Mass flow and energy efficiency in a large water reclamation plant in Singapore

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ABSTRACT

This paper presents the results of a measured data-based mass flow and balance study in UluPandan Water Reclamation Plant (WRP), the second largest municipal wastewater treatment plant in Singapore. The results are benchmarked against the Strass wastewater treatment plant in Austria, which has achieved energy self-efficiency. The gaps between the two plants have been identified and areas for process improvement in UluPandan WRP, especially those related to energy efficiency, have been proposed. This case study demonstrates that mass flow and balance is an effective tool in improving process performance and the energy efficiency of a municipal wastewater treatment plant.

Key words | benchmark, energy efficiency, mass balance, municipal wastewater treatment, optimisation, strass wastewater treatment plant

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INTRODUCTION

The study of mass flow and balance in municipal wastewater treatment plants is essential to obtain a deeper understanding of process performance and energy efficiency, including energy consumption and generation. The results of such studies can be adopted for benchmarking (Jonasson 2009), process optimisation (Wett & Alex 2003; Wett *et al.* 2007) and reduction of the carbon footprint and greenhouse gas emissions of wastewater treatment (WERF 2009; STOWA 2010). A number of studies have been reported, but they are often limited to solids or the reject stream (Narayanan 2007; Stinson 2007; Wilson 2009) and single components such as phosphorus (Nyberg *et al.* 1994; Heinzmann & Engel 2003). Likely due to a lack of sufficient quantitative data, only a few studies have taken an integrated and holistic approach or have covered carbonaceous matter (chemical oxygen demand; COD), solids, nitrogen and phosphorus. This paper presents the results of a measured data-based study of these components in UluPandan Water Reclamation Plant (UPWRP), the second largest municipal wastewater treatment plant in Singapore (Cao 2011).

UPWRP was commissioned in 1961 and has been expanded and upgraded in phases. Currently, the whole wastewater is treated in three concurrent liquid streams, i.e. South, North [using Modified Ludzack-Ettinger (MLE)] and Liquid Treatment Module (LTM) (utilizing A-B stage) activated sludge processes. All three streams are served by a common solids line. Most of the treatment units in the plant are now covered for odour containment and equipped with odour treatment facilities to minimise odour nuisance to the surrounding area. The plant receives wastewater mainly from municipal sources (~90%), and is currently operating close to its total designed capacity of 361,000 m^3/d. About 60% of the secondary effluent is further purified to produce NEWater (which is the brand name for reclaimed water produced by the Public Utilities Board in Singapore). The biogas produced from mesophilic anaerobic digesters is used for electricity generation for energy recovery and utilisation in the plant.

The objectives of this study are: (i) to obtain a quantitative overview of the mass flow and balance of COD

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(including particulate COD), nitrogen and phosphorus at the plant level; (ii) to evaluate the performance and efficiency of key individual units; (iii) to identify the gaps in unit performance regarding energy efficiency between UPWRP and Strass wastewater treatment plant (WWTP) in Austria, which has achieved high energy efficiency (108%) (Wett *et al.* 2007); and (iv) to identify areas for improvement and optimisation of the processes and operations, in particular, increase energy efficiency for UPWRP. Due to limited space in this paper, only results of COD and nitrogen balance are presented.

METHODS AND APPROACHES

The major data used in the study were collected from the UPWRP sampling and analysis programme covering:

(i) hydraulic flow, continuously measured with flow meters and pumping records;
(ii) concentrations of the constituents in the influent and effluent of the liquid line, measured twice daily (morning and afternoon);
(iii) biogas flow from anaerobic digesters, continuously measured;
(iv) volatile suspended solids/total suspended solids (VSS/TSS) of mixed liquor sludge and biogas compositions, etc., measured weekly, and total nitrogen (TN)/TSS and total phosphorus (TP)/TSS of the solids line, measured monthly.

