Demand/Response System for Wastewater Aeration Using On-line Off-gas

DR15.18 Report

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EXECUTIVE SUMMARY

The most strategic approaches to optimize aeration efficiency in two water resources recovery facilities (WRRFs) (RP-4 and RP-5) were investigated. A comprehensive twelve-month characterization of process dynamics, together with energy-associated costs, provided the required data to draw significant conclusions that can both enhance plant performance and reduce operational cost savings. The aeration efficiency in WRRF RP-4 and RP-5 was monitored continuously and the seasonal, monthly, and daily dynamics concerning aeration efficiency were successfully captured. The long-term characterization of the aeration tanks enabled the compilation of enough data to maximize the reliability of cost saving projections using commercial modeling software. The facility was modeled using a simulator reproducing the exact same conditions, treatment train characteristics, intrinsic dynamics, and energy tariff structures (e.g., time-of-use (TOU) rates, energy usage, and peak power demand charges). The dynamics captured were introduced to minimize the process uncertainty during the process simulation. Once the WRRF was successfully modelled, a set of operational strategies involving potential savings in aeration were investigated.

Four main operational strategies impacting the total amount of oxygen required and the distribution strategy of the supplied air were applied to the constructed model of RP-4. This set of selected strategies targeted potential changes in current aeration practices and they sought to maximize aeration costs savings while maintaining the effluent quality.

Table ES1 shows the summary results of the four strategies evaluated during this study. Reducing the dissolved oxygen (DO) setpoint from the current 2.5 mg/L to a 1.5 mg/L following a set of different strategies resulted in the savings shoed below while maintaining the same effluent quality.

TABLE ES1. SUMMARY RESULTS FOR THE FOUR STRATEGIES UNDER STUDY

DELTA DO	DO SETPOINT [O_2 MG/L]	AERATION SAVINGS (%)
Strategy #1: Change in DO Setpoint		
0.2	2.3	3.7
0.4	2.1	7.8
0.6	1.9	11.8
0.8	1.7	15.2
1.0	1.5	19.1
Strategy #2: Intermittent Aeration		
0.2	2.3	17.3
0.4	2.1	18.0
0.6	1.9	18.5
0.8	1.7	18.1
1.0	1.5	19.9
Strategy #3: Ammonia Peak Equalization		
0.2	2.3	12.0
0.4	2.1	11.9

DELTA DO	DO SETPOINT [O_2 MG/L]	AERATION SAVINGS (%)
0.6	1.9	12.8
0.8	1.7	11.0
1.0	1.5	11.3
Strategy #4: Flow Equalization		
0.0	2.5	8.5*
1.0	1.5	7.8*

**Limitations apply for this set of simulations.*

Continuously capturing the aeration efficiency dynamics was possible using the developed demand/response system for wastewater aeration efficiency monitoring. The demand/response system includes an innovative on-line off-gas analyzer. While traditional off-gas analyzers measure the oxygen fraction and the flow rate from a set of sensors and a mobile hood that needs to be moved manually through various locations along the aeration basin, which is generally very time-consuming and labor-intensive for every set of data collected, the developed on-line analyzer not only outperforms previous versions of analyzers with new capabilities and a compact design. It also automates the data collection and analysis process by sending and processing data continuously. Continuous monitoring of the efficiency enables further control, can improve plant performance, and supports decision-making by providing critical information regarding the most convenient aeration strategy saving methods to implement in WRRFs.

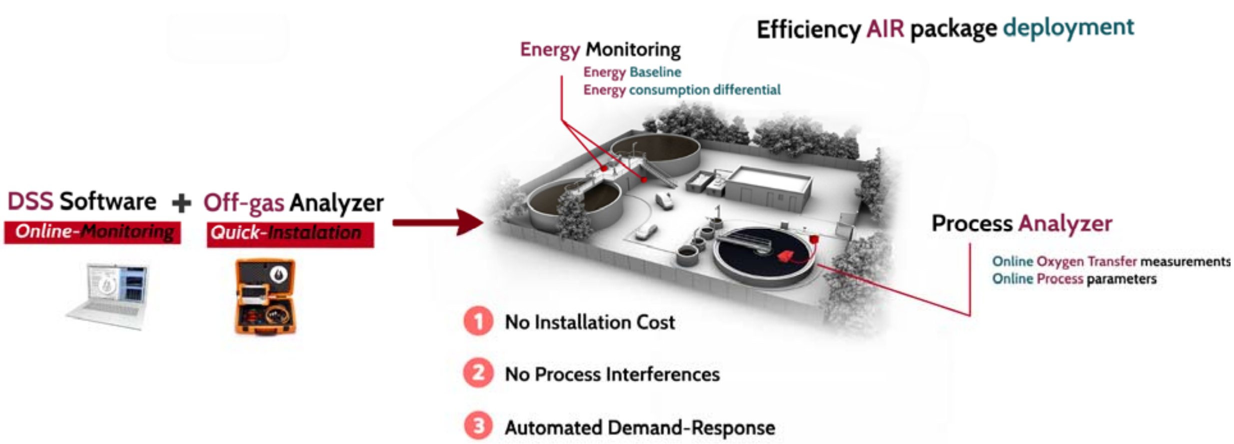

FIGURE ES1. SIMPLIFIED DESCRIPTION OF THE EMERGING DEMAND/RESPONSE PRODUCT FOR WASTEWATER AERATION MONITORING USING AN ON-LINE OFF-GAS ANALYZER

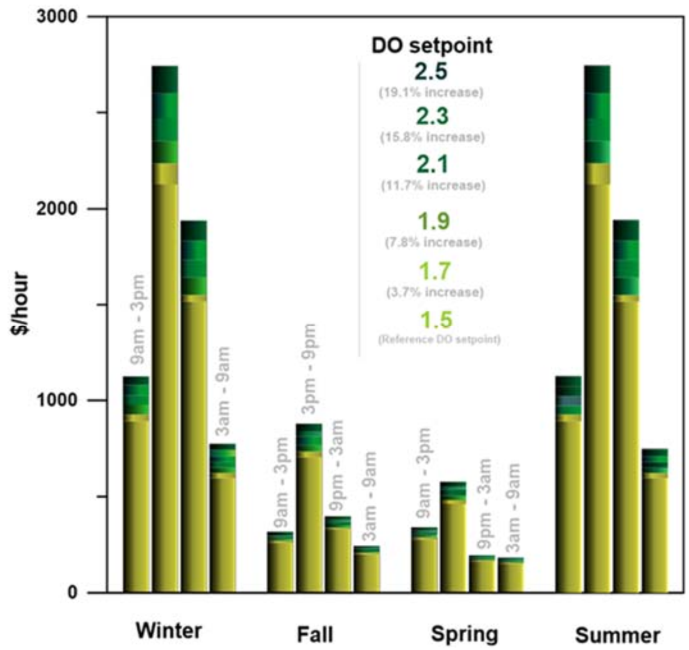

FIGURE ES2. COST INCREASE PROJECTIONS FOR STRATEGY #1. FOR THIS STRATEGY IT CAN BE SEEN THAT AS THE SETPOINT INCREASES THE COSTS EXPRESSED IN $/HOUR ALSO INCREASE ALSO (DARKER GREEN BARS).

Benefits:

- Understand process conditions associated with seasonal and daily dynamics and identify process control strategies for optimized energy efficiency.
- A tailored model for the plants under study was developed. The simulated wastewater facilities are now available to further investigate alternative strategies or a combination of them.
- The results showed decreasing the DO from 2.5 mg/L to 2.3mg/L can result in an average of 4% in aeration cost savings. The use of lower DO setpoints (1.5 mg/L) could maximize cost savings up to 22% while maintaining the effluent quality.
- Two operational strategies (e.g., intermittent aeration and ammonia equalization) resulted in an average cost savings close to 15-20% when compared to current operational strategy.
- The theoretical implementation of flow equalization will result in savings close to 15%. Nevertheless, this strategy will fail to be feasible during some periods of the year and further investigations are required before being recommended.
- Provide the site-specific data necessary for accurate quantification of the cost-benefit analysis and potential savings for the different aeration-associated strategies.

Emerging product:

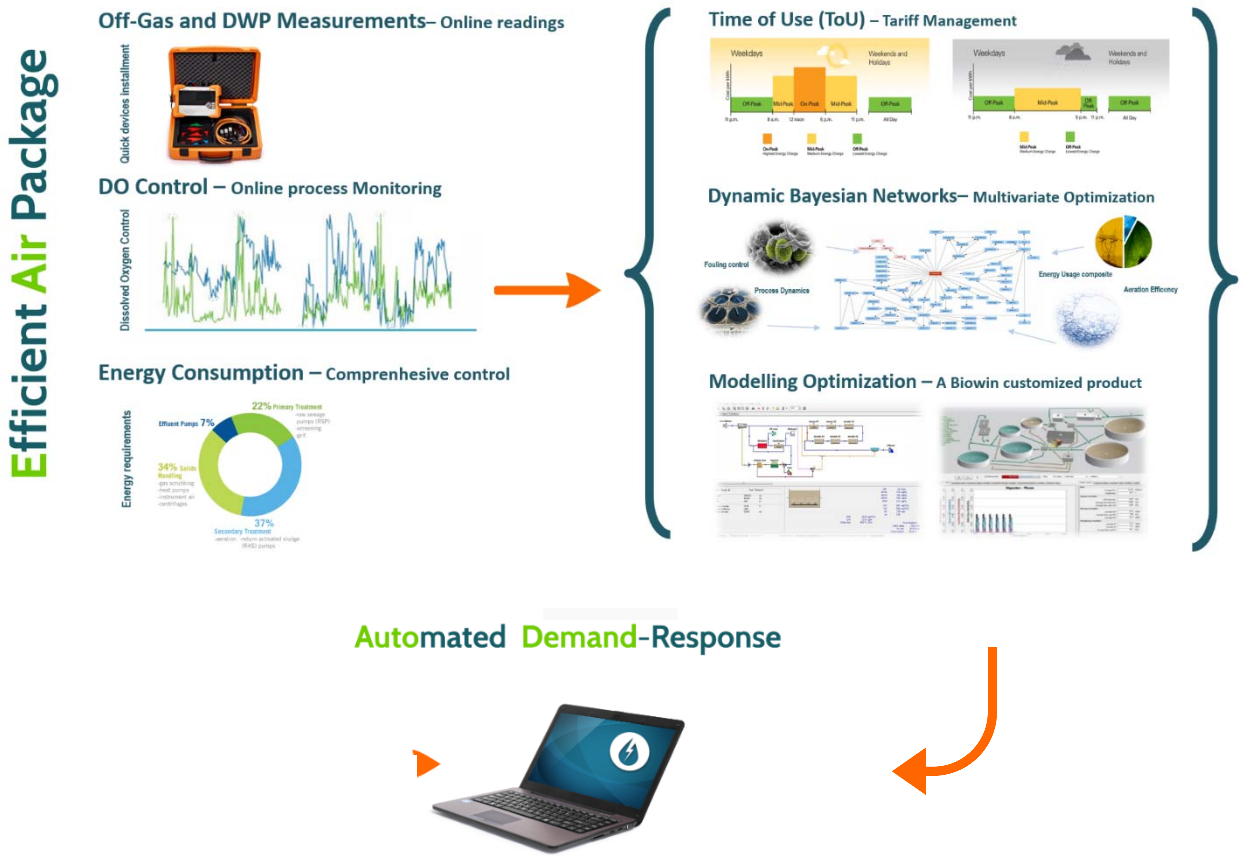

FIGURE ES2. SCHEMATIC OF THE EMERGING DEMAND/RESPONSE PRODUCT FOR WASTEWATER AERATION MONITORING USING AN ON-LINE OFF-GAS ANALYZER

ABBREVIATIONS AND ACRONYMS

ASP	Activated Sludge Process
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
DO	Dissolved oxygen concentration (mg l^{-1})
EFP	Aeration energy footprint (kWh kg_{O2}^{-1})
EPA	Environmental Protection Agency
EPS	Extracellular polymeric substances
GHG	Greenhouse gas
MCRT	Mean cell retention time (d)
MLSS	Mixed-liquor suspended solids (mg_{TSS} l^{-1})
MLVSS	Mixed-liquor suspended solids (mg_{VSS} l^{-1})
OTE	Oxygen transfer efficiency
OTR	Oxygen transfer rate (kg d^{-1})
OUR	Oxygen uptake rate (mg_{O2} l^{-1} h^{-1})
Q	Wastewater flow rate (m^3 d^{-1})
R_o	Oxygen requirements (kg d^{-1})
SAE	Standard aeration efficiency (kg_{O2} kWh^{-1})

SOTE	Standard oxygen transfer efficiency in clean water (%)
SOTR	Standard oxygen transfer rate
TSS	Total suspended Solids
$[bCOD]_{util}$	Concentration of bCOD in the influent flow that is utilized (mg l^{-1})
WRRF	Water resources recovery facility

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FIGURES

TABLES

BACKGROUND

The first reference to a technique like what is currently referred to as off-gas analysis for water resource recovery was presented by Sawyer and Nichols (1939). When this technique was initially used, the equipment was called an ''Oxy-Utilometer,'' and a volumetric method was used to measure the amount of oxygen consumed by the activated sludge during water resource recovery. Decades later, starting in the 1960s, discussions of the oxygen transfer efficiency (OTE) in aeration systems for water resource recovery that used techniques similar to off-gas analysis appeared in the scientific literature. These analyses were conducted to define aeration system performance, with each analysis opting for a different focus, including considering the volume of air used per mass of biological oxygen demand removed, determining the diffuser placement pattern that would provide the best oxygen transfer performance, or comparing different diffuser configurations (Leary et al., 1968). In the 1983, Boyle and Redmon, presented generalities for the functions of off-gas analyzers (as they are known today) as well as guidelines for their use in field studies. In the 1980s, off-gas analyzers were composed of the following four principal components: (1) a floating hood to capture the gas; (2) a hose connecting the hood to the analytical circuit; (3) an analytical circuit for monitoring the off-gas composition, temperature, pressure, and gas flow rate; and (4) a vacuum source for drawing gas from the hood through the analytical circuit.

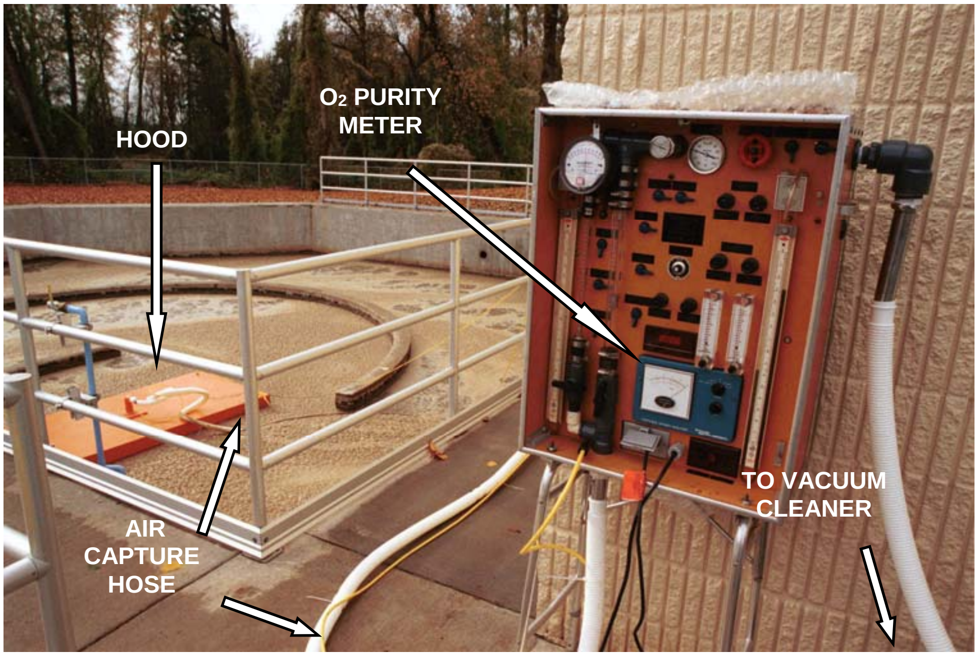


FIGURE 1. OFF-GAS TESTING SETUP

Regarding recent trends connected to real time off-gas monitoring, the work performed by Libra et al (2005) is notable. These authors reported experiences and results related to the construction and operation of off-gas analyzers coupled with floating collection hoods used in 24-hour experiments. Leu et al (2009) extended this line of inquiry, directly measuring the OTE and airflow rate through a flow pipe that collects data at hourly intervals using semi-automatic analyzers. In their work, data from water resources recovery facilities (WRRFs) in various Southern California facilities were gathered. A long-term demonstration of fully automated analyzers employed in four plants over periods spanning 3 to 12 months was presented by Jeung et al (2013). The results of their study indicate that real-time off-gas monitoring can be applied to continuously monitor the efficiencies of wastewater aeration processes over extended periods. (ASCE, 1997; Gillot et al., 2005; Iranpour and Stenstrom, 2001; Jeung et al., 2013; Leu et al., 2009; Libra et al., 2002, 2005; Redmond et al., 1992; Trillo et al., 2004)

A configuration of the off-gas analyzer, similar to that described by Redmon et al (1983), is presented in the ASCE 18-96 standard (American Society of Civil Engineers, 1997). This document also contains a graphic representation of the analyzer that is still employed today. Details regarding the required materials (including costs), drawbacks, instruments, hood assembly for permanent installation, operation and maintenance of off-gas analyzers, data processing information, and reference analysis are available in Jeung et al. (2013).

OFF-GAS ADVANTAGES

The net result of the improved testing methods is an increase in accuracy and precision in designing and quantifying aeration systems. These methods are now widely used in the United States (e.g., Iranpour and Stenstrom, 2001; Libra et al., 2002; Redmond et al., 1992), Europe (e.g., Gillot et al., 2005). Off-gas analysis is also being proposed as an additional aeration control mechanism (Trillo et al., 2004).

Overall, off-gas monitoring can be used to determine the best options for designing and expanding aeration systems. Examples of analyses that can be conducted with off-gas monitoring while considering cost-benefit ratios include the following: (1) evaluation of several diffuser types in side-by-side tests under process conditions; (2) evaluation of diffuser fouling problems and diffuser cleaning procedures in terms of effectiveness; (3) optimization of cleaning schedules by comparing the energy required and cleaning costs; (4) comparison of fixed and variable flow blowers, and the evaluation of the benefits of using an equalization basin; (5) evaluation of aeration system control procedures; and (6) real-time analysis of OTE signals which can have dynamic operational implications, such as feed-forward off-gas control and energy minimization when connected to facility data systems (Boyle and Redmon, 1983, Trillos et al, 2004; Jeung et al., 2013).

PROCESS WATER TESTS

For process water conditions, results are reported as OTE, Oxygen transfer rate (kg d^{-1}) (OTR), and Aeration Efficiency, which include the impacts of non-standard conditions. For off-gas results, it is convenient to use (standard oxygen transfer efficiency in clean water (%)) αSOTE, or standard oxygen transfer rate (αSOTR); these two variables are corrected for all non-standard conditions except the α factor. This is possible because the other non-standard conditions are easily measured and corrected. The α factor, which is a ratio of mass transfer coefficients in process-to clean-water, can be calculated from off-gas results if clean water data are available (e.g., *a posteriori*). In fouled aeration systems, a second parameter, F, is used to define the degree of fouling. Therefore, the efficiency of a new fine pore aeration system can be defined by αSOTE and a used or fouled system by αFSOTE. αSOTE or αFSOTE is used for process water transfer efficiencies. To compare the results presented here to actual process conditions, the other corrections, such as dissolved oxygen (DO) concentration and temperature, must be applied.

In order to better define aerator performance, the off-gas testing technique has been extensively used to measure diffused aeration efficiency. Off-gas testing was developed by Redmon et al. (1983) in conjunction with the United States Environmental Protection Agency (EPA) sponsored ASCE Oxygen Transfer Standards Committee. This committee produced a fine pore manual (US EPA, 1989), a clean water oxygen transfer standard (US EPA, 1984, 1991, 2007), and guidelines for process water testing (Warriner and Brenner, 1996). Clean water testing and off-gas testing are described in detail in these publications (ASCE, 2007; EPA, 1989; Redmon et al., 1983; USEPA, 1985; Warriner and Brenner, 1996).

Off-gas is the gas emitted from the surface of the liquid volume being aerated. By measuring the oxygen concentration in off-gas and determining the oxygen concentrations or molar percentages (e.g., 20.9% for air, 100% for pure oxygen) of the gas being diffused into the system, the OTE can be calculated from any location within the aerobic reactor. Ample evidence that demonstrates how off-gas testing is the best technique for determining the in situ performance of diffused aeration systems is available. The basic principles of off-gas testing involve studying the oxygen mass balance of the volume or system being aerated.

