Diurnal variations of the energy intensity and associated greenhouse gas emissions for activated sludge processes

Nasir Emami, Reza Sobhani and Diego Rosso

ABSTRACT

A model was developed for a water resources recovery facility (WRRF) activated sludge process (ASP) in Modified Ludzack-Ettinger (MLE) configuration. Amplification of air requirements and its associated energy consumptions were observed as a result of concurrent circadian variations in ASP influent flow and carbonaceous/nitrogenous constituent concentrations. The indirect carbon emissions associated with the ASP aeration were further amplified due to the simultaneous variations in carbon emissions intensity (kgCO$_2$eq (kWh)$^{-1}$) and electricity consumption (kWh). The ratio of peak to minimum increased to 3.4 (for flow), 4.2 (for air flow and energy consumption), and 5.2 (for indirect CO$_2$eq emission), which is indicative of strong amplification. Similarly, the energy costs for ASP aeration were further increased due to the concurrency of peak energy consumptions and power demands with time of use peak electricity rates. A comparison between the results of the equilibrium model and observed data from the benchmark WRRF demonstrated under- and over-aeration attributed to the circadian variation in air requirements and limitations associated with the aeration system specification and design.

Key words | activated sludge, aeration, amplification, carbon emissions, energy tariff, time of use

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>a</td>
<td>diffuser specific area [m$^2$]</td>
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<tr>
<td>$\text{CO}_2,i$</td>
<td>carbon emission intensity [kg(kWh)$^{-1}$]</td>
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<tr>
<td>$\text{CO}_2,eq$</td>
<td>equivalent carbon emission [kg(h)$^{-1}$]</td>
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<tr>
<td>$N_D$</td>
<td>total diffusers number</td>
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<tr>
<td>$P_b$</td>
<td>barometric pressure [psi]</td>
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<tr>
<td>$Q_N$</td>
<td>normalized air flux [s$^{-1}$]</td>
</tr>
<tr>
<td>$R_h$</td>
<td>relative humidity [-]</td>
</tr>
<tr>
<td>$T_a$</td>
<td>ambient temperature [K]</td>
</tr>
<tr>
<td>$T_d$</td>
<td>dew point temperature [K]</td>
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<tr>
<td>$T_w$</td>
<td>water temperature [F]</td>
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<tr>
<td>$z$</td>
<td>diffuser submergence [m]</td>
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GREEK LETTERS

<table>
<thead>
<tr>
<th>Symbol</th>
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<tbody>
<tr>
<td>$\alpha$</td>
<td>alpha factor, ratio of process-to-clean-water mass transfer [-]</td>
</tr>
<tr>
<td>$\eta$</td>
<td>blower efficiency [-]</td>
</tr>
<tr>
<td>$\chi$</td>
<td>plant characteristic number [s$^{-2}$]</td>
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INDICES

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<thead>
<tr>
<th>Symbol</th>
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<tbody>
<tr>
<td>a</td>
<td>refers to ambient</td>
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<td>b</td>
<td>refers to barometric</td>
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<tr>
<td>eq</td>
<td>equivalent</td>
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<tr>
<td>d</td>
<td>refers to dew point</td>
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<td>h</td>
<td>refers to humidity</td>
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<tr>
<td>i</td>
<td>refers to intensity</td>
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<tr>
<td>in</td>
<td>refers to influent</td>
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<tr>
<td>N</td>
<td>refers to normalized</td>
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<tr>
<td>W</td>
<td>refers to water</td>
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ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AFR</td>
<td>air flow rate</td>
</tr>
<tr>
<td>AMEL</td>
<td>average monthly effluent limitation</td>
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<tr>
<td>ASM</td>
<td>activated sludge model</td>
</tr>
<tr>
<td>ASP</td>
<td>activated sludge process</td>
</tr>
<tr>
<td>AWEL</td>
<td>average weekly effluent limitation</td>
</tr>
<tr>
<td>BOD</td>
<td>biological oxygen demand</td>
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19% of the California water and wastewater accounts for 2 et al. (Monteith).

