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An In-Use Energy Efficiency Comparison of Aeration Technologies in Wastewater Treatment

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Technical report

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Executive Summary

Wastewater treatment aeration energy consumption is significant and accounts for a notable portion of a developed country's electricity usage and carbon emissions. The in-use energy performance of aeration technologies is not well understood in practice, with limited studies carried out on the aeration efficiency in process conditions. This report presents the findings of a comprehensive study undertaken on the several aeration technologies used in wastewater treatment. Three sample site investigations are described in this report. The study was funded by the SEAI RD&D grant (Grant Number RDD-377). The key findings of the study are outlined as follows:

- The in-use process efficiency of aeration technologies is usually lower than values quoted equipment manufacturers from clean water tests. The disparities are due to the alpha factor, fouling factor and system configuration defects. A correction factor used to describe this collection of factors is defined in this report by C_c .
- The C_c value for surface aeration equipment was found to range between 0.5 to 1.06, mostly attributed to varying alpha factors.
- The C_c value for diffused aeration systems varied between 0.1 and 0.25. This is largely attributed to fouling and system defects resulting in inefficiency (i.e. best efficiency point) as well as the alpha factor. This suggests that diffused systems in-use performance is more complicated to predict due to these two additional degrees of freedom.
- The aeration efficiency of diffused aeration equipment can be better maintained if the practical design closely agrees with the conditions specified during clean water testing. In addition, regular cleaning of diffuser heads should be implemented to minimise the effects of fouling on energy usage.
- The cyclonic aeration system provided the highest in-use aeration efficiency with an average value of 1.99 with up to a 30% (maximum recorded) decline in efficiency (C_c of between 0.7 and 1.17) in process conditions mostly attributed to the alpha factor.

It is clear from these findings that a better understanding of system performance in real process conditions can better inform design, ensuring the highest aeration efficiency in future wastewater treatment plant upgrades. As part of the study, the research team also investigated the scope of implementing energy efficiency instruments available from the energy industry and SEAI to help stimulate uptake of energy efficient measures in the water industry. The client case study evaluated for implementation of the energy credit scheme, ESCO model and energy efficiency grants bode well for wide scale implementation of such water-energy nexus incentives and energy efficiency technologies.

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1. Introduction

1.1. The Global Challenge of Aeration

Wastewater treatment is a highly energy intensive process which consumes up to 3 % of the electricity generated in a typical developed nation¹. This equates to about 418 TWh of electrical energy every year which results in approximately 235 million tonnes of CO₂ emissions annually². The macro level imperatives of climate change, increasing energy costs, rising volumes of wastewater as a result of global population growth and increasingly stringent environmental regulations are collectively compelling the wastewater treatment industry to improve efficiency and/or increase capacity through energy-efficient technologies⁴.

It is well known that the aeration process in biological wastewater treatment comprises between 45 and 75% of a wastewater treatment plant's (WWTP) total energy usage^{2,3}. The need for innovation in this sector is clear and demonstrated by the fact that market value for aeration technologies will be approximately \$8.4 billion by 2020^{3,4}.

In wastewater treatment processes, the overall objectives of aeration technologies are typically to (a) effectively transfer oxygen from the air into the activated sludge, (b) disperse the oxygen throughout the tanks and (c) to do so concurrently at the lowest energy cost. Although aeration is a proven and well-respected process within the industry, the problem of its highly intensive energy use remains largely unaddressed³. Furthermore, capital and maintenance costs of the most efficient technologies tend to offset many benefits.

1.2. Objectives of this Report

This report presents the findings from a comprehensive study carried out by the National University of Ireland, Galway on the In-Use Energy Efficiency Comparison of Aeration Technologies in Wastewater Treatment which was funded by the Sustainable Energy Authority of Ireland (SEAI) Research, Demonstration and Deployment (RD&D) Fund in 2018 (Grant Number RDD-377). The project was carried out over a 16-month period and investigated the in-use process performance of six aeration systems (comprising 5 different technologies) in various WWTPs ranging from municipal to industrial wastewater treatment. The report presents a summary of the findings for each technology and comments in detail on comparisons between each. The report also presents the findings on novel technology, operational and control measures and incentives/financing models available from the energy industry which can motivate widescale deployment of energy efficiency measures (EEMs) across the wastewater treatment industry.

2. Oxygen Transfer and Aeration Efficiency Analysis

2.1. Existing Metrics

The metrics for defining “aeration efficiency” are outlined in this section. The oxygen transfer rate (*OTR*) is the rate at which oxygen is transferred to a body of liquid and is usually expressed in kgO₂/hr. The rate of transfer is dependent on several parameters including the oxygen transfer coefficient (*kLa*) which is in turn dependent on pressure, temperature, turbulence and mixing and other process conditions which will be

discussed in Section 2.3. Measurement methods for this parameter are outlined in Section 2.2. Oxygen transfer is dependent on a source of energy (E) to mix air and water phases, thus inducing the transfer of oxygen. Therefore, to express oxygen transfer in terms of specific energy use, the parameter Aeration Efficiency (AE) is defined as follows:

$$AE = OTR/P_a \quad (\text{kg O}_2/\text{kWh}) \quad \text{Eqn (1)}$$

where P_a is the wire power consumed by the aeration equipment.

It should be noted that the definition of power must always be stated clearly. Herein, power is defined as the total input energy of any mechanical equipment required to achieve the rate of oxygen transfer for the biological process as stipulated by American Society of Civil Engineers Standards (ASCE)⁹ and the German ATV Standards¹⁰.

Another parameter often used to describe efficiency is the oxygen transfer efficiency (OTE). This is expressed as:

$$OTE = M_{O_2\text{Transferred}}/M_{O_2\text{In}} \quad (\%) \quad \text{Eqn (2)}$$

where $M_{O_2\text{Transferred}}$ is the mass of oxygen transferred to the liquid and $M_{O_2\text{in}}$ is the oxygen supplied by aeration equipment.

The higher the OTE , the more effective the aeration system is at transferring oxygen across the bubble interface. However, it must be noted that a high OTE does not necessarily reflect a high AE as there is often a requirement for increased power consumption that may offset increases in OTE .

When OTE and AE are measured under standardized conditions, as described by American Society of Civil Engineers⁹ and the German ATV Standards¹⁰, the term Standard OTE ($SOTE$) and Standard AE (SAE) is adopted. Comparing performance of different equipment for aeration must be carried out under standardized conditions to validate and normalize performance data. Standard conditions are defined for clean water with zero salinity at 20°C and atmospheric pressure. kLa can be corrected to a certain temperature using the temperature correction coefficient $\theta = 1.024$ through the following equation:

$$kLa_{20} = kLa_t \times \theta^{(20-T)} \quad (1/\text{hr}) \quad \text{Eqn (3)}$$

Equations for OTR , $SOTR$ and SAE are therefore defined as follows:

$$OTR = kLa_t \cdot C_{S,t} \cdot V \quad (\text{kg O}_2/\text{hr}) \quad \text{Eqn(4)}$$

$$AE = \frac{kLa_t \cdot C_{S,t} \cdot V}{P_a} \quad (\text{kg O}_2/\text{kWh}) \quad \text{Eqn(5)}$$

$$SOTR = kLa_{20} \cdot C_{S,20} \cdot V \quad (\text{kg O}_2/\text{hr}) \quad \text{Eqn(6)}$$

$$SAE = \frac{kLa_{20} \cdot C_{S,20} \cdot V}{P_a} \quad (\text{kg O}_2/\text{kWh}) \quad \text{Eqn(7)}$$

In process conditions, several other parameters effect the *OTR*, *OTE* and *AE* and these are summarised in Table 1:

