Development of an auditing methodology for Irish wastewater treatment plants

Award: M.Eng

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DISCLAIMER

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

EPA RESEARCH PROGRAMME 2014-2020

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Nomenclature

ANN	Artificial Neural Network
APC	Advanced Process Control
ASHRAE	American Society for Heating, Refrigeration and Air-Conditioning Engineers
ASM	Activated Sludge Model
BOD	Biochemical Oxygen Demand
CAS	Conventional Activated Sludge
COD	Chemical Oxygen Demand
DMC	Dynamic Matrix Control
DO	Dissolved Oxygen
EIA	Energy Information Administration
EPA	Environmental Protection Agency
FST	Final Settlement Tank
HVAC	Heating, Ventilation and Air Conditioning
IAWA	International Association on Water Quality
IAWPRC	International Association on Water Pollution Research and Control
IAWQ	International Association on Water Quality
ICA	Instrumentation, Control and Automation
IWA	International Water Association
MBR	Membrane Bioreactor
MLSS	Mixed Liquor Suspended Solids
PE	Population Equivalent
PF	Power Factor
PFT	Picket Fence Thickener
PI	Proportional, Integral
PID	Proportional, Integral, Derivative
PM	Preventative Maintenance
PQA	Power Quality Analyser
RAS	Return Activated Sludge
SBR	Sequence Batch Reactor

SCADA	Supervisory Control and Data Acquisition
SRT	Sludge Retention Time
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
TSS	Total Suspended Solids
USEPA	United States Environmental Protection Agency
UWWTD	Urban Waste Water Treatment Directive
UV	Ultra-Violet
VFD	Variable Frequency Drive
WAS	Waste Activated Sludge
WWT	Wastewater Treatment
WWTP	Wastewater Treatment Plant

Abstract

Wastewater treatment is an energy and resource intensive process. The treatment objective is to produce an effluent that meets environmental discharge limits. As the limits become ever more stringent, it is predicted that energy consumption will increase. This research focuses on the development of an energy auditing methodology for wastewater treatment plants (WWTPs) and investigates potential measures for increasing plant energy efficiency. In-depth energy audits and water quality testing were performed simultaneously on four WWTPs in Ireland. Two small plants (400 – 500 P.E.[1]) and two medium sized plants (12,000 P.E.) were chosen for this study. These plants are representative of many WWTPs across Ireland, with 87% of all Irish WWTPs being smaller than 10,000 P.E. Additionally, one large plant (50,000 P.E.) was selected for a preliminary evaluation of energy consumption and distribution. The plant energy audits identified numerous opportunities to improve energy efficiency. Plant layout issues, ineffective control/automation systems and various electrical inefficiencies were discovered. Another important finding of this study showed that influent composition can have a large effect on the interpretation of the energy efficiency results and perceived plant performance. Energy audits alone do not tell the full story and parallel water quality monitoring is required in order to make comparisons from plant to plant.

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

1 Introduction

Wastewater treatment is a vital operation in today's society to protect human health and to protect the environment from the negative effects of pollution. However, the treatment of wastewater can also have a significant environmental toll, particularly in terms of energy consumption and chemical usage. According to the United States Environmental Protection Agency, the wastewater treatment industry accounts for approximately 1% of the world's total energy consumption [2]. With increasing environmental standards [3] coupled with the predicted rise in WWTP energy consumption over the next 10-15 years [2, 3], wastewater treatment will face tough challenges to meet environmental standards while treating water in an energy efficient manner.

Electrical energy consumption typically accounts for 25 – 40% of a WWTP's operational budget [4, 5]. Effective energy management is essential for the successful management of Irish WWTPs; WWTP energy usage is predicted to rise by 60 – 100% to meet environmental standards over the next 15 years [6]. With this in mind, energy management will become an increasingly important aspect of WWTP operations.

1.1 Objectives

The objective of this research was to develop comprehensive and practical energy auditing methodologies for Irish wastewater treatment plants (WWTPs) and to undertake detailed audits of several Irish WWTPs. The work was conducted with the aim of providing guidelines and data to aid plant operators, engineers and regulators to improve plant energy efficiencies. A number of WWTPs were assessed and analysed using a variety of auditing approaches:

- Energy auditing
- Power quality analysis
- Water quality analysis.

This objective was to incorporate each of the individual approaches into a useful WWTP auditing methodology. Five Irish WWTPs were audited in terms of energy consumption, power quality and water quality. Table 1 shows an overview of the audited plants including basic characteristics of each plant.

Table 1: Plant descriptions

Plant	Design Capacity (P.E.[2])	Agglomeration Served[3] (P.E.)	Receiving water	Level of treatment (P),(S),(T)	Type of secondary treatment[4]
A	50,000	37,200[5]	Freshwater	Primary + Secondary	Activated Sludge +P
B	12,000	12,284	Freshwater	Primary + Secondary	Activated Sludge +P
C	12,000	9,036	Freshwater	Primary + Secondary	Activated Sludge +P
D	600	1,024	Freshwater	Primary + Secondary	Activated Sludge +P
E	820	590	Freshwater	Primary + Secondary	Activated Sludge +P

Plant selection was carefully considered during this study. It was important to select plants that are representative of Irish WWTPs in terms of size and treatment technology. In order to have a variety of plant sizes one relatively large plant was selected (Plant A). Two plants (Plant B and C) with a population equivalent (P.E.) of 12,000 were selected. These plants are representative of medium sized Irish WWTPs. Finally, two small plants (Plant D and E) were selected. These plants are typical of the majority of Irish WWTPs which serve a P.E. of less than 2,000.

Plant selection was not the only consideration prior to conducting this research; the availability of monitoring equipment dictated how detailed the WWTP audits could be. A wide range of energy monitoring equipment was selected from low cost portable meters to sophisticated energy analysis monitors. The subsequent deployment of the energy meters, with the aforementioned range of functionality and sophistication, facilitated in assessing the merits of investing in expensive monitoring equipment over more cost effective alternatives.

Due to the high level of energy and water quality monitoring in this study, data processing was a challenging task. With audits lasting up to three weeks in some plants, there was a large amount of data analysis required. Additionally, there were

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

[3] Annual Environmental Report data. Agglomeration, as defined in the Waste Water Discharge (Authorisation) Regulations, means an area where the population or economic activities or both are sufficiently concentrated for a waste water works to have been put in place

[4] +P = with phosphorus removal

[5] Latest calculated data would suggest this plant may be operating over design capacity (see section 3.1.1)

various challenges encountered while conducting the plant audits. Water and energy monitoring can often be a time consuming process. The completion of the five energy audits required continuous coordination with plant caretakers, engineers and local council officials. For many of the audits, plant access was not straightforward. Furthermore, in some cases, plants could only be accessed at certain times of the day.

This thesis is divided into a number of chapters. Chapter 2 presents a high level background of the wastewater treatment industry along with various methods of wastewater treatment. A detailed review of the available literature is then presented in Chapter 3. The review focuses primarily on areas such as: energy auditing methodologies, instrumentation, control and automation. The main body of this report develops and documents a practical energy auditing methodology for WWTPs along with the results of the energy and water quality audits that were undertaken. The benchmarking data, plant audit metrics and the significant findings from the five plant audits are discussed in Chapter 5. The conclusions of this research are presented in Chapter 6. Finally, a comprehensive list of plant auditing recommendations for plant managers and operators are presented in Chapter 7.

2 Background and Literature Review

On the 21st of May 1991 the European Economic Community (EEC) issued a directive on wastewater treatment plant discharge [7]. The Urban Waste Water Treatment Directive (UWWTD) stated that all treatment agglomerations[2] greater than 2000 P.E. that discharge into sensitive waters would require secondary treatment. Additionally, all agglomerates above 10000 P.E. regardless of discharge location would require secondary treatment. This directive caused Irish authorities to take a closer look at the current status and management of Irish WWTPs with a view to meeting the directive targets [8].

2.1 Treating Wastewater

There are various methods of treating wastewater which differ from small scale domestic treatment to large scale wastewater treatment plants. Many homes choose to treat their own wastewater on site through septic systems. According to the 2011 Irish census, 27.5% of homes in the Ireland were served by personal septic systems [9]. The overwhelming majority of these homes were based in rural and suburban locations. In larger towns and cities, centralised wastewater treatment plants are more prevalent. These treatment facilities range in size and sophistication of technologies.

2.2 Wastewater Treatment Plants

WWT can generally be broken down into four seemingly simple processes:

1. Primary treatment
2. Secondary treatment
3. Tertiary treatment
4. Sludge treatment

However, in reality, each of these processes has their own complexities. Additionally, the interactions and dependencies between the processes add to the overall WWTP complexity. Wastewater treatment can be performed using a variety of methods and technologies. This section introduces the basic techniques used within each of the areas listed above.

2.3 Primary Treatment

2.3.1 Screening

The raw sewage entering WWTPs will contain large quantities of debris (rags, wood, paper, etc.) The first process that sewage undergoes upon reaching the WWTPs is screening. The wastewater is directed through channels which are fitted with a series of screens. Some screens can be as simple as evenly spaced horizontal bars that stop large pieces of wood or rags. Additionally, finer strainer screens can be used to capture smaller pieces of debris. Due to the inconsistent nature of the raw sewage, these inlet screens require a large amount of maintenance and need to be cleaned regularly to prevent blockage. Mechanically racked screen bars use conveyor belt driven brushes or rakes to remove the debris from the screen bars, lifting it away from screen and disposing of it appropriately [10].

2.3.2 Grit Removal

The removal of grit at an early stage of the treatment process is vital to prevent unnecessary wear on mechanical equipment. Grit can consist of sand, small bones, seeds, coffee grounds, eggshells and other materials that are heavier than organic matter [11]. An acceptable grit removal unit should remove 95% of particles with a diameter greater than 0.2mm [12]. This is generally achieved by maintaining a water velocity of approximately 0.3 m/s through a grit chamber. The grit chamber collects the heavier particles and allows the suspended organic matter to pass through. Grit separator technologies are generally classified under three categories; horizontal flow, aerated and vortex type grit chambers [4]. In horizontal flow grit chambers, the wastewater flows into a tank where the water velocity through the tank is maintained at the 0.3 m/s. This is a calculated optimum velocity and is based on factors such as; particle size, specific gravity of the particle to be removed, gravitational acceleration and a friction factor [13]. The grit material sinks to the bottom of the tank and rotating scrapers on the base of the chamber discharge the grit. In some systems the grit can be washed and organic matter can be returned to the chamber. Aerated chambers, in contrast, use compressed air blowers to create a spiral flow pattern through the chamber. This creates a condition where the water velocities at the surface are greater than those at the bottom, allowing the grit particles to settle and be removed. Finally, vortex chambers can have different designs from one plant to another [14]. The main principle is that they create a mechanically or hydraulically induced vortex which separates the grit from other suspended particles.

2.3.3 Primary Settlement

Primary settlement tanks are usually circular or rectangular in shape. The main role of these tanks is to facilitate the removal of settle-able solids (see Figure 1). In circular settling tanks, this is done by reducing the velocity of the incoming waste to allow the solids to fall to the bottom of the tank. The tank scraper, which rotates along the bottom of the tank, collects the settled solids and they are pumped away as primary sludge. The removed sludge can be then be stabilised or processed for resource recovery as discussed further in Section 2.6. Rectangular tanks operate in a similar manner except that the sludge scraper mechanism moves linearly over and back across the tank as show in Figure 2[15, 16]

Generally a primary settlement tank removes 50-70% of suspended solids and reduces Biochemical Oxygen Demand (BOD) by 20-50% [15, 16]. The most important factor that influences the performance of the primary settlement units is the local velocities of the wastewater within the tank. In order to achieve solids removal of greater than 50% these local velocities must be kept below 0.015 m/s. To keep local velocities below this level, inlet configuration is key as varied flowrates into the tank can cause turbulence [12, 16].

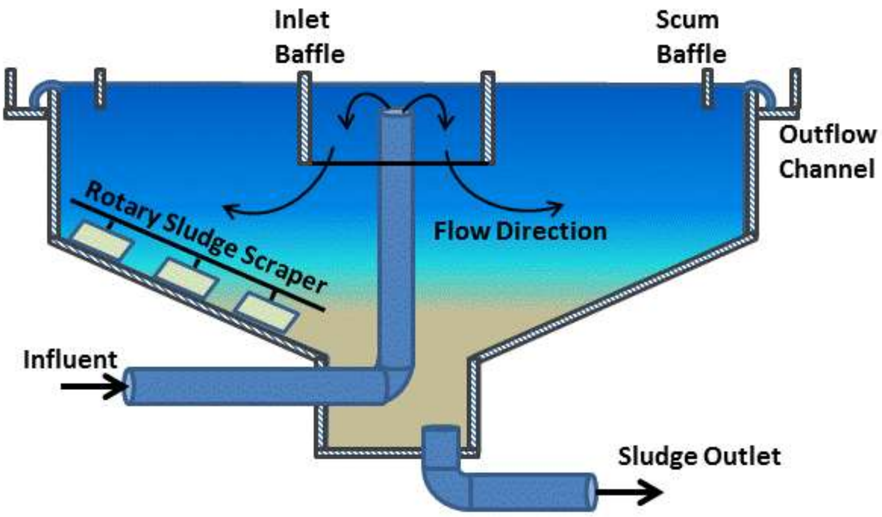


Figure 1: Circular primary settlement tank adapted from EPA report "Wastewater Treatment Manuals" [15]

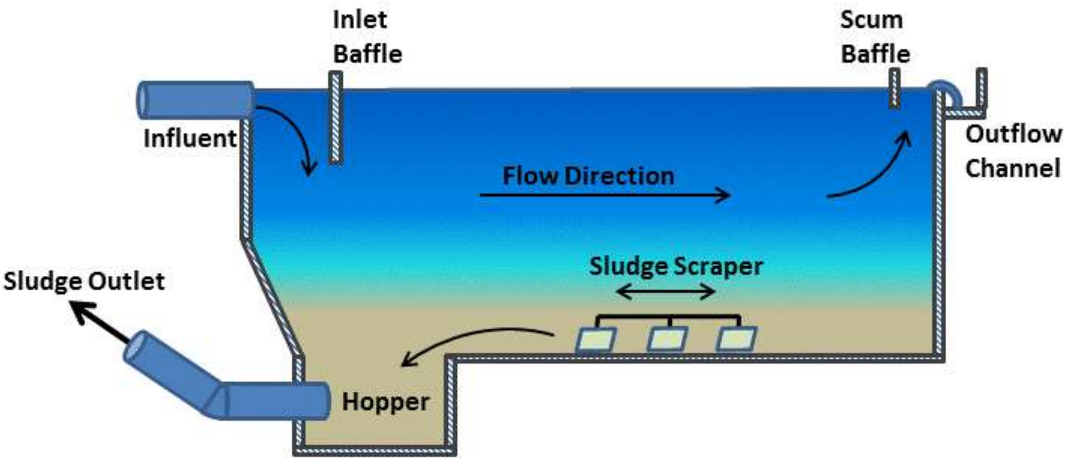


Figure 2: Rectangular primary settlement tank adapted from EPA report "Wastewater Treatment Manuals" [15]

Aside from the tanks discussed above, there are a number of other technologies that work on similar principles. Imhoff tanks, incline settlement tanks and dissolved air flotation systems are some of the alternative methods of primary treatment that are used internationally [15].

2.4 Secondary Treatment

Secondary wastewater treatment generally involves a biological process to remove organic matter. There are a number of different methods utilised in secondary treatment, and the selection of a process depends upon factors such as quantity and biodegradability of the wastewater and also the building space available [17]. The most popular processes implemented in wastewater treatment plants include:

1. Conventional activated sludge (CAS)
2. Sequence batch reactor (SBR)
3. Membrane bio-reactor (MBR)
4. Bio-film reactor (PFBR).

2.4.1 Conventional Activated Sludge

The most common method employed for secondary treatment is the activated sludge process. In the UK approximately 50% of WWTPs employ activated sludge treatment systems [18, 19]. In this process, wastewater is transferred into an aeration tank where it encounters various micro-organisms. The combination of these micro-organisms and wastewater is often referred to as activated sludge or mixed liquor. In this aeration tank, diffused air blowers or mechanical aerators are used to keep the activated sludge in suspension and the oxygen introduced helps the micro-organisms to consume the organic matter. A flow diagram for the activated sludge process is shown in Figure 3. The activated sludge in the aeration tank is transferred to a settling tank where heavier particles settle to the bottom. A portion of this sludge is pumped away as waste activated sludge (WAS) and the rest, referred to as return activated sludge (RAS), is pumped back into the aeration tank to maintain a healthy population of micro-organisms. Clean water (supernatant) overflows the settling tank and is either pumped away to tertiary treatment or becomes final effluent and flows into receiving waters (rivers/lakes/seas) [4].

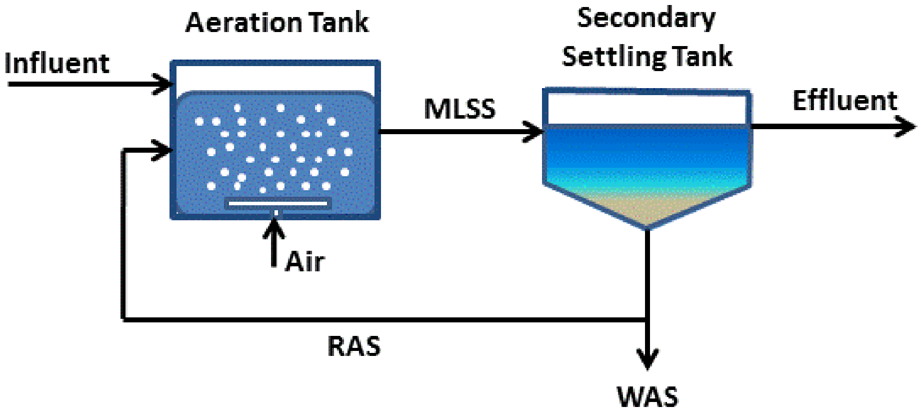


Figure 3: Model of conventional activated sludge system [15]

2.4.2 Sequence Batch Reactors

As mentioned in Section 2.4.1 conventional activated sludge systems are implemented with two tanks, one for aeration and another for sludge settling. SBR systems on the other hand operate by the same principles as CAS systems except that the whole process is carried out in one tank. Unlike CAS, which is a continuous process, SBR systems operate according to a four stage process as shown in Figure 4. Firstly, the mixed liquor is pumped into the SBR tank (stage one). Once the tank is filled to the required volume, compressed air blowers transfer oxygen to the tank for a period of time to create an aeration stage (stage two). The aeration is then stopped and the settlement process begins (stage three). During this stage, gravity settling is used to separate the mixed liquor from the clean supernatant. Finally, the supernatant is decanted off and the mixed liquor at the bottom of the tank is pumped away as WAS (stage four) [15]. Total cycle time is dependent on various factors such tank size, influent loading, effluent discharge regulations. Depending on the plant, the total cycle time can vary from hours to days [20, 21].

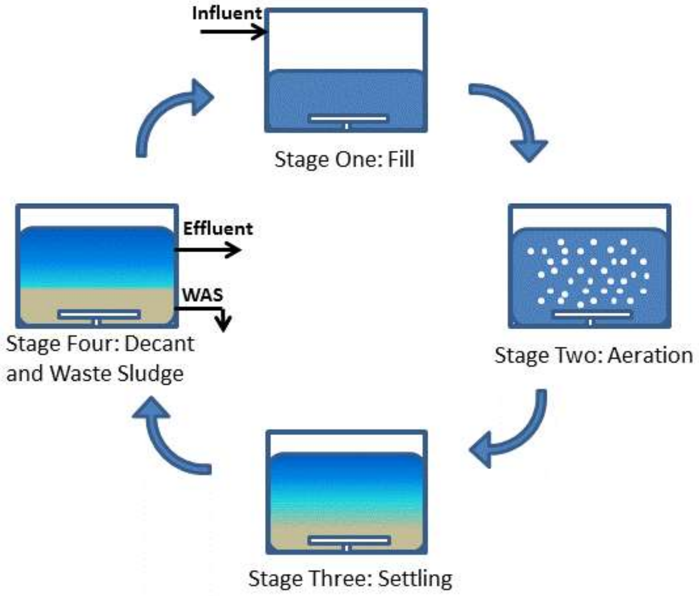


Figure 4: Model of sequence batch reactor [15]

SBR technology is becoming more popular in many Irish wastewater treatment plants [22]. They are often chosen over CAS systems because of their small physical footprint and they can be easily adjusted to create aerobic, anaerobic, and anoxic conditions. Additionally, older WWTP can be retrofitted with SBR systems using the old treatment tanks to create an SBR setup [23].

2.4.3 Membrane Bio-reactors

The first commercial membrane bio-reactors were developed in the 1960s. Since then the technology has come a long way; in the last 20 years the cost of MBR systems and process costs have decreased seemingly exponentially [24]. MBRs operate in a similar way to CAS systems and SBRs. The major difference is that instead of gravity settling of the mixed liquor, MBRs use filtration to separate sludge from the clear supernatant. There are two general classifications of MBRs, sidestream and immersed reactors (see Figure 5 and Figure 6). Sidestream reactors use the conventional aeration process followed by a membrane filter tank. This filter stops the MLSS from passing through. The MLSS are then returned to the aeration tank as RAS. The immersed reactor was developed as an improvement on the sidestream design in the mid-1980s. The immersed reactor operates with the membrane filter mounted inside the aeration tank. The membrane filter draws out the treated effluent (as before) while the MLSS remains in the tank. Here, the entire process takes place inside the aeration tank, thus reducing the amount of pumping required [24].

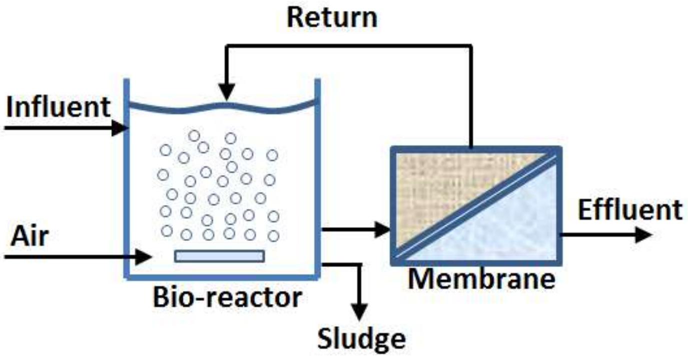


Figure 5: Sidestream reactor adapted from Judd [24]

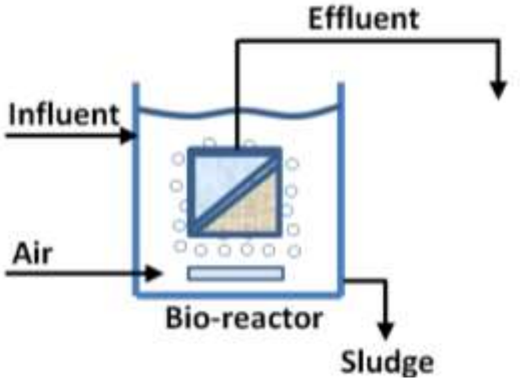


Figure 6: Immersed reactor adapted from Judd [24]

In recent years, MBR have been identified as, and shown to be, a viable alternative to CAS systems [25]. Abdel Kader’s study on the comparison of a CAS systems and MBR system found that the treatment efficiency (based on percentage of BOD removed) of the MBR was greater than that of the CAS system for all tested BOD concentrations (225 g/m^3 - 450 g/m^3). There are, on the other hand, some downsides to the MBR setup. Membrane fouling has proven to be a big problem for this type of treatment [24, 26]. The fouling causes the membrane surface and internal pores to become blocked. Due to this fact, regular maintenance and chemical cleaning is required to keep the MBR system functioning efficiently [27]

2.4.4 Bio-film Reactors

Not to be confused with MBRs, bioflim reactors use a polymeric media which is used as a substrate to grow a biomass film. Biofilm growth has three stages (Figure 7). Firstly, the bacteria attaches to the substrate. The bacteria grow in multiple layers over time and form a micro-organism population which consume organic matter. The biomass film then detaches naturally and is collected as sludge [28].

