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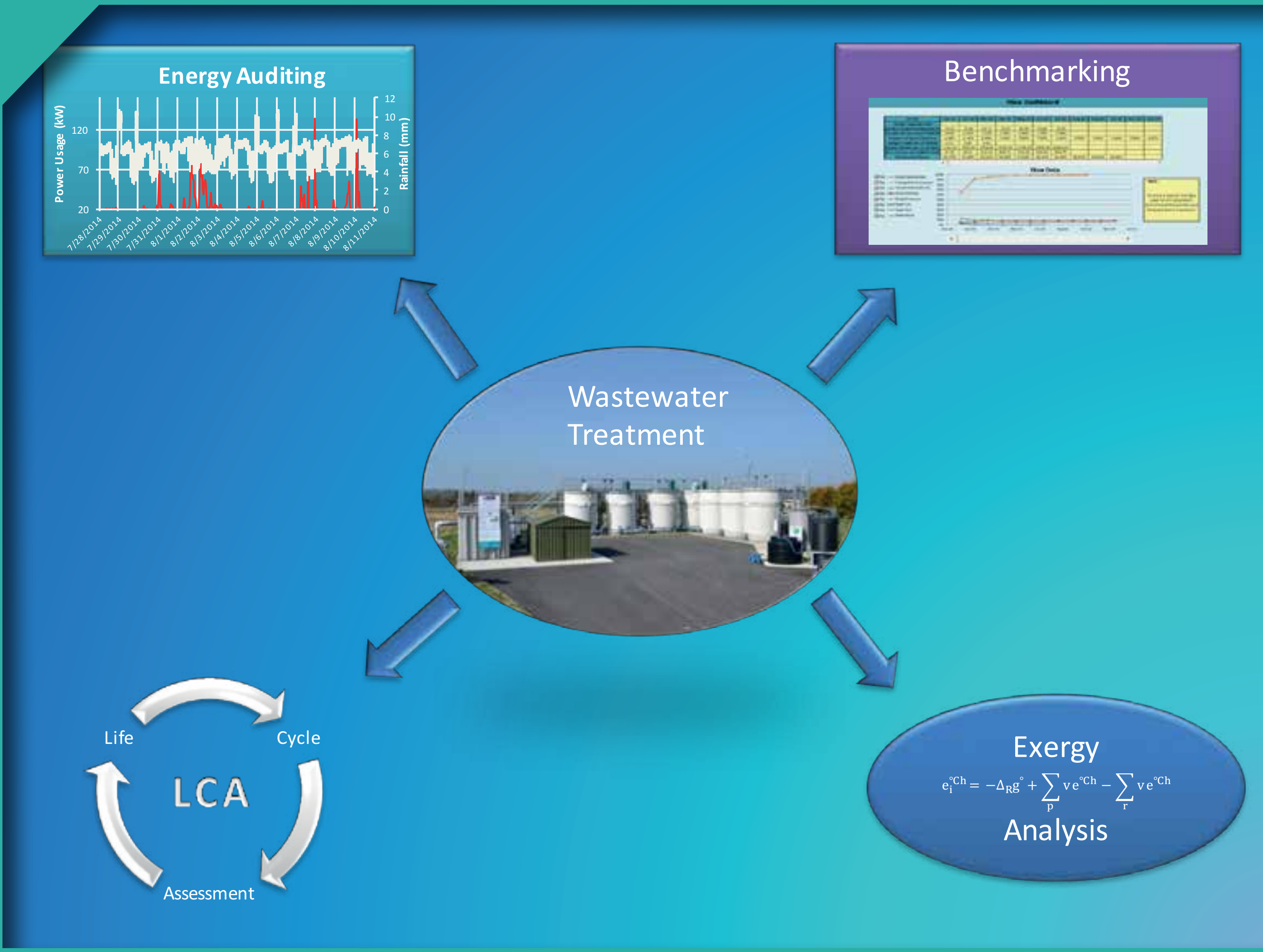
Increasing Resource Efficiency in Wastewater Treatment Plants

Authors: Lorna Fitzsimons, Eoghan Clifford, Greg McNamara, Edelle Doherty, Thomas Phelan, Matthew Horrigan, Yann Delauré and Brian Corcoran



Comhshaol, Pobal agus Rialtas Áitiúil
Environment, Community and Local Government

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EPA Research Programme 2014–2020

Increasing Resource Efficiency in Wastewater Treatment Plants

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EPA Research Report

Prepared for the Environmental Protection Agency

by

School of Mechanical and Manufacturing Engineering, Dublin City University, Dublin

Authors:

Lorna Fitzsimons, Eoghan Clifford, Greg McNamara, Edelle Doherty, Thomas Phelan, Matthew Horrigan, Yann Delauré and Brian Corcoran

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie

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Project Partners

Dr Lorna Fitzsimons
Mechanical and Manufacturing Engineering
Dublin City University, Dublin
Ireland
Tel: +353 1 700 7716
Email: lorna.fitzsimons@dcu.ie

Dr Eoghan Clifford
Civil Engineering
College of Engineering and Informatics
NUI Galway, Galway
Ireland
Tel: +353 9 149 2219
Email: eoghan.clifford@nuigalway.ie

Dr Brian Corcoran
Mechanical and Manufacturing Engineering
Dublin City University, Dublin
Ireland
Tel: +353 1 700 8047
Email: brian.corcoran@dcu.ie

Dr Yann Delauré
Mechanical and Manufacturing Engineering
Dublin City University, Dublin
Ireland
Tel: +353 1 700 8720
Email: yan.delaure@dcu.ie

Greg McNamara
Mechanical and Manufacturing Engineering
Dublin City University, Dublin
Ireland
Tel: +353 1 700 7716
Email: greg.mcnamara5@mail.dcu.ie

Edelle Doherty
Civil Engineering
College of Engineering and Informatics
NUI Galway, Galway
Ireland
Tel: +353 9 149 2219
Email: e.doherty4@nuigalway.ie

Thomas Phelan
Mechanical and Manufacturing Engineering
Dublin City University, Dublin
Ireland
Tel: +353 1 700 7716
Email: thomas.phelan4@mail.dcu.ie

Matthew Horrigan
Mechanical and Manufacturing Engineering
Dublin City University, Dublin
Ireland
Tel: +353 1 700 7716
Email: matthewhorrigan@gmail.com

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Executive Summary

Background

Wastewater treatment is a resource-intensive process that utilises several inputs, such as energy, chemicals and water, to produce an effluent that meets designated environmental standards. Driven by environmental regulations, the focus of wastewater treatment plants (WWTPs) has traditionally been the quality of the effluent and not necessarily the energy or resource efficiency of the plant. Regulations and penalties provide incentives to meet environmental effluent standards; however, to date, there are no such analogous penalties or incentives to expedite a focus on resource efficiency. It is imperative to recognise that resource utilisation and, indeed, sludge management also have significant environmental consequences, and therefore WWTP performance should be viewed holistically. This research sought to address this challenge by adopting a multi-pronged approach to audit and benchmark the resource efficiency of Irish WWTPs, including the use of life-cycle analysis (LCA) and exergy analysis.

