Opportunities for process control optimisation in Irish municipal wastewater treatment plants

Thomas Phelan
School of Mechanical Engineering
Dublin City University (DCU), Dublin 9, Ireland
e–mail: thomas.phelan4@mail.dcu.ie

Greg McNamara, Matthew Horrigan, Yan Delauré, Brian Corcoran, and Lorna Fitzsimons*
School of Mechanical Engineering
Dublin City University (DCU), Dublin 9, Ireland
e–mail: lorna.fitzsimons@dcu.ie

Eoghan Clifford
Civil Engineering, College of Engineering and Informatics
National University of Ireland Galway (NUIG), Galway, Ireland

ABSTRACT

As societies ever increasing reliance on electrical energy continues, the role of process optimisation becomes more and more prevalent. This paper presents an energy audit of a typical Irish wastewater treatment plant (P.E. 30,000[1]) and attempts to investigate measures to increase the energy efficiencies within treatment plants across Ireland. Based on an in depth review of international energy efficient wastewater treatment plants, energy savings opportunities exist via the use of variable frequency drives to control pumps and blowers; the introduction of inter-basin dissolved oxygen control systems to provide the varying, relevant oxygen requirements to the aeration basin; and effective plant management using appropriate control strategies via accurate sensor feedback and real-time, online monitoring.

KEYWORDS

Wastewater, water treatment, process control, environmental monitoring, energy monitoring, resource efficiency, instrumentation, control and automation.

INTRODUCTION

The increasing cost of supplied electricity has caused energy conservation to become a top priority for industry worldwide. One area where this priority has become apparent is municipal wastewater treatment. Budget restrictions and cutbacks have caused treatment plants to re-think their methods of water treatments and look at how energy savings can be made using process control optimisation.

In Ireland, wastewater treatment services for the most part are delivered by 34 Local Authorities. Over the past year, the Irish government has set up a governing body (Irish Water) to bring together the water and wastewater services of these local authorities under one national water utility [2]. The Environmental Protection Agency (EPA) are tasked with the job of ensuring that wastewater treatment plants (WWTP) across the country conform to

[1] 1 P.E. (person equivalent) is estimated to be 0.2 m^3 of waste water influent and 60g of BOD (biological oxygen demand) [1]

the European directives on pollution limits for effluent waters [3]. Due to Ireland's sparse population distribution, the delivery of public services such as wastewater treatment and the supply of power to homes becomes difficult. The ROI contains just two cities with populations over 100,000 people. The municipal wastewater treatment services are delivered through small treatment plants scattered all over the country. Of the 512 Irish wastewater treatment plants approximately 87% have population equivalence (P.E) of less than 10,000 [4].

In recent years, global industry has been seeking to reduce and become more responsible in relation to energy consumption and management. The wastewater treatment industry is lagging behind many others such as chemical and paper production industries who have demonstrated significant savings with short investment payback times [5]. This is partly due to the nature of wastewater treatment which experiences hugely varied flow rates, large process disturbances and zero wastewater rejection (all wastewater must be accepted and treated) [6]. In terms of Ireland, the fact that there are a large amount of small plants makes the task of implementing energy efficiency improvements across the country a slow process.

Many Irish treatment plants with secondary treatment facilities are based on an activated sludge aeration system. International studies on municipal wastewater treatment plants have shown that for an activated sludge wastewater treatment plants, up to 66% of total plant energy use is dedicated to sludge pumping and aeration [7](Figure 1). If energy can be conserved in these areas, there may be significant potential for large cost savings within wastewater treatment plants.

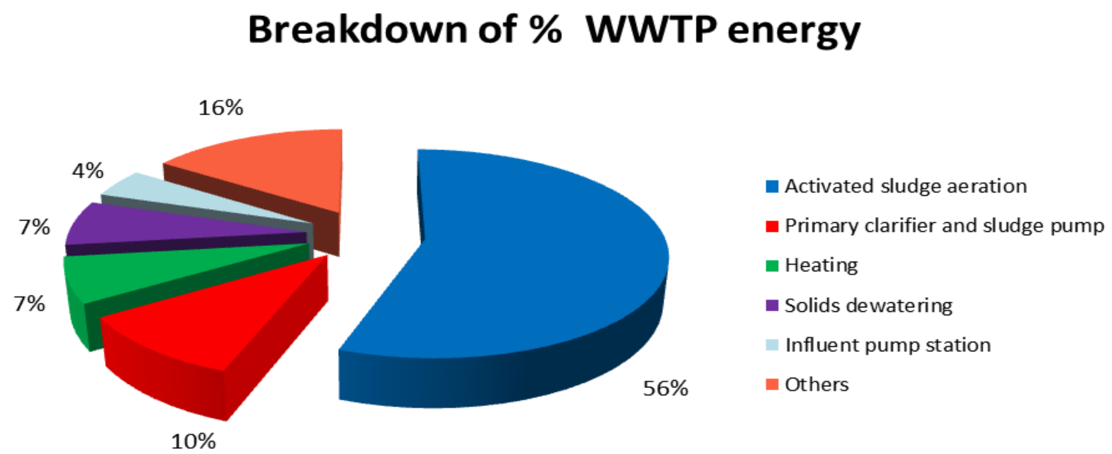

Figure 1: Breakdown of energy use across the different processes of a WWTP [7]