CLEAN WATER TESTS

Clean water testing (ASCE, 2007) can be performed to compare different equipment and configurations. The results are reported as SOTE (%), SOTR (kg_{O2} hr^{-1}), and SAE (kg_{O2} kWh^{-1}). Care must be exercised when using SAE, given that different power measurements can be used. Generally, “wire” power is usually preferable, which includes blower, coupling, gearbox and motor inefficiencies. Clean water test results can be used as warranty to verify performance and can also create a competitive bidding environment among manufacturers. Figure 2 shows a schematic of the experimental setup used in a clean water test.

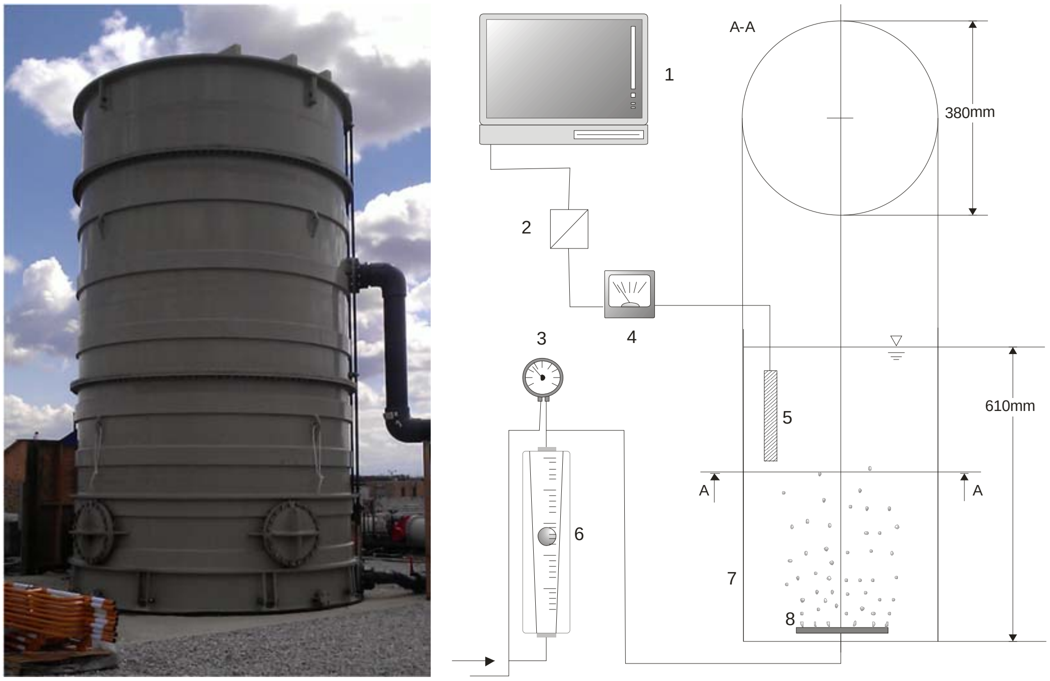


FIGURE 2. EXAMPLE OF CLEAN WATER TEST SETUPS

On the left side of Figure 2 is a full-depth continuous reactor (7.5m deep; 4.8m in diameter). On the right of the figure is the schematic of a laboratory-scale batch apparatus: (1) data logger; (2) D/A converter; (3) pressure gauge; (4) DO meter; (5) DO probe; (6) air flow meter; (7) aeration tank; (8) aerator.

PROTOTYPE DEVELOPMENT

Sub-Task period: *August 1, 2017 – November 30, 2017.*

During the early stages of the project, the research team gathered preliminary data to assess the functionality of the off-gas analyzer and calibrate the analyzer accordingly. The task encompassed the data collection process, data auto-calibration, and dissolved oxygen (DO) probe calibration. During the duration of this subtask, repairs and changes to initial prototyping were conducted, resulting in an improved analyzer requiring minimal maintenance and enhanced durability.

PRELIMINARY DATA COLLECTION

In traditional off-gas analysis, the off-gas is collected by a mobile hood and is conveyed through a flexible hose to the instrumentation (See Figure 3). The data collection occurs by measuring the oxygen fraction and the flow rate of the off-gas using an analyzer, which records the readouts from the sensors. This process is repeated as necessary at various locations along the aeration basin by manually moving the mobile hood. Conducting the data collection this way is generally very time-consuming and requires continuous manual labor for every set of data collected due to moving the mobile collection hood to the various locations. By automating the data collection process and placing the hood in a strategic stationary location, the need for continuous manual labor and the time consumption that comes with data collection is eliminated.

FIGURE 3. EXAMPLES OF OFF-GAS COLLECTION HOODS

On the left side of the figure is a hood constructed with marine plywood; on the right side of the figure is a picture of a modular hood constructed with plastic bins.

The analyzer utilized for the mobile process and the automated process used in this project are similar, however the difference lies in the collection process and some of the hardware. In the automated process, the hoods are fixed to a specific location, utilizing rigid piping to convey off-gas to the analyzer, and the analyzer is equipped with carbon dioxide sensors and moisture sensors. Further, the analyzer instruments are encased in a waterproof case to provide all-weather protection. (See Figure 4.) Moreover, the data that would normally be manually collected by the technician from the mobile analyzer is now also collected on an onboard computer that can be both visually inspected in person or remotely controlled. By fixing the hoods in place, the need for manual labor is reduced to a one-time installation and minimal maintenance. By being able to remotely send data, the need for periodic onsite collection of data is drastically reduced

FIGURE 4. ANALYZER (IN BACK, CENTER) WITH FIXED COLLECTION HOODS AND PIPING (FLOATING ON THE WATER, (LEFT))

The data collection using the onboard computers was automated utilizing an Opto-22 automation unit and controller. (See Figure 5.) Each sensor is equipped with a 4-20 mA output, which can be connected to both a meter and to the Opto-22 unit. The readings from the meters (and each sensor) can therefore be read by visual inspection and/or be continuously collected. The Opto-22 unit also allows for remote manipulation of the analyzer and its hardware. For example, air flow can be redirected using the three-way valve that can be adjusted remotely to allow for ambient air or off-gas to flow through the analyzer, thus eliminating the need for human supervision. Once the data is collected in the desired analyzer configuration, it is available on the onboard computer for local inspection of transmission via telemetry to a remote server.

FIGURE 5. OPEN ANALYZER WITH OPTO-22 AUTOMATION UNIT

DATA AUTO-CALIBRATION

In traditional off-gas testing, the data collected is the Dissolved Oxygen (DO) content of the wastewater, oxygen levels in the off-gas, and flow rate of the off-gas. The off-gas is collected from floating collection hoods on the surface of the wastewater which then flows to the off-gas analyzer. Before the off-gas is exposed to the analyzer, the gas is conditioned through a column to remove moisture and carbon dioxide using desiccant and sodium hydroxide pellets respectively. The moisture and the carbon dioxide affect the analysis of the off-gas, since it is a compressible flow.

For the permanently installed analyzers used in the wastewater plants, minimal maintenance is ideal. In the most recent analyzer prototypes, the use of gas conditioning columns is abandoned and sensors for both moisture and CO_2 are installed. (See Figure 6 and Figure 7.) Columns are now limited to mobile analyzers for supervised tests. The moisture sensors measure the relative humidity of the off-gas, increase the heat of the off-gas to eliminate condensation that would otherwise damage the analyzer, and the carbon dioxide sensors provide carbon dioxide levels in the off-gas that would be used as part of the corrections for the data.

FIGURE 6. MOISTURE SENSOR (GREY BOX ON THE BOTTOM LEFT), HEATING CHAMBER (BLACK CYLINDER ON THE RIGHT), AND CARBON DIOXIDE SENSOR (INSIDE THE HEATING CHAMBER)

FIGURE 7. CARBON DIOXIDE SENSOR DETAIL

For the permanent analyzers, the need for manual calibration of the analyzer is eliminated by using the Opto-22 unit (Figure 8and Figure 9) to switch air and off-gas, a necessary step to conduct auto-calibration. A three-way valve operated by the Opto-22 controller allows for either ambient air or off-gas to be cycled through the analyzer by an automated process or by remotely controlling the three-way valve. The Opto-22 controller also activates a 12VDC diaphragm vacuum pump to circulate the gas stream inside the analyzer for analysis. In this way, the Opto-22 unit eliminates the need for human input.

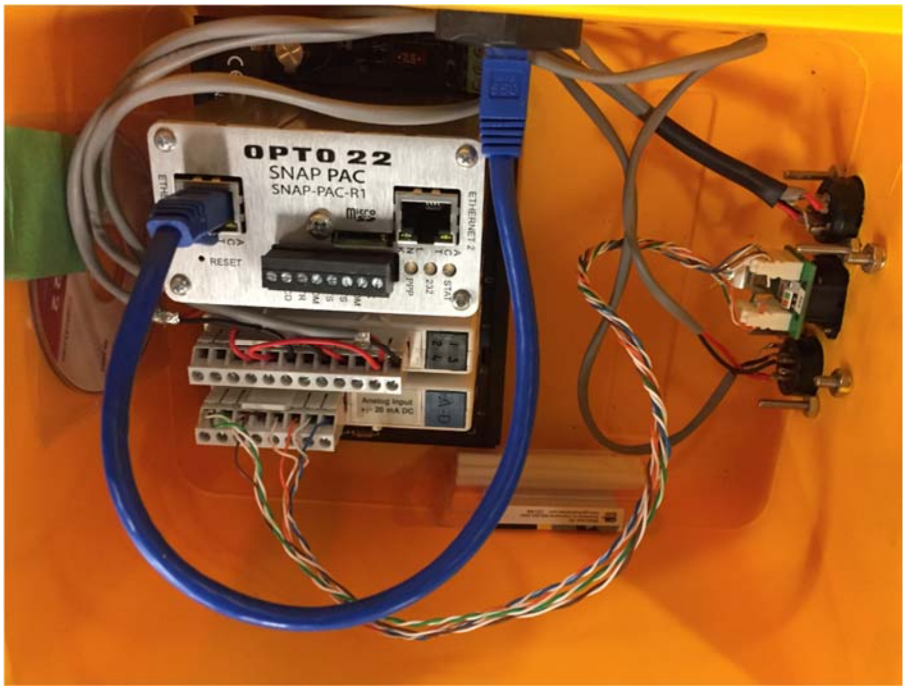


FIGURE 8. DETAIL OF THE OPTO22 CONTROLLER UNIT

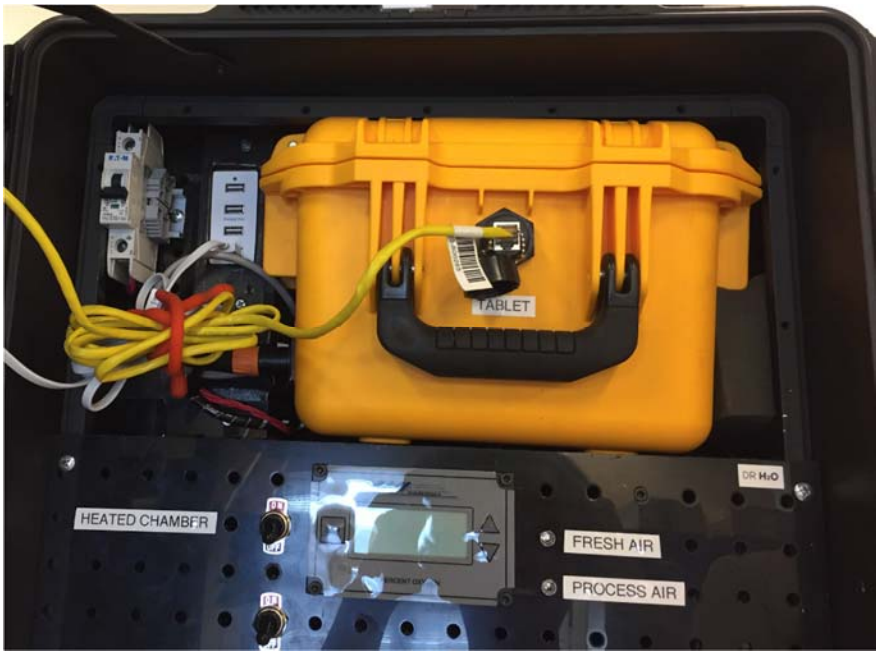


FIGURE 9. OPTO22 HOUSING BOX INSIDE ANALYZER CONTAINER

In sum, the alternate measurements of air and off-gas provide an avenue to minimize experimental variability, since their ratio essentially cancels out measurement errors. Hence, the measurement of atmospheric air before each off-gas reading obviates the need for the periodic calibration of the gas sensors and limits it to factory calibration as prescribed by the sensor manufacturers.

DO PROBE CALIBRATION

Over time, the DO probe will require calibration by the user. Calibration can be required if results from the DO probes become implausible or as part of regular periodic maintenance of the analyzer. It is recommended by the provider, Hach, not to calibrate the probe unless periodically required by regulatory agencies. If the probe requires calibration, it is recommended that the calibration should be done when the probe is in a relatively equilibrium position before calibration. (e.g., The sensor should not be calibrated at startup.) The three methods of calibration listed by Hach are calibration by air, calibration by comparison with a hand-held DO meter, and a calibration reset to factory defaults. The detailed steps for calibration of the Hach DO probe employed in this project are detailed in the technical specifications by the manufacturer.

TELEMETRY SYSTEM DEVELOPMENT

Sub-Task period: *November 1, 2017 – April 1, 2018.*

The telemetry system utilized in the DR Analyzer was developed and accordingly installed at the IEUA RP-5 facility. During this period, the project team finalized the design and implementation of the telemetry system necessary to communicate with the analyzers that monitor plant behavior over extended periods. The telemetry allows for both information harvest (e.g., output) and analyzer control e.g., input).

FUNCTIONALITY OF THE TELEMETRY SYSTEM

The telemetry unit transmits periodically or continuously the harvested data and information from remote locations to the point of data use (e.g., office of an engineering consultant, the laboratory of a researcher, or ultimately the control room of a wastewater treatment plant). In the future, the analyzers will be connected via telemetry to the display of a resident computer or to a dedicated website for plant operators and engineers in their control room or wherever convenient.

The telemetry system is located inside the off-gas analyzer and connected via Ethernet to the Opto22 automated controller (mod. SNAP-ODC5-I 4-Channel Isolated 5-60VDC Module). Figure 10 illustrates the structure of the telemetry system. The signal from the Opto22 unit is transmitted via a CAT-6 cable to a modem for transmission. The modem is mod. ALC MW41TM LINKZONE HOTSPOT, relying on a GSM cellular network for transmittal. The modem receives the signal and relays it via static IP, a necessary detail for I/O direct remote connection.

Using the remote connection, one can access the DR Analyzer's graphic interface. The displays are mirror images; the resident display is identical to the remote connection.

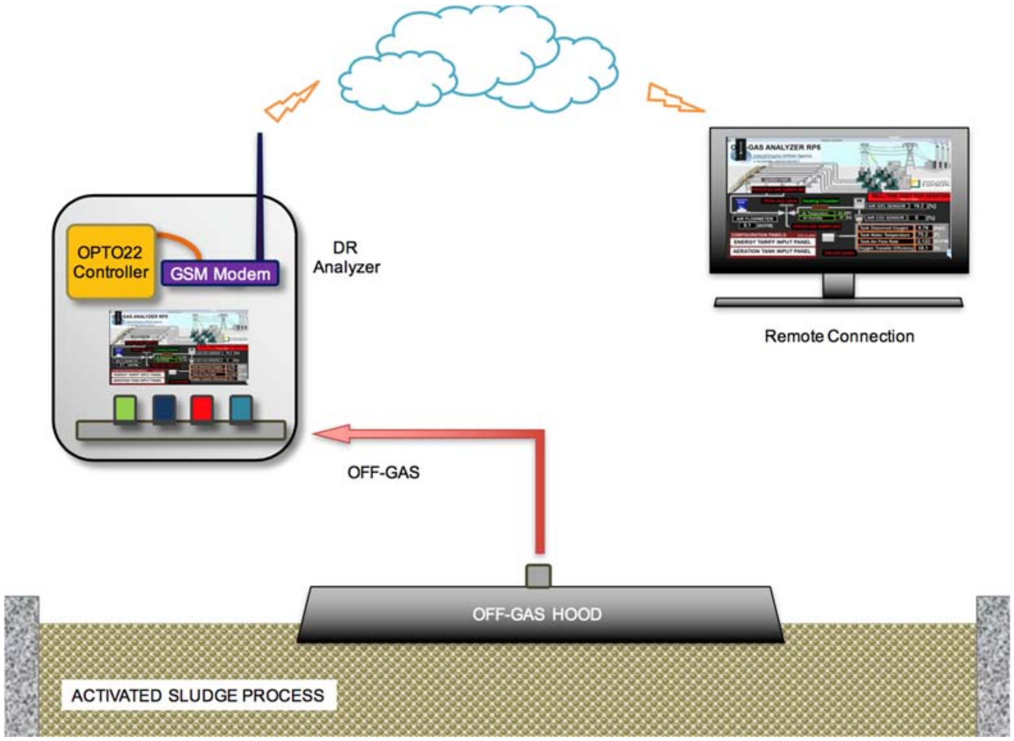


FIGURE 10. ILLUSTRATION OF THE TELEMETRY FOR THIS UNIT

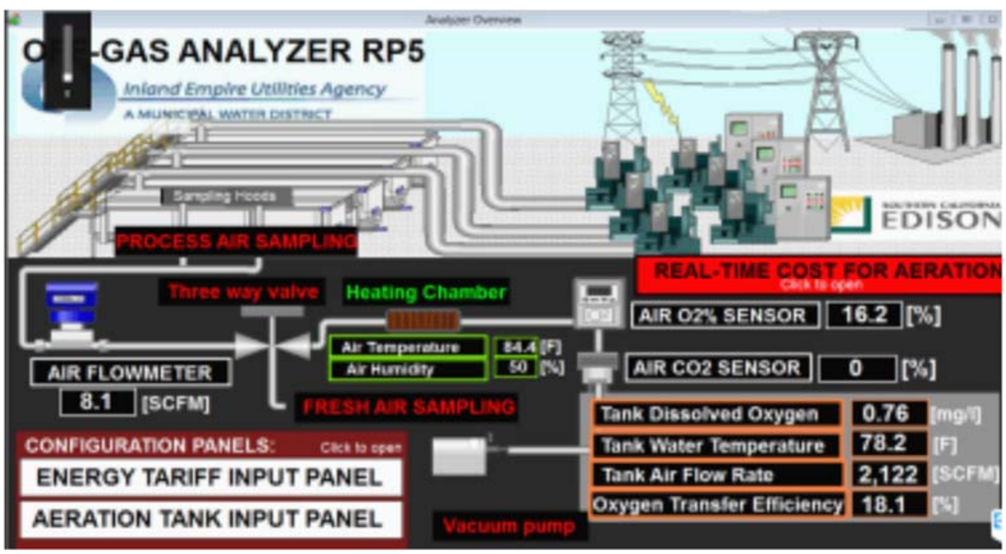


FIGURE 11. SCREENSHOT OF THE DR ANALYZER DISPLAY, AS VISIBLE ON THE ANALYZER COMPUTER DISPLAY OR ON A REMOTE CONNECTION VIA TELEMETRY

TECHNOLOGY NOTES

The telemetry system relies on a modem whose lifespan is affected by high temperatures. To prevent the accumulation of moisture within the analyzer gas-sensors chamber, a moisture absorber that incorporated a heating system was installed in the OTE analyzer at RP-4. However, the heating system affected the lifespan of the telemetry modem and required replacement of that modem within six months.

To solve this thermal challenge, the team reconfigured the analyzer and the modem was thermally shielded. The entire enclosure was covered with an aluminum shield. From the experience gained from the OTE analyzer at RP-4, the team implemented an improved thermal design for the DR analyzer at RP-5. (See Figure 12.)

To guarantee the autonomous operation of the unit, a ground-fault circuit interrupter, or GFCI, was installed. Ground faults occur when electrical current finds an unintended path to ground, which was likely to occur due to the condensation during some moist winter nights. GFCI are fast-acting circuit breakers designed to shut off electric power in the event of a ground-fault within as little as 1/40 of a second. In such event, the current will switch to the installed solar panel connected to a chargeable battery pack located in an additional enclosure (Figure 13) without interrupting operation.

FIGURE 12. IMAGE OF THE DR ANALYZER AT IEUA RP-5, IN ITS CURRENT CONFIGURATION. THE SOLAR PANELS ON THE LEFT WALL AND ON THE TOP WERE INSTALLED TO CHARGE THE BATTERY PACK FOR AUTONOMOUS ANALYZER OPERATION.

FIGURE 13. ANOTHER IMAGE OF THE DR ANALYZER AT IEUA RP-5. NOTE THE ADDITIONAL ENCLOSURE ON THE RIGHT, TO HOUSE THE RECHARGEABLE BATTERY PACK CONNECTED TO THE SOLAR PANELS.

PROTOTYPE DEPLOYMENT AND DATA ANALYSIS

Sub-Task period: *January 1, 2018 – June 30, 2018.*

The data and knowledge collection retrieved by the DR Analyzer installed at the IEUA RP-5 facility was accordingly assembled. During this sub-task, the project team developed the software components necessary to calculate:

- Blower power from off-gas flow measured from the OTE analyzer;
- Aeration energy from the blower power; and
- Cost from aeration energy and blower power.

