The Use of Exergy Analysis to Benchmark the Resource Efficiency of Municipal Waste Water Treatment Plants in Ireland

By

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Masters of Engineering

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DECLARATION

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Masters of Engineering is entirely my own work, that I have exercised reasonable care to ensure that the work is original, and does not to the best of my knowledge any law of copyright, and has not been acknowledged within the text of my work.

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Table of Contents

NOMENCLATURE

Acronyms

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEP	Break Efficiency Point
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
ECM	Energy Conservation Measures
EMS	Energy Management Systems
EPA	Environmental Protection Agency
KPI	Key Performance Indicators
LCA	Life Cycle Analysis
MABR	Membrane Aerated Biofilm Reactor
PE	Population Equivalent
PFBR	Pumped Flow Biofilm Reactor
PID	Proportional Integral Derivative
RE	Reference Environment
THOD	Theoretical Oxygen Demand
TN	Total Nitrogen
TOC	Total Organic Carbon
TOD	Total Oxygen Demand
TP	Total Phosphorus
US	United States
UWWTD	Urban Waste Water Treatment Directive
VFD	Variable Frequency Drives
WWTP	Waste Water Treatment Plant

Symbols

a	Activity
b	Specific Exergy (kJ/kg)
c	Velocity (m/s)
$C\ p,_{H20}$	Specific heat capacity of water (kJ/kgK)
g	Gravitational acceleration of the earth (m/s2)
m	Mass (kg)
n	Mole number (mol/kg)
p	Pressure (kPa)
R	Universal gas constant (kJ/kg K)
T	Temperature (K)
v	Specific volume of the aqueous solution (m3/kg)
x	Molar fraction of the substance i in the solvent
y	Relative molality (kmol/kg)
z	Height (m)
ΔG_f	Gibbs free energy (kJ/kmol)
Υ	Activity Coefficient
Σ	Sigma

Subscripts

ch	Chemical
$ch,_c$	Chemical (concentration)
$ch,_f$	Chemical (formation)
e	Each element forming the substance i
H_2O	Water
i	Any considered substances
k	Kinetic
m	Mechanical
o	Under reference conditions
p	Under ambient conditions
t	Thermal
$_T$	Total

z	Potential

Table of Figures

Table of Tables

PUBLICATIONS FROM THIS RESEARCH

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ABSTRACT

The use of Exergy Analysis to Benchmark the Resource Efficiency of Municipal Waste Water Treatment plants in Ireland

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With ever increasing environmental standards and waste water loading rates, energy consumption for waste water treatment is predicted to rise by over 20% by 2020 in the United States. When considering the resource efficiency of waste water treatment plants factors such as effluent quality, carbon footprint and increasing electricity rates act as a driving force for sustainable design of these facilities. Exergy analysis has been identified in the literature as a powerful tool in the analysis of thermal systems. It enables the resource efficiency of systems to be benchmarked, where the process with the greatest exergy destruction represents the greatest energy efficiency opportunity. The objectives of this research are: (i) calculate the chemical exergy of the relevant process streams within waste water treatment plants; (ii) identify the most suitable parameter to calculate the chemical exergy of organic matter; (iii) identify exergy losses from process streams that could be utilised to produce work. Exergy analysis of three separate waste water treatment plants has been performed. Having identified and measured all the key process input and outputs, a comprehensive exergy analysis has been undertaken. Following an extensive literature review, earlier methods to calculate chemical exergy of organic matter are critically assessed; chemical oxygen demand was identified as the most useful parameter when calculating the chemical exergy of organic matter in waste water. Results for the work indicate that organic matter is the principal contributor to chemical exergy values in waste water treatment plants. Influent organic matter loading rates also greatly impact the exergy destruction rates across a waste water treatment plant.

1 Introduction

Energy is a key input in the operation of a number of Waste Water Treatment Plant (WWTP) processes. It is used in the initial transportation of waste water to the plant, the biological treatment of organic matter and the eventual discharge of treated waste water from the plant. Additionally, substantial quantities of other resources such as coagulants and disinfectants are consumed in the treatment of waste water. With WWTPs accounting for approximately 1% of the world's total energy consumption [1] and the current instability in the cost of supplied electricity, greater emphasis has been placed on proficient use of these fundamental resources. Therefore, characterisation and optimisation of all resources within a WWTP is crucial. Establishing a connection between energy, resources and sustainability necessitates the use of a method to quantify resources and resource consumption within WWTPs; exergy analysis is a potential method.

Exergy is a thermodynamic property, which combines the first and second law of thermodynamics and can be defined as the maximum theoretical work that can be achieved when two systems at different states are brought into equilibrium [2]. Exergy analysis is recognised as an important instrument in the analysis of thermal and chemical systems [3, 4]. Exergy analysis takes into consideration thermodynamic irreversibilities often neglected by the conventional energy balance such as energy losses in heat transfer and chemical reactions [5]. However, exergy analysis has rarely been applied to WWTP optimisation. By quantifying the exergy content of process streams, the exergy destruction across plant processes can be calculated. A hierarchy of inefficient processes can be identified, allowing informed design decisions to be made with regard to WWTP sustainability.

This research takes a holistic view of all aspects of WWTP treatment with a number of WWTPs across Ireland benchmarked based on certain characteristics such as; (i) Population Equivalent (PE) load; (ii) type of treatment (i.e. primary, secondary, tertiary); (iii) discharge location; (iv) aerobic versus anaerobic treatment of waste water. The benchmarking methodology is composed of a number of steps, measurement of:

- Energy demand of all equipment and processes
- Waste water treatment parameters (i.e. Chemical Oxygen Demand etc.)
- Waste water flow rate.

Once all the information was obtained from the respective WWTPs, the following objectives were defined for this research:

- Determine most suitable method to calculate the chemical exergy of organic and inorganic matter for waste water treatment
- Conduct exergy analyses of a number of WWTPs, quantifying the exergy content or work potential of process streams
- Establish a hierarchy of wastewater treatment plant processes with the greatest exergy destruction
- Determine the exergy losses from WWTP processes that could be utilised to produce work.

The pertinent WWTP resource efficiency and exergy research literature is reviewed in Chapter 2. The key sections include an introduction to the current state of the waste water sector in Ireland and an investigation into the most suitable energy efficient technologies applicable to WWTPs; allied to this, a method to achieve sustained savings such as energy management systems is also reviewed. The fundamentals of exergy analysis are reviewed along with its application to benchmarking the resource efficiency of WWTPs. The review of exergy analysis discusses the pertinent issues relevant to this research such as:

- How is exergy analysis used to benchmark the resource efficiency of WWTPs?
- What is the most suitable organic measurement parameter to calculate the chemical exergy of organic matter in waste water?

Chapter 3 details the chemical exergy calculation methodology associated with the exergy analysis of WWTPs and provides guidance on how to calculate the chemical exergy of process inputs and outputs from WWTP plant processes. In addition, a number of practical examples are presented.

The results of the exergy analyses of the respective WWTPs are presented in Chapter 4. The site layouts and site descriptions are characterised for each plant. The process inputs and outputs for each WWTP process are detailed for each plant, with associated exergy value detailed. The exergy destruction for each process is then calculated.

Chapter 5 provides detailed discussion of the results from the exergy analyses of the WWTPs in Chapter 4. Finally the conclusions of the research and recommendations for future work that could be undertaken are presented in Chapter 6.

2 Literature Review

The objective of this chapter is to discuss the relevant research in relation to exergy analysis of waste water treatment plants. Due to the cross-discipline nature of this research project, research findings from other academic fields are reviewed and incorporated in this literature review.

2.1 Overview of Waste Water Treatment Processes and Relevant Parameters

A brief overview of the processes involved in the treatment of waste water is now provided and the relevant organic matter parameters in relation to waste water quality are also reviewed.

2.1.1 Organic matter in waste water

Domestic waste water can contain both solid and dissolved pollutants with organic compounds in waste water generally composed of a combination of carbon, hydrogen, and oxygen. As all waste water is eventually discharged back into the aquatic environment, untreated waste water can have a significant negative effect on the water environment. Proper treatment of waste water reduces the risk of waterborne diseases, eutrophication etc. and therefore significantly reduces any threat to public health.

Typical waste water constituents are sugars, carbohydrates, fats, soluble proteins, and urea. Various techniques have been established to determine the organic content of waste water. Gross quantities of organic matter in waste water can be measured by laboratory analysis such as Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), Theoretical Oxygen Demand (THOD), Total Organic Carbon (TOC) and Total Oxygen Demand (TOD). These measurement parameters are defined below; as they are of paramount importance when assessing the organic chemical matter present in waste water.

2.1.2 Organic matter parameters

Biological oxygen demand. BOD is the quantity of dissolved oxygen consumed by aerobic biological organisms in the oxidation of organic matter present in waste water.

Chemical oxygen demand. COD is the quantity of oxygen required to chemically oxidise all organic and inorganic compounds in waste water. The COD value is usually larger than BOD, as some organic substances are oxidised more easily chemically than biologically.

Theoretical oxygen demand. THOD represents the quantity of oxygen required to oxidise a compound to its final oxidation products.

Total organic carbon. TOC represents the quantity of organic carbon contained within an aqueous sample. It can be used to measure the pollution characteristics within waste water.

Total oxygen demand. TOD is a measure of all matter oxidised in a sample of waste water, determined by measurement of the depletion of oxygen after chamber combustion.

2.2 Wastewater treatment plant discharge regulation

The Urban Waste Water Treatment Directive (UWWTD) has set out acceptable measures of water quality for WWTPs. Table 1 and Table 2 detail the UWWTD discharge limits for urban areas with populations greater than 2,000 PE. Municipal WWTP influent flow rates are determined by PE; PE can be defined as, one person within the WWTP collection area is expected to produce 200 litres of sewage flow per day containing 60 grams of BOD.

Table 1: Regulations concerning discharges from urban wastewater treatment plants and subject to the measures of the Directive from 21 May 1991a (Urban Waste Water Treatment Directive 91/271/EEC)

Parameters	Discharge Concentration	Minimum Percentage Reduction[2]
5-Day biochemical oxygen demand (BOD5 at 20°C) without nitrification[1]	25 mg/l O_2	70 - 90 %
COD	125 mg/l O_2	75%
TSS	35 mg/l [3] • 35 mg/l in high mountain regions for agglomerations with more than 10,000 PE • 60 mg/l in high mountain regions for agglomerations whose size falls between 2,000 and 10,000 PE	90 % [3] • 90% in high mountain regions for agglomerations of more than 10,000 PE •70% in high mountain regions for agglomerations whose size falls between 2,000 and 10,000 PE

1. This parameter can be replaced with another parameter: Total Organic Carbon (TOC) or Total Oxygen Demand (TOD) if a relationship can be established with BOD5 and the substitute parameter
2. Reduction relative to influent values.
3. Requirement Optional

Table 2: Requirements for discharges from urban wastewater treatment plants to sensitive areas (Urban Wastewater Treatment Directive 91/271/EEC)

Parameters	Discharge Concentration	Minimum Percentage Reduction[1]
TP	2 mg/l (10,000 - 100,000 P.E.) 1 mg/l > (100,000 P.E.)	80%
TN	15 mg/l (10,000 - 100,000 P.E.) 10 mg/l > (100,000 P.E.)	70 - 80%

1. Reduction relative to influent values.

The UWWTD requires secondary treatment of all discharges from agglomerations > 2,000 PE [6]; consequently €4.6 billion in Irish Exchequer resources have been spent on both the waste water sector to ensure compliance with the UWWTD and also to deliver quality drinking water to the Irish public [7]. As a result, secondary treatment for agglomerations > 2,000 PE now stands at 92%, compared to 25% in 2000 [7]. However, according to a recent Environmental Protection Agency (EPA) report [8, 9], only 69% of Irish WWTPs with secondary treatment are meeting the minimum effluent quality standards (i.e. BOD, COD) set out under UWWTD. Additionally, 44 (26%) of the 170 large urban did not comply with the European Union quality standards for such areas.

The treatment of waste water generally can be divided into mechanical, biological and sludge treatment, with the selection of a waste water treatment process or sequence of processes dependent on a number of factors summarized below [10]:

- Characteristics of influent waste water (BOD, COD, pH etc.)
- Effluent quality required
- Cost and availability of land
- Consideration of possible future upgrading of waste water quality standards.

2.3 Mechanical treatment

Large suspended solids such as pieces of plastic, wood, toilet paper residue and fabric are removed through the use of screens. The sewage then flows into a grit chamber, where minerals such as gravel and sand are separated by sedimentation. The sewage then passes into large sedimentation tanks where the majority of the solids, known as primary sludge, settle to the bottom in a process known as primary clarification.

2.3.1 Biological treatment

Biological treatment is achieved by microorganisms consuming organic matter; it involves the manipulation of oxygen conditions to grow specific types of bacteria to consume organic matter. There are three different methods of biological treatment, detailed as follows:

- Aerobic Treatment – Dissolved oxygen is present in this process with aerobic bacteria utilising oxygen in the tank provided by aerators. The main products of this process are biomass, carbon dioxide and water.

- Anaerobic Treatment – Dissolved oxygen is not available, but anaerobic bacteria can utilize the oxygen bound in sulphate to breath. The main products of this process are hydrogen sulphide, carbon dioxide and water.

- Anoxic Treatment – Dissolved oxygen is not available, but anoxic bacteria can utilize the oxygen bound in nitrate to breath. The main product of this process is nitrogen gas.

WWTP managers can utilise any number of the processes detailed above when designing their biological treatment systems. Clearwater WWTP in Florida for example operates a 5 – stage Bardenpho process consisting of anaerobic zone followed by two anoxic and anaerobic zones [11]. The second anoxic zone provides an opportunity to denitrify the nitrates created in the aeration zone, allowing lower total nitrogen effluent concentrations.

2.3.2 Activated Sludge Process

The activated sludge process is a biological treatment process where air is introduced to waste water to produce a biological floc. The floc then settles to the bottom of the aeration basin enabling it to be removed from the process and thus reducing the organic content of the waste water. This clarified effluent is categorised into two categories:

- Return activated sludge
- Waste activated sludge.

Return activated sludge is re - introduced to the beginning of the process through a sludge recycling system as they are very efficient at digesting organic matter in the aeration basin. Excess solids and organisms removed from the process are referred to as waste activated sludge.

2.3.3 Sludge treatment

Following biological treatment, the waste water flows to secondary settlement tanks where the majority of biological solids are deposited as sludge while the clarified effluent passes to the outfall pipe for discharge. If aerobic treatment of organic matter is being utilised in the plant, a portion of the sludge is returned to the inlet of the aeration tanks to reseed the new waste water entering the tank. Typically, sludge is thickened to reduce its volume and transported off-site for disposal. Alternative methods such as incineration, anaerobic digestion and land application can also be utilised.

2.4 Irish waste water treatment sector

Municipal waste water treatment in Ireland is provided by small treatment plants distributed throughout the country. Approximately 66% of municipal WWTPs in Ireland have a PE of less than 2,000, while only 12% (65) of Irish WWTPs have a PE of greater than 10,000 [12]. Irish Water has recently been established to amalgamate the water and waste water services of the 34 Local Authorities under one national service provider. Prior to January 2014, waste water services within Ireland had been provided by these 34 Local Authorities. This led to a large degree of division in the provision of services, with this division hindering the standardisation of procedures and technology [13]. The recent economic crisis has led to increased pressures on local authorities to deliver services, for example local authorities such as Limerick County Council saw a 3% decrease in overall budget expenditure while expenditure for the operation and maintenance of WWTPs in Limerick increased by 3% between 2012 -2013 [14].

The majority of energy consumption in municipal WWTPs is associated with the secondary treatment process [15] (Figure 1), with approximately 90% of WWTP utilising the activated sludge treatment process in Ireland [16]. According to the United States (US) Environmental

Protection Agency (EPA), aeration and waste water pumping typically consume 68% of electrical energy usage within the activated sludge process (Figure 1). This would suggest that WWTP plant managers should therefore focus on efficient operation of their aeration and waste water pumping systems by using a combination of more energy efficient retrofits, effective process control, pro-active equipment maintenance and good operational practice.

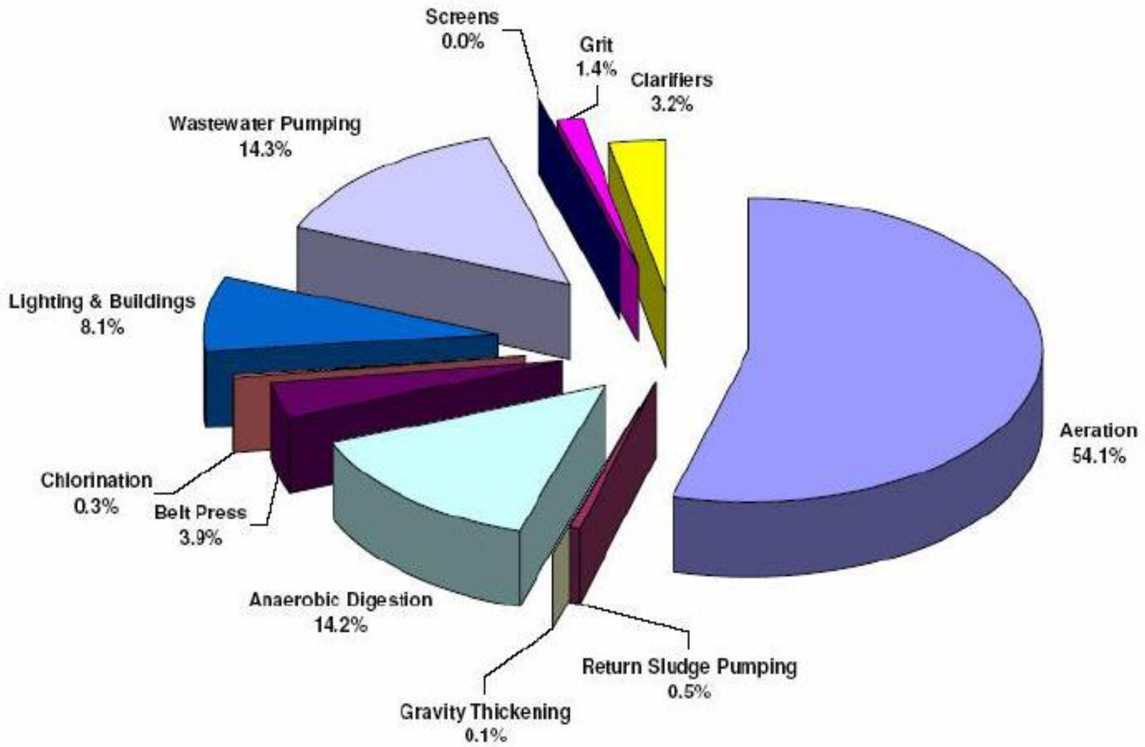

Figure 1: Electricity requirements for Activated Sludge Waste Water Treatment [15]

2.5 Good practice guide for WWTP equipment

2.5.1 Aerators

Waste water aeration accounts for up to 54% of electrical energy usage within the activated sludge process [15]; therefore WWTP plant managers should spend a significant amount of time monitoring, characterising and optimising their aeration system as significant energy savings opportunities exist. Within the activated sludge treatment process, micro -organisms degrade organic matter converting it into carbon dioxide, water and biomass. As these micro-organisms require oxygen to survive, air is introduced to the system through a number of methods. Mechanical aerators introduce air to the system by agitating the waste water surface with either blades or propellers. Alternatively, waste water can be aerated by bubbling air or high purity oxygen through it from below. Cantwell et al. [17] estimated that aeration energy consumption can be reduced by up to 40% by retrofitting mechanical and coarse bubble aeration systems with fine bubble diffused aeration systems. Fine bubble diffused aeration systems support higher oxygen transfer rates due to in an increase in bubble surface area per unit volume of fine bubbles over coarse bubbles [18].However, fine bubble diffused aeration systems require more routine cleaning and are more prone to plugging leading to an increase in maintenance costs. Killarney WWTP replaced mechanical rotor aerators with fine bubble diffused aeration systems reducing the power demand in the aeration ditch from 45 kW to less than 15 kW, as reported in a study of both Killarney and Dingle WWTPs [19]. The installed fine bubble diffused aerators have a payback period of two years with respect to the initial capital investment. In order for the aeration system to address real time operating conditions within the plant, aeration control strategies should be implemented. However, biological treatment of waste water is not a simple process; appropriate aeration control is a balance between energy efficiency and effective waste water treatment.