Activated sludge aeration systems consist of compressed air blowers which transfer air into the activated sludge tank in order to aid in the reduction of organic matter and the removal of nutrients. In order to realise significant energy savings within the wastewater treatment plant sector, strategies for the control of these compressed air blowers are essential. Through the use of Instrumentation, Control and Automation (ICA), wastewater treatment plants can realise significant energy savings. For example, Olsson [5] predicts that "improvements due to ICA may reach another 20-50% of the system investments within the next 10-20 years". Instrumentation is a cornerstone of any energy efficient plant. In WWTPs instrumentation is any device that feeds process data to the operator. This could be anything from the influent water flow rate to dissolved oxygen levels in the biological reactor. In order to develop a process control system you must first have instrumentation that you trust is correct or are aware of its limitations. This instrumentation feeds into a central monitoring system that can perform operations such as, display the process data, detect abnormal situations, assist in diagnosis, and simulate consequences of operational adjustments [5]. Control systems in any plant are used to help meet the operational goals. Within WWTPs, local control systems use the feedback from instrumentation and monitoring systems to make adjustments to plant processes. They can be used to control airflow rates to the biological reactors, adjust water/sludge pumping speeds and they can be used to automatically rotate plant machinery use, in order reduce machine wear due to overuse. Master control systems help coordinate all the plant's control systems and can incorporate the sewer system and surrounding pumping stations.

Currently the use of sophisticated ICA in WWTPs in Ireland is limited to the medium to large scale plants. Many of small to medium sized plants employ control systems such as dissolved oxygen (DO) control within activated sludge. This is generally done using binary control of aeration blowers, where the blower is turned on to full power to raise the DO levels and turned off to reduce DO [8]. Although this approach can offer plant energy savings, there are significant disadvantages, such as slow reaction time and machine wear. Additionally, due to the non-linear of DO dynamics within an activated sludge system, this approach offers limited control to the WWTP.

The main focus of this work is energy conservation through process control optimisation. This paper aims to assess various energy savings opportunities within Irish wastewater treatment plants by reviewing technologies and control systems used in energy efficient wastewater treatment plants around the world. Furthermore, the paper presents a preliminary energy audit of an Irish wastewater treatment plant (P.E. 35,000). One important issue that became apparent while undertaking this research was that not all plants are suitably instrumented to monitor, and hence manage, their energy consumption.

REVIEW OF ENERGY SAVINGS OPPORTUNITIES

Variable Frequency Drives (VFDs)

Significant energy savings opportunities exist via the use of variable frequency drives to control pumps and blowers. Variable frequency drives are devices that alter the frequency of the input signal to an AC motor. In an induction motor, the speed is directly proportional to the supply frequency [9]. By changing this supply frequency the motor speed and synchronous speed can be controlled. These devices however do have limitations and are not suitable for all applications, for example, situations where the ratio of static to dynamic head of the pump is large. This ratio depends on the pump efficiency and system curves and guidelines for upper limits are presented by the British Pump Manufacturers Association [10]. Springman et al. [11] describes the energy savings made through the installation of VFD devices in a small wastewater treatment facility. This plant was running two 75W Hoffman centrifugal blowers at 100% speed 24/7. The airflow was reduced using a mechanical valve in order to achieve the desired dissolved oxygen levels in the oxidation tank. These blowers were each fitted with VFDs and the blower speed was reduced to 80% with the removal of the mechanical valve. This adequately met the desired dissolved oxygen levels while reducing the total plant energy usage by 16.7%. On a larger scale, East Bay Municipal Utility District in northern California implemented a refit of treatment plant technology [12]. They replaced two smaller blowers with one large unit and installed high-efficiency motors with VFDs on pumps, reducing electricity use by the pumps by 50%. These are just simple examples of how the introduction VFD devices and energy efficient equipment within wastewater treatment plants can realize quick and substantial energy savings. In order to fully utilise the control that a VFD offers and maximise energy savings, aeration control systems are essential.