Table 1: Parameters effecting the *OTR*, *OTE* and *AE* in-process conditions

Value	Unit	Description
Alpha Factor	α	<p>Accounts for the effects of surface-active agents that depress gas transfer at gas-liquid interfaces. It is defined by:</p> $\alpha = \frac{kLa_{20} \text{ Process Water}}{kLa_{20} \text{ Clean Water}} = \frac{\alpha kLa_{20}}{kLa_{20}}$ <p>The α factor is a dynamic value as the presence of surface-active agents in wastewater vary hourly, daily and seasonally. The effect of the α factor is reduced in high mean cell retention time process conditions due to the ability of activated sludge to sorb surface active agents. High turbulence also limits the effect of the α factor and this is influenced by the type of aeration technology being used.</p>
Fouling Factor	F	<p>The fouling factor accounts for the effect of fouling in applications such as fine bubble diffused aeration (FBDA). As fouling increases, there is an increase in energy demand to overcome the increased dynamic wet pressure of the diffusers. In addition, fouled diffusers can promote large bubble sizes which decrease the <i>OTE</i>. Typical values for F are such that it decreases <i>OTR</i> by 5 to 10% per annum</p>
Beta Factor	β	<p>The β factor is used to correct for the effect of dissolved solids concentration in the wastewater on the solubility of dissolved oxygen. Typical values range between 0.95 and 0.97.</p>
Delta Factor	δ	<p>Describes the remaining residual differences between tests undertaken in clean water and in-process conditions. Primarily, δ is attributed to as-built configurations which may affect the duty point of the aeration system along with effects such as fluid density, solids and rags etc.</p>
Other energy demand	P_{other}	<p>Additional power of the aeration system due to mixing, low-power factor (wattless power) etc.</p>

In summary, the real or true aeration efficiency of a technology is dependent on the in-process transfer characteristics defined here as follows:

$$OTR = \delta \cdot F \cdot \alpha k_L a_{20} \cdot \beta C_{S,20} \cdot V \quad (\%) \quad \text{Eqn(8)}$$

$$AE = \frac{\delta \cdot F \cdot \alpha k_L a_{20} \cdot \beta C_{S,20} \cdot V}{P_a + P_{other}} \quad (\%) \quad \text{Eqn(9)}$$

$$OTR = \delta \cdot F \cdot \alpha k_L a_t \cdot \beta C_{S,t} \cdot V \quad (\%) \quad \text{Eqn(10)}$$

$$AE = \frac{\delta \cdot F \cdot \alpha k_L a_t \cdot \beta C_{S,t} \cdot V}{P_a + P_{other}} \quad (\%) \quad \text{Eqn(11)}$$

Due to the parameters α , F and δ all contributing to derating the oxygen transfer coefficient, it is useful to define a system correction coefficient as follows:

$$C_c = \alpha \cdot \delta \cdot F \quad (\%) \quad \text{Eqn(12)}$$

Currently there are many values quoted for the *SAE* of various equipment in textbooks¹¹ and by equipment suppliers. However, there are few studies that provide an overview of how this aeration efficiency degrades under real conditions. The key objective of this study is therefore to further such insights by studying the C_c factor for a wide variety of technologies.

2.2. Measurement Methodology

The key parameter which requires physical measurement to resolve the *OTR* and *AE* is the oxygen transfer coefficient kLa_{20} . kLa_{20} is measured differently in clean water and in process conditions^{9,10}. For clean water, the test method is based upon removal of dissolved oxygen (DO) from the water volume using reaction of sodium sulphite (Na_2SO_3) catalysed by cobalt chloride ($\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$) followed by re-oxygenation to near the saturation level using the aeration equipment. A number of sensors are deployed in the tank and the data is analysed by a simplified mass transfer model to estimate the apparent volumetric mass transfer coefficient, kLa_t , and the steady state DO saturation concentration $C_{S,t}$. The basic model is described by:

$$C_t = C_{S,t} - (C_{S,t} - C_0) \cdot e^{(-K_L a_t t)} \quad \text{Eqn(13)}$$

In process conditions, an oxygen uptake rate (*OUR*) acts on the system which limits the application of clean water approaches in the determination of the process oxygen transfer coefficient αkLa . Instead, the theoretical basis for in-process conditions is derived from consideration of a mass balance around a completely mixed aeration system under steady-state and non-steady-state process conditions, where respiration rate (R), influent flow rate (Q_i) and dissolved oxygen concentration (C_i) are analysed. The steady state oxygen concentration in the tank in process conditions is defined as C_r . Through steady state analysis, the model for $\alpha k_L a_t$ at temperature t is as follows:

$$\alpha k_L a_t = \frac{R - \frac{Q_i(C_i - C_r)}{V}}{C_{s,t}^* - C_r} \quad (\%) \quad \text{Eqn(14)}$$

In the non-steady state approach, dissolved oxygen is naturally removed from the water through respiration (for example by reducing oxygen input or switching off aerators) followed by re-oxygenation to steady state oxygen saturation. In this way, $\alpha k_L a_t$ can be resolved by

$$C_t = C_r - (C_r - C_0) \cdot \exp\left[-\left(\alpha k_L a_t + \frac{Q_i}{V}\right) \cdot t\right] \quad \text{Eqn(15)}$$

where in some cases $\alpha k_L a_t + \frac{Q_i}{V}$ can be equated to K for simplicity. The limitations of the non-steady state approach are that it requires constant respiration rate (R) for the duration of the test. In cases where a low C_r is expected ($C_r = 2$ mg/L), it is often necessary to adopt the steady state approach as a change in OUR in the system can effect a short re-oxygenation curve significantly^{9,10}.

2.3. Alternative Specific Energy Metrics

Demand for aeration energy fundamentally comes down to the demand for oxygen in a reactor and how efficiently oxygen is transferred to meet this demand. For example, to aerobically treat wastewater, about 58 kg O₂ per person per year (or 0.16 kg/day/person) is required (based on typical influent 5-day biochemical oxygen demand (BOD₅) and ammonium values of municipal wastewater). Typical aeration technologies have a SAE of 1.8 to 3.0 kg O₂/kWh which means that the cost of aeration treatment ideally should be about 19 to 32 kWh per person per year (based on the typical oxygen required to treat a person's wastewater per year). This is significantly lower than the 70 kWh per person per year that is frequently measured in the field. The difference between measured clean-water and in-situ aeration efficiencies are a consequence of three main issues: (1) the initial interpretation of total energy costs, (2) effects of real 'in-use' wastewater conditions on the above quoted SAEs and (3) limited aeration control - the lack of control over an aeration system can have a significant impact on the energy intensity whereby oxygen is often supplied when it is not needed.

The challenge is therefore to match the supply and demand of oxygen through the ability of turning up or down the equipment or by switching off the aerator and resorting to mixers when no oxygen is required. Often, aeration equipment has a limited capability for regulating oxygen transfer and thus equipment often operates outside of its best efficiency point resulting in further differences δ to the SAE . An alternative approach to understanding the efficiency of an aeration system is therefore to consider the energy consumed as a function of oxygen required for BOD, Ammonium removal and maintenance biomass respiration rate. Therefore, the following specific energy metrics can also be considered during evaluation to relieve dependence complex oxygen transfer measurements:

$$B_e = \text{kWh/kgBOD}_{5\text{removed}} \quad \text{Eqn(16)}$$

$$A_e = \text{kWh/kgNH}_4\text{-N}_{\text{removed}} \quad \text{Eqn(17)}$$

$$Pe_e = \text{kWh/PE/annum} \quad \text{Eqn(18)}$$

3. Aeration Systems

3.1. Summary of Sites and Aeration Equipment

In this project the following monitoring equipment was employed for aeration efficiency analysis at each of the sites:

- Hach luminescent dissolved oxygen probe and temperature sensor
- Hach SC1000 controller
- Efergy E2 three-phase electricity monitor with current transformer (CT) clamps.