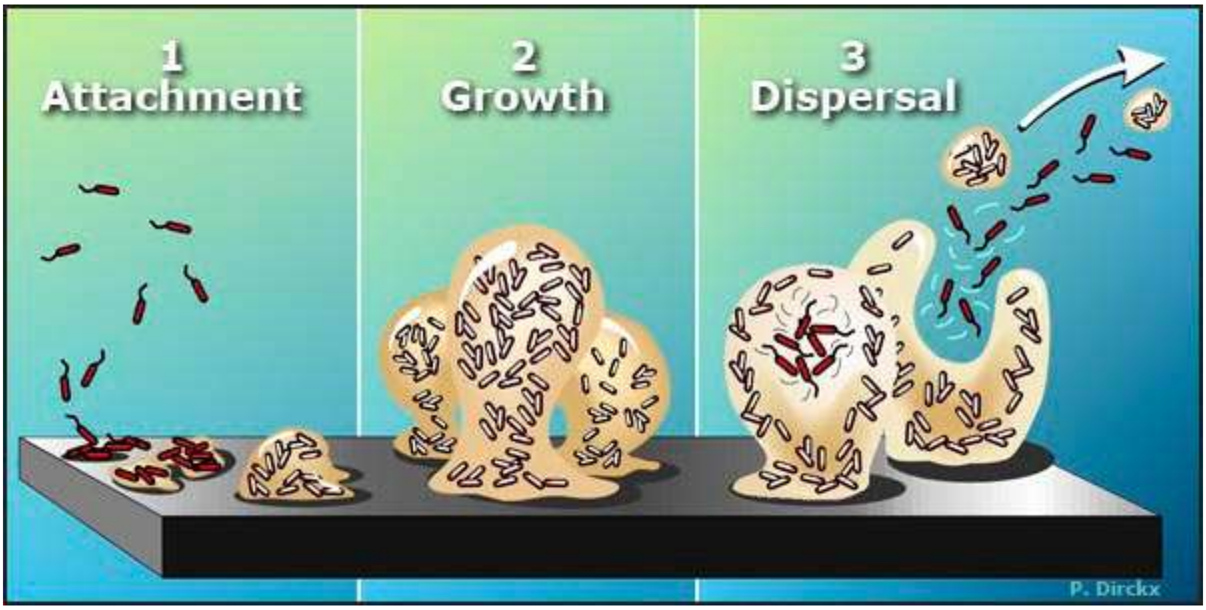


Figure 7: Biomass growth process [28]

There are a number of different types of biofilm reactor technologies that are employed in WWTPs today, for example:

1. Moving bed biofilm reactor (MBBR)
2. Hybrid biofilm membrane reactor (BF-MBR)
3. Pump flow biofilm reactor (PFBR).

2.5 Tertiary Treatment

Tertiary treatment has not been widely implemented in Ireland. In 2009, approximately 70% of the North and Central European population were connected with tertiary treatment. In Ireland the proportion of the population connected is 12% [29]. Tertiary treatment is much more prevalent in countries such as Germany, the Netherlands and Switzerland (>95% connectivity). In these regions there is a range of tertiary treatment technologies used. The most popular treatment methods include:

1. Micro-strainers
2. Rapid gravity sand filters
3. Upward flow sand filters
4. Slow sand filters
5. Pebble bed clarifiers
6. Reed bed systems
7. Lagoons/Artificial lakes.

2.6 Sludge Treatment

Section 2.4 describes the many processes and methods of separating clean water from sludge. The handling and disposal of the WAS is challenging and is also a very important environmental issue. After WAS is separated and pumped away from the biological reactors, there are a number of possible processes that this sludge can undergo including:

1. Sludge thickening and dewatering
2. Lime stabilisation
3. Anaerobic digestion

2.6.1 Sludge thickening and dewatering

The WAS from primary and secondary treatment often has a high water content [30]. To increase the solids content of the sludge it goes through a process of thickening and dewatering. Thickening is generally achieved by mechanical means. Table 2 describes typical sludge thickening methods.

Table 2: Sludge thickening technology breakdown, adapted from Metcalf and Eddy [30]

Method	Sludge Type	Resultant solids concentration	Notes
Gravity thickening	Primary	n/a	Commonly used with good results
	Untreated primary and WAS	4% - 6%	Often used for small plants only
	WAS	2% - 3%	Seldom used
Dissolved air floatation	Primary	n/a	Seldom used
	WAS	3.5% - 5%	Use is decreasing due to high operating costs
Solid bowl centrifuge	WAS	4% - 6%	Often used
Gravity belt thickener	WAS	3% - 6%	Often used
Rotary drum thickener	WAS	5% - 9%	Seldom used

2.6.2 Lime Stabilisation

This is a simple process whereby lime is added to the sludge to increase the pH levels to above 12 for a period of at least 2 hours. This helps to reduce the amount of bacteria and viruses in the sludge and reduces the sludge odour [31].

2.6.3 Anaerobic Digestion

Anaerobic digestion (AD) is a fermentation process whereby organic matter is degraded and biogas is produced (mostly methane and carbon dioxide). In the last 35 years, the number of WWTP utilising AD has increased year on year [32]. In 1980 there were less than twenty plants worldwide with AD systems; by 2015 the number of AD plants had increased to 2250 [32]. AD involves four general phases of sludge degradation: hydrolysis, acetogenesis, acidogenesis and methanogenesis (as shown in Figure 8)[33, 34].

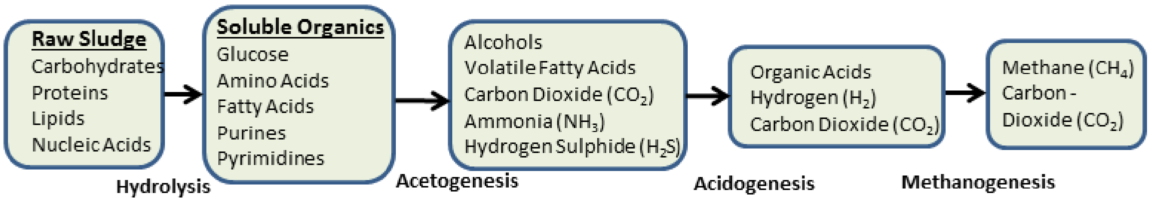


Figure 8: Anaerobic digestion process flow, adapted from Dahiya [33] and Turovskiy [34]

In an anaerobic digestion system, temperature is very important as different types of bacteria thrive at various temperature ranges. There are two temperature ranges used in anaerobic digesters; mesophilic and thermophilic ranges. Mesophilic digesters operate at a temperature range of 30 – 38 °C, while thermophilic digesters operate at 50 – 57 °C [34]. There are a number of advantages and disadvantages to using AD in wastewater treatment:

Advantages:

1. Methane gas produced can be used to produce energy to run plant equipment
2. Sludge mass is reduced, 30 – 65% of raw sludge solids are destroyed [34]
3. Very little use of chemicals
4. Help to removes sludge odours
5. High rate of pathogen destruction
6. Digested solids retain nutrients making them suitable for use as soil fertilisers
7. Stabilises the raw sludge removing the need for lime stabilisation
8. Creates a market for excess sludge.

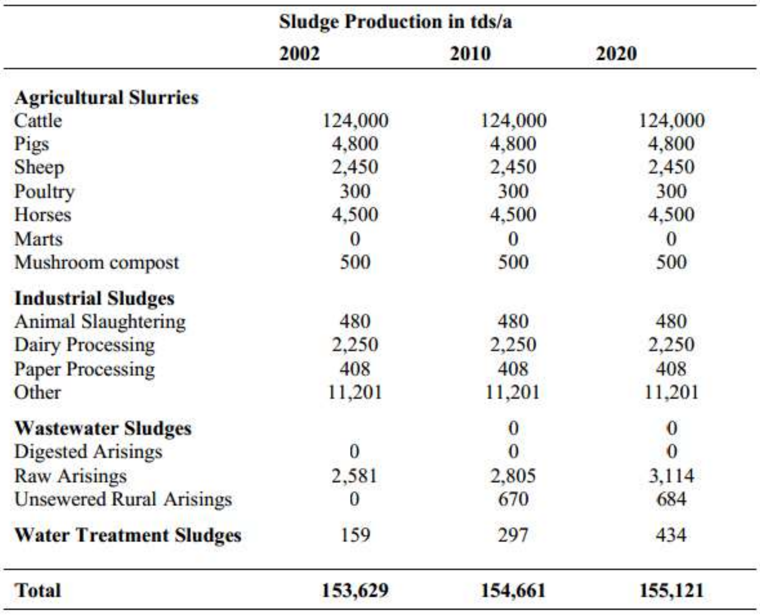
Disadvantages:

1. Micro-organisms used are sensitive to fluctuation in conditions such as variation in sludge composition, temperature and pH
2. Large reactors are required to stabilise the sludge effectively
3. High initial capital cost
4. Expertise is required to understand, operate and control the process parameters.

2.6.4 Irish Sludge treatment

WWTPs are not the only sectors that contribute to sludge production. Due to Ireland’s large agricultural sector, sludge handling and disposal is an important environmental concern for the country [35]. Table 3 shows the sludge production for Co. Kilkenny which is a relatively rural county with a large agricultural industry. The sludge production is reported as total sludge volumes in tonnes of dry solids per year (tDS/a). Wastewater sludge is broken down by the source of the sludge arisings (materials forming the secondary or waste products of industrial operations [36]). The WWTP contribution to sludge production in this county is small compared to the waste produced by agricultural industries. The breakdown will differ in other counties with more urban areas having a greater proportion of WWT sludge.

Table 3: Sludge production data for Co. Kilkenny [35]



	Sludge Production in tds/a		
	2002	**2010**	**2020**
Agricultural Slurries			
Cattle	124,000	124,000	124,000
Pigs	4,800	4,800	4,800
Sheep	2,450	2,450	2,450
Poultry	300	300	300
Horses	4,500	4,500	4,500
Marts	0	0	0
Mushroom compost	500	500	500
Industrial Sludges			
Animal Slaughtering	480	480	480
Dairy Processing	2,250	2,250	2,250
Paper Processing	408	408	408
Other	11,201	11,201	11,201
Wastewater Sludges		0	0
Digested Arisings	0	0	0
Raw Arisings	2,581	2,805	3,114
Unsewered Rural Arisings	0	670	684
Water Treatment Sludges	159	297	434
Total	**153,629**	**154,661**	**155,121**

Regardless of the source of the sludge, Ireland has a problem with sludge treatment and disposal. Taking Kilkenny as an example, there are no sludge digesters operating in the county with wastewater, industrial and agricultural sludge all spread onto the land. A 2014 EPA SRIVE report on domestic wastewater treatment systems [37] found that this is a widespread problem across Ireland.

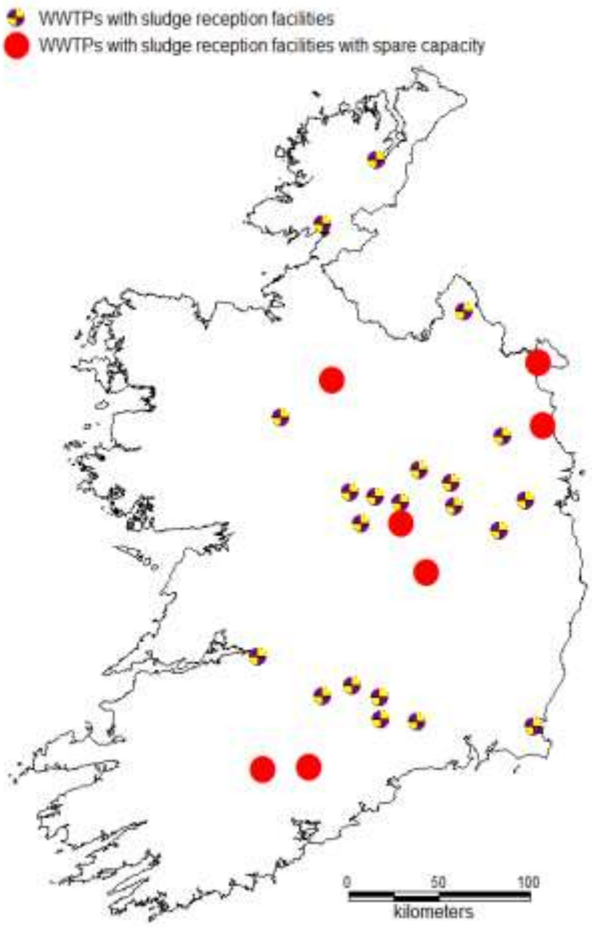


Figure 9: Domestic sludge capacity map

Figure 9 shows the locations of twenty-eight WWTPs with sludge reception facilities. Only seven of the twenty-eight WWTPs have spare sludge processing capacity. This report describes sludge reception facility as any facility equipped with the following;

1. A dedicated area for the reception of sludge and the facility for trucks to enter and exit
2. Screens to remove any large debris from the primary sludge
3. A sludge blending tank or picket fence thickener (PFT).

2.7 Energy Usage

Many factors including the UWWTD, energy cost fluctuations, budget restrictions and cutbacks have caused treatment plants to re-think their methods of water treatment and look at how energy savings can be made using process optimisation. Historically in Ireland, wastewater treatment services were delivered by 31 Local Authorities [38]. In 2013, the Irish government set up a governing body (Irish Water) to bring together the water and wastewater services of these local authorities under one national water utility [39]. The Environmental Protection Agency (EPA) are tasked with the job of ensuring that wastewater treatment plants (WWTP) across the country conform with the European directives on pollution limits for effluent waters [40]. Due to Ireland's sparse population distribution, the delivery of public services such as wastewater treatment and the supply of power to homes can be difficult and expensive. Ireland contains just two cities with populations over 100,000 people. In general, the municipal wastewater treatment services are delivered through small treatment plants distributed around the country. Of the 512 Irish wastewater treatment plants approximately 87% have a population equivalent (P.E.) of less than 10,000 [41].

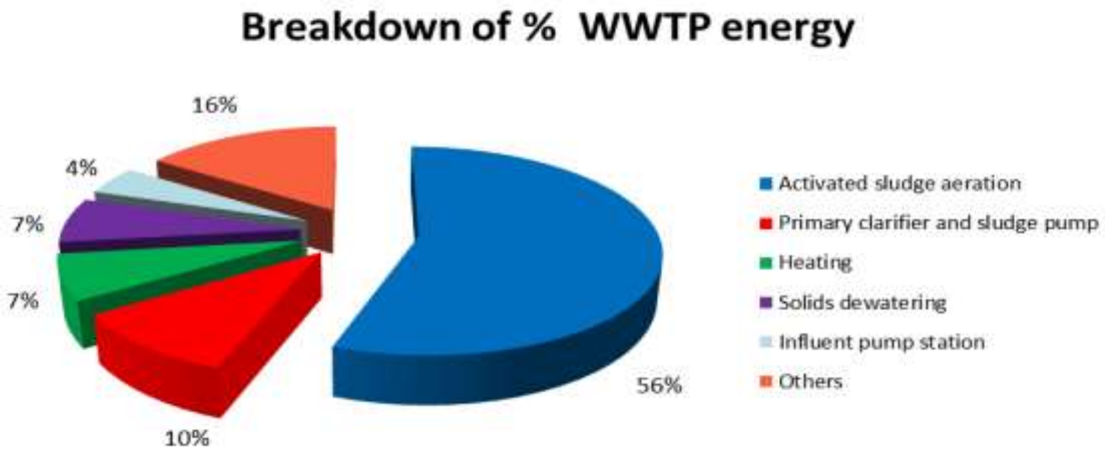


Figure 10: Breakdown of typical energy use in activated sludge wastewater treatment plants (US) [4]

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 activated sludge wastewater treatment plants, up to 66% of total plant energy use is dedicated to sludge pumping and aeration [4] (see Figure 10). This would indicate that if energy can be conserved in these areas, there may be potential for large cost savings within wastewater treatment plants.

2.8 Energy Auditing and Benchmarking

2.8.1 Industrial Energy Auditing

Several researchers have reported auditing strategies across a wide range of industries. Kong et al. [42] presented a case study of a Chinese paper mill and detailed a full scale energy audit for the mill. Using the auditing procedure outlined below in Table 4, this plant identified nine key energy efficiency opportunities and calculated a potential total energy savings of 14.4%. If energy savings such as this can be achieved in the paper industry, the key question is can the same methods be applied to the wastewater treatment industry? Olsson [43] outlined that WWTP are lagging behind the chemical/paper industries, which have demonstrated significant savings in short payback times. This is partly due to the nature of wastewater treatment which experiences large variations in flow rates, large process disturbances and zero wastewater rejection (all wastewater must be accepted and treated). In recent years the wastewater industry has begun to address this gap with other industries. For example, Fenu et al. [44] presented an energy audit of a full scale membrane bio-reactor (MBR) in an attempt to quantify the performance of the reactor under various operating conditions and compare the system with other similar technologies. Post energy audit, this study offered some suggestions for an energy friendly layout of the MBR but stopped short of outlining significant energy saving strategies. Instead they chose to focus on the calibration of a dynamic biological model called Activated Sludge Model 2 (ASM2). This modelling presented an extra insight into plant performance as the model was successfully calibrated for simulating total nitrogen (TN) removal for the CAS and MBR systems.

Table 4: Energy auditing breakdown [42]

Energy audit preparation	Energy audit execution	Post audit activities
Audit criteria	Initial walk-through	Writing audit report
Selection of audit team	Analysing energy use patterns	Preparing action plan
Audit scope	Benchmarking	Implementing action plan
Audit plan	Identifying energy efficiency potentials	
Checklists preparation	Cost-Benefit Analysis	
Data inventory and measurement		
Collecting energy bills and available data		
Preliminary analysis		

ENERGY STAR was established by the United States Environmental Protection Agency (USEPA) in 1992 in conjunction with the Lawrence Berkeley National Laboratory. The group provides energy guidelines and reports for specific sectors of industry. These guides outline trends in energy use as well as an analysis of energy efficiency opportunities for each industry. The guides are aimed towards assisting companies in analysing energy use patterns, identifying energy efficiency potentials, preparing and implementing an energy saving action plan and educating employees on best practice for energy efficiency [45, 46]. Currently, ENERGY STAR has developed industry specific "Energy Efficiency Improvement and Cost Saving Opportunity" guides for:

- Baking
- Breweries
- Cement manufacturing
- Wet corn milling
- Dairy processing
- Food processing
- Glass manufacturing
- Iron and steel manufacturing
- Motor vehicle manufacturing

- Petroleum refining
- Petrochemical manufacturing
- Pharmaceutical manufacturing
- Pulp and paper manufacturing
- Ready mix concrete manufacturing
- Small and medium manufacturing enterprises
- Textile manufacturing.

In recent years ENERGY STAR has performed significant work in the area of wastewater treatment. This includes work on benchmarking of WWTPs [47] and the development of WWTP energy recovery guidelines/fact sheets. A full sector-specific guide for wastewater industry has not yet been produced by this group.

The American Society for Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) document three key levels of energy audits for its industry [48]. As the energy audit levels (listed in Table 5) increase, the analysis becomes more detailed and complex.

Table 5: ASHRAE energy audit levels for HVAC industry [48]

ASHRAE Energy Audit Levels	
Level 1	Walkthrough assessment
Level 2	Energy survey & analysis
Level 3	Detailed analysis/ modelling

ASHRAE Audit Level 1 generally involves a walkthrough assessment of the plant, interviews with building operating staff, an analysis of utility bills and analysis of available plant data. The Level 1 audit should outline any outstanding energy efficiency issues. Level 2 audits should start with the findings from the Level 1 report. This is coupled with an in-depth energy survey, analysis of seasonal variations, and in the HVAC industry this also includes analysis of lighting, air quality, temperature, ventilation, humidity, and other conditions that could affect energy performance and occupant comfort [48]. Finally, ASHRAE Audit Level 3 (highest level audit) can include continued long term energy monitoring as well as plant-wide digital simulation. Relevant building energy simulation software is used to find further energy savings opportunities as well as assess plant changes made following the Level 2 audit recommendations. In comparison to the ASHRAE guide, Hasanbeigi & Price [46] presented a more detailed guidebook of how to perform energy audits. Although this guidebook describes energy auditing procedures effectively and describes audit preparation and analysis of energy usage patterns, it is once again not a sector specific guide for WWTPs.

The ASHRAE guidelines were used by Daw et al. [49] in a case study of Crested Butte WWTP, Colorado. This treatment plant was built in 1997 and serves a town of population 1,500 people. The plant consists of grit removal, influent pumping, aeration, clarification, UV disinfection, sludge thickening and sludge dewatering. For this facility an ASHRAE Level 1 audit was performed. This involved an evaluation of historical data, utility bills, equipment inventory and an estimation of potential energy savings. Additionally, for this audit, emphasis was placed on low or no cost energy saving measures. Consequently, the findings from this case study lacked an in-depth analysis of strategies for energy reduction. The study did however point out the main areas for potential energy savings within the WWTP. Some of the interesting strategies that were flagged included balancing water quality goals with energy needs, considering trade-offs between treatment energy and improved biosolids quality and educating the community on water conservation. These findings are typical of the type of outcomes from a Level 1 study and can be used as a starting point for the more detailed Level 2 and Level 3 audits.

Although the WWT industry is lagging behind other industries in energy efficiency, as discussed by Olsson [43], numerous WWTPs across the world have investigated energy efficiency and optimisation strategies. Audits of various degrees of complexity have been carried out in WWTPs in various international locations in recent years [50-52]. There are only a small number of published studies of level 3 energy audits of full-scale WWTPs. As discussed above, Fenu et al. [44], performed such a study on Schilde (Belgium) municipal WWTP which operates with a membrane bioreactor

(MBR) setup. In addition to analysing the MBR performance and comparing it with other technologies, the authors documented the parallel water quality analysis performed. This was an interesting area of the study as this water analysis coupled with plant energy usage may offer key information about how efficiently the plant is operating.

The wastewater treatment industry differs from many others in that auditing is not as simple as looking at energy usage and distribution. One of the difficulties associated with auditing WWTPs is that there are environmental considerations such as the strict discharge limits imposed on water quality. For this reason an energy audit alone is not enough to understand what is happening in a wastewater treatment plant. Water quality auditing has been an area that has become more prevalent in recent years [53, 54]. One of the issues when auditing wastewater facilities is the uncertainty regarding the effects that potential changes may have on the effluent water quality. Earnhart and Harrington [55] analysed the effects of conducting water quality audits on the plants compliance with wastewater discharge limits. They found that in the case of wastewater treatment it is very difficult to use water quality audits to reduce the concentration of multiple pollutants at the same time. This study outlines the complexity involved in controlling the level of pollutants when making process changes. It shows that energy auditing alone does not give an accurate representation of what is happening in any given WWTP and that audits must include an analysis of plant environmental performance.

There are few studies that outline practical energy auditing methodologies. However, in one such study, Foladori et al. [56] perform energy audits in five Italian WWTP. This study describes basic energy monitoring in each plant along with water quality data. The energy data collected consisted of overall plant voltage, current and power factor. These variables were then used to calculate power and energy consumption. The metrics considered in this study included:

1. Energy consumption per volume of influent (kWh/m^3)
2. Energy consumption per unit BOD/COD removed ($kWh/kgBOD_{rem}$ or $kWh/kgCOD_{rem}$)

3. Energy consumption per year and per P.E. served (kWh/(P.E.·yr)
4. Energy consumption per year and per P.E designed (kWh/(P.E.·yr)

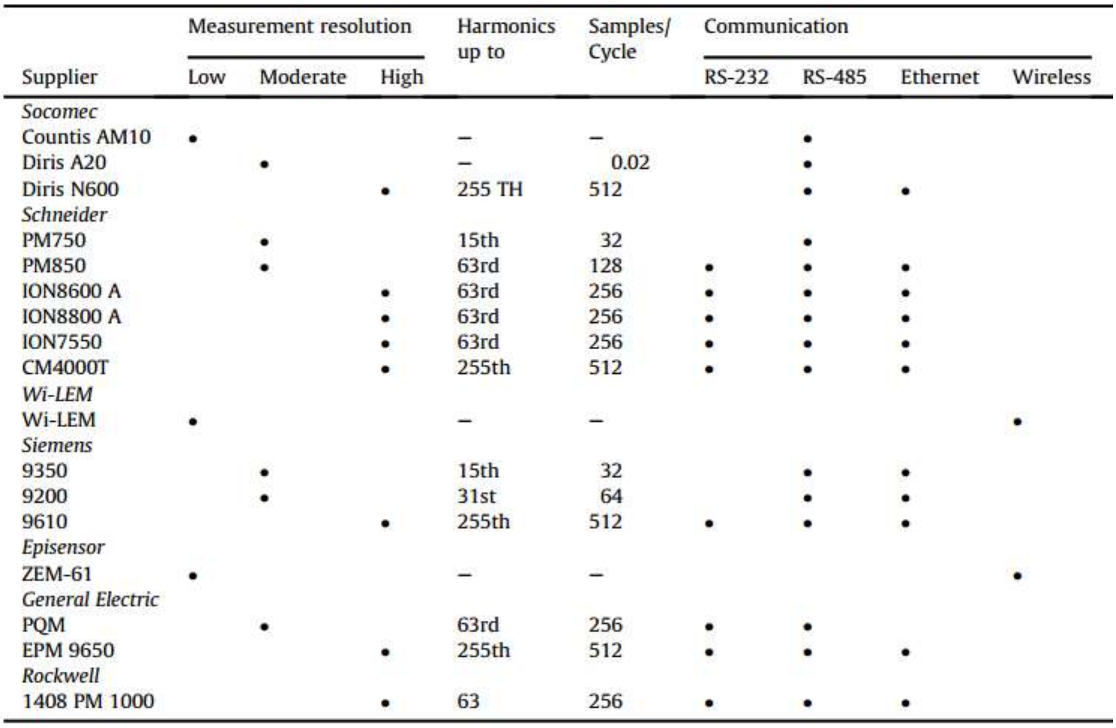
This study also presented recommendations for performing energy audits in WWTP. These recommendations include:

1. Inventory of equipment
2. Operational adjustments using control and automation
3. Implementation of FVDs and DO control systems
4. Monitoring of settled sludge recirculation energy.

2.8.2 Instrumentation

O'Driscoll et al. [57, 58] outlined the difficulties in implementing facility-wide energy metering, focusing on issues such as types of meters, meter locations, number of meters required, and the interpretation of the data. This work gives a detailed review of various power metering equipment as shown in Table 6. The survey offers a very useful breakdown of the available power meters for long term monitoring of process operation. This study could be beneficial for many industries when attempting to put in place an energy monitoring system. This research, however, does not consider the area of short term energy auditing so in reality, the spectrum of available power meters/analysers is much broader than outlined below.