Control Systems

Studies on wastewater treatment plants show that automatic control systems reduce energy usage while also allowing for more precise control of process parameters [7]. Dissolved oxygen is the most widely used control variable in the WWTP industry [5,13]. Due to the high operating cost of the compressed air blowers, and coupling this with the dynamic response nature of dissolved oxygen (in the order of fractions of hours), the control of airflow to the aeration process is desirable [14,15]. Figure 2 illustrates a simple DO control system. A Proportional, Integral and Derivative (PID) controller is used to vary the airflow rates to a biological reactor based on the dissolved oxygen levels in the tank. The airflow to the tank is continuously varied in order to maintain a specific DO set-point [16]. Controlled tests by the US Environmental Protection Agency [13] show that energy savings of 38% can be achieved through the use of automated dissolved oxygen control over manual control. This study shows also that depending on plant characteristics such as plant size, mixing limitations, types of aeration equipment and plant loading, savings between 0 – 50% savings can be achieved.

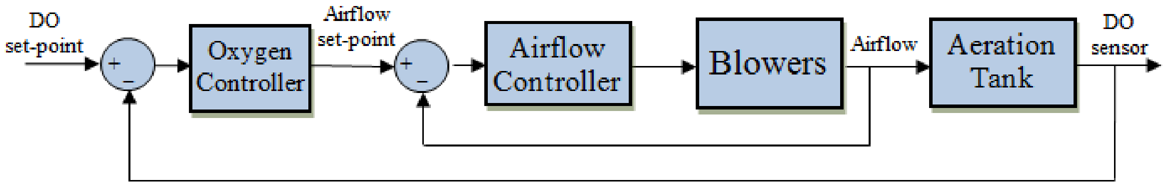

Figure 2: DO cascade feedback control diagram [16]

Recently, some WWTP have started using ammonium based cascade control using dissolved oxygen set-point [17,18]. This is a system whereby a controller varies the airflow rates to the biological reactor based on the dissolved oxygen sensor readings. The controller adjusts the airflow in order to maintain a specific DO set-point. This set-point however can be changed based on the ammonium levels at the effluent (Figure 3). When the ammonium levels in the biological reactor are low then the controller can set a low DO set-point. Conversely, when the ammonium levels rise, the DO set-point is reset to a higher level [16]. In a UK based case study, Esping [19] shows that switching to NH_3 control can decrease airflow requirements by 20%.

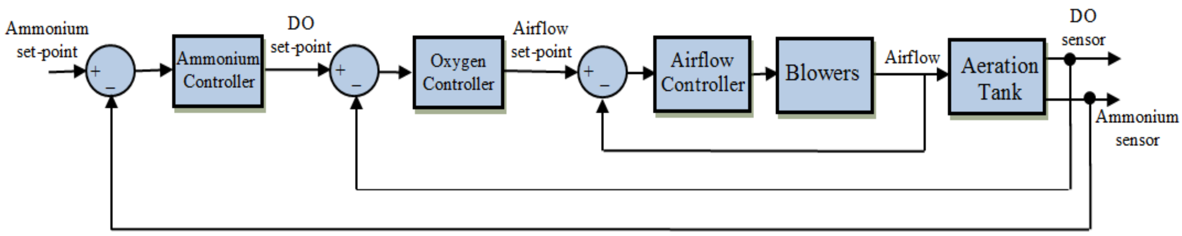

Figure 3: Ammonium/DO cascade feedback control diagram [16]

Another important factor to consider when implementing an aeration control system such as those discussed above is variations in dissolved oxygen and nutrient levels within the aeration tank. In the case of a DO controlled aeration tank, multiple DO sensor zones with independent air supply to each zone maximises potential energy savings [20]. Instead of over or under supplying areas of the tank, each zone controls the airflow to match the DO needs for that zone [20]. Although this style of control system may involve large scale changes to plant layout, significant energy savings can be achieved.

Electrical Energy Losses

Electrical energy losses can cause serious issues within WWTPs. Harmonic disturbance on the three phase blower power lines can result in non-negligible monetary losses. With the addition of devices such as VFDs this harmonic disturbance can often be exacerbated. Harmonic losses can cause dangerous heat build ups in conductors [21]. Solutions to this issue outlined by Troy et al. [21] include the use of harmonic filters or multistage converters to reduce the unwanted harmonic frequencies from the voltage lines. Other issues such as load unbalance, neutral line current and poor power factor can cause significant problems in wastewater treatment equipment. If these losses are detected, corrective measures should be taken in order to avoid energy losses, heat build-up or accelerated machine wear. Springman et al. [11] discusses the installation of load balancers in conjunction with VFD's to reduce system wear.