2.5.2 Control Systems

The most frequently used control variable in the WWTP industry is Dissolved Oxygen (DO) [20, 21]. Through the use of automatic control systems, DO levels can be adjusted to real-time process requirements, thus reducing aeration blower energy consumption requirements [22]. DO control systems build flexibility into a WWTP's aeration system, by adjusting the oxygen requirements to the real time variable conditions within its aeration basin [23]. One of the most common DO control systems is the cascade feedback control system, illustrated in Figure 2 below [24].

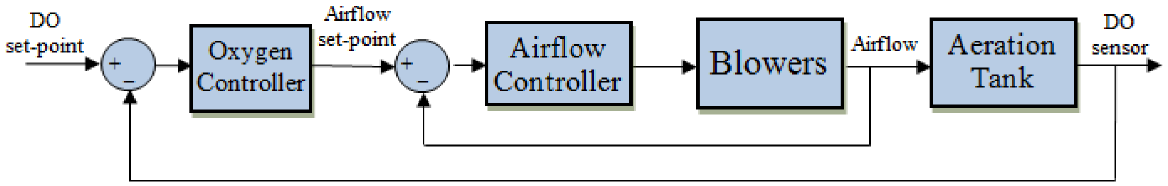

Figure 2: DO cascade feedback control diagram [24]

To achieve specific DO set points the airflow in the tank is constantly manipulated; this is achieved through the use of a Proportional, Integral and Derivative (PID) controller [24].Olsson [25] noted that the use of PIDs is only one approach to achieve specific DO set point control, other methods such as genetic algorithm and fuzzy logic control can be used, but not much evidence exists to suggest they are more effective than PIDs. The US EPA undertook a series of control tests demonstrating energy savings of approximately 40% can be obtained by using automated dissolved oxygen control over manual control [21]. Although biological oxygen demand within the aeration basin varies with the proportion of organic and ammonia loading in the influent waste water [23], variations in DO and ammonia levels within the WWTP basin should also be considered. Over aeration can increase energy costs, while under aeration leads to problems such as poor sludge settling and an increase in the number of filamentous organisms [23]. Therefore, multiple DO sensor zones with independent air supply for each zone reduce energy consumption by matching the airflow to the DO needs for that particular zone [26]. When placing the sensor within the zone, areas that experience instability should be avoided as hunting problems in the control system could be represented in the measured value from the sensor [27].

2.5.3 Pump Energy

Waste water pumping accounts for up to 14% of electrical energy usage within the activated sludge process [15], second only to aeration. Within the plant, pumps are used to transport waste water and sludge between the various treatment processes. Operating conditions within the WWTP greatly affect overall WWTP pump efficiency [28], inefficiencies arise when pumps are expected to operate over a wide range of conditions. Additional losses may occur if pumps are sized for peak flow conditions that occur infrequently, therefore the pump will not operate at its Best Efficiency Point (BEP)[1]. Signs of an inefficient pumping system are detailed below in Table 3 [23].

Table 3: Inefficiencies associated with pump systems [23]

Signs of an inefficient pumping system include
1) Highly or frequently throttled control valves
2) Bypass line (recirculation) flow control
3) Frequent on/off cycling
4) Cavitation noise at the pump or elsewhere in the system
5) A hot running motor
6) A pump system with no means of measuring flow, pressure, or power consumption
7) Inability to produce maximum design flow

2.5.4 Variable Frequency Drives

As waste water pumps experience a large variation in diurnal flow, Variable Frequency Drives (VFD) can be applied to WWTP pumps and blowers to manipulate their speed to match waste water flow conditions. VFD alter the frequency of the input signal to the motor, by controlling this frequency the speed of the motor may be regulated (Figure 3). Numerous alternative methods such as stop/start control, throttling valves and bypass control may be used to control waste water flow, all of which are detailed in Figure 3. Stop/start control is symptomatic of an over - sized pump that matches flow. Throttling valves move the operating point on the pump's curve to the left, thereby reducing flow. Bypass control returns a percentage of the water pumped back to the suction side of the pump, wasting a percentage of the energy used to recirculate the water with no beneficial work achieved. VFD are the most efficient method to control waste water flow (Figure 3) [29]. The energy savings potential of

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[1] BEP is the flow rate and head that gives the maximum efficiency on a pump curve

VFD was reported in a study carried out at Dingle WWTP where a fine bubble diffused aeration system was coupled to a low speed variable output blower, reducing energy consumption within the plant by 37% [19]. However, VFD are not applicable in all situations, for example, when a large ratio of static to dynamic head exists.

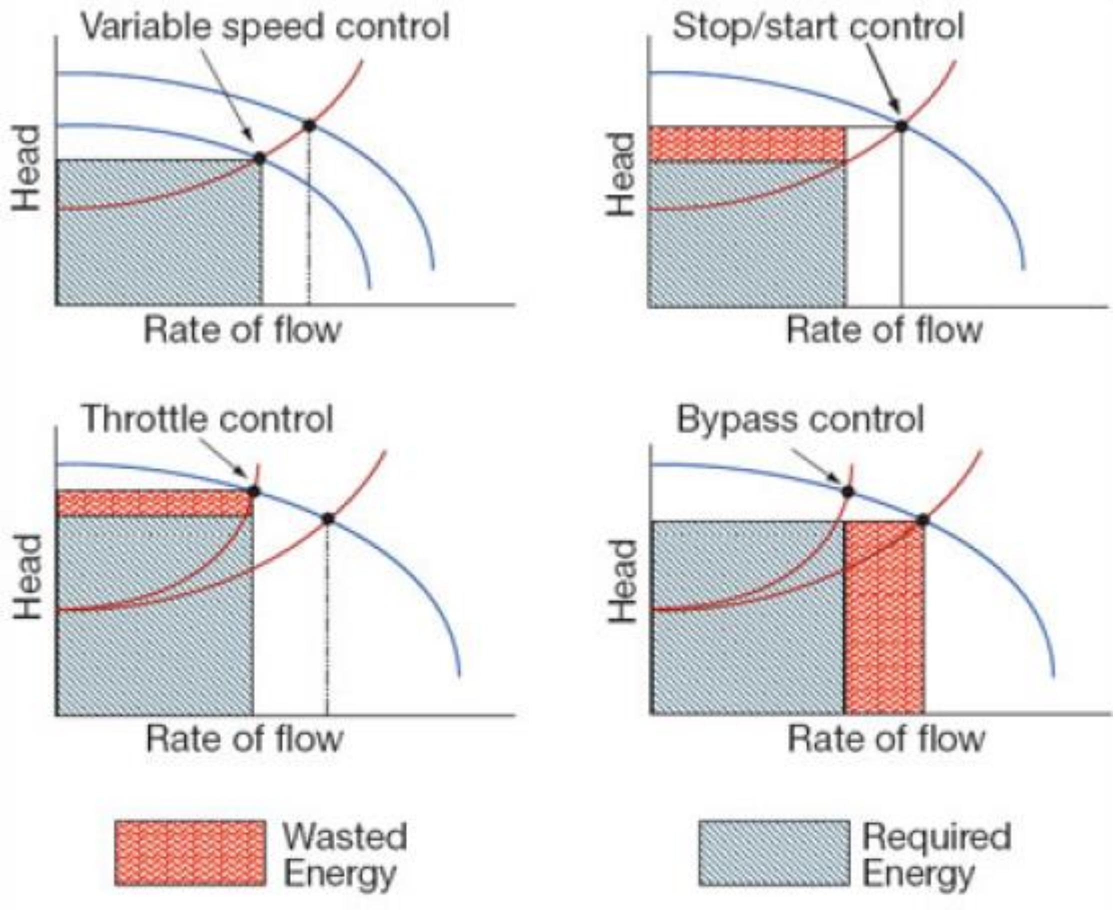

Figure 3: Wasted Energy in Alternative Control Schemes Compared to Variable Frequency Drives [29]

2.6 New Energy Efficient Technologies

2.6.1 OxyMem

The OxyMem Membrane Aerated Biofilm Reactor (MABR) is a secondary treatment system. As the waste water travels through the OxyMem MABR the organic matter is consumed by biofilm cultures that live on the membranes inside the reactor. This enables oxygen to be transferred directly to the bacteria resulting in oxygen transfer efficiency rates of up to 99%, leading to a reported direct reduction in operating costs of up to 75% [30]. It is important to note that a whole life cycle costing should be carried out on the OxyMem MABR to take into consideration such issues as membrane cleaning etc.

2.6.2 Anaerobic Ammonium Oxidation

Anaerobic Ammonium Oxidation is an ammonium removal technology, developed at Delft University of Technology. The initial step in the process is partial nitrification of half of the ammonium to nitrite by ammonia oxidising bacteria. A growth rate exists at higher temperatures where ammonium is oxidised but nitrite is not converted; both processes can take place in the one reactor. This results in the ammonium and nitrite being converted into dinitrogen gas [31]. In anaerobic ammonium oxidation systems, oxygen demand is greatly reduced by up to 50% as only half of the ammonium needs to be oxidised to nitrite, as opposed to full conversion to nitrate [11].

2.6.3 Pumped Flow Biofilm Reactor

The Pumped Flow Biofilm Reactor (PFBR) is a two reactor technology that enables aerobic, anoxic and anaerobic conditions to be sequenced. Biofilm grow on plastic media modules within the two reactors. The two reactors empty and fill a numerous times during a typical aeration sequence, exposing the biofilm to atmospheric air and waste water [32]. Operational costs of the PFBR have been shown to be 66% less than the conventional activated sludge system [33].

2.7 Sustainable Energy Efficiency

An ad-hoc approach to energy efficiency within WWTPs leads to initial savings that address immediate energy problems within WWTPs. In order for sustained savings to be achieved a cohesive and consistent approach is needed and therefore a spirit of energy efficiency needs to be fostered within the plant.

2.7.1 Energy Audit

A key step in establishing the baseline energy usage within a WWTP is an energy audit; from which future energy efficiency improvements can be measured. An energy audit is an inspection and analysis of energy usage within a facility [34]. An audit identifies energy use patterns, the potential for energy and cost savings, and can include recommendations for actions to improve energy efficiency and reduce energy costs [35]. Energy audits identify potential capital improvements such as retrofits (motors, blowers etc.) and operational improvements such as operation time of equipment.

Plant operation data in conjunction with waste water parameters such as BOD and TN can be used to establish the various operating seasons of a WWTP [36]. The seasons reflect variances in infiltration rates in the water collection system and temporary changes in population (i.e. schools). Once operating seasons are established, measurements of influent plant load should be taken to benchmark plant energy usage.

The conditions and seasonal variations in Irish WWTP load are summarised below [37]:

- Season 1 (October – March): High flow, High load (BOD, TN etc.), and low wastewater temperature
- Season 2 (April – June): Average flow, average load, and low wastewater temperature
- Season 3 (July – September): Low flow, low load, and higher wastewater temperature.

2.7.2 Types of Audits

An energy audit of a WWTP can take many forms; the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) have developed 3 levels of energy audits [38]. The variations in these audits are seen through their intricacy, level of analysis and quantity of information the audit can provide. Audits range from Level 1 (Walk though) to Level 3 (Process Audit); they are detailed below in Table 4.

Table 4: Levels of ASHRAE Energy Audits [38]

(ASHRAE Level I) - Walk Through Audit
• Duration: Several hours in the facility • Proposal: Suggestions for low cost improvements to lights/HVAC • Results: Quick payback projects that take advantage of utility rebates
(ASHRAE Level II) - Energy Survey and Analysis
• Duration: Several hours in facility plus additional time to review energy bills, etc. • Proposal: Suggestions for low cost improvements to lights/HVAC and equipment upgrades in existing processes (e.g. VFD, premium efficiency motors) • Results: Quick payback projects that take advantage of utility rebates
(ASHRAE Level III) - Process Energy Audit
• Duration: One or more days in the facility, time to analyse energy bills, develop pump curves, and possibly several weeks of data gathering • Proposal: – Energy use in existing processes, alternative processes – Potential design modifications – Optimization of processes, equipment, design modifications • Results: Detailed operational and process suggestions with both short and long pay backs

Table 5, detailed below, provides an example of an ASHRAE level 1 audit where equipment inventories are used to categorise the horsepower of plant equipment, usage and control type in place.

Table 5: ASHRAE Level 1 Audit [36]

Equipment Type	Quantity	Horsepower	Usage	Control
Mechanical Aerator	1	90	Continuous	Variable Frequency Drive (VFD), manual adjustment
Blowers	1	20	Intermittent	Fixed Speed
Mixer	1	4	Continuous	Fixed Speed
Influent Pump (No. 1 & 2)	2	15	Continuous	VFD, speed based on flow
Influent Pump (No. 3)	1	5	Back Up	VFD, speed based on flow
Centrifuge	1	50	30-40 hrs. /week	VFD, fixed speed

2.7.3 Energy Management System

An energy audit is the initial component of a continuous process known as an Energy Management System (EMS). An EMS is a critical management tool that “clearly articulates the measures that are, or will be, deployed by a department to reduce its energy consumption” [39]. An EMS is an example of an operational improvement that could be implemented in a WWTP.

The EMS is a relatively new approach to energy auditing where sustained savings is the main objective. In order to achieve sustained savings a real commitment is necessary from all parties in an organisation.

2.7.4.1 Key performance indicators (KPI)

An instrumental aspect of an EMS is its use of Key Performance Indicators (KPI). KPI help an organization identify and appraise progress toward organizational goals. Once an organization has identified the various stakeholders and defined its goals, it needs a process to measure progress towards these goals. Key performance indicators are these measurements.

The main KPI for assessing the efficiency of waste water treatment can be allocated to a number of areas of focus or pillars [40, 41]. KPI applicable to waste water treatment are illustrated below in Table 6:

Table 6: Main KPI associated with waste water treatment plant efficiency [40, 41]

Area of focus	Sections	Key Performance Indicators
Customer Service	• complaints • service Quality • public Relation	• complaints in relation to waste water disposal per service connection
Sustainability	• resource protection • resource consumption • staff & social criteria	• specific energy consumption per waste water disposal [kwh/PE] • energy production rate [%] • conservation of value ratio (waste water collection and transport) [%]
Economic Efficiency	• cost transparency • cost analysis • investments • staff	• specific total waste water disposal expenditure [€/PE] • specific capital costs of waste water disposal [€/PE] • specific total revenue of waste water disposal [€/PE]
Reliability	• reliability disposal • facility utilisation • central monitoring • fault monitoring • maintenance	• average sewer age • 85% percentile degree of utilisation of waste water treatment plant [%] • reactive maintenance ratio - unplanned maintenance hours to planned maintenance hours [%]

Table 6 is focused on four pillars of WWTP efficiency, the KPI assess the sustainability, customer service quality, reliability and economic efficiency of WWTPs. KPI in relation to the environmental performance of WWTPs could also be considered. Instruments such as

WWTP discharge requirements and influent COD, BOD etc. percentage removal rates could be used to assess the environmental performance of WWTPs

2.7.4.2 KPI Benchmarking of WWTPs

KPI provided the platform for the Austrian benchmarking system to be established. Its initial objective was to develop KPI and best practice guidelines for the operation of WWTPs. Plants were benchmarked for yearly total, capital and operating costs based on compliance with a number of criteria detailed below:

- Austrian emission standards
- Minimum quality of technical data
- Available operating and yearly total costs.

Data was acquired from the plants through an internet platform, enabling technical and financial data to be processed. During the processing stage plausibility checks were conducted, with KPI for cost categories and processes also calculated for each plant. Currently, over 40% of WWTPs in Austria upload information via the internet platform to the benchmarking system [42]. A decline in specific operating costs with increasing plant size was observed; in additional, and importantly, no correlation between treatment efficiency and operating costs could be found, with excellent treatment efficiency often achieving the lowest specific costs [42].

2.7.4.3 Deming cycle – (Plan-Do-Check-Act)

Although KPI enable an organisation to measure progress towards goals, this is not sufficient unless a system is in place which implements and maintains progress. Approaches such as the Deming cycle can help in this respect. The European standards in relation to EMS are based on the methodology known as Plan-Do-Check-Act system (Figure 4); the system provides a communication mechanism between plant managers and upper management, thus incorporating important stakeholders in energy management activities [43]. It can be described as follows [44]:

- Plan: establish the goals and processes necessary to achieve results in accordance with the organizations energy policy.
- Do: implement the process. Often on a small scale if possible.
- Check: monitor and measure processes against energy policy, objectives, targets, legal obligations and other requirements to which the organization subscribes, and report the results.
- Act: take actions to continually improve performance of the energy management system.