DATA COLLECTION

The data collection occurs continuously from all sensors (via their respective 4-20mA isolated outputs). The frequency of collection of the raw signals is >0.1Hz. To match data calculation frequency, process time-constants, and Southern California Edison's (SCE's) D/R time intervals, a running average of 15 minutes is continuously calculated.

DATA ANALYSIS

To quantify the power demand and cost for each aeration zone, a sequence of calculations must be carried out by the programmable controller. The first step is the calculation of adiabatic blower power from the measured off-gas flow (See Equation 1.).

EQUATION 1. RELATIONSHIP BETWEEN THE ADIABATIC BLOWER POWER (PW) AND THE OFF-GAS FLOW (W), AS REPORTED IN METCALF & EDDY (2014)

$$P_w = \frac{wRT_1}{550\,n\,e}\left[\left(\frac{p_2}{p_1}\right)^n - 1\right]$$

where P_w = power requirement of each blower, kW (hp)
w = weight of air flowrate, kg/s (lb/s)
R = universal gas constant for air, 8.314 J/mole·K (SI units)
53.3 ft·lb/(lb air)·°R (U.S. customary units)
T_1 = absolute inlet temperature, K (°R)
p_1 = absolute inlet pressure, atm ($lb_f/in.^2$)
p_2 = absolute outlet pressure, atm ($lb_f/in.^2$)
n = $(k - 1)/k$ where k is the specific heat ratio. For single-stage centrifugal blower power calculations a value of 1.395 is used for k for dry air and n = 0.283.
28.97 = molecular weight of dry air
550 = conversion factor from ft·lb/s to hp
e = efficiency (usual range for compressors is 0.70 to 0.90)

An example of power demand output calculated from the software is shown in Figure 14. In this figure, a week's worth of calculations is reported. Note the several-fold variation over the diurnal cycle, but the relatively contained variation between subsequent days.

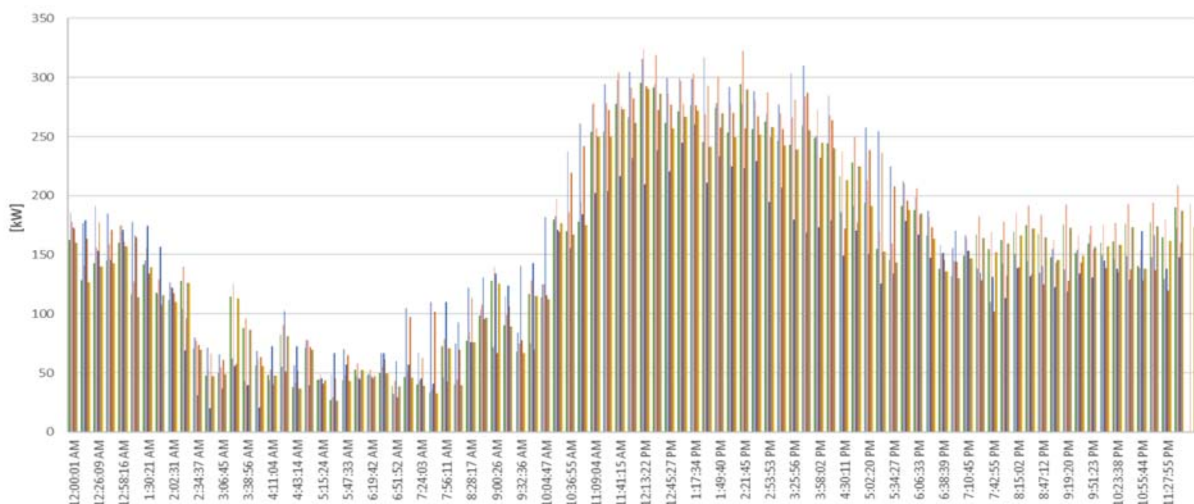


FIGURE 14. EXAMPLE OF ONE WEEK OF POWER DEMAND RESULTS. THE DATA WAS PLOTTED IN 24-HOUR CYCLES; HENCE TIME LABEL REPRESENTS A GROUP OF RESULTS CALCULATED EVERY DAY OVER SEVEN DAYS.

IMPLEMENTATION OF ENERGY TARIFF STRUCTURES

Power demand and energy consumption are priced following a set of structures established to promote a rational use of the existing infrastructure. The application of different energy pricing structures (e.g., time-of-use (TOU) rates) and charges (e.g., energy usage, peak power demand charges) in the different billing terms results in very different operational costs depending on when the energy is used (hour, day, month, and season).

WRRFs typically receive the highest loading flowrate (to be treated) when the cost of energy is also the highest. The consequent overlap between the receiving influent peak and the most expensive energy price exacerbates both the cost of treatment and the concurrent greenhouse gas (GHG) emissions. Even small shifts in peak demand have a large effect on savings to consumers and avoided costs for additional peak capacity. A study concluded that a 1% shift in peak power demand will result in savings of 3.9% (billions of dollars at the system level (Spees et al., 2008)). SCE tariff structure prices can be almost 25% more expensive depending on the time of use in a plant with a ratio of 4.2-fold (for air flow rate and energy consumption) from peak to minimum (Emami et al., 2018).

Therefore, it is of the utmost importance to consider the tariff structure when assessing the cost savings from aeration optimization strategies. The software was equipped with an energy input panel, where details of the TOU tariff (main structures listed in Table 1) were entered. The power demand calculations are converted to aeration energy costs by using the same TOU tariff structure that SCE adopts for computing the charges to their industrial customers. Figure 15 shows the logical chart that structures the calculations.

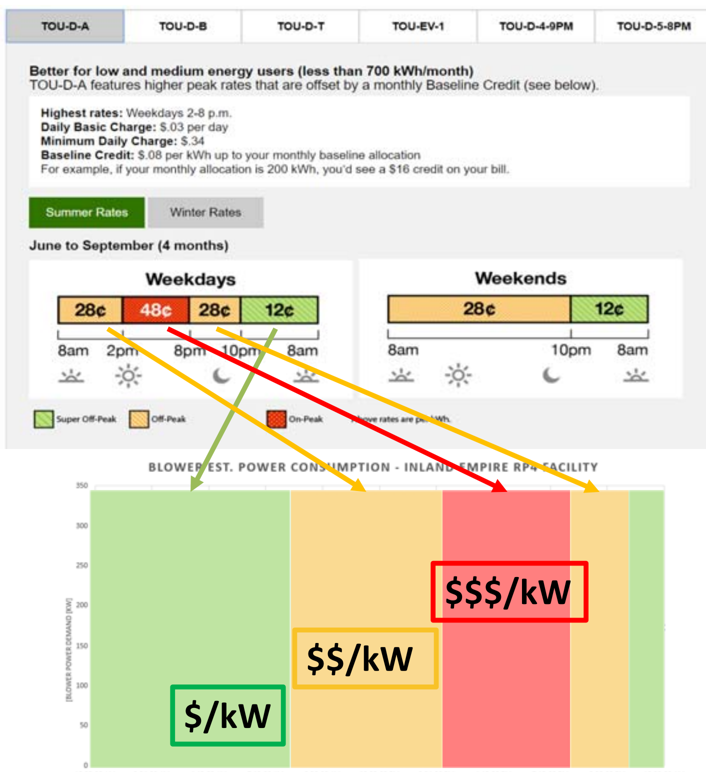


FIGURE 15. EXAMPLE OF TARIFF STRUCTURE WITH BASELINE CHARGE, SHOULDER, AND PEAK FOR WEEKDAY'S AND WEEKENDS WITHIN THE SUMMER SEASON TOU ENERGY PRICING (FROM JUNE TO SEPTEMBER). WINTER RATES ARE ALSO AVAILABLE AND INCLUDED FROM MAY TO OCTOBER.

TABLE 1. LIST OF TOU TARIFF STRUCTURES CONSIDERED.

RATE SCHEDULE	DESCRIPTION
TOU-8 TOU-8 Option R	Mandatory accounts >500kW
	On-peak, mid-peak, and off-peak energy charges that are lower in winter and higher in summer
	Interval Meter Required
TOU-8-RBU	Available for accounts >500kW enrolled in TOU-8
	On-peak, mid-peak, and off-peak charges that are lower in winter and higher in summer
	Interval Meter Required
TOU-EV-3	Those who use most energy during off-peak hours (after 6:00 PM)
	Those who own and operate electric vehicles for business
TOU-EV-4	For businesses that own and operate electric vehicles with a maximum demand of 500 kW or less
	You can reduce your charging costs by charging between 9:00 PM and noon.
	This schedule includes demand changes, but they are applied only once to either the TOU-EV-4 account, or to your normal business account, whichever registers the higher demand.

Figure 16 shows a screenshot of the graphic user interface where the energy tariff input panel button is highlighted.

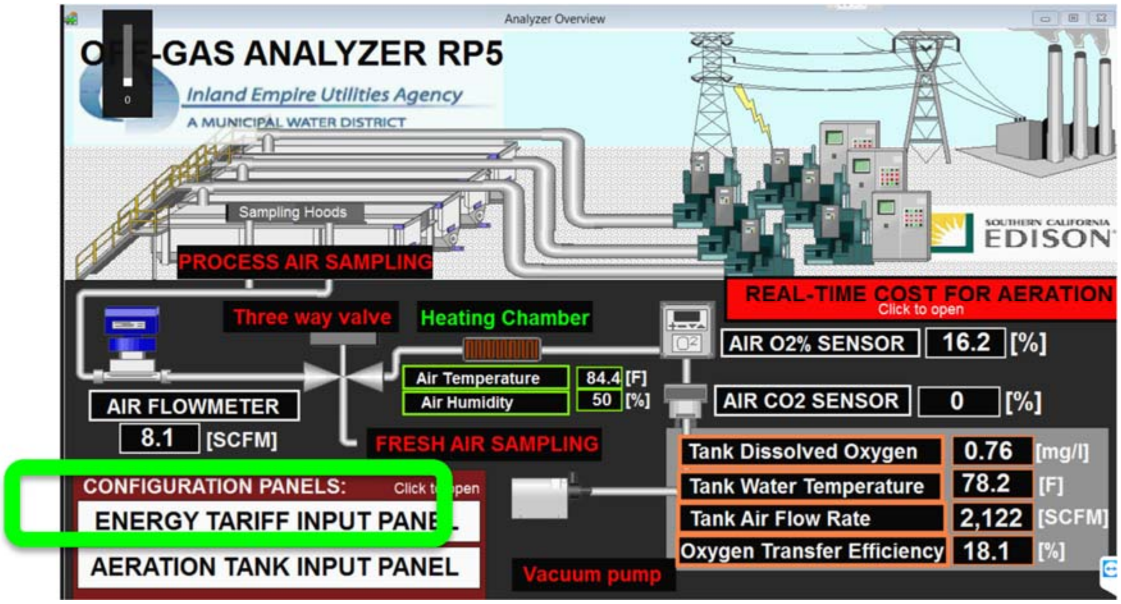


FIGURE 16. GRAPHIC USER INTERFACE WITH DETAIL OF THE ENERGY TARIFF INPUT PANEL

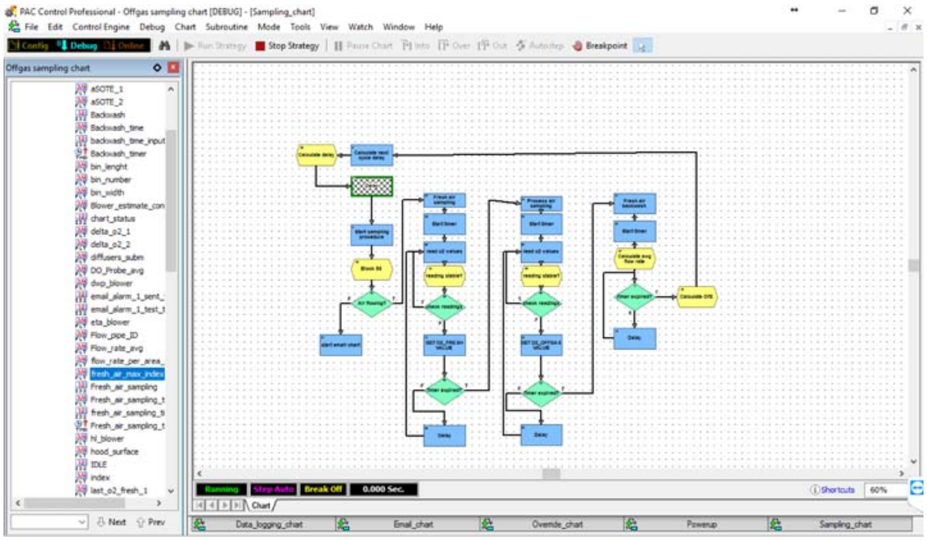


FIGURE 17. SCREENSHOT OF THE SOFTWARE KERNEL, WHERE THE CALCULATIONS FOR POWER DEMAND TAKE PLACE

The calculations are sensitive to seasonality. In fact, a different tariff is applicable for summer and winter. Figure 17shows a detail of the logical chart where the peak periods and seasons are sought by queries. The program calculates the real-time and daily/monthly cost for aeration power demand, modifying the unit costs for $/kW and $/kWh seasonally (WINTER/SUMMER – peak).

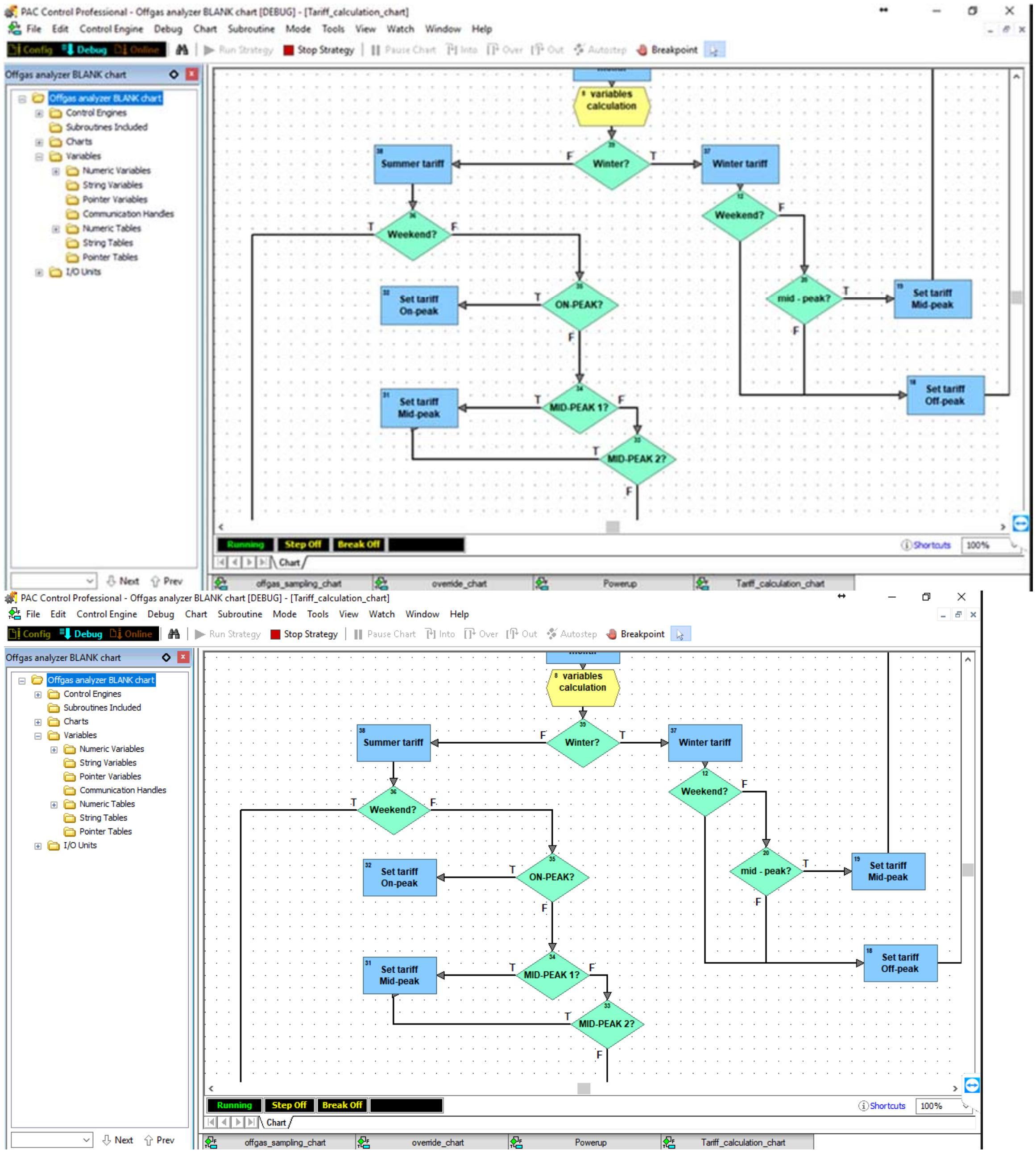


FIGURE 18. DETAIL OF THE LOGICAL CHART WHERE PEAKS AND SEASONS ARE SOUGHT BY QUERIES

The data collected are sufficient to track and demonstrate the daily dynamics and part of the seasonal trends for power demand and aeration efficiency.

The final goal is to populate a database to track and model the dynamic of both power demand and energy cost. This database will be used to develop the real-time cost and the potential economic benefit of different operating strategies applied during the day (e.g., modification of DO setpoint, flow equalization, etc.) and for design purposes (e.g., case of study for similar WWTPs, rates optimization for dynamic treatment operations, etc.).

The power demand calculations are converted to aeration energy costs by using the same TOU tariff structure that SCE adopts for computing the charges to their industrial customers. Figure 18 shows the logical chart that structures the calculations.

AERATION EFFICIENCY CHARACTERIZATION

The continuously retrieved data from the deployed analyzer at IEUA RP-4 facility allowed us to monitor, analyze, and improve our understanding of the process dynamics at resource recovery plants. The analyzer systematically collected data to characterize seasonal, monthly, and daily variations.

Verification of the plausibility of the retrieved raw data and the detection of potential outliers was conducted by calculating the coefficient of variance (CV) and the use of traditional data reconciliation techniques. A set of representative days (from six to eight days) for each season period was selected in order to illustrate the plant performance at different environmental conditions. Representative days were only chosen when the co-variance was not exceeding 30% between collected and averaged values. Averaged values from one week's worth of representative data were calculated to show the main differences between the seasons of winter, fall, spring, and summer. Similarly, continuous hourly measurements enabled the calculation of the hourly average per each day in order to obtain 24-hour profiles.

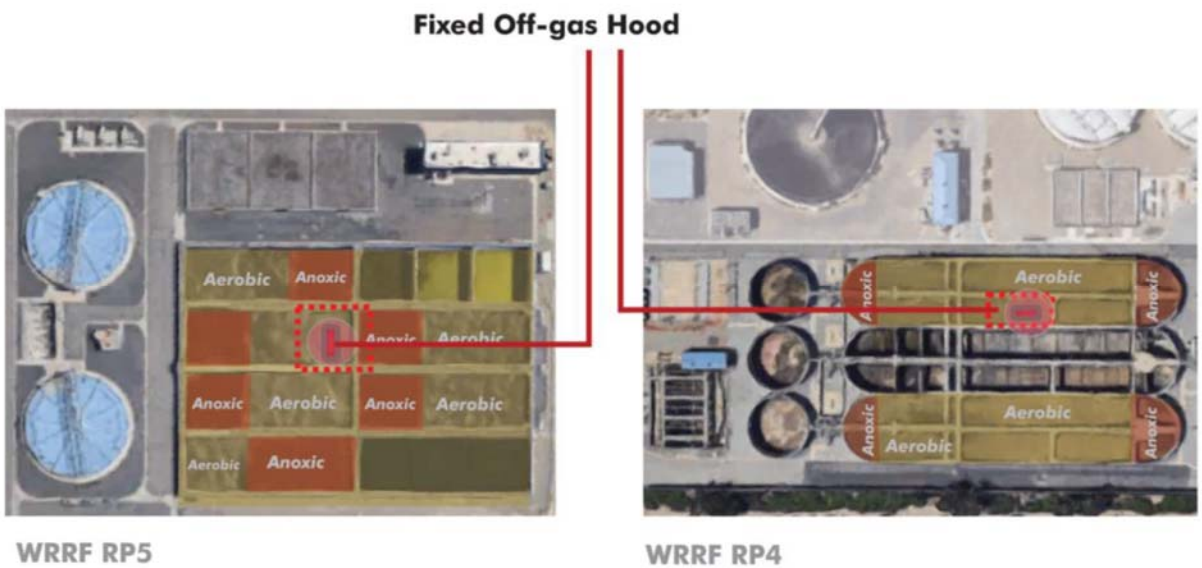


FIGURE 19, SCHEMATIC OF IEUA RP-4 AND RP-5 SHOWING THE CHARACTERIZED SECONDARY TREATMENT REACTORS. THE RED DOTS REPRESENTS THE OFF-GAS HOOD APPROXIMATE LOCATION WHERE THE AERATION EFFICIENCY INDICATORS WERE MEASURED DURING THE 12-MONTH PERIOD.