This is an energy-intensive process and is associated with organic carbon and nitrogen from influent wastewater. ASMs typi- 

INTRODUCTION

Municipal water resources recovery facilities (WRRFs) typically utilize the activated sludge process (ASP) to reduce organic carbon and nitrogen from influent wastewater. This is an energy-intensive process and is associated with the direct and indirect release of greenhouse gases (GHG) (Monteith et al. 2005; de Haas et al. 2008; Kampschreur et al. 2009; Ahn et al. 2010; Foley et al. 2010; Park et al. 2010; Flores-Alsina et al. 2011; Corominas et al. 2012; Law et al. 2012).

Electrical energy consumption to treat and transport water and wastewater accounts for 2-3% of the world’s, 19% of the California’s, and 1-18% of urban areas’ electrical energy consumption (CEC 2005; Olsson 2012, 2015). ASP aeration typically accounts for 45-75% of the overall plant energy costs (Reardon 1995; Rosso & Stenstrom 2005; Rosso et al. 2008; WEF 2009). Energy consumption patterns strongly influence electricity generation and power distribution. Demand-side management (DSM) includes a portfolio of measures such as smart energy tariffs to improve energy efficiencies in ASP. While there is plenty of experi-

The indirect marginal emissions of electricity demand vary spatially and temporally across the USA (Zivin et al. 2014). This paper utilizes Zivin et al. (2014) estimated carbon emission intensities to demonstrate the circadian variations in equivalent CO2 (CO2,eq) emissions that are associated with ASP energy consumption. It should be noted that the direct CO2 emissions from WRRF ASP are considered short-cycle and do not represent a net flux to the atmosphere. ASP direct CO2 emissions are of biogenic origin and are not accounted in the Intergovernmental Panel on Climate Change (IPCC) Guidelines (IPCC 2006).

Energy costs are site specific and depend on local energy tariff structures applied at various WRRFs (Aymerich et al. 2015). The ASP energy costs are strongly influenced by time of use (TOU) and power demand charges. Using average energy prices in lieu of energy tariff structures may lead to biased conclusions (Rieger et al. 2015). In this paper, a Southern California Edison (SCE) tariff structure for industrial clients (SCE, TOU-8 2014) is used as an example to present the importance of DSM in reducing the energy cost associated with WRRF ASP.

The aeration/energy requirements, associated costs, and GHG emissions are influenced by variations in flow rates and carbonaceous/nitrogenous constituent composition and fractionation factors in the influent (Gori et al. 2011; Mannina et al. 2016a). Due to general human activities, the variations in chemical oxygen demand (COD) and total sus- pended solids (TSS) follow the pattern of flow rate variations (Metcalff & Eddy Inc. 2014). The ASP requires higher rates of aeration during the peak flow and carbonaceous/nitrogenous constituent loadings to maintain the dissolved oxygen (DO) set points, and to comply with the effluent water quality standards. As air flow increases, larger bubbles are formed. This lowers the surface-to-volume ratio and increases the bubble rise velocity. The net effect reduces the oxygen transfer from the gas to liquid phases (Rosso et al. 2005). Moreover, the high concen-

...
decrease the \( \alpha \) factor and depress the oxygen transfer efficiency (OTE) in the aeration tanks (Rosso & Stenstrom 2006; Leu et al. 2009). Sobhani et al. (2013) shows how those variations amplify the energy consumption during peak hours, and consequently cause higher energy costs and carbon emissions.

Biokinetic simulation of WRRFs provide detailed insight into the ASP design, operational optimization, performance assessment, controller design, and model-based process control. Coupling WRRF supervisory control and data acquisition (SCADA) systems with biokinetic models allows for evaluating optimization strategies and implementing complex computational algorithms to enhance system design and control strategy to improve aeration efficiency and energy requirements (Langergraber et al. 2004; Åmand & Carlsson 2012; Flores-Alsina et al. 2014; Caniani et al. 2015; Karpinska & Bridgeman, 2016; Mannina et al. 2016).

The goal of this research is to assess the amplification during circadian cycles of the energy intensity and energy-associated GHG emissions from ASP caused by the compounding of peak flow, peak load, and dynamics of the aeration system performance. The comparison between the results of the equilibrium model developed here and the data from a full-scale facility underline the mismatch between the design limitations and the actual process dynamics as a gap to be addressed as energy-efficiency measure.