In UPWRP, there are regular monthly reports prepared on the influent and effluent quality, hydraulic flow, gas production and composition, sludge flow and quality as well as energy consumption. Information from the January to June 2010 monthly reports was adopted in the study. Additional sampling and testing, mainly on the solid content, were performed to verify the data. Reliable key parameters and data were adopted to establish a calculated set of mass balance data, which was then compared against the actual measured values to assess the reliability of the measured data. For example, the sludge retention time (SRT) values of the activated sludge process were used to evaluate the flow and solids concentration of waste activated sludge (WAS); the data on VSS destruction in anaerobic digesters, biogas production and composition were used to evaluate the concentrations of solids entering and exiting the digesters; dewatered sludge cake solid composition was used to check the TSS after digesters and flow of the returned centrate from dewatering centrifuges. The verification indicated that most of the monitoring data were reliable.

Simplification in mass balance

A simplified hydraulic flow schematic layout of UPWRP is shown in Figure 1. Among the three liquid treatment streams (South, North and LTM), the South stream is the largest. The simplified mass balance treats the South stream as the only liquid stream that treats the entire influent flow, and all secondary effluents exit from the South stream. The primary settling tanks (PSTs), activated sludge, final settling tanks (FSTs), anaerobic digesters, sludge thickener and dewatering units were shared by the three streams.

In this simplified layout, special attention may be drawn to the calculation of PST removal efficiency, and the following points should be noted. (i) The contributions of influent TSS from all three streams are included in the single, combined influent stream. However, in reality, A-stage wasted sludge from the LTM stream is fed into the WAS stream of the South stream, and is not considered primary sludge, while in Figure 1 data for the primary sludge from the North and South streams are adopted in the PST operation. As a result of the simplified combined influent stream, the removal efficiency of the PSTs calculated according to Figure 1 would be lower than the 'true' removal efficiency of the South and North stream PSTs. (ii) To exclude the factor mentioned in item (i), the 'true' removal efficiencies of the South and North stream PSTs were calculated by excluding the LTM stream influent and taking only the South and North streams into account. (iii) However, the simplification would not affect the calculation of the amount of sludge flowing into the digesters.

RESULTS

Hydraulic and solids flow

The hydraulic flow data in Figure 1 were mostly obtained from plant records; the inclusion of calculated values was