The data collected includes the following parameters of concern: OTE,%; hood airflow rate (SCFM); dissolved oxygen (DO,%); alpha factor (☐); and the influent flow rate variation (MGD). The information extracted from the data made it possible to create dynamic seasonal and hourly profiles which can be found in the Figure 20 – Figure 27. The obtained dynamics of these efficiency indicators were used to maximize the predictive capabilities of modelling software in the consulting industry specializing in the wastewater treatment field.

AERATION EFFICIENCY INDICATORS: SEASONAL PROFILE

The following figures illustrate the seasonal dynamics at RP-4 after 12 months of continuous monitoring. Smoothing spline fits were used to visualize the impact of seasonality and the importance of capturing and considering these variations during the modelling efforts.

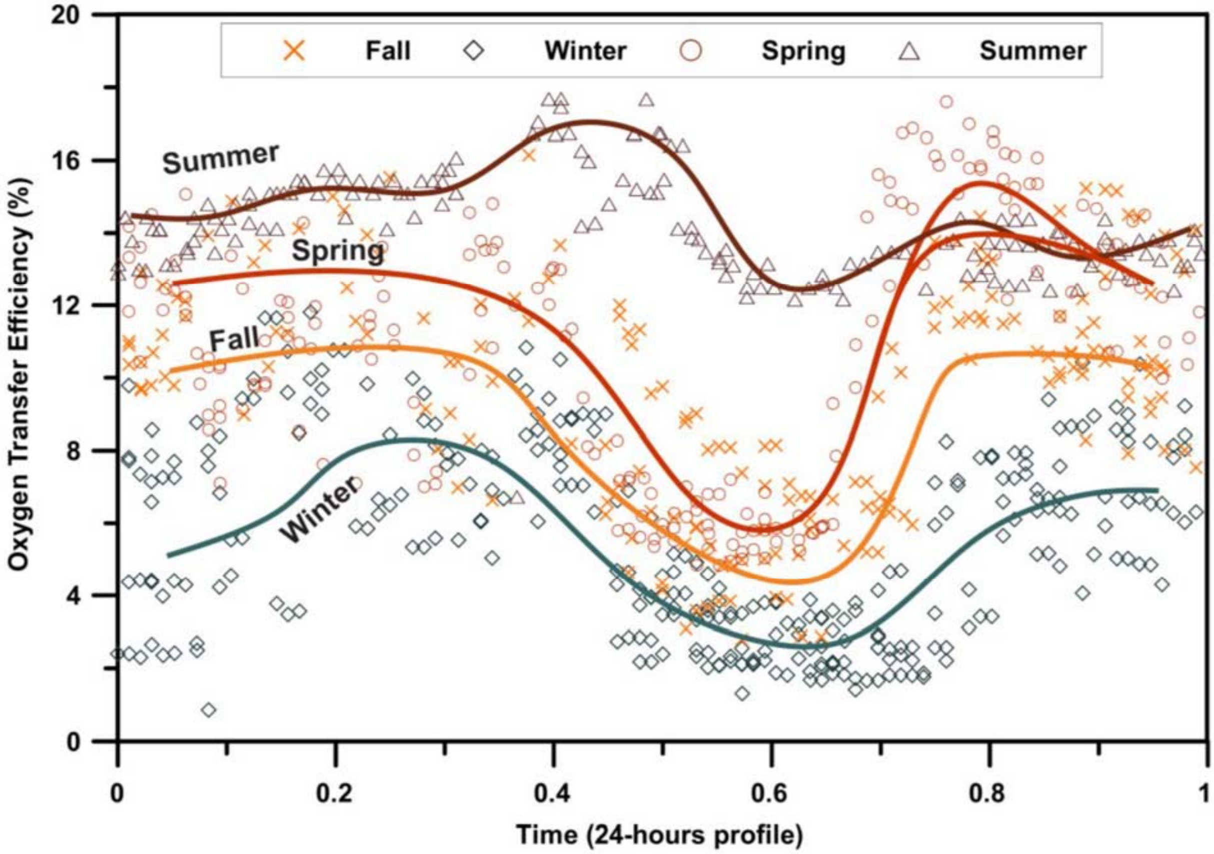


FIGURE 20. SEASONAL OXYGEN TRANSFER EFFICIENCY (OTE, %). SMOOTHING SPLINE FITS OBTAINED FROM SEVEN REPRESENTATIVE DAYS (CV <30%) ARE PROVIDED FOR EACH SEASON (E.G., FALL, WINTER, SPRING, AND SUMMER).

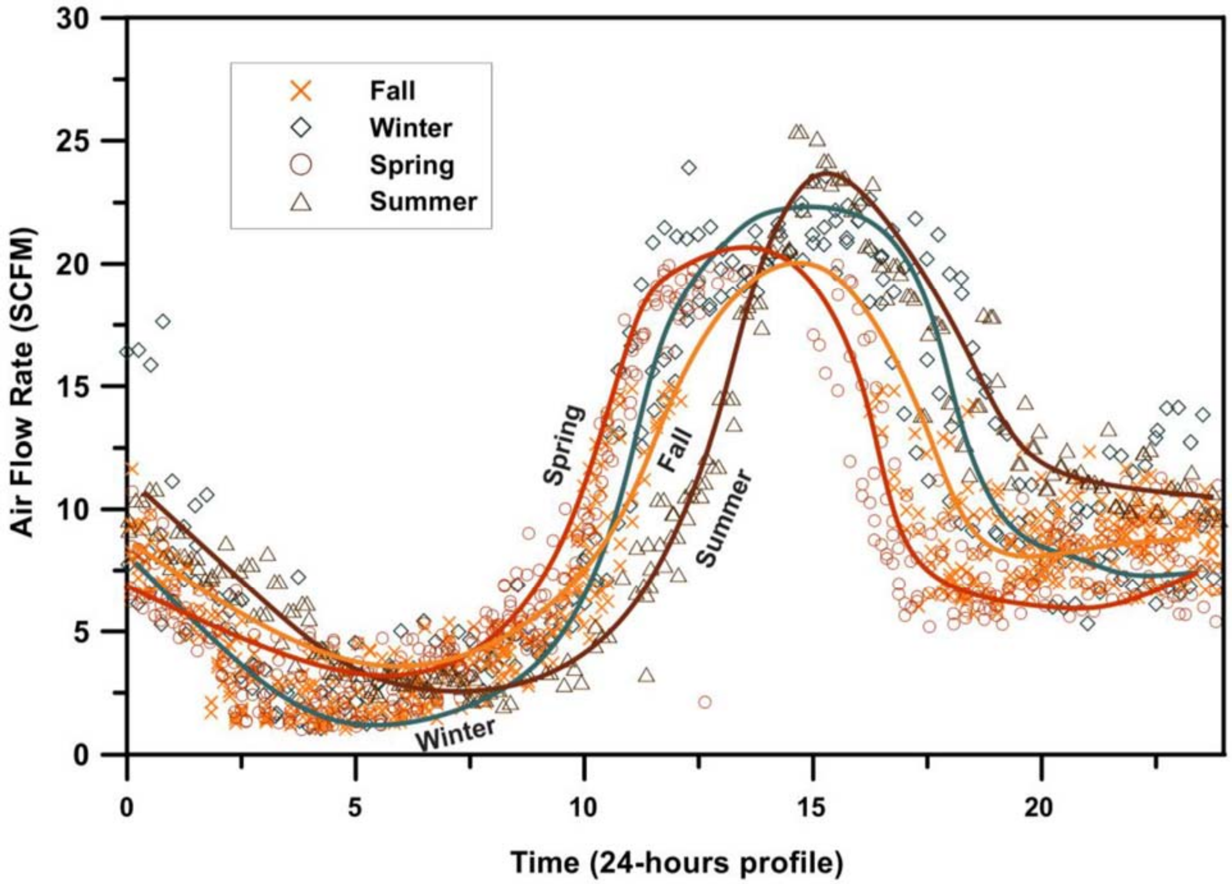


FIGURE 21. RECORDED AIRFLOW MEASUREMENTS (SCFM) DURING DIFFERENT SEASONS AT THE INSTALLED OFF-GAS HOOD

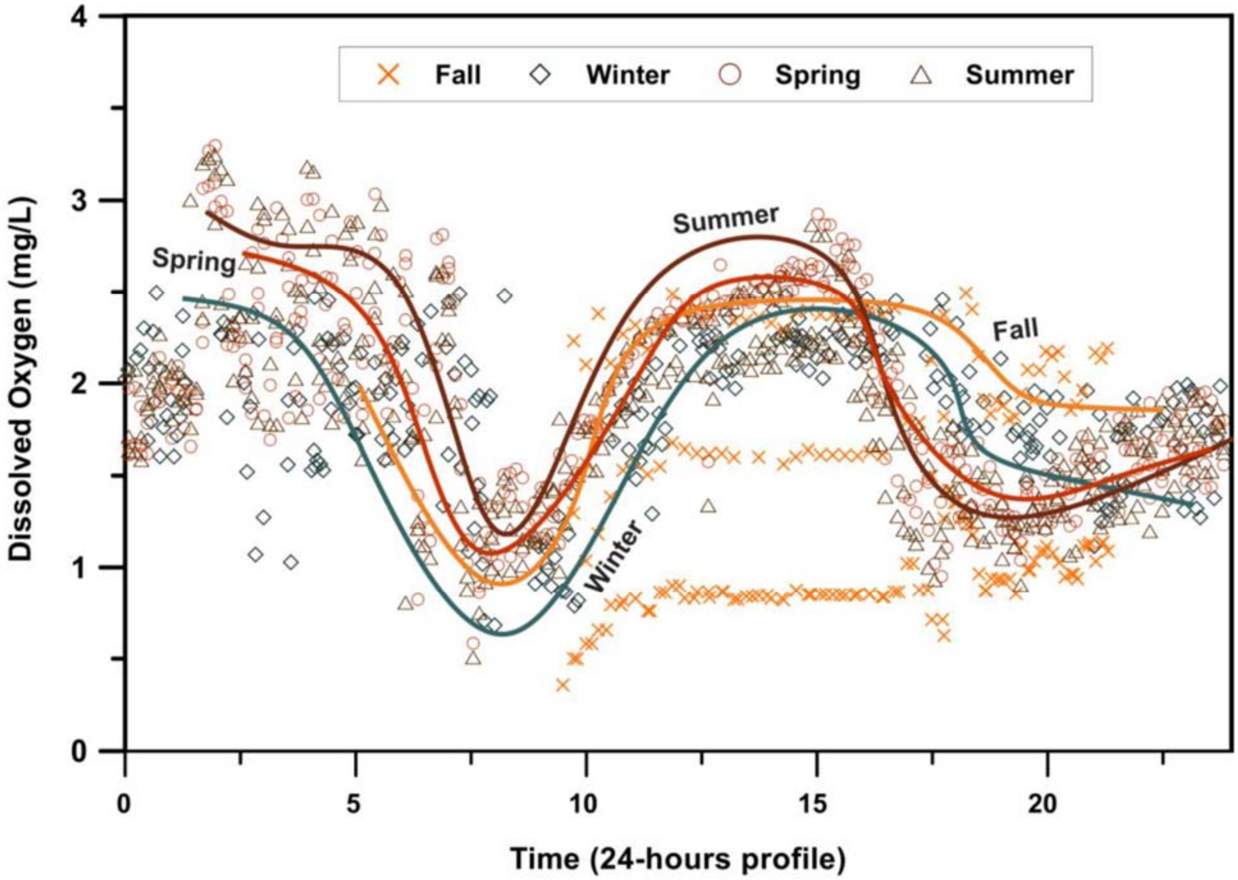


FIGURE 22. SEASONAL DISSOLVED OXYGEN CONCENTRATION (MG/L) AT THE HOOD LOCATION. SMOOTHING SPLINE FITS OBTAINED FROM SEVEN REPRESENTATIVE DAYS (CV <30%) ARE PROVIDED FOR EACH SEASON (E.G., FALL, WINTER, SPRING, AND SUMMER).

OBSERVATIONS ON THE SEASONAL PROFILE

The obtained oxygen transfer measurements confirmed the influence of seasonality at the treatment facility (Figure 20). As expected, OTE values for warmer summer and spring periods consistently showed superior efficiency in comparison to colder winter or fall seasons. The averaged value for winter was close to 5.4±2%, while 14±2% efficiency was observed during summer months. Despite the temperate climate of California, it was possible to capture the seasonality in the region, and the results are in accordance with most WRRFs experiencing temperature variations similar to such seasons. The enzymatic activity of their microbial populations is enhanced by warmer temperatures.

Figure 20 shows how the oxygen transfer efficiency fluctuates through daily cycles because of the effects of wastewater contaminants and hydraulic loadings. High concentrations of contaminants such as surfactants and biodegradable COD showed the highest impact on depressing the oxygen transfer efficiency during 7:00 AM and 9:00 PM at RP-5. From 12:00 PM to 4:00 PM the WRRF reports the highest hydraulic loadings, thus driving aeration efficiency to its lowest value when the oxygen demand is the highest.

By comparing Figure 20 and Figure 21, the effect of the circadian amplification of air requirements can be observed. Figure 21 shows how the airflow increases to satisfy the DO requirements when the aeration efficiency is the lowest during the peak period (12:00 PM – 4:00 PM). During this period of higher organic loadings, the aeration efficiency is not only decreased by the effects of the contaminants hindering the mass transfer from gas to liquid phase, but also by two physical effects: the combined net effect of 1) formation of larger bubbles, lowering the surface to volume ratio and 2) increase in bubble rise velocity, reducing the contact time for oxygen mass transfer.

Interestingly, the airflow measurements presented in Figure 21 show almost identical magnitude orders among the represented seasons. Similar magnitude values were unexpected considering the previously observed variations in aeration efficiency (expressed by OTE), which can be halved during winter months. Therefore, airflow measurements indicate that the same airflow is being delivered all year round, independent of tank conditions and without considering efficiency variations. In other words, decreasing the airflow when the efficiency is higher seems to be a promising strategy to improve aeration at this WRRF.

Figure 22 shows an increase in DO in warmer months. Although DO concentrations should decrease as water temperature increases because oxygen is less soluble in warm water than in cool water, the specific characteristics of WRRFs usually demonstrate opposite results. While in natural systems, DO concentrations are highest during the winter when water temperatures are lowest, and in WRRF the above-mentioned enzymatic activity of the bacteria in warmer months is able to partially compensate for this inverse relationship between dissolved oxygen and temperature. Nevertheless, with respect to the dissolved oxygen, the differences between seasons are close to negligible.

AERATION EFFICIENCY INDICATORS: DAILY PROFILE

The continuous monitoring in RP-4 enabled a comprehensive characterization of its daily and seasonal dynamics. While the previous section presented the daily averages of representative days to create a seasonal profile, in this section an hourly average of those days was used to produce the 24-hour profiles.

The following figures illustrate the seasonal dynamics at RP-4 after 12 months of continuous monitoring. Smoothing spline fits were used to visualize the impact of seasonality and the importance of capturing and considering these variations during the modelling efforts.

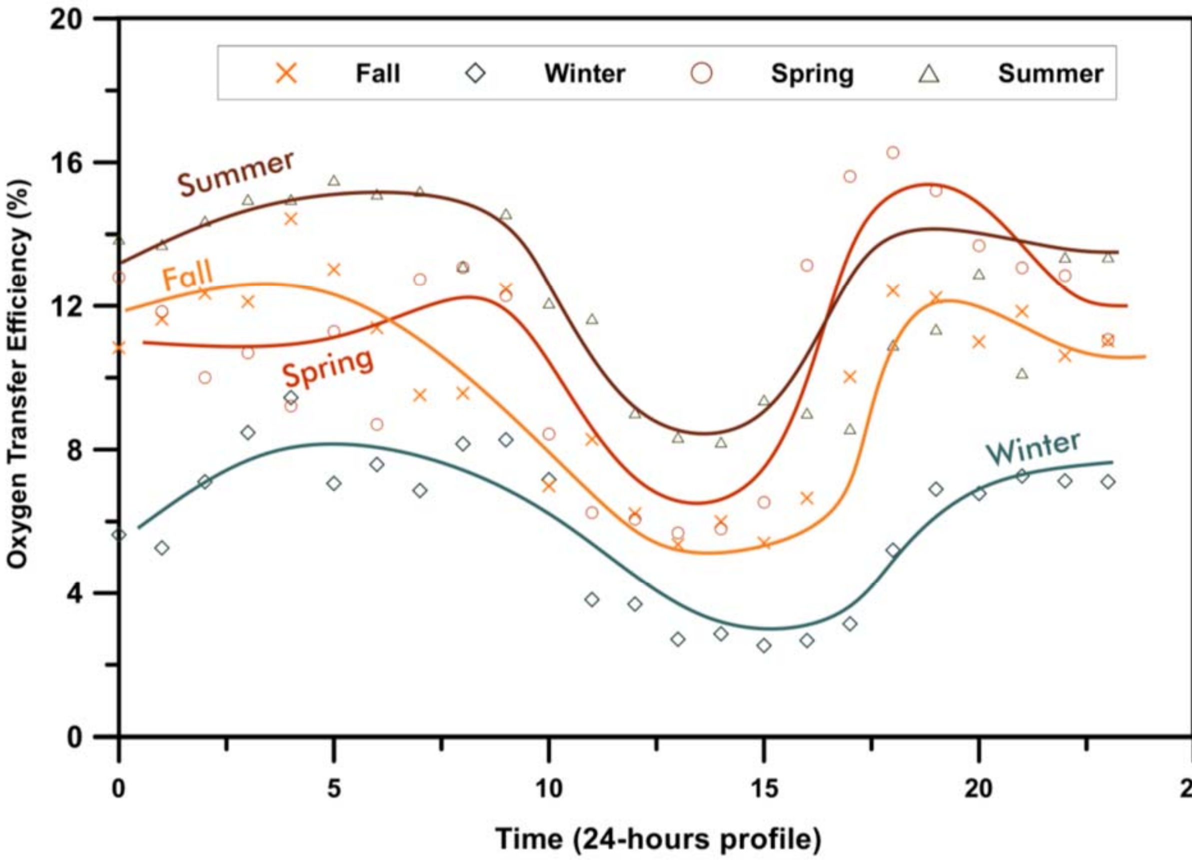


FIGURE 23. SEASONAL DAILY AVERAGE OF OXYGEN TRANSFER EFFICIENCY (%) FOR WINTER, FALL, AND SPRING SEASON, USING A 5 -7 DAY AVERAGE FOR EACH SEASON. THE HOURLY AVERAGE WAS CALCULATED TO GENERATE A DYNAMIC 24-HOUR PROFILE.

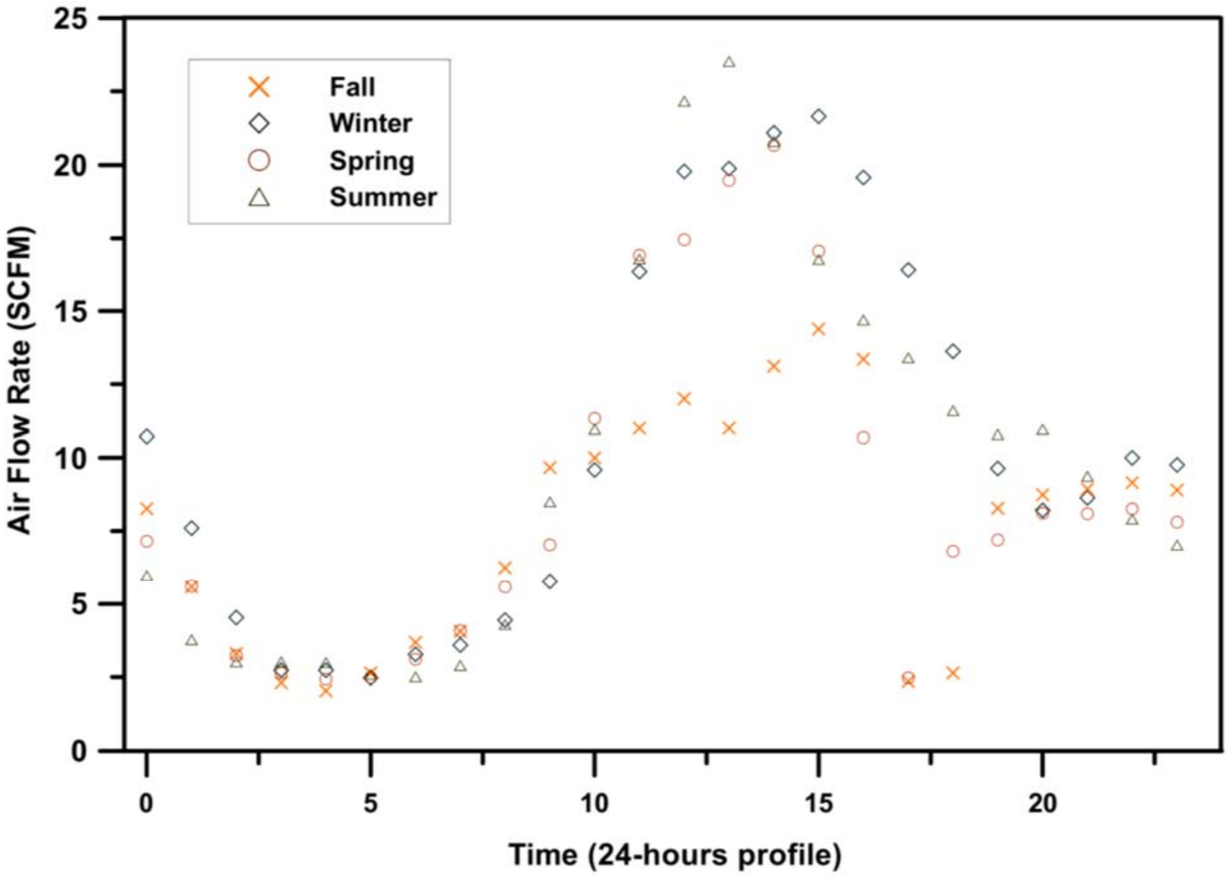


FIGURE 24. DAILY AIR FLOW RATE (SCFM) FOR DIFFERENT SEASONS. THE HOURLY AVERAGE WAS CALCULATED TO GENERATE A DYNAMIC 24-HOUR PROFILE.