Ten representative Irish WWTPs were audited in detail. The plants varied in scale, with regard to their design capacities [which were quantified in terms of units of population equivalent (PE)], from 600 PE to 186,000 PE. Simultaneous energy and resource consumption and water quality audits were undertaken, resulting in the development of benchmarking tools and auditing methodologies, and the detailed performance evaluation of the plants in order to support better resource management and to provide baseline data on the holistic performances of the WWTPs.

This work involved several key considerations: (1) the selection of representative plants; (2) the development of an appropriate auditing methodology; (3) the lack of functioning and appropriate monitoring equipment, particularly flow meters; (4) the access to plant data and water quality samples; (5) the identification of essential data requirements for each of the individual approaches and the subsequent development and implementation of data acquisition strategies; and (6) the determination of metrics that allow a fair comparison across WWTPs despite the many variables, such as scale, influent quality, discharge requirements, technology and nutrient removal requirements, that exist.

Summary of Key Findings and Outcomes

It was found that plant performance varies significantly, both across the range of audited WWTPs and as a result of the chosen metric. In general, economies of scale were evident, with the larger WWTPs consuming less energy per cubic metre of treated wastewater and per unit mass reduction in pollutants. The research shows that the performance of a WWTP is a function of many complex variables, and, therefore, assessing plant performances over a range of metrics provides a fairer comparison and offers better insights into potential optimisation strategies. Specific comparisons between two WWTPs (named plant E and plant F), which are of a similar scale and use similar technologies, demonstrated significant differences in perceived performance. For example, the daily energy consumption for plant E was 1705 kWh/day, whereas it was 1451 kWh/day for plant F. However, when the metric compared was energy consumption per unit mass of pollutant removed, the energy consumption for plant E was 4.68 kWh/kg biochemical oxygen demand (BOD), as opposed to 7.3 kWh/kg BOD for plant F. There was one important mitigating factor over which a plant manager has little control: significant differences in the quality of the influent for these plants.

While it was found that energy monitoring equipment can be expensive and requires calibration and maintenance, detailed energy audits provide accurate baselines for energy management and optimisation. Furthermore, they can highlight and pinpoint specific issues that may otherwise go unnoticed. Importantly, such detailed energy audits revealed several WWTP issues, such as poor power factors, blower control issues (e.g. switching from automatic to manual, which results in increased and unnecessary energy consumption), equipment breakdowns and poor equipment reliability. Addressing these issues can have short payback times and can, in some cases, be relatively simple. Other important issues that became apparent throughout this research were related to flow measurement and the determination of appropriate sampling regimes. For example, some WWTP flow meters were not installed in the correct locations, some were impeded by other upstream and downstream WWTP elements and some were infrequently calibrated.

The LCA studies confirmed the importance of assessing WWTP performance holistically and identified two important considerations that are often overlooked in the assessment of WWTP environmental performance: (1) the energy required to operate WWTPs; and (2) the management of the sludge produced by plants.

A suite of software tools to assist WWTP benchmarking and performance management was developed and tested: Key Performance Indicator Advisor (KPIAdvisor) and Key Performance Indicator Calculator (KPICalc). These tools are easily accessible, highly automated and suitable for implementation in WWTPs with varying treatment processes, PE capacity, staffing numbers and resource consumption. In addition, this toolkit can assist stakeholders with the identification of faults in data acquisition methods, offers users an incentive for improving data acquisition methods and is flexible in terms of the frequency of data acquisition.

Summary of Key Recommendations

This study showed that the performance of WWTPs is a function of many variables, including some that the plant manager has little control over, such as influent concentrations and discharge requirements. Therefore, common, simple benchmarking metrics, such as kWh/m^3 or kWh/PE, are unlikely to allow fair comparisons across plants. Similarly, energy audits or water quality testing alone are not sufficient for comprehensive audits and benchmarking plant performance. Effectiveness and efficiency should not be considered separately, and the ultimate goal should be to operate WWTPs that are both effective and efficient. In general, this is best achieved at the design phase, during which the longer term life-cycle costs and performance of the WWTP can be anticipated and optimised, rather than by solely focusing on the initial capital costs. The key recommendations are as follows:

- assess plant performance using multiple criteria and key performance indicators;
- design for efficiency at the outset;
- specify and provide adequate monitoring, and monitor instrumentation and equipment;
- adopt a holistic approach to the evaluation of environmental performance;
- use energy-efficient equipment;
- introduce and implement preventative maintenance schedules for plant process equipment, and ensure that plant monitoring equipment is calibrated regularly;
- review plant power factors and control strategies regularly;
- identify data requirements prior to managing, benchmarking and optimising WWTP performance.

The publications arising from this research are listed at the end of the report.

1 Introduction

The focus of this project was the resource efficiency of Irish wastewater treatment plants (WWTPs). The perspective of the report is both operational (economic) and environmental. Wastewater treatment is a resource-intensive process, with three main resources being identified as those of greatest concern: energy, chemicals and water. According to the United States Environmental Protection Agency, wastewater treatment accounts for approximately 1% of the world's total energy consumption and 3% of the electrical load in the USA (USEPA, 2010). This current estimation is mirrored in Europe, in which energy consumption is expected to increase significantly as a result of population growth and increasing environmental standards (Olsson, 2012a). These figures should be seen in the context of the highly underdeveloped wastewater infrastructures in many countries and the expected increases in energy consumption resulting from new investments and regulations.

The United Nations and World Health Organization estimate that 32% of the world's population lack improved sanitation facilities (Unicef, 2015), while many countries with wastewater infrastructures require significant investment. Meanwhile, in the USA, increases in WWTP energy consumption of over 20% are expected by 2020 (USEPA, 2010), whereas a second European source predicts "conservative" increases of 60 to 100% over the next 15 years to meet the new EU directives (Olsson, 2012a). Some wastewater treatment companies in the UK have reported increases in electricity usage of 60% since 1990 (Olsson, 2012a). Coupling these trends and predictions with recent energy cost fluctuations means that energy is, and will increasingly be, one of the major operational costs faced by many WWTPs.

Driven by environmental regulations, the focus of WWTPs has traditionally been the quality of the effluent and not necessarily the energy or resource efficiency of the plant. Regulations and penalties incentivise the meeting of environmental effluent standards; however, to date, there are no such analogous penalties or incentives to expedite a focus on resource efficiency. It is important to recognise that resource utilisation also has significant environmental consequences and it is important to view WWTP performance holistically. [Note that, even with the effluent quality penalties/incentives in place, many Irish treatment plants still do not meet minimum EU standards (EPA, 2012); this situation is mirrored across Europe (EC, 2015).]

Operational effectiveness and efficiency should not be thought of in isolation. The ultimate goal should be to operate plants that treat wastewater in accordance with designated standards at an acceptable environmental and economic cost. However, it can often be difficult to measure, assess and compare individual plant performances, particularly when WWTPs vary in scale, use different technologies or technology configurations, treat to achieve different effluent standards and accept influents with differing compositions and concentrations.

1.1 Objectives

The objectives of this project were to assess and quantify the resource efficiency of a number of representative Irish WWTPs, with the aim of providing tools, guidelines and data to support and facilitate plant operators, regulators and other stakeholders in order to improve plant efficiencies. To do this, a number of synergistic approaches and methodologies were used and further developed:

- benchmarking;
- plant auditing (water quality and energy efficiency);
- life-cycle analysis (LCA);
- exergy analysis.