**MATERIALS AND METHODS**

**Selected facility**

The selected plant is an upstream satellite water reclamation plant in Modified Ludzack-Ettinger (MLE) configuration with \( 8.50 \times 10^4 \text{ m}^3 \text{ d}^{-1} \) (22 MGD) capacity. When the sewage flows beyond its capacity, the outfall sewer carries the excess water to the downstream WRRF. The removed biomass is conveyed to the downstream treatment plant. The plant utilizes head works, influent pumping, primary treatment, activated sludge secondary treatment, secondary clarifiers, and tertiary treatment. The plant’s secondary treatment employs six identical parallel MLE and secondary clarifier trains. Each process train utilizes three anoxic zones, three aerobic zones, and a rectangular secondary clarifier as shown in Figure 1. The volumes of anoxic and aerobic zones in each train are equal to 1,020 m\(^3\) (36,000 ft\(^3\)) and 2,268 m\(^3\) (80,100 ft\(^3\)), respectively. The submerged depth of each bioreactor is 4.9 m (16.1 ft). The surface area of each secondary clarifier is 632 m\(^2\) (6,800 ft\(^2\)) with a submerged depth of 2.93 m (9.6 ft).

Primary effluent is equally distributed among the operating trains. Under normal dry-weather conditions, five process trains operate at a time and one is idling. The plant utilizes three 1,100 kW blowers, one operating at a time with a design capacity of \( 4.30 \times 10^4 \text{Nm}^3 \text{ h}^{-1} \) (27 kSCFM). Table 1 presents the average water quality at this plant.

**Process simulation**

Process simulation was conducted using an equilibrium biokinetic model (ASM1) with circadian inputs of influent flow rates and constituent concentrations as presented in the supplementary material (available with the online version of this paper). ASP air requirements were simulated using process inputs and effluent water qualities identical to the benchmark plant. The effluent water quality meets the average monthly effluent limitation (AMEL) and average weekly effluent limitation (AWEL) set by State Water Resources Control Board (SWRCB; Tentative Order R4-2017-00XX). Table 2 summarizes the ASP effluent water quality objectives.

Oxygen transfer efficiencies were integrated into the model using a regression analysis developed by Rosso and Stenstrom (2006) that showed how those variations amplify the energy consumption during peak hours, and consequently cause higher energy costs and carbon emissions.
et al. (2005) to determine $\alpha$SOTE as a function of diffuser type, tank geometry, airflow rates, and mean cell residence time (MCRT) as follows:

$$\alpha\text{SOTE} = 5.717 \log{\chi} - 6.815$$ (1)

$$\alpha = 0.172 \log{\chi} - 0.131$$ (2)

$$Q_N = \frac{AFR}{a_N D Z}$$ (3)

$$\chi = \frac{MCRT}{Q_N}$$ (4)

We estimated alpha using Equation (2) because for this particular plant there was no availability of site-specific oxygen transfer efficiency to correlate with process load (as in Jiang et al. 2017). Datasets from summer dry-weather condition (June and July 2016) were used for simulation and analysis to minimize the effects of inflow and infiltration (I&I) on the plant influent flow.

The model calibration involved comparison of the simulated air requirement values with the data extracted from the plant’s SCADA system. During model calibration, the model was run with plant data collected from one dry-weather operation dataset (June 2016) under steady-state conditions. The simulation was performed with the literature values of the kinetic, stoichiometric, and aeration parameters and then the simulated air requirement values were compared with the observed field data. Discrepancies (expressed as root mean square error, RMSE) between the measured and simulated values of the output variables were minimized by adjusting ASP kinetic, stoichiometric, and aeration parameters. Four parameters ($K_s$, $Y_{H,b}$, $b_N$, $b_n$) were adjusted to calibrate the model. The values of the calibrated parameters for the steady-state simulation and literature values are compared in supplementary Table S1 (available with the online version of this paper).

During validation, datasets on air flow from dry-weather operation (July 2016) were used for modelling and the results were compared and verified.