Five WWTPs and five individual types of aeration equipment (low speed surface, high speed surface, horizontal brush, diffused and cyclonic) were investigated as part of the study. The wastewater treatment plants varied from industrial abattoirs treatment to municipal wastewater treatment providing varying influent concentrations and loads for evaluation of the in-process oxygen transfer conditions. Some of these sites and investigations are described in Sections 3.2 to 3.4 below.

3.2. Site 1: High-Speed and Low-Speed Surface Aeration

High-speed and low-speed surface aeration systems were investigated at an abattoir (beef and lamb) WWTP. The facility had five key treatment processes as follows:

1. Primary Screen & Balance Tank
2. Dissolved Air Flotation (DAF)
3. Anoxic tank
4. Aeration tank
5. Clarification

Before entry into the plant's balance tank, the wastewater passes through a screen to remove large solids. The balance tank is used to buffer the incoming raw waste and provide storage for onward pumping. After the balance tank, the wastewater is dosed with a polymer (poly) and aluminium sulphate (Alum ($\text{Al}_2(\text{SO}_4)_3$)) to coagulate and flocculate heavy suspended solids which are removed from the influent using a scraper. Combined, these steps function to precipitate phosphorus and reduce the BOD load before feeding into the activated sludge system.

The activated sludge configuration was designed to remove a combination of BOD, ammonium, and nitrate/nitrite through both anoxic and aerobic processes to treat wastewater. Ammonium removal is designed to occur in the aeration tanks which produces a nitrate rich mixed liquor. This nitrate rich mix is then recycled back to the anoxic tank to facilitate denitrification (nitrate and nitrite removal) alongside associated BOD removal. This combined nitrification (aeration tanks) and denitrification (anoxic tank) processes are required to reduce both ammonium and nitrate concentrations to keep the total nitrogen (TN) concentrations in the final effluent below discharge limits (or Emission Limit Values (ELVs)).

In addition to ensuring that the TN concentrations are low, the anoxic tank also functions to reduce BOD concentrations prior to entry into the aeration tank. This step is useful in aiding nitrification (conversion of ammonium into oxidised nitrogen – mostly nitrate).

After treatment in the activated sludge process, the mixed liquor flows into the final clarifier. In this tank, the solids separate from the treated effluent. This step functions to both produce a clear final effluent and separate solids for recycling back into the activated sludge system. Solids are also wasted from this location to ensure a suitable MLSS concentration/sludge age to both remove BOD, ammonium and nitrates/nitrites. This waste stream is pumped into a belt filter press for solid/liquid separation prior to solids disposal.

The total energy used in the WWTP was calculated based on accumulations of rated power and their associated duty times as provided by the plant operator. The total energy demand was estimated to be approximately 896,488 kWh/annum, including a reactive power factor of 7.5%, with an estimated annual usage cost of €101,951.

Table 2: Summary of Energy Users at Site 1

Motor ID	Rated Power	Power Consumed	Operation hours		Energy (kWh)		Annual Energy (kWh/year)	Annual cost (€/year)	% use	CO ₂ emissions (tonnes per annum)
			D	N	Day	Night				
M1	1.50	1.61	5	0	8.1	0.0	2,660	€340.43	0.30%	1.3
M2	0.55	0.59	5	0	3.0	0.0	975	€124.82	0.11%	0.5
P1	2.20	2.36	5	0	11.8	0.0	3,901	€499.30	0.44%	1.9
P2	3.00	3.22	17	7	54.8	22.6	25,532	€2,771.43	2.85%	12.3
P5	3.00	3.22	17	7	54.8	22.6	25,532	€2,771.43	2.85%	12.3
M3	5.50	5.91	17	7	100.5	41.4	46,809	€5,080.96	5.22%	22.6
P4	5.50	5.91	12	0	70.9	0.0	23,405	€2,995.80	2.61%	11.3
M4	0.55	0.59	17	7	10.0	4.1	4,681	€508.10	0.52%	2.3
P7	4.00	4.30	17	7	73.1	30.1	34,043	€3,695.24	3.80%	16.4
P8	3.00	3.22	17	7	54.8	22.6	25,532	€2,771.43	2.85%	12.3
P9	2.20	2.36	17	7	40.2	16.5	18,724	€2,032.38	2.09%	9.0
P11	2.20	2.36	17	7	40.2	16.5	18,724	€2,032.38	2.09%	9.0
P13	7.50	8.06	8	0	64.5	0.0	21,277	€2,723.45	2.37%	10.3
P15	7.50	8.06	17	7	137.0	56.4	63,831	€6,928.58	7.12%	30.8
P14	0.25	0.27	17	7	4.6	1.9	2,128	€230.95	0.24%	1.0
M5	5.50	5.91	17	7	100.5	41.4	46,809	€5,080.96	5.22%	22.6
P18	7.50	8.06	17	7	137.0	56.4	63,831	€6,928.58	7.12%	30.8
A1	18.50	19.88	17	7	338.0	139.2	157,450	€18,903.13	17.56%	76.0
A2	18.50	19.88	17	7	338.0	139.2	157,450	€18,903.13	17.56%	76.0
P16	7.50	8.06	17	7	137.0	56.4	63,831	€6,928.58	7.12%	30.8
P17	7.50	8.06	17	7	137.0	56.4	63,831	€6,928.58	7.12%	30.8
M8	3.00	3.22	17	7	54.8	22.6	25,532	€2,771.43	2.85%	12.3
					1,970	746	896,488	€101,951	100%	433

Notes:

- 0.489 kg CO₂/kWh adopted for conversion from energy to carbon emissions
- Assumption is made that the plant is operating 330 days per year, but the surface aerators are operating 365 days per year to maintain aerobic conditions
- Electricity prices shown are per kWh @ €0.128-day rate and €0.0613-night rate and do not include standing charges, PSO Levy or taxes.
- A day/night rate tariff is assumed but if not in place, the total electricity cost per year increases from €101,951 to €114,750.
- A reactive power element was observed during measurement which will increase the electricity cost by approximately 7.46% (additional €7,077 if day/night rate tariff or €7,965 if no day/night rate tariff).

The daily power demand across the entire WWTP is presented in Figure **Error! Reference source not found.** From this, it is apparent that the highest energy demand is associated with the Aeration Tanks A1 and A2, accounting for 37% of the plant's total energy usage.