Table 6 Energy analyser tool specification list [58]



Supplier	Measurement resolution			Harmonics up to	Samples/ Cycle	Communication			
	Low	Moderate	High			RS-232	RS-485	Ethernet	Wireless
Socomec									
Countis AM10	•			–	–		•		
Diris A20		•		–	0.02		•		
Diris N600			•	255 TH	512		•	•	
Schneider									
PM750		•		15th	32		•		
PM850		•		63rd	128	•	•	•	
ION8600 A			•	63rd	256	•	•	•	
ION8800 A			•	63rd	256	•	•	•	
ION7550			•	63rd	256	•	•	•	
CM4000T			•	255th	512	•	•	•	
Wi-LEM									
Wi-LEM	•			–	–				•
Siemens									
9350		•		15th	32		•	•	
9200		•		31st	64		•	•	
9610			•	255th	512	•	•	•	
Episensor									
ZEM-61	•			–	–				•
General Electric									
PQM		•		63rd	256	•	•		
EPM 9650			•	255th	512	•	•	•	
Rockwell									
1408 PM 1000			•	63	256	•	•	•	

2.8.3 Benchmarking Energy Use

The United States, through their Environmental Protection Agency (USEPA) have been one of the leaders in energy efficient wastewater treatment. They have recently published a number of documents [50, 59] in the area of benchmarking energy usage in drinking water and wastewater treatment. This document archive contains publications across a wide range of relevant topics, for example:

1. Guidelines for energy auditing
2. Excel based benchmarking tools
3. Guidelines for designing contracts to promote energy efficiency in contract-operated plants
4. EPA checklists for self-assessment of energy use

In Ireland a similar document archive is maintained by the Irish EPA. As a result of their various research funding streams [60], and through the Irish government's investment in a new water utilities agency [61], research in areas such as energy optimisation of water and wastewater system has increased greatly. Up to now there have not been any official Irish EPA guidelines for topics like energy auditing or benchmarking resource efficiency that are specific to the Irish WWT industry. Even the USEPA guidelines for energy auditing do not take into account the significant advancements in technology as they were published over 20 years ago.

Carlson and Walburger [62] benchmarked the energy consumption of WWTPs. Their study, published by American Water Works Association (AWWA), was based on a multi-parameter benchmarking score method. This method is similar to that used by the USEPA ENERGY STAR for building ratings [63]. In this study 2725 WWTPs of various size and characteristics were surveyed. A representative sample of 266 WWTPs was used for the analysis. Six parameters were identified as key energy usage variables:

1. Daily average flowrate
2. Design Flowrate
3. Influent BOD concentration
4. Effluent BOD concentration
5. Fixed vs. suspended solids
6. Conventional treatment vs. biological nutrient removal.

The final energy use model is based on multi-parameter log regression analysis:

$$\begin{aligned}\ln(E_s) = {} & 15.8741 + [0.8941 \times \ln(inf_{avg})] + [0.4510 \times \ln(inf_{BOD})] - [0.1943 \times \ln(eff_{BOD})] \\ & - \left[0.4280 \times \ln\left(\frac{inf_{avg}}{inf_{des}} \times 100\right)\right] - \left[0.3256\left(trickle\ filter\,\frac{yes = 1}{no = 0}\right)\right] \\ & + \left[0.1774\left(nutrient\ removal\,\frac{yes = 1}{no = 0}\right)\right]\end{aligned}$$

(Equation 1)

Where:

E_s = modelled plant energy

inf_{avg} = average influent flowrate

inf_{des} = Influent designed flowrate

inf_{BOD} = average influent BOD conc.

eff_{BOD} = effluent BOD conc.

This study goes on to show how plants of various types can be compared by analysing the AWWA energy score and actual energy usage (with the addition of an adjustment factor). These calculations give a rough guide to plant performance. The main problem with the accuracy of an energy benchmark score is that WWTP processes are extremely complex systems that depend on more than just the six parameters which serve as inputs into this model. Additionally, it is very hard to know the true value that each of the benchmarking coefficients should have. Scofield's [64] study on the error propagation in the ENERGY STAR rating systems also questions the validity of the energy score due to the significant possible errors in the log regression coefficients. There are also a number of other areas that are not considered, for example, whether the plant is utilizing energy recovery through sludge digestion and what proportion of this energy is being utilised.

From the available literature on auditing within wastewater treatment, there is a distinct lack of up-to-date information regarding practical issues that are unique to modern WWTPs. Issues such as appropriate sampling frequency for energy monitors, monitoring of water quality as well as selection of the appropriate and relevant power/energy variable (ie kW, kWh, PF etc.). Although some papers outline audits performed within WWTPs, these stop short of describing the auditing methods and issues involved.

2.9 Process Control Optimisation

A recent ARC advisory group study [65] found that there has been a rapidly growing market for automation and field devices for wastewater treatment applications. Based on increased investment from countries such as Brazil, Russia, China, and India, the ARC study predicts that the wastewater sector presents one of the greatest opportunities for the automation industry over the next 20 years. Additionally, many of the developed countries are working with older systems and infrastructure. The ongoing updating of such infrastructure to newer technologies that incorporate system control and automation will also contribute to the growth of the automation industry.

Instrumentation, control and automation (ICA) in wastewater treatment is an area that has continuously grown since its introduction over 40 years ago [66]. This is an area that has been brought into focus over that time by researchers such Gustaf Olsson, the International Water Association and Water Environment Research. In the WWT industry, ICA can be utilised to increase system reliability, improve plant efficiency and achieve significant energy savings. For example, Olsson [43] predicts that “improvements due to ICA may reach another 20-50% of the system investments within the next 10-20 years”.

As outlined above, ICA can offer significant improvements to the wastewater treatment industry. The successful implementation of an ICA system as outlined by Olsson can be split into several separate areas:

1. Personnel
2. Instrumentation and monitoring systems
3. Control systems.

2.9.1 Personnel

Personnel are often forgotten when it comes to a discussion about ICA. With the rate of technological advancement, it is important that there is a skilled workforce available to implement and operate WWTPs. Hug et al. [67] outlines the growing mismatch in recent years between education and requirements for engineers skilled in wastewater process dynamics, modelling and simulation. As a result of this study a number of recommendations have been made calling for an increased awareness of this mismatch between education and skills. This study also recommends an assessment of current education methods and highlights the necessity for continuous professional training and development for employees in the WWT sector. In addition to training and development Olsson also addresses this issue in a number of publications [43, 66], where he suggests that successful implementation of ICA requires a workforce that are committed and enthusiastic about making process changes in order to create efficiencies within the plant. When operators have a sense of WWTP ownership, significant energy and environmental improvements can be realised.

2.9.2 Instrumentation and Monitoring Systems

Instrumentation is a cornerstone of any energy efficient plant. In WWTPs instrumentation can be defined as 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. Ideally, this instrumentation would feed into a central monitoring system that could perform operations such as displaying the process data, detecting abnormal situations, assisting in diagnosis, and simulating consequences of operational adjustments [43]. 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 to reduce machine wear due to overuse.

2.9.3 Energy Efficient Equipment

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 [68]. 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 [69]. Springman et al. [51] describe the energy savings made through the installation of VFD devices in a small wastewater treatment facility. This plant was running two 56 kW Hoffman centrifugal blowers at 100% speed all day and night. 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. It was reported that 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 [52]. 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 of VFD devices and energy efficient equipment within wastewater treatment plants can realise quick and substantial energy savings. In AS treatment plants, in order to fully utilise VFD controlled equipment (blowers) and maximise energy savings, aeration control systems are essential.

2.9.4 Control

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. Studies on wastewater treatment plants show that automatic control systems reduce energy usage while also allowing for more precise control of process parameters [4]. Dissolved oxygen is the most widely used control variable in the WWTP industry [43, 70]. 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 O_2 to the biological reactor is desirable [71, 72]. From a European based study, Jeppsson et al. [73] concluded that at the turn of the last century, PI (Proportional-Integral) control systems were the most common strategies implemented in full scale WWTP. Figure 11 illustrates a simple DO control system. A PI controller was used to vary the airflow (air + O_2) 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 [74]. Controlled tests by the USEPA [70] 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% can be achieved.

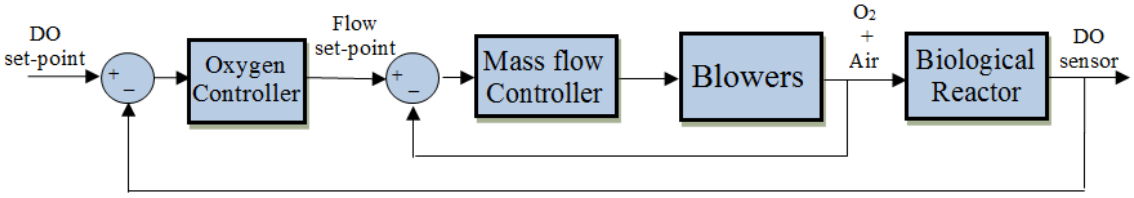


Figure 11: Feedback control block diagram for DO control to a biological reactor [74]

Some WWTP have started using ammonium based cascade control in conjunction with dissolved oxygen set-points [75, 76]. 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 (air + O_2) 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 12). 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 [74]. In a UK based case study, Esping [77] shows that switching to NH3 control can decrease airflow requirements by 20%. Additional international studies on switching WWTPS to ammonium control have also reduced airflow by 10% – 24% [74, 78, 79].

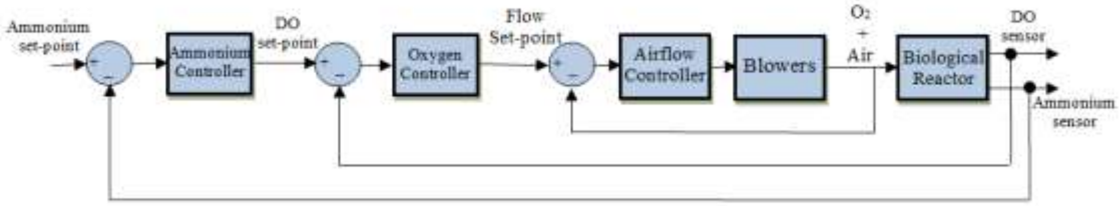


Figure 12: Feedback control block diagram for DO control to a biological reactor [74]

Currently the use of sophisticated ICA in WWTPs in Ireland is limited to the medium to large scale plants. Many of the small to medium sized plants employ control systems such as DO control within activated sludge. This is generally done using binary control of aeration blowers; the blower is turned on to full power to raise the DO levels and turned off to reduce DO [80]. Although this approach can offer plant energy savings, there are significant disadvantages, such as slow reaction time and machine wear. Additionally, due to the DO dynamics within an activated sludge system, this approach offers limited control to the WWTP. This is because the relationship between the O_2 supplied to the tank and DO levels in the tank is non-linear.

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. Instead of over or under supplying areas of the tank, each zone controls the airflow to match the DO needs for that zone [81]. Although significant energy savings can be achieved, this style of control system may involve large scale changes to plant layout and is heavily reliant on DO sensor accuracy.

Black [82] presented an alternative to simple DO control schemes in Bran Sands WWTP, Northumbria (PE: 900,000). This 2013 study documented the methods used to improve the capability of the plant to deal with storm evens, improve plant compliance and reduce aeration energy. Black achieved these improvements through a number of process changes within the activated sludge and final settlement process. In this study a PID (Proportional-Integral-Derivative) DO controlled system was replaced with an advanced process control (APC) system. This APC controller not only monitored and adjusted aeration locally based on DO, other variables such as energy usage targets and flow data were incorporated to distribute airflow to appropriate areas of the tanks.

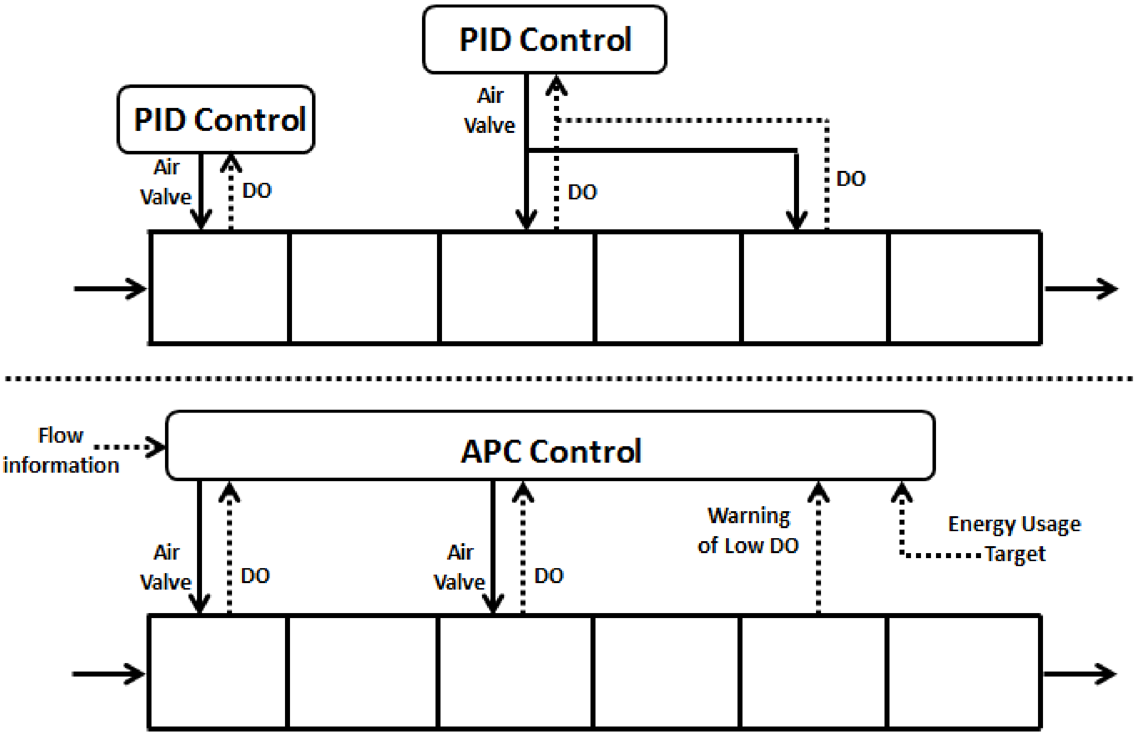


Figure 13: Layout of PID controlled system (top) and APC controlled system (bottom) [82]

A similar APC system was implemented in the final settlement tanks to monitor and control the rate of return activated sludge (RAS) and waste activated sludge (WAS) using sludge blanket level control. Many wastewater treatment plants run RAS pumps with fixed flowrates or vary RAS pumping based on the influent flowrate [83]. Using sludge blanket level control this flowrate can be continuously adjusted to more accurately control sludge age and quality.

Although, to date, there are limited publications reporting process optimisation in Irish WWTPs, there are a number of recent studies that would suggest that there is an increasing amount of research in this area. Gordon and McCann [84] are currently performing work on the development of a sustainable optimisation indicator system for small to medium sized activated sludge WWTPs in Ireland. This type of plant is typical of most Irish WWTPs. Theoretically this system will allow for continuous monitoring and rating of plant performance. The emergence of recent Irish based papers such as this shows there are optimisation opportunities in the WWT industry in Ireland.

There are many future challenges that must be faced in the area of process control in WWT. Olsson discusses the need for incorporating ICA into the plant design phase. Often plants are built to ensure that they meet the final effluent requirements and energy optimisation and the creation of other plant efficiencies is a secondary concern [85]. Technology is another limiting factor outlined by Olsson; future ICA improvements depend heavily on the improvement of instrumentation, computer processing, modelling, data validation and fault detection. This includes increasing the reliability of sensors such as DO probes. Probes that operate in wastewater tanks are subjected to harsh conditions. DO probe failure due to biofouling is a common problem in WWTPs [86].

2.10 WWTP Modelling

2.10.1 Activated Sludge Model

In 1982 a task group was set up by the International Association of Water Pollution Research and Control (IAWPRC). This task force focused on mathematical modelling for design and operation of activated sludge processes [87]. The outcome of this task group was the development of the Activated Sludge Model 1 (ASM1). The ASM1 modelled the activated sludge processes of carbon oxidation, nitrification and denitrification. Although this model involves 8 processes and 13 different mass balance equations, three fundamental areas were considered [88]:

1. Growth and decay of (heterotrophic and autotrophic) biomass
2. Ammonification of organic nitrogen
3. Hydrolysis of particulate organics.

In 1995 the International Association on Water Quality (IAWQ) published a paper by Gujer and Henze which described the development and calibration of the Activated Sludge Model 2 (ASM2) [89]. This subsequent work built on the previous ASM1 model by incorporating dynamic simulation of chemical oxygen demand (COD), nitrogen and phosphorus removal. In 1999, ASM2 was improved upon resulting in ASM2d [90]. The main improvements included increased accuracy when modelling nitrate and phosphate dynamics. Finally, in the same year IAWQ published Gujer's complete model of activated sludge ASM3 [91]. This model attempted to correct a number of defects present in the previous ASM1, ASM2 and ASM2d.

Following the publication of the activated sludge models, there have been many studies that have used the ASM for applications such as plant design and plant control [32, 92, 93]. In one example, Holenda et al. [94] used ASM1 model and predictive control strategies to assess dissolved oxygen in activated sludge WWT. ASM1 was used in this case to simulate the WWTP process in order to design, calibrate and assess the performance of a model predictive controller. A number of other studies attempted to improve on the ASM models. Smets et al. [88] presented a linearization of ASM1 to reduce the complexity and allow for faster computation time. This was achieved by rewriting the ASM1 model calculations in state space form with linear approximations for non-linear kinematic terms. The Smets et al. model performed well compared to the full ASM model, accurately predicting most process variables. The ammonium level, however, was not accurately predicted using the linearized model and the author notes that "future research will therefore focus on the improvement of the ammonium prediction".

2.10.2 Soft sensors

Soft sensors have been increasing in popularity over the last decade. The term is derived from the blending of words, software and sensors [95]. Soft sensors are used as an alternative approach to obtaining key process variables and can be classified into two different categories: model driven and data driven sensors. Model driven soft sensors generally use first principle calculations to derive theoretical sensor data.

On the other hand, data driven sensors make less assumptions instead relying on recorded process data.

As discussed in section 2.9.4, Bran Sands WWTP made significant plant adjustments to improve the capability of the plant to deal with storm events, improve plant compliance and reduce aeration energy. In that study, Black [82] developed and tested soft sensors which were used as a fail-safe mechanism for when the existing sensors malfunctioned. The developed predictive model received data from various sensors within the system to accurately predict the trend of the dissolved oxygen in the aeration tanks and sludge blanket level in the final settling tank. The study simulated the malfunction of input sensor values such as a flowrate sensor flat-lining. The soft sensor continued to track the dissolved oxygen level in the tank, however, the model confidence intervals were widened to reflect the deterioration of the model quality. Additional tests were also performed on DO sensor malfunction, showing the soft sensors’ ability to continue to predict DO levels for the aeration tank using all other available data

Artificial neural networks (ANNs) can be described as a computational simulation of the way in which the human brain processes information [96]. Essentially, ANNs are an interconnected network of nodes, each node consisting of multiple weighted inputs, a node transfer function and a node output (see Figure 14).

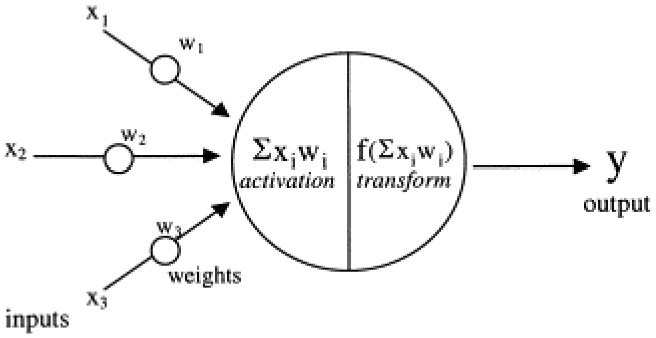


Figure 14: Simulation diagram of ANN node (neuron) [96]

Through interconnecting multiple nodes, ANNs are capable of modelling complex systems. Using a back propagation learning setup as shown in Figure 15, the ANN output is compared to an expected output creating an error signal which is used to adjust the weights to minimise the error. This is one of the most common types of supervised learning ANNs.

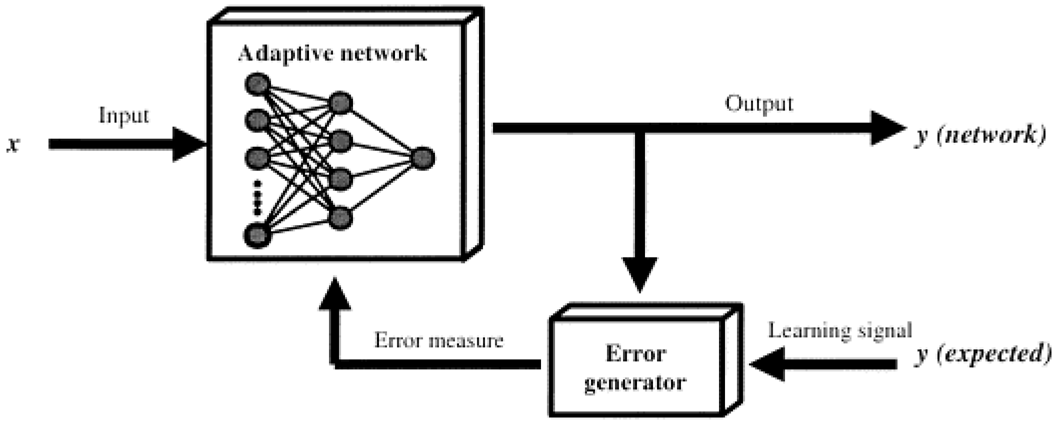


Figure 15: Back propagation learning algorithm [96]

Luccarini et al. [97] presented a case study of soft sensors application in a pilot study of a 500 L aeration tank. The soft sensors system was designed for sensing compounds such as ammonium, ammonia and nitrogen compounds. The system was tested against a conventional nitrogen sensor in the same tank. In this pilot study a real nitrogen sensor was replaced with a soft sensor based on a back-propagation, feed-forward ANNs [98]. The data presented by Luccarini demonstrates the issues with using intelligent control systems such as this. For example, the results of this experiment were mixed, the soft sensors were capable of predicting the trend of ammonium levels with a 10% offset. The nitrate trend predictions were more erroneous. This was attributed to the unpredictable and variable nature of wastewater influent flow, loading and nutrient levels.

2.10.3 Advanced Control

In addition to the ANN and model predictive controllers discussed in Section 2.10.2, there are a large number of additional publications based on other advanced control techniques such as fuzzy logic control, genetic algorithms, dynamic matrix control (DMC) and other hybrid controllers ([99-104]) These advanced controllers are still very much in development phase and have been shown to contribute significant positive attributes in full scale WWTP. However, according to Amand [105], as of 2013 there have been no reported cases of advanced controllers outperforming conventional feedback/feedforward controllers in full scale or pilot study applications.

This review has conveyed the significant research being undertaken in WWTPs across the world. This research has focused on many areas including: energy auditing, instrumentation, process control, and automation. International studies have shown that optimisation of these four areas can offer numerous benefits to WWTPs. This review has highli studies that have achieved energy savings of up to 50%, enhanced plant efficiency and improved plant equipment reliability.

This review has also outlined a number of Irish studies in the area of WWTP optimisation. To date, there has been very little focus on energy auditing Irish WWTPs. There are no Irish studies that have attempted to develop an energy auditing methodology for WWTPs. A number of recent international studies have worked towards the development of an energy auditing methodology. These methodologies do not focus on the practical issues involved in WWTP energy auditing, for example, the selection of energy auditing equipment, sampling frequencies, what metrics to record, and audit duration considerations.

3 Methodology and Equipment

3.1 Energy Auditing Methodologies

When choosing to audit a WWTP there are many factors to consider. Regardless of the size or type of plant being audited the same considerations must be made in relation to:

1. Plant selection
2. Size and scope of the proposed audit
3. Type of audit required
4. Equipment selection
5. Measured and tested variables
6. Sampling frequencies
7. Duration of audit
8. Plant access
9. Health and safety
10. Pre/post-audit assessments.

3.1.1 Plant Selection

When choosing to perform a WWTP audit, plant selection is not always a consideration that is required. For plant operators performing an audit, plant selection is not applicable. However, in the case of governing bodies or research projects, plant selection is an issue that must be carefully considered. Plants must be selected as a representative subset of all the WWTPs under investigation.

3.1.2 Pre-audit Assessment

Pre-audit tasks are performed to gather useful information to address the considerations listed above in Section 3.1. Pre-audit tasks include, but are not limited to:

1. Plant walkthrough
2. Assessment of plant technology
3. Review of plant schematics (including piping and instrumentation drawings)

4. Interviews with plant staff (caretakers, engineers, plant managers, etc.)
5. Equipment inventory
6. Assessment of the available monitoring equipment (energy monitors, auto-samplers, flowmeters etc.)
7. Acquisition of all available plant energy and water quality data
8. Examination of suitable energy and water monitoring locations.

One of the most important outcomes of the pre-audit assessment is that the auditor acquires all the necessary information to be fully prepared for the audit. In some cases all of this information may not be necessary or available. The amount of information necessary to prepare will also depend on the comprehensiveness of the proposed audit.