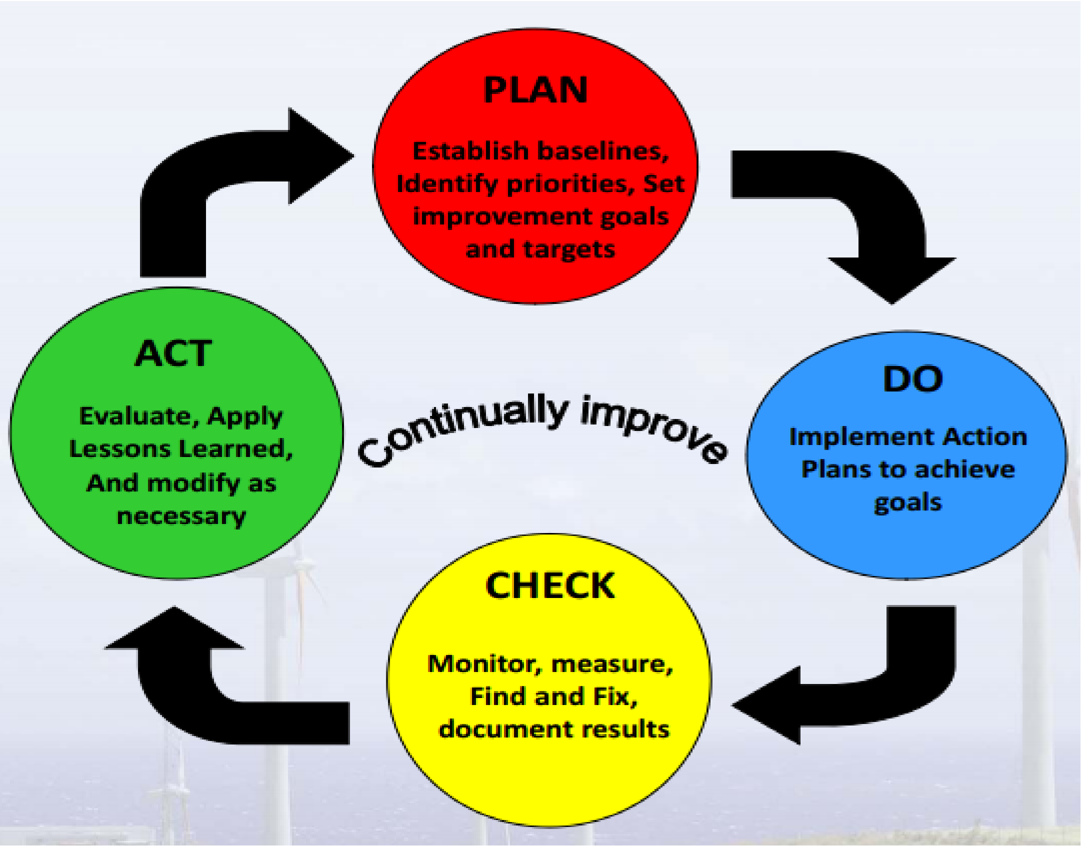

Figure 4: Deming Cycle - Focused on continual improvement [38]

2.8 Life cycle analysis

Following the introduction of the UWWTD, an increased focus was placed on the environmental performance and footprint of WWTPs. Life Cycle Analysis (LCA) is a cradle–to–grave approach that quantifies the environmental cost at every stage of a product's life; From the energy needed to extract the product's raw materials, to the use and eventual disposal or recycling of the product. WWTP consume electricity, chemicals and numerous other resources, while concurrently emitting pollutants to water, soil and air. LCA holistically examines all environmental impacts from a WWTP. Although LCA can be used to benchmark the resource efficiency of WWTPs, the compilation of a Life Cycle Inventory and subsequent impact assessment, provides only a certain amount of meaningful data. It is not necessary to make comprehensive inventories as the impact classifications are very sensitive to few compounds released in large quantities. Thus, to obtain useful data a limited number of indicators should be selected. [45] Alternative methods can be used to benchmark the resource efficiency of a WWTP; exergy analysis has been advocated as a useful tool for WWTP characterisation through the quantification of system irreversibilities.

2.9 Exergy analysis of WWTP

The US EPA reported that local governments allocate up to 10% of their annual operating budget on energy [46] and with WWTPs in the US accounting for 3% of the electrical load [1], energy efficiency within WWTPs is essential. Additionally, the US EPA states energy consumption for waste water treatment systems is expected to rise by 20% by 2020 [47]. Energy is vital in all steps of a WWTPs treatment process, from the collection of raw sewage to the discharge of treated effluent. Exergy analysis has been identified as an important tool in the analysis of thermal and chemical processes [5]. However, to date, this approach has seldom been applied to the study of WWTP optimisation. Exergy is a thermodynamic property, which combines the first and second law of thermodynamics, and can be defined as the maximum theoretical work obtainable as two systems interact to equilibrium [2]. By conducting an exergy balance across plant processes, the exergy destruction in each process can be quantified, and in turn used to focus energy efficiency efforts. Several researchers have used this approach to identify inefficiencies in thermal and chemical systems [3, 4]. Furthermore, exergy analysis can be used to quantify the work potential of waste streams. In WWTPs the generation of waste streams is unavoidable and exergy analysis may provide invaluable insight into their potential to do useful work. Exergy analysis can therefore be used to quantify waste streams enabling informed design decisions with regard to optimisation of WWTPs.

Initial works by Tai et al. [48] related the chemical exergy of organic matter to waste water indices Total Oxygen Demand (TOD) and Total Organic Carbon (TOC). In recent years exergy analysis has been applied to the quantification and optimisation of the environmental performance of a WWTP [49], it has also been used to quantify chemical exergy assessment of organic matter in water flow [50]. Hellström [51] showed that exergy analysis can be used to estimate the flow and consumption of physical resources within WWTPs.

The objective of this research is to conduct exergy analysis on several WWTPs, quantifying the exergy content or work potential of process streams. Consequently, a hierarchy of WWTP processes and plants with the greatest exergy destruction will be established, with exergy destruction rates being utilised to benchmark plant performance.

2.9.1 Total Specific Exergy

Martinez et al. [50], proposes the following approach to calculate the total specific exergy (b_T) of a waste water body. The total specific exergy (b_T) of a waste water is defined by six variables, characterizing its thermodynamic status: temperature, pressure, composition, concentration, velocity and altitude [52]. Each variable is associated with its corresponding exergy component: thermal (b_t), mechanical (b_m), chemical (b_{ch}), kinetic (b_k) and potential (b_z). The model assumes an approximation to an incompressible liquid. The total specific exergy (b_T) of a waste water is defined in Eq. (1) below:

$$\begin{aligned}\underbrace{b(kJ/kg)}_{b_T} = {} & \underbrace{c_{p,\,H2O}\,[T_p - T_o - T_o \ln(T_p/T_o)]}_{b_t} + \underbrace{v_{H2O}\,(p_p - p_o)}_{b_m} + \\ & \underbrace{\Sigma_i\,[y_i(\Delta G_f + \Sigma n_e b_{ch})]}_{b_{ch,f}} + \underbrace{[RT_o \Sigma x_i \ln a_i/a_o]}_{b_{ch,c}} + \\ & \underbrace{1/2\,(c_p^{\,2} - c_o^{\,2}/1000)}_{b_k} + g\underbrace{(z_p - z_o/1000)}_{b_z}\end{aligned} \tag{1}$$

Assumptions of incompressible fluid with a constant specific heat capacity have been made in Eq. (1). Table 7 below provides a definition of terms and their units for Eq. (1).

Table 7: Symbols & Subscripts for Total Specific Exergy Equation

Symbols			
a	activity	Subscripts	
b	specific exergy (kJ/kg)	ch	chemical
c	velocity (m/s)	ch,c	chemical (concentration)
$c_{p, H20}$	specific heat capacity of water (kJ/kg K)	ch,f	chemical (formation)
g	gravitational acceleration of the earth (m/s^2)	e	each element forming the substance i
m	mass (kg)	H_2O	water
n	mole number (mol/kg)	i	any considered substances
p	pressure (kPa)	k	kinetic
R	universal gas constant (kJ/kg K)	m	mechanical
T	temperature (K)	o	under reference conditions
v	specific volume of the aqueous solution (m^3/kg)	p	under ambient conditions
x	molar fraction of the substance i in the solvent	t	thermal
y	relative molality (kmol/kg)	T	total
z	height (m)	z	potential
ΔGf	Gibbs free energy (kJ/kmol)		

As the majority of WWTPs operate isothermally, thermal exergy is negligible. Mechanical exergy is also negligible as pressure changes within WWTPs are not significant. Potential exergy is often also insignificant, depending on plant configuration. Therefore, when calculating the total specific exergy (b_T) of a waste water body, it is sufficient to focus on its chemical exergy component. The total chemical exergy ($b_{ch,\ T}$) component combines two chemical exergy components: formation ($b_{ch,\ f}$) and concentration ($b_{ch,\ c}$) exergy which are detailed in Eq. (2):

$$\underbrace{b(kJ/kg)}_{b_{ch,T}} = \underbrace{\Sigma_i [y_i(\Delta G_f + \Sigma n_e b_{ch})]}_{b_{ch,f}} + \underbrace{[RT_o \Sigma x_i \ln a_i/a_o]}_{b_{ch,c}} \tag{2}$$

2.9.2 Reference environment

The chemical exergy of a substance is dependent on the environmental model that is selected as its Reference Environment (RE). The RE from a technical perspective should be as close as possible to the natural environment [53]. Therefore, when defining the RE for a WWTP its composition should be close as possible to that of its receiving waters. This is in contrast to the Szargut RE, where he defined a reference substance for every element in the environment; the exergy of other substances may be then calculated by means of a balanced chemical reaction between the specific substance and its reference substances [54].

If a substance is not contained within the defined RE, its formation chemical exergy is the only component considered and is calculated by Eq. (3) detailed below [55]:

$$b_{ch,\,f} = \Sigma_i \, [y_i \, (\Delta G_f + \Sigma n_e b_{ch})] \tag{3}$$

This is the equation to calculate the chemical of a compound, ΔGf is the formation of Gibbs energy of the ith element, n_e is the amount of kmol of the element e in the compound i and bch is the standard chemical exergy of the element e.

If a substance is already contained within the defined RE its concentration chemical exergy is the only component required and is calculated by Eq. (4) detailed below:

$$b_{ch,\,c} = [RT_o \Sigma x_i \ln a_i / a_o] \tag{4}$$

X_i is the molar fraction and a_i and a_0 are the activity coefficients of substance i in the water sample and in the RE. The activity of each substance can be calculated by applying the Eq. (5):

$$a_i = \Upsilon_i \, .ml_i \tag{5}$$

Υ_i the activity coefficient and ml_i is the molality of the *i*th substance. The activity coefficient is calculated by applying the Debye–Hückel Theory [56] which explains the unexpected behaviour of electrolyte ions in a dilute solution by considering their electrostatic interactions. The Debye–Hückel Theory applies only to electrolytic solutions; other activities that are non-electrolytic in nature can exist in the mixture. Additionally, Fitzsimons [57] demonstrated that the Debye–Hückel Theory is relevant for very low molalities.

Martinez *et al.* [55] analysed a number of different RE scenarios in calculating the chemical exergy of river water, in particular:

- Sea water without organic matter and nutrients
- Sea water with organic matter and nutrients
- A completely degraded RE, with very high organic matter and nutrient concentrations
- Pure Water.

As the final discharge location for Martinez's river case study is located in the eastern Spanish coast, sea water without organic matter was chosen as the RE. Pure water and the completely degraded RE models were easily discarded as they are not representative of the rivers final discharge location in that case. Sea water with organic matter and nutrients was also discarded as only trace elements of nutrients and organic matter exist in sea water. The reference environment analysis carried out by Martinez is more of a dead state choice than a defined RE as defined by Szargut [54]. Chen and Ji utilised an indicator called specific relative chemical exergy with reference to a range of substances when assessing water quality. This method was again in contrast to the Szargut [54] approach with chemical exergy based on global reference substances.

When analysing the RE for a WWTP its discharge location impacts greatly on the selection of a suitable RE. For example, a WWTP discharging to an inland river would have a significantly different RE than a WWTP discharging to the sea. Therefore, two different REs are defined for WWTPs below.

2.9.2.1 WWTP discharging to inland rivers

Nutrients and organic matter have higher concentrations in river water than in sea water and thus they are included in the RE as they are representative of the real environment. Therefore, the RE for a WWTP discharging to inland rivers is defined as: river water containing organic matter and nutrients (Table 8) [58, 59] . If organic matter and nutrients are not included in the defined RE their exergy contribution will be their composition chemical exergy. If this option is selected the exergy value of nutrients and organic matter is increased when compared with the defined RE. Clearly, pure water and any form of sea water are non-realistic REs for WWTPs discharging to inland rivers.

Table 8: RE for WWTPs discharging to inland rivers

RE - River Discharge	Cl	HCO_3	K	Mg	Na	SO_4	Ca	Fe	S_iO_2	PO_4	NH_3	NO_3
ppm	6.9	95	1.7	5.6	5.4	24	31.1	0.8	7.5	0.03	0.083	1.46

2.9.2.2 WWTP discharging to the sea

The RE for WWTPs discharging to the sea will have identical characteristics to that of rivers whose final discharge location is the sea [55]. The defined RE is found several kilometres from the coast where complete mixing of waste water and sea water has occurred. Therefore, as previously detailed above the RE is defined as: sea water (Table 9)

Table 9: RE for WWTPs discharging to the sea

RE - Sea Discharge	Cl	HCO_3	K	Mg	Na	SO_4	Ca
ppm	19,345	145	390	1,295	10,752	2,701	416

The chemical exergy of disinfectants in this research are calculated with the above methodology. For example, a disinfectant such as sodium hydroxide is clearly not contained within either RE detailed above; therefore the formation exergy component will be used when calculating its chemical exergy.

In the context of this work, only one input component to WWTP plant A was calculated using an RE scenario (Table 9) as detailed above. This is due to the organic nature of the WWTP process inputs and outputs.

2.9.3 Organic matter calculation methodology

Tai *et al.* [48] established a relationship between the standard chemical exergy of a 138 organic compounds and the organic matter parameter TOD and TOC, as indicated below by Eqs. (6) and (7):

$$b_{ch}\,(J/l) = 13.6\,(kJ/g) \times TOD\,(mg/l) \tag{6}$$

$$b_{ch}\,(J/l) = 45\,(kJ/g) \times TOC\,(mg/l) \tag{7}$$

Tai stated that it is very difficult to identify and determine every organic compound found in waste water. Therefore, he selected a reference substance to calculate the chemical exergies of the atmospheric gases, allocating zero exergy to several stable chemical compounds. He then conveniently expressed a generic organic compound as $C_aH_bO_c$ [55] and plotted theoretical TOC and TOD against chemical exergy to develop linear best fit equations to obtain Eqs. (6) and (7).

As it is difficult to determine the composition of organics in waste water, certain practical limitations exist when using the method proposed by Tai et al. to calculate the chemical exergy of organic compounds. In order to tackle this issue, Martinez et al. [55] proposed that the analyses may be divided into measurements of aggregate organic matter greater than 1.0 mg/l and trace concentrations ranging from 10^{-12} mg/l – 1.0 mg/l.

Tai stated that organic matter parameters BOD and COD could also be used as approximate measures of effective energy, as TOD indirectly represented the magnitude of utilisable energy from wastewater. However, alternative methods exist for the measurement of organic matter parameters listed above. For example, potassium dichromate or potassium permanganate can be used to chemical oxidise organic matter, thus allowing COD to be quantified. Tai et al. [48] noted that the BOD and COD (permanganate) relationship with TOD is not as strong as the COD (dichromate) and TOD relationship. Tai et al. used theoretical values of TOD and TOC when developing Eqs. (6) and (7); therefore analysis should be conducted on how closely theoretical values of organic matter parameters relate to measured values for these substances.

A clear link exists between theoretical TOD and measured COD (dichromate), with an equivalence ratio of 95% demonstrated by Moore et al. [60]. Hellström [51] suggested that BOD is the most reliable indicator of available exergy within waste water because it represents the amount of easily biodegradable organic matter. However, he did not demonstrate how measured values of BOD relate to the chemical exergy of organic matter. Martinez [50] demonstrated that using the COD and BOD parameters provided coherent results when compared with TOC in calculating the chemical exergy of organic matter in surface waters as opposed to waste waters.

Khosravi et al. [49] identified potential limitations with the Tai approach because typical compounds found in WWTP were not included in the development of the correlations.

Khosravi et al. [49] proposed that theoretical TOD could be used to estimate the chemical exergy of organic matter in waste water, as indicated below by Eq. (8):

$$b_{ch}\ (J/l) = 13.7\ (kJ/g) - 116 \times COD\ (mg/l) \qquad (8)$$

Khosravi et al. carried out an exergy analysis of a WWTP in Qod, Iran. Khosravi et al. [49] provides COD values for all organic matter inputs and outputs in their process exergy analysis. (Note that these are not the same chemical exergy values determined by Tai, however, the different approaches used to calculate the chemical exergy result in similar values for the majority of the elements under consideration). Two different approaches have been proposed, it is important to see how they differ in terms of calculating the chemical exergy. In order to achieve this, the two approaches have been compared in Table 10.

The first column of Table 10 takes a random sample of COD input/output values from the Khosravi et al. paper. The obtained COD value is multiplied by 13.6 (Eq. (6)) and then the WWTP flow to obtain the exergy values in column 2. Column 3 details the exergy values of organic matter obtained by Khosravi et al. using Eq.8 above and then multiplying it by the flow. As you can see little difference exists between the two methods.