In total, 10 Irish WWTPs were comprehensively audited in terms of energy consumption and water quality. A brief overview of the specific plant characteristics is presented in Table 1.1. The plants differ with regard to their design capacities and the agglomerations served; both of these factors are quantified using population equivalent (PE) units. The PE unit provides a measure of organic biodegradable load. There are two widely used definitions. The Irish Environmental Protection Agency (EPA) defines a population equivalent of 1 (1 PE) as the organic biodegradable load that has a 5-day biochemical oxygen demand (BOD_5) of 60 g of oxygen per day; for this definition, the load is calculated on the basis of the maximum average weekly load entering the wastewater

Table 1.1. WWTP descriptions

Plant	Design capacity (PE)	Agglomeration served (PE)[a]	Receiving water body type	Level of treatment (P), (S), (T)	Type of secondary treatment
A	186,000	79,133	Seawater	P, S	AS
B	25,000	18,659	Freshwater	P, S	AS
C	24,834	22,440	Freshwater	P, S, T	AS + P
D	18,517	25,633	Freshwater	P, S	AS
E	12,000	12,284	Freshwater	P, S	AS + P
F	12,000	9036	Freshwater	P, S	AS + P
G	5000	2500	Freshwater	P, S	AS + P
H	820	590	Freshwater	P, S	AS + P
I	750	422	Freshwater	P, S	PFBR
J	600	1024	Freshwater	P, S	AS + P

[a] Annual Environmental Report data: an agglomeration, as defined in the Waste Water Discharge (Authorisation) Regulations, is an area in which the population or economic activities or both are sufficiently concentrated for a wastewater works to have been put in place.

AS, activated sludge; AS + P, activated sludge with phosphorus removal; P, primary; PFBR, pump flow biofilm reactor; S, secondary; T, tertiary.

works in a year, excluding unusual situations such as those due to heavy rain. The second definition is that 1 PE is equivalent, in terms of volume, to 200 L per day (Henze *et al.*, 2008). For the purposes of this report, the second definition is used, unless stated otherwise. The plants also differ in terms of their effluent discharge locations, the level of treatment (i.e. primary, secondary or tertiary) and their key treatment technologies (i.e. activated sludge, activated sludge with phosphorus removal or pumped flow bioreactor). The plants were selected because they are representative of large-, medium- and small-scale Irish WWTPs.

1.1.1 Benchmarking through the use of key performance indicators

Reliable benchmarking requires standardised and accurate information on WWTP performance (Lindtner *et al.*, 2008). However, it is recognised that a key challenge for the development of key performance indicators (KPIs) for benchmarking is the identification of reliable data sources for KPI variables (Matos and IWA, 2003). Inaccurate data acquisition can significantly impact on the reliability of benchmarking, especially in the case of decentralised WWTPs for which there is often limited data availability (O'Reilly *et al.*, 2014).

This research has developed a benchmarking system that utilises KPIs to aid in the reduction of resource consumption in WWTPs. The benchmarking system comprises two sections, namely Key Performance Indicator Advisor (KPIAdvisor) and Key Performance Indicator Calculator (KPICalc). KPIAdvisor provides a means of surveying WWTPs to (1) account for the level of available data; (2) identify available KPIs by analysing this data; and, more importantly, (3) highlight the confidence involved in the KPI calculation resulting from the accuracy of the data provided. Subsequently, KPICalc calculates, validates and reports KPIs to the user.

1.1.2 Energy audit and process control

Plant management and optimisation require accurate information on current plant performance. This research strand was broken down into two focus areas:

1. plant auditing methodologies;
2. instrumentation, control and automation (ICA).

To assess and develop plant auditing methodologies, a subset of four typical WWTPs were selected from the plants used for this study. These plants were used to perform in-depth energy auditing and analysis. The energy audits focused on areas such as identification of plant energy distribution, the assessment of energy inefficiencies, the assessment of equipment required for energy audits and the determination of appropriate sampling frequencies.

ICA could offer significant improvements to the wastewater treatment industry. ICA systems cover a wide range of areas and this study focused on ICA systems such as plant monitoring and instrumentation systems, "smart" control systems and plant operations, and people management systems. The ICA principles were used to assess the feasibility of incorporating modern control strategies and sophisticated instrumentation into medium to small WWTPs in Ireland. In addition, this study investigated strategies for improving resource efficiency with regard to, for example, equipment management and the creation of an energy efficiency culture among plant staff.

1.1.3 Life-cycle analysis

Life-cycle assessment or LCA is an analytical tool used to quantify the environmental loading associated with the life cycle of a product or system from "cradle to grave", where the "cradle" refers to the acquisition of raw materials from the natural environment or ecosphere, and the "grave" is the disposal or end-of-life stage of a product or system (Figure 1.1).

Between cradle and grave, resource use and emissions data from each stage of the life cycle are gathered and compiled in a life-cycle inventory (LCI). Once complete, the data are classified and characterised to identify which areas of the environment are being impacted upon, and by how much. The strength of LCA as an analytical tool lies in its ability to determine which components within a system have significant environmental loadings associated with their inputs and outputs, loadings that may not have been predicted or detected with other assessment tools. In relation to wastewater treatment, the information that LCA provides allows plant operators to make more informed decisions with regard to implementing system changes, and has been the analytical tool of choice for a large body of work in this particular field.

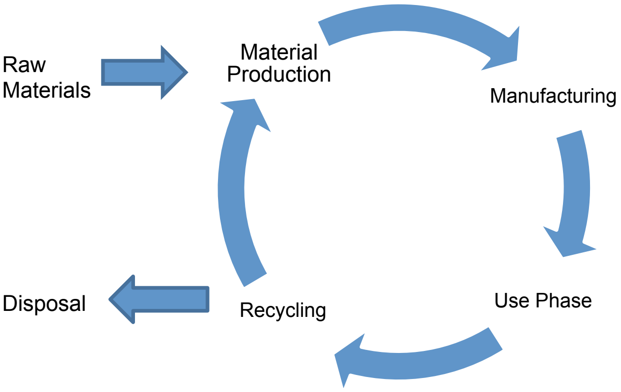

Figure 1.1. Stages of the life cycle of a product or service.

1.1.4 Exergy analysis

Exergy is a thermodynamic property that combines the first and second laws of thermodynamics. A system can do work as a result of the potential difference in the thermodynamic state that exists between the system and its environment (or dead state). This potential difference may exist because of differences in, inter alia, temperature, pressure or chemical composition. Exergy analysis is an analytical method that has been widely used to assess and quantify the thermodynamic performance of energy and water systems, such as thermal power plants and desalination plants. Methodologies for the assessment of WWTPs have been developed previously by several researchers (Tai *et al.*, 1986; Hellström, 1997; Khosravi *et al.*, 2013) and have been used to estimate the consumption of physical resources in a WWTP in Sweden (Hellström, 1997) and to assess the thermodynamic efficiency of a WWTP in Iran (Khosravi *et al.*, 2013). To the knowledge of the authors of this report, there have been no reported Irish WWTP studies to date.

With regard to WWTPs, exergy analysis can be used to assess the work potential of the various plant flows, including those that may be perceived as waste streams, and to account for the loss in potential difference that occurs in plant processes (i.e. exergy destruction). Exergy analysis involves conducting an exergy balance across plant processes, which allows the exergy destruction in each process to be quantified and, in turn, allows energy efficiency efforts to be focused. 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 work and to inform design decisions with regard to optimisation of WWTPs. Two WWTP exergy analyses were undertaken in this project using the correlations originally developed by Tai *et al.* (1986) and the exergy analysis approach further developed by Hellström (Hellström, 1997).