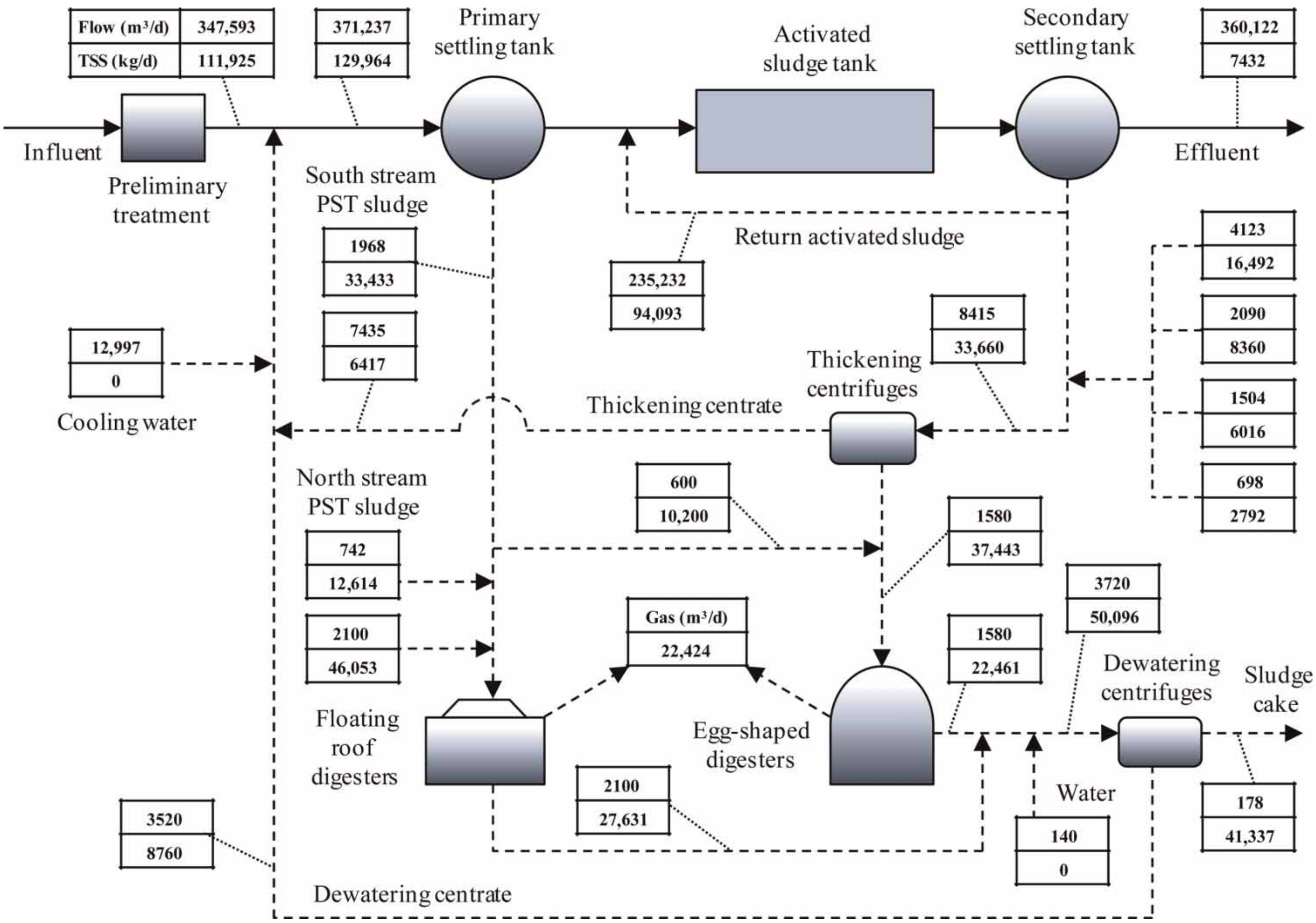

Figure 1 | Schematic layout of the hydraulic and solids flow in UluPandan WRP.

minimised. The recorded daily average inflow of wastewater after preliminary treatment was 347,593 m^3/d, and the flow after blending with the return stream was 371,237 m^3/d. The combined flow of the centrate from the thickening and dewatering units was 15,177 m^3/d. A portion of the secondary effluent, with a flow of 12,997 m^3/d, was reused as cooling water within the plant and returned together with the returned centrate from the thickening and dewatering units to the headworks. The difference between the sum of the influent, return centrate and cooling water and the flow recorded after mixing was 290 m^3/d. This figure indicates the reliability and accuracy of the hydraulic flow data recorded at the plant.

As shown in Figure 1, a large portion (82%) of primary sludge from both the South and North streams was sent to the conventional digesters without thickening. All WAS from the South, North and LTM streams was mixed and thickened by centrifuges (from 0.4 to 4.0% solids), then mixed with a portion of primary sludge from the South and North streams (600 m^3/d) and fed to the egg-shaped digesters. The ratio of hydraulic flow to the digesters (including both floating roof and egg-shaped types) to the influent flow is 1.06%, and the ratio of WAS from the activated sludge processes to the influent is 2.4%. The ratios of return stream flow from the dewatering centrate to the influent flow is around 1%, which is near to the upper limit of the range reported (0.5–1%) (Stinson 2007). Polymers were blended with 140 m^3/d of secondary effluent and fed to the dewatering centrifuges, which concentrated the digested sludge from 1.35 to 21.5% solids. For solids data, significant differences between measured and calculated values of the two centrates were observed. Many of the measured values were lower than the calculated values derived from solids balance after the preliminary treatment and before primary settling. After analysing the centrifuge operations, centrate sampling and data from the literature, it was decided that the calculated values should be adopted in the mass balance analysis.