ENERGY AUDIT

An energy audit was carried out within an Irish wastewater treatment plant in order to assess how Irish treatment plant energy usage compared to international studies. Table 1 details the characteristics of the audited plant. The audit was performed using the Fluke 435 Energy Quality Analyser. This device can accurately measure three phase load variables such as voltage, current, power, energy, power factor, harmonics, phase angle, % umballance, etc. [22]

Table 1: Inventory list for audited WWTP outlining the facilities available and the equipment currently being used.

Plant Characteristic	***Design Specifications***	***Trial Period Usage***
Plant Name	Plant A	Plant A
Plant PE	Designed for 50,000	38,000
Primary Treatment	Grit Screening	Yes
	Primary Settling	Yes
Secondary Treatment	Activated Sludge Aeration	Yes
	Secondary Settling	Yes
Sludge Treatment	Picket Fence Thickening (PFT)	No
	Rotary Drum Thickening (RDT)	No
	Anaerobic Digestion	No
	Belt Filtration	Yes
Receiving Waters	Inland River (Sensitive waters)	Yes
Treatment Obligations	Nutrient Removal	Yes

Over a two month period, an initial energy analysis was performed within Plant A. This analysis focused on the overall energy consumption of the WWTP over a week long period. Further analyses on major sub-processes were then performed to find which processes were consuming large amounts of energy. Three key areas were audited:

1. Main power inlet
2. Secondary treatment sub-system
    a. 2 compressed air blowers
    b. 2 sludge return pumps
    c. 4 aeration mixers
    d. 2 secondary settling tank motors
    e. Power for adjoining building
3. Primary aeration tank blower

Main Power Inlet

In order to quantify the total plant energy usage, the main power inlet to the WWTP was analysed from 11th – 17th December 2013 (Figure 4). The sampling frequency was set to 1 minute and a 30 point moving average filter was then applied to the data.

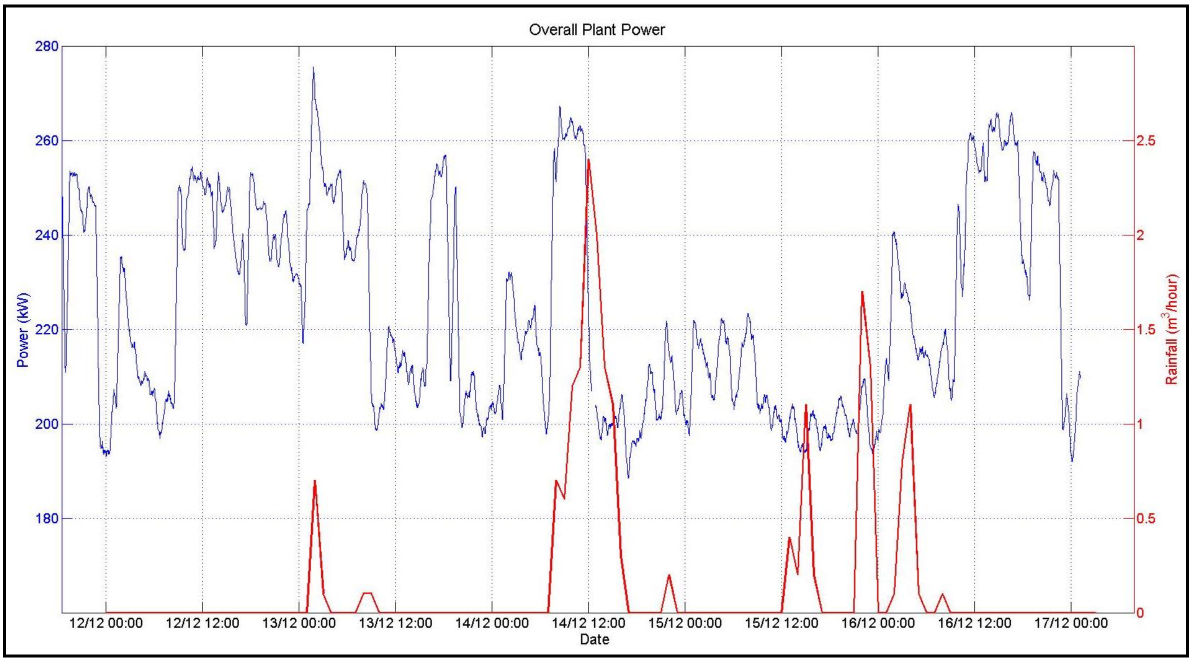

Figure 4: Overall plant Power overlaid with hourly rainfall data from nearby weather station.

The average power during the trial period was 223.13 kW, equating to an average monthly energy usage of 164,737 kWh. There were large fluctuations in the power output over the trial period. From the graph, fluctuations of ±35 kW from the average can be seen frequently. There was a noticable period of sustained low power between the 14th and 15th of December. This may be atributed to the low plant activity over the weekend period.