1.2 Project Outputs

The key outputs of this project include tools, guidelines, plant performance datasets and analyses that can support policymakers, regulators, plant operators and researchers to improve the efficiency of existing WWTPs and to design new treatment plants with resource efficiency in mind. Specifically, these outputs include:

- KPI software tools;
- the development of WWTP audit methodology;
- life-cycle models and analyses of representative Irish WWTPs;
- exergy analyses of representative Irish WWTPs.

1.3 Report Structure

The report is broken down into a number of chapters and sections. Chapter 2 presents an overview of the literature for the various approaches. Chapter 3 details the materials and methods used throughout the project. Chapter 4 presents and discusses the results of the WWTP audits. Finally, the project conclusions and recommendations are presented in Chapter 5 and Chapter 6, respectively.

2 Literature Summary

2.1 Benchmarking Wastewater Treatment Plants

Benchmarking is a tool that can be applied to achieve performance improvements by systematically defining one's own performance and comparing it against leading practices (Cabrera *et al*., 2010). Numerous benchmarking systems have been developed for WWTPs, including the International Water Association's wastewater KPI application (Matos and IWA, 2003) and the International Benchmarking Network for Water and Sanitation Utilities' benchmarking tool (van den Berg and Danilenko, 2011). Both of these systems include a broad spectrum of KPIs for wastewater treatment (including staffing numbers, number of sick days per year, etc.) in order to give a complete view of a WWTP in terms of its performance.

2.1.1 Problems associated with benchmarking systems

A number of key challenges have been identified that can affect both the usability and validity of a benchmarking system:

- Broad, all-inclusive boundaries in terms of KPI development can act as a hindrance as they can impede the usability of the benchmarking system. Implementing expansive lists of KPIs as part of a benchmarking scheme can initially appear justified in order to adequately encapsulate a WWTP's performance. However, previous literature suggests that, if possible, KPIs should be kept to a minimum to ensure a focused approach to benchmarking and also to prevent users from becoming inundated with KPI data requirements (Peterson, 2006; Parmenter, 2015).
- Permitting the user to manually select the KPIs that can be incorporated into a benchmarking system in an undefined manner can reduce the relevance of the benchmarking system. If a WWTP manager aims to assess their own plant's performance irrespective of other WWTPs, enabling the manager to select their own KPIs may be acceptable because such a study is independent from a benchmarking system. However, common KPI selection across WWTPs, if relevant, is still desirable, particularly if the objective is to benchmark WWTPs against one another. KPIs should thus be selected using a well-defined and researched framework.
- Data availability and data accuracy can restrict the success of benchmarking, often in a substantial but undetected manner. The lack of data management can often be the key limiting factor for benchmarking WWTPs (Beltrán *et al*., 2012; O'Reilly *et al*., 2014); this is especially the case for both decentralised and small-scale (< 500 PE) WWTPs (O'Reilly *et al*., 2014). As a consequence of poor data management, the feasibility of a KPI/benchmarking system must be assessed prior to investing time and money in WWTP benchmarking.

2.2 Energy Audit and Process Control

In recent years, many industry sectors have started to focus on energy efficiency. According to Olsson (2008), the wastewater treatment industry has been quite slow to react to this global movement and lags behind many other sectors, such as chemical and paper production industries, which have demonstrated significant energy savings with short investment payback times. This lag is manifest in the relatively small number of publications available in the area of WWTP energy auditing. ENERGY STAR was established by the United States Environmental Protection Agency (USEPA) and has produced detailed energy audit guides for over 16 different industry sectors, including the cement manufacturing, dairy processing and pharmaceutical industries (ENERGY STAR, 2014). These guides assist companies with the analysis of energy use patterns, the identification of energy efficiency potentials, the preparation and implementation of energy saving action plans and the education of employees on best practices for energy efficiency (Neelis, 2008; Hasanbeigi and Price, 2010). Currently, there is a drive by ENERGY STAR to bridge the gap between the wastewater treatment industry and other sectors. They have recently published numerous fact sheets and energy recovery guidelines for WWTPs. However, a full sector-specific guide has not yet been produced by ENERGY STAR.

Many of the recent publications that document energy auditing in WWTPs have attempted to adapt philosophies from other industries (Daw *et al*., 2012). The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) documents three key levels of energy audits for its industry (Deru and Kelsey, 2011):

- Level 1: walkthrough assessment;
- Level 2: energy survey and analysis;
- Level 3: detailed analysis and modelling.

ASHRAE Level 1 audits generally involve a walkthrough assessment of the plant, interviews with building operating staff, analysis of utility bills and the analysis of available plant data. Level 1 audits should outline any outstanding energy efficiency issues. Level 2 audits should start with the findings from the Level 1 report and proceed to an in-depth energy survey and analysis of seasonal variations. In the heating, ventilation and air conditioning industry, this would also include an analysis of lighting, air quality, temperature, ventilation, humidity and other conditions that could affect energy performance and occupant comfort (Deru and Kelsey, 2011). Finally, ASHAE Level 3 audits, the highest audit level, can include continued long-term energy monitoring, as well as plant-wide digital simulation.

Fenu *et al*. (2010) performed a study on the municipal WWTP in Schilde, Belgium. In the report by Fenu *et al*. (2010), the authors only briefly outlined a procedure for Level 3 energy auditing; the authors do, however, document the parallel water quality analysis performed. This is an interesting area of the study as water analysis, coupled with an analysis of plant energy usage, can offer key information about how efficiently a plant is operating. The wastewater treatment industry differs from many others in that auditing is not as simple as looking at energy usage and distribution. One of the difficulties associated with auditing WWTPs is that there are environmental considerations, such as strict discharge limits on water quality. For this reason, an energy audit alone is not sufficient to reveal what is happening in a WWTP; thus, environmental auditing has been prevalent in recent years (Evans *et al*., 2011; Khanna and Widyawati, 2011).

The implementation of ICA in wastewater treatment has grown continuously over the past 40 years (Briggs and Grattan 1990; Olsson, 2012b). As a result of the continued development of ICA in the wastewater industry, WWTPs can potentially realise significant energy savings in the future. The findings of a recent Automation Research Corporation (ARC) Advisory Group study (Deru and Kelsey, 2011; ARC Advisory Group, 2015) suggest that the market for automation and instrumentation in the wastewater treatment industry is rapidly growing. This study (ARC Advisory Group, 2015) predicts that the wastewater sector will provide one of the greatest opportunities for the automation industry over the next 20 years. Similarly, Olsson *et al*. (2014) commented that “improvements [in the wastewater treatment industry] due to ICA may reach another 20–50% of the system investments within the next 10–20 years”.

Historically, dissolved oxygen (DO) control has been the most widely used process-control method. Thunberg *et al*. (2009) presented a full-scale example of a zone-specific DO control system in an aerated bioreactor. This study used two DO sensors, placed at either end of the aeration tank. Total airflow to the tank was controlled by the first DO sensor, while the second sensor determined the slope of air distribution across the tanks zones. This control strategy reduced the air requirement by 26%. Similar multi-zone based airflow control strategies were investigated by Sahlmann *et al*. (2004); these authors were successful in reducing air requirements by 15%.