**Energy and CO₂ emission model**

A model was developed to quantify the electricity consumption (kWh), power demand (kW), and their associated CO₂ eq emissions (kgCO₂ eq h⁻¹) for the ASP. The model input includes ASP air requirements, temporal carbon emission intensities, system curve for the aeration system, and local weather variables. Figure 2 illustrates the structure of the combined process, energy, and CO₂ emissions model.

To quantify the energy-associated CO₂ eq emissions, the model utilizes the temporal marginal CO₂ eq emission intensities for the electricity demand of the Western Electricity Coordinating Council (WECC) interconnection. WECC CO₂ eq emission intensities were obtained from the regression model developed by Zivin et al. (2014). The model accounts for the generation mix within interconnected electricity markets and shifting diurnal load profiles, with a focus on carbon dioxide. The benchmark plant falls under the WECC interconnection since it is located in California.

**RESULTS AND DISCUSSION**

**Variations in ASP influent characteristics**

The dry-weather (summer) data analysis indicates that the diurnal influent flow increases rapidly from a minimum of $4.46 \times 10^3$ m³ d⁻¹ (1.2 MGD) at 6:00 to a near maximum...
of $1.53 \times 10^4$ m$^3$ d$^{-1}$ (4.0 MGD) at 12:00. The peak COD, ammonia ($\text{NH}_4^+$-N), and total Kjeldahl nitrogen (TKN) concentrations occur between 10:00 to 12:00, nearly coinciding with the peak flow. The concurrency of these circadian variations amplifies carbonaceous/nitrogenous constituent loadings into the process trains between 10:00 and 12:00, resulting in a peak air requirement that will be discussed later. Figure 3 illustrates the circadian variations in flow and key ASP influent constituent concentrations (COD, $\text{NH}_4^+$-N, and TKN) in each process train during the summer dry-weather conditions.

**Simulation of ASP air requirements**

The ASP was simulated with circadian inputs of flow rates and constituent concentrations with a DO set point of 2.0 mgl$^{-1}$. The model was calibrated by the comparison of its results with the observed data from the plant. Figure 4 compares the simulated air requirements (Nm$^3$ h$^{-1}$) with the observed plant data for each process train. The results indicate that from 19:00 to 2:00, the simulated air requirements and observed air discharges are fairly matched and DO levels are fairly maintained at 2.0 mgl$^{-1}$ set point (Figure 4). As influent flow starts declining rapidly at 2:00, the observed air discharges from the plant exceed the simulated results. This is possibly an over-aeration condition due to a sudden decrease in air requirements and limitations associated with the turn down ranges of aeration blowers in throttling the supplied air. Both curves reach their troughs at around 6:00 and start to rise after that. Due to the over-aeration condition, the observed DO levels within this timeframe (2:00–8:00) exceed the set point (2.0 mgl$^{-1}$) with a peak DO of 2.8 mgl$^{-1}$ at 7:00. In later hours, both datasets present a significant increase. The increase in air requirements is attributed to the increase in influent flow rates and constituent loadings, prompting aeration blowers to ramp up to maintain the DO set point. The observed air discharges from the plant are at lower levels in comparison to
the simulated results during this timeframe (8:00–14:00). This is possibly an under-aeration condition due to a sudden increase in air requirements and limitations associated with the aeration blowers to ramp up the supplied air effectively. Correspondingly, the observed DO drops to 1.3 mg/L at 10:00, which is indicative of under-aeration.

The simulated air requirement starts declining from its peak at 11:00, $7.84 \times 10^3$ Nm$^3$ h$^{-1}$ (4.88 kSCFM), as the influent flow rates and constituent loadings decrease. There are sporadic over- and under-aeration conditions between 15:00 and 1:00, possibly due to abrupt fluctuations in influent flow and the lag time associated with instrumentation and control (I&C) and aeration system in response.

The over- and under-aeration in ASP cause excessive energy use while compliance with effluent water quality standards is targeted.

As part of a future study, an extensive DO profiling at the benchmark plant will be conducted to analyse the dynamics of under- and over-aeration conditions in more detail and to study the effects of DO level on ASP stability.