Carbonaceous mass flow and distribution

Figure 2 shows that 30.2% of the influent COD was removed by the PSTs. The 'true' PST removal efficiency of the South and North streams was 39.2% after reducing the LTM streamflow from the PST influent (as explained in the Methods and Approaches section). Of the inflow COD, 52.8% (i.e. 117,876 kg COD/d) was dissimilated into carbon dioxide in the activated sludge process. Combining COD mass flow from the PSTs and the thickened WAS, 44.9% of the influent COD was fed into the anaerobic digesters.

The VSS destruction in the egg-shaped and conventional digesters were 46 and 40%, respectively, with similar methane (CH_4) biogas volumetric ratio of ~64%. The net daily biogas production was 22,424 m^3/d, equivalent to 36,944 kg COD/d, calculated according to the gas compositions, stoichiometric coefficient of 0.35 m^3 CH_4/kg COD and temperature correction factor (Metcalf & Eddy 2003). According to the daily COD mass loading rate to the digesters, a stoichiometric coefficient of 1.25 kg COD/kg TSS and VSS/TSS ratio of 79% of the feed sludge, it was calculated that 28,083 kg VSS/d was destroyed, which is equivalent to 39,900 kg COD/d according to 1.42 kg COD/kg VSS. This illustrates that 17.9% of the influent COD was converted in the digesters. Most of the COD was converted into CH_4 gas, with some remaining as dissolved organics in the liquid phase. The ratio of gas production and VSS destruction was 0.80 m^3 gas/kg VSS destroyed, which is within the normal range of 0.8 to 1.0 m^3 gas/kg (Metcalf & Eddy 2003), although at the lower limit.

Nitrogenous mass flow and distribution

Figure 3 shows that 11.2% of the influent nitrogen was removed by the PSTs. The 'true' PST removal efficiency of the South and North streams was 14.5% after reducing the LTM streamflow from the PST influent; 11.4% of influent nitrogen was captured in the wasted sludge and 22.6% of influent nitrogen was fed to the anaerobic digesters, which was much less than the COD portion (44.7%). Nitrogen dissimilated into nitrogen gas during denitrification in the activated sludge process was 48.0%, the largest percentage among other components. Nitrogen release due to cell (VSS) destruction in anaerobic digesters

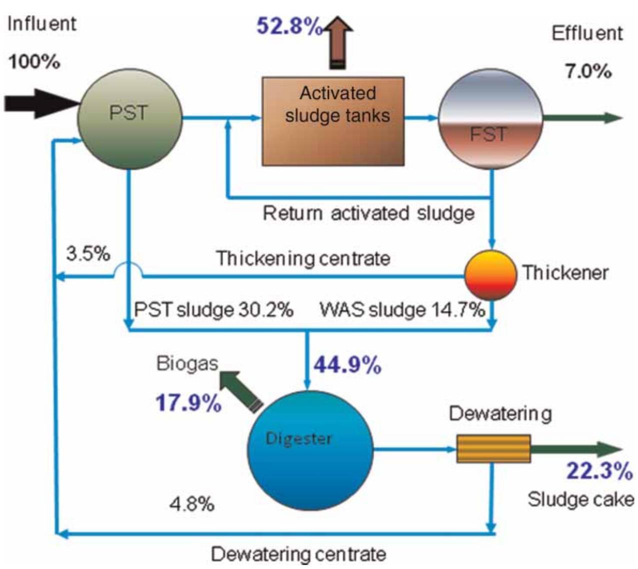

Figure 2 | COD mass flow and distributions in UluPandan WRP.