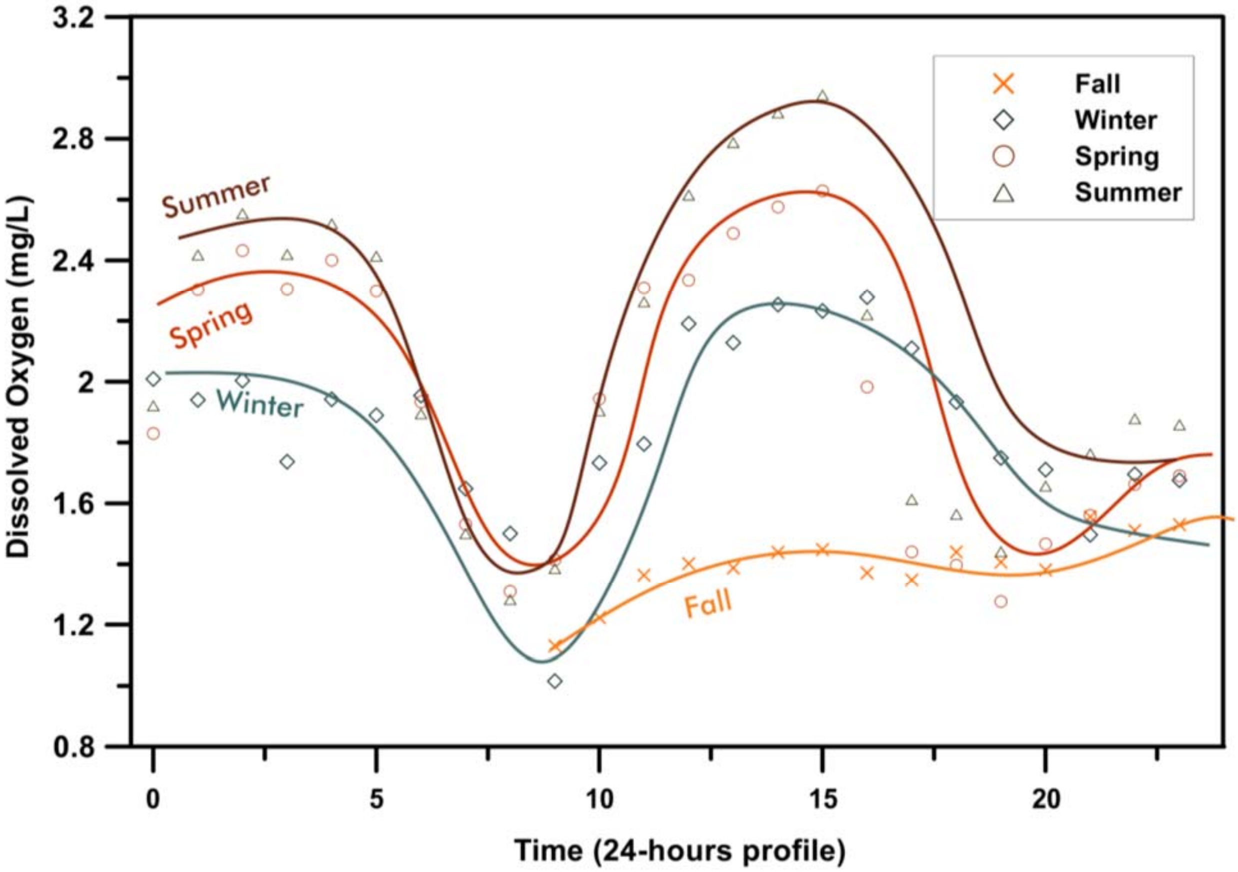


FIGURE 25. SEASONAL DISSOLVED OXYGEN CONCENTRATION (MG/L) AT THE HOOD LOCATION. SMOOTHING SPLINE FITS OBTAINED FROM SEVEN REPRESENTATIVE DAYS (CV <30%) ARE PROVIDED FOR EACH SEASON (E.G., WINTER, FALL, AND SPRING). THE HOURLY AVERAGE WAS CALCULATED TO GENERATE A DYNAMIC 24-HOUR PROFILE.

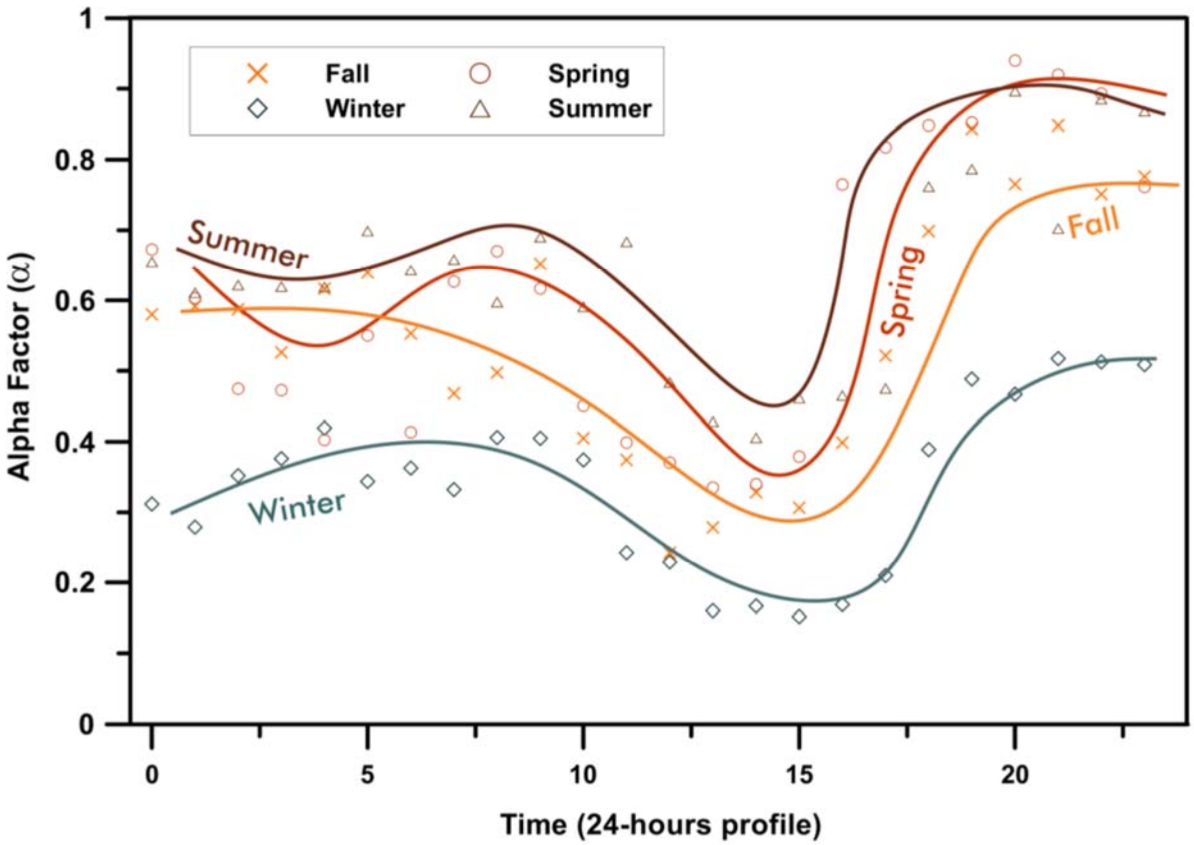


FIGURE 26. DAILY ALPHA FACTOR FOR THE DIFFERENT SEASONS UNDER STUDY. ALPHA VALUES WERE CALCULATED BY USING THE 24-HOUR PROFILE OF AFR (FIGURE 24) AND OTE (FIGURE 23).

OBSERVATIONS ON THE DAILY PROFILE

The trends in daily profiles showed similar characteristics to those observed during the seasonal profiles, and the above discussion can also be applied to these observed dynamics.

One of the most important results is the calculation of the alpha factor which was determined through continuous monitoring. The observed differences between winter and warmer months (e.g., summer and spring) of the alpha factor in Figure 26 are especially relevant. It shows how the aeration efficiency is easily doubled during summer months than in winter months, highlighting the importance of considering such mass transfer dynamics during the design of operational strategies.

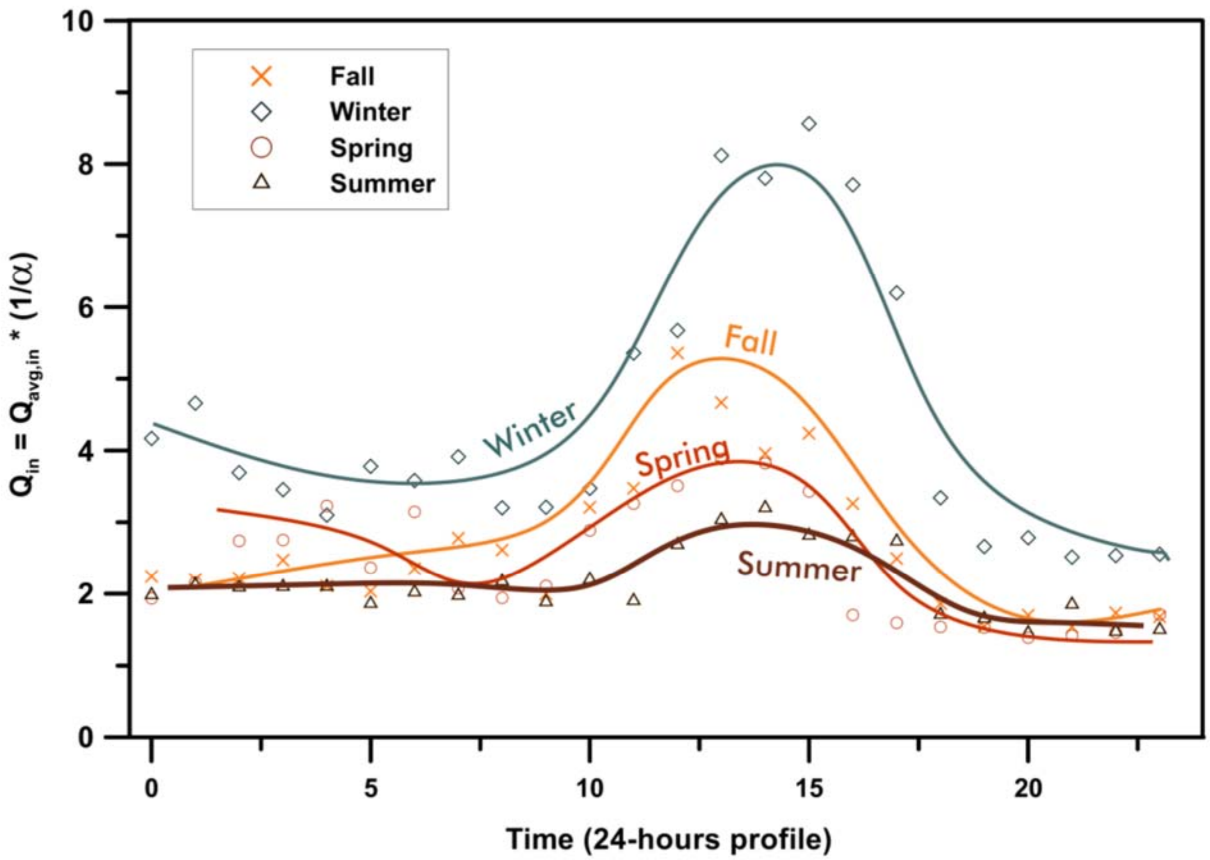


FIGURE 27. DAILY INFLUENT FLOW RATE FOR THE DIFFERENT SEASONS UNDER STUDY. THE DIFFERENT ALPHA FACTORS 24-HOUR DAILY PROFILES WERE USED TO CALCULATE THE MOST CONSERVATIVE SCENARIO (E.G., INFLUENT PEAK ~ LOW EFFICIENCY). THEY WERE CALCULATED WITH THE FOLLOWING APPROACH: QIN [0-24 HOURS] = Q AVERAGE IN * (1/ALPHA FACTOR).

PERFORMANCE AND COST PROJECTIONS

As previously mentioned, the 12 months of intensive sampling and monitoring were conducted to obtain the dynamics of the main aeration efficiency indicators as well as plant operating and performance data, averages which were used to calibrate the WTTP model, a commonly used process simulator in the consulting industry. The influent and other required operating parameters were obtained from the plant personnel together with some plant historical records.

Reactors at IEUA RP-4 facility were modeled using a commercial simulator, and steady state and dynamic modeling was conducted for each alternative. The WWTP model was developed with 9 CSTR in series in a Denitrification-Nitrification-Denitrification-Nitrification (D-N-D-N) configuration. The geometry and diffuser characteristics were carefully implemented to mimic RP4 plant conditions.

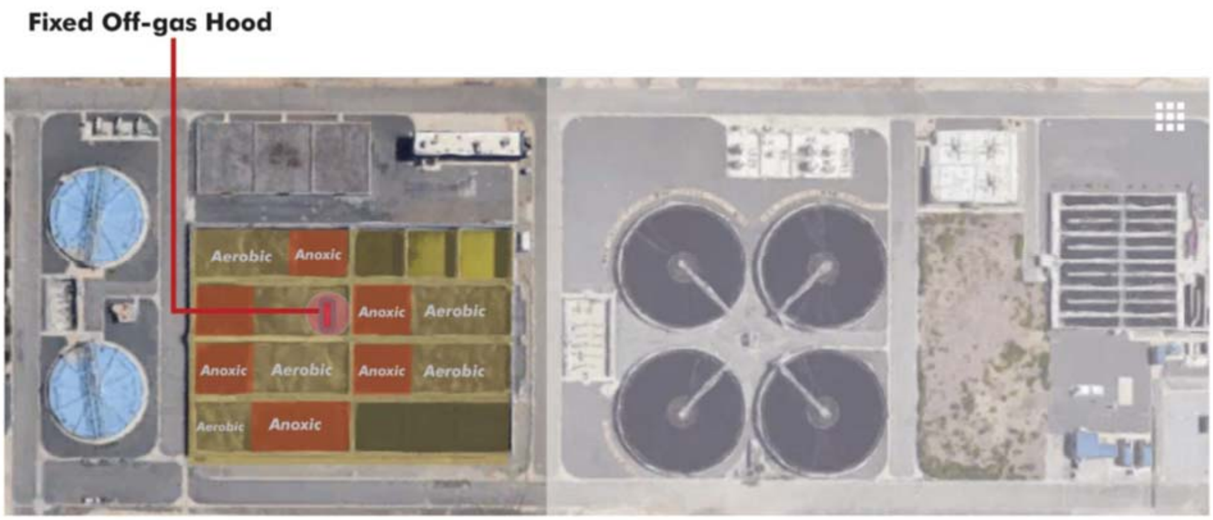


FIGURE 28. SCHEMATIC DRAWING OF IEUA RP-4 AND ITS CORRESPONDING MODEL CONSISTING IN 9 CSTR IN SERIES IN D-N-D-N CONFIGURATION. THE RED DOT AT THE REACTOR SHOWS THE APPROXIMATE LOCATION OF THE OFF-GAS HOOD DURING THE STUDIED PERIOD.

Furthermore, obtaining reliable cost projections for the strategies under study is of utmost importance when considering the energy price. Power demand and energy consumption are priced following a set of structures established by the energy providers. Therefore, the corresponding tariff structure for RP-4 was implemented accordingly in the modelling software.

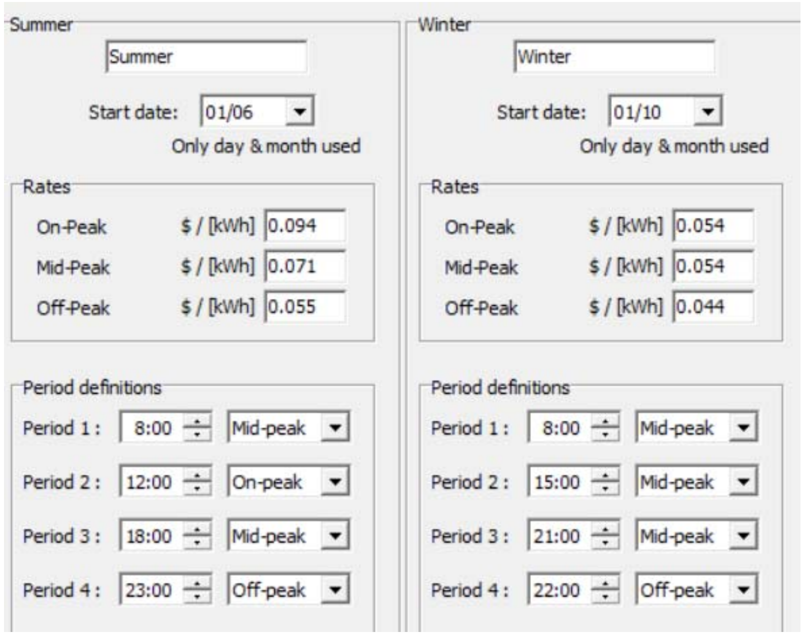


FIGURE 29. THE CORRESPONDING TOU TARIFF FOR SOUTHERN CALIFORNIA WAS IMPLEMENTED IN THE MODEL, AS SHOWN IN THIS FIGURE.

Through the consideration of the specific energy pricing structures (e.g., TOU rates) and charges (e.g., energy usage, peak power demand charges), it is possible to optimize and reduce or shift peak power demands. Costs savings or investments in additional infrastructures can be avoided by balancing energy use and peak hours.

The modeling results were used to predict the potential costs savings of a set of aeration-associated strategies. The set of selected strategies targets potential changes in the current aeration practices and are designed to maximize aeration costs savings while maintaining the effluent quality; thus, providing a basis for cost comparisons between strategies and the combination of them.

The studied strategies include:

- **Variation in DO setpoints:** Consisting of capturing the concurrent changes by varying the DO setpoint from the current value at 2mg/L to lower values compatible with acceptable/tolerable effluent quality.
- **Intermittent aeration:** This strategy refers to operating aeration intermittently (with on and off cycles) during peak hours to enhance mixing and increase aeration savings.
- **Ammonia peak shifting *(change in the Ammonia return flow)*:** Explore how avoiding the peaks of the main oxygen consumer can reduce the aeration requirements.
- **Variation of the influent flowrate (*equalization*):** To avoid the detrimental effect of the amplification phenomena occurring during on-peak periods (higher energy costs when aeration efficiency is the lowest).

SCENARIO ANALYSIS PROCEDURE

- **Step 0**: Raw data from the DR Analyzer was processed and a week of representative data (CV% < 30%) for each season (winter, fall, spring) was selected. Daily averaged values for different seasons were produced. Using the raw data recorded by the instrument, a daily average was calculated for winter, fall, and spring seasons, using a week average for each season. The hourly average was calculated per each day in order to build a 24-hour profile.
- **Step 1 – Daily averaged alpha factor for different seasons:** Using the daily 0-24 hours schedule for AFR and OTE%, daily variation for alpha factor has been calculated.
- **Step 2 – Daily influent flow rate for different seasons:** Using the daily 24-hour profile for alpha factor, the influent flow rate has been calculated as follows in order to project the most conservative scenarios (e.g., influent peak ~ low efficiency)

  *Qin [0-24 hours] = Q average in * (1/alpha factor)*

- **Step 3 – Data input at the developed model:** The model was built with 9 CSTR in series an N-DN configuration reproduce RP4 plant conditions. A simulation was run for each season, for each DO setpoint or case study scenario, and for each time period (depending on the strategy)

Each season was characterized by:

- **Alpha factor:** 24-hour profile, calculated from OTE (%) and AFR (SCFM) measured on site
- **Influent:** 24-hour profile, calculated from alpha factor schedule
- **Energy tariff with TOU of the plant**

- **Step 4 – Scenario Simulation:** Four different aeration operational strategies were evaluated.