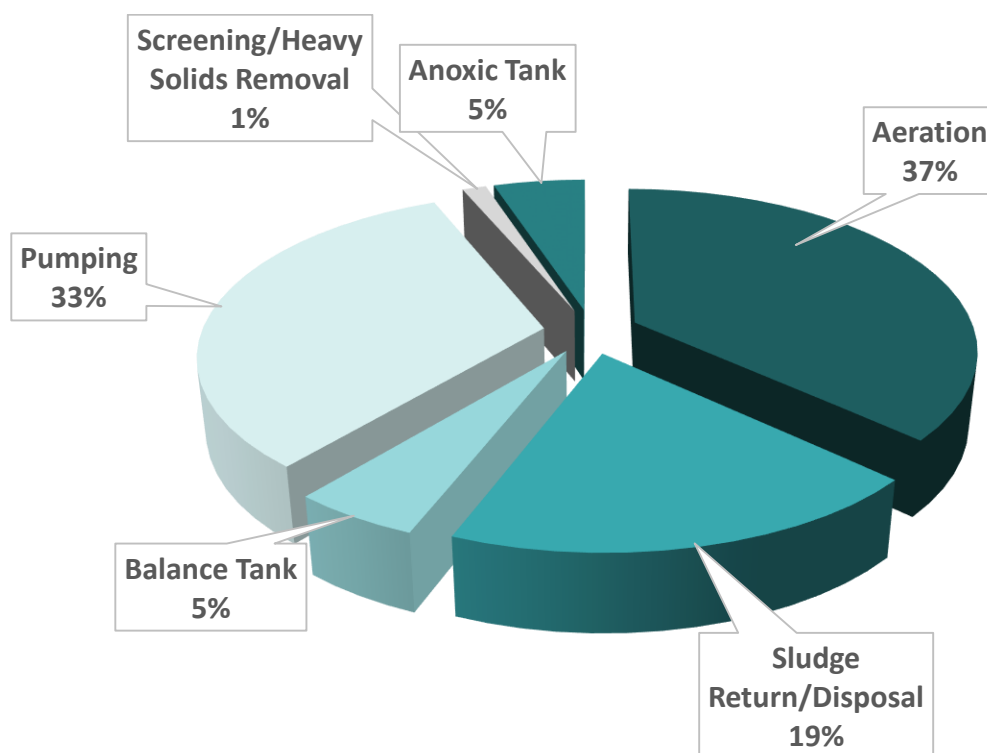


Figure 1: Pie chart summary of main electrical energy users at the WWTP

A specific energy efficiency investigation was undertaken on the aeration tanks A1 and A2 which are the WWTP's two largest energy users (circa 37% of total electrical energy use). This involved undertaking the following activity:

- Monitoring the line power to each of the surface aerators
- Determining the oxygen uptake rate in A1 and A2

- Determining the in-use aeration efficiency of both aerators using the non-steady state² approach.
- Investigating aeration mixing performance

Two types of surface aerators are used in either aeration tank (see Figure 2 and 3).



Figure 2: High-Speed Surface Aeration System in Aeration Tank 1



Figure 3: Low-Speed Surface Aeration System in Aeration Tank 2

In aeration tank 1, an improvised high-speed surface aeration system was in use with a rated motor power of 18.5 kW (wired in star configuration). This high-speed aerator was installed on a floating pontoon tethered to the tank wall and central access gantry. The system was installed following failure of the low-speed surface aerator which was originally mounted centrally in the tank.

Aeration tank 2 functions with its original low-speed surface aerator which is suspended in the tank on a permanent structure with access gantry. The A2 aerator had a motor rated power of 18.5 kW wired in delta configuration.

The line power to each of the aerators was determined using an Efergy E2 three-phase electricity monitor with current transformer (CT) clamps. Despite the rated power of each aerator motor being 18.5 kW, the actual power draw from both surface aerators was found to be approximately 19.9 kW during monitoring which is 7.5% higher than the rated power of the motor due to reactive power.

The *OUR* was measured using two methods. The first method was undertaken by retrieving a sample of biomass (800 ml) and stirring without oxygen supply to correspondingly track the rate of dissolved oxygen depletion in the sample (mg/L/s). The second *OUR* test was determined in-situ in the aeration tank by turning off the aerators and determining the oxygen depletion rate in-situ accordingly (see Figure 4).

The aerator oxygen transfer rate (*OTR*) was then computed using the steady and non-steady state approach with changing power levels². In this case, the field saturation concentration in each tank A1 and A2 were noted to be 1.75 mg/L and 5.15 mg/L respectively. After turning off each aerator, the dissolved oxygen in each tank A1 and A2 was reduced to 0.5 mg/L and 1.5 mg/L respectively. The aerator was subsequently turned on again to monitor the growth of dissolved oxygen in the tank and determine the non-steady state re-aeration curve (see Figure 4 (a) and (b)). The field oxygen transfer coefficient αkLa and *OTR* could then be determined from the non-steady state curve, influent flow and tank volume accordingly. The *AE* was then calculated using the motor wire power input identified above. To compare to standard aeration conditions as quoted by manufacturers, the *AE* was expressed in terms of the standard aeration efficiency (*SAE*) by accounting for the effects of temperature and salinity.

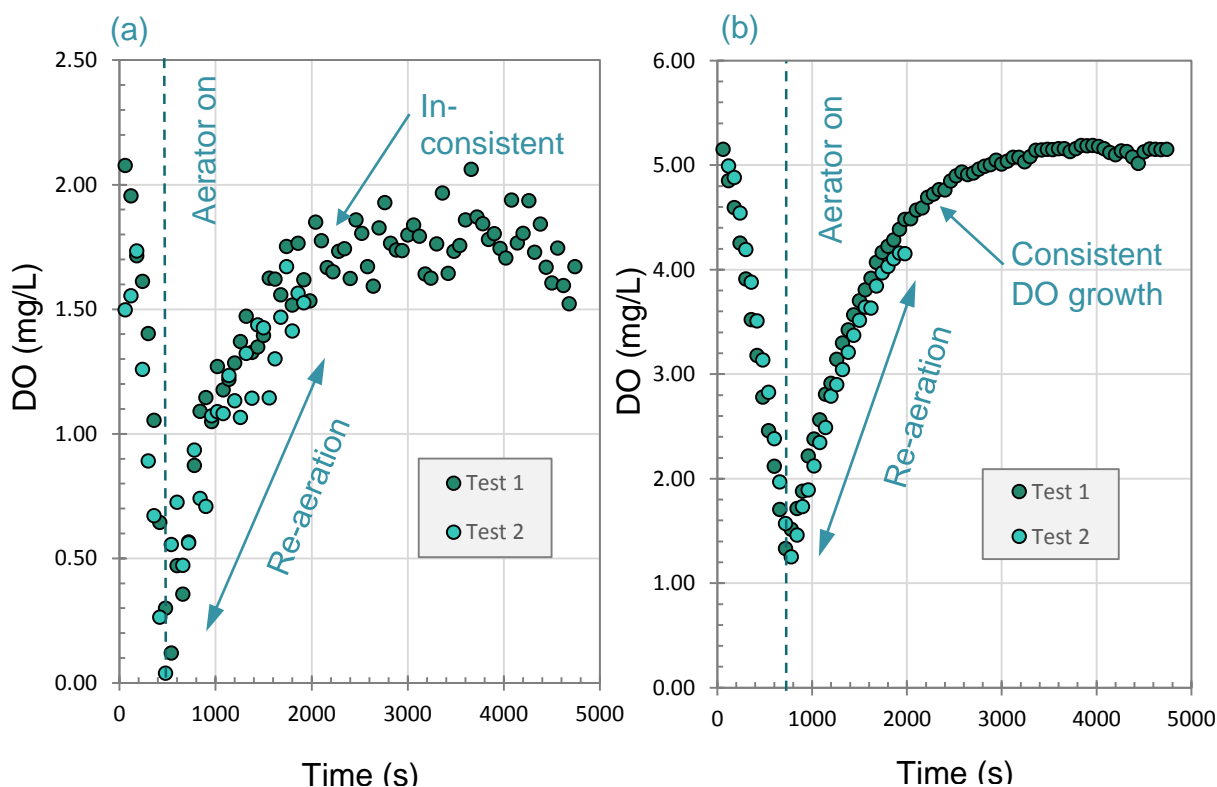


Figure 4: Non-steady state aeration curves for (a) A1 & (b) A2

Table 3 provides a summary of the results from the aeration efficiency survey.