3.1.3 Size and Scope

Once the plant is selected, one of the first considerations necessary before conducting an audit is deciding on the size and scope of the audit. Audit size refers to how in-depth the audit will be, what metrics will be assessed, audit duration (see section 3.1.7) and the amount of resources available to dedicate to the audit. At this stage of the process a basic overview of the type of audit should be decided, for example:

1. A basic energy assessment of the plant including assessment of monthly energy bill and general equipment health check
2. A basic energy consumption and distribution assessment of the plant including in-situ energy monitoring equipment
3. A basic energy assessment coupled with in-depth high frequency water quality testing
4. A detailed plant audit including energy monitoring, power quality assessment, and water quality testing.

The scope of the audit is also a very important consideration especially when comparing multiple audited plants. It can often be hard in WWTPs to decide the boundaries of the audit. Many plants are supplied by one or more rising or pumping stations. These pumping stations take in wastewater from the surrounding area and pump it to the WWTP. It is important to decide whether the audit boundaries are purely the plant itself or if the surrounding sewer network also needs to be assessed. In the case of multiple plant audits, regardless of the chosen boundaries, consistency must be demonstrated in order to achieve valid plant comparisons.

3.1.4 Audit Equipment Selection

The amount of equipment necessary for plant auditing will be dictated primarily by the scale and type of audit set out in Section 3.1.3. For basic energy monitoring a single 3 phase energy monitor can record the total plant energy consumption and can subsequently be used to monitor other plant equipment. This method can be time consuming as each piece of equipment must be monitored individually. It is more beneficial to monitor all major equipment concurrently. By utilising multiple energy monitors strategically placed around the plant the time to conduct the audit is reduced and a more complete energy consumption and distribution assessment can be obtained. Additionally, this method is compatible with parallel water quality testing and flow monitoring. With all energy data recorded simultaneously, spikes in total energy consumption can be correlated to specific plant events such as: an increase in wastewater flow to the plant, higher influent loadings or even increased usage of one particular piece of plant equipment

Energy monitoring equipment may not be the only consideration when performing a plant audit. In the case of parallel water quality monitoring, the ability to acquire regular samples is essential. Preferably, water quality testing would be done with in-situ analysers that feed immediate results to the online SCADA system. This technology is not available for all wastewater nutrients and contaminants. Additionally, these systems are relatively expensive so the majority of Irish WWTPs do not utilise them. Often auto-sampling machines are used to collect individual or composite samples throughout the day. Individual sampling over a full day gives a good indication of the daily variation of each contaminant. Composite sampling, however, can be beneficial in cases where testing of multiple samples per day is not viable. The sampling methodology is therefore largely dependent on the available resources for testing equipment and wastewater analysis specialists.

3.1.5 Measured and Tested Variables

In WWTP auditing, the choice of plant variables to be tested must be considered. This is applicable to energy and water testing. With energy monitoring, there is an array of different variables that can be monitored. Many low cost monitors are only capable of recording a small number of variables such as: voltage, current, frequency, power and energy metrics. More sophisticated equipment can offer a wider range of metrics, such as:

1. Scope Waveform & Phasor
2. Voltage/Current/Frequency
3. Dips & Swells
4. Harmonics
5. Power & Energy
6. Energy Loss
7. Power Inverter Efficiency
8. Unbalance
9. Inrush Currents
10. Power Quality Monitoring
11. Flicker
12. Transients.

Energy monitors such as the ones utilised in this study (see Appendix A) are capable of recording numerous variables from the areas listed above. Selecting the right variables for an audit can be difficult. Basic power and energy data can often be sufficient variables to achieve an overview of plant energy performance. Additionally, areas such as harmonics, unbalance and transients can often be very helpful in identifying areas of inefficiency in WWTPs. Section 3.4.1 below discusses the rationale for selecting the energy auditing variables for this study.

Similar considerations must be given to water quality metrics. As with energy monitoring, there are a wide range of water quality parameters, for example, BOD, COD, total suspended solids, total nitrogen, nitrate, nitrite, total phosphorous, phosphates, ammonia, and heavy metals. The choice of which water quality parameters to analyse is dependent on the availability of water quality analytical test equipment. In cases where access to sophisticated water quality analytical equipment is limited, a subset of these parameters should be selected.

3.1.6 Sampling Frequency

After selecting the metrics and monitoring equipment that will be used during the audit, appropriate sampling frequencies must be selected. For energy monitoring, different plant machinery will require different sampling frequencies. There are a number of factors that will dictate the appropriate sampling frequencies. Firstly, the energy monitoring equipment will be a limiting factor. Some monitors will have a number of set frequencies, others allows the frequency to be varied between an upper and lower frequency limit. It is not only the frequency limits of the equipment that determines the correct sampling frequency, the device memory capabilities plays a significant role. In many energy monitors the memory capacity will limit how low the sampling frequency can be set in trials that may last for days or weeks. To demonstrate this, one of the energy monitors used in this study had a maximum capacity of 21,000 records. Assuming the desired sampling frequency for this device was 1 recording every 5 seconds:

$$Max\ Capacity = 21{,}000\ data\ points$$

$$Sampling\ Freq. = 0.2\ Hz$$

$$Recordings\ per\ Day = 0.2 \times 60 seconds \times 60 minuites \times 24\ hours$$

$$Recordings\ per\ Day = 17{,}280$$

At this sampling frequency the data would have to be downloaded and erased from the monitor every day of the trial. Furthermore, the amount of data that must be analysed after the trial must be considered. Another similar factor that can affect some energy monitors is battery life. Many smaller energy monitors are battery powered. In some cases higher sampling frequencies will lead to decreased battery life.

One of the most important factors that dictate the correct sampling frequency is the dynamics of the equipment being monitored. The mains incomer to a WWTP is very dynamic as it fluctuates constantly based on varied power usage of all plant equipment. For this reason the monitor sampling frequency should be as high as possible. Conversely, plant equipment such as circulation pumps and centrifuge feed pumps are much less dynamic. These pumps draw a steady current while on, therefore, setting a lower monitor sampling frequency is unlikely to introduce large inaccuracies in the energy data recorded.

3.1.7 Duration of Audit

The length of the audit can often be dictated by external factors such as the available resources and plant accessibility. Depending on the extensiveness of the audit being performed, plant audits can be as short as a few hours or up to months for more in-depth audits. WWTPs can have large fluctuations in power usage at different times. This can be attributed to a number of factors, such as:

1. Day to night plant loading
2. Wet weather and dry weather loadings
3. Seasonal variations
4. Sludge processing equipment.

Firstly, all detailed plant audits should capture the plant performance during the day when plant loading is high and at night when influent flow is decreased and plant activity is low. Weather factors can also affect plant performance. Where possible, energy/water quality audits should capture data during wet and dry periods. This is particularly relevant in Irish WWTPs due to the high precipitation levels experienced year-round in Ireland.

Sludge processing equipment such as sludge thickening centrifuges are often not used continuously throughout the day. Depending on the plant sludge production and the delivery of imported sludge, these high power machines can often go for days or weeks without being utilised. In a plant that operates with sludge processing equipment it is important to capture energy data during periods that these machines are running.

3.1.8 Post Audit Tasks

Once a plant audit is complete the work is not finished. The days or weeks of energy, water or flow data must be carefully processed. As discussed in Section 3.1.6, the sampling frequency and number of variables selected dictates the amount of data to be processed. In many cases, to process all acquired data may require a computer with above average processing capabilities. Not only can energy and power quality data take a long time to process, water quality testing is also quite a time consuming process. Consideration should be given to the method of water testing as some tests for BOD can take up to one week to process.

3.2 Wastewater Treatment Plant Selection

In order to conduct the study a number of Irish WWTPs were selected. These plants were chosen to be representative of the size and type of WWTPs across Ireland. Appendix B shows the important characteristics of the five selected plants, including information regarding the type of treatment technologies employed in each of the plants, the influent characteristics and the plant loadings. Four of the five plants underwent detailed nutrient testing over numerous days. This involved frequent influent and effluent sampling. Where possible, daily composite samples were taken at 4 hour intervals. In plants where this was not possible grab samples were taken at 8 hour intervals.

This was coupled with much higher frequency energy and power quality data acquisition as well as daily flow data. Flow data was obtained at each plant from a combination of sources: WWTP SCADA systems, plant flowmeters and the plant caretaker's daily logs. The level and availability of data acquisition equipment was a significant issue throughout this study. Some plants lacked basic flowmeters and auto sampling equipment, while none of the plants had energy monitoring equipment in place. WWTP monitoring and optimisation relies heavily on accurate and consistent data acquisition which cannot be obtained without the basic instrumentation.

Ammonium-nitrogen (NH_4-N), total oxidised nitrogen (TON), nitrite-nitrogen (NO_2-N), and phosphate-phosphorus (PO_4-P) concentrations were determined using a Thermo Clinical Labsystems, Konelab 20 Nutrient Analyser (Fisher Scientific, Waltham, Massachusetts, United States). Suspended solids (SS) were measured in accordance with standard methods [106]. Total nitrogen (TN), total phosphorous (TP), total organic carbon (TOC) and total inorganic carbon (TIC) were analysed using a BioTector TOC TN TP Analyser (BioTector Analytical Systems Limited, Cork, Ireland) in accordance with standard methods [106]. Biochemical oxygen demand (BOD) and chemical oxygen demand (COD) were measured in accordance with standard methods [106].

3.3 Plant descriptions

To understand the performance of a plant, it is important to investigate the plant operations and to have an understanding of the flow routes of the wastewater (and other flows) through the plant.

3.3.1 Plant A

Plant A is the largest plant in this study with a design capacity of 50,000 P.E. with provision in the design to increase this capacity to 60,000 P.E.. In 2013, the calculated organic loading indicated that the plant had exceeded the design capacity with a loading of 63,306 P.E.. This loading increased from 37,221 P.E. the previous year and was attributed in part to new developments in the surrounding area. The plant personnel, however, were confident that the true loading is under the design specification and attribute the high P.E. to possible inaccuracies with the plant sampling procedure. In 2013, the influent composite sampler serving Plant A was malfunctioning for a substantial period of the year resulting in the organic loading of the plant being calculated, for the most part, using grab samples. This plant discharges into sensitive waters (river), so nutrient reduction is a requirement. Figure 16 shows the wastewater and sludge flow through the plant. The inlet works consists of bar screens and a circular grit trap and a washpactor system. The pre-treated wastewater is then sent to primary clarifiers. Biological nitrogen removal is achieved in the secondary treatment tanks which are separated into anoxic and aerobic zones. Phosphorus reduction is also accomplished in the anoxic zone by ferric dosing. Following secondary sedimentation the RAS is pumped back to the anoxic zone, the WAS is pumped to the sludge handling zone and treated water is discharged into the receiving waters. WAS is thickened in a Picket Fence Thickener (PFT) tank followed by further thickening and dewatering in a centrifuge. The dewatered sludge (approximately 18% dry solids) is collected and sent off-site for lime stabilisation. The return liquor from the centrifuge is pumped back to the secondary treatment tank. This plant also accepts sludge from other local wastewater treatment plants as well as industrial and agricultural sludge.

This plant has the facilities on site for anaerobic digestion and biogas storage. The plant operators have had issues with the anaerobic digestion equipment since the plant was built. This has meant that the digesters have been out of commission for the last number of years. During the assessment of this plant, there were upgrades being made to the DO control system and the aeration tanks. The size of the anoxic zone was being increased to optimise the nitrification/denitrification process.

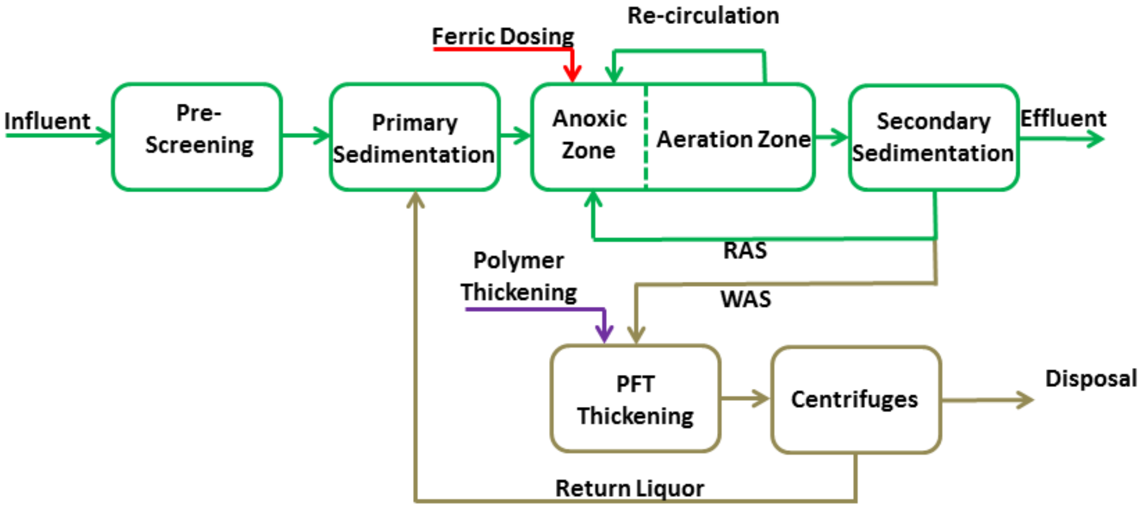


Figure 16: Flow diagram for wastewater and sludge in Plant A

3.3.2 Plant B

Plant B has a design capacity of 12,000 P.E. and is currently operating above capacity. The agglomeration is currently serving a P.E. of approx. 12,284. This plant discharges into sensitive waters (river), and so nutrient reduction is again a requirement. Figure 17 shows the wastewater and sludge flows through the plant. The influent is pumped from a deep sump to the inlet works. The inlet works consists of various sized bar screens and a grit removal system (grit blower and classifier). After the pre-screening the wastewater is transferred directly to the secondary treatment tank. In this plant there are no primary sedimentation tanks. The secondary treatment tanks have separated anoxic and aerobic zones for full biological nitrogen removal and additional phosphorus reduction by ferric dosing. WAS is thickened in a PFT tank followed by further thickening and dewatering in a centrifuge using the same methods as Plant A.

There were a number of operational problems within this plant over the period of the auditing. After 2-3 days of the plant monitoring, the ferric dosing system was shut down as the plant ran out of ferric chloride. Due to this the phosphorous levels during the audit were higher than normal. There were also a number of mechanical problems in the plant. One of the two centrifuges was not operational at all and the other had issues with a broken seal. This meant that the only working centrifuge was leaking return liquor and not operating at optimal efficiency.

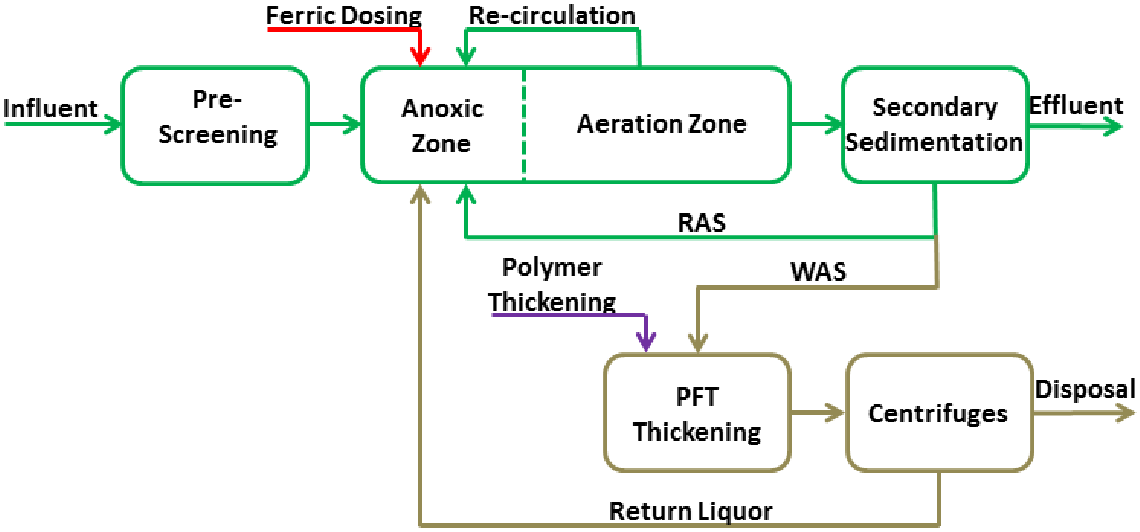


Figure 17: Flow diagram for wastewater and sludge in Plant B

3.3.3 Plant C

Plant C has a design capacity of 12,000 P.E. and is operating below capacity. The agglomeration is currently serving a P.E. of approx. 9,036. The plant operates with similar technologies to Plant B and also discharges into sensitive waters (river). The plant treats wastewater from domestic sources and imports sludge from industry/agriculture. Figure 18 shows the wastewater and sludge flows through the plant. The primary and secondary treatment operates using the same technologies as Plant B. This plant, however, induces phosphate precipitation using pickle liquor instead of ferric chloride. The pickle liquor is a by-product of the steel finishing industry and is therefore a cost effective alternative [107]. WAS from the secondary sedimentation tank is transferred into the PFT tanks. Additionally, any imported sludge is screened and pumped into the PFT tanks. Further sludge thickening and dewatering is performed using the same techniques as in Plant B. In addition to primary and secondary treatment, Plant C also treats a small quantity of the effluent with high speed filters which are capable of reducing suspended solids, chlorine, iron, manganese, arsenic and other contaminants. This filtered effluent is used as wash water for various pieces of equipment around the plant (e.g. primary screen cleaning).

Plant C had a number of operational problems over the period of the audit. During the initial plant assessment and monitoring phase the plant operators were making adjustments to the aeration tank operations. They were also in the process of replacing all fine bubble diffusers in the bottom of the aeration tanks.

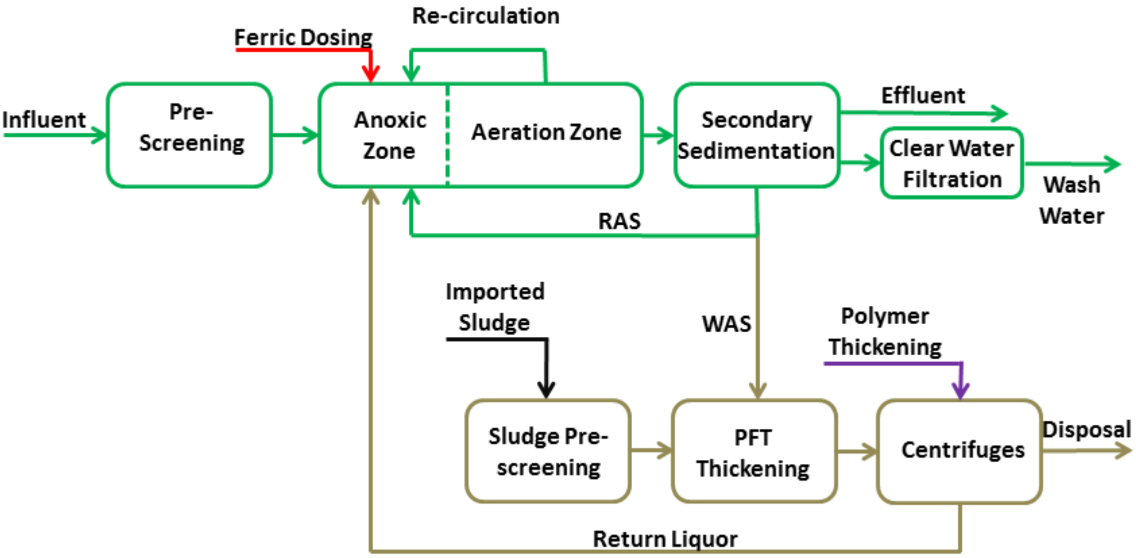


Figure 18: Flow diagram for wastewater and sludge in Plant C

3.3.4 Plant D

Plant D is the smallest WWTP in this study with a design capacity of 600 P.E.. This plant was built to treat wastewater in a small rural community. Figure 19 shows the wastewater and sludge flow through the plant. From 2001 to 2011, the population in this town increased significantly, with a growth in that period of over 210%. The agglomeration is currently serving a P.E. of approximately 1,024. This plant is currently heavily loaded with a dry weather flow of 240m^3/day and the effluent is discharged into sensitive river waters. The plant is built on a small footprint and has limited space for expansion of the facilities. Ferric dosing is not employed in this plant even though nutrient reduction is required by the EPA. The plant has frequently failed EPA testing for reduction of BOD, ammonia and ortho-phosphate.

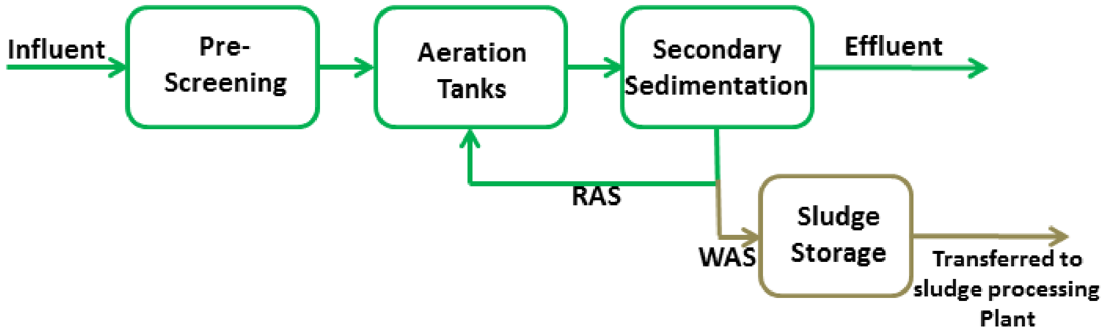


Figure 19: Flow diagram for wastewater and sludge in Plant D

3.3.5 Plant E

Plant E is one of the smaller treatment plants analysed in this study with a design capacity of 820 P.E. and a dry weather flow of 75m^3/day. The agglomeration is currently serving a P.E. of approximately 590. This treatment plant is a good representative of the many small wastewater treatment plants around Ireland. The final effluent is discharged into sensitive river waters. The influent enters the inlet works where pre-treatment screens remove rags and debris (see Figure 20). The screened wastewater flows directly into the secondary treatment aeration tank without primary sedimentation. Ferric dosing occurs in the aeration tank before the activated sludge is transferred to secondary sedimentation. The RAS, as in all AS systems is pumped back to the aeration tank. The WAS is stored in a sludge holding tanks and transferred regularly to a sludge processing WWTP.

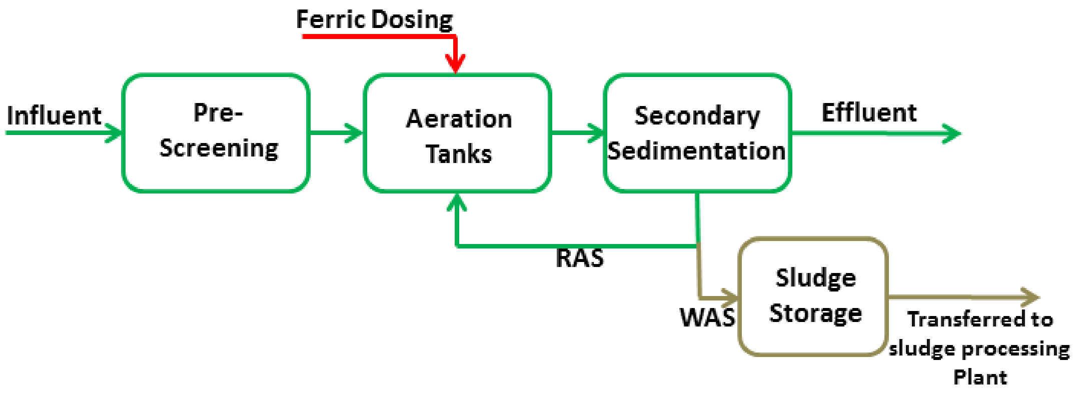


Figure 20: Flow diagram for wastewater and sludge in Plant E

3.4 Equipment

3.4.1 Energy Monitoring

The choice of power/energy monitoring equipment was carefully considered. To prepare for the energy audits, the chosen plants were analysed to assess the number and sophistication of the monitors required to effectively conduct the audits at each plant. The range of meters currently available varies in price and specification. Highly sophisticated monitors can cost up to €10,000 whereas monitors in the low specification range can cost less than €100. In order to perform an in-depth analysis on any of the WWTP machinery, it was desirable to have an energy/power meter with high specification and the ability to record a wide range of parameters. Table 7 shows the variables monitored in this study. The first column shows the list of preferred variables, and where possible these variables were recorded. The second column shows additional variables that can help with analysis of plant performance. These variables, when recorded, facilitate a more in-depth diagnosis of individual plant machinery as well as overall plant power quality.

Table 7: List of electrical variables recorded in this study including basic variables and additional desirable variables

Basic Variables	Additional Variables
Voltage (V)	Current Harmonic Distortions (%)
Current (A)	Voltage Harmonic Distortions (%)
Active Power (kW)	Frequency (Hz)
Apparent Power (kVA)	Unbalance (%)
Reactive Power (kVAR)	Dips and Swells (%)
Power Factor	Energy Losses (kWh)
Phase angle (^{o})	-----
Harmonic Distortion (%)	-----
Neutral Current (A)	-----

Additionally, due to the nature of the audit performed in this study (Energy, flow and water quality), it was required that all measurements were taken simultaneously. For this reason multiple energy/power meters were needed. All detailed analysis was performed using the Fluke 435 Series II power quality analyser (PQA), which is a high-specification energy analyser. This device was used to monitor mains incomer and for further diagnostic purposes. The PQA was supplemented with three Amprobe PQ 55A energy analysers. These devices are mid-range cost and specification and were capable of recording all basic variables. The Amprobe monitors were used primarily on high powered blowers, pumps and sludge thickening centrifuges. Finally, eight Iso-Tech IPM2005 meters were used to monitor smaller plant equipment. Although these meters were capable of monitoring all basic variables, this could not be done simultaneously. Table 8 outlines in more detail the basic specifications of each metering device.