Ammonium-based cascade control (feedforward feedback) using DO set-points has been employed in a number of WWTPs (Thunberg *et al*., 2009; Ingildsen, 2002). This is a system in which a controller varies the airflow rates to the biological reactor based on the DO sensor readings. The controller adjusts the airflow in order to maintain a specific DO set-point, which can be changed based on the ammonium concentrations in the effluent. In full-scale studies, Husmann *et al*. (1998) used this type of control system to achieve a reported aeration energy reduction of 16%, and an overall reduction in effluent ammonia and nitrate concentrations. Similarly, Yong *et al*. (2006) used ammonia and DO control to reduce airflow rates by 10% in a pilot plant test. More sophisticated feedforward controllers were implemented by Thornton *et al*. (2010) in a full-scale WWTP in the UK, in which the feedforward controller used the Activated Sludge Model 1 to provide the controller with modelled information regarding ammonium levels, suspended solids, chemical oxygen demand

(COD), flow rates and water temperature. Thornton *et al*. (2010) documented plant airflow rates that were 20% less than those achieved with fixed DO set-point control.

There are large numbers of additional publications based on advanced control techniques, such as fuzzy logic control, genetic algorithms, dynamic matrix control and other hybrid controllers (Tong *et al*., 1980; Rauch and Harremoes, 1999; Cho *et al*., 2004; Gernaey *et al*., 2004; Zeybek and Alpbaz, 2005; Yang *et al*., 2013). These controllers are still very much in the development phase and have been shown to contribute significant positive attributes to full-scale WWTPs. However, according to Åmand *et al*. (2013), there have been no reported cases (at least prior to 2013) of advanced controllers that can outperform conventional feedback/feedforward controllers in full-scale or pilot study applications.

2.3 Exergy Analysis

Initial work by Tai *et al*. (1986) to assess the chemical exergy values of organic matter in wastewater has related the chemical exergy of organic matter to wastewater indices, namely total oxygen demand (TOD) and total organic carbon (TOC), using Equations (2.1) and (2.2) below, where b_{ch} is the chemical exergy of the wastewater stream.

$$b_{ch}(\text{J/L}) = 13.6\ (\text{kJ/g}) \times \text{TOD (mg/L)} \qquad (2.1)$$

$$b_{ch}(\text{J/L}) = 45\ (\text{kJ/g})\ ) \times \text{TOC (mg/L)} \qquad (2.2)$$

This was achieved by developing correlations between the calculated chemical exergy of 138 short-chain organic compounds, consisting of carbon, hydrogen and oxygen, and TOD and TOC. Tai *et al*. (1986) stated that the organic matter parameters biochemical oxygen demand (BOD) and COD could also be used as approximate measures of effective energy, because TOD indirectly represents the magnitude of utilisable energy from wastewater. A clear link exists between theoretical TOD and measured COD (Tai *et al*., 1986; Roberts Alley, 2007). However, no clear link has been established between BOD and theoretical TOD. Hellström (1997) proposed the use of BOD in place of theoretical TOD, because BOD_7 was a better representation of the “amount of easily biodegradable organic matter”. Because of the lack of a clear link between BOD and theoretical TOD, however, COD (dichromate) is used to estimate the chemical exergy of organic matter in wastewater in this research. The chemical exergy of sludge, return liquors and mixed liquor suspended solids in this research is calculated using Equation 2.3 below (Tai *et al*., 1986).

$$b_{ch}\ (\text{J/L}) = 13.6\ (\text{kJ/g}) \times \text{COD (mg/L)} \qquad (2.3)$$

Khosravi *et al*. (2013) extended the correlation analyses of Tai *et al*. (1986) to include long-chain compounds, including nitrogen, which the authors stated were more typical of urban and industrial wastewater compounds. Their analysis resulted in the correlation represented by Equation 2.4.

$$b_{ch}\ (\text{J/L}) = 13.7\ (\text{kJ/g}) \times \text{TOD (mg/L)} - 116 \qquad (2.4)$$

Based on a comparison carried out between the two approaches to calculate the chemical exergy of organic matter, little difference exists with regard to the concentrations under consideration in this project; therefore, the correlation developed by Tai *et al*. (1986) was used in the current study.

2.4 Life-Cycle Assessment

The application of LCA to wastewater treatment began in the mid-1990s (Emmerson *et al*., 1995) and, since then, more than 40 studies on this approach have been published in peer reviewed journals (Corominas *et al*., 2013). The growth of this area of research appears to have coincided with the implementation of the Urban Wastewater Treatment Directive (UWWTD) (EC, 1991), which presented authorities with the task of improving aspects of their wastewater treatment systems (Gallego *et al*., 2008). LCA is regarded by many as an ideal tool for the assessment of the environmental performance of WWTPs. The individual objectives of studies vary but, in general, they aim to assess the environmental trade-off between competing technologies, processes or system configurations (Vidal *et al*. 2002; Kalbar *et al*., 2013).

Much of the research focuses on biological (i.e. secondary) treatment, as this is the most energy-intensive stage of the treatment process – this stage uses almost 70% of the total energy used in some cases (Gallego *et al*., 2008; Pasqualino *et al*., 2009). This section focuses on studies involving the conventional activated-sludge process, as these studies are by far the most common in Ireland and, indeed, internationally.

Several studies have determined that the construction phase of the life cycle of a WWTP makes a negligible contribution (i.e. <1%) to the total environmental loading (Kalbar *et al.*, 2013) and that the most significant impacts are made during the operation phase. However, Lundin *et al*. (2004) stated that this is dependent on plant size, and that the construction phase of relatively small plants (<900 PE) may have a more significant impact and should be included.

The primary purpose of a WWTP is to improve the quality of the final effluent; however, recently the push for ecological sustainability has seen a paradigm shift towards also reducing resource, energy and water use (Corominas *et al*., 2013). Emmerson *et al*. (1995) were one of the first groups to recognise the significant contribution that electricity production has on the overall environmental loading of a WWTP. This was disputed by others who claimed that energy generation had a minimal impact and that improvement of a system should be focused on reducing the impact of effluent pollution and sludge discharge (Roeleveld *et al*., 1997). Since then, however, it has been widely accepted that energy generation is one of the main sources of environmental loading, from both a resource-depletion and an emissions perspective (Gallego *et al*., 2008; Pasqualino *et al*., 2009), and it has been identified as one of the major sustainable development indicators for wastewater treatment systems (Palme *et al*., 2005).

A further outcome of the UWWTD was an almost 50% increase in annual sludge production in the EU-15[1] Member States between 1992 and 2006 (Kelessidis and Stasinakis, 2012). The issue of sludge management has been addressed by a number of researchers, as both an element within WWTP LCA and as a standalone assessment of different management and disposal options. The sludge handling alternatives reported in the literature vary. It is generally accepted that the direct application of sludge to farmland is one of the least favourable options from an environmental perspective (Lundin *et al*., 2004), and future legislation may prohibit the practice completely (Pasqualino *et al*., 2009). Indeed, in some European countries, such as Switzerland and the Netherlands, a ban on the use of sludge in agriculture has already been implemented (Fahrni, 2011), and it is currently under review in Sweden. However, it should be made clear that the direct application of sewage sludge to farmland and the application of biosolids are two different things; biosolid processing and classification are subject to strict controls and quality standards. Landfilling is also not recommended for several reasons (Houillon and Jolliet, 2005). Currently, the leading alternatives are incineration, anaerobic digestion (AD) and composting. AD offers the benefit of energy reclamation through the production of biogas, and reduces transport emissions and the need for lime stabilisation (Suh and Rousseaux, 2002; Hospido *et al*., 2008). However, there is a general agreement that there is no “one-size-fits-all” solution and that sludge disposal should be dealt with on a case-by-case basis (Pasqualino *et al*., 2009; Corominas *et al*., 2013).