Hourly rainfal data from the national meteorological service in Ireland has been presented here also [23]. The rainfall in m^3/hr for the trial period was recorded by a weather station 14 km from the WWTP. Athough some spikes in rainfall coincide with power usage spikes, rainfall is just one factor in a complex interaction that affects the plant's activity. Other factors that could cause such fluctuations are plant inactivity at off peak hours, high influent flowrates during mornings and evenings from local housing or additional wastewaters from industry.

Secondary Treatment

In order to quantify energy distribution within the WWTP, the secondary treatment process was analysed. This involved the recording of energy usage for the secondary treatment system as a whole. Figure 5 shows the overall plant power (top) with the overall secondary treatment power (bottom). This secondary treatment system trial was performed from 17th – 23rd January 2014.

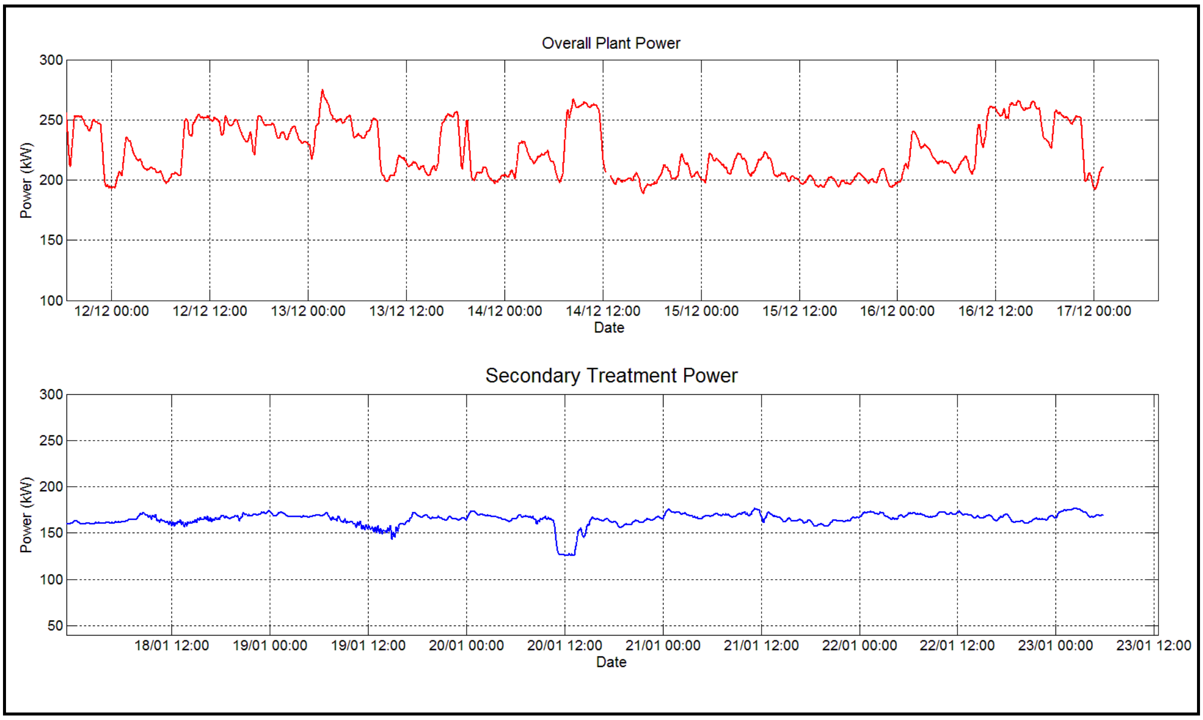

Figure 5: Overall power usage for the WWTP over a week long trial (Top) and the power usage for the secondary treatment sub-system for another different week long trial (Bottom)

The average power for secondary treatment was 164.78 kW. This contributes to an energy consumption of approx. 76% of the overall plant energy usage. Figure 6 illustrates the power usage of one of the compressed air blowers during a 7-day trial period from 1st – 8th February. This blower experienced a 12 hour downtime period during the trial. At the start of the trial period there is a sharp drop in power down to 50 kW which may be the result of relatively low plant activity from the 1st – 3rd February (weekend). The blower power then seems to experience some fluctuations in power as seen in the inlet power (Figure 4)