Table 8: Specifications of chosen power/energy meters

Monitor	Power	Capability	Logger	Sampling Freq. (Hz)	Harmonics (up to)	Coms
Fluke 453 Series II	Mains	Single and 3 phase	SD Card (8 GB)	$1.3e^{-4}$ – 4	50th	USB
Amprobe PQ 55A	Mains	Single and 3 phase	21000 records	$8.0e^{-3}$ – 0.2	31st	RS-232
Iso-Tech IPM 2005	Battery	Single and balanced 3 phase	8000 records	$1.6e^{-3}$ – 1	n/a	USB optical

The determination of appropriate sampling frequencies was an important consideration that was assessed and developed throughout this study. Sampling at too high a rate reduced data storage capacity, whereas too low a rate risked missing energy events. Table 9 documents the sampling frequency methodology and outlines the frequencies used for different types of WWTP plant equipment.

Table 9: Sampling frequency methodology for WWTP equipment in this study

High frequency (>2 recording/min)	**Moderate frequency** (1 - 2 records/min)	**Low frequency** (<1 recording/min)
Mains Power Unit	All compressed air blowers	Recirculation pumps
---	Primary grit blowers	RAS pumps
---	All sludge centrifuges	WAS pumps
---	Influent and effluent pumps	Centrifuge feed pumps

4 Results and Discussion

As discussed in Section 3, there were five WWTPs audited in this study. Energy and power quality data was gathered along with composite influent and effluent samples for water quality testing, and influent/effluent flowrate data. Additionally, local rainfall data was obtained from Met Eireann and was included overlaid on the graphs to help identify unexpected events. Table 10 shows a summary of the results of the WWTP audits. Firstly, the table presents a general overview of plant capacity, flow and energy data for each of the five plants. A summary of water quality data is then presented for influent and effluent waters in each plant.

Table 10: Summary of energy, flow and water quality results for each of the audited plants

General	**Plant**	**Plant A**	**Plant B**	**Plant C**	**Plant D**	**Plant E**
	P.E. Design	50000	12000	12000	600	900
	P.E. Served	37200	8650	5850	1804	604
	Average Flow (m^3/day)	7149	1848	1980	387	150
	Electricity (KWh/day)	5433.24	1894.96	1381.87	221.99	122.44
Influent	BOD (mg/l)	300.00	209.37	96.82	134.17	123.26
	COD (mg/l)	-	428.44	245.33	196.00	296.00
	TSS (mg/l)	-	296.00	159.33	142.25	233.13
	TN (mg/l)	-	71.46	29.60	13.64	23.54
	TP (mg/l)	-	7.66	3.63	1.82	2.67
	Ortho-P	-	5.61	2.53	1.38	2.15
	Ammonia	-	91.49	40.58	15.67	26.98
	Nitrite	-	0.09	0.26	0.41	0.24
Effluent	BOD (mg/l)	10.00	9.32	10.05	14.11	8.20
	COD (mg/l)	-	83.56	64.89	42.67	112.00
	TSS (mg/l)	-	17.05	18.17	69.40	65.30
	TN (mg/l)	-	50.06	18.66	8.68	20.59
	TP (mg/l)	-	0.98	0.85	0.92	0.21
	Ortho-P	-	0.74	0.49	0.59	0.02
	Ammonia	-	1.02	0.19	2.22	0.75
	Nitrite	-	0.05	0.02	1.20	0.27

4.1 Audit Results

A medium to large scale WWTP (Plant A) was audited early in the study and was analysed using only the Fluke PQA. Due to a lack of data this plant was not assessed in detail in terms of water quality and as such was omitted from Appendix C. Figure 21 shows the plant power usage over a 1 week period. Over this time the average power usage was approximately 200 kW. This plant exhibited clear power fluctuations from day to day. Power fluctuations of up to 80kW over a 24 hour period are attributed to the large variation between the peak water usage times during the day and lower usage overnight. Additionally, the weekend period (15/12/2013 – 16/12/2013) experienced lower power demands with average power usage of 185.8 kW compared with 202.4 kW average midweek. Three wet periods occurred over this week long trial. These spikes in rainfall coincided with some increases in power usage. Up to 2.5mm of rainfall on the 14/12/2013 seemed to have caused some power fluctuations that continued into 15/12/2015.

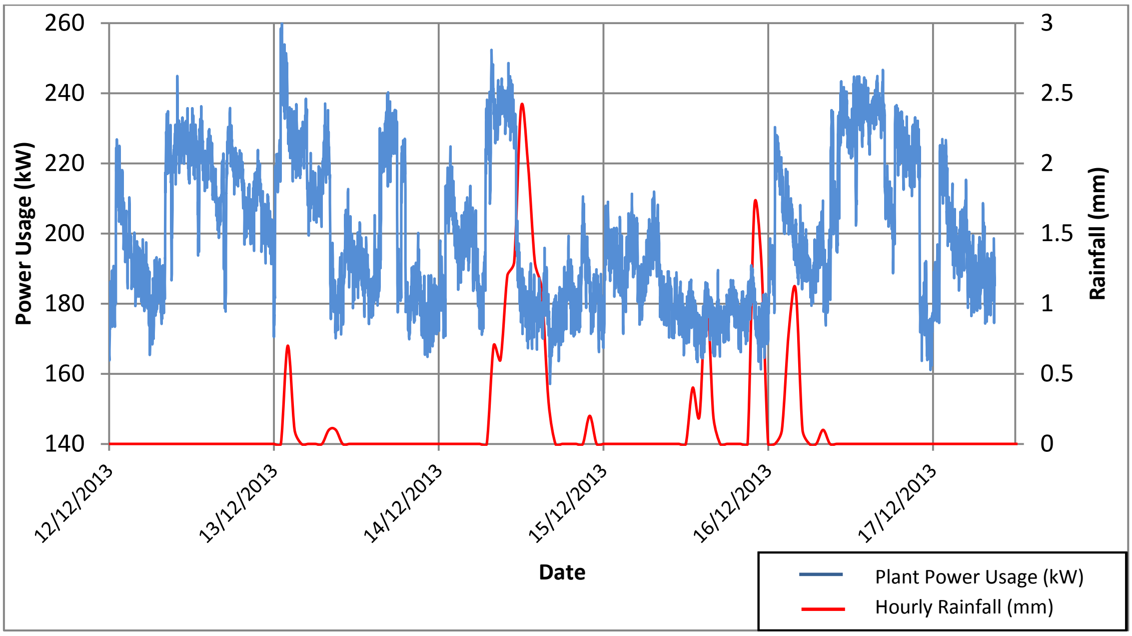


Figure 21: Plant A power usage and hourly rainfall

The breakdown of energy consumption across the plant was analysed and the energy distribution is highlighted in Figure 22. The secondary treatment systems contribute the majority (83%) of the overall plant energy consumption. Figure 22 also shows that the compressed air blowers contribute 42% of the total plant energy.

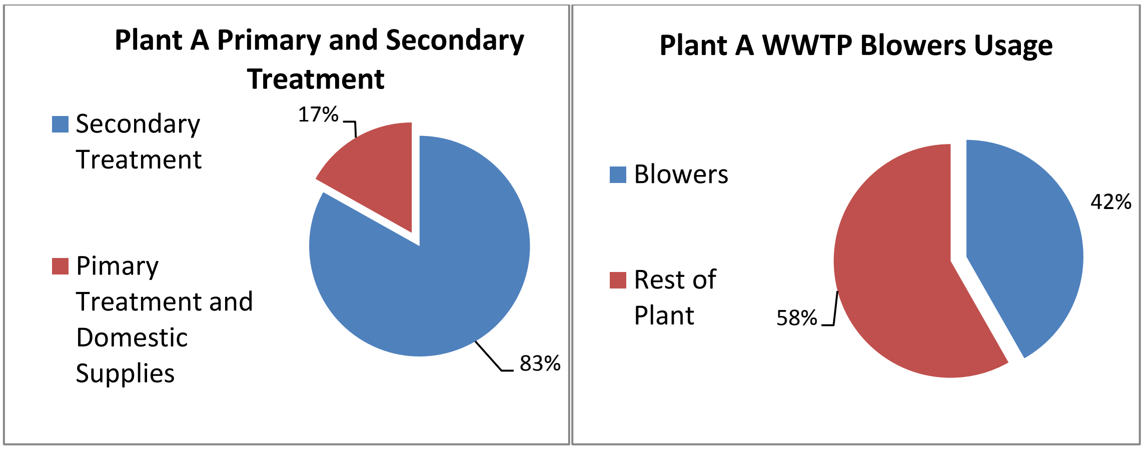


Figure 22: Plant A energy distribution

Plants B and C are two plants of similar technology and the same design capacity. Figure 23 shows the power usage for Plant B over a two week period. As with Plant A, there are distinctive power variations from peak to off-peak times. During the night the plant's power usage can dip to as low as 51 kW while during the day the power averages approximately 100 kW. The graph shows five sustained spikes in power usage. These spikes represent an increase in energy consumption of as much as 40 kW. These spikes are a result of running the sludge dewatering centrifuge system. The effect of increased rainfall on the plant power usage was also assessed. The graph suggests that the increased rainfall disturbs the normal night/day pattern. Large amounts of rainfall (up to 8mm) from the 01/08/214 – 03/08/2014 caused elevated power usage during a weekend period that should have otherwise been lower. Although these rainfall events disrupt the daily power usage pattern, the power does not increase beyond the normal daily levels.

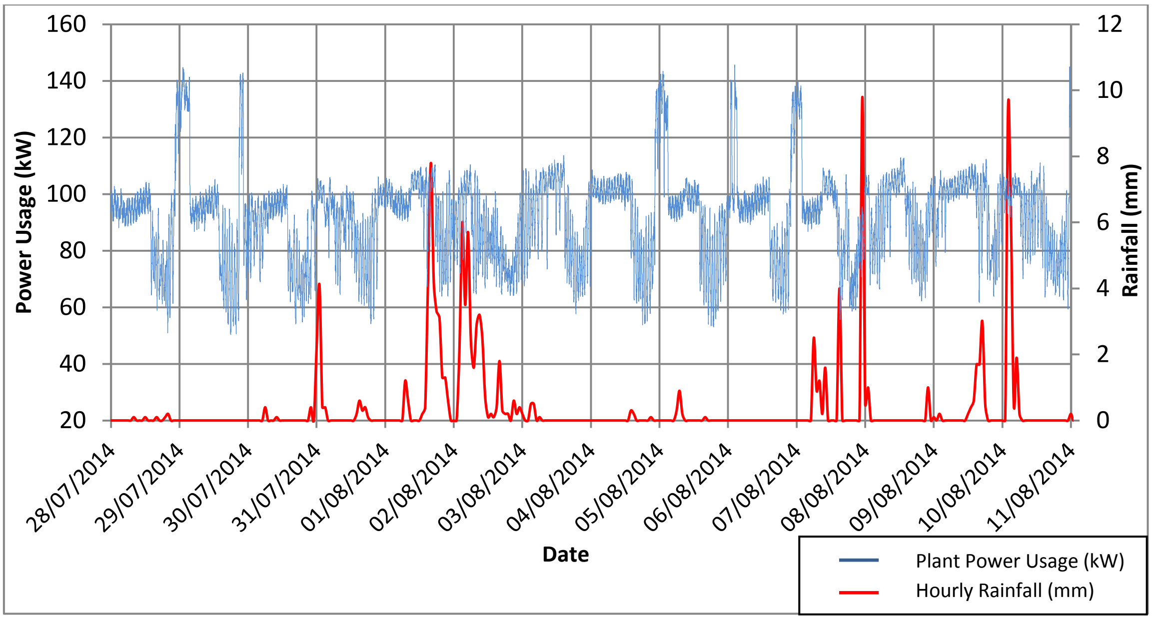


Figure 23: Plant B power usage and hourly rainfall

Figure 24 shows the same data for Plant C, over a three week period. The power for this plant does not display the same night to day fluctuations. Plant C power usage is steady at an average of 58.8 kW. Towards the end of the trial there are four distinctive spikes in the power usage with increases in power of up to 30kW. Like Plant B, these spikes are from the sludge dewatering centrifuge system. Rainfall in this plant does not appear to have a significant impact on power usage.

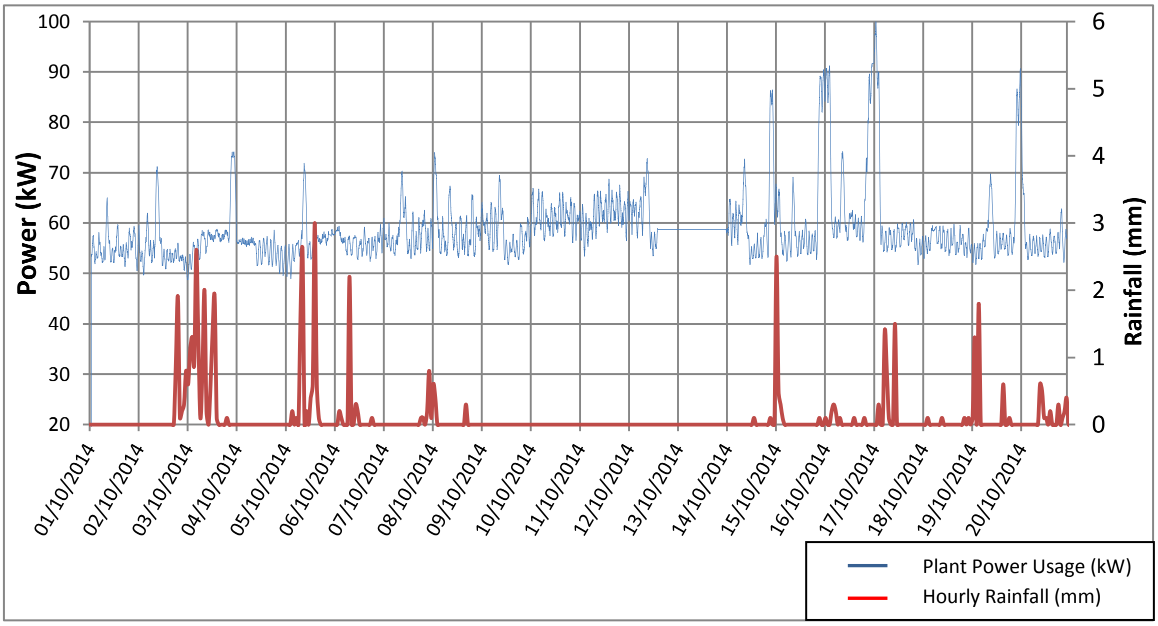


Figure 24: Plant C power usage and hourly rainfall.

With an average power usage of 58.8 kW, Plant C power use is lower than that of Plant B. This is a significant finding given that these two plants are of relatively similar size and operate using the same technology. There are many factors that may have caused this power mismatch. Firstly, the control system governing the compressed air blowers in Plant C. During this trial the control system was set to manual mode rather than automatic, which meant that the blowers were not being adjusted based on DO concentration in the aeration tank. The system was switched to manual due to frequent power cuts at the plant. These cuts caused the plant to go without power for just a few seconds, which, although was not long enough to trigger the backup generator, did cause the control systems to crash and not re-start again after the power returned. Secondly, plant loading can play a role in the quantity of power used. The wastewater nutrient concentrations will in part dictate the amount of aeration required. This is discussed in more detail below. Finaly, a factor that is certainly linked to the increased power usage in Plant B is the use of effluent pumps. Plant B must pump the final effluent over 100m to the receiving waters. To do this high efficiency pumps with VFDs transfer the final effluent to the receiving waters. These pumps consume 8% of the total plant energy.

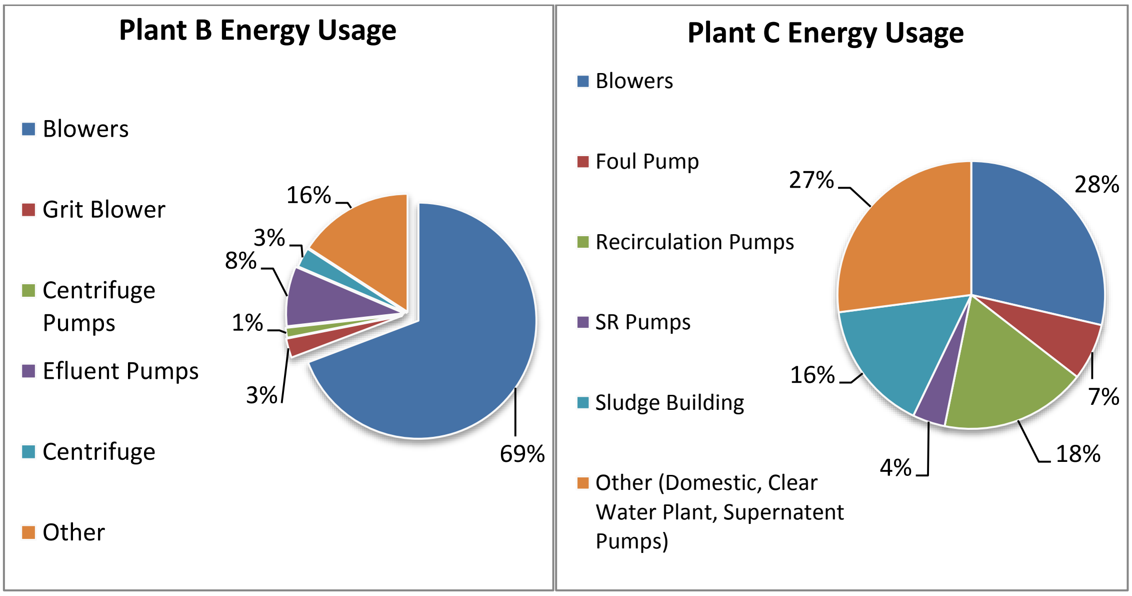


Figure 25: Plant B and Plant C energy distributions

The energy distribution for these plants varied (see Figure 25). The compressed air blower energy in Plant B was responsible for 69% of the total energy consumption. In comparison, 28% of total energy consumption was due to the blowers in Plant C.

These significant differences in energy distribution are partly due to the plant loadings. Figure 26 below shows the influent BOD, COD and TSS (Total Suspended Solids) concentrations for Plant B and Plant C. Plant B is treating influent with over two times the concentration of BOD compared with Plant C. Consequently, the plant was required to run all three available blowers at peak hours to meet the DO concentration demands.

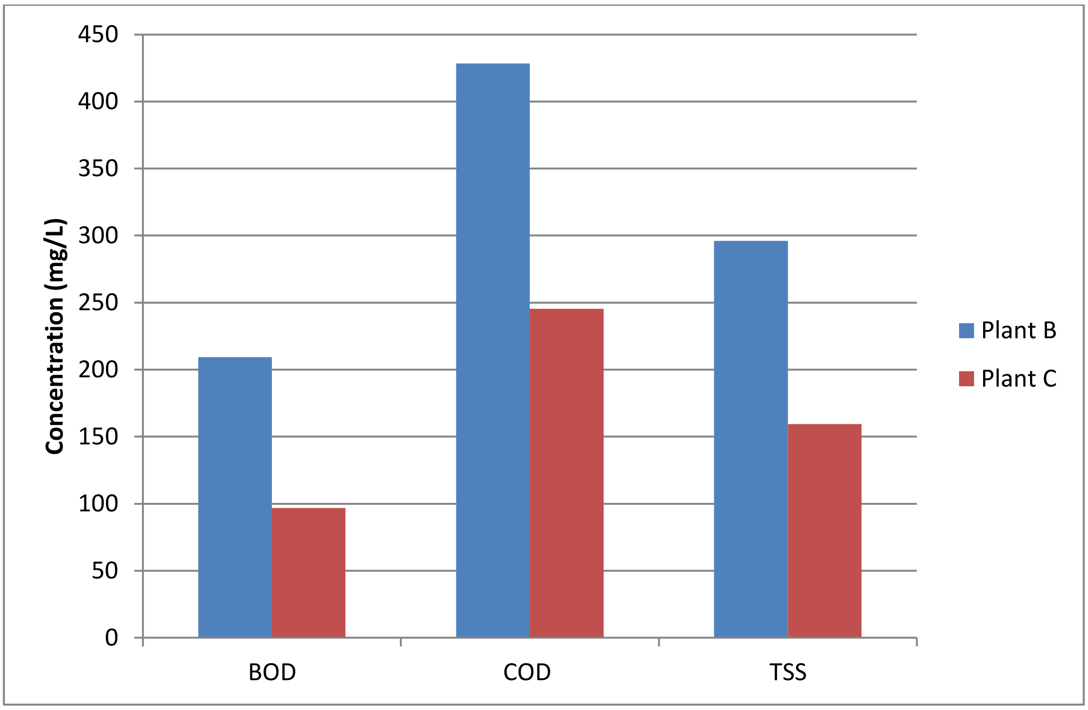


Figure 26: Breakdown of influent composition of BOD, COD and Total Suspended Solids for Plant B and Plant C

Plant D and Plant E are small-scale WWTPs that have comparable technologies and design capacities. Figure 27 shows the power usage for Plant D over a two week period. Like Plant B there is a clear pattern from peak demand during the day to lower power usage during the night. One interesting part of this graph is the rise in power usage after 2 days of the trial. Upon investigation it was found a breakdown of one of the compressed air blowers, which was fixed and brought back online on the 31/10/2014, resulted in an increase in daytime power consumption from approximately 7 kW to above 11 kW. From the graph it can be observed that this plant is reactive to sustained rainfall. Excluding the short spike of rainfall on the 4/11/2015, the longer periods of rain caused fluctuations in power usage. The average power during the relatively dry weather period (02/11/2014 – 06/11/2014) was 8.77 kW. This power usage increased by 7% to 9.61kW towards the end of the trial (06/11/2014 – 10/11/2014) when there were periods of sustained rainfall.

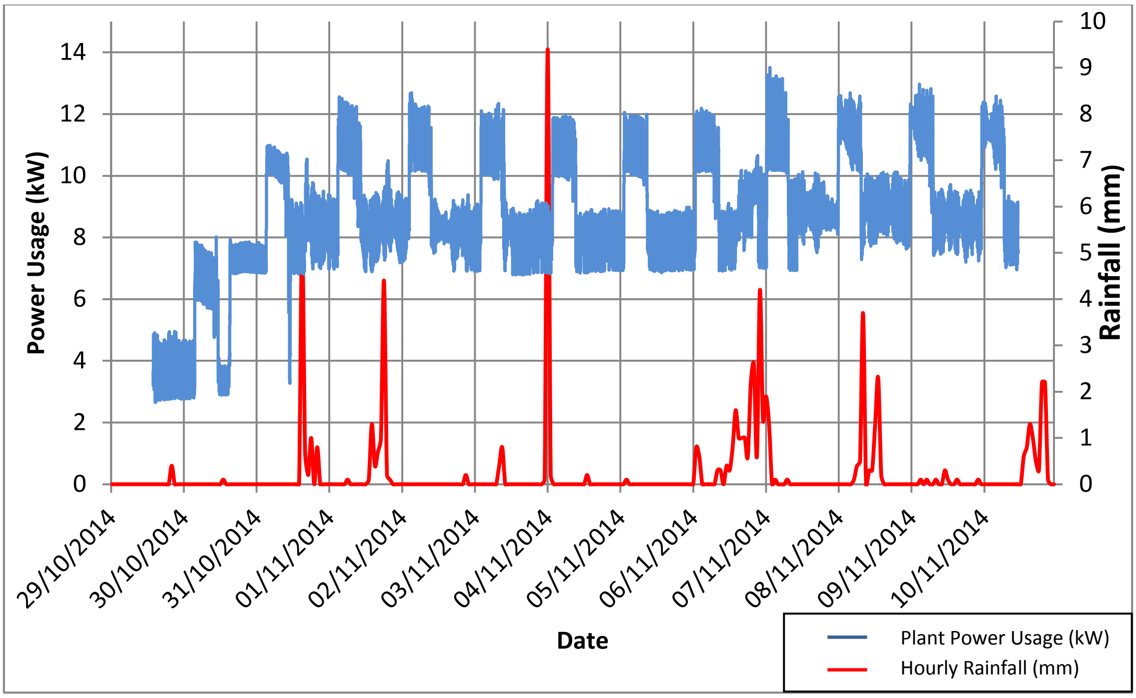


Figure 27: Plant D power usage and hourly rainfall.

Figure 28 shows the power and rainfall data for Plant E over a one week period. The power usage for this plant, like Plant C, does not display a clear night to day power fluctuation. Plant E power usage is constantly fluctuating about an average of 5.08 kW. Additionally, the sustained rainfall on the 21/11/2015 did not significantly raise the power usage in the plant.