As previously discussed, $\alpha$SOTE is a function of diffuser type, tank geometry, airflow rates, MCRT, and influent wastewater quality (Rosso et al. 2005; Gillot & Heduit 2008). $\alpha$SOTE variations are inversely proportional to airflow rate. The peak $\alpha$SOTE (0.116) and the trough of air requirements ($1.86 \times 10^3$ Nm$^3$ h$^{-1}$) occur concurrently. Similarly, the trough of $\alpha$SOTE (0.096) occurs close to peak air requirements at 21:00.

The plot in Figure 4 illustrates the discrepancy between the recorded air discharge and the modelled air required for discharge, a combination of the technological limits of the blower battery, the varying DO during the diurnal cycle,

**Figure 3** | Circadian variations in ASP influent characteristics for each train.
and the generalized correlation (Equation (2)) used in our model to estimate alpha. The discrepancy in the two curves appears in the form of areas between the two curves, even though the peak/average ratios are consistent (1.33 and 1.35 for modelled and observed air, respectively). In fact, we modelled the diurnal cycle using the plant DO pattern and a constant pattern, and the results exhibited minor differences, leading to the conclusion that a combination of blower limitations and alpha estimation contributed to the discrepancy. The issue of under- and over-aeration at this facility was confirmed through interviews with the operations personnel, who attributed the cause to the blower operations, limited in latitude of air flow discharge. At this point it is impossible to assign weight to the two causes of the discrepancy in Figure 2 (i.e., the contribution from blower limitations vs. the error committed in modelling through the use of Equation (2) instead of a site-specific correlation). One of the goals of this work is to underline the importance of using modelling as a tool to quantify such site-specific issues and to assign a proper weight to the personnel reports on operating limitations. Moreover, the placement of flow meters and the compounding uncertainty of multiple metering units may lead in general to conclude that the metered air flow at a full-scale facility should in fact be a bandwidth of possible flow rates, rather than a single point measurement. Finally, despite the regular calibration of the flow meters in this facility, in many others there was no recent calibration of the metering units, leading to further uncertainty on the measured air discharge (Alex et al. 2016). For all the considerations above, the quantification of the diurnal variations of aeration energy and of its associated indirect GHG emission, presented below, is based on the modelled air flow. Hence, the results presented below would only change in absolute value by changing the basis of calculation (i.e., actual air flow vs. modelled air flow) but not in significance.

**Model performance evaluation**

The performance of the calibrated model versus the observed air flow rates was assessed using statistical
performance indices such as the RMSE and coefficient of determination ($R^2$). A RMSE value of zero and $R^2$ value of unity represent an ideal model performance. The $R^2$ and RMSE values for the simulated results are 0.69 and 0.65 respectively as shown in supplementary Figure S3 (available with the online version of this paper).

**Circadian amplification of air requirements**

To demonstrate the amplification of air requirement, circadian variations in influent flow, COD, TKN, $\alpha$SOTE, and simulated air are compared collectively (Figure 5). To make the scale of variations comparable, variables have been normalized by dividing them by their daily average values. The results indicate that the normalized flow and COD concentration vary between 0.38 and 0.90 in their troughs, and 1.29 and 1.20 at their peaks, respectively. Normalized TKN concentration varies between 0.95 in its trough and 1.21 at its peak.

Figure 5 indicates that peak values for COD, TKN, and air requirements occur during influent peak flow rates. The peak air flow rate is fairly concurrent with peak COD with a 1-hour lag time. The lag time could be attributed to the overarching effect of hydraulic retention time (HRT) and constituents’ loadings.