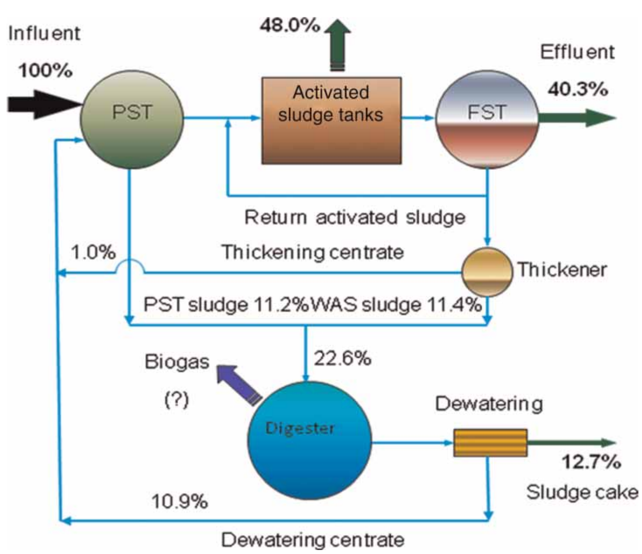

Figure 3 | Nitrogen mass flow distributions in the UluPandan WRP.

was 1,139 kg N/d, equivalent to 320 mg N l^{-1} released, but nitrogen reduction through NO_3-N to nitrogen gas from denitrification as studied by Wett *et al*. (2007) could not be quantified. Nitrogen in the final effluent was 40.3% of the influent nitrogen, while nitrogen content in the sludge cake was 12.7%. The sum of nitrogen in the effluent, dissimilation in activated sludge, and sludge cake percentages amounted to 101%.

The ratio of nitrogen mass loading rates of dewatering centrate to the influent nitrogen mass loading was 10.9%. The ratio of the dewatering centrate NH_4-N mass loading rate to the influent NH_4-N was 15.7%.

Energy utilization distributions and efficiency

The global specific energy consumption of UPWRP was 0.52 kWh/m^3, while electricity generation was 0.15 KWh/m^3, and the resulting energy efficiency is 28.8%. Figure 4 shows that aeration for biological treatment is 42.4% of the total energy consumed, the largest component of electricity consumption, which is similar to other wastewater treatment plants. The energy consumption for odour removal and inlet pumping accounted for 27.6%, which is notably higher than in similar wastewater plants elsewhere in the world due to the considerations of protecting the surrounding area and the high inlet pumping locations of the plant.

DISCUSSION

Benchmark with Strass WWTP

Table 1 shows the key performance indicators calculated from the results of the mass flow and balance study on UPWRP. Table 2 shows the data of UPWRP and Strass WWTP in Austria (Wett *et al*. 2007) on COD mass flow and balance. The differences stem from five main aspects.

(i) In UPWRP, the PST's COD removal efficiency is 39.2% of the influent COD (for solids, 51.2% of the influent solids), which is 21.5% lower than that of Strass WWTP (60.7%). The high COD retaining efficiency in Strass WWTP is due to the specific design of the A-stage activated sludge (Wett, personal communication, 2010).