The main point to be taken from previous LCA studies is that there is a trade-off between impact categories. The cost of lowering eutrophication and toxicity potentials leads to an increase in several other impact categories as a result of the energy and chemicals required. Sludge management alternatives also have their unique set of environmental loadings and must be considered independently in order to reach an optimal environmental balance.

It is evident that the efficiency and environmental performance of WWTPs has been considered from multiple individual research perspectives in the literature; however, a multi-pronged, holistic approach has not yet been applied to Irish WWTPs and this research seeks to bridge that gap.

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[1] Austria, Belgium, Denmark, Finland, France, Greece, Germany, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden and the United Kingdom.

3 Materials and Methods

3.1 Wastewater Treatment Plant Selection

In order to provide useful audit data to stakeholders and to effectively test the benchmarking system, a number of representative Irish WWTPs were selected for this research. One primary objective was to incorporate the various combinations of treatment processes utilised by WWTPs in Ireland. The characteristics of the selected WWTPs are detailed in Table A1 of the appendix.

3.2 Wastewater Treatment Plant Testing

Selected WWTPs underwent intensive water quality 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 for which each portion of the sample was collected at 4-hour intervals (flow proportional samples could not be taken). Energy data and power quality data were gathered at intensive frequencies. Daily flow data were collected from the corresponding WWTPs' supervisory control and data acquisition (SCADA) systems or daily logs. These testing methods are detailed further in Table A2 of the appendix.

One crucial issue that should be highlighted is that some of the WWTPs lacked certain pieces of monitoring equipment. For example, some WWTPs lacked basic flow meters and few WWTPs had energy monitoring equipment. Monitoring, management and plant optimisation depend on reliable data, which cannot be obtained without the prerequisite equipment and instrumentation.

3.2.1 Testing

The concentrations of ammonium nitrogen (NH_4-N), total oxidised nitrogen (TON), nitrite nitrogen (NO_2-N) and phosphate phosphorus (PO_4-P) were determined using a Thermo Clinical Labsystems Konelab 20 Nutrient Analyser (Fisher Scientific, Waltham, MA, USA). Suspended solids were measured in accordance with standard methods (APHA *et al*., 2005). Total nitrogen (TN), total phosphorus (TP), TOC and total inorganic carbon were analysed using a BioTector TOC TN TP Analyser (BioTector Analytical Systems Limited, Cork, Ireland) in accordance with standard methods (APHA *et al*., 2005). BOD_5 and COD were measured in accordance with standard methods (APHA *et al*., 2005).

3.3 Resource Benchmarking Tool Development

3.3.1 Description of the benchmarking system

The resource (chemical, energy and water consumption) benchmarking system was developed to address the challenges documented in section 2.1 of this report. The resource benchmarking system can be broken down into two components: (1) a preliminary WWTP survey toolkit (KPIAdvisor); and (2) a KPI calculation, analysis and reporting toolkit (KPICalc).

The development of KPIAdvisor was informed by a literature review and the outcomes of stakeholder meetings, both of which strongly identified the need for a tool which could distinguish, in a consistent manner, between (1) KPIs that could be measured in a standardised manner, for any particular WWTP, and (2) KPIs that could not be calculated because of the accuracy and frequency of the available data at any given site.

KPICalc employs up to 44 KPIs that capture the WWTPs performance in terms of discharged effluent quality, and chemical, energy and water consumption, along with the associated costs. These KPIs have been split into five separate categories: (1) wastewater/sludge volume and water consumption data; (2) regulatory compliance; (3) contaminant removal rates; (4) chemical consumption; and (5) energy usage for both the treatment plant and the pump house. A schematic of the resource benchmarking system is shown in Figure 3.1.

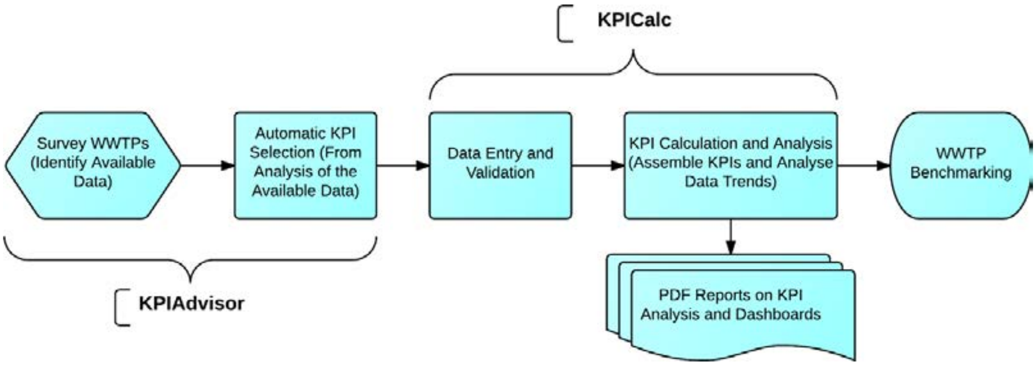


Figure 3.1. Basic overview of the benchmarking and KPI system.

3.3.2 Overview of Key Performance Indicator Advisor

The key goals of KPIAdvisor are outlined in Figure 3.2.

Initially, the end-user (e.g. an engineer, a facility manager, etc.) completes a short Excel-based survey as part of KPIAdvisor. This survey asks users to identify data that are readily available for KPI analysis and also requests that users rate the self-defined accuracy of the data on a provided scale. The survey can be completed in minutes with the use of simple user inputs. Some of the key details required include information on:

- the PE capacity of the WWTP;
- the flow data availability;
- the various treatment processes used on-site from a predefined list, with the option to add additional information if desired;
- the enforced regulatory discharge licence requirements for effluent contaminant concentrations;
- the chemicals used as part of the wastewater treatment process and their unit costs;
- the energy consumption monitoring that actively takes place on-site.

Once the survey is complete, KPIAdvisor then informs the end-user of KPIs that could be accurately utilised in the subsequent KPICalc benchmarking system and informs the user about on-site data gathering processes that require attention, as a result of data inaccuracies, before being utilised in the benchmarking system (Figure 3.3). KPIAdvisor overcomes the challenge of safeguarding the performance of a benchmarking system across numerous WWTPs through the implementation of a rigid and unaltered framework for the automated selection of KPIs in each WWTP.

3.3.3 Overview of Key Performance Indicator Calculator

KPICalc is designed to calculate and report KPIs in an autonomous manner; the toolkit architecture encompasses various processing and data analysis stages, along with detailed reporting elements. The reporting dashboard is a reporting method that displays the most relevant data (Figure 3.4).