Under normal conditions, low influent hydraulic loadings coincide with low constituent concentrations (e.g., BOD and $\text{NH}_4$). Conversely, high influent hydraulic loadings coincide with high constituent concentrations. The concurrency of these variations amplifies the alterations among the air

![Figure 5](https://iwaponline.com/wst/article-pdf/77/7/1838/214336/wst077071838.pdf)

**Figure 5** | Normalized values of influent flow, BOD, TKN, oxygen transfer efficiency ($\alpha$SOTE) and modelled air flow vs. time.
requirements. The amplification in the air requirement is shown in Figure 5 with normalized air requirement fluctuating between 0.33 in its trough (6:00) and 1.39 at its peak (11:00). The increase of bCOD can decrease the $\alpha$ value (Leu et al. 2009), and concurrently the increase of air flow has a similar impact on standard oxygen transfer efficiency ($\alpha$SOTE) (Rosso et al. 2005). Therefore, $\alpha$SOTE typically is expected to vary over the diurnal cycle in a reciprocal pattern to the process load. The diurnal cycle of $\alpha$SOTE is presented in Figure 5. The peak normalized COD (1.2 at 10:00), and peak normalized air requirements (1.39 at 11:00) correspond with a normalized $\alpha$SOTE of 0.99. Conversely, peak normalized $\alpha$SOTE (1.12 at 6:00) fairly coincides with the trough of normalized COD (0.9 at 4:00), and trough of normalized air requirements (0.33 at 6:00). The peak over minimum ratio increases from 3.4 to 4.2 for the influent flow and air requirements, respectively (Figure 5), which is indicative of amplification. Future studies on $\alpha$SOTE will focus on fully understanding the role of bCOD on the depression of $\alpha$, and the integration of $\alpha$SOTE in process models and simulators.

**Circadian amplifications of the energy demand and CO$_2$$_{eq}$ emissions**

The concurrency of ASP influent flow, COD and TKN peak values with the trough of $\alpha$SOTE induces an amplified circadian air requirements response (Figure 6). Accordingly, the ASP power demand and its associated indirect CO$_2$$_{eq}$ emissions follow the same pattern as the developed model. The spatial and temporal variations in carbon emission intensities (kgCO$_2$$_{eq}$/(kWh)$^{-1}$) suggested by the regression model (Zivin et al. 2014) were discussed earlier in this paper. The concurrency of circadian variations in CO$_2$$_{eq}$ emission intensities with the influent flow and energy demand is significant. It further amplifies the circadian variations in CO$_2$$_{eq}$ emissions. Peak influent flow of $15.0 \times 10^3$ m$^3$/d (4.0 MGD), and peak CO$_2$$_{eq}$ emission intensity (0.4 kgCO$_2$$_{eq}$/(kWh)$^{-1}$) occur at 11:00, corresponding to peak CO$_2$$_{eq}$ emission of 64.0 kgCO$_2$$_{eq}$/h and a peak energy demand of 160 kWh. The troughs of ASP influent flow, 4.46 $\times 10^3$ m$^3$/d (1.18 MGD) at 6:00, and CO$_2$$_{eq}$ emission intensity (0.3 kgCO$_2$$_{eq}$/(kWh)$^{-1}$) at 7:00 are fairly concurrent (1-hour lag time). Correspondingly, the troughs of energy demand (37.9 kWh) and CO$_2$$_{eq}$ emission (12.2 kgCO$_2$$_{eq}$/h) at 6:00 are concurrent. Circadian amplification of CO$_2$$_{eq}$ emissions is more pronounced due to the combined effect of emission intensities and energy demand, as shown in Figure 6.

To make the scale of variations comparable, all variables were normalized by their daily average values. The results indicate that the normalized energy consumption varies between 0.33 and 1.4 while the normalized CO$_2$$_{eq}$
emission varies between 0.29 and 1.51. The observed amplification effect is due to the concurrency of variations in energy consumption and emission intensity. Figure 7 illustrates the variations in normalized variables, indicating amplification in CO$_2$,-eq emissions. The ratio of peak to minimum increases from 3.4 (flow) to 4.2 (air and energy consumption) and finally 5.2 (CO$_2$,-eq emission), which is indicative of amplification.

Circadian amplification of the electricity consumption and TOU economic implications

TOU electricity rates are based on the time at which customers use electricity. Energy rates vary seasonally and diurnally during off-, mid-, and peak hours. In this section the economic implications of circadian electricity consumption is demonstrated using a SCE tariff structure. The benchmark plant is not served by SCE and using this tariff is for demonstration purposes. The aim of this exercise is to demonstrate a typical case applicable to many WRRF while recognizing caveats and limitations.