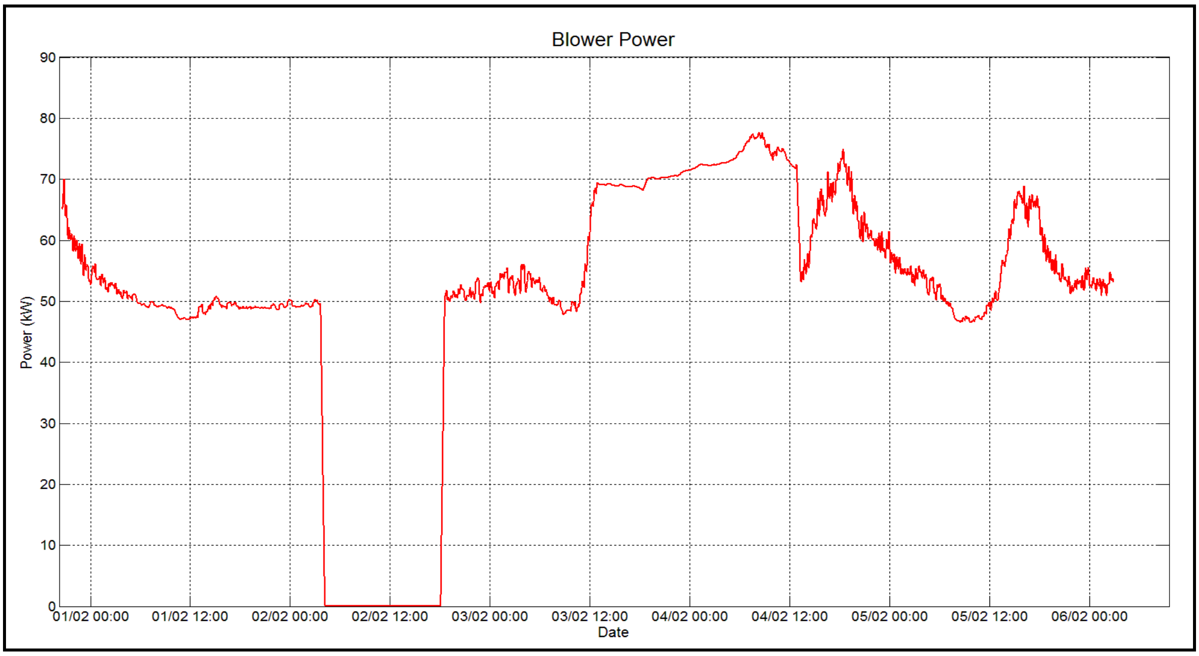

Figure 6: Power usage for one of the secondary treatment compressed air blowers.

The overall breakdown of energy consumption within the WWTP (Figure 7) shows that the plants aeration blowers consume approximately 47% of the total plant energy consumption. The aeration tank mixers, sludge return pumps and secondary settling tank motors consume a further 28%.

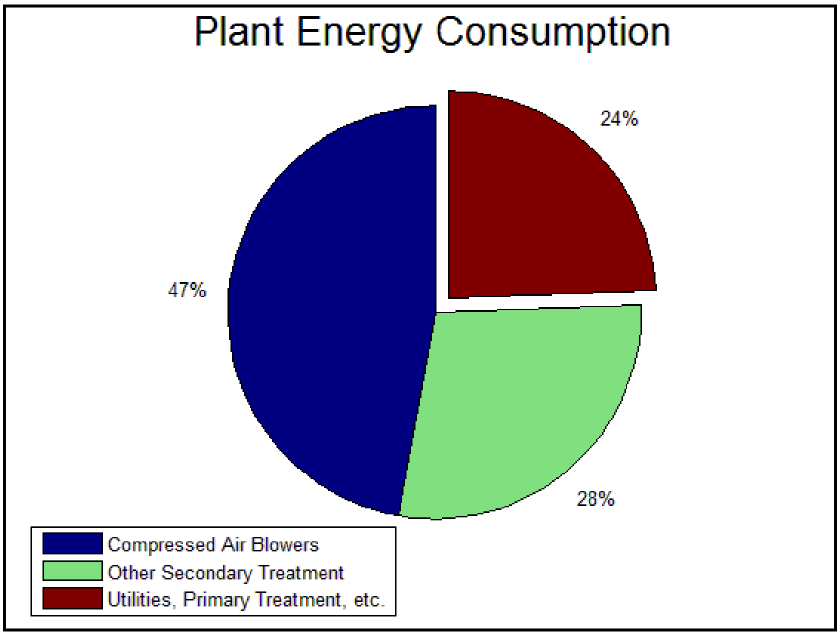

Figure 7: Energy consumption breakdown for the Audited WWTP

Electrical Issues

As discussed above the Fluke 435 allows for the analysis of electrical losses within the system. For the compressed air blower the electrical losses were recorded for the duration of the trial. These are enegy losses calculated using gathered data and an energy loss algorithem developed by Fluke in conjuction with Polytechnic University, Valencia, Spain [24]. The energy losses were then converted to energy loss per month in Euro based on €0.15 per kWh.