The reporting dashboard is part of a series of dynamic dashboards, each presenting the results from one KPI group (e.g. compliance or energy use per mass unit BOD_5 removed). Users can toggle on/off the series plotted in the KPI result chart and can also identify the data from which each series point was calculated by hovering the mouse pointer over the point in question, prompting the note box to the right of the chart to display the associated data and dates.

KPICalc allows deeper data analysis and can rank KPIs in terms of a WWTP's effectiveness and its performance trends; an example of this ranking system is shown in Figure 3.5. Each KPI result is compared against a result

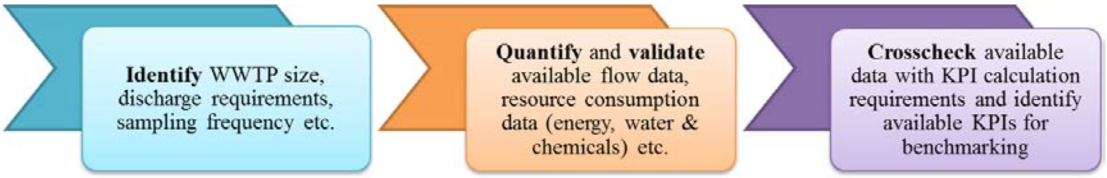
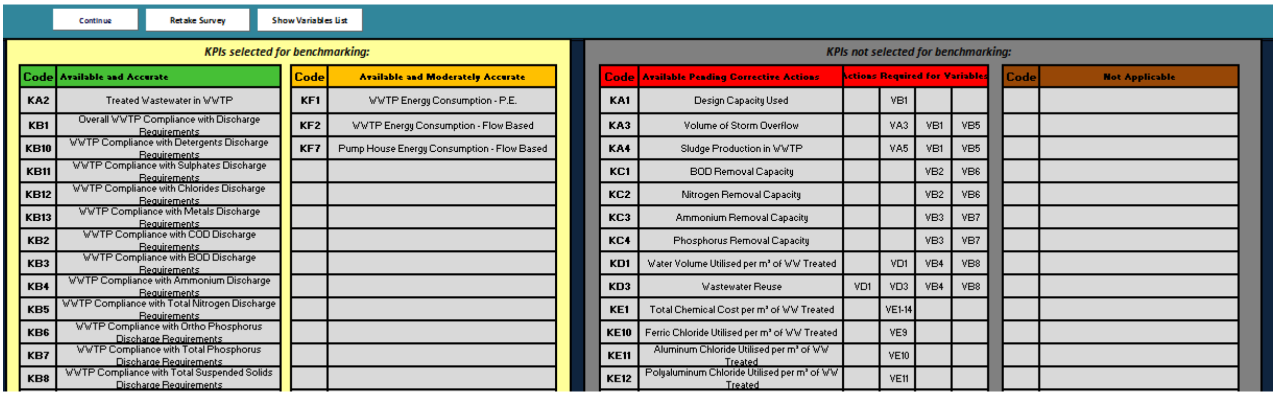


Figure 3.2. Key goals of the WWTP survey tool KPIAdvisor.



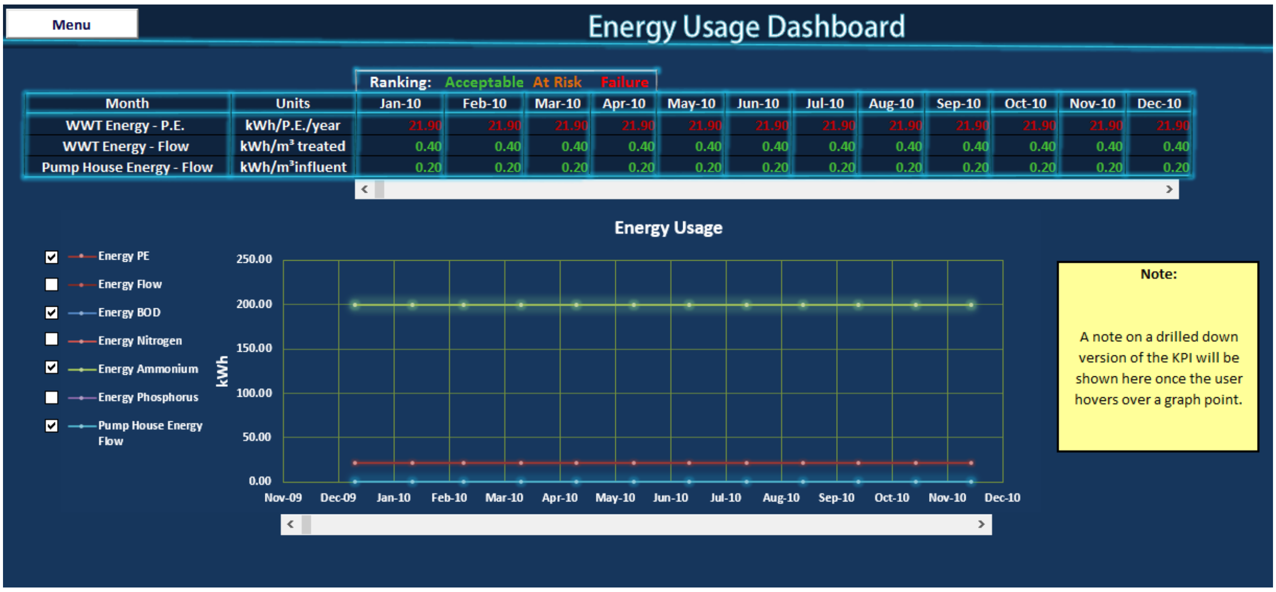
KPIs selected for benchmarking:

Code	Available and Accurate	Code	Available and Moderately Accurate
KA2	Treated Wastewater in WWTP	KF1	WWTP Energy Consumption - P.E.
KB1	Overall WWTP Compliance with Discharge Requirements	KF2	WWTP Energy Consumption - Flow Based
KB10	WWTP Compliance with Detergents Discharge Requirements	KF7	Pump House Energy Consumption - Flow Based
KB11	WWTP Compliance with Sulphates Discharge Requirements		
KB12	WWTP Compliance with Chlorides Discharge Requirements		
KB13	WWTP Compliance with Metals Discharge Requirements		
KB2	WWTP Compliance with COD Discharge Requirements		
KB3	WWTP Compliance with BOD Discharge Requirements		
KB4	WWTP Compliance with Ammonium Discharge Requirements		
KB5	WWTP Compliance with Total Nitrogen Discharge Requirements		
KB6	WWTP Compliance with Ortho Phosphorus Discharge Requirements		
KB7	WWTP Compliance with Total Phosphorus Discharge Requirements		
KB8	WWTP Compliance with Total Suspended Solids Discharge Requirements		

KPIs not selected for benchmarking:

Code	Available Pending Corrective Actions	ctions Required for Variables				Code	Not Applicable
KA1	Design Capacity Used		VB1				
KA3	Volume of Storm Overflow		VA3	VB1	VB5		
KA4	Sludge Production in WWTP		VA5	VB1	VB5		
KC1	BOD Removal Capacity			VB2	VB6		
KC2	Nitrogen Removal Capacity			VB2	VB6		
KC3	Ammonium Removal Capacity			VB3	VB7		
KC4	Phosphorus Removal Capacity			VB3	VB7		
KD1	Water Volume Utilised per m³ of WW Treated		VD1	VB4	VB8		
KD3	Wastewater Reuse	VD1	VD3	VB4	VB8		
KE1	Total Chemical Cost per m³ of WW Treated		VE1-14				
KE10	Ferric Chloride Utilised per m³ of WW Treated		VE9				
KE11	Aluminum Chloride Utilised per m³ of WW Treated		VE10				
KE12	Polyaluminum Chloride Utilised per m³ of WW Treated		VE11				

Figure 3.3. Outputs of KPIAdvisor (screenshot from a typical survey taken by an end-user).

