2010) Best practice for Sustainable Wastewater Treatment: Initial Case Study Incorporating European Experience and Evaluation Tool Concept WERF, IWA Publishing 2010

Haberkern, B., Maier, W., Schneider, U. (2008) Steigerung der Energieeffizienz auf kommunalen Klaeranlagen (Increasing the energy efficiency of WWTPs), Umweltbundesamt, 2008

Heidrich, E.S., Curtis, T.P., Dolfing, J. (2011) Determination of the internal chemical energy of wastewater, Env. Sci. Technol., Vol 45, pp 827 – 832, 2011, doi:10.1021/es103058w

Kapp, H. (1984) Schlammfaulung mit hohem Feststoffgehalt (Anaerobic digestion at high solid content), Stuttgarter Berichte zur Siedlungswasserwirtschaft, Bd 86, Oldenbourg Verlag, München

Lindtner, S., Schaar, H., Kroiss, H. (2008) Benchmarking of large municipal waste water treatment plants > 100,000 PE in Austria, Water Science & Technology, Vol 57, No 10 pp 1487 – 1493, 2008, doi:10.2166/wst.2008.214

Mizuta, K., Shimada, M. (2010) Benchmarking energy consumption in municipal wastewater treatment plants in Japan, Water Science & Technology, Vol 62, No 10, pp 2256 – 2262, 2010, doi:10.2166/wst.2010.510

Müller, E.A., Thommen, R., Stähli, P. (1994) Handbuch Energie in ARA (Handbook Energy in WWTPs), Bundesamt für Konjunkturfragen, Bern, 1994

Nowak, O. (2003) Benchmarks for the energy demand of nutrient removal plants, Water Science & Technology, Vol 47, No 12, pp 125 – 132, 2003

Nowak, O., Keil, S., Fimml, C. (2011) Examples of energy self-sufficient municipal nutrient removal plants, Water Science & Technology, Vol 64, No 61, pp 1 – 6, 2011, doi:10.2166/wst.2011.625

Svardal, K., Kroiss, H. (2011) Energy requirements for waste water treatment, Water Science & Technology, Vol 64, No 6, pp 1355 – 1361, 2011, doi:10.2166/wst.2011.221