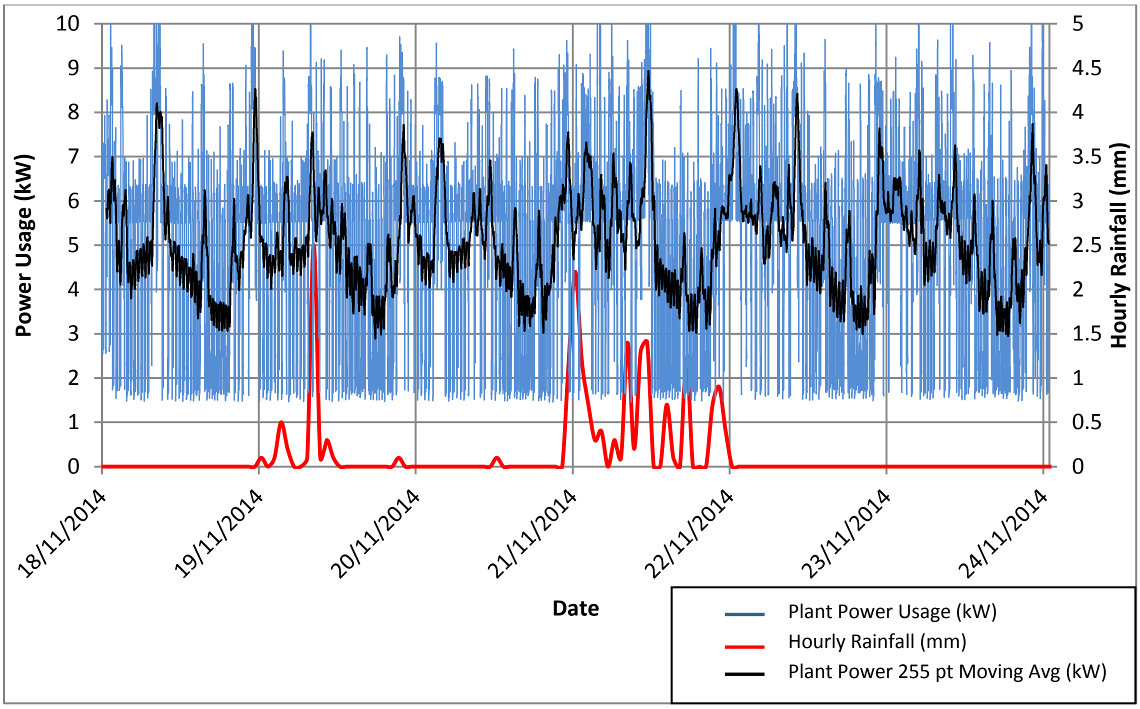


Figure 28; Plant E power usage and hourly rainfall.

The power usage in Plant E is highly variable across the day, which is partly due to the type of control system being utilised. The blowers operate using an on/off control system. When the DO in the aeration tank reduces the blowers switch on. This raises the DO concentration and once this reaches a set point the blowers switch off again. It is therefore much harder to see a distinct pattern from night to day. The black line in the graph shows the moving average for the power usage. This trend shows that there are fluctuations from day to night in the average power usage. At an average of 8.77 kW, Plant D runs at a higher power usage than Plant E (5.08 kW average). Again, although these two plants have similar designed P.E. and employ the same WWT technologies, there is a mismatch in power usage. The major factor that drives this is the plant loadings. Plant D is serving a greater population and is also operating at close to double the design capacity PE. As a result, the plant is running both available blowers at their limits with no backup blower.

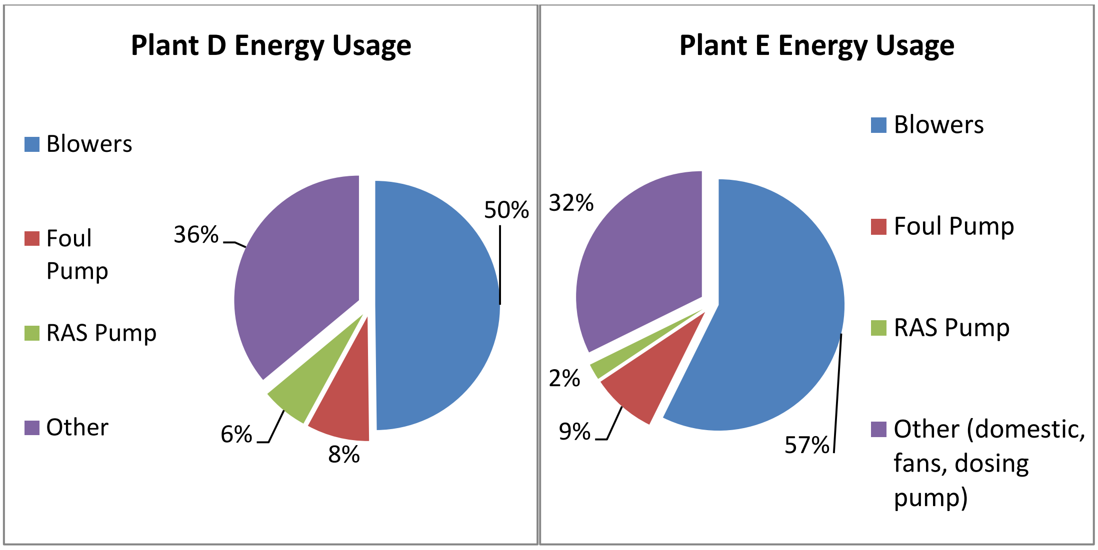


Figure 29: Plant D and E energy distributions

The energy distribution in both plants is similar, as displayed above in Figure 29. Due to the compact nature of the electrical panels in these smaller plants it was difficult to monitor all equipment, and because of this over 30% of the plant equipment was not monitored. The blowers in Plant E contribute to 7% more energy than in Plant D. This again is attributed to the influent loadings, as graphed in Figure 30. The influent to Plant E has a similar BOD concentration to Plant D but a greater concentration of COD and more suspended solids.

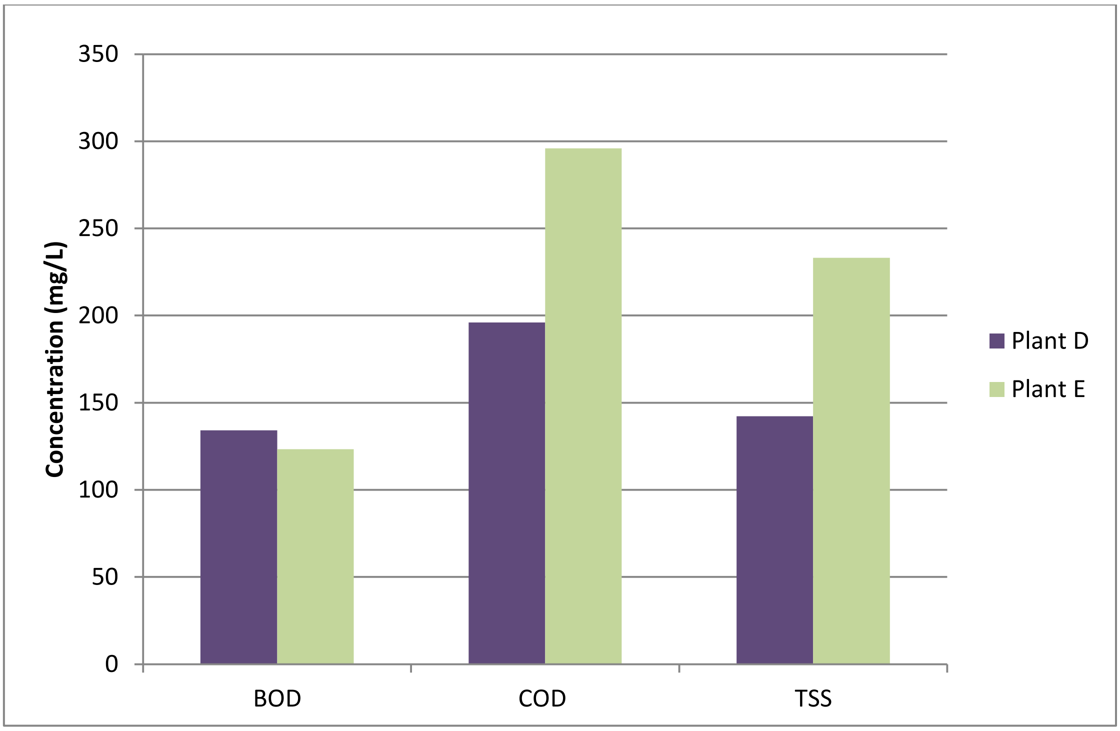


Figure 30: Breakdown of influent composition of BOD, COD and Total Suspended Solids for Plant B and Plant C

4.1.1 Water Quality Testing

Monitoring influent organic loading concentrations does not reveal anything about the performance of each plant. In order to compare plants to each other, the organic/solids removal data is required. Figure 31 shows the energy consumption for Plants B and C broken down into a number of KPIs. Firstly, the energy consumption per day (MWh/day) and energy consumption per volume of influent (kWh/m^3) for both plants is quite similar. Without water quality data these two plants would be considered matched for plant performance. Only by incorporating water quality metrics such as the amount of BOD, COD, and TSS removed, can a more accurate picture of plant performance be achieved.

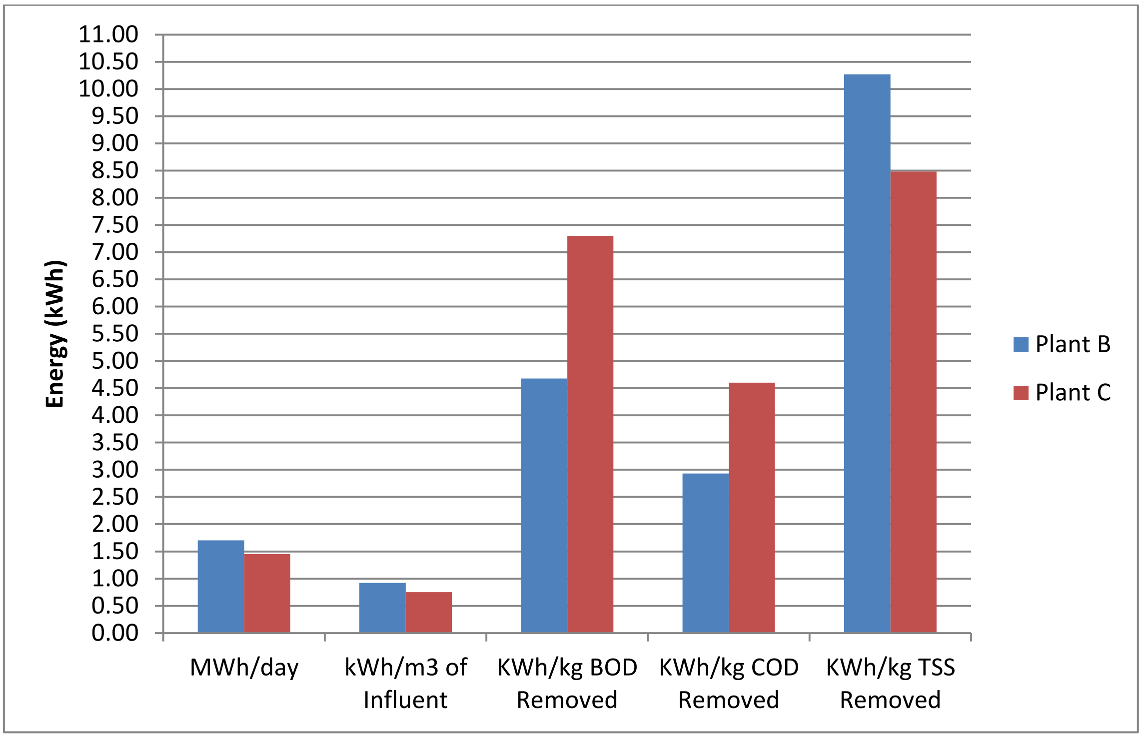


Figure 31: Breakdown of Plant B and Plant C Performance Indicators

Although Plant B has greater energy consumption, it is removing more BOD and COD per kWh than F. These results show the value that water quality analysis adds to WWTP auditing. With energy data alone it is hard to accurately assess plant performance. Using only energy and flow data (MWh/day and kWh/m^3) Plant C would seem to slightly outperform Plant B. However, by factoring in water composition data Plant B displays greater efficiency. These efficiencies may also be due the influent loadings being higher in Plant B. This plant is therefore operating close to its design capacity.

Similar results are observed when comparing the smaller WWTPs (Plant D and Plant E). Plant D had significantly higher energy consumption per day than Plant E. This extra energy was being utilised more efficiently however as shown in Figure 32. Energy consumption per volume of influent (kWh/m3) was 84% higher in Plant D. The energy consumption per BOD and COD removed were higher in Plant E also with BOD and COD removal energy consumption 267% and 186% higher respectively.

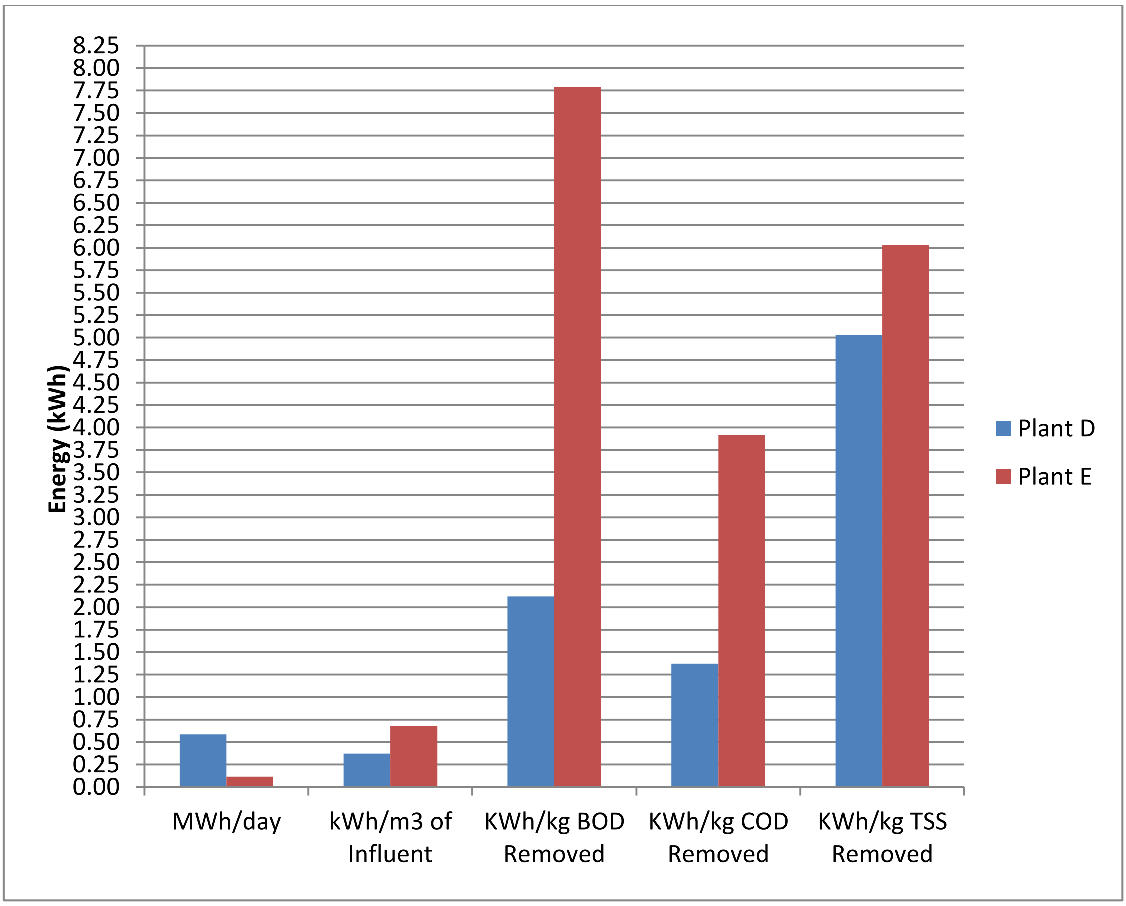


Figure 32: Breakdown of Plant D and Plant E Performance Indicators

The large variation between Plant D and Plant E is partially due to the fact that plants perform better if they are operating close to their respective design capacities. As discussed in section 3.3.4 Plant D is operating far beyond its design capacity. In both comparisons the plant that is more heavily loaded can perform more efficiently from a nutrient removal perspective.

4.1.2 Benchmarking

The data from this trial shows that there are a variety of factors to consider when assessing the performance of WWTPs. Energy alone does not give a complete picture of plant performance. To achieve this, energy data must be assessed along with water quality metrics and plant treatment technology considerations. Ideally, all these metrics would be brought together to give an overall benchmarking score for plant performance. Due to the complex nature of wastewater treatment it is not a trivial task to develop an accurate benchmarking system. As discussed in section 2.8.3, there have been a number of attempts to develop a benchmarking system to accurately assess WWTP performance. Carlson and Walburger's [62] energy model is based on multiparameter log regression analysis:

$$\begin{aligned}\ln(E_s) = 15.8741 + [0.8941 \times \ln(inf_{avg})] + [0.4510 \times \ln(inf_{BOD})] - [0.1943 \times \ln(eff_{BOD})] \\ - \left[0.4280 \times \ln\left(\frac{inf_{avg}}{inf_{des}} \times 100\right)\right] - \left[0.3256\left(trickle\ filter\frac{yes = 1}{no = 0}\right)\right] \\ + \left[0.1774\left(nutrient\ removal\frac{yes = 1}{no = 0}\right)\right]\end{aligned}$$

(Equation 2)

Where:

E_s = modelled plant energy (kBtu/y)

inf_{avg} = average influent flowrate (m^3/day)

inf_{des} = Influent designed flowrate (m^3/day)

inf_{BOD} = average influent BOD conc. (mg/l)

eff_{BOD} = effluent BOD conc. (mg/l)

The data for Plant A was input into the benchmarking equation:

$$\begin{aligned}\ln(E_s) = 15.8741 + [0.8941 \times \ln(7141)] + [0.4510 \times \ln(300)] - [0.1943 \times \ln(10)] \\ - \left[0.4280 \times \ln\left(\frac{7141}{10000} \times 100\right)\right] - [0.3256 \times (0)] + [0.1774 \times (1)]\end{aligned}$$

$$\ln(E_s) = 15.8741 + 0.5687 + 2.5724 - 0.4474 - 1.8274 - 0 + 0.1774$$

$$\ln(E_s) = 16.9179$$

This result is the natural log of the estimated energy usage (kBtu/year). In order to compare the energy estimation for this plant against the 266 plants surveyed plants, this result must be adjusted. This is done by finding the ratio of predicted performance to the average performance of the plants used to derive this benchmark equation. Figure 33 below shows the benchmarked plants' distribution curve.

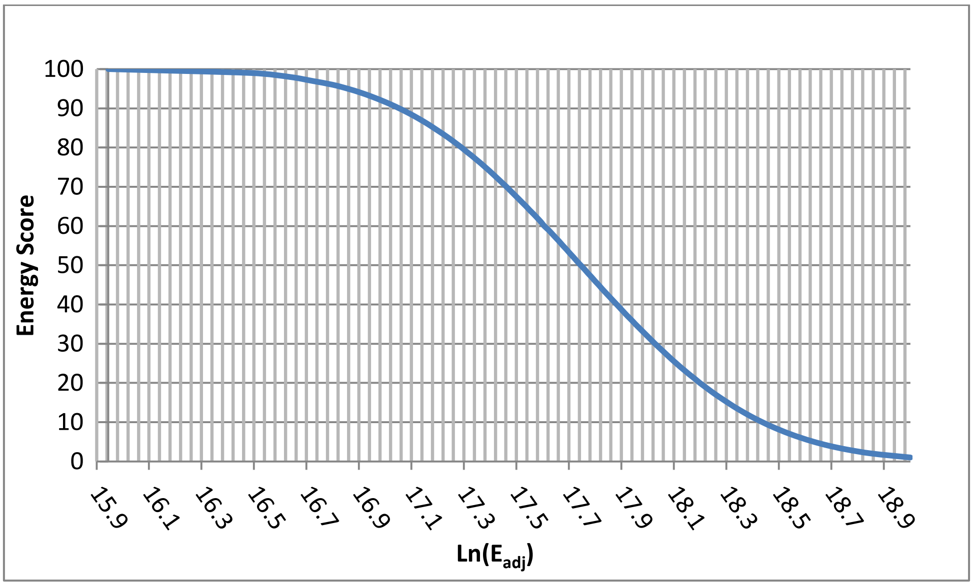


Figure 33: Benchmarking curve for Carlson and Walburger's final energy model [62]

The average energy score (at the 50th percentile) is 17.8 kBtu/year. The adjustment factor is found by dividing the estimated plant score by the average benchmark score:

$$F_{adj} = \frac{Ln(E_s)}{Ln(E_{avg})}$$

$$F_{adj} = \frac{16.9179}{17.8}$$

$$F_{adj} = 0.9504$$

This benchmark score was developed for WWTPs in the United States and is therefore based on US customary units. SI conversion is necessary to obtain energy scores for Irish treatment plants. Additionally, the actual source energy for Plant A (E_{as}) must be found; this is the amount of raw fuel energy required to run the plant. Due to energy losses during production and transmission, the energy data recorded at the point of use in the plant (E_u) is only a fraction of the total raw energy used. Carlson and Walburger [62] state that "On a national basis 11,100 BTUs are used to produce and deliver a kWh of electricity". This statistic is derived from U.S. Energy Information Administration (EIA) annual energy review (2004) [108]. This source energy conversion factor (F_s) (based on the United States national average) equates to 11.1 kBtu/kWh.

$$E_u = Daily\ Plant\ Energy\ Consumption\ \times 365$$

$$E_u = (5433.24 \times 365)$$

$$E_u = 1983132.61 \quad kWh/year$$

$$E_{as} = E_u \times F_s \quad kBTU/year$$

$$E_{as} = (1983132.61) \times (11.1)$$

$$E_{as} = 22012772 \quad kBtu/year$$

The final adjusted source energy is found by calculating the natural log of the actual source energy divided by the adjustment factor. The result is a normalised log value for plant energy use.

$$Ln(E_{adj}) = \frac{Ln(E_{as})}{F_{adj}}$$

$$Ln(E_{adj}) = 17.7886$$

This result is then compared to the energy benchmarking curve (Figure 33) and a final score is given:

$$Plant\ A\ Score = 47$$

The computed value indicates that Plant A is in the 47th percentile of wastewater treatment plants. This score is close to an average score for US WWTPs (50th percentile). The same process was performed for Plants B, C, D and E. Table 11 shows the benchmarking calculation results for each of the audited plants.

Table 11: Energy benchmarking calculation and results for all audited WWTPs

Plant	Units	Plant A	Plant B	Plant C	Plant D	Plant E
Ln(E_s)	--	16.918	15.514	15.197	13.231	13.034
F_{adj}	--	0.950	0.872	0.854	0.743	0.732
E_u	kWh/year	1983132.61	691659	504381.13	81026.56	44691
E_{as}	kBtu/year	22012772	7677415	5598631	899395	496070
Ln(E_{adj})	--	17.789	18.190	18.199	18.443	17.910
Score		47	21	20	4	38

The flaws of this energy benchmarking calculation have been discussed in Section 2.8.3 above. Although the validity of these results are questionable, the fact that all of the audited plants are below average would indicate that the energy performance of these plants and possibly many Irish WWTPs are not on par with the international average. To gain a wider view of how Irish WWTPs perform this benchmark score calculation was applied to a further 4 WWTP plants across the four provinces of Ireland. The data for these plants was obtained through plant audits performed by colleagues in National University of Ireland Galway (NUIG) and Dublin City University (DCU). Table 12 below shows the score breakdown for the additional plants (see Appendix D) for full details of the additional 4 plant audits)

Table 12: Energy benchmarking calculation and results for additional WWTPs audited by NUIG and DCU

Plant	Plant F	Plant G	Plant H	Plant I
Ln(E_s)	14.936	17.852	12.307	17.088
F_{adj}	0.839	1.003	0.691	0.960
E_{as}	2371100	62986456	254238.4	10507322
Ln(E_{adj})	17.493	17.501	18.001	16.841
Score	68	67	37	95

The results from the supplementary WWTPs show another plant below average and two others just above average. The fourth plant scored well, i.e. in the 95th percentile. There is a wide variability in benchmark score in this study, with plants ranging from the 5th to the 95th percentile.

4.1.3 Metrics

Ultimately it is difficult to incorporate all the complex processes in WWT into one all-encompassing benchmark score. One performance metric does not give an insight into the merits or shortcomings of an audited plant. In this study the goal of a performance indicator was not to compare the performance of a number of similar plants against each other to see which one was superior. The KPI were chosen in this study to help identify areas of interest or possible inefficiencies in each of the plants. Without water quality data, the opportunities for in-depth plant analysis are limited. The energy and water data measured and analysed during the audits in Plants B-E led to significant findings with regards to how the plant was operating.

4.1.4 Harmonic Distortion

As discussed in section 2.9.2, variable frequency drives (VFDs) can offer significant savings to wastewater treatment plants. In all of the plants audited in this study, variable speed drives were implemented where possible. The larger plants in this study (A, B and C) all implemented VFDs on a wide range of plant equipment including sludge return pumps, effluent pumps and blowers. The smaller plants (D and E) had also retrofitted VFDs to the compressed air blowers. Alongside the energy efficiency benefits, there are a number of drawbacks associated with these devices. The increased harmonic distortion caused by the pulse rectifier in variable frequency drives can have detrimental effects on plant equipment and power factor. Figure 34 shows phase line 1 and neutral line current in Plant D. This graph shows high harmonic distortion in the current line. This distortion is also observed in the neutral line which ideally should not have any current.