Table 10: Comparison of organic matter exergy values using COD and THOD organic matter measurement parameters

COD value (mg/l)	Tai COD Exergy Method (GJ/Day)	Khosravi THOD Exergy Method (GJ/Day)	% Difference
371.1	227.11	224.4	1.19
204.1	124.21	121.07	2.53
6800	23.12	23.35	- 0.99
260.7	158.76	155.3	2.18

As theoretical TOD signifies the quantity of oxygen required to oxidise a compound to its final oxidation products, it represents an unrealistic and worst case scenario of oxygen requirements. The actual oxygen demand of any organic compound is its biodegradability;

but as no clear link has been established with BOD and theoretical TOD, COD (dichromate) will be used to estimate the chemical exergy of organic matter in waste water in this research. The chemical exergy of sludge, return liquors and mixed liquor suspended solids in this research will also be calculated by Eq. (8), indicated below:

$$b_{ch}\,(J/l) = 13.6\,(kJ/g) \times COD\,(mg/l) \qquad (8)$$

The numerous chemical exergy calculation models are detailed below in Table 11.

Table 11: Relevant/Specific Waste Water Chemical Exergy Equations

Relevant/Specific Waste Water Chemical Exergy Equations	Source
$e = n[u^o - u_o^o + R\,T_o \ln c/c_o]$	[51, 55, 61, 62]
$e = \Sigma_i\,[y_i(\Delta G_f + \Sigma n_e b_{ch}) + RT_o\Sigma x_i \ln a_i/a_o]$	[55]
$e = \Sigma_i\, x_i\, e_i^{ch} + RT_o\Sigma x_i \ln a_i$	[62, 63]
Chemical Exergy of Organic Matter Equations	
$e^o = 13.6 \times TOD$	[55]
$e^o = 45 \times TOC$	[55]
$e^o = 13.6 \times COD$	[51, 62]
$e^o = 13.6 \times BOD$	[51, 55]
$e^o = 13.7 \times THOD - 116$	[49]

Extensive further work may be needed to study and compare each of these approaches in detail; however, this is beyond the scope of this research.

3 Exergy Calculation Methodologies

This chapter outlines the chemical exergy calculation methodology associated with the exergy analysis of WWTPs in chapter 4. It provides guidance on how to calculate the chemical exergy of process inputs and outputs from WWTP plant processes. As can be seen in Figure 5, WWTPs have numerous waste streams containing differences in the concentration of organic matter, sludge, nutrients and coagulants. Other typical inputs include electricity usage from compressors, blowers and pumps within the plant.

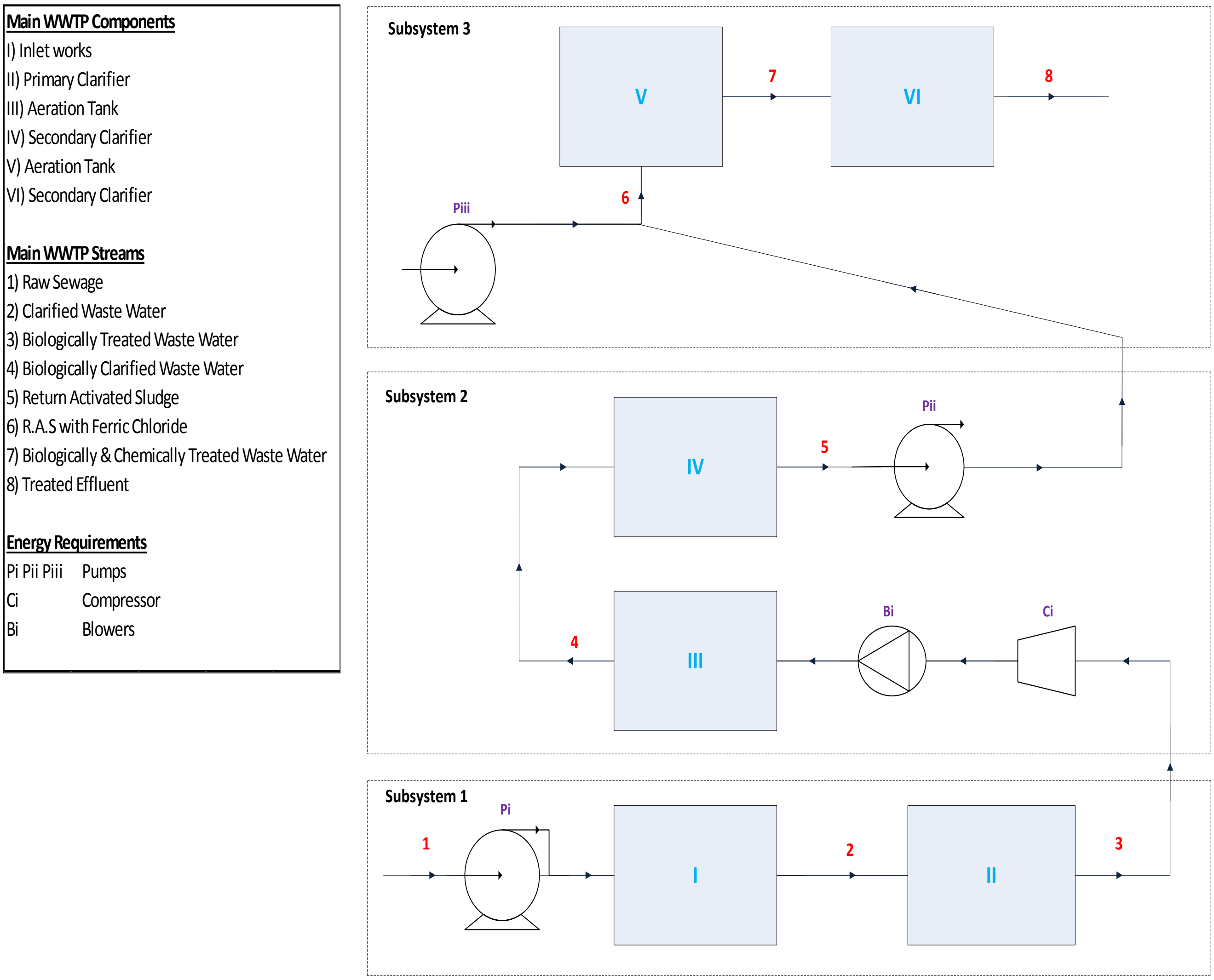

Figure 5: Example of typical process inputs & outputs associated with WWTP operation

3.1 Wastewater Treatment Plant Selection

Three Irish WWTPs were selected for this research with exergy analyses conducted on all three plants. The characteristics of the selected WWTPs are detailed in Table 12. Plant A has a very large PE and discharges its final effluent to the sea. This is in contrast to plants B and C, which are of a much smaller scale. Plants B and C utilise similar treatment technologies, are of a similar scale and both plants discharge their final effluent to inland rivers. Plants B and C enable comparative analysis to be conducted due to their similar characteristics and the selection of plant A provides a valuable comparison to differences in discharges requirements, PE etc.

Table 12: Plant Descriptions

Plant	Design Capacity (PE)	Agglomeration Served (PE)	Receiving water body type	Level of treatment	Type of secondary treatment[1]
A	186,000	79,133	Seawater	Secondary	AS
B	12,000	12,284	Freshwater	Secondary	AS+P
C	12,000	9,036	Freshwater	Secondary	AS+P

3.2 Materials and methods

The data used in the study are a combination of measured, site-specific data, and data obtained from the literature. The selection, deployment and gathering of WWTP data was done by my colleagues on the EPA project Mr Thomas Phelan and Mr Niall Durham. Table 13 lists the site-specific data used in the study.

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[1] AS = Activated Sludge, +P = with phosphorus removal

Table 13: Site - specific data used in exergy analysis

Parameter	**Description**
Volume of wastewater treated	m^3 of wastewater treated
Chemical oxygen demand	The quantity of oxygen required to chemically oxidise all organic and inorganic compounds in waste water
Total nitrogen	See testing section 3.2.1, no inter-process data were available
Total phosphorus	See testing section 3.2.1, no inter-process data were available
Energy	
Electricity	Electricity usage (measured)
Chemicals	
Ferric chloride	Ferric chloride used for phosphorus precipitation
Sodium hydroxide	Sodium hydroxide used for deodorisation
Sludge	Monthly average of sludge produced on site

3.2.1 Waste water treatment plant testing

Selected WWTPs underwent intensive nutrient concentration testing over a number of days. Influent and effluent samples were taken at a maximum of 8 hour intervals in the case of grab samples or as daily composite samples where each portion of the sample was collected at 4 hour intervals. Energy data and power quality data were gathered at intensive frequencies. Daily flow data were collected from the respective WWTPs SCADA system or daily logs. These testing methods are detailed further in Table 1 of the appendix.

3.2.2 Testing

TN and TP were analysed using a BioTector TN TP Analyser (BioTector Analytical Systems Limited, Cork, Ireland) in accordance with standard methods [64]. COD were measured in accordance with standard methods [64].

3.2.3 Energy monitoring

Many power/energy monitors will cater for a large range and quantity of variables. Conversely, many will not be capable of capturing a comprehensive list of desired variables and/or will not be capable of simultaneously monitoring multiple variables. Therefore, the specifications of the monitoring equipment play a big role in the scope of an energy audit. Table 14 shows the variables monitored in this study. The first column lists the basic criteria, wherever possible these variables were recorded. The additional variables allowed for a more detailed diagnosis of plant machinery or power characteristics.

Table 14: List of electrical variables recorded in this study including basic variables and additional desirable variables

Basic Variables	Additional Variables
Voltage	Current Harmonic Distortions (A)
Current	Voltage Harmonic Distortions (A)
Active Power	Frequency (Hz)
Apparent Power	Unbalance (%)
Reactive Power	Dips and Swells
Power Factor	Energy Losses (kWh)
Phase angle	-----
Harmonic Distortion	-----
Neutral Current	-----

This detailed diagnosis was performed using the Fluke 435 Series II power quality analyser (PQA), which is a high-specification energy analyser. 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. Finally, smaller plant equipment was metered using eight Iso-Tech IPM2005 meters. Although these meters were capable of monitoring all basic variables, this could not be done simultaneously. Table 15 outlines in more detail the basic specifications of each metering device.

Table 15: Basic specifications for power/energy monitors utilised in plant audits

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	20000 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

3.3 Exergy analysis methodology

The basic exergy calculation methodology is detailed below:

- Quantify the exergy content of process streams, and importantly, waste streams
- Calculate exergy destruction across plant processes
- Determine a hierarchy of inefficient processes
- Identify opportunities to recoup and make use of potential energy sources.

By analyzing the exergy destroyed in each process in a WWTP, the focus area to improve overall system efficiency can be identified. Therefore, it can be used to compare components or systems to help make informed design decisions.

The chemical composition of waste water can be broken down into two separate components:

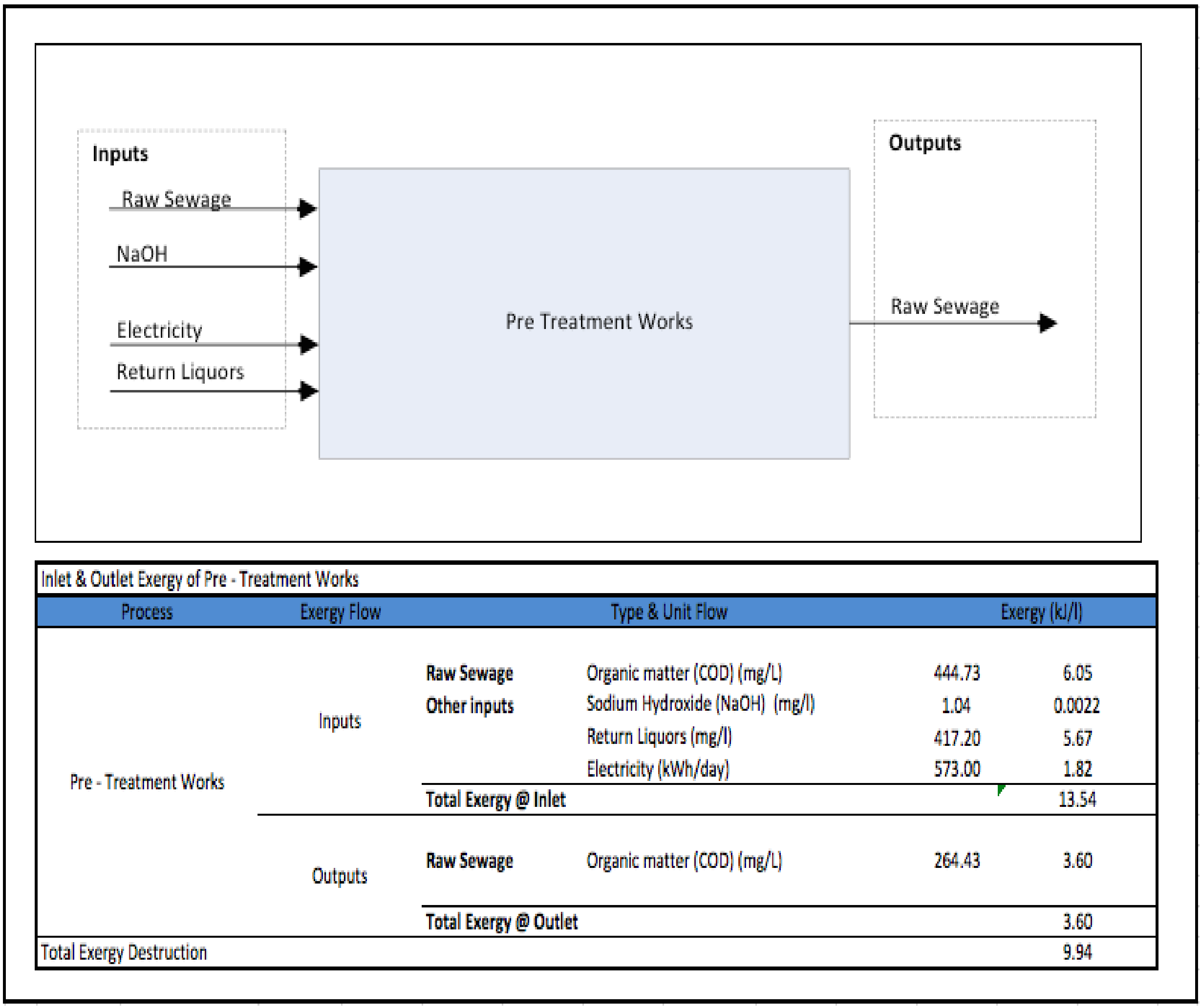
- Organic matter containing hairs, food, paper fibres, plant material, humus etc
- Inorganic matter containing nutrients, metals, gases etc.

Therefore, the calculation of the chemical exergy of WWTP process inputs and outputs can be broken down into two distinct calculation methodologies:

1) The calculation of the chemical exergy of organic matter including raw sewage, waste water, mixed liquor suspended solids, return liquors, return activated sludge and sludge.
2) The calculation of the chemical exergy of inorganic matter including nutrients, metals and coagulants.

Now consider a practical example from the exergy analysis of plant A. Table 16 details the process inputs & outputs across the pre-treatment works in plant A. Table 16 is displayed again on page 44 as Table 19 with the additional treatment processes for plant A.

Table 16: Process inputs & outputs across the pre-treatment works in plant A



Inlet & Outlet Exergy of Pre - Treatment Works

Process	Exergy Flow	Type & Unit Flow			Exergy (kJ/l)
Pre - Treatment Works	Inputs	**Raw Sewage**	Organic matter (COD) (mg/L)	444.73	6.05
		Other inputs	Sodium Hydroxide (NaOH) (mg/l)	1.04	0.0022
			Return Liquors (mg/l)	417.20	5.67
			Electricity (kWh/day)	573.00	1.82
		Total Exergy @ Inlet			13.54
	Outputs	**Raw Sewage**	Organic matter (COD) (mg/L)	264.43	3.60
		Total Exergy @ Outlet			3.60
Total Exergy Destruction					9.94

3.3.1 Organic matter exergy calculation methodology

The chemical exergy of organic matter is calculated using Eq. (8) below:

$$b_{ch}\ (J/l) = 13.6\ (kJ/g) \times COD\ (mg/l) \qquad (8)$$

- Multiply the COD value (mg/l) of the constituent by the coefficient of 13.6 (kJ/g) and divide by a 1000 to obtain the value in kJ/l.

3.3.2 Organic matter calculation example 1

- Looking at the first process input in the pre-treatment works from Figure 6 above, the chemical exergy of raw sewage with a COD (mg/l) value of 444.73 can be calculated as detailed below:

$$b_{ch}\ (J/l) = 13.6\ (kJ/g) \times COD\ (mg/l)$$

$$b_{ch}\ (J/l) = 13.6 \times 444.73$$

$$b_{ch}\ (J/l) = 6{,}048\ (J/l)$$

$$b_{ch}\ (kJ/l) = 6.048\ (kJ/l)$$

3.4 Inorganic matter exergy calculation methodology

- Sodium hydroxide is not contained within either defined RE above, therefore its formation chemical exergy is the only component considered and is calculated using (Eq.3).
- Looking at the second process input in the pre-treatment works from Figure 6 above, the chemical exergy of sodium hydroxide can be calculated as detailed below in Table 16:
    - Obtain the molar mass of the solute (g/mol) and the concentration of the solute (g/l, i.e. grams of solute per litre of solution)
    - To convert to the molar concentration (mol/l) of the solute divide the concentration of the solute (g/l) by the molar mass of the solute (g/mol)
    - To convert to the standard chemical exergy of the solute (kJ/l), obtain the standard chemical exergy value (kJ/mol) from the literature and multiply it by molar concentration (mol/l).

Table 17: Exergy Calculation of Sodium Hydroxide

NaOH		
Molar mass	39.98800	g/mol
NaOH Concentration	0.00104	g/l
	0.00003	mol/l
Total Specific Exergy of NaOH	85.56	KJ/mol
Total Specific Exergy of NaOH	0.0022	kJ/l

3.5 Exergy Value of Electricity

- Electricity is the fourth process input in Figure 6 above.
- The first step to calculate the exergy value of electricity in (kJ/l) is to initially divide its value in (kWh/day) by 24. So 573 (kWh/day) is simply divided by 24. Then it is found by multiplying its 23.88 (kW) value by a time period of a day in seconds (24 x 60 x 60) and dividing by the daily flow through the plant in litres.

3.6 Notes

- A limitation of the work is the lack of inter - process nutrient data for all analysed plants and the inability to quantify the exergy value of gaseous emissions from the various treatment processes.
- As this data did not exist neither of these components was included in the exergy process exergy analyses, however, the nutrients were included in the overall plant analysis.