Table 3: Summary of OTR and AE Analysis

	A1	A2
Aerator Type	High-Speed Surface	Low-Speed Surface
Power input (aerators) (kW)	19.88	19.88
Ambient DO C _R (mg/L)	1.75	5.15
OUR (kg O ₂ /h)	9.46	10.54
OTR (kg O ₂ /h) (non-steady state)	4.33	12.30
OTR (kg O ₂ /h) (steady state)	1.61	10.07
SOTR (kg O ₂ /h)	18.88	24.33
CcSAE (kg O ₂ /kWh)	0.95	1.22
Rated mixing performance	Poor	Good

3.3. Site 2: Horizontal Brush Aeration

A horizontal brush surface aeration system was investigated at a beef abattoir WWTP. Raw wastewater from the processing facility enters the effluent plant at the intake works where it is screened and pumped to the balance tank. The balance tank contains a mixer which operates intermittently to homogenise the contents of the tank. The influent is then pumped continuously at a rate of approximately 10 m³/hr to a dissolved air floatation (DAF) system. This system removes up to 88% of the organic load coming into the WWTP yielding an effluent with a BOD concentration of 2,000-3,000 mg/L for secondary (aerobic and anoxic) treatment in the oxidation ditch. A flocculant is also added at the DAF in order to remove heavier solids and precipitate phosphorus for removal.

Following primary treatment, the remaining BOD and nitrogen removal is achieved in the oxidation ditch. The oxidation ditch is an activated sludge process which is used to degrade BOD and if operated effectively may achieve ammonium removal (nitrification) and nitrate/nitrite removal (denitrification) all in one tank to yield a final effluent with a low total nitrogen (TN) concentration. Oxidation ditches are characterised by their long hydraulic and solids retention times.

The oxidation ditch employs three horizontal brush aerators which operate with two duty (Aerators 1 and 3) and one standby (Aerator 2). Each aerator has a rated power of 37 kW. The aerators function by generating flow and oxygen transfer simultaneously in the ditch. Oxygen transfer is controlled by varying the water level in the ditch via the overflow weir which discharges mixed liquor to the clarifier. An aerobic zone is created downstream of the aerators which becomes an anoxic zone after DO is consumed and remains in this state for the majority of the lane and around the bend flow before entering an aerobic zone at Aerator 3 and subsequently back into an anoxic zone until it reaches Aerator 1 again and so on.

Following the oxidation ditch, a clarifier separates the activated sludge and effluent which is discharged to the local river. Return activated sludge (RAS) is conveyed back to the oxidation ditch upstream of the influent and Aerator 1 at a flow rate of approximately 15 to 30 L/s.



Figure 5: Site 2 Overview

Based on the energy survey, the total average power consumed at the WWTP was 63 kW with a total energy use of 1,512 kWh/day equating to €151/day based on the average cost of €0.1/kWh provided on a sample energy bill for the facility. Of the total power consumed, average aeration power was measured to be 50 kW with a total daily energy use of 1,200 kWh equating to (€120 per day). This accounts for approximately 79 % of the WWTP's total electricity consumption. The power factor on the aerators was found to be approximately 0.8 which may result in additional charges by the energy utility due to excessive reactive power if not corrected. Figure 6 summarises the main energy users at this WWTP.

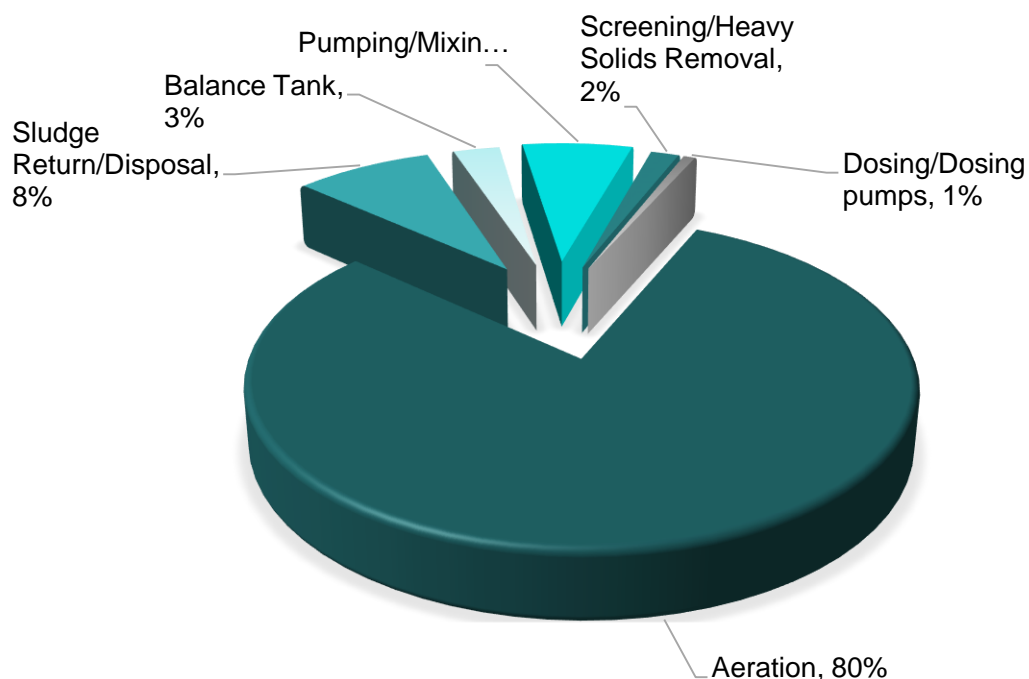


Figure 6: Site 2 Energy User Summary

In-situ steady state oxygen transfer testing was undertaken by deploying 8 LDO probes at various positions along each lane (4 DO probes in each lane). The aerators were switched off to determine the in-situ oxygen uptake rate (OUR). Circulation in the tank lasted for several minutes after turning the aerators off, prohibiting settlement of the biomass during OUR measurement. Once the dissolved oxygen reached 0.1 to 0.2 mg/L, both aerators were switched on again to track the increase of dissolved oxygen in the tank at the various locations. From this analysis, it was determined that Aerator 1 and Aerator 3 had a standard oxygen transfer rate (*SOTR*) of 32.44 kg O₂/h and 21.13 kg O₂/h respectively yielding alpha-standard aeration efficiencies (*αSAE*) for both aerators of 1.27 kg O₂/kWh and 0.82 kg O₂/kWh respectively.

The above analysis considers the actual energy drawn and does not account for reactive power consumed as a result of low power factor (PF). A power factor of 0.8 was determined for the horizontal brush aerators. This means that, although aerator 1 and 3 were consuming 24.04 kW and 27.15 kW respectively, the actual power draw being charged by the electricity supplier was 29.90 kVA and 33.32 kVA respectively. If power factor is considered in the aeration efficiency, it reduces the *αSAE* of Aerators 1 and 3 to 1.02 kg O₂/kWh and 0.67 kg O₂/kWh respectively.



Figure 7: Horizontal brush surface aerator under operating conditions (aerator 1).

Table 4: Dissolved oxygen concentrations, C_R , and oxygen uptake rates OUR, for lane 1 and 2 calculated based on equal areas approach and measurements.

Lane 1				Lane 2			
Location	Distance, x (m)	DO, C_R (mg/L)	OUR, R (mg/L/min)	Location	Distance, x (m)	DO, C_R (mg/L)	OUR, R (mg/L/min)
L1	1	0.71	1.20	L6	1	0.33	0.59
L2	6	0.56	0.92	L7	6	0.35	0.59
L3	13	0.49	0.78	L8	16	0.33	0.45
L4	21	0.25	0.36	L9	31	0.16	0.09
L5	39	0.10	0.01	L10	48	0.00	0.00

Table 5: In-process standard oxygen transfer rate and in-process standard aeration efficiency. Alpha factor based on SAE (in clean water) of 2.0 kg O_2 /kWh (as referenced from www.corgin.co.uk).