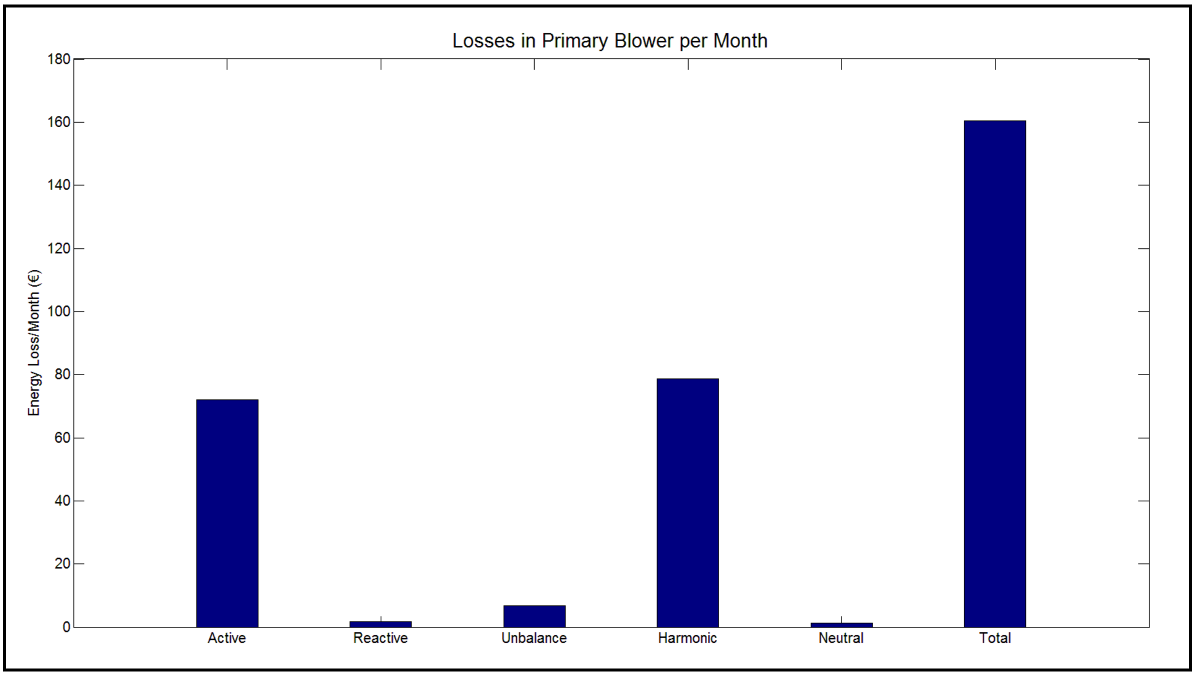

Figure 8: Electrical energy losses per month for the compressed air blower in Euro

The energy loss calculator breaks down the losses into 5 categories; active, reactive, unbalance, harmonic and neutral. Figure 8 shows significant losses in the active and harmonic categories. The active losses are due to resistances within the system and are inherent to the device. Harmonic losses, however, are due to small sinusoidal oscillations on the voltage lines and cause heat build ups in conductors.

DISCUSSION

This research has identified that there are major energy saving opportunities available for Irish WWTP. However, until treatment plants can perform in depth audits and provide effective instrumentation and monitoring to their key processes then these opportunities cannot be realised. Because every WWTP is different, there is no one size fits all solution. This study suggests that electrical disturbance issues within plant equipment can be an area of potential energy loss. Also, the installation of variable frequency drives has been found to introduce additional electrical issues such as harmonic distortion and load imbalance. From the electrical energy loss analysis, the audited plant compressed air blowers display issues with harmonic distortion which would be made worse with the addition of a VFD. This shows the importance of monitoring within a WWTP when introducing ICA. This energy audit has highlighted the challenges faced by Irish WWTPs to increase energy efficiencies across plant processes. The proportion of energy consumed by secondary treatment is greater in the audited plant than described in the literature. This indicates that plant sub-system would greatly benefit from the implementation of some of the proposed process improvements.

CONCLUSION

This research paper had two main objectives: 1) assess the literature and identify energy savings opportunities in WWTP, and 2) undertake an energy audit of an Irish WWTP. Results from the Irish treatment plant audit show that 76% of total plant energy consumption was used in secondary treatment and aeration. This is somewhat higher than published typical values. In addition, significant electronic losses within the compressed air blowers have been identified. Mitigation strategies and corrective measures to combat these electrical losses have been identified in the literature. Furthermore, the literature points to significant energy savings through the implementation of instrumentation, control and automation.