Exergy analysis was conducted on three WWTP; a brief overview of the specific plant characteristics is presented in Table 12.

4 Results

4.1 Plant A Site Description and Results

This facility has a PE of 186,000. The inlet works consists of four one metre-wide channels for the purpose of screening. Sand and grease are removed from the screened water within the pre – treatment building. The plant's biological reactor consists of initial anaerobic treatment followed by aerobic treatment. Waste water is pumped from the secondary clarifier to the sludge pump station, with return activated sludge pumped to the inlet of the biological reactor. The site layout of the plant is detailed below in Figure 6:

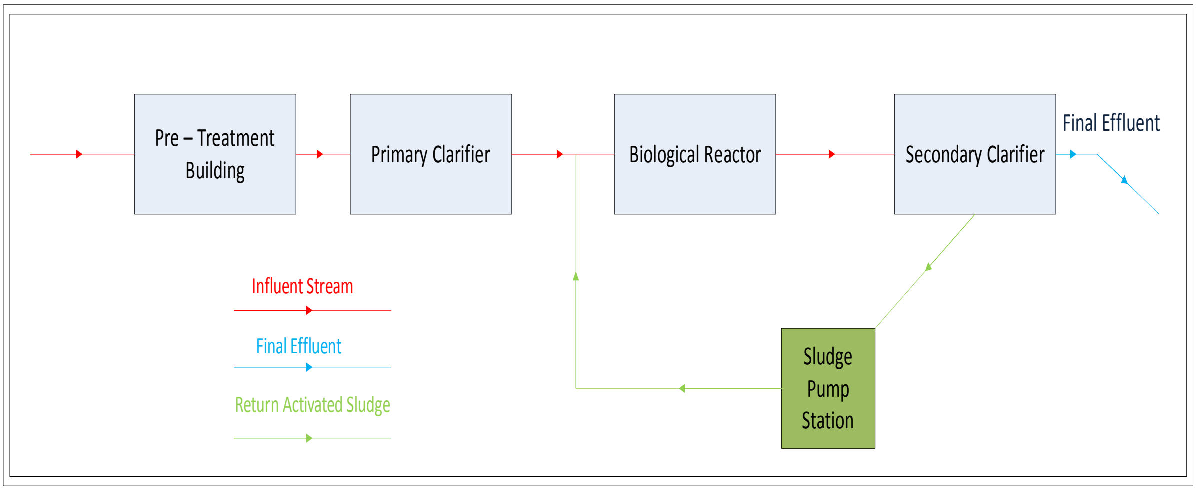


Figure 6: Site Layout Plant A

4.1.1 Calculation Assumptions

- Return liquors, sodium hydroxide and mixed liquor suspended solids are drip fed into the WWTP
- Electricity (kWh/day) usage is split evenly between the pre-treatment building and primary clarifier
- No inter – process nutrient data exists for plant A, nutrient exergy reduction is therefore only included in the analysis at the end of the calculations.
- Nitrogen (kJ/mol) is assumed to exist as the ammonium ion; the chemical exergy value of ammonium hydroxide electrolyte has been previously calculated by Szargut.

This value obtained from Szargut (kJ/mol) is multiplied by the concentration of the component in (mol/l), this provides the exergy value in kJ/l.

Table 18 below provides a breakdown of the measured data across each of the processes recorded from the plant A. The table is included for the readers’ ease of reference when looking for specific values from plant A.

Table 18: Summary of Plant A's Process inputs and outputs

Process stage	*Flow type*	*Flow (m3/day)*	*COD (mg/l)*	*TN (mg/l)*	*TP (mg/l)*	*Energy (kWh/day)*	*Chemical exergy (kJ/l)*	*Work (kJ/l)*	*Total exergy (kJ/l)*
Pre-treament (in)	Wastewater	27,270	444.73	32.75	-	573	6.05	1.82	13.54
	Return Liquors		417.2				5.67		
Pre-treatment (out)	Wastewater		273.47				3.72		3.72
Primary Clarifier (in)	Wastewater		273.47			573	3.72	1.82	5.54
Primary Clarifier (out)	Wastewater		153.5				2.09		3.47
	Sludge		101.25				1.38		
Aeration basin (in)	Wastewater		153.5			1306	2.09	4.14	9.35
	Return Liquors		229.47				3.12		
Aeration basin (out)	Mixed Liquors		328.3				4.46		4.56
	Wastewater		7.61				0.10		
Secondary clarifier (in)	Mixed Liquors		328.3				4.46		4.56
	Wastewater		7.61				0.10		
Secondary clarifier (out)	Final Effluent	25,720	34.03	25.91	-		0.46		0.46
	Wastewater		39.28				0.53		0.53

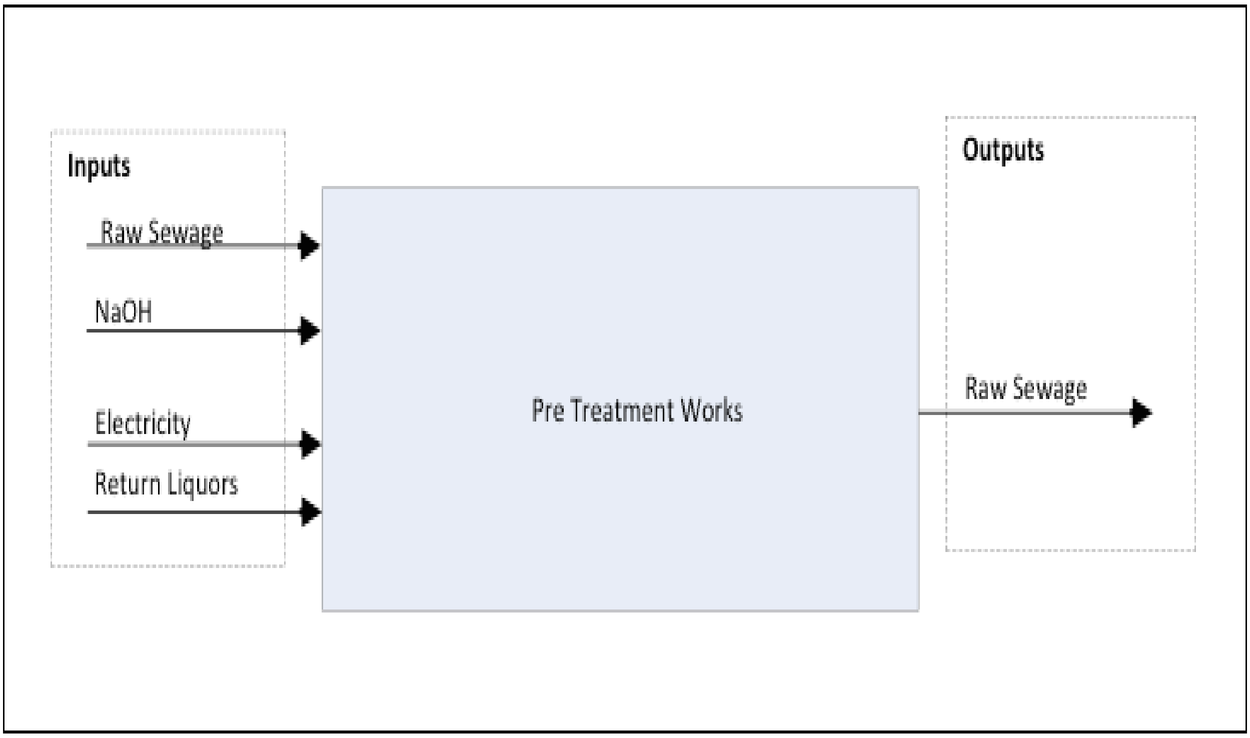
Note:

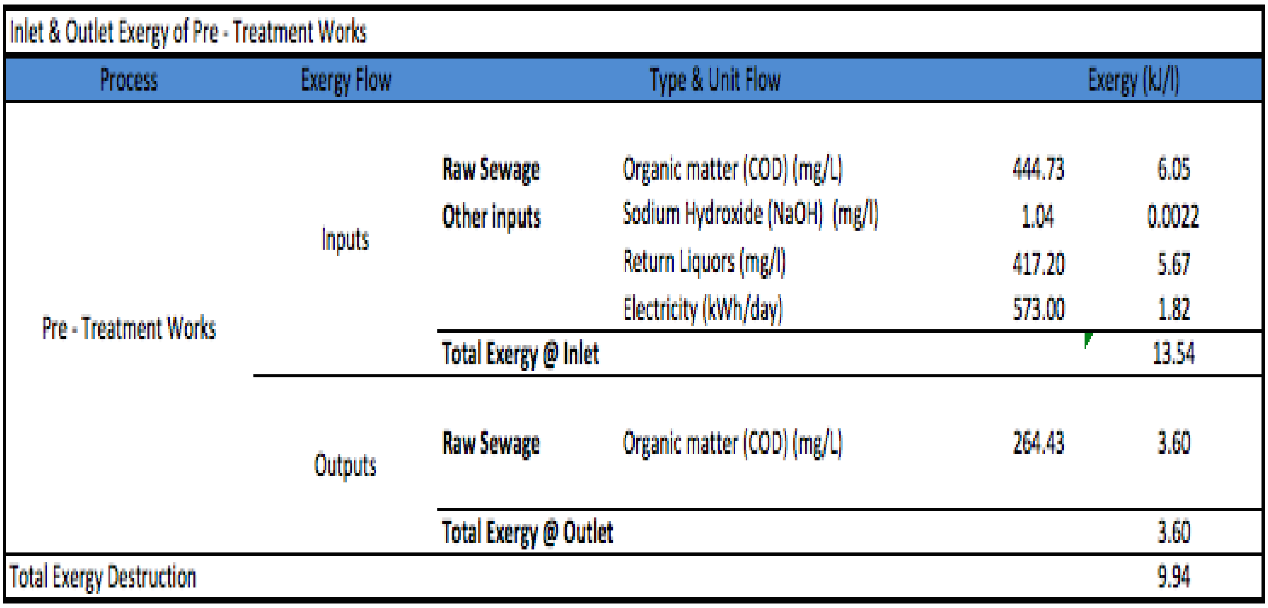
- The return activated sludge calculation in the aeration basin was determined by summating the daily return liquors value (mg/l) taken at the plant and divides it by the total days in the month. Samples were randomly taken ten days for the month, it is unclear from the data whether return liquors are sent to the inlet of the aeration basin daily or just on the days of sampling.
- The mg/l concentration of the return liquors samples varies from 2000 mg/l to 500 mg/l over the course of the month, suggesting that the return liquors concentration is

carefully analysed to maintain the balance of microorganisms within the aeration basin.

Tables 19 – 22 detail the exergy values of the process inputs & outputs across each of the treatment processes in plant A and the overall exergy destruction across the process. Table 19 is also displayed as an example on page 38 as Table 16.

Table 19: Plant A – Pre Treatment Works

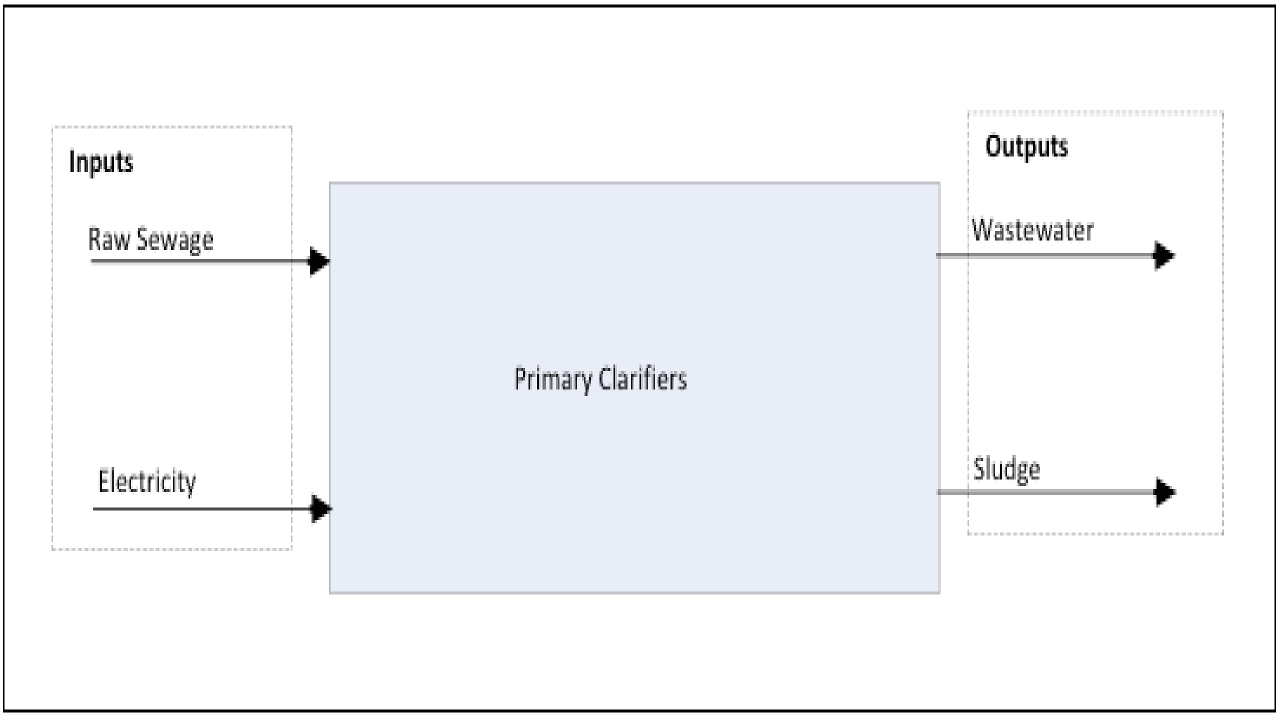


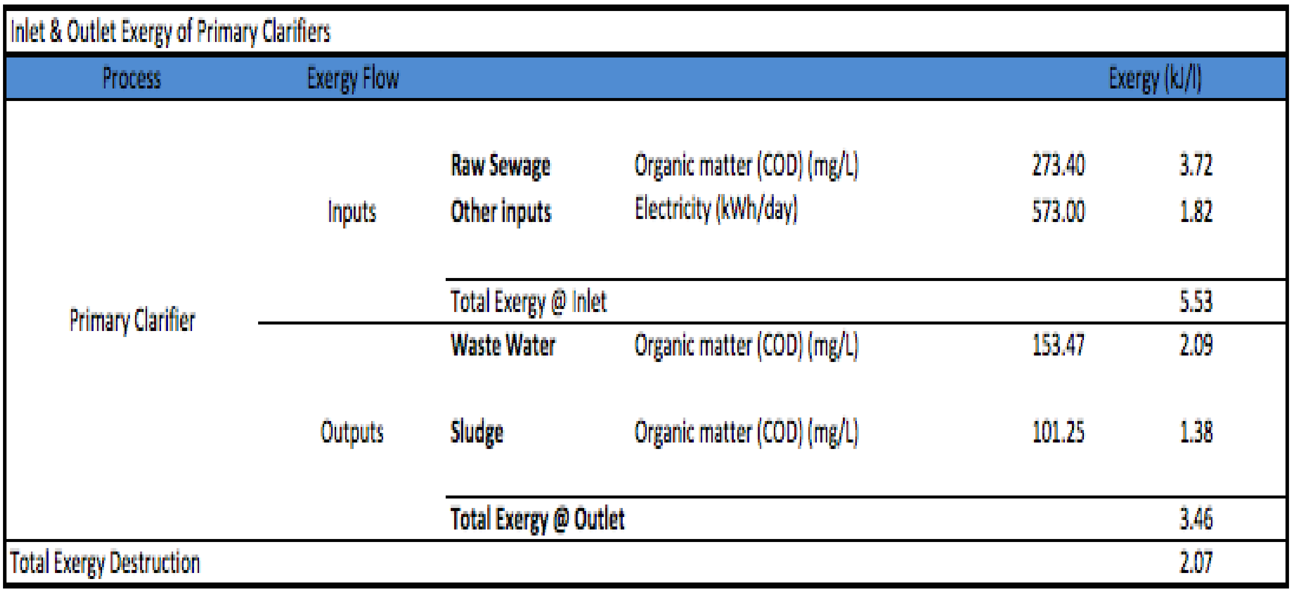


Inlet & Outlet Exergy of Pre - Treatment Works

Process	Exergy Flow	Type & Unit Flow			Exergy (kJ/l)
Pre - Treatment Works	Inputs	**Raw Sewage**	Organic matter (COD) (mg/L)	444.73	6.05
		Other inputs	Sodium Hydroxide (NaOH) (mg/l)	1.04	0.0022
			Return Liquors (mg/l)	417.20	5.67
			Electricity (kWh/day)	573.00	1.82
		Total Exergy @ Inlet			13.54
	Outputs	**Raw Sewage**	Organic matter (COD) (mg/L)	264.43	3.60
		Total Exergy @ Outlet			3.60
Total Exergy Destruction					9.94