	α SOTR (kg O_2 /h)	α SAE (kg O_2 /kWh)	α
Lane 1	32.5	1.27	0.63
Lane 2	21.3	0.83	0.42

3.4. Site 3: Cyclonic Aeration (Vortex Powered Aeration)

A novel cyclonic (Vortex Powered Aeration) technology developed at NUIG was investigated at a municipal wastewater treatment plant located at the NUI Galway/EPA Water Research Facility (WRF) located on the site of the Tuam wastewater treatment plant in Galway, Ireland (see Figure 8). This is a large-scale research facility that comprises a fully operational WWTP located on the site of the Tuam WWTP.



Figure 8: NUI Galway/ EPA Water Research Facility (WRF) Tuam WWTP, Galway, Ireland.

The WWTP consisted of coarse screen, primary settlement and secondary treatment (completely mixed activated sludge - CMAS) where the VPA technology provided aeration for aerobic treatment. Secondary treatment and secondary settlement (clarification) was provided in a 4.90 m x 2.27 m x 2.23 m (L x W x H) tank. The tank had a dividing wall to provide a secondary treatment reactor (18.7 m³ working volume) and a secondary clarifier (4.08 m³ working volume).

At the WRF, known volumes of raw wastewater were pumped from the main Tuam WWTP just after passing the coarse screen into the research facility. After entering the facility, the influent passed through two primary settlement tanks where larger solids were removed. The wastewater was then pumped to the CMAS system where the VPA was installed. Forward feed from the balance tank activated every 3 minutes and 45 seconds to pump wastewater into the activated sludge system. The high frequency of forward feed pumping allowed for a quasi-constant flow through the system. Water left the activated sludge tank through an overflow into the secondary clarifier. Clear effluent was then decanted through the effluent pipe.

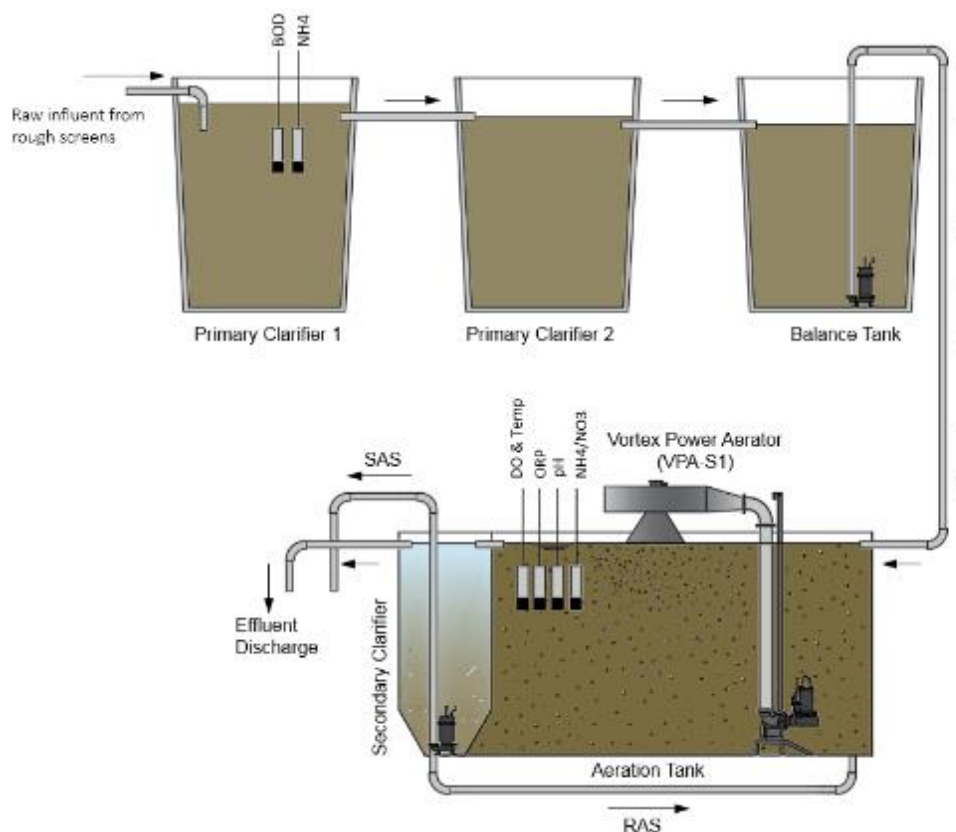


Figure 9: Schematic of the VPA-S1 Pilot Plant

The pump at the bottom of the CMAS tank lifted the mixed liquor from the bottom of the tank and injected it into the vortex chamber residing above the water surface which circulated air and water to provide aerobic treatment. The speed of the pump controlled the oxygen transfer process which was adjusted using a variable frequency drive (VFD) depending on the oxygen requirement in the reactor. As the VPA functions as both an aeration and mixing device there was no requirement for any additional mixing equipment in the tank during the trial. Air flow to the reactor was controlled using an automated vent switch and variable speed operation which enabled dissolved oxygen regulation in the reactor between 1.5 mg/L and 2.5 mg/L.

The reactor also had a return activated sludge (RAS) line which returned sludge from the bottom of the clarifier to the forward feed location of the reactor. Similarly, surplus activated sludge (SAS) was generated and removed from the facility using a second sludge pump located at the bottom of the clarifier.

The treatment system was operated at various hydraulic loading rates in order to both stress test the VPA and/or keep the Food-to-Mass (F/M) ratio within the required range of 0.1-0.2 kg BOD/kg MLVSS. As there was a large degree of variability observed with loading rates (organic carbon and nutrient) over the course of this study, hydraulic loading rates ranged from 19.2 m³/day to 57.6 m³/day (this is mainly due to the combined storm and sewerage collection system in place in the town).

The SAS removal rate was varied throughout the investigation, depending on the temperature and BOD removed, with the aim of maintaining the solids retention time (SRT) between 12- and 16-days during times when nitrification was to be achieved. This was required in order to yield a sludge with both a healthy population of

heterotrophic and autotrophic bacteria to facilitate organic carbon and ammonium removal (respectively) from the wastewater.

The varying SAS rates throughout the investigation to assess the effect of both high and low solids concentration on the VPAs ability to transfer oxygen and sustain effective treatment. This often-limited nitrification rates due to the absence of nitrifying bacteria during low SRT investigations.

Aeration and mixing conditions were investigated in the reactor by monitoring DO concentrations at various locations across the CMAS over time. Figure 10(a) outlines the growth of oxygen in the tank from 0 mg/L to saturation during clean water testing to ASCE Standard. With reference to dissolved oxygen probes in Figure 10(b) it is evident that good mixing was achieved in the tank due to synchronous growth of oxygen at all locations indicating also that no dead spots were present.