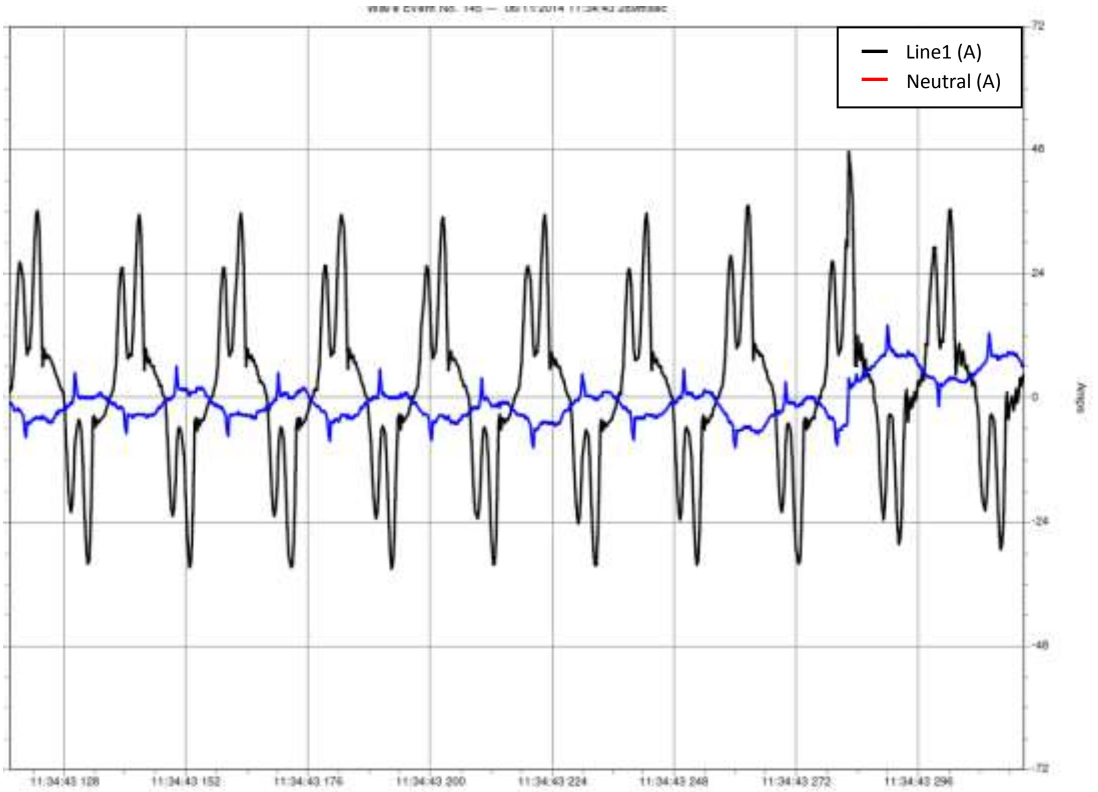


Figure 34: Average L1 current and neutral line current waveforms with harmonic disturbance

The IEEE 519 standards [109] for voltage Total Harmonic Distortion (THD) are shown in Table 13.

Table 13: Voltage THD distortion limits based on IEEE-519 standards adapted from [109]

Voltage distortion limits		
Bus voltage at PCC	Individual Voltage distortion (%)	Total Voltage distortion (THD) (%)
69 kV and below	3	5
69.001 through 161 kV	1.5	2.5
161.001 kV and above	1	1.5
Note: High-voltage systems can have up to 2% THD where the cause is an HDVC terminal that will attenuate by the time it is tapped by the user.		

In the treatment plants analysed in this study the limits for voltage THD (see Table 14) are not exceeded, however, many plants have high levels of current THD and voltage harmonics. Plant E in particular has high levels of 3rd and 5th order harmonics. Third order harmonics can cause heating in neutral line wires while 5th order harmonics create negative torque in 3-phase motors. This negative torque causes inefficiency in motors and can lead to reduced lifespan [110].

Table 14: Voltage and Current THD for four audited plants

Plant	Average THD (Voltage)			Average THD (Current)			Voltage range
	Line 1 (%)	Line 2 (%)	Line 3 (%)	Line 1 (%)	Line 2 (%)	Line 3 (%)	(kV)
B	2.33	1.84	2.17	41.52	40.97	47.4	>69
C	1.58	0.99	1.39	28.6	31.23	39.27	>69
D	1.31	1.06	1.18	6.33	2.66	3.15	>69
E	3.09	3.34	3.56	62.28	70.16	86.99	>69

4.1.5 Plant Design

A number of other issues arose during the completion of these detailed energy audits. By conducting the plant walkthroughs and staff interviews, areas of energy waste were identified. Many of the plants had poorly designed pipe routing. Unnecessary pipe bends across the plant causes increased pumping work. In plants with sludge dewatering facilities, sludge was often pumped from ground level vertically up to the roof across the room and back down again, as shown in Figure 35. Here the partially solid cake sludge pipe routing unnecessarily increases the pump work and energy consumption.

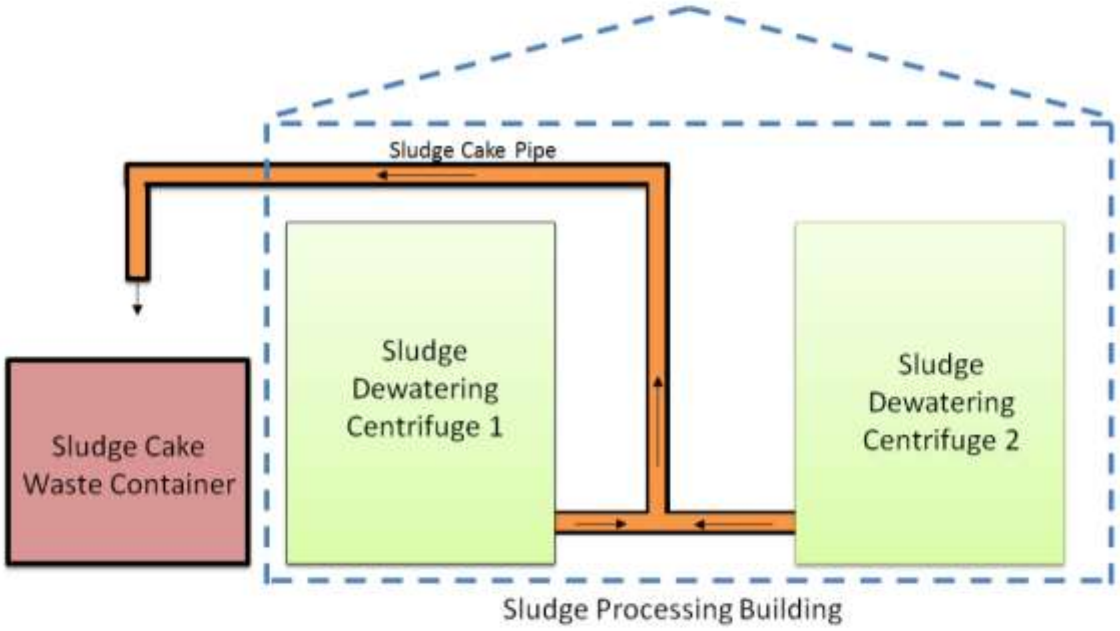


Figure 35: Visual representation of plant piping design issues in Plant C sludge dewatering building

Some potential electronic design issues were found in a number of plants also. Much of the equipment in WWTPs are three phase devices. Single phase equipment therefore is extracted from one of the 3 phase lines. It is important when doing this that single phase equipment across the plant is not all taken from one phase alone. When too much current is drawn from a single line the phases become unbalanced. Unbalanced phases can cause issues such as heating losses in 3 phase motors [111].

There were a number of wave error events during the trials. Figure 36 shows a wave event in Plant E. Here there is a spike in current in phase line 1. This graph indicates that current is being drawn from only this phase as the other phases are unaffected.

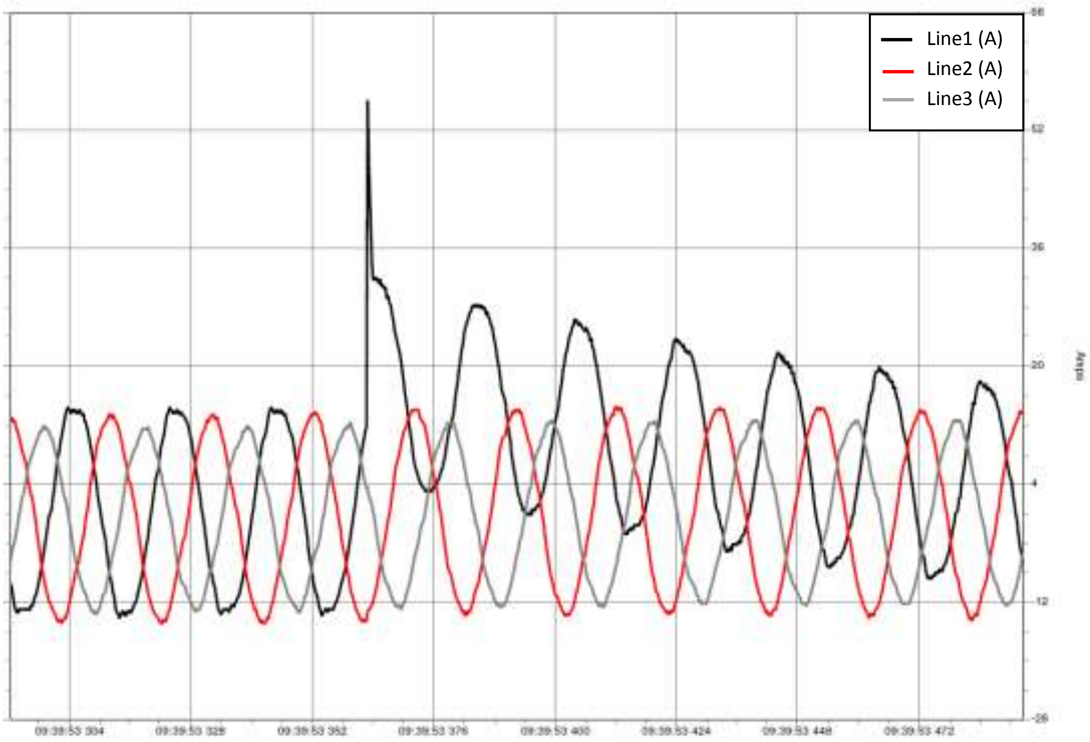


Figure 36: Unbalance on the L1 current waveform as current is only drawn from this line

Following this wave event, the current unbalance was investigated further. Figure 37 displays the current unbalance over a 24 hour period in Plant E. This plant experiences frequent events that raise the percentage unbalance from a baseline of 8% to over 40%.

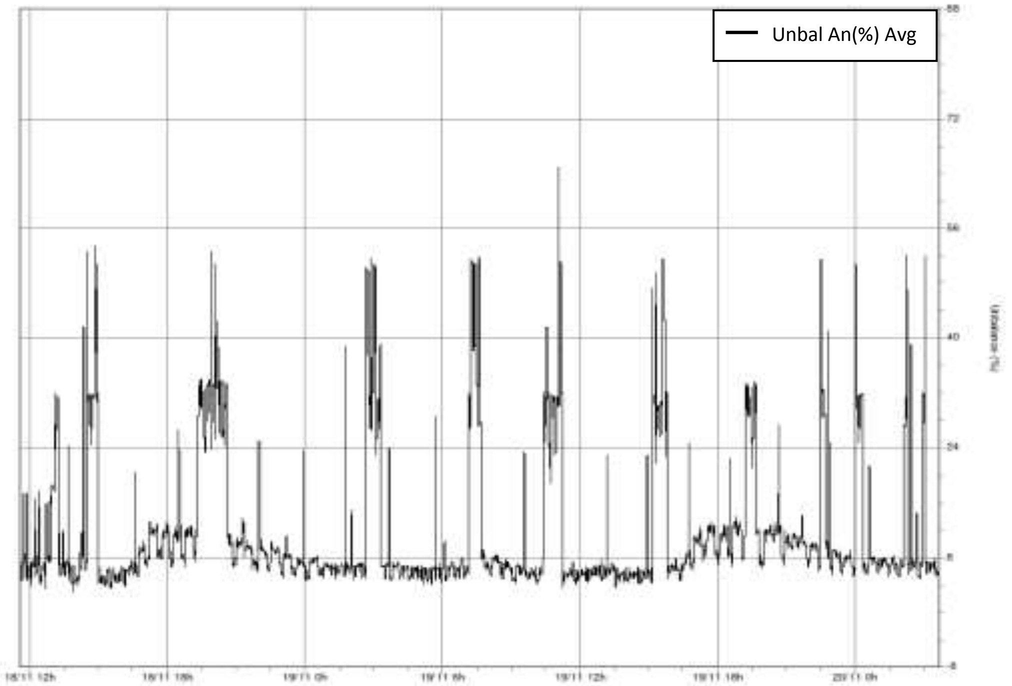


Figure 37: Percentage unbalance in Plant E over 24hours showing sustained periods of current unbalance

4.1.6 Power Factor Correction

Power factor is a metric that can give a good indication of plant power/energy performance. Poor power factor is an issue that was found in a number of the audited plants. Table 15 shows the average power factor over the duration of each of the trials. Plants A, B and C all employ power factor correction. Power factor correction is important for these plants as they have a large quantity of high power equipment. From the larger plants, Plant C flagged as having unusually low PF levels. Additionally, Plant C pays fines to the electricity supplier for power factor levels below the allowable limits. The plant was being fined an average of €358.26 per month. This equates to a yearly financial burden of €4300. The root cause of this problem was found after discovering that the power factor correction unit was turned off and that the capacitors were not suitable for the size of the plant.

Table 15: Average power factor for all audited plants

Plant ID	Power Factor (PF)
Plant A	0.894
Plant B	0.866
Plant C	0.798
Plant D	0.777
Plant E	0.664

The identification of the powered down PF correction unit shows the value of energy audits. Energy and power data recorded in this trial proved to be useful for troubleshooting plant issues such as this. In the case of Plant C the savings made from the discovery of this problem justify the investment in energy monitoring equipment.

4.1.7 Maintenance Schedules

It is important to note that the level of detail in the plant audit conducted in Plant A differs from the other four plants. The reason for that is the availability of flow and energy monitoring equipment. This study shows the merits of recording and analysing energy data across the whole plant. With more equipment monitored, the analysis became more detailed and plant inefficiencies were identified. One of the biggest problems identified in this study was the amount of equipment break downs and reliability issues experienced. The plants studied experienced issues with harmonic distortion, poor power factor, capacity overload and equipment overuse. All of these issues can lead to deterioration of plant equipment. Without a rigorous preventative maintenance (PM) schedule in these WWTPs the service life of pumps, blowers and dewatering systems could be reduced.

4.1.8 Night and Day Energy Rates

Many of the audited plants had large storm tank facilities. These storm tanks were only used in cases of heavy rainfall where the plant was not capable of processing the quantity of water flowing to the site. These storm tanks could potentially be used to store influent waters during the day and process that water in the night time when energy rates are lower. This strategy was discussed with plant operators in the audited facilities. The feedback was that it would be a risk that the influent would go septic in the storm tank and heavy duty cleaning would be required. The plant operators did not want to store large quantities of untreated influent water. Plant C, as commented previously, needed to pump effluent waters away to receiving waters.

This was done with two high capacity, energy efficient pumps which utilised state of the art VFDs. However, the energy savings potential of these pumps was not fully utilised. They were operating based on an on/off control system. The pumps would switch on once the levels in the effluent sump reached a certain point and then switch off when the levels were lower. These pumps could be utilised more efficiently if they pumped at a lower rate continuously. This method of effluent pumping would require a large effluent sump or storm tanks to contain the larger quantities of effluent.

4.1.9 Control Systems

All of the plants audited implemented dissolved oxygen control systems. Plant A was in the process of upgrading to new ammonia and DO control system. This was not in place when the monitoring was performed at the plant. Plant B, C and D all utilised a basic control system based on DO feedback. The compressed air blowers were adjusted continuously to maintain required DO levels in each of the activated sludge tanks. As discussed in section 2.9.4, the control system in Plant C was switched off automatic control due to frequent power cuts. Finally, Plant E was the only plant that operated using on/off control of tank DO levels. This system switched on the blowers until the tank DO levels reached an upper limit and then the blower was stopped. When the DO levels then dropped below a lower limit the blowers would switch on again. Figure 38 below shows the plant power usage over a four hour period in this plant. The graph shows a clear pattern where the blower is being switched on and off at regular intervals.

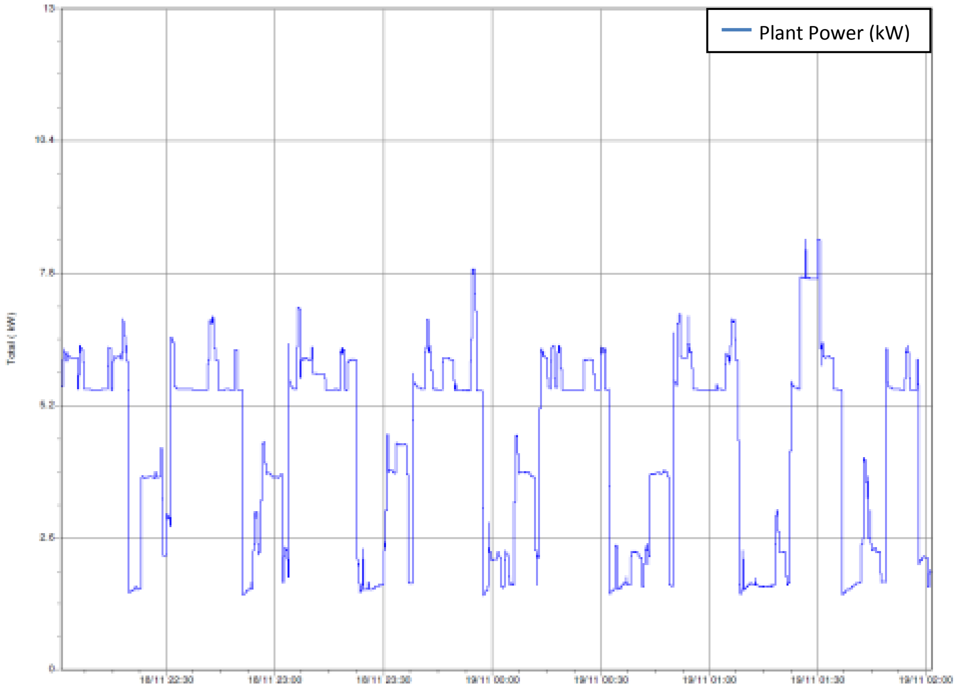


Figure 38: Power fluctuations in Plant E over a 4 hour period in the trial

This study highlights the difference control systems can have on energy usage. Plant B used DO control to almost half the power usage during off peak times. Plant C, operating temporarily without DO control, maintained a steady power use across peak and off-peak hours.

4.1.10 SCADA Energy Monitoring

The lack of energy monitoring in WWTP plants has been outlined in this study. The plants audited did not have any energy monitoring equipment in place. The only energy metrics available were monthly energy bills from an energy service provider. These bills only outlined the energy use for the entire plant and any fines for poor power factor. Each of the plants had SCADA systems implemented. These SCADA systems are capable of having energy monitoring equipment integrated.

5 Conclusions

Preliminary research on energy management in WWTPs identified a number of important shortcomings. It was clear that there were a lack of detailed auditing methodologies for the WWT industry. Furthermore, there were limited detailed energy auditing studies performed in Irish WWTPs. Following the completion of this research a number of objectives have been achieved, these include:

1. Development of an energy auditing methodology for WWTPs
2. Completion of detailed energy audits in five Irish WWTPs
    a. Power usage and energy distribution analysis presented for each plant
    b. Comprehensive power quality testing performed for each plant
    c. Detailed energy and water quality analysis completed (for four of the five plants).

Sophisticated energy monitoring equipment can be an expensive investment. The findings in this study show the positive aspects of investing in such devices. The power quality analyser helped to uncover power issues that would not have been otherwise discovered such as harmonic distortion, load imbalance, poor power factor, aeration control issues, and plant equipment reliability. In Plant C, power factor correction issues were identified. The discovery of a powered down power factor correction unit led to potential monetary savings of €4,300 per year. This study has demonstrated that energy auditing can identify issues to improve plant efficiency and power factor performance, thus leading to monetary savings.

This research has outlined numerous examples of reliability and efficiency concerns in relation to plant equipment. These issues are all linked, to various degrees, to the lack of preventative maintenance in all of the audited plants. These audited plants operate on a ‘run to failure’ policy. PM systems may seem costly in the short term but have been shown to improve the reliability and to ensure reduced variation in equipment performance.

One of the key findings from this research is the benefit of parallel energy and water quality testing. Plant A did not undergo any water quality assessment. The analysis performed on this plant was quite basic (limited to power and energy analysis). By comparing this level of analysis with the data presented for Plants B and C, the added dimension that water quality analysis adds is evident. Plants B and C are plants of the same size and technology. Comparing energy consumed per day and energy consumed per volume of influent these two plants appeared to be performing in a similar manner. However, with added water quality metrics it was found that Plant B was consuming less energy per kg of BOD, COD and TSS removed. This may be due to several factors including:

1. Plant C had temporarily switched off its DO control system
2. Plant B was operating at close to its designed organic loading capacity.

Similarly, Plant D was operating in excess of its design flow and organic capacity. This again became evident in the water quality analysis. Comparing Plants D and E, Plant E BOD and COD removal energy was 267% and 186% higher respectively than Plant D. This suggests that plants operating at their design capacity perform more efficiently. With rapid population growth around some plants and slow growth around others it is difficult to predict what capacity will be needed at the design phase.

Some plant design considerations have been addressed in this study. Sub-optimal electrical wiring, pipe routing and general plant layout were discovered across many of the plants analysed. Poor electrical wiring in Plant E was the probable cause of frequent current unbalance events. These events caused increases in the percentage current unbalance from a baseline of 8% to over 40%.

Plant energy benchmarking was performed for all plants using the Carlson and Walburger energy model. This showed that each of these plants performed below average compared to the 266 (American) WWTPs included in the model. Plant D performed poorly in relation to the other plants assessed in this study; this may be due to the plant operating at almost double its design capacity.

This thesis has presented numerous deficiencies in the audited WWTPs and made recommendations to address these issues. The implementation of these recommendations presents an opportunity for future work on this project. Reassessment of each plant once any of the proposed changes has been implemented would be an interesting exercise. By analysing the plant performance before and after a change is made, the impact of that change can be quantified.

6 Future Work

6.1 Apply energy monitoring strategies

Energy monitoring is vital to understanding the performance of a WWTP plant. A good place to start is the plant energy bill. This gives basic information such as total plant energy consumption, reactive power and night to day usage breakdown. This data may help the plant manager to decide what level of energy monitoring is appropriate. Ideally all energy monitoring would be continuous and link in with the plant SCADA system. A comprehensive energy audit is recommended as it can help uncover potential energy efficiency opportunities and safety issues that would otherwise go unnoticed.

6.2 Consider thorough water quality analysis especially when performing plant audits

When performing plant energy audits it is important to consider all the factors that drive energy use. This study shows the benefit of parallel energy and water quality monitoring. This practice is not only beneficial during plant audits as continuous water quality monitoring is vital for plant managers/engineers to understand how well the plant is performing. There are a number of commercially available automated water quality sensor systems on the market today.

Irish WWTPs must report effluent quality data to the EPA several times per year. Much of the plants' water quality resources are focused on effluent monitoring. It is important not to overlook influent water quality. By analysing both influent and effluent, useful data can be obtained for example:

1. Kg BOD/COD removed
2. TSS removed
3. kWh/kg of BOD removed
4. kWh/kg of COD removed
5. kWh/kg of TSS removed.

With this in mind this study recommends frequent and consistent water quality monitoring of influent and effluent waters.

6.3 Employ energy efficient equipment

Older plant equipment like pumps and blowers should be upgraded to more energy efficient alternatives. Upgrading to energy efficient pumps and blowers is cost effective in the long term. Where appropriate, new pumps and blowers should utilise VFD technology. If replacing pumps is not an option, VFDs should be retrofitted (choosing a VFD with a higher number of pulse converters will induce less harmonics distortion).

6.4 Consider plant efficiency from the design phase

Many of the recommendations in this study relate to the improvement in energy efficiency of WWTP equipment and systems. These are corrective measures to improve plant efficiency. Ideally these corrective measures would be considered at the plant design stage. During plant design and development steps, initial capital cost should not be the sole motivating factor. Cost savings over the life-cycle of the WWTP can be achieved by incorporating other concepts into the design phase. Optimal plant layout, energy efficient piping networks and well designed, executed and future-proofed electrical wiring are just a few areas that could minimise long term energy consumption.

6.5 Regularly monitor plant power factor

Poor power factor can lead to increased machine wear and fines from energy providers. Perform checks of plant power factor correction units to ensure the unit is correctly configured. Check the capacitor sizes are adequate for the plant and where possible record data over a long period (days) as the power factor will continuously change depending on what equipment is running in the plant at that time.

6.6 Retro-fit harmonic filters

If possible, retrofit passive or active harmonic filters to reduce harmonic distortion in plant power lines. Harmonic distortion and power factor are closely linked as high distortion will cause a decrease in plant power factor. A high level of harmonic distortion also has a detrimental effect on the service life of plant equipment. Any subsequent new or upgraded equipment added to a plant may require the harmonic filters adjustment to adapt to the new load.