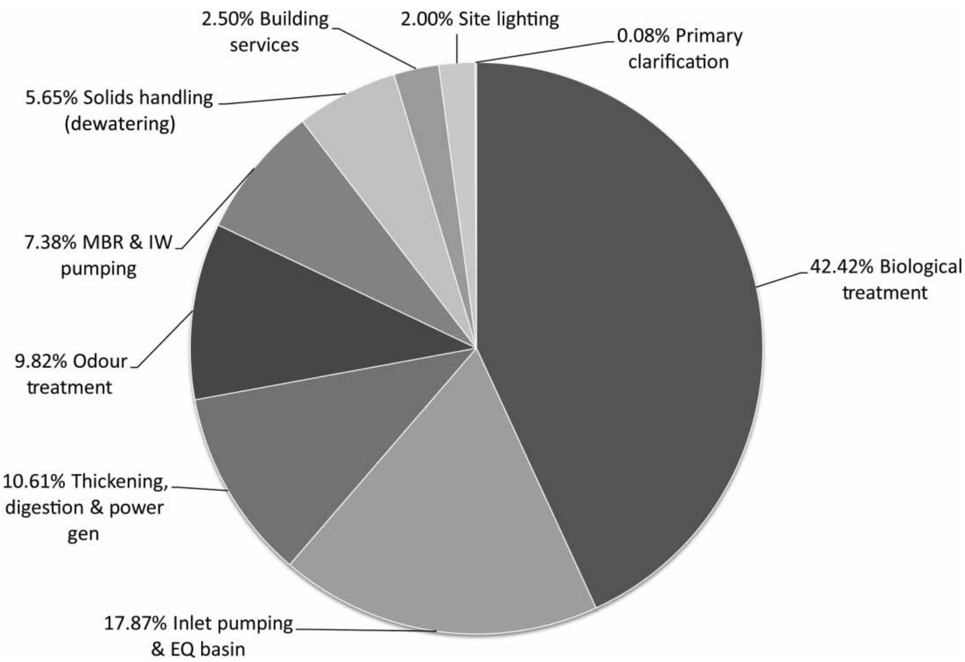

Figure 4 | Electricity consumption distribution of UluPandan WRP.

Table 1 | Performance indicators of UPWRP

Biogas production		Solids generation		Energy efficiency	
Influent sewage (l/m^3)	Solids in influent sewage (m^3/kg)	Dry solids (kg/m^3 raw sewage)	Dry solids (kg/kg solids in raw sewage)	Energy generated[a] (kWh/m^3 raw sewage)	Energy used (kWh/m^3 raw sewage)
65	0.18	0.11	0.34	0.15	0.52

[a]Energy generated in plant through biogas.

(ii) In UPWRP, the COD fed to anaerobic digesters is 44.9% of the influent COD, which is 29.4% less than that in Strass WWTP (74.3%), as a consequence of the high efficiency in COD pre-concentration at the A-stage activated sludge process and appropriate SRT control in the B-stage SRT in Strass WWTP;

(iii) In UPWRP, the percentage of CH_4-COD due to the influent COD is 17.9%, which is half of that in Strass WWTP (35.9%) due to the factors mentioned in items (i) and (ii). These factors, together with the longer SRT of the anaerobic digesters in Strass WWTP (22–35 days in Strass versus 16–25 days in UPWRP) and higher efficiency of the electricity generator engine in Strass WWTP (38% in Strass WWTP versus 30% in UPWRP) results in electricity generation of Strass WWTP of 0.33 kWh/m^3 sewage against 0.15 kWh/m^3 sewage of UPWRP;

(iv) In UPWRP, the ratio of COD dissimilated in the activated sludge process to the influent COD (52.9%) is 31.2% more than that in the Strass WWTP (21.8%). This can be attributed to: (a) much more COD entering the activated sludge process in UPWRP because of the low efficiency of the PSTs as compared to A-stage; (b) higher aeration efficiency in Strass WWTP because of the on-line sensor based control of the blowers and activated sludge process SRT (Wett *et al.* 2007); (c) higher oxygen requirement from the lower total denitrification efficiency in UPWRP (Table 3) compared to that in Strass WWTP (due to use of deammonification in the side stream). These differences result in the higher aeration energy consumption (0.23 kWh/m^3 sewage) in UPWRP compared to the low aeration energy (0.12 kWh/m^3 sewage) in Strass WWTP; and (d) high microbial metabolism due to the hot tropical climate in Singapore.

(v) In UPWRP, the COD in the sludge cake is 22.3%, which is 15.3% less than that in the Strass WWTP (37.6%) as a consequence of more solids COD dissimilated (aerobic digestion) in the activated sludge process at the expense of aeration in the UPWRP and the smaller biomass yield under high temperature in Singapore.