In summary, the results from this study indicate that there are opportunities for significant energy savings within Irish wastewater treatment plants. By working closely with the Irish Environmental Protection Agency (EPA), the implementation of the proposed process optimisation strategies within municipal treatment plants across Ireland should result in substantial energy savings, and thus, improved environmental performance.

REFERENCES

[1] M. Henze., *Wastewater Treatment: Biological and Chemical Processes,* ,Second Edition ed.Springer, 1997.

[2] Irish Water. Development of Water Services Strategic Plan (WSSP) for Irish Water [Online]. http://www.water.ie/about-us/future-plans/ [accessed: May 29, 2014]

[3] European Commission, "Council Directive: concerning urban waste water treatment (91/271/EEC)," 21 May 1991.

[4] D. Shannon, B. Wall and D. Flynn, "Focus on urban waste water treatment in 2012: A report for the year 2012," Irish Environmental Protection Agency, Wexford, Ireland, 2014.

[5] G. Olsson, in *Biological Wastewater Treatment – Principles, Modelling and Design* Henze, M. van Loosdrecht, M. Ekama, G. Brdjanovic, D., Ed. London: IWA Publishing, (2008),

[6] K. Gernaey, L. Benedetti, L. Corominas, G. Langergraber, U. Jeppsson, X. Flores-Alsina, C. Rosen and P. Vanrolleghem, "Wastewater treatment plant influent disturbance models," in *2nd IWA/WEF Wastewater Treatment Modeling Seminar,* 2010, pp. 283.

[7] G. Tchobanoglous, F. L. Burton and H. D. Stensel, *Wastewater Engineering: Treatment and Reuse*, Fourth Edition ed.USA: McGraw-Hill, 2003, pp. 1819.

[8] W. Solnik and Z. Zajda, "Automation of oxygenation process in biological treatment plants," in *Scientific Proceedings of Riga Technical University,* 2000,

[9] J. Mistry, et al, "Variable Frequency Drive," vol. 2, pp. 252, September. 2012.

[10] GAMBICA Association Ltd. and British Pump Manufacturers Association, "Variable speed driven pumps: Best practice guide," GAMBICA Association Ltd., England, Tech. Rep. 1, August, 2003.

[11] M. Springman and D. Marsch, "Energy Efficiency at a small wastewater treatment plant: Use of variable frequency drives to control aeration blowers," Illinois Sustainable Energy Centre, Prairie Research Institute, Illinois, Tech. Rep. TN13-105, December, 2013.

[12] A. Lekov, L. Thompson, A. McKane, K. Song and M. A. Piette, "Opportunities for energy efficiency and open automated demand response in wastewater treatment facilities in california – phase I report," Lawrence Berkeley National Laboratory, California, USA, Tech. Rep. 1, April, 2009.

[13] United States Environmental Protection Agency, "Fine pore aeration systems," US EPA Centre for Environmental Research Infromation, Cincinnati, OH, Tech. Rep. EPA/625/1-89/023, September, 1989.

[14] G. Olsson and B. Newell, *Wastewater Treatment Systems. Modelling, Diagnosis and Control,* London: IWA Publishing, 1999, pp. 728.

[15] A. Lazic, V. Larsson and Å. Nordenborg, "Energy savings potential of new aeration system: Full scale trials," *Water Practice & Technology,* vol. 7, 2012.

[16] D. Vrecˇko, et al, "Improvement of ammonia removal in activated sludge process with feedforward-feedback aeration controllers," vol. 53, pp. 125, 2006.

[17] P. Ingildsen, "Realising full-scale control in wastewater treatment systems using in situ nutrient sensors," *PhD Thesis,* 2002.

[18] A. Thunberg, A. Sundin and B. Carlsson, "Energy optimization of the aeration process at käppala wastewater treatment plant," in *10th IWA Conference on Instrumentation, Control and Automation*, 2009.

[19] Don Esping, "Ammonia controlled aeration," in *CSWEA 85th Annual Conference,* 2012,

[20] L. Ferrell, "Aeration efficiency and optimization," Schneider Electric Water Wastewater Competency Center, Tennessee Water Wastewater Utility Partnership, March, 2012.

[21] K. Tory and R. Pope, "Eliminating harmonics from the facility power system," *Power Transmission Design,* pp. 43, April. 1997.

[22] Fluke Corporation. Fluke 435 Series II Power Quality and Energy Analyser [Online]. http://www.fluke.com/fluke/ieen/power-quality-tools/logging-power-meters/fluke-435-series-ii.htm?PID=73939 [accessed: May 25, 2014]

[23] Met Eireann. Weather Station Data [Online]. http://www.met.ie/climate/daily-data.asp [accessed: May 23, 2014]

[24] Fluke Corporation, "The Valencia algorithm: Calculating costs of energy loss due to poor power quality," 2012.