The analysis was conducted using industrial rates (SCE 2014 TOU Option B, 2–50 kV) for the summer season as the electricity rates vary drastically during summer (extreme case). The summer season begins on June 1, and continues until October 1.

The results present a circadian amplification in hourly energy costs of ASP (Figure 8). The maximum electricity consumption (160 kWh) occurs during the mid-peak period rates ($0.071/kWh) while the trough of electricity consumption (37.9 kWh) falls within off-peak rates ($0.056/kWh). It is expected that by including power demand charges, energy

![Figure 7](https://iwaponline.com/wst/article-pdf/77/7/1838/214336/wst077071838.pdf)

**Figure 7** Normalized circadian variation in flow, air, energy consumption and CO$_2$,-eq emissions.
costs will be further amplified. The analysis indicates that energy tariff structures can drastically impact the ASP energy costs.

The analysis also indicates that the peak CO$_{2\,eq}$ emissions occur during peak hours as illustrated in Figure 8. The effect of amplification could be observed as the peak over minimum ratio increases from 4.2 to 5.2 for the hourly electricity consumptions (kWh) and hourly emission rates (kgCO$_{2\,eq}$ h$^{-1}$), respectively (Figure 8).

**Implications for process design and equipment specification**

The analyses indicate that circadian variations in influent flow and constituents' concentrations substantially affect the dynamics of air requirements, energy consumption and its associated costs and GHG emissions in ASP.

Over- and under-aeration conditions are caused by circadian variations in influent flow, carbonaceous/nitrogenous constituent loadings, and their associated air requirements. The over- and under-aeration in ASP could result in excessive energy use and non-compliance with effluent water quality standards, respectively. Furthermore, it was concluded that under- and over-aeration conditions are mainly introduced due to limitations associated with the turn-down-turn-up ranges of aeration blowers and control system in modulating air supply to maintain DO control set points promptly and accurately. To compound the issue, a wide range of variations in ASP air requirements induced by circadian variations in influent flow and carbonaceous/nitrogenous substrates could shift aeration blowers’ system curves away from the desired high-efficiency ranges.

**SUMMARY AND CONCLUSIONS**

This paper analysed the effects of circadian variations in influent flow and carbonaceous/nitrogenous constituent concentration on the aeration requirements and its associated energy consumption, energy costs, and carbon emissions in an ASP in MLE configuration. A model was developed to determine the ASP air requirements and its associated energy consumptions. The spatial and temporal variations in marginal carbon emissions were quantified using carbon emission intensities from the regression model developed by Zivin et al. (2014). Furthermore, the economic implications of TOU energy consumption...
associated with ASP aeration was demonstrated using an SCE tariff structure.

The results indicate that the concurrency of circadian variations in flow and constituent concentrations amplifies the loadings into the process trains, and causes amplification in air requirements. Meanwhile, circadian variations in influent bCOD and air requirements induce a reciprocal response in aSOTE, which further amplifies the air requirements by reducing OTE during high BOD loadings.

The variations in air requirement induce a circadian amplification response in energy consumption occurring during the TOU electricity peak hours with high electricity rates. The concurrency of energy consumption and TOU electricity rates further amplifies the aeration energy associated costs.

The temporal variations in carbon emission intensities overlap with those of energy consumptions. The concurrency of circadian variations in energy consumptions and carbon emission intensities further exacerbates the ASP carbon emissions. The ratio of peak to minimum increases to 3.4-fold (for flow rate), to 4.2-fold (for air flow rate and energy consumption), and to 5.2-fold (for the indirect CO₂eq emissions associated with energy consumption), indicating a strong amplification effect.

Additionally, the study indicates that comparing the results of simulation with the observed plant data provides detailed insight into the system behaviour, such as identifying over- and under-aeration conditions with environmental, economical, and water quality implications.

Understanding the intertwined relations among influent flows rates, constituent concentrations, GHG emission intensities, electricity rates, and aeration parameters are instrumental for the successful implementation of ASP energy and cost-efficiency measures. Mechanistic models are essential tools to optimize design and operation of WRRF and to develop strategies aimed at reducing energy consumption and GHG emissions.

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