RESULTS

COST SAVING STRATEGIES ANALYSIS AND RESULTS

Four main strategies impacting operational aeration costs were applied to the simulated model of RP-4. The set of selected strategies targeted potential changes in current aeration practices and are aimed at maximizing aeration costs savings while maintaining the effluent quality.

All the strategies were investigated under the different seasonal conditions previously characterized winter, fall, and spring. The implementation in the simulation platform of the seasonal and daily dynamics together with the corresponding tariff structures, which are also seasonal and daily dependent, enabled the calculation of cost savings per each different season as well as per daily time fraction (depending on the strategy).

STRATEGY #1: OPTIMIZATION OF DO SETPOINT

Short description: This strategy refers to the study of operational costs savings by applying different DO setpoints (1.5, 1.7, 1.9, 2.1, 2.9, 2.5 mg/L) at the modelled WRRF.

Strategy #1 is aimed at confirming the plausibility of reducing the current DO setpoint of 2.5mg/L without producing a lower quality effluent. Different DO setpoints ranging from 2.5 to 1.5mg/L were investigated. The study considered four different daily time fractions to better understand the process dynamics and improve the diagnosis of future actions or strategies. For this scenario, the following time periods were considered: 9:00 AM to 3:00 PM, 3:00 PM to 9:00 PM, 9:00 PM to 3:00 AM, 3:00 AM to 9:00 AM for each season.

Cost savings projections for strategy #1: DO setpoint Optimization

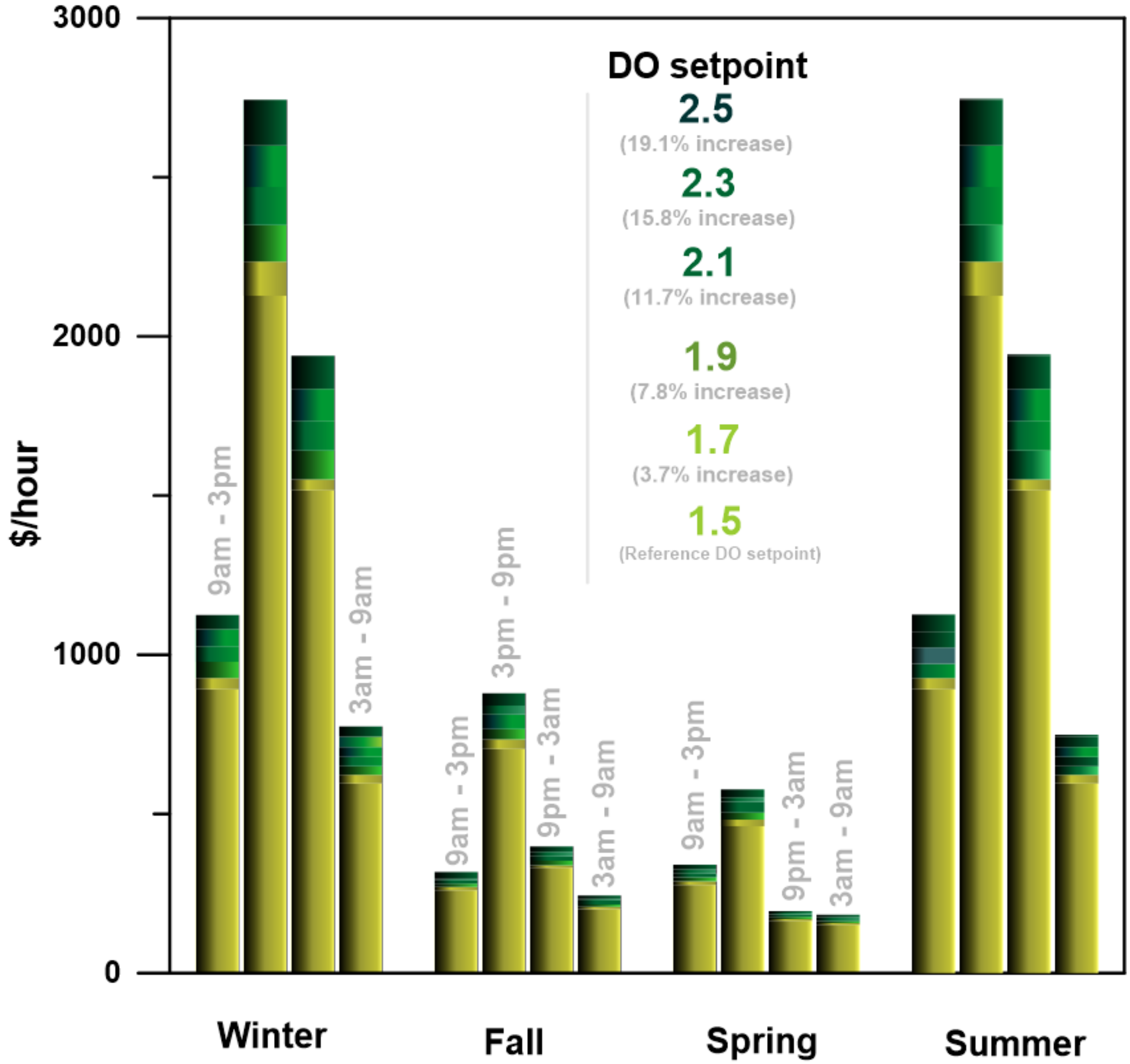


FIGURE 30. COST INCREASE PROJECTIONS FOR THE DIFFERENT SEASONS AND TIME FRAMES UNDER STUDY. LOWER BAR (LIGHT GREEN) CORRESPONDS TO OPERATIONAL COSTS OF USING A SETPOINT OF 1.5MG/L. AS THE SETPOINT INCREASES THE COSTS EXPRESSED IN $/HOUR INCREASES ALSO (DARKER GREENS).

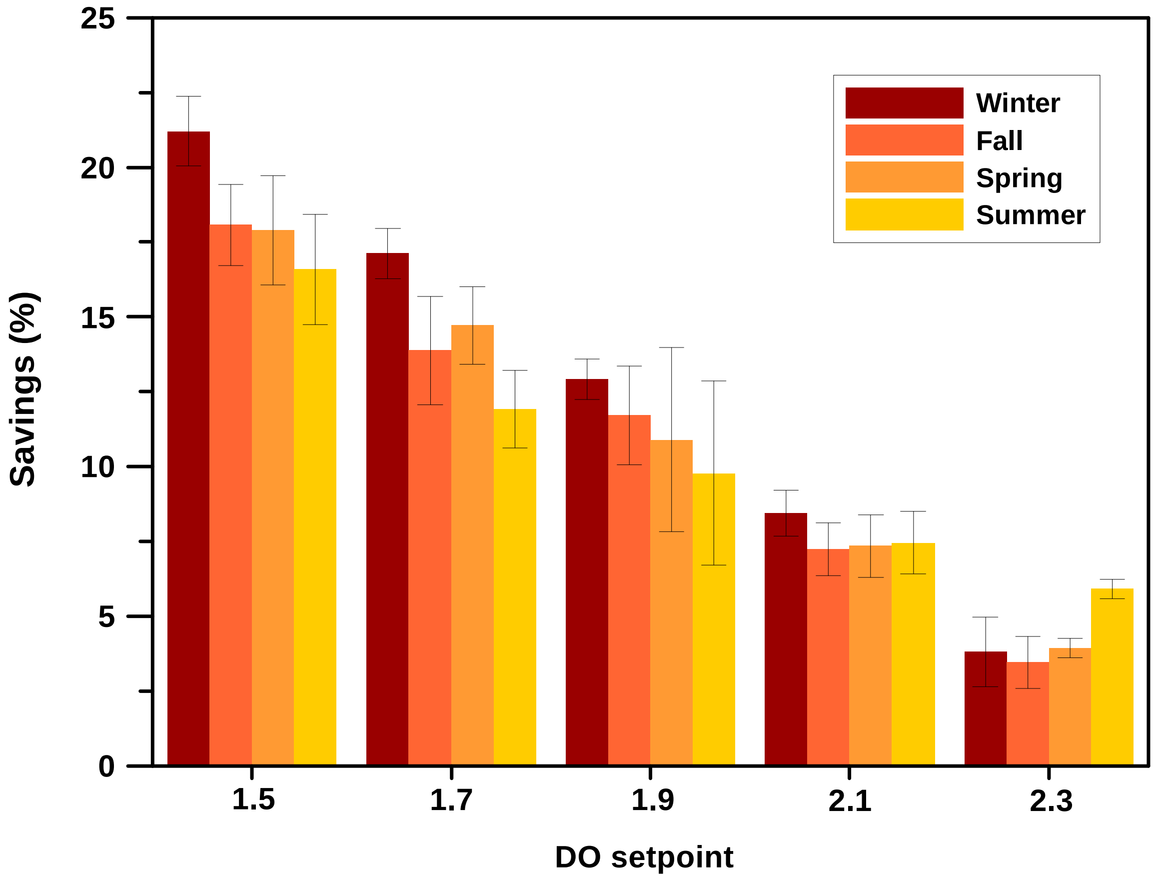


FIGURE 31. COST SAVING PROJECTIONS FOR THE DIFFERENT SEASONS AND TIME FRAMES UNDER STUDY BASED ON DO SETPOINTS RANGING FROM 1.5MG/L T0 2.3MG/L

The results show that decreasing the DO to 2.3mg/L, with a delta DO of only 0.2mg/L, savings close to 5% could potentially be obtained. Similarly, reducing the DO 0.6mg/L to just 1.9mg/L will result in cost savings of approximately 12%, depending on the season. This study also investigates the minimum feasible DO to run the aeration reactors without producing an effluent of unacceptable quality. Decreasing the DO to 1.5mg/L not only maintains the effluent quality parameters within expected limits, but also results in cost savings exceeding the 20% for those months with lower efficiency (e.g., winter) and higher than 17% for warmer months (e.g., fall and spring).

TABLE 2. SUMMARY RESULTS FOR STRATEGY #1. REDUCING THE DO SETPOINT FROM THE CURRENT 2.5 MG/L TO A 1.5 MG/L RESULTED IN SIMILAR EFFLUENT QUALITY AND THE FOLLOWING SAVINGS. SAVINGS WERE DIVIDED BY SEASON AND FOUR DIFFERENT TIME FRAMES.

DELTA DO	DO SETPOINT O2 [MG/L]	ESTIMATED SAVINGS PER TIME FRAME (%)				SEASON AVERAGE
Winter		**9:00 AM – 3:00 PM**	**3:00 PM – 9:00 PM**	**9:00 PM – 3:00 AM**	**3:00 AM – 9:00 PM**	**24hour Average**
0.0	2.5	0.0	0.0	0.0	0.0	0.0
0.2	2.3	3.8	4.8	2.2	4.4	3.8
0.4	2.1	8.3	9.4	7.6	8.4	8.4
0.6	1.9	12.9	13.9	12.6	12.3	12.9
0.8	1.7	16.9	18.2	17.3	16.1	17.1
1.0	1.5	20.8	22.4	21.8	19.8	21.2
Fall						
0.0	2.5	0.0	0.0	0.0	0.0	0.0
0.2	2.3	3.8	4.1	2.2	3.7	3.5
0.4	2.1	7.5	8.2	6.1	7.2	7.2
0.6	1.9	11.1	13.4	9.7	12.7	11.7
0.8	1.7	12.0	16.2	13.2	14.1	13.9
1.0	1.5	18.0	19.9	16.7	17.7	18.1
Spring						
0.0	2.5	0.0	0.0	0.0	0.0	0.0
0.2	2.3	4.0	4.3	3.5	3.9	3.9
0.4	2.1	7.9	8.4	7.1	6.9	7.6
0.6	1.9	11.6	14.4	10.7	6.0	10.7
0.8	1.7	15.2	16.3	13.5	13.8	14.7
1.0	1.5	18.7	20.0	15.8	17.1	17.9
Summer						
0.0	2.5	0.0	0.0	0.0	0.0	0.0
0.2	2.3	3.2	3.1	14.7	10.7	7.9
0.4	2.1	3.3	2.8	14.1	9.7	7.5
0.6	1.9	5.6	5.6	16.3	11.6	9.8
0.8	1.7	8.2	8.3	18.8	12.4	11.9
1.0	1.5	15.4	11.9	22.1	17.0	16.6

Table 3 shows a nine- month average summary results for Strategy 1. Reducing the DO setpoint from the current 2.5 mg/L to a 1.5 mg/L resulted in similar effluent quality and the savings (See Table 3.). Saving were divided by season and four different time frames.

TABLE 3. NINE-MONTH AVERAGE SUMMARY RESULTS FOR THE STRATEGY 1

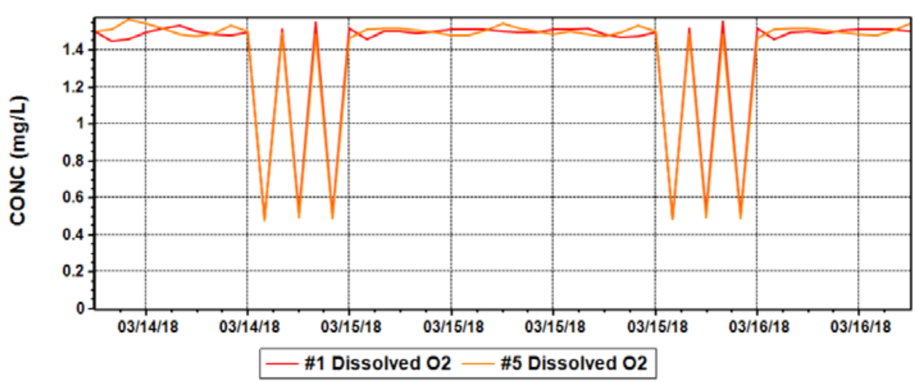
DELTA DO	DO SETPOINT O2 [MG/L]	ESTIMATED SAVINGS PER TIME FRAME (%)				9-MONTH AVERAGE
9-Month Average		9:00 AM – 3:00 PM	3:00 PM – 9:00 PM	9:00 PM – 3:00 AM	3:00 AM – 9:00 PM	24hour Average
0.0	2.5	0.0	0.0	0.0	0.0	0.0
0.2	2.3	3.9	4.4	2.6	4.0	4.8
0.4	2.1	7.9	8.7	6.9	7.5	7.6
0.6	1.9	11.8	13.9	11.0	10.3	11.3
0.8	1.7	14.7	16.9	14.7	14.7	14.4
1.0	1.5	19.1	20.8	18.1	18.2	18.4

STRATEGY #2: INTERMITTENT AERATION.

Short description: This strategy refers to operating aeration intermittently (with on and off cycles) during peak hours. This strategy was applied using different DO setpoints (1.5, 1.7, 1.9, 2.1, 2.9, 2.5 mg/L).

The intermittent aeration ASP is now widely attractive for reducing the power requirements of aeration facilities (Doan and Lohi, 2009; Li et al., 2014; Van den Eynde et al., 1984). The contacting time between air and water is an important parameter for obtaining the required level of pollutant removal. Long contacting time between air and water results in a higher amount of oxygen transferred from air to water in the column. Nevertheless, the biological oxidation is a relatively slow reaction process. The biological oxidation of the wastewater could initially be oxygen-diffusion controlled under a high concentration of biodegradable organics and subsequently become reaction controlled in later stages of the treatment. Thus, it may be unnecessary to aerate the wastewater continuously and intermittent aeration may result in energy savings.

It should be noted that different configurations of intermittent aeration are possible with each possibility yielding different results. In this study, the intermittent operation was only applied during peak periods, which corresponds to conditions of maximum air requirements and lower mass transfer efficiency. Two different scenarios were considered for the intermittent aeration strategy (Figure 32). One scenario was applied during the peak period from 9:00 AM to 3:00 PM and 3:00 PM to 9:00 PM Figure 33 shows the averaged values of applying both strategies.



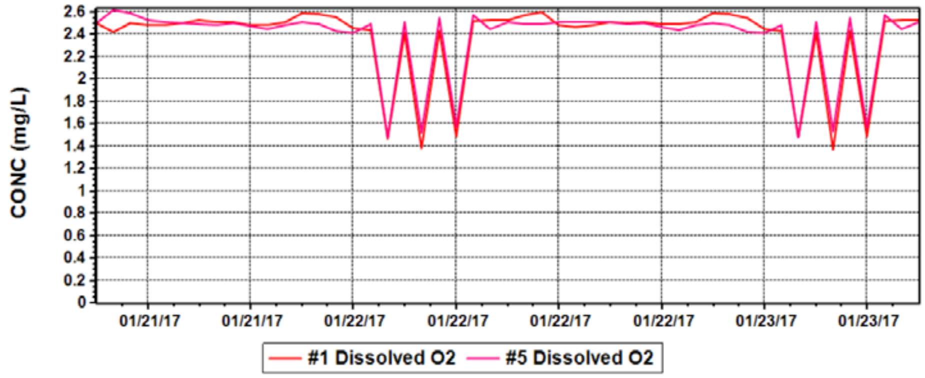


FIGURE 32. SCREEN CAPTURE SHOWING THE IMPLEMENTED INTERMITTENT AERATION REGIME DURING THE TWO PEAK PERIODS: 9:00 AM TO 3:00 PM

Cost savings projections for strategy #2: Intermittent Aeration

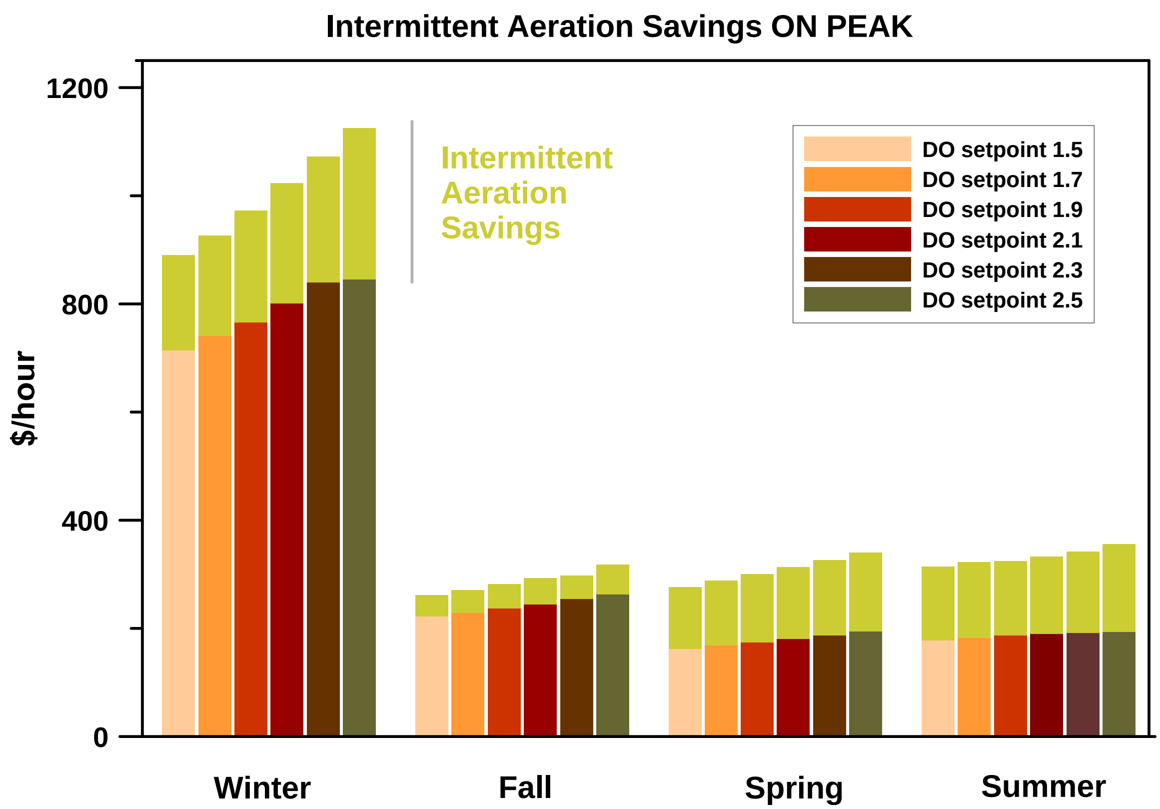


FIGURE 33. COST SAVINGS PROJECTIONS FOR THE DIFFERENT SEASONS UNDER STUDY. TOP BARS (LIGHT GREEN) CORRESPONDS TO AVOIDED COSTS BY IMPLEMENTING STRATEGY #2 (INTERMITTENT AERATION)