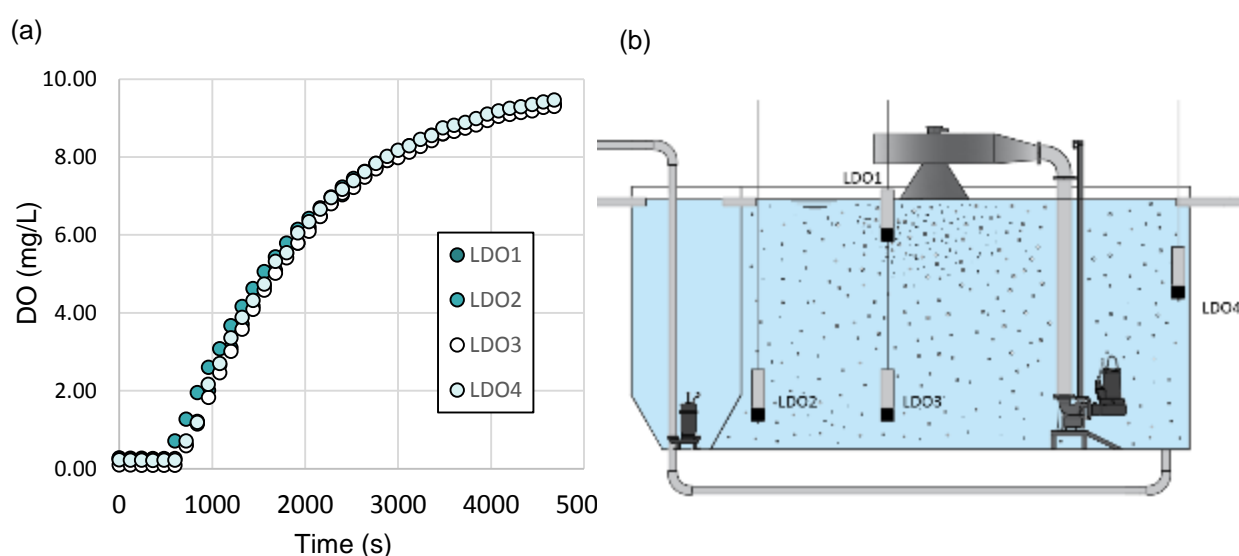


Figure 10: (a) Dissolved oxygen time series during an oxygen transfer test in clean water and (b) schematic of aeration tank during clean water tests highlighting position of LDO probes

During process testing, aeration was carried out in cycles to regulate the dissolved oxygen between 1.5 and 2.5 mg/L. Cycles were enabled using the anoxic (single phase) mixer setting on the VPA, which turned off the supply of oxygen resulting in a cyclical variation of dissolved oxygen as shown during the 'normal operation' period in Figure 11. Figure 11 also outlines a process saturation test to substantiate process mixing ($MLSS \approx 1,800$ mg/L) for a wide range of dissolved oxygen levels. In this case, one of the DO probes was located at the free-surface and the other at the bottom of the tank. From Figure 11, during aeration, anoxic and process saturation it is evident that full mixing was also ascertained in the tank during process conditions.

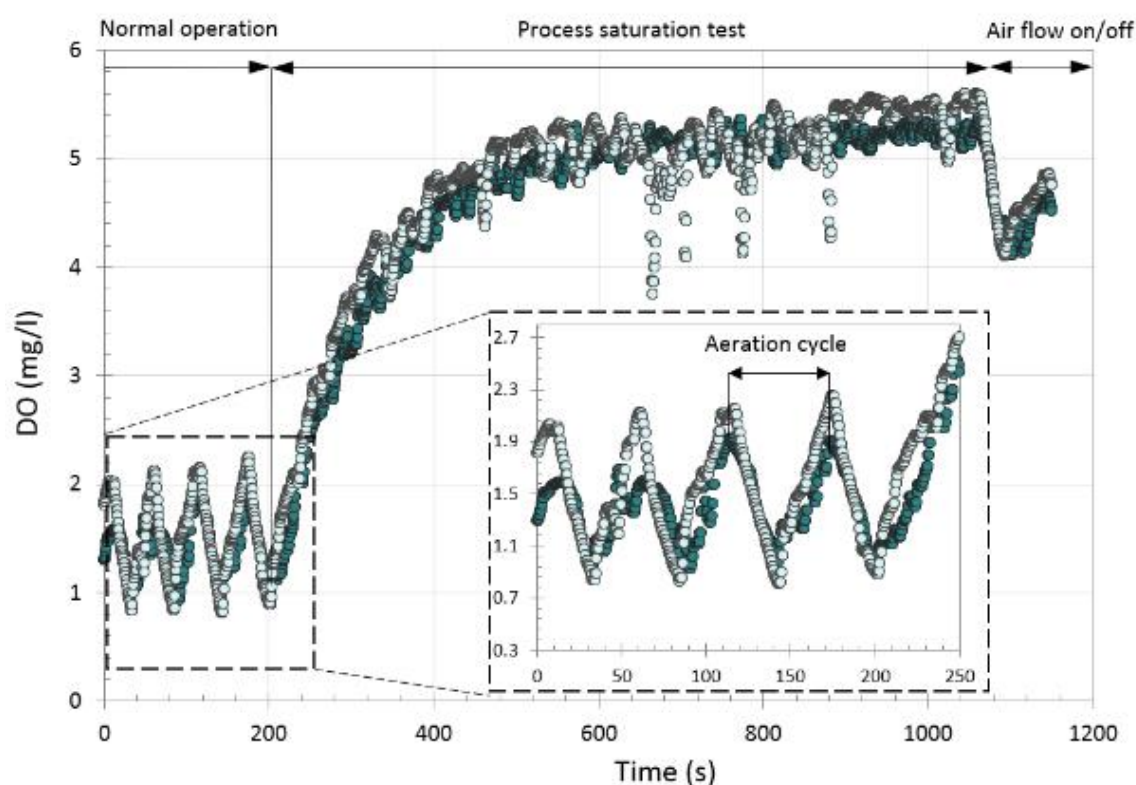


Figure 11: Dissolved oxygen time series during normal operation (on/off aeration) and process saturation test

During clean water testing according to American Society of Civil Engineering (ASCE) Standards², values for standard oxygen transfer rate (SOTR) of between 0.5 kg O₂/h and 1.2 kg O₂/h were measured for the range of VPA-S1 flowrates. In-situ determination of the oxygen transfer rate was subsequently determined using the steady-state and non-steady state method³. The results of the tests are outlined in Table 6 together with the influent process parameters of mixed liquor suspended solids MLSS, chemical oxygen demand (COD) and ammonium (NH₄-N). From this, an average alpha factor of 0.90 was determined with a range of between 0.897 and 1.132. Alpha factors greater than unity are possible. For example, at sufficiently high turbulence conditions, α can be restored to 1 or indeed exceed 1 resulting from ionic interfacial effects due to the presence of inorganic salts, aliphatic alcohols or the entrainment of foams generated by surfactants which contain fine bubble aggregates⁵.

Table 6: Results of in-situ oxygen transfer rates and alpha factor for various influent conditions

Q _{VPA} l/sec	MLSS mg/L	COD mg/L	NH ₄ -N mg N/L	R mg/L/s	Q L/s	C mg/L	C _r mg/L	T °C	$\alpha K_L a$ 1/h	αOTR kg O ₂ /h	$\alpha SOTR$ kg O ₂ /h	SOTR kg O ₂ /h	C _C
26.94	1740	159	18.35	0.0039	0.722	2.5	10.45	11.8	3.03	0.592	0.638	0.639	1.00
29.45	1525	373	32.4	0.0072	0.844	2.0	10.45	12.1	3.65	0.713	0.762	0.940	0.81
29.45	1525	373	32.4	0.0060	0.844	2.0	10.45	12.1	3.16	0.616	0.659	0.940	0.70
29.45	1090	737.5	39.25	0.0064	0.585	2.0	9.77	15.2	4.16	0.760	0.807	0.940	0.86
27.66	1090	737.5	39.25	0.0069	0.585	2.0	9.77	15.4	4.13	0.755	0.798	0.705	1.13
27.66	1340	511	35.5	0.0055	0.585	2.0	9.98	14.5	3.15	0.588	0.622	0.705	0.88

After performing the steady-state method, the non-steady state approach was carried out for comparison between the two different methods. Where the steady-state approach considers only a mass balance around a completely mixed activated sludge tank under steady state conditions, the non-steady state approach also considers non-steady state process conditions. These methods measure the oxygen transfer coefficient in process ($\alpha K_L a$).