Table 20: Plant A - Primary Clarifier

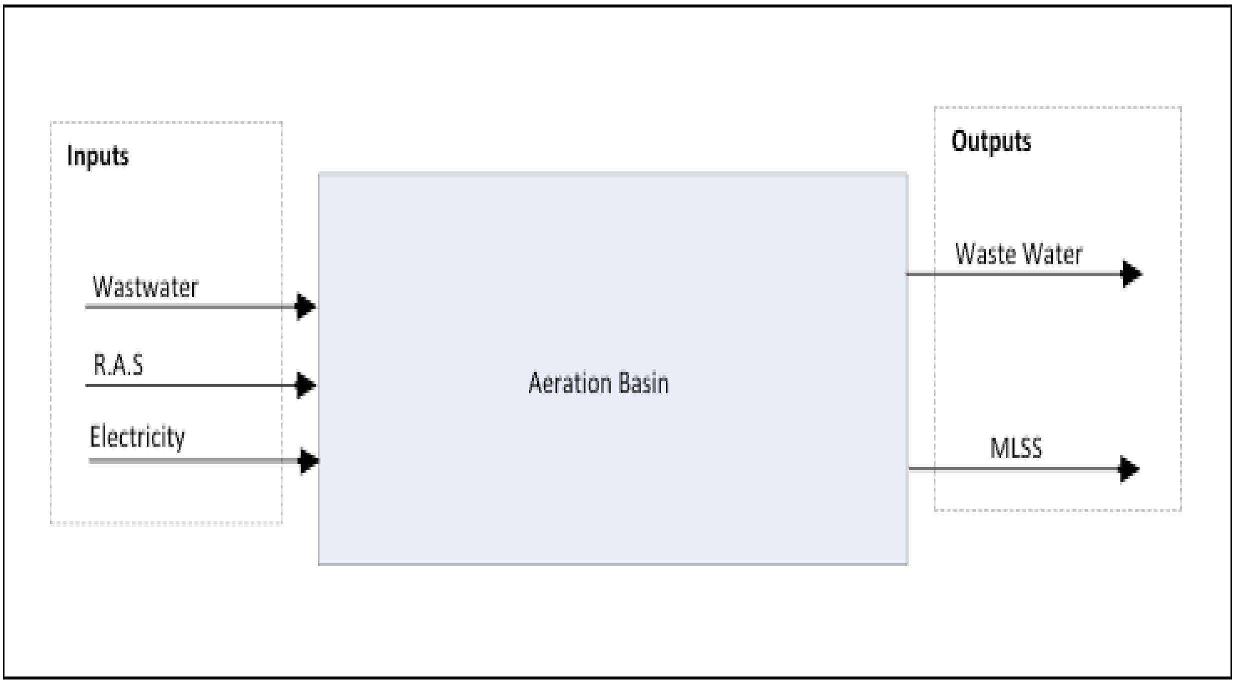


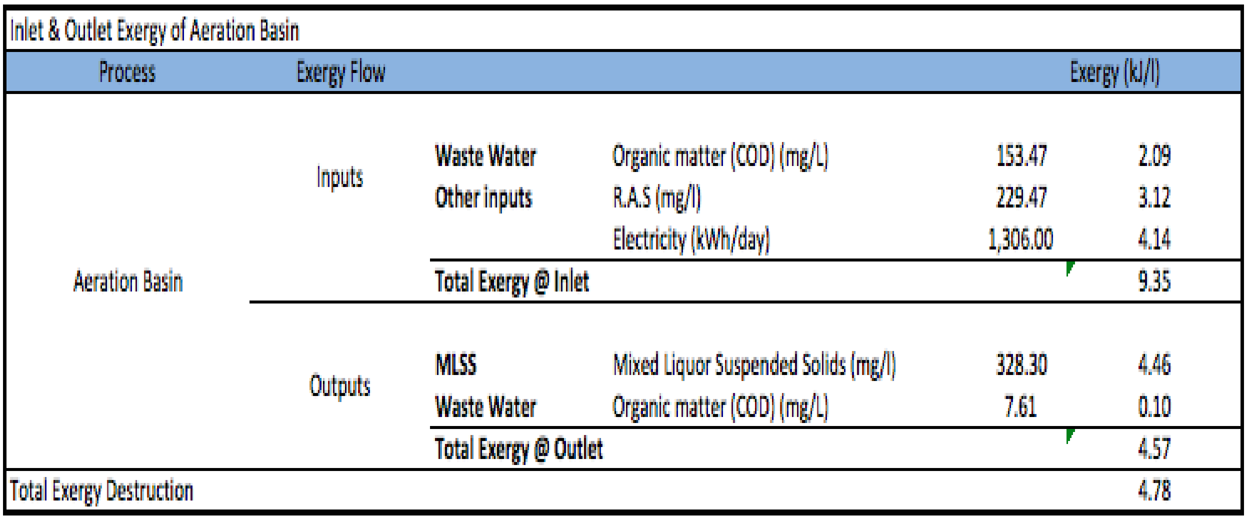


Inlet & Outlet Exergy of Primary Clarifiers

Process	Exergy Flow				Exergy (kJ/l)
Primary Clarifier	Inputs	**Raw Sewage**	Organic matter (COD) (mg/L)	273.40	3.72
		Other inputs	Electricity (kWh/day)	573.00	1.82
		Total Exergy @ Inlet			5.53
	Outputs	**Waste Water**	Organic matter (COD) (mg/L)	153.47	2.09
		Sludge	Organic matter (COD) (mg/L)	101.25	1.38
		Total Exergy @ Outlet			3.46
Total Exergy Destruction					2.07

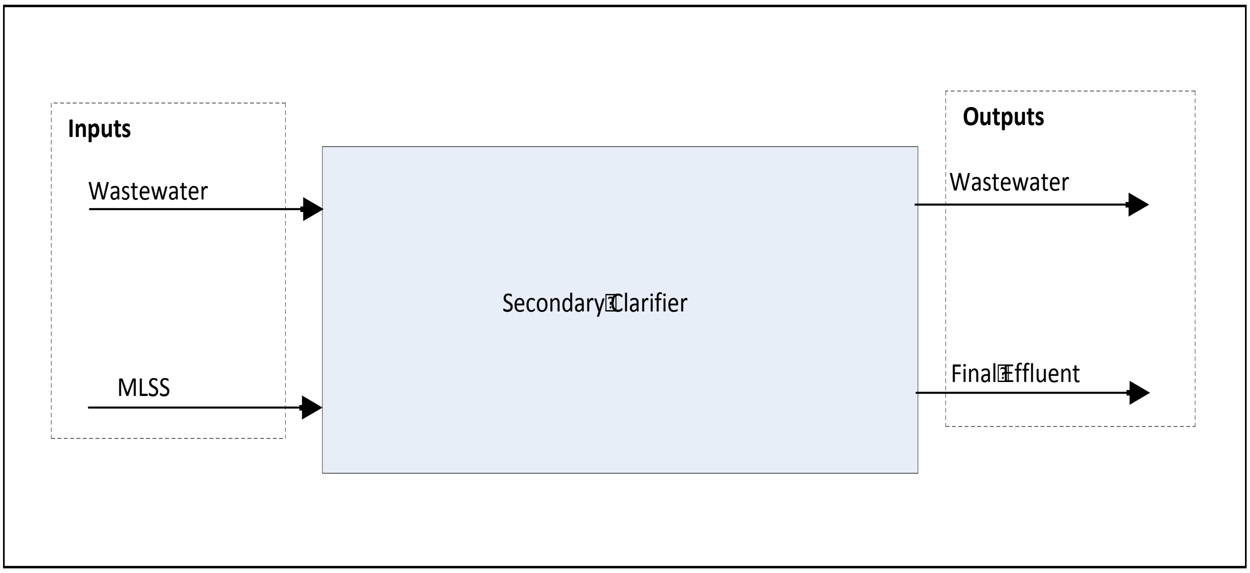
Table 21: Plant A - Aeration Basin




Inlet & Outlet Exergy of Aeration Basin

Process	Exergy Flow				Exergy (kJ/l)
Aeration Basin	Inputs	**Waste Water**	Organic matter (COD) (mg/L)	153.47	2.09
		Other inputs	R.A.S (mg/l)	229.47	3.12
			Electricity (kWh/day)	1,306.00	4.14
		Total Exergy @ Inlet			9.35
	Outputs	**MLSS**	Mixed Liquor Suspended Solids (mg/l)	328.30	4.46
		Waste Water	Organic matter (COD) (mg/L)	7.61	0.10
		Total Exergy @ Outlet			4.57
Total Exergy Destruction					4.78

Table 22: Plant A - Secondary Clarifier



Inlet & Outlet Exergy of Secondary Clarifiers

Process	Exergy Flow				Exergy (kJ/l)
Secondary Clarifier	Inputs	**MLSS**	Mixed Liquor Suspended Solids (mg/l)	328.30	4.46
		Waste Water	Organic matter (COD) (mg/L)	7.61	0.10
		Total Exergy @ Inlet			4.57
	Outputs	**Final Effluent**	Organic matter (COD) (mg/L)	34.03	0.46
		Waste Water to SPS	Organic matter (COD) (mg/L)	39.28	0.53
		Total Exergy @ Outlet			1.00
Total Exergy Destruction					3.57

Overall Exergy Plant Destruction	**20.24**

Overall Exergy Plant Destruction including nutrient reduction across the plant	**20.33**

4.2 Plant B Site Description and Results

Plant B has a max design PE of 12,000 but is licensed by the Irish EPA to cater for a PE of only 9,683. This WWTP comprises of screening, grit removal, three aeration tanks (diffused aeration system), two clarifiers, phosphorus removal, sludge thickening and sludge dewatering. Storm water storage tanks and a picket fence thickener are also included as part of the waste water works. The WWTP discharges to an inland river. The site layout of the plant is detailed below in Figure 7:

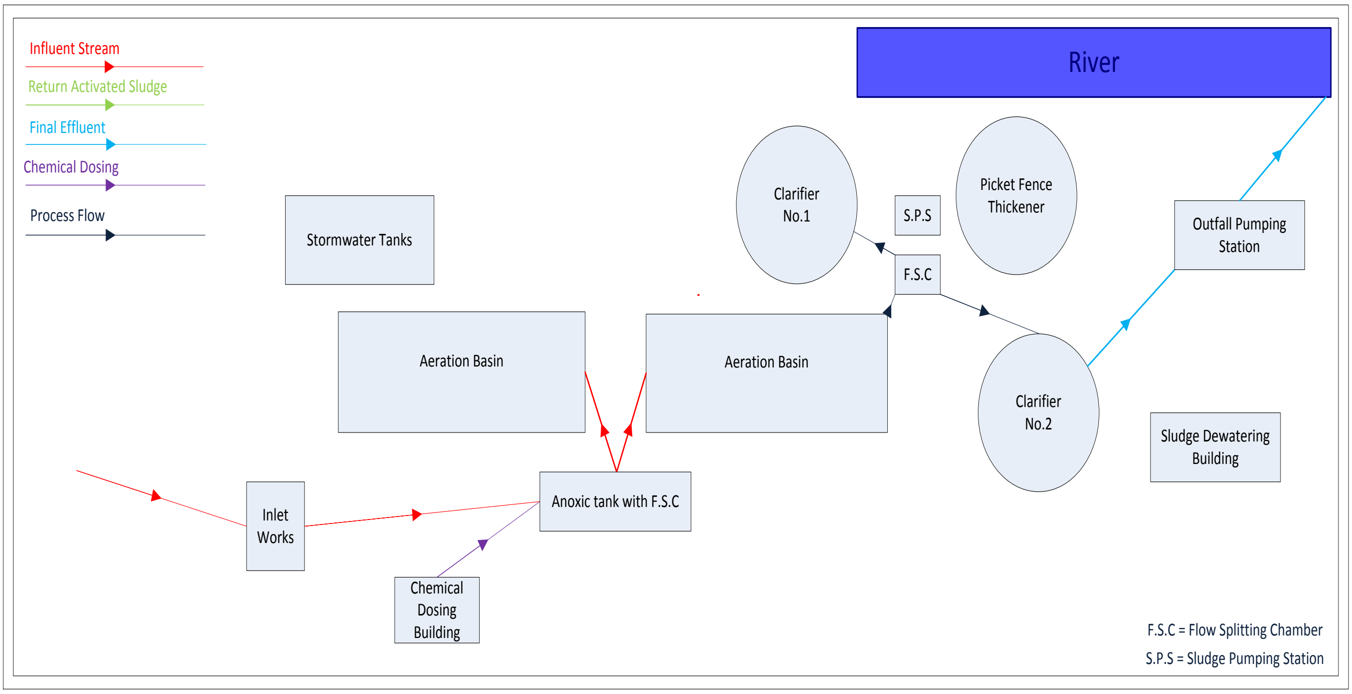


Figure 7: Site Layout Plant B

4.2.1 Calculation Assumptions

- A 13.57% reduction in organic matter across the pre – treatment works was assumed. This figure was obtained from organic matter reductions in eight different waste water treatment plants [65].
- As no inter – process nutrient data exists for plant B, nutrient exergy reduction is therefore only included in analysis at the end of the calculations.
- No inter – process sludge existed for plant B. The sludge output calculation in the secondary clarifier was determined by dividing the daily average of sludge out of the plant (kg/day) by the daily average of flow through the plant in m^3/day.
- The chemical exergy of nutrients (kJ/mol) has been previously calculated by Szargut. This value obtained from Szargut (kJ/mol) is multiplied by the concentration of the component in (mol/l). Resulting in an exergy value in kJ/l.
- No return activated sludge line to the inlet of the aeration basin was present on the site layout plans was there any mention of return activated sludge on the discharge licence application for the plant to the Environmental Protection Agency. It was quite possible that activated sludge is returned to the inlet of the aeration basin but the figure was not included in analysis for these reasons. Also, this data was not available when the analysis was performed. Hence return activated sludge is excluded from the analysis.

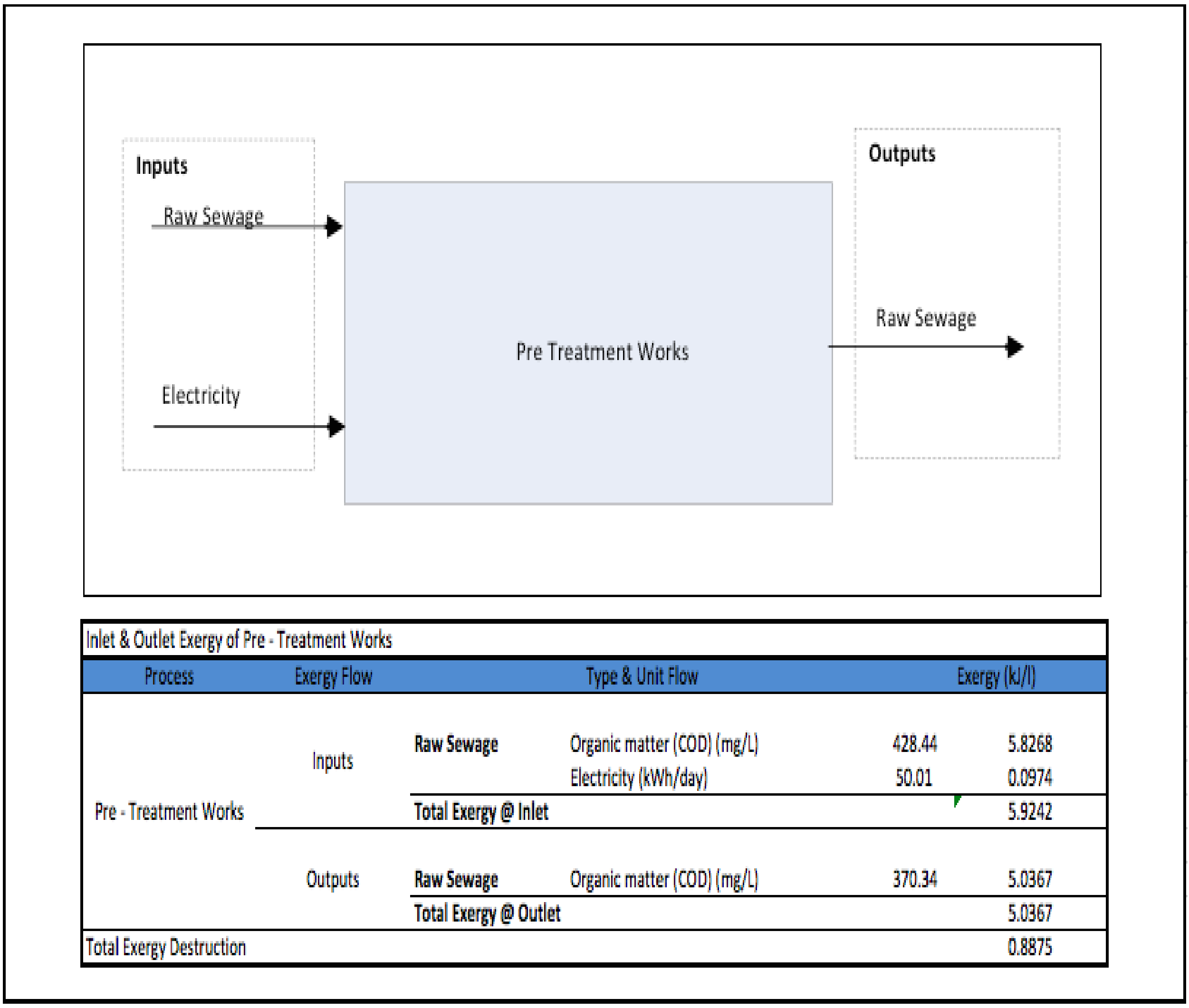
Table 23 below provides a breakdown of the measured data across each of the processes recorded from the plant B. The table is included for the readers' ease of reference when looking for specific values from plant B.

Table 23: Summary of Plant B's Process inputs and outputs

Process stage	*Flow type*	*Flow (m3/day)*	*COD (mg/l)*	*TN (mg/l)*	*TP (mg/l)*	*Energy (kWh/day)*	*Chemical exergy (kJ/l)*	*Work (kJ/l)*	*Total exergy (kJ/l)*
Pre-treament (in)	Wastewater	1,848	428.4	71.46	7.66	50.01	5.82	0.097	5.92
Pre-treatment (out)	Wastewater		370.34				5.03		5.03
Aeration basin (in)	Wastewater		370.34			1312.46	5.03	2.55	7.58
Aeration basin (out)	Wastewater		315.83				4.29		4.29
Secondary clarifier (in)	Wastewater		315.83				4.29		4.29
Secondary clarifier (out)	Wastewater	1,696	104.53	50.06	0.98		1.42		1.42
	Sludge		50				0.68		0.68

Tables 24 – 26 detail the exergy values of the process inputs & outputs across each of the treatment processes in plant B and the overall exergy destruction across the process.