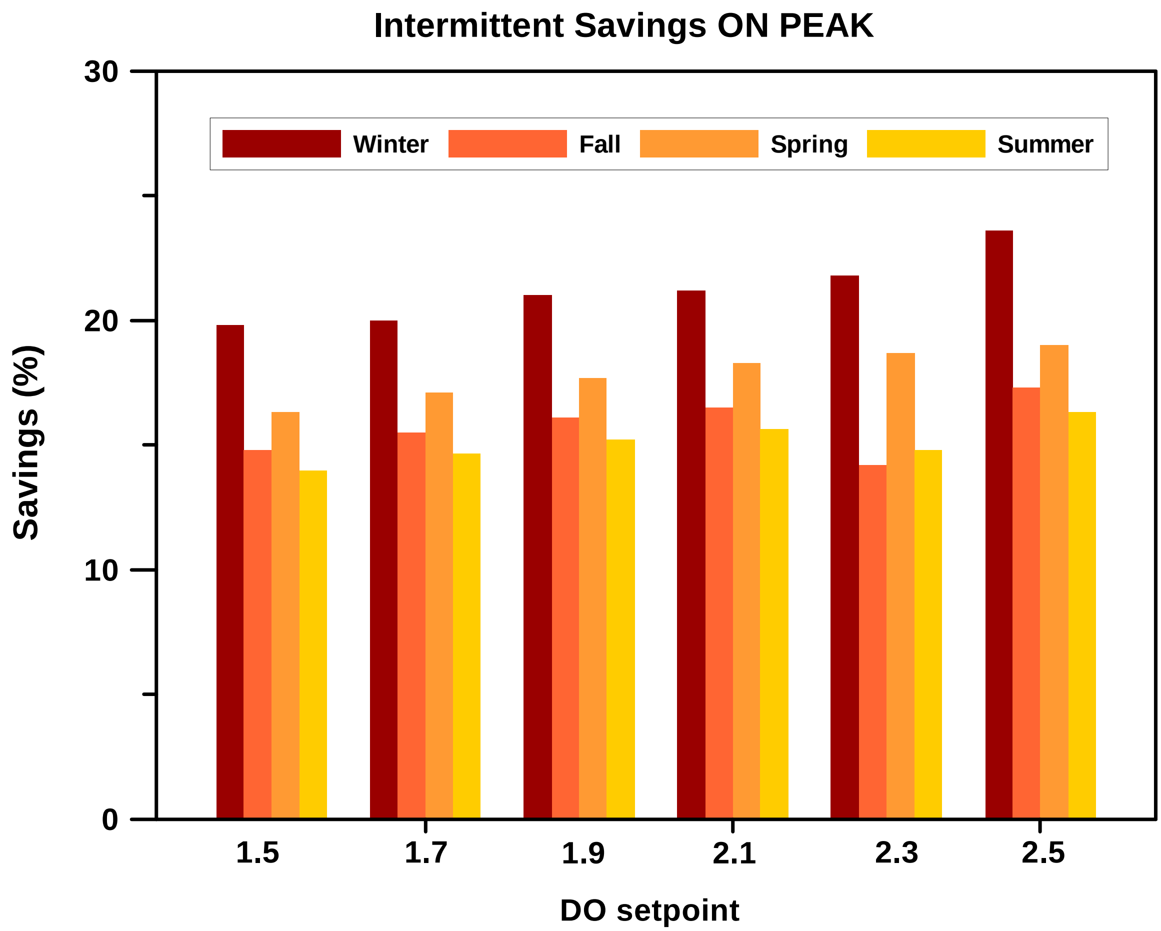


FIGURE 34. COST SAVING PROJECTIONS USING INTERMITTENT AERATION STRATEGY AT DIFFERENT SEASONS. THIS FIGURE CORRESPONDS TO POTENTIAL SAVINGS BY IMPLEMENTING INTERMITTENT AERATION BETWEEN 9:00 AM TO 3:00 PM. RESULTS ARE ORGANIZED BASED ON DISSOLVED OXYGEN SETPOINTS RANGING FROM 1.5MG/L TO 2.3MG/L.

The results demonstrate that implementing an intermittent aeration strategy during peak hours can result in significant cost savings ranging from 15% to 20% depending on the seasonality. The data shows no relevant differences between the two differentiated peak periods under study (e.g., 9:00 AM to 3:00 PM and 3:00 PM to 9:00 PM). Applying intermittent aeration from 9:00 AM to 3:00 PM has an average cost savings of 18.4±2%, and an almost identical cost can be observed if the strategy was applied from 3:00 PM to 9:00 PM (18.1±2%).

Interestingly, the DO setpoint seems to have little effect (<4%) on the overall savings, suggesting that aeration is already optimized during those periods where the intermittent aeration strategy is applied.

TABLE 4. SUMMARY RESULTS FOR THE STRATEGY 2 AND THE COMBINATION OF STRATEGY 2 AND 1. IMPLEMENTING INTERMITTENT AERATION DURING TWO ON PEAK HOURS RESULTS IN COST SAVINGS. THE OPERATIONAL COST SAVINGS WERE DIVIDED BY SEASON AND FOUR DIFFERENT TIME FRAMES.

DELTA DO	DO SETPOINT O_2 [MG/L]	STRATEGY #2 SAVINGS (%)		SEASON AVERAGE
Winter		**9:00 AM -3:00 PM**	**3:00 PM -9:00 PM**	**12-Hour peak Average**
0.0	2.5	19.7	19.8	19.8
0.2	2.3	20.1	20.0	20.0
0.4	2.1	21.2	20.7	21.0
0.6	1.9	21.8	20.6	21.2
0.8	1.7	21.7	22.0	21.8
1.0	1.5	24.8	22.3	23.6
Spring				
0.0	2.5	16.3	16.2	16.3
0.2	2.3	17.1	17.1	17.1
0.4	2.1	17.8	17.6	17.7
0.6	1.9	18.3	18.2	18.3
0.8	1.7	18.7	18.7	18.7
1.0	1.5	19.0	18.9	19.0
Spring				
0.0	2.5	16.3	16.2	16.3
0.2	2.3	17.1	17.1	17.1
0.4	2.1	17.8	17.6	17.7
0.6	1.9	18.3	18.2	18.3
0.8	1.7	18.7	18.7	18.7
1.0	1.5	19.0	18.9	19.0
Summer				
0.0	2.5	11.5	11.8	11.6
0.2	2.3	3.4	5.9	4.6
0.4	2.1	5.9	6.7	6.3
0.6	1.9	8.6	11.4	10
0.8	1.7	11.6	10.6	11.1
1.0	1.5	9.9	8.7	9.3

Table 5 shows a nine-month average summary of results for Strategy 1. Reducing the DO setpoint from the current 2.5 mg/L to a 1.5 mg/L resulted in similar effluent quality and the following savings. Saving were divided by season and four different time frames.

TABLE 5. NINE-MONTH SUMMARY OF RESULTS FOR STRATEGY 1

DELTA DO	DISSOLVED O_2 [MG/L]	STRATEGY #2 SAVINGS (%)		12-MONTH AVERAGE
		9:00 AM -3:00 PM	3:00 PM -9:00 PM	12-hour peak Average
0.0	2.5	17.4	17.2	17.3
0.2	2.3	17.3	17.2	17.3
0.4	2.1	18.2	17.9	18.0
0.6	1.9	18.7	18.2	18.5
0.8	1.7	18.1	18.1	18.1
1.0	1.5	20.3	19.4	19.9

STRATEGY #3: AMMONIA PEAK CONTROL IN THE INFLUENT

Short description: This strategy refers to controlling ammonia returns into the influent with the objective to smooth or equalize the addition of nitrogen along the day, avoiding ammonia peaks. This strategy was applied at different DO setpoints (1.5, 1.7, 1.9, 2.1, 2.9, 2.5 mg/L).

Ammonia-based aeration control of the activated sludge process can lead to significant aeration energy savings and potential performance improvements for nitrogen removal plants. Nitrogen or ammonia nitrogen requires four times more oxygen than organics to be successfully removed by autotrophic bacteria from the wastewater through aeration. Therefore, how nitrogen (and especially the ammonia peak) is managed during wastewater treatment is of the utmost importance if the objective is to reduce aeration requirements. Several studies report that ammonia control leads to energy savings in the range of 15 to 25% and to significant increases in nitrogen removal (Rieger et al., 2014).

Ammonia peaks from daily circadian cycles or high nitrogen concentrations arriving from sludge-processing technologies (e.g., centrifuges, anaerobic digesters, etc.) will negatively impact the circadian amplification of air requirements as more air/oxygen will be required when the mass transfer efficiency is the lowest (and the energy price is the highest). Therefore, by avoiding the increase in nitrogen concentration during peak times, the aeration efficiency will not be hampered by this extra overload.

In this study, shifting the ammonia a few hours from the traditional peak period was studied in two different case studies. Shift delays were investigated by applying a theoretical delay of three hours to the peak of ammonia for Case Study #1 and six hours for Case Study #2. It should be noted that different types of managing ammonia equalization are possible, with different distribution or peak delays yielding different results (Rieger et al., 2014).

Cost savings projections for Strategy #3: Ammonia peak shifting

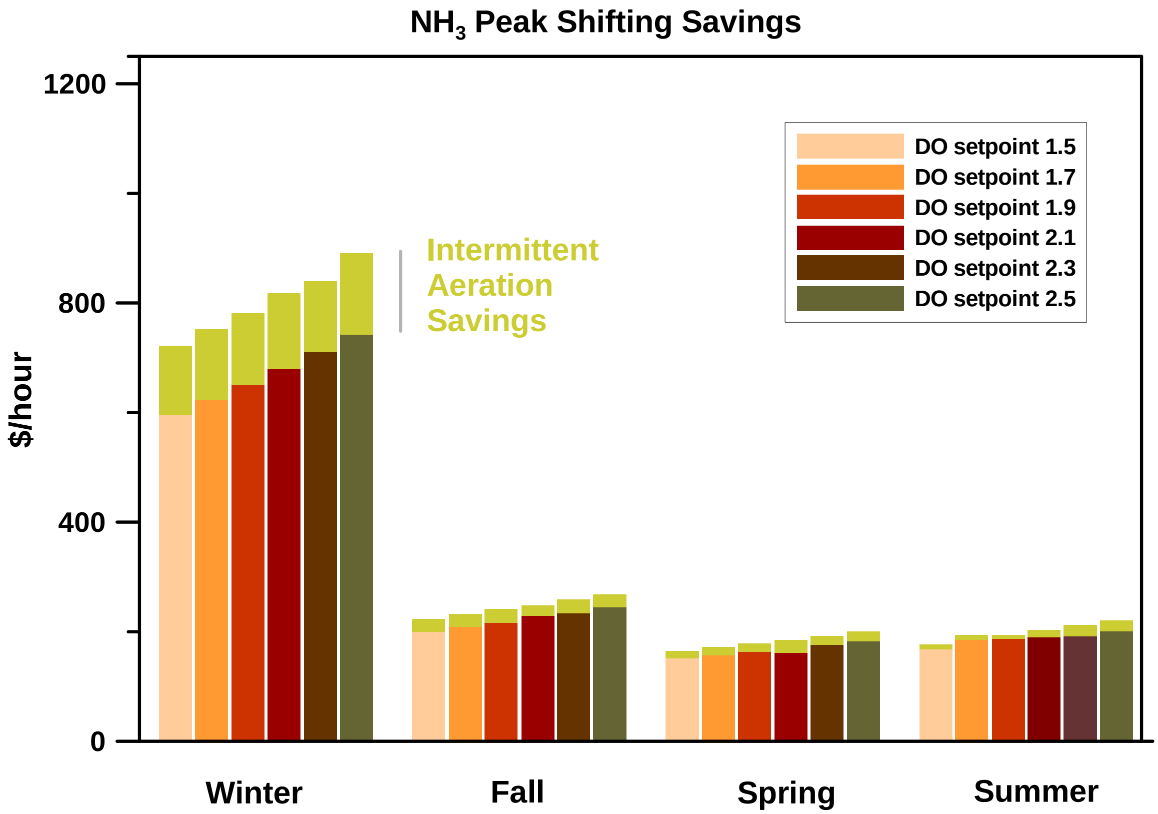


FIGURE 35. COST SAVINGS PROJECTIONS FOR THE AMMONIA EQUALIZATION STRATEGY AT THE DIFFERENT SEASONS UNDER STUDY. TOP BARS (LIGHT GREEN) CORRESPONDS TO AVOIDED COSTS BY IMPLEMENTING STRATEGY #3 (AMMONIA EQUALIZATION).

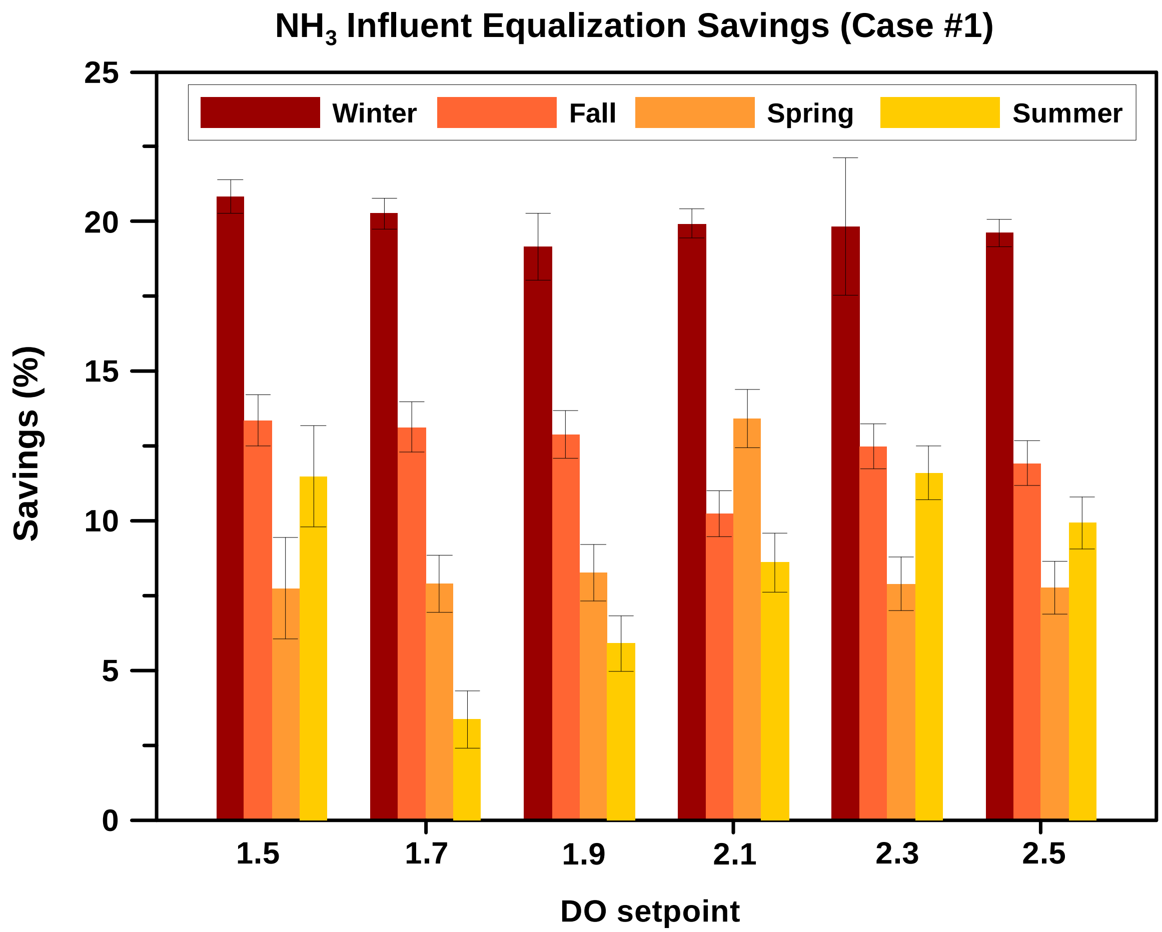


FIGURE 36. COST SAVING PROJECTIONS USING AMMONIA EQUALIZATION STRATEGY AT DIFFERENT SEASONS. RESULTS ARE ORGANIZED BASED ON DISSOLVED OXYGEN SETPOINTS RANGING FROM 1.5MG/L T0 2.3MG/L.

The results show that implementing ammonia equalization can result in significant cost savings ranging from 20±1% during winter months, 12.3±0.7% during fall months, and the least savings at 8.8±1% during spring season. Twelve-month averaged costs savings are estimated at 12±1%. It should be noted that during winter months when the aeration efficiency is the lowest, the implementation of this strategy will significantly improve the performance compared to other seasons.

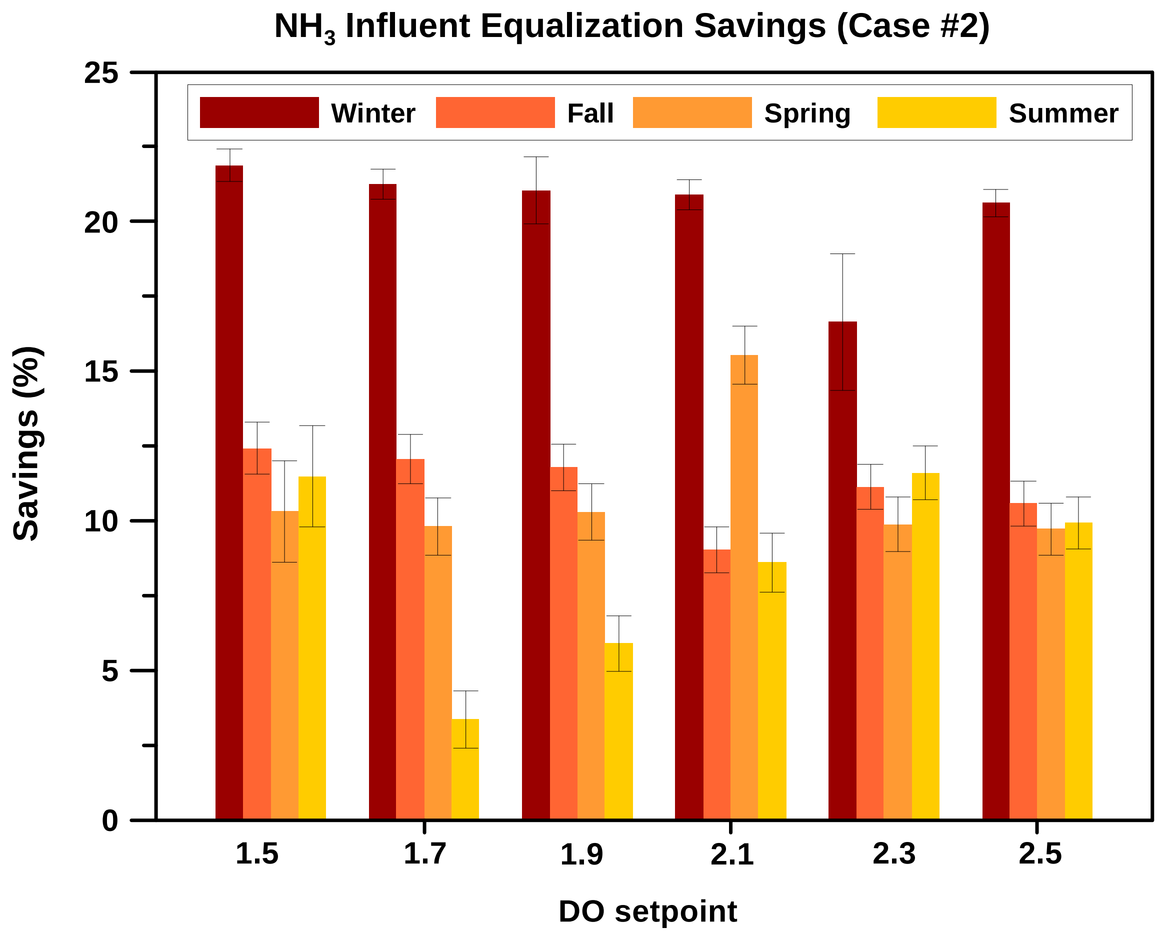


FIGURE 37. COST SAVING PROJECTIONS USING AMMONIA EQUALIZATION STRATEGY AT DIFFERENT SEASONS. RESULTS ARE ORGANIZED BASED ON DISSOLVED OXYGEN SETPOINTS RANGING FROM 1.5MG/L T0 2.3MG/L.

The data shows no relevant differences between the two different case studies, yielding almost identical results (<1.5%). Interestingly, the DO setpoint did not have a significant impact on the overall savings (6% winter season to 11% spring season).

TABLE 6. SUMMARY RESULTS FOR THE CASE STUDY 2AND THE COMBINATION OF CASE STUDY 2 AND 1. IMPLEMENTING INTERMITTENT AERATION DURING TWO ON PEAK HOURS RESULTS IN COST SAVINGS. THE OPERATIONAL COST SAVINGS WERE DIVIDED BY SEASON AND FOUR DIFFERENT TIME FRAMES.