Table 7: In-process standard oxygen transfer rate analysis

Q_{VPA} l/sec	C_0 mg/L	C_r mg/L	C_{Sat} f mg/L	T °C	$\alpha K_L a$ 1/h	αOTR kg O ₂ /h	$\alpha SOTR$ kg O ₂ /h	SOTR kg O ₂ /h	C_C
26.94	2.18	5.07	10.45	11.8	2.979	0.582	0.626	0.639	0.980
29.45	0.96	2.73	10.45	12.1	3.769	0.736	0.787	0.940	0.837
29.45	0.72	2.88	10.45	12.1	4.255	0.831	0.888	0.940	0.944
29.45	1.20	3.60	9.77	15.2	5.194	0.949	1.008	0.940	1.072
27.66	1.14	3.17	9.77	15.4	4.279	0.782	0.827	0.705	1.172
27.66	1.22	3.12	9.98	14.5	3.383	0.631	0.668	0.705	0.947

In the non-steady state approach the $C_C SAE$ values of the 0.48 kW rated unit ranged from 1.68 – 2.19 kg O₂/kWh in process with a much narrower range of C_C values from 0.837-1.172 and an average of 0.992.

4. Discussion and Conclusions: Energy Efficiency Showdown

4.1. Discussion and Conclusions

Table 8 provides a summary of all in-process aeration efficiencies for the various technologies studied in this project (Sections 3.1 to 3.4). Although relative site information is not presented in this report, an additional study for a fine bubble diffused aeration system is outlined for completeness in comparing the spectrum of aeration technologies.

In cases where both the steady state and non-steady state approaches were used, the steady state results were always lower than the non-steady state approach. For simplicity, the non-steady and steady state approaches in these cases were averaged for the purpose of comparison. SAE values were obtained from standard textbook values¹¹ and the notation $C_C SAE$ was adopted to synthesise findings between mechanical and diffused equipment. It is worth noting that $C_C SAE \rightarrow \alpha SAE$ for surface aerators as F and δ approximate to 1, particularly for new equipment. For surface based aeration equipment, the in-process oxygen transfer rate varied between 0.5 and 2.0 (depending on aerator type and loading conditions). The C_C factors for surface aeration equipment (low-speed, high-speed and horizontal brush) closely agreed with typical values described in the literature for α factor ranging from 0.5 to 1.06¹¹. The higher C_C values characterise how the effect of surfactants can be overcome by higher turbulence generation during oxygen transfer.

In the diffused aeration system, the C_C value varied between 0.1 and 0.25. This was suspected to be due to collection of low alpha factors, fouling and system deficiencies (e.g. blowers not operating at best efficiency point etc.). What this research suggests is that, although FBDA systems have a perceived higher aeration efficiency in theory

or at design stage based on assumed constant alpha factors ($\alpha = 0.6$ commonly adopted), in practice the equipment will fail to maintain efficient oxygen transfer unless (1) diffuser heads are regularly cleaned to maintain a fouling factor F close to unity, (2) the system is designed and controlled to closely match the conditions upon which the SAE was declared, (3) high mean cell retention times are maintained in the activated sludge. With that, it may be possible to achieve higher aeration efficiencies with diffused aeration however at the expense of higher maintenance costs.

Ultimately, the effect of C_c should be considered carefully at the design stage to properly size aeration systems and to forecast realistic future aeration energy demands at the facility.

Table 8: Results of in-situ oxygen transfer rates and alpha factor for various influent conditions

Technology	Application	Non-Steady State $C_c \cdot SAE$	Steady State $C_c \cdot SAE$	SAE	C_c
Low-Speed Surface Aeration	Abattoir Influent	1.34	1.11	1.5–2.1	0.58-0.82
High-Speed Surface Aeration	Abattoir Influent	1.39	0.51	0.9–1.3	0.73-1.06
Horizontal Brush Surface Aeration	Abattoir Influent		1.05	1.5–2.1	0.50-0.70
Fine Bubble Diffused Aeration	Municipal	0.48 to 0.69		2.8–4.8	0.10-0.17
Cyclonic Aeration	Municipal	1.99	2.04	1.5-2.5	0.7-1.17

5. Water-Energy Industry Nexus

As was demonstrated in this project, the efficiency of various aeration technologies varies significantly, and in-use energy consumption of aeration can be substantial (with one case demonstrating over 80% of total plant energy consumption attributed to aeration alone). At the same time, in a number of cases the combination of high-capital outlay and low upgrade budgets amongst many end-users is a barrier which is prohibiting energy efficient upgrades. Therefore, a key focus of the project was also to highlight incentives available from the energy industry to relieve these barriers and enable wider implementation of energy efficiency measures within the wastewater industry. These incentives, and the efforts made by the team to link stakeholders within the water and energy industry is outlined in the following sections.

5.1. Energy Credit Obligation Scheme

The Energy Efficiency Obligation Scheme is a legislative mechanism that places requirements on Obligated Parties such as energy retailers and energy distributors to meet energy savings targets across their customer portfolio. The obligated parties are provided the freedom to choose the measures and energy efficiency delivery routes that best suit their constraints. In this way, the energy market as a whole can discover the most cost-effective way to achieve energy savings in various applications which

supports the EU in achieving a 20% reduction in energy usage by 2020. For every unit of energy saved through these projects, the obligated parties achieve energy credits towards their targets. Therefore, the obligated party must financially support their client by either: (1) direct monetary contribution, (2) reduced energy tariff, (3) loan instruments or (4) negotiating discounts on materials.

During the project, one of the research facilities could benefit from significant savings by implementation of an energy efficiency upgrade, yielding savings of approximately 240,900 kWh per year (55% savings) by upgrade of aeration and control systems. Discussions were held between the client and their energy utility on the financial benefits of implementation of the EEOS where a financial benefit of €10,841 could be provided to the client for €0.045/kWh saved.

5.2. Energy Contracting (ESCO)

The project also explored the mechanisms of Energy Contracting as applied to wastewater treatment energy efficiency upgrades (and easily adapted for water treatment upgrades). Energy Contracting is a 'pay for performance' approach to installing and operating energy efficiency technologies in a business. In a performance related payment plan, a contractor undertakes energy efficiency works and guarantees the energy savings for an agreed fee. If savings fall short of expectations, the contractor loses a part of their fee which therefore alleviates many of perceived risks of the client, particularly in the case of deployment of new technologies. An alternative, more advanced form of this is an Energy Supply Company (ESCO) which fronts the capital, installs works and operates the facility for a number of years, until the payment for energy by the client amortises the value of the project. This is highly disruptive as it (a) brings capital from the energy industry into the water/wastewater treatment industry and (b) de-risks the project for the client in the case. This ESCO approach was explored along with the EEOS scheme at the above-mentioned site. The project would see a full retrofit of new technology introducing energy savings of 240,900 kWh per annum over a contract duration of 7 years if implemented. In conclusion, the client reacted very positively to this proposition, particularly where the approach is combined with the EEOS and energy grants to assess the feasibility and implement the project available from SEAI.

With this novel approach to financing energy efficient upgrades in wastewater treatment, the research team were successful to qualify to the Free Electrons Accelerator Bootcamp in 2019. The project team qualified amongst 515 applications, from 65 different countries to a short-list of 30 projects.

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