Table 3 shows that the nitrogen dissimilation in the activated sludge process in UPWRP is 48.0%, which is 6.1% higher than that of Strass WWTP (41.9%). The lower value of B-stage activated sludge process in Strass WWTP could be attributed to insufficient carbon for denitrification due to the extremely high efficiency of COD retention in the A-stage activated sludge process, while the opposite is true for UPWRP. This also illustrates a fundamental dilemma in process optimisation: excellent COD pre-concentration is favourable for energy generation, but could impose a negative effect on nitrogen removal (denitrification) in the main stream activated sludge process due to carbon shortage. A balance should be maintained based on the trade-off and balance between effluent quality and energy recovery. However, due to Strass WWTP employing denitrification in the side stream by deammonification, the total nitrogen

Table 2 | Comparisons of COD mass flow distributions between UPWRP and Strass WWTP[a] (%)

Plant	Removed by PST	Feed to digesters	CH_4-COD	Dissimilated in ASTs[b]	Dewatering sludge	Final effluent
UPWRP	39.3	44.9	17.9	52.9	22.3	7.0
Strass	(60.7)[c]	74.3	35.9	21.8	37.6	4.7

[a]Wett *et al.* (2007).
[b]Activated sludge treatment.
[c]Wasted sludge from the A-stage activated sludge process.

Table 3 | Comparison of nitrogen mass flow distributions between the UluPandan WRP and the Strass WWTP[a] (%)

Plant	Dissimilation by denitrification	Feed to digesters	Dewatering sludge	Final effluent
UPWRP	48.0	20.6	12.0	40.3
Strass	56.6 (41.9 + 14.7[b])	43.4	17.9	16.3

[a]Wett & Alex (2003).
[b]Due to denitrification by using anammox in the side line.

dissimilation efficiency (56.6%) in Strass WWTP is still 8.6% higher than that of UPWRP (48.0%), and it results in a lower total nitrogen mass load in the Strass WWTP final effluent. Similarly to COD, nitrogen fed to the digesters in the UPWRP was 23.4% less than at Strass WWTP.

Areas for performance improvement and road map to high energy efficiency

Three main areas for improving process performance and energy efficiency in UPWRP have been identified: (i) pre-concentration of the influent wastewater to supply more COD to the anaerobic digesters for increased biogas and electricity production; (ii) increasing aeration efficiency through application of on-line sensor aeration control, reduction of oxygen demand and appropriate aerobic SRT; and (iii) enhancement of the solids line performance and operation by several alternatives such as improving performance of the anaerobic digester, pre-treatment of sludge, using high efficiency engines and side stream deammonification, etc. By adopting items (i) and (ii), the energy efficiency can be increased to ~50% from the current 28.8%. Prior to forming a plan, cost–benefit analysis and life cycle analysis should be carried out to study the feasibility and to define the time sequences of each alternative for implementation.

CONCLUSIONS

The COD removal efficiency of the PSTs in UPWRP was 39.3% of the influent COD. The COD fed to the anaerobic digesters was 44.9% of the influent; 7.0% of the influent COD was in the final effluent; 52.8% dissimilated in the activated sludge process; 17.9% as CH_4-COD and 22.3% accounted for the dewatering sludge. The balance and distributions for solids, nitrogen and phosphorus were calculated as well.

The results of the study were used to benchmark against Strass WWTP, Austria. Gaps have been identified in five aspects: (i) the COD retention of the PSTs; (ii) the COD fed to the anaerobic digesters; (iii) the COD generated as CH_4-COD in the anaerobic digesters; (iv) the COD dissimilated in the activated sludge process; and (v) the COD in the sludge cake. The factors causing these differences were analysed.

Three main areas to improve process performance and energy efficiency were identified: (i) pre-concentration of the influent COD by the PSTs to supply more COD to the anaerobic digesters for biogas and electricity production; (ii) reduction of aeration energy consumption by using online sensor automatic control of aeration and aerobic SRT; and (iii) enhancement of the solid line performance and operation by pre-treatment of sludge, effective operation of anaerobic digester, applications of high efficiency engines and side line deammonification, etc. By adopting these alternatives, the energy efficiency can be increased to ~50% from the current 28.8%.

The results of the investigation demonstrate that mass balance study of wastewater treatment plants provides a quantitative illustration on material conversions in both liquid and solids lines and the inter-relationships between them at plant level. It is an effective tool for process analysis and optimisation, especially increasing energy efficiency.

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