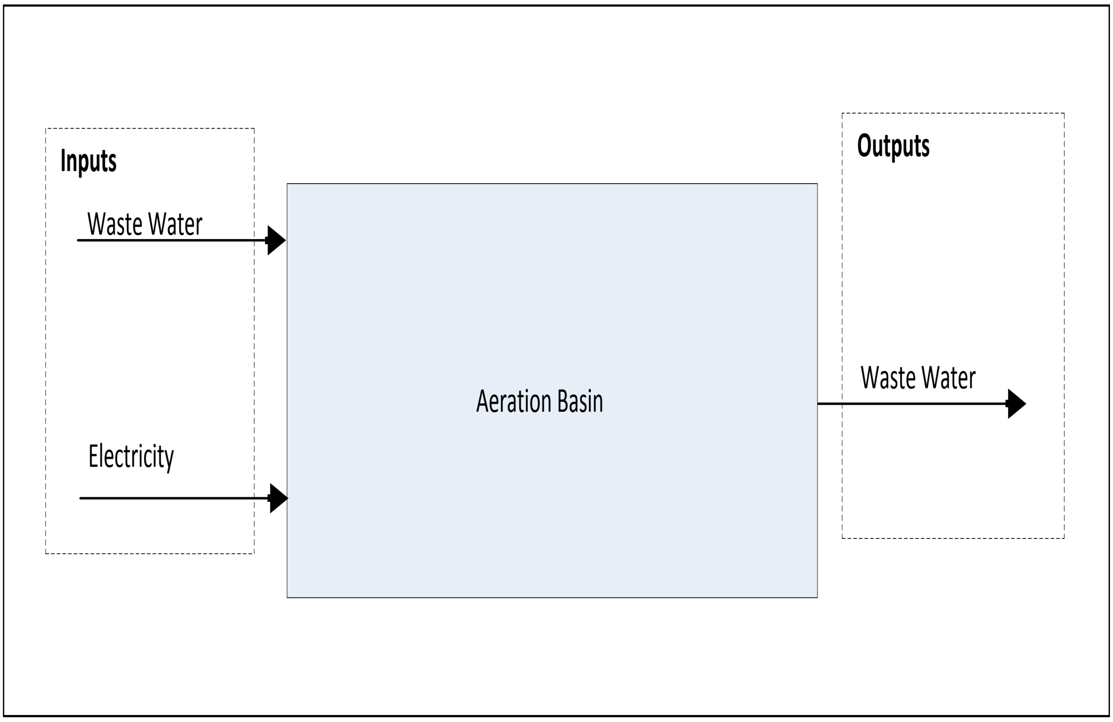
Table 24: Plant B - Pre - Treatment Works



Inlet & Outlet Exergy of Pre - Treatment Works

Process	Exergy Flow	Type & Unit Flow			Exergy (kJ/l)
Pre - Treatment Works	Inputs	**Raw Sewage**	Organic matter (COD) (mg/L)	428.44	5.8268
			Electricity (kWh/day)	50.01	0.0974
		Total Exergy @ Inlet			5.9242
	Outputs	**Raw Sewage**	Organic matter (COD) (mg/L)	370.34	5.0367
		Total Exergy @ Outlet			5.0367
Total Exergy Destruction					0.8875

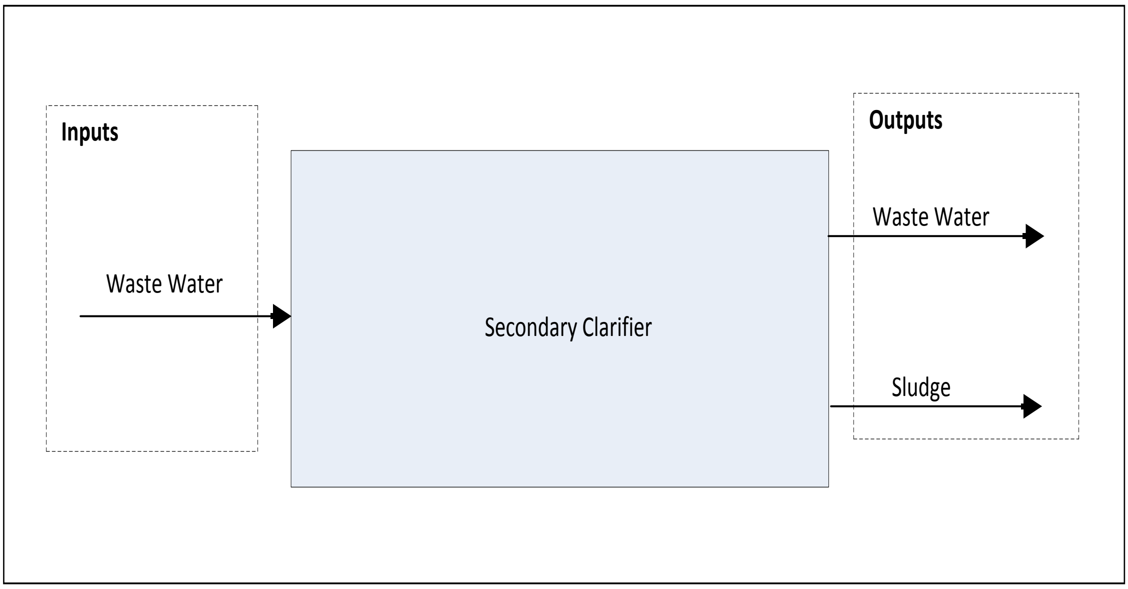
Table 25: Plant B - Aeration Basin



Inlet & Outlet Exergy of Aeration Basin

Process	Exergy Flow	Type & Unit Flow			Exergy (kJ/l)
Aeration Basin	Inputs	**Waste Water**	Organic matter (COD) (mg/L)	370.34	5.0367
		Other inputs	Electricity (kWh/day)	1,312.46	2.5567
		Total Exergy @ Inlet			7.5934
	Outputs	**Waste Water**	Organic matter (COD) (mg/L)	315.83	4.2953
		Total Exergy @ Outlet			4.2953
Total Exergy Destruction					3.2981

Table 26: Plant B - Secondary Clarifier



Inlet & Outlet Exergy of Secondary Clarifiers

Process	Exergy Flow				Exergy (kJ/l)
Secondary Clarifier	Inputs	**Waste Water**	Organic matter (COD) (mg/L)	315.83	4.2953
		Total Exergy @ Inlet			4.2953
	Outputs	**Final Effluent**	Organic matter (COD) (mg/L)	104.53	1.4216
			Sludge (mg/l)	50.00	0.6800
		Total Exergy @ Outlet			2.1016
Total Exergy Destruction					2.1937

Overall Exergy Plant Destruction	**6.3793**

Overall Exergy Plant Destruction including nutrient reduction across the plant	**6.7265**

4.3 Plant C Site Description and Results

This facility has a PE of 12,000 with a reserve capacity of 4,000 PE. The inlet works comprises mechanical and manual screens together with a compaction unit, overflow unit and grit traps.

The influent is then passed to the anaerobic tanks where it is mixed with RAS. The effluent from each anaerobic tank is spilt between the two aeration basins. The secondary treatment process is a single stage anoxic zone extended aeration process followed by clarification. The clarified effluent is discharged to an inland river. This is the primary discharge point. The site layout of the plant is detailed below in Figure 8:

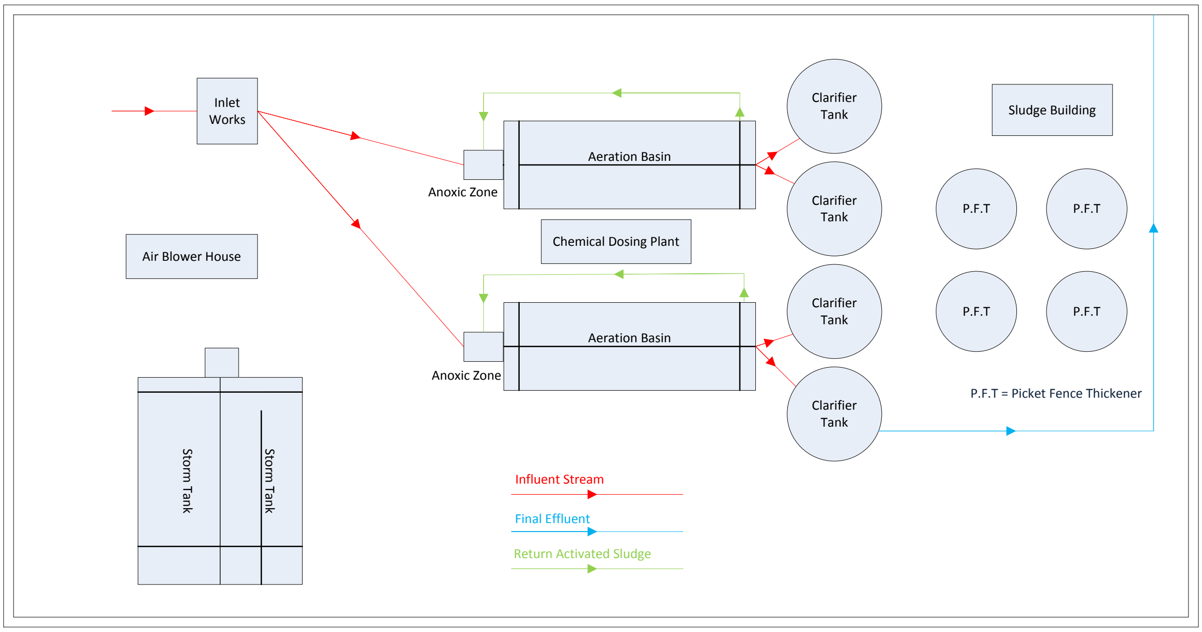


Figure 8: Site Layout Plant C

4.3.1 Calculation Assumptions

- A 13.57% reduction in organic matter across the pre – treatment works was assumed. This figure was obtained from organic matter reductions in eight different waste water treatment plants [64].
- As an intermittent process sample for organic matter was not taken for plant C WWTP, the reduction in organic matter across plant B was used as a reference as both plants are of similar scale and similar treatment processes in place.
- As no inter – process nutrient data exists for plant C, nutrient exergy reduction is therefore only included in analysis at the end of the calculations.
- No inter – process sludge existed for plant B. The sludge output calculation in the secondary was determined dividing the daily average of sludge out of the plant (kg/day) by the daily average of flow through the plant in m^3/day.
- The chemical exergy of nutrients (kJ/mol) has been previously calculated by Szargut. This value obtained from Szargut (kJ/mol) is multiplied by the concentration of the component in (mol/l), resulting in an exergy value in kJ/l.
- No return activated sludge line to the inlet of the aeration basin was present on the site layout plans. It was quite possible that activated sludge is returned to the inlet of the aeration basin but the figure was not included in analysis for this reason. Also, this data was not available when the analysis was performed. Hence return activated sludge is excluded from the analysis.

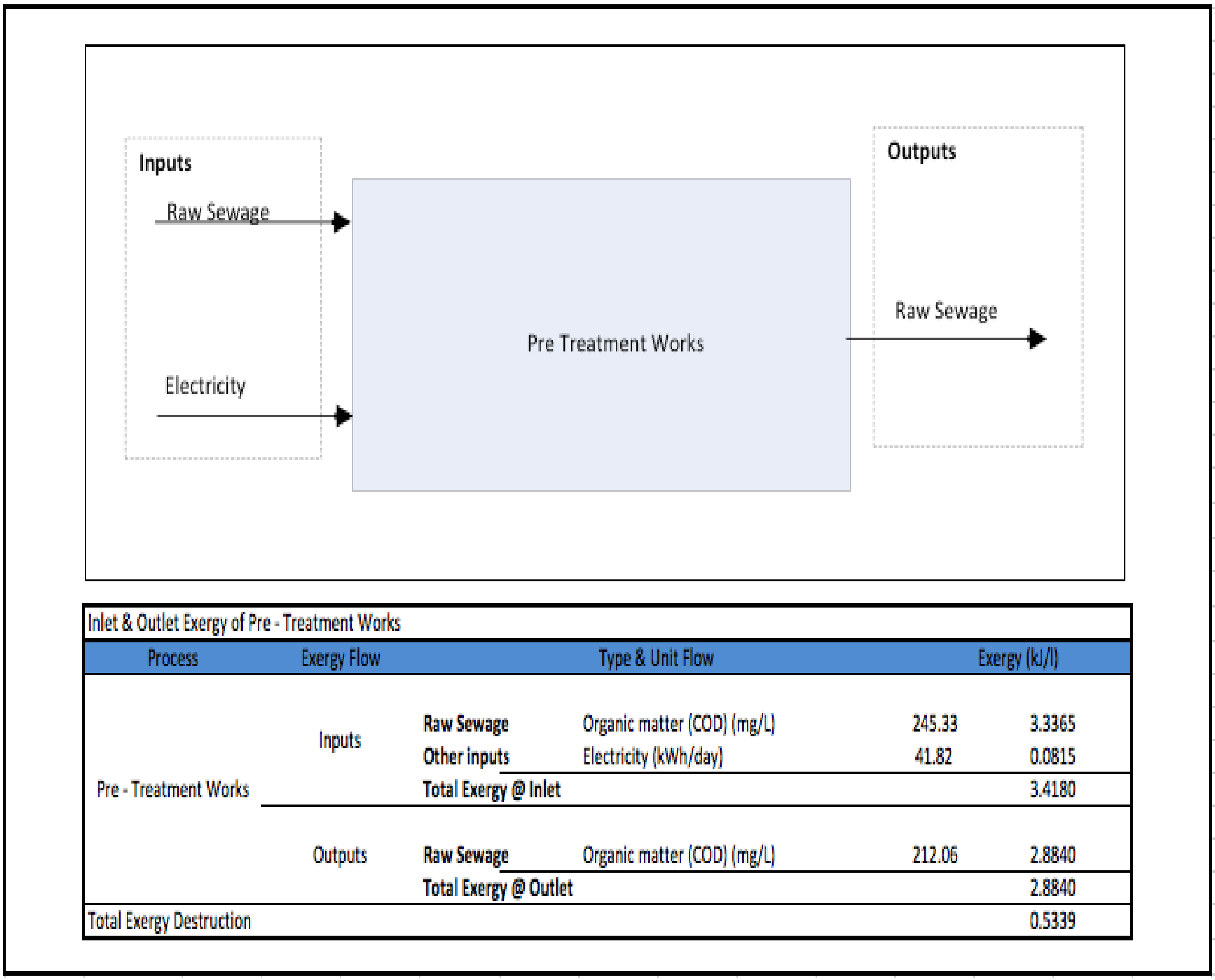
Table 27 below provides a breakdown of the measured data across each of the processes recorded from the plant C. The table is included for the readers' ease of reference when looking for specific values from plant C.

Table 27: Summary of Plant C's Process inputs and outputs

Process stage	*Flow type*	*Flow (m3/day)*	*COD (mg/l)*	*TN (mg/l)*	*TP (mg/l)*	*Energy (kWh/day)*	*Chemical exergy (kJ/l)*	*Work (kJ/l)*	*Total exergy (kJ/l)*
Pre-treament (in)	Wastewater	1,980	245.33	29.8	3.8	41.82	3.33	0.08	3.41
Pre-treatment (out)	Wastewater		212.1				2.88		2.88
Aeration basin (in)	Wastewater		212.1			395.56	2.88	0.77	3.65
Aeration basin (out)	Wastewater		180.9				2.46		2.46
Secondary clarifier (in)	Wastewater		180.9				2.46		2.46
Secondary clarifier (out)	Wastewater	1,944	64.89	17	0.9		0.88		0.88
	Sludge		30				0.40		0.40

Tables 28 – 30 detail the exergy values of the process inputs & outputs across each of the treatment processes in plant C and the overall exergy destruction across the process.

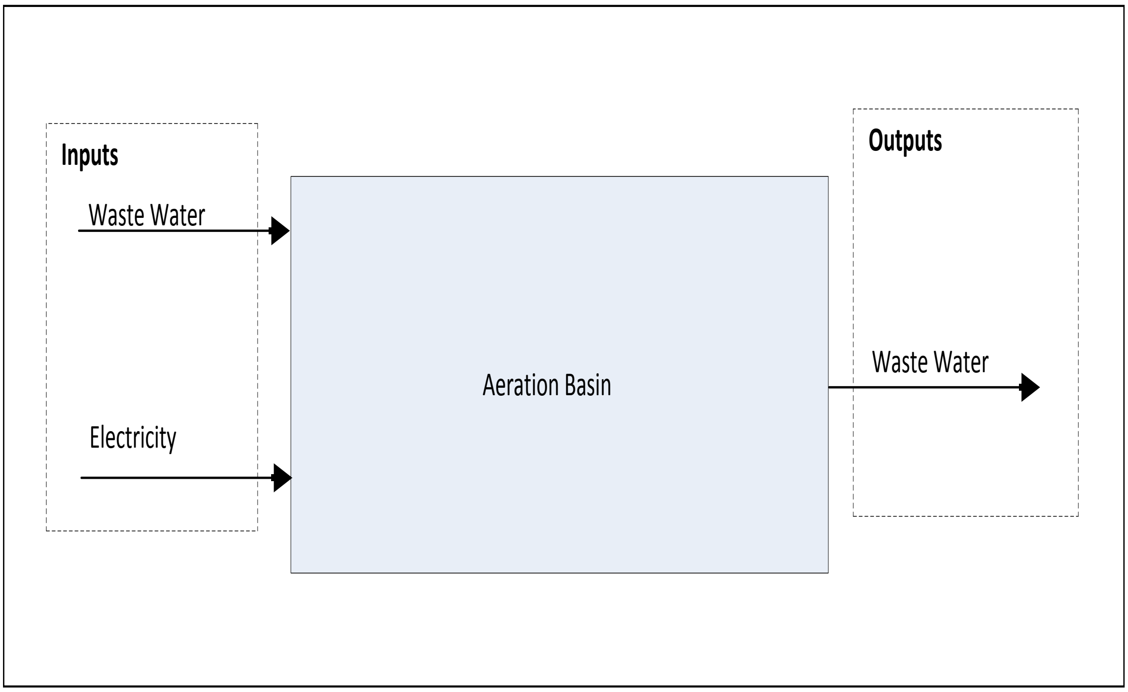
Table 28: Plant C – Pre Treatment works



Inlet & Outlet Exergy of Pre - Treatment Works

Process	Exergy Flow	Type & Unit Flow			Exergy (kJ/l)
Pre - Treatment Works	Inputs	**Raw Sewage**	Organic matter (COD) (mg/L)	245.33	3.3365
		Other inputs	Electricity (kWh/day)	41.82	0.0815
		Total Exergy @ Inlet			3.4180
	Outputs	**Raw Sewage**	Organic matter (COD) (mg/L)	212.06	2.8840
		Total Exergy @ Outlet			2.8840
Total Exergy Destruction					0.5339