DELTA DO	DISSOLVED O_2 [MG/L] (SETPOINT)	STRATEGY #3 SAVINGS (%)		SEASON AVERAGE
Winter		**Case Study #1**	**Case Study #2**	**Average**
0.0	2.5	20.8	21.9	21.4
0.2	2.3	20.3	21.2	20.8
0.4	2.1	19.2	21.0	20.1
0.6	1.9	19.9	20.9	20.4
0.8	1.7	19.8	16.6	18.2
1.0	1.5	19.6	20.6	20.1
Fall				
0.0	2.5	11.1	12.4	11.8
0.2	2.3	10.5	12.1	11.3
0.4	2.1	10.6	11.8	11.2
0.6	1.9	7.8	9.0	8.4
0.8	1.7	9.9	11.1	10.5
1.0	1.5	9.3	10.6	9.9
Spring				
0.0	2.5	7.6	10.3	9.0
0.2	2.3	8.3	9.8	9.1
0.4	2.1	8.8	10.3	9.6
0.6	1.9	14.0	15.5	14.8
0.8	1.7	8.5	9.9	9.2
1.0	1.5	8.3	9.7	9.0
Summer				
2.5	6.5	11.5	10.2	10.9
2.3	7.2	3.4	9.8	6.6
2.1	7.6	5.9	9.9	7.9
1.9	12.7	8.6	11.1	9.8
1.7	7.3	11.6	9.5	10.5
1.5	7.1	9.9	9.1	9.5

Table 7 shows a nine-month average summary for Strategy 1. Reducing the DO setpoint from the current 2.5 mg/L to a 1.5 mg/L resulted in similar effluent quality and the following savings. Saving were divided by season and four different time frames.

TABLE 7. NINE-MONTH AVERAGE SUMMARY RESULTS FOR THE STRATEGY 1.

DELTA DO	DISSOLVED O2 [MG/L]	STRATEGY #3	SAVINGS (%)	AVERAGE
Four Seasons		Case Study 1	Case Study 2	
0.0	2.5	12.8	13.7	13.2
0.2	2.3	10.6	13.2	11.9
0.4	2.1	11.1	13.3	12.2
0.6	1.9	12.6	14.1	13.4
0.8	1.7	12.5	11.8	12.1
1.0	1.5	11.8	12.5	12.2

STRATEGY #4: INFLUENT FLOW EQUALIZATION

Short description: This strategy refers to peak shaving the influent by using equalization tanks to avoid the circadian amplification on air requirements due to influent load peaks. For this scenario, four case studies were considered. For this strategy only the range limit in DO setpoints were evaluated (e.g., 2.5 and 1.5 mg/L).

One of the more traditional methods for peak shaving to avoid the effects of the circadian amplification involves storing the wastewater in equalization basins or keeping it contained in movement through pipelines. Using these types of approaches makes it possible to control when to treat the wastewater influent with more flexibility, preferably at night when energy is cheaper and aeration efficiency is at highest. The theoretical advantages of equalizing the flow as a strategy to shift power demand has been extensively considered in the literature (Leu et al., 2009; Rosso and Shaw, 2015). The energy consumption reduction will always depend on the investment capacity to build equalization tanks, the specific tariff structures at the site, and WRRFs and influent load characteristics.

Taking advantage of RP5 having an equalization basin to implement this strategy, two case studies were investigated. The first case study considered the availability of a basin capacity of 1.5 MGD, while the second case study considered a 3 MGD capacity. The study considered four different daily time fractions to better understand the process dynamics and improve the diagnosis of future actions or strategies. For this scenario, the following timer periods were considered: 9:00 AM to 3:00 PM, 3:00 PM to 9:00 PM, 9:00 PM to 3:00 AM, 3:00 AM to 9:00 AM for each season.

Cost savings projections for Strategy #4: Flow Equalization

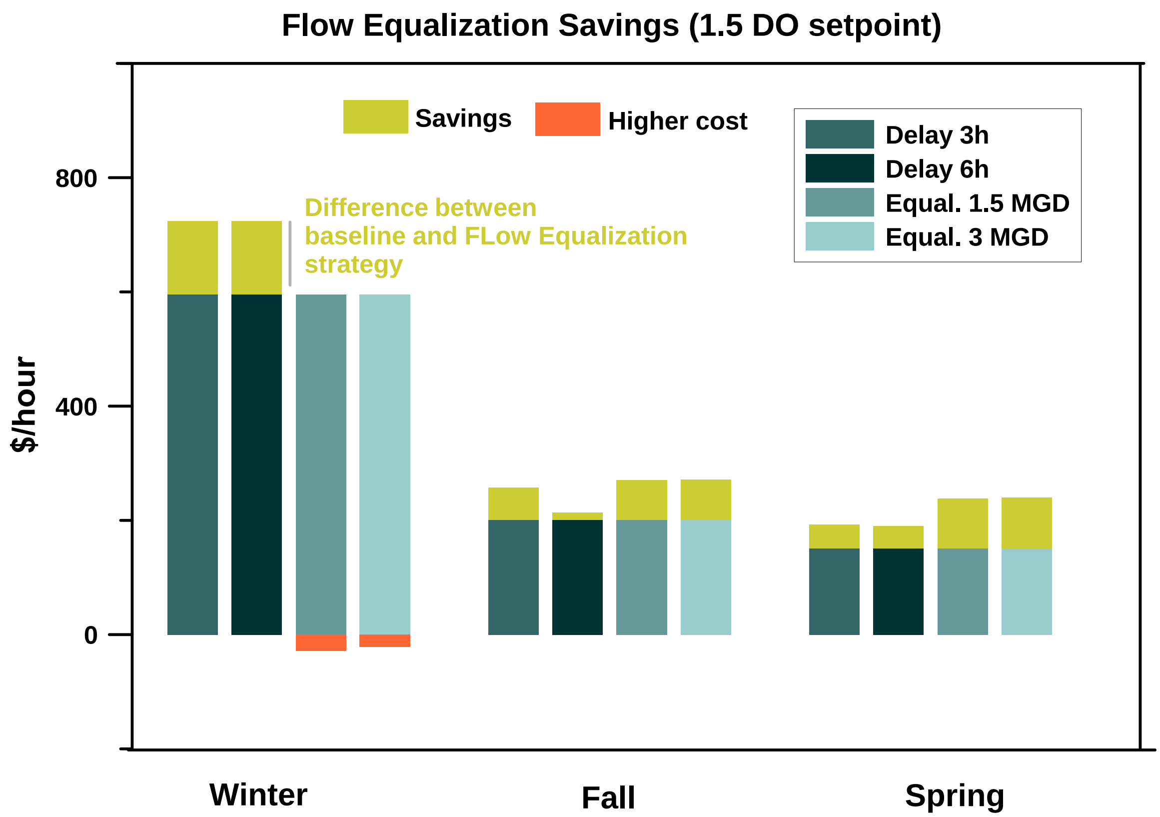


FIGURE 38. COST SAVINGS PROJECTIONS FOR THE FLOW EQUALIZATION STRATEGY AT DIFFERENT TIME FRAME WITHIN THE DIFFERENT SEASONS UNDER STUDY. TOP BARS (LIGHT GREEN) CORRESPONDS TO AVOIDED COSTS BY IMPLEMENTING STRATEGY #4 (FLOW EQUALIZATION) WHEN A DO SETPOINT OF 1.5MG/L IS BEING USED.

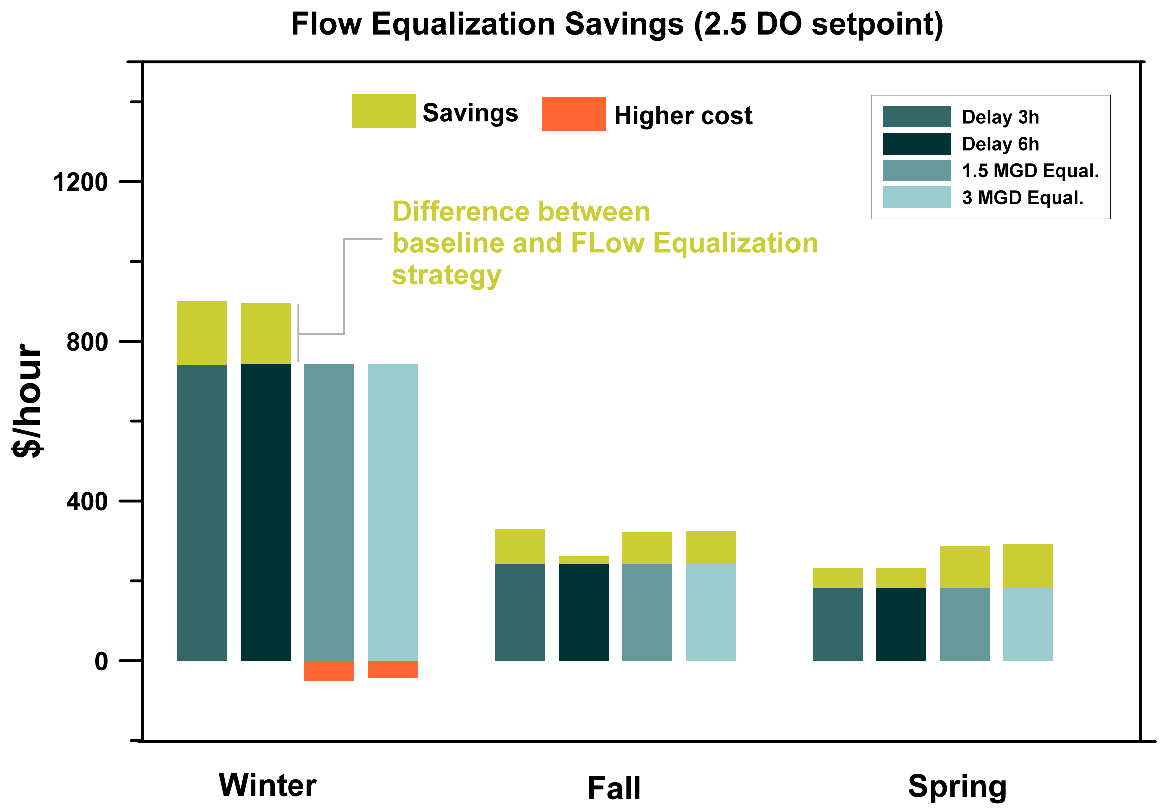


FIGURE 39. COST SAVINGS PROJECTIONS FOR THE FLOW EQUALIZATION STRATEGY AT DIFFERENT TIME FRAME WITHIN THE DIFFERENT SEASONS UNDER STUDY. TOP BARS (LIGHT GREEN) CORRESPONDS TO AVOIDED COSTS BY IMPLEMENTING STRATEGY #4 (FLOW EQUALIZATION) WHEN A DO SETPOINT OF 2.5MG/L IS BEING USED.

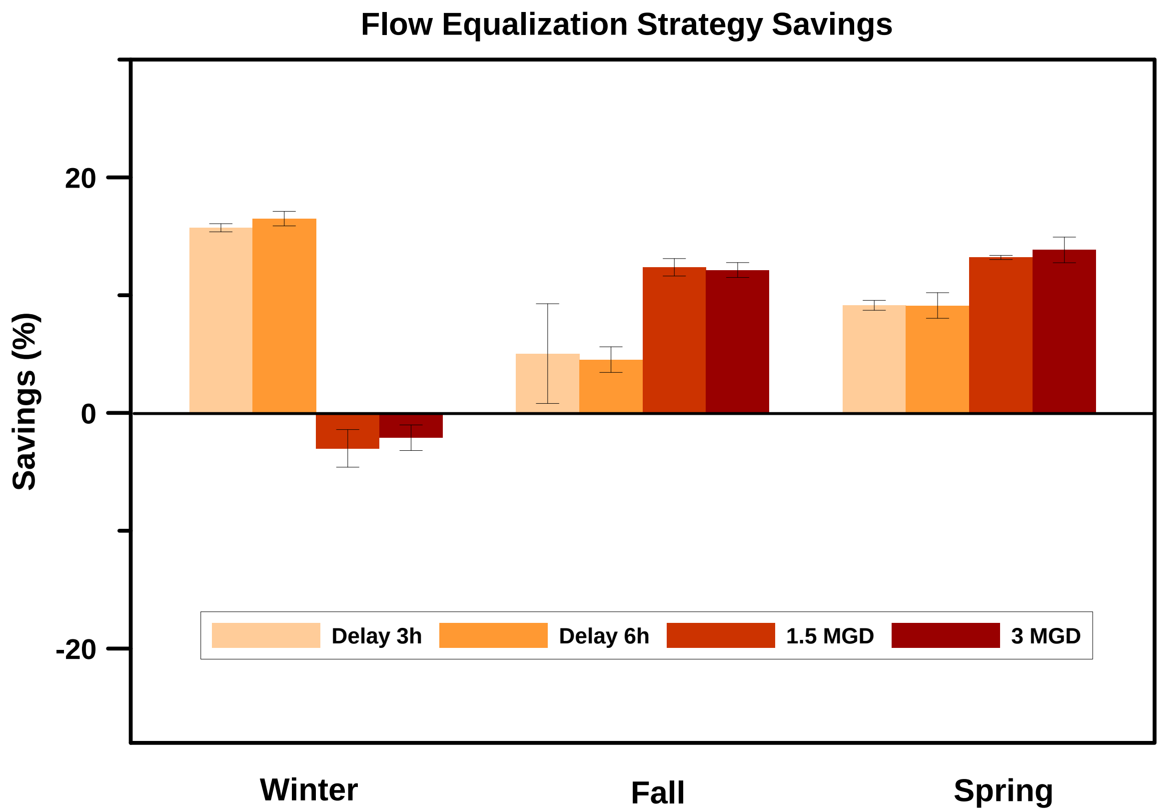


FIGURE 40. COST SAVING PROJECTIONS USING A FLOW EQUALIZATION STRATEGY AT DIFFERENT SEASONS

The results concerning the implementation of the flow equalization by implementing a load delay strategy can result in cost savings ranging from 5-6% during fall months to 16±0.8% during the winter months.

Nevertheless, the results for this section, especially for case studies 3 and 4 using equalization basins, are still under revision. The simulation of the equalization tanks was performed using a constant alpha due to the incapacity to predict the impact of the equalization tanks on the aeration efficiency indicators. The initial simulations were run using a constant alpha factor of 0.5, which resulted in higher costs than the baseline. The observed negative values in winter for case studies 3 and 4 highlighted the importance of understanding the real and dynamic variations of mass transfer in each scenario. Therefore, the flow equalization scenario needs to be reviewed considering a dynamic alpha that can better represent the actual value of these kinds of systems or strategies. Similarly, no summer data was used as the results were still showing inconsistencies. Therefore, nine-month averaged costs savings are estimated at 8% and 10%, with the DO setpoints of 2.5 and 1.5mgL respectively.

It should be noted that the potential savings increased in correlation with the equalization tank capacity. Case studies 3 and 4 during winter months yielded negative values, which was not surprising given the characteristics of the case study. Therefore, such practices should be carefully considered in order to improve the overall average for winter months. The DO setpoint had an almost negligible impact on the overall savings (<1%).

Table 8 provides a summary of results for Strategy 4: Flow Equalization. The scenario of using a DO setpoint of 2.5 mg/L and 1.5 mg/L were used to model this strategy. Savings were divided by season and four different time frames.

TABLE 8. SUMMARY RESULTS FOR STRATEGY 4: FLOW EQUALIZATION

DELTA DO	DO SETPOINT O2 [MG/L]	CASE STUDIES SAVINGS (%)				SEASON AVERAGE
Winter		**Case Study #1**	**Case Study #2**	**Case Study #3**	**Case Study #4**	**Average**
0.0	2.5	13.6	13.7	-5.0	-2.9	4.8
1.0	1.5	13.1	12.8	-7.3	-4.6	3.5
Fall						
0.0	2.5	4.1	6.5	11.4	12.3	8.6
1.0	1.5	5.0	4.5	12.4	12.1	8.5
Spring						
0.0	2.5	8.9	10.3	16.7	12.8	12.2
1.0	1.5	9.1	9.1	13.2	13.8	11.3

TABLE 9. THE 9-MONTH AVERAGE SUMMARY RESULTS FOR THE STRATEGY 1. REDUCING THE DO SETPOINT FROM THE CURRENT 2.5 MG/L TO A 1.5 MG/L RESULTED IN SIMILAR EFFLUENT QUALITY AND THE FOLLOWING SAVINGS. SAVING WERE DIVIDED BY SEASON AND FOUR DIFFERENT TIME FRAMES.

DELTA DO	DO SETPOINT O2 [MG/L]	CASE STUDIES (%, COST SAVINGS)				9-MONTH AVERAGE
9-Month Average		**Case Study #1**	**Case Study #2**	**Case Study #3**	**Case Study #4**	**24-Hour**
0.0	2.5	8.9	10.2	7.7	7.4	8.5
1.0	1.5	9.1	8.8	6.1	7.1	7.8

SUMMARY OF AERATION STRATEGIES

The aeration efficiency in WRRF RP-4 was monitored semi-continuously over a period of twelve months. Seasonal, monthly, and daily dynamics concerning aeration efficiency were successfully captured. (See the Aeration Efficiency Indicators: Seasonal Profile section of this report). The long-term characterization of the aeration tanks enabled the compilation of enough data to maximize the reliability of cost saving projections using commercial software. The facility was simulated using a modelling software. The exact same treatment train characteristics, intrinsic dynamics, and energy tariff structures (e.g., TOU rates; energy usage and peak power demand charges) were introduced accordingly to minimize the process uncertainty during the process simulation. Once the WRRF was successfully modelled, operational strategies involving potential savings in aeration were investigated.

TABLE 10. SUMMARY RESULTS FOR THE STRATEGY 1. REDUCING THE DO SETPOINT FROM THE CURRENT 2.5 MG/L TO A 1.5 MG/L RESULTED IN SIMILAR EFFLUENT QUALITY AND THE FOLLOWING SAVINGS. SAVINGS WERE DIVIDED BY SEASON AND FOUR DIFFERENT TIME FRAMES.

DELTA DO	DO SETPOINT [O_2 MG/L]	AERATION SAVINGS (%)
Strategy #1: DO Setpoint		
0.0	2.5	0.0
0.2	2.3	3.7
0.4	2.1	7.8
0.6	1.9	11.8
0.8	1.7	15.2
1.0	1.5	19.1
Strategy #2: Intermittent Aeration		
0.0	2.5	17.3
0.2	2.3	17.3
0.4	2.1	18.0
0.6	1.9	18.5
0.8	1.7	18.1
1.0	1.5	19.9
Strategy #3: Ammonia Equalization		
0.0	2.5	12.2
0.2	2.3	12.0
0.4	2.1	11.9
0.6	1.9	12.8
0.8	1.7	11.0
1.0	1.5	11.3
Strategy #4: Flow Equalization		
0.0	2.5	8.5*
1.0	1.5	7.8*

**Please read the limitations for this set of simulations.*

Four main operational strategies impacting the total amount of oxygen required were applied to the constructed model of RP-4. The set of selected strategies targeted potential changes in the current aeration practices and were aimed at maximizing aeration cost-savings while maintaining the effluent quality, thus providing the required basis for cost comparisons between strategies and the combination of them.

The first strategy was designed to confirm the plausibility of reducing the current DO setpoint of 2.5mg/L without producing a lower quality effluent. Different DO setpoints ranging from 2.5 to 1.5mg/L were investigated. The results show that while just decreasing the DO to 2.3mg/L, savings close to 4% could potentially be obtained, and the use of more aggressive lower DO setpoints could maximize cost-savings up to 19%. Table 10 shows how selecting lower DO setpoints leads to higher operational costs-savings being achieved. Three other strategies were also studied, including changing the air distribution regime and the equalization of flow and ammonia. All three strategies were complemented with the previous DO setpoint reduction strategy. Each strategy was run in the developed model using all the above ranges of DO setpoints (e.g., 2.5; 2.3; 2.1, 1.9; 1.7 and 1.5 mg/L). Applying these strategies at different DO setpoints helped to better capture the potential window of cost-savings.

Intermittent aeration is a strategy that refers to operating aeration intermittently (with on and off cycles) during peak hours to enhance mixing and increase aeration savings. The simulations of this strategy resulted in cost-savings improvements close to 18% for almost all the seasonal periods. The simplicity of this strategy plus the potential savings obtained should position this strategy as one of the most promising operational strategies to gradually implement at RP-4.

On the other hand, delaying the ammonia peak also resulted in cost-savings close to 12% independently of the season or DO setpoint applied. Although an interesting strategy from the cost saving point of view, some investment or skilled personnel may be required to deploy such a strategy. Therefore, further studies are required to better define and understand how avoiding the peaks of the main oxygen consumer could further reduce the aeration requirements.

Finally, the implementation of influent flowrate equalization strategies could not be fully explored due to some technical limitations which the co-authoring team expects to overcome in the following weeks. Therefore, the detrimental effect of the amplification phenomena occurring during on-peak periods (higher energy costs when aeration efficiency is the lowest) will be further explored in the upcoming final report.

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