6.7 Implement and maintain effective control strategies

Evaluate and optimise plant control strategies where possible (DO control/Ammonium-DO cascade control). Many of the plants in this study had issues with plant control systems. Plant C operated without DO control while the Plant E DO control system operated inefficiently. Investment in a reliable and optimised control system is recommended in order to minimise aeration energy consumption.

6.8 Implement and inforce robust preventative maintenance schedules

Preventative maintenance (PM) reduces equipment wear, increases service life and potentially increases energy efficiency across the plant. It is important to implement PM schedules that are followed consistently. Any changes made should be logged and tracked. These logs can be very useful for troubleshooting potential issues with equipment. There are numerous PM software packages available that provide services such as PM checklists, equipment use tracking, and notifications when PMs are due/overdue. These software packages are highly flexible and can be used to schedule anything from short weekly visual checks to monthly or yearly machine maintenance.

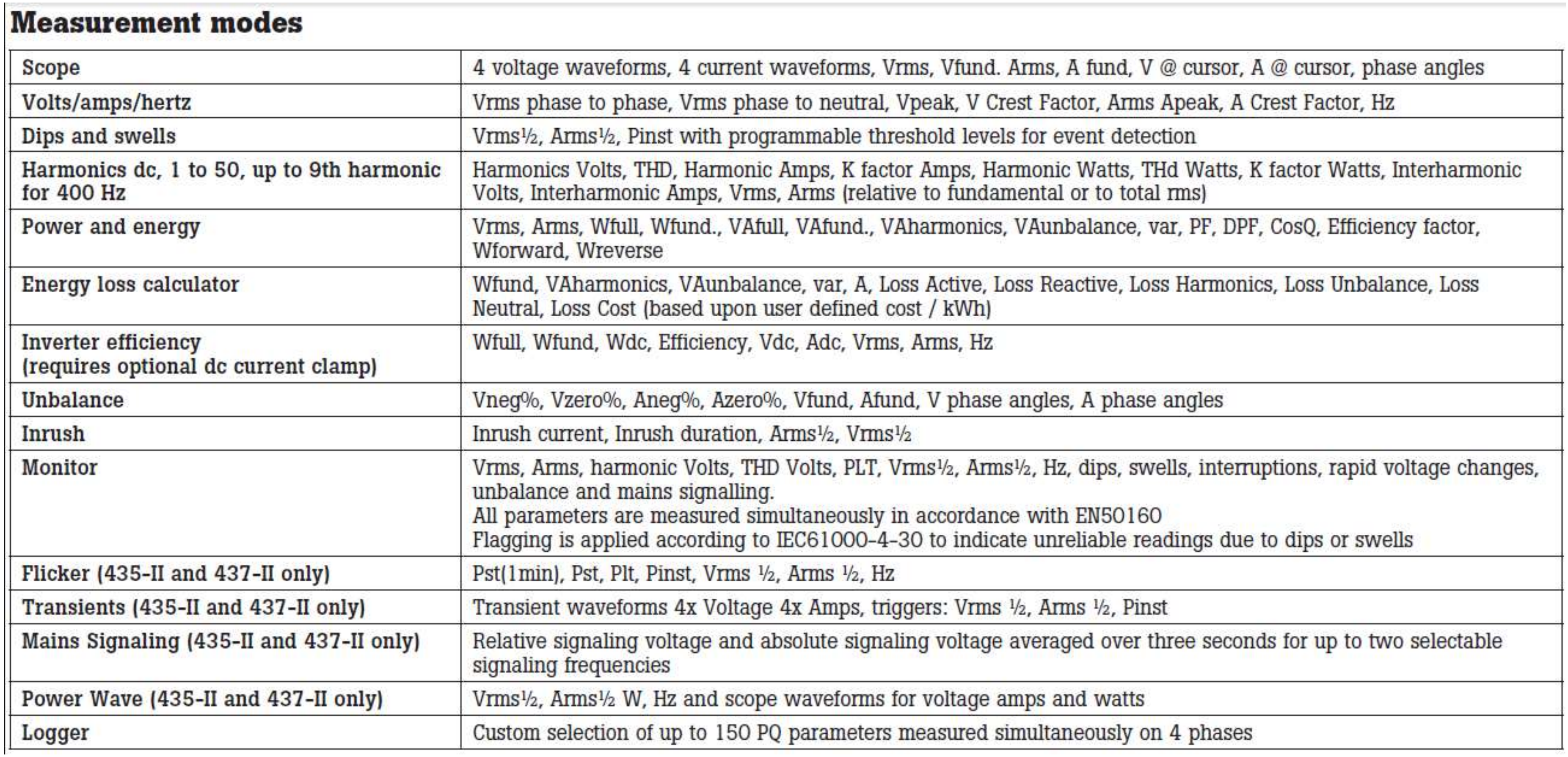
6.9 Ensure the plant is equipped with reliable instrumentation

Adequate and reliable instrumentation and monitoring strategies should be implemented across the plant. This study has recommended numerous methods for improving plant performance through instrumentation, control and automation. Further methods for optimising plant performance include:

1. Ensuring all plant equipment and instrumentation is incorporated into the plant SCADA system
2. Investing in reliable flowmeters for the monitoring of influent, effluent, storm and in process flows.
3. Monitoring mains water usage and consider tertiary treatment of effluent water for use in the plant (as implemented in Plant C)

Appendix A

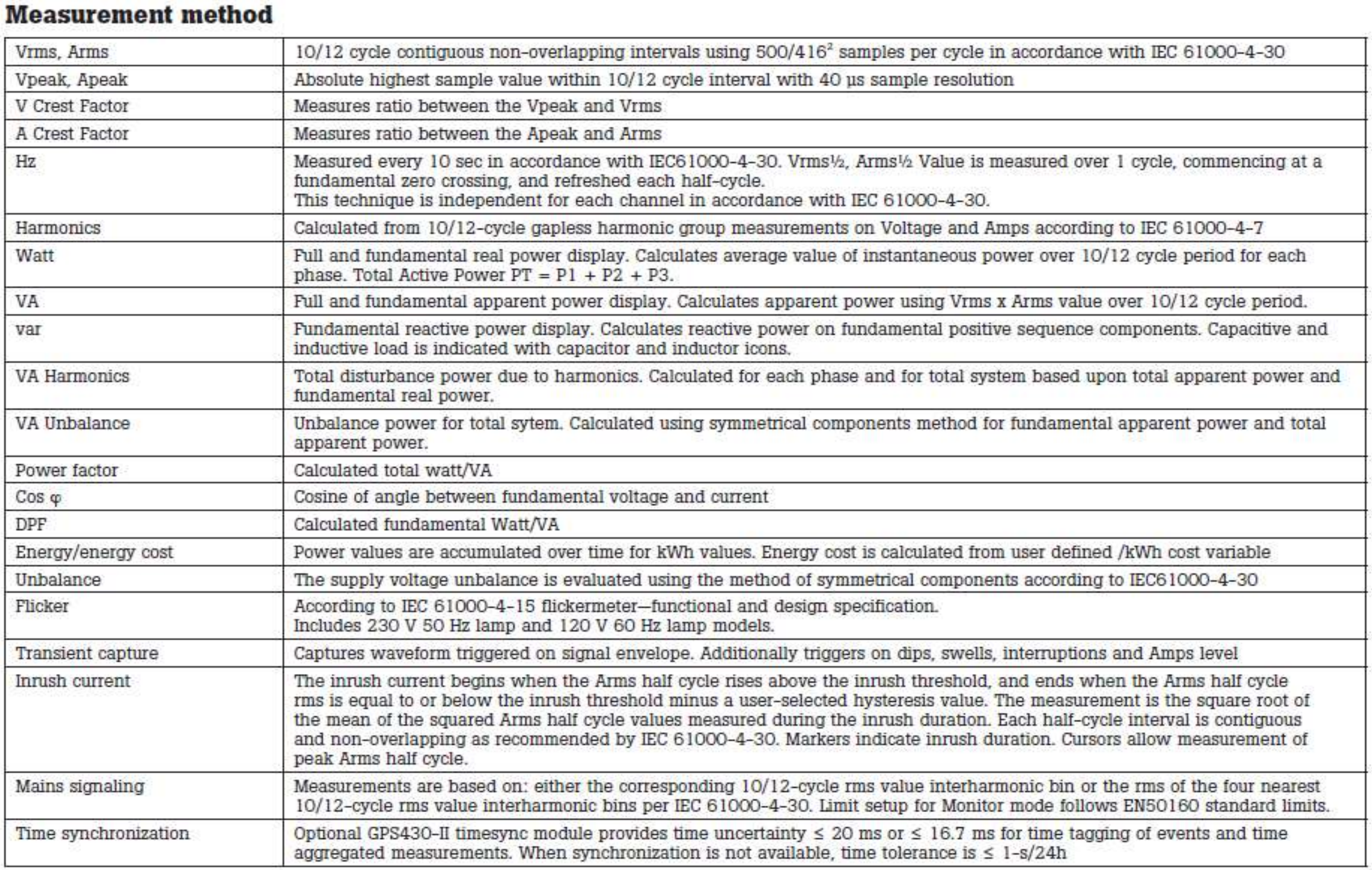
Table A1: Fluke 430 Series II PQA measurement modes data sheet [112]



Measurement modes

Scope	4 voltage waveforms, 4 current waveforms, Vrms, Vfund. Arms, A fund, V @ cursor, A @ cursor, phase angles
Volts/amps/hertz	Vrms phase to phase, Vrms phase to neutral, Vpeak, V Crest Factor, Arms Apeak, A Crest Factor, Hz
Dips and swells	Vrms½, Arms½, Pinst with programmable threshold levels for event detection
Harmonics dc, 1 to 50, up to 9th harmonic for 400 Hz	Harmonics Volts, THD, Harmonic Amps, K factor Amps, Harmonic Watts, THd Watts, K factor Watts, Interharmonic Volts, Interharmonic Amps, Vrms, Arms (relative to fundamental or to total rms)
Power and energy	Vrms, Arms, Wfull, Wfund., VAfull, VAfund., VAharmonics, VAunbalance, var, PF, DPF, CosQ, Efficiency factor, Wforward, Wreverse
Energy loss calculator	Wfund, VAharmonics, VAunbalance, var, A, Loss Active, Loss Reactive, Loss Harmonics, Loss Unbalance, Loss Neutral, Loss Cost (based upon user defined cost / kWh)
Inverter efficiency (requires optional dc current clamp)	Wfull, Wfund, Wdc, Efficiency, Vdc, Adc, Vrms, Arms, Hz
Unbalance	Vneg%, Vzero%, Aneg%, Azero%, Vfund, Afund, V phase angles, A phase angles
Inrush	Inrush current, Inrush duration, Arms½, Vrms½
Monitor	Vrms, Arms, harmonic Volts, THD Volts, PLT, Vrms½, Arms½, Hz, dips, swells, interruptions, rapid voltage changes, unbalance and mains signalling. All parameters are measured simultaneously in accordance with EN50160 Flagging is applied according to IEC61000-4-30 to indicate unreliable readings due to dips or swells
Flicker (435-II and 437-II only)	Pst(1min), Pst, Plt, Pinst, Vrms ½, Arms ½, Hz
Transients (435-II and 437-II only)	Transient waveforms 4x Voltage 4x Amps, triggers: Vrms ½, Arms ½, Pinst
Mains Signaling (435-II and 437-II only)	Relative signaling voltage and absolute signaling voltage averaged over three seconds for up to two selectable signaling frequencies
Power Wave (435-II and 437-II only)	Vrms½, Arms½ W, Hz and scope waveforms for voltage amps and watts
Logger	Custom selection of up to 150 PQ parameters measured simultaneously on 4 phases

Table A2: Fluke 430 Series II PQA measurement methods data sheet [112]



Measurement method

Vrms, Arms	10/12 cycle contiguous non-overlapping intervals using 500/416[2] samples per cycle in accordance with IEC 61000-4-30
Vpeak, Apeak	Absolute highest sample value within 10/12 cycle interval with 40 µs sample resolution
V Crest Factor	Measures ratio between the Vpeak and Vrms
A Crest Factor	Measures ratio between the Apeak and Arms
Hz	Measured every 10 sec in accordance with IEC61000-4-30. Vrms½, Arms½ Value is measured over 1 cycle, commencing at a fundamental zero crossing, and refreshed each half-cycle. This technique is independent for each channel in accordance with IEC 61000-4-30.
Harmonics	Calculated from 10/12-cycle gapless harmonic group measurements on Voltage and Amps according to IEC 61000-4-7
Watt	Full and fundamental real power display. Calculates average value of instantaneous power over 10/12 cycle period for each phase. Total Active Power PT = P1 + P2 + P3.
VA	Full and fundamental apparent power display. Calculates apparent power using Vrms x Arms value over 10/12 cycle period.
var	Fundamental reactive power display. Calculates reactive power on fundamental positive sequence components. Capacitive and inductive load is indicated with capacitor and inductor icons.
VA Harmonics	Total disturbance power due to harmonics. Calculated for each phase and for total system based upon total apparent power and fundamental real power.
VA Unbalance	Unbalance power for total sytem. Calculated using symmetrical components method for fundamental apparent power and total apparent power.
Power factor	Calculated total watt/VA
Cos φ	Cosine of angle between fundamental voltage and current
DPF	Calculated fundamental Watt/VA
Energy/energy cost	Power values are accumulated over time for kWh values. Energy cost is calculated from user defined /kWh cost variable
Unbalance	The supply voltage unbalance is evaluated using the method of symmetrical components according to IEC61000-4-30
Flicker	According to IEC 61000-4-15 flickermeter—functional and design specification. Includes 230 V 50 Hz lamp and 120 V 60 Hz lamp models.
Transient capture	Captures waveform triggered on signal envelope. Additionally triggers on dips, swells, interruptions and Amps level
Inrush current	The inrush current begins when the Arms half cycle rises above the inrush threshold, and ends when the Arms half cycle rms is equal to or below the inrush threshold minus a user-selected hysteresis value. The measurement is the square root of the mean of the squared Arms half cycle values measured during the inrush duration. Each half-cycle interval is contiguous and non-overlapping as recommended by IEC 61000-4-30. Markers indicate inrush duration. Cursors allow measurement of peak Arms half cycle.
Mains signaling	Measurements are based on: either the corresponding 10/12-cycle rms value interharmonic bin or the rms of the four nearest 10/12-cycle rms value interharmonic bins per IEC 61000-4-30. Limit setup for Monitor mode follows EN50160 standard limits.
Time synchronization	Optional GPS430-II timesync module provides time uncertainty ≤ 20 ms or ≤ 16.7 ms for time tagging of events and time aggregated measurements. When synchronization is not available, time tolerance is ≤ 1-s/24h

Appendix B

Table B1: Basic information of all five audited WWTPs

CHARACTERISTIC	WWTP A	WWTP B	WWTP C	WWTP D	WWTP E
TREATMENT TECHNOLOGY	Activated sludge with P removal	Activated sludge with P removal	Activated sludge with P removal	Activated sludge with P removal	Activated sludge with P removal
INFLUENT CHARACTERISTICS	Wastewater & landfill leachate	Municipal Wastewater only	Municipal Wastewater only	Municipal Wastewater only	Municipal Wastewater only
TERTIARY TREATMENT	None	None	None	None	None
DESIGN CAPACITY (BOD)	50,000 PE	12,000 PE	12,000 PE	600 PE	820 PE
ORGANIC LOADING	37,200 PE (as of 2013)	12,284 PE (2014)	9,036 PE (2015)	1,024 PE (2015))	590PE (2015)
HYDRAULIC CAPACITY (DWF) (M^3/YEAR)	-	1,642,500	821,250	49,275	36,500
HYDRAULIC CAPACITY (PEAK FLOW) (M^3/YEAR)	-	4,927,500	2,463,750	147,825	109,500
HYDRAULIC LOADING (M^3/YEAR)	-	839,135	1,072,005	110,960	41,245
DISCHARGES INTO	River	River	River	River	River
TEST FREQUENCY	Monthly	Monthly	Monthly	Bi-monthly	Monthly

Table B2: Discharge requirements and sludge treatment details for audited WWTPs

CHARACTERISTIC	WWTP A	WWTP B	WWTP C	WWTP D	WWTP E
DISCHARGE REQUIREMENTS:					
PH	-	6 - 9	6 - 9	6 - 9	6 - 9
TEMPERATURE	-	-	-	-	-
CBOD	25mg/l	25mg/l	20mg/l	10mg/l	25mg/l
COD	125mg/l	125mg/l	125mg/l	50mg/l	125mg/l
SUSPENDED SOLIDS	35mg/l	35mg/l	30mg/l	25mg/l	35mg/l
TOTAL NITROGEN (AS N)	-	-	20mg/l	-	-
TOTAL PHOSPHORUS (AS P)	-	2 mg/l	1 mg/l	-	-
AMMONIA (AS N)	-	5mg/l	-	1mg/l	5mg/l
ORTHOPHOSPHATE (AS P)	-	1 mg/l	-	0.5 mg/l	2mg/l
SLUDGE TREATMENT:					
YEARLY SLUDGE OUTPUT (KG - DS)	-	183,600	108,000	N/A	N/A
SLUDGE OUT PER M^3 OF INFLUENT (KG - DS)	-	0.22	0.10	N/A	N/A
SLUDGE TREATMENT	Centrifugal dewatering and thickening, chemical stabilisation, anaerobic digestion	Picket fence thickeners Centrifugal dewatering and thickening, chemical stabilisation	Picket fence thickeners Centrifugal dewatering and thickening, chemical stabilisation	None (Sent for external treatment)	None (Sent for external treatment)
SLUDGE DISPOSAL METHOD	Land application	Land application	Land application	Land application	Land application

Table B3: Audit details for each WWTPs

CHARACTERISTIC	WWTP A	WWTP B	WWTP C	WWTP D	WWTP E
SAMPLING DATES	12/12/2013 to 18/12/2013	02/09/2014 to 07/09/2014	07, 08, 09, 14, 15, 16, 19 of October 2015	06/11/2015 to 09/11/2015	18, 19, 20, 24 of November 2015
NUMBER OF DAYS	7 days	6 days	7 days	4 days	4 days
FLOW STREAMS SAMPLED	-	Influent and Effluent	Influent and Effluent	Influent	Influent
NUMBER OF SAMPLES PER STREAM PER DAY	As per plant managers schedule	6	6	6	6
TIME BETWEEN SAMPLES	N/A	4 hours	4 hours	4 hours	4 hours
INFLUENT TESTING LOCATION	Influent Stream	Screening	Screening	Influent Stream	Influent Stream
INFLUENT SAMPLING METHOD	-	24 hour composite	24 hour composite	24 hour composite	24 hour composite
EFFLUENT TESTING LOCATION	-	Leaving Final Clarifier	Leaving Final Clarifier	Leaving Final Clarifier	Effluent Channel
EFFLUENT SAMPLING METHOD	-	24 hour composite	24 hour composite	24 hour composite	24 hour composite
ENERGY DATA	Yes	Yes	Yes	Yes	Yes
DATA POINT FREQUENCY	1-60 seconds	30-60 seconds	30-60 seconds	30-60 seconds	30-60 seconds
INFLUENT FLOW DATA	Yes	Yes	Yes	Yes	Yes
FREQUENCY AND TYPE	Daily Total	Daily Total	Daily Total	Daily Total	Daily Total
EFFLUENT FLOW DATA	Yes	Yes	Yes	No	No
FREQUENCY	Daily Total	Daily Total	Daily Total	N/A	N/A

Appendix C

Table C1: Water quality test results for Plants B-E

Plant			BOD		COD		TSS		TN FILTERED		TP FILTERED		Ortho-P		Ammonia		Nitrite	
Day	Date	Time	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff
WWTP B																		
1	02-Sep	09:00	235.00	6.00	384.00	80.00	532.00	6.36	63.698	53.272	5.582	0.102	4.868	0.039	64.229	1.508	0.125	0.030
2	03-Sep	09:00	211.11	16.13	480.00	138.67	164.00	34.80	63.778	59.682	6.382	1.034	4.811	0.977	78.193	2.416	0.024	0.072
3	04-Sep	09:00	183.33	9.41	421.33	32.00	300.00	10.00	77.843	38.028	8.349	0.737	6.105	0.394	99.614	0.096	0.004	0.029
4	05-Sep	09:00	223.89	7.08	n/a	n/a	348.00	n/a	67.644	48.243	8.086	1.194	5.467	0.947	94.338	0.935	0.257	0.062
5	06-Sep	09:00	193.50	8.00	n/a	n/a	136.00	n/a	84.323	51.075	9.911	1.855	6.78	1.331	121.061	0.159	0.045	0.053
	Average		209.37	9.32	428.44	83.56	296.00	17.05	71.46	50.06	7.66	0.98	5.61	0.74	91.49	1.02	0.09	0.05
WWTP C																		
1	07-Oct	9:00	113.06	12.67	288.00	53.33	172.00	26.00	33.177	21.214	5.037	1.712	2.862	1.026	40.908	0.067	0.044	0.018
2	08-Oct	9:00	90.00	6.50	n/a		110.00	13.20	40.000	18.403	4.454	0.733	2.96	0.053	57.421	0.408	0.617	0.023
3	09-Oct	9:00	105.00	8.08	245.33	85.33	193.33	19.20	26.892	19.549	2.994	0.385	1.971	0.079	33.323	0.258	0.286	0.032
4	14-Oct	9:00	126.63	12.93	149.33	53.33	178.00	14.53	29.764	20.963	3.589	0.806	2.56	0.688	42.830	0.208	0.561	0.007
5	15-Oct	9:00	49.41	n/a	256.00	48.00	170.00	19.20	25.067	n/a	3.683	n/a	2.519	n/a	35.762	n/a	0.010	n/a
6	16-Oct	9:00	n/a	n/a	341.33	117.33	152.00	14.80	23.984	9.690	2.915	0.818	2.536	0.596	32.462	0.113	0.020	0.004
7	19-Oct	9:00	n/a	n/a	192.00	32.00	140.00	20.27	28.320	22.163	2.717	0.660	2.32	0.474	41.319	0.101	0.278	0.061
	Average		96.82	10.05	245.33	64.89	159.33	18.17	29.60	18.66	3.63	0.85	2.53	0.49	40.58	0.19	0.26	0.02
WWTP D																		
1	06-Nov	9:00	66.67	24.00	410.67	106.67	72.00	56.40	16.635	9.196	1.380	0.766	1.021	0.534	21.571	0.323	0.702	1.606
2	09-Nov	9:00	100.00	7.74	96.00	21.33	90.00	17.20	10.972	8.967	0.972	1.007	0.395	0.734	11.772	4.664	0.163	1.554
3	11-Nov	9:00	263.33	8.71	160.00	21.33	55.00	56.00	6.813	7.241	0.972	0.590	0.703	0.309	8.115	2.766	0.490	0.628
4	12-Nov	9:00	106.67	16.00	117.33	21.33	352.00	148.00	20.148	9.307	3.962	1.334	3.41	0.769	21.218	1.132	0.296	1.010
	Average		134.17	14.11	196.00	42.67	142.25	69.40	13.64	8.68	1.82	0.92	1.38	0.59	15.67	2.22	0.41	1.20
WWTP E																		
1	17-Nov	9:00	225.83	6.70	384.00	138.67	244.00	48.80	20.384	24.293	2.296	0.177	1.771	0.03	23.259	0.698	0.003	0.463
2	18-Nov	9:00	80.00	8.40	266.67	117.33	288.00	38.40	24.888	20.594	2.867	0.429	2.412	0.03	24.512	0.717	0.675	0.230
3	19-Nov	9:00	128.89	12.90	234.67	74.67	158.00	104.00	25.001	20.732	3.482	0.131	3.107	0.003	33.925	0.981	0.003	0.239
4	22-Nov	9:00	58.33	4.80	298.67	117.33	242.50	70.00	23.889	16.742	2.027	0.114	1.307	0.024	26.217	0.618	0.262	0.165
	Average		123.26	8.20	296.00	112.00	233.13	65.30	23.54	20.59	2.67	0.21	2.15	0.02	26.98	0.75	0.24	0.27

Appendix D

Table D1: Details regarding additional WWTPs used in energy benchmarking equation.

CHARACTERISTIC	WWTP F	WWTP G	WWTP H	WWTP I
REGISTRATION NUMBER	D0077-01	D0038-01	A0169-01	D0020-01
TREATMENT TECHNOLOGY	Activated sludge with P removal	Activated Sludge	PFBR (Biofilm)	Activated Sludge
INFLUENT CHARACTERISTICS	Municipal Wastewater & landfill leachate	Municipal Wastewater only	Municipal wastewater with storm water	Municipal Wastewater & landfill leachate
TERTIARY TREATMENT	None	None	None	None
DESIGN CAPACITY (BOD)	5,000 PE	186,000 PE	750 PE	18,517 PE
ORGANIC LOADING	2,500 PE (2014)	79,133 PE (2015)	422 PE	25,633 (2014)
HYDRAULIC CAPACITY (DWF) (M^3/YEAR)	200,750	13,140,000	-	1,420,215
HYDRAULIC CAPACITY (PEAK FLOW) (M^3/YEAR)	602,250	39,420,000	-	4,260,645
HYDRAULIC LOADING (M^3/YEAR)	570,228	14,940,180	-	3,544,150
DISCHARGES INTO	River	Long Sea Outfall	River	River
TEST FREQUENCY	Monthly	Monthly	3 times per year	Monthly

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