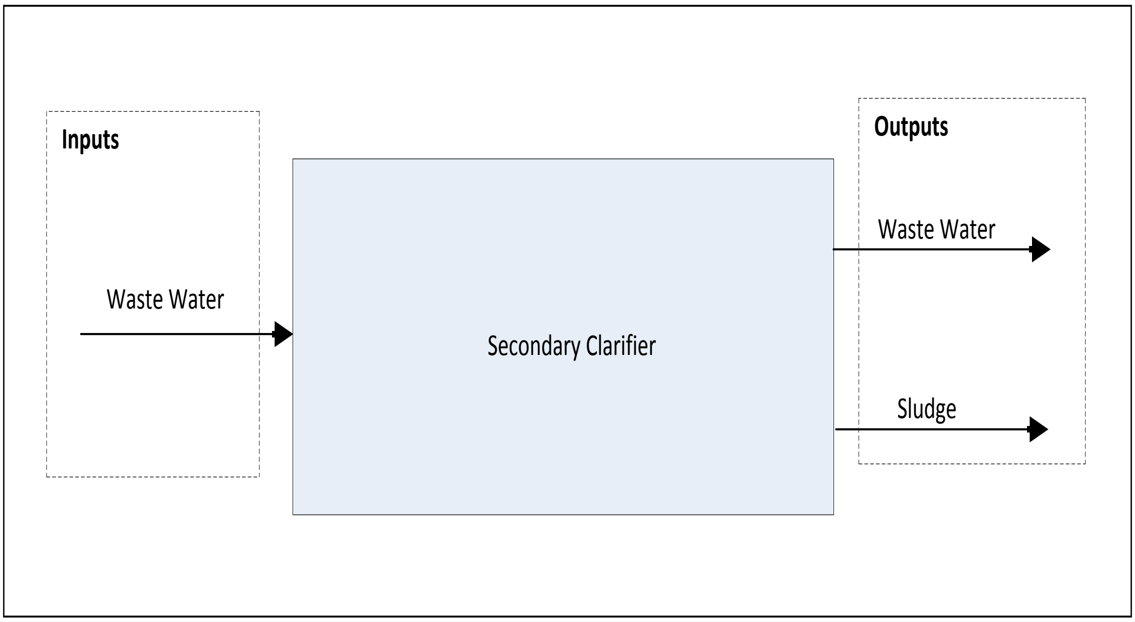
Table 29: Plant C - Aeration Basin



Inlet & Outlet Exergy of Aeration Basin

Process	Exergy Flow	Type & Unit Flow			Exergy (kJ/l)
Aeration Basin	Inputs	**Waste Water**	Organic matter (COD) (mg/L)	212.06	2.8840
		Other inputs	Electricity (kWh/day)	395.56	0.7706
		Total Exergy @ Inlet			3.6546
	Outputs	**Waste Water**	Organic matter (COD) (mg/L)	180.89	2.4601
		Total Exergy @ Outlet			2.4601
Total Exergy Destruction					1.1945

Table 30: Plant C - Secondary Clarifier



Inlet & Outlet Exergy of Secondary Clarifiers

Process	Exergy Flow				Exergy (kJ/l)
Secondary Clarifier	Inputs	**Waste Water**	Organic matter (COD) (mg/L)	180.89	2.4601
		Total Exergy @ Inlet			2.4601
	Outputs	**Final Effluent**	Organic matter (COD) (mg/L)	64.89	0.8825
			Sludge (mg/l)	30.00	0.4080
		Total Exergy @ Outlet			1.2905
Total Exergy Destruction					1.1696

Overall Exergy Plant Destruction	**2.8980**

Overall Exergy Plant Destruction including nutrient reduction across the plant	**3.1040**

5 Discussion

Table 31 below provides a breakdown of results of all three analysed plants. Exergy destruction is compared across all plants and exergy destruction including nutrient exergy destruction is also detailed. Exergy losses meaning the lost opportunity do with work with WWTP process outputs is also detailed for all analysed plants.

Table 31: Exergy Analysis Results Comparison

	Exergy kJ/l		
Process	**Plant A**	**Plant B**	**Plant C**
Pretreatment			
Exergy In	13.5	5.9	3.4
Exergy out	3.7	5.0	2.9
Exergy destruction	9.8	0.9	0.5
Exergy Loss	0	5.0	2.9
Primary Clarifier		n/a	n/a
Exergy In	5.5		
Exergy out	3.5		
Exergy destruction	2.1		
Exergy Loss	0		
Aeration			
Exergy In	9.4	7.6	3.7
Exergy out	4.6	4.3	2.5
Exergy destruction	4.9	3.3	1.2
Exergy Loss	3.9	0	0
Secondary clarifier			
Exergy In	4.6	4.3	2.5
Exergy out	1	2.1	1.3
Exergy destruction	3.6	2.2	1.2
Exergy Loss	0.4	1.6	0.7
Overall plant exergy destruction	**20.2**	**6.4**	**2.9**
Overall Exergy Loss	**4.3**	**6.6**	**3.6**

5.1 Overall Plant Exergy Destruction Comparison

- Figure 9 provides a breakdown of the cumulative exergy destruction across all treatment processes in Plants A, B and C.

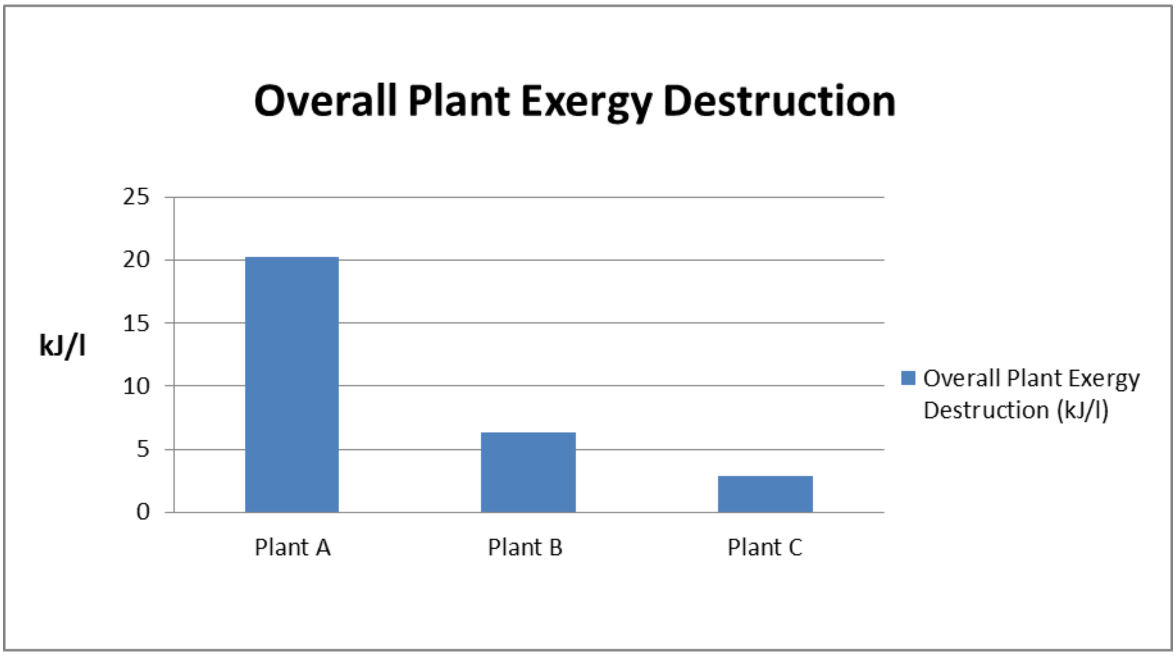


Figure 9: Exergy Destruction across analysed plants

- The influent COD loading rate in Plant A is quite similar to that of Plant B and almost double that of Plant C. The main discrepancy between exergy destruction between Plant A and Plants B & C is that Plant A utilises return liquors in the pre-treatment works. These return liquors COD loading rates are double that of the influent load in Plant C and quite similar to the initial load in Plant B.
- Plants B and C have similar PEs and plant configurations. The discrepancy between exergy destruction (kJ/l) across both plants can to a certain extent be related to the influent COD loading rates. The organic composition of the influent load in Plant B was almost twice that of Plant C during the sample period thus Plant B has greater oxygen requirements in its aeration basin to maintain DO concentration levels.

Therefore, a larger quantity of electricity will be used in Plant B, resulting in larger exergy destruction rates across the plant.

5.2 Plant A exergy destruction and exergy loss discussion

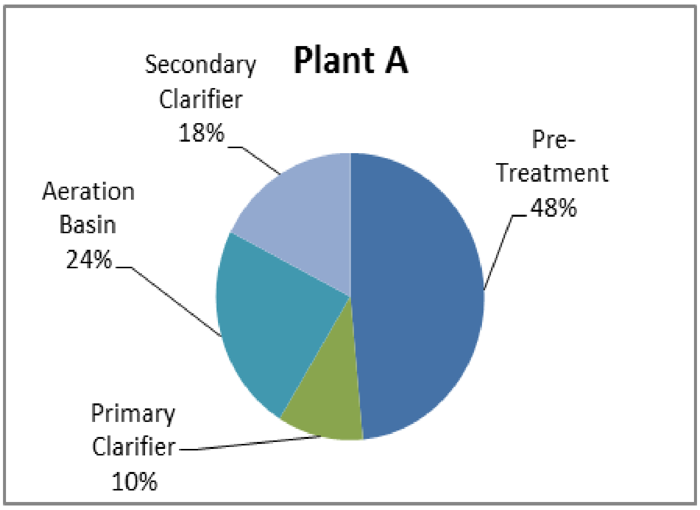


Figure 10: Exergy Destruction breakdown for Plant A

- The pre-treatment works account for 48% of the exergy destruction across the whole WWTP. This is due to the excess activated sludge that is refed to the inlet works from the activated sludge system. These return liquors have very high organic loading rates, quite similar to the influent COD loading rates received by the plant.
- Uncertainty exists regarding the exergy destruction rate across the aeration basin in Plant A as organic matter samples were randomly taken ten days for the analysed month, it is unclear from the data whether return liquors are sent to the inlet of the aeration basin daily or just on the days of sampling. If the return liquors are returned daily to the inlet of the aeration basin the magnitude of exergy destruction across the aeration could potentially increase by approximately a factor of 3.
- As the return liquors are refed into the pre – treatment works for further processing, 70% of the thickener return liquors will be utilised in conjunction with the primary sludge to produce energy in the anaerobic digestion system. It was not possible to

quantify the work potential of this process stream but the electricity produced from this process is utilised within the aeration basin, resulting in minimal exergy destruction across the aeration basin.

- The aeration basin is normally the chief energy consumer within the majority of WWTPs, as is the case with Plants B and C. Plant A employs anaerobic digestion while Plant B and C utilise a combination of anoxic and aerobic zones to treat activated sludge. This anaerobic digestion system produces almost 40% of the electricity requirements for plant. Allied to this, Plant A discharges its final effluent to the sea therefore it has the least stringent discharge limitations. Less energy is therefore required to purify the waste water to the required standards.
- The secondary clarifier has the second highest exergy destruction with 28%; the chemical exergy lost in the destruction of the Mixed Liquor Suspended Solids (MLSS) is the chief source of exergy destruction.
- Khosravi [49] noted similar losses across the secondary clarifier and minimal losses across the aeration basin were also noted.
- To minimise this exergy loss across the secondary clarifier in Plant A, the MLSS should be diverted to the thickening/digesting systems for further processing directly from the aeration basin and then utilised within the anaerobic digestion system to produce energy. A source of exergy loss from the output of the secondary clarifier is the nitrogen in the sludge that could be utilised as fertiliser.

5.3 Plant B & C exergy destruction and exergy loss discussion

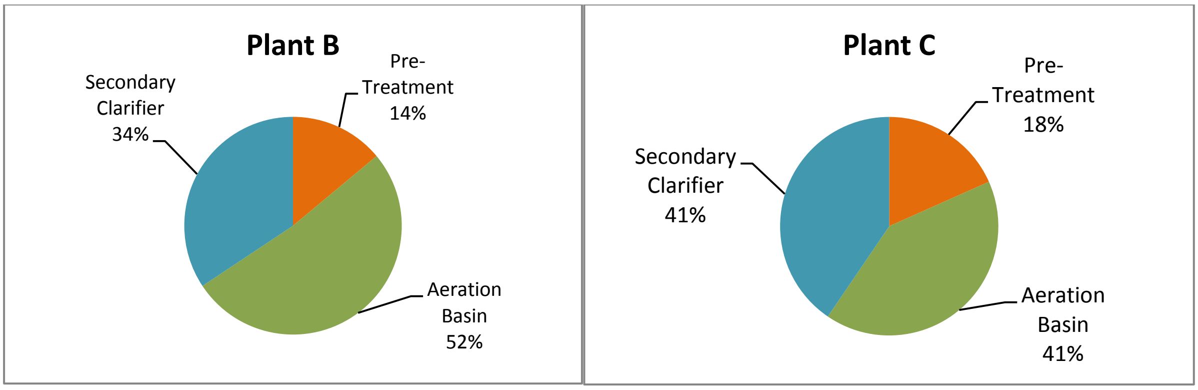


Figure 11: Exergy Destruction breakdown for Plants B & C

- Although significant differences exist in terms of exergy destruction magnitude, Plants B and C are similar regarding the order of their process exergy destruction; the hierarchy of exergy destruction being the aeration basin, the secondary clarifier and the pre-treatment works
- In contrast to Plant A, the pre-treatment works account for only 16% of the exergy destruction across the whole WWTP on average between plants B and C. This is interesting as Plants B and C have a very similar PE and both discharge to inland rivers. A source of exergy loss from the output of the pre-treatment works from both Plants B and C is the pre-treated sewage which may have the correct volatile fatty acid mix to be utilised in an anaerobic digestion system.
- The aeration basin has the highest exergy destruction with 46% on average between Plants B and C. The exergy value of electricity comprises a far greater proportion of total exergy destruction across both Plants B and C than in plant A.
- The exergy value of electricity in Plant B comprises 78% of total exergy destruction across the entire process and 40% of total exergy destruction across the entire plant.

This exergy destruction is unavoidable due to the influent loading in plant B forcing all blowers in the aeration basin to operate during peak hours to meet oxygen requirements within the basin.

- One potential explanation may be due to the primary treatment. The pre-treatment works and primary clarification in Plant A reduces the organic loading substantially prior to the aeration basin thus reducing the subsequent blower work input required.
- This is not the case for Plants A and B, where there is no primary clarification and consequently the aeration basins receive higher organic loads.
- Similar to Plant A the secondary clarifier has the second highest exergy destruction with 37% on average between Plants B and C.
- Therefore, when optimising Plants B and C the aeration basin followed by the secondary clarifier should be the focus of optimisation improvements.
- The waste sludge from this process could be utilised for composting if thermal drying process was implemented in both Plants B and C. Another source of exergy loss from the output of the secondary clarifier is the nutrients in the sludge that could be utilised as fertiliser from both Plants B and C.

6 Conclusions and Recommendations

An exergy analysis of three WWTPs has been completed; the chemical exergy of waste streams such as organic matter, nutrients, disinfectants and electricity has been quantified.

6.1 Conclusions

The conclusions of this research thesis are now presented:

- Exergy analysis is a useful tool to characterise WWTPs. However, in order to conduct an accurate exergy analysis of a WWTP plant information regarding sludge, emissions to air etc. is required. Lack of accurate data is a barrier to accurate exergy analyses.
- Chemical exergy is the chief contributor to the total specific exergy of waste water treatment.
- Organic matter has been identified as the chief contributor to the chemical exergy of waste water treatment.
- The magnitude of exergy destruction (kJ/l) differed significantly for all three analysed plants.
- Influent organic matter loading rates also greatly impact the electrical exergy destruction rates across a waste water treatment plant, if an anaerobic digestion system is not utilised to mitigate electrical energy consumption within the plant.
- The plants of similar scale that were analysed experienced a two-fold difference in exergy destruction across the plants, with the plant with the lower organic loading exhibiting significantly less exergy destruction.

- The pre – treatment works had the lowest exegry destruction across the plants of similar scale that were analysed and the aeration basin had the highest exergy destrcution rate across both analysed plants.
- The exergy destruction rate of the large scale plant was quite large in comparison to the plants of smaller scale. A large proportion of the exergy destruction in the larger scale plant is attributed to the pre – treatment works, this process is quite efficient removing 39% of the organic load. This efficiency comes at a cost, with large exergy destruction therefore associated with this process.

6.2 Research Limitations

- A limitation of the work is the lack of inter - process nutrient data for all analysed plants and the inability to quantify the exergy value of gaseous emissions from the various treatment processes.
- Lack of available return activated sludge data is a limitation of this work.
- Lack of available sludge data concentrations and flow rates is also a limitation of this work.
- Subject to a better suite of data becoming available an additional assessment could be carried out.

6.3 Recommendations for further research

Further work is needed to identify the most relevant/specific waste water chemical exergy model, which is not within the scope of this research project.

Further work could also consider a comprehensive analysis of all identifiable WWTP inputs and outputs. Analysis and quantification of plant inputs such as metals, gases, sulphur, chloride, alkalinity etc. would provide extremely accurate characterisation of a WWTP from an exergy analysis perspective.

Further work could characterise WWTP processes from an economic perspective. For example, exergy destruction across the aeration basin in plant A was insignificant in this research. However, it is widely known the aeration basin is the chief energy consumer in WWTPs, thus this process may require consideration from an economic perspective.

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Appendix

Table 1: Waste water treatment plant characteristics

CHARACTERISTIC	WWTP A	WWTP B	WWTP C
Sampling dates	03 to 07, 10 to 14 17 to 21, 24 to 26 of Nov. (2013)	02/09/2014 to 07/09/2014	07, 08, 09, 14, 15, 16, 19 of October 2015
Number of days	18 days	6 days	7 days
Flow streams sampled	Influent and Effluent	Influent and Effluent	Influent and Effluent
Number of samples per stream per day	As per plant managers schedule	6	6
Time between samples	N/A	4 hours	4 hours
Influent testing location	Influent Stream	Screening	Screening
Influent sampling method	Grab Sample (Automatic Sampler)	24 hour composite	24 hour composite
Effluent testing location	Outfall channel	Leaving Final Clarifier	Leaving Final Clarifier
Effluent sampling method	Grab Sample (Automatic Sampler)	24 hour composite	24 hour composite
Energy data	Yes	Yes	Yes
Data point frequency	Daily totals and process breakdown	30-60 seconds	30-60 seconds
Influent flow data	Yes	Yes	Yes
Frequency and type	Daily Total	Daily Total	Daily Total
Effluent flow data	Yes	Yes	Yes
Frequency	Daily Total	Daily Total	Daily Total