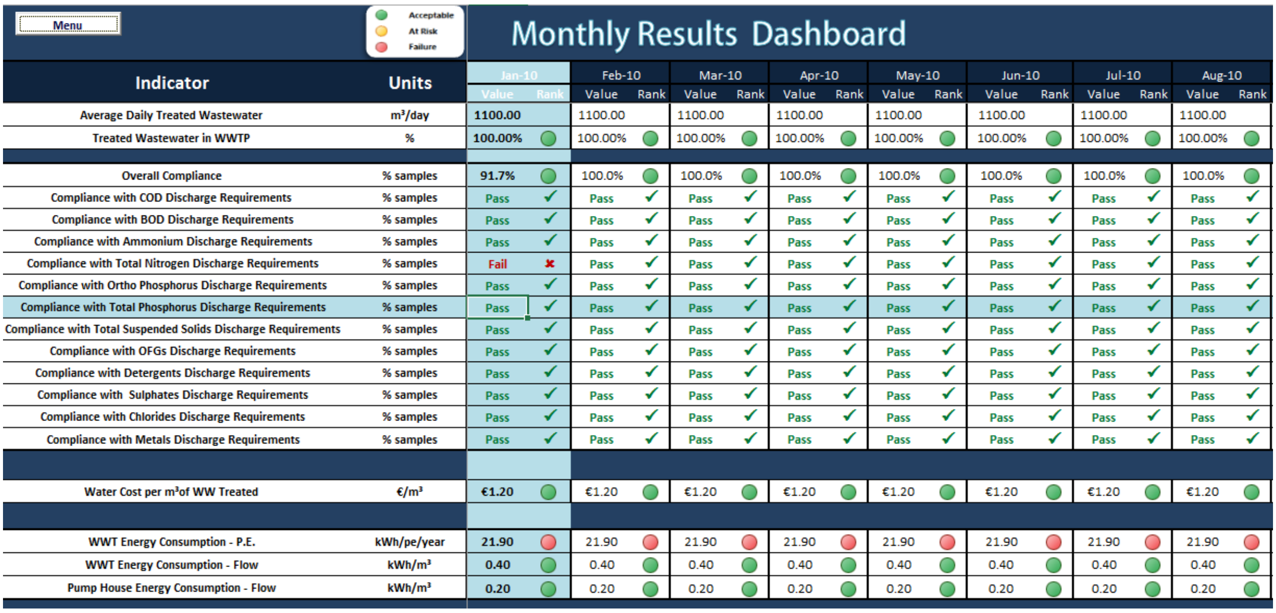


Ranking: Acceptable At Risk Failure

Month	Units	Jan-10	Feb-10	Mar-10	Apr-10	May-10	Jun-10	Jul-10	Aug-10	Sep-10	Oct-10	Nov-10	Dec-10
WWT Energy - P.E.	kWh/P.E./year	21.90	21.90	21.90	21.90	21.90	21.90	21.90	21.90	21.90	21.90	21.90	21.90
WWT Energy - Flow	kWh/m³ treated	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Pump House Energy - Flow	kWh/m³influent	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20

A note on a drilled down version of the KPI will be shown here once the user hovers over a graph point.

Figure 3.4. Screenshot of a reporting dashboard populated with sample data.



🟢 Acceptable
🟡 At Risk
🔴 Failure

Indicator	Units	Jan-10		Feb-10		Mar-10		Apr-10		May-10		Jun-10		Jul-10		Aug-10	
		Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
Average Daily Treated Wastewater	m³/day	1100.00		1100.00		1100.00		1100.00		1100.00		1100.00		1100.00		1100.00	
Treated Wastewater in WWTP	%	100.00%	🟢	100.00%	🟢	100.00%	🟢	100.00%	🟢	100.00%	🟢	100.00%	🟢	100.00%	🟢	100.00%	🟢
Overall Compliance	% samples	91.7%	🟢	100.0%	🟢	100.0%	🟢	100.0%	🟢	100.0%	🟢	100.0%	🟢	100.0%	🟢	100.0%	🟢
Compliance with COD Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with BOD Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with Ammonium Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with Total Nitrogen Discharge Requirements	% samples	Fail	✗	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with Ortho Phosphorus Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with Total Phosphorus Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with Total Suspended Solids Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with OFGs Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with Detergents Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with Sulphates Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with Chlorides Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Compliance with Metals Discharge Requirements	% samples	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓	Pass	✓
Water Cost per m³of WW Treated	€/m³	€1.20	🟢	€1.20	🟢	€1.20	🟢	€1.20	🟢	€1.20	🟢	€1.20	🟢	€1.20	🟢	€1.20	🟢
WWT Energy Consumption - P.E.	kWh/pe/year	21.90	🔴	21.90	🔴	21.90	🔴	21.90	🔴	21.90	🔴	21.90	🔴	21.90	🔴	21.90	🔴
WWT Energy Consumption - Flow	kWh/m³	0.40	🟢	0.40	🟢	0.40	🟢	0.40	🟢	0.40	🟢	0.40	🟢	0.40	🟢	0.40	🟢
Pump House Energy Consumption - Flow	kWh/m³	0.20	🟢	0.20	🟢	0.20	🟢	0.20	🟢	0.20	🟢	0.20	🟢	0.20	🟢	0.20	🟢

Figure 3.5. Screenshot of a reporting dashboard populated with sample data.

ranking, which details the ranges within which the KPI result can be deemed “acceptable”, “at risk” or “failed”, as shown by green, yellow or red markers, respectively. This feature allows users to quickly and easily assess the performance of the WWTP in question.

3.3.4 Process architecture of the benchmarking system (KPIAdvisor and KPICalc)

The architecture of the benchmarking system is shown in Figure 3.6, which also highlights the processes of KPIAdvisor and KPICalc separately. A unique and critical element of this benchmarking system is the initial user survey (KPIAdvisor) that enables stakeholders to easily (1) assess the current level and accuracy of data collection undertaken at a WWTP; (2) decide whether or not opting into a benchmarking system would be feasible, based on the level of data collection on-site; and (3) identify data sources that may require corrective action before the adoption of a benchmarking system.

KPIAdvisor automatically informs the construction and customisation of a KPI calculation and reporting tool (KPICalc), in order to ensure its applicability to a wide variety of WWTPs. This feature ensures that KPICalc users have standardised and relevant outputs, and it streamlines data entry, thus increasing the toolkit’s usability.

KPICalc provides users with two distinct sets of reports for viewing KPI results: (1) a month-to-month comparison report that allows users to select any two months for result comparison; and (2) a series of reports that show users the results for each KPI group in a separate report, accompanied by adjustable graphs, charts and tables.

3.4 Energy Monitoring

Many power/energy monitors can cater for a large range and quantity of variables. Conversely, many are not 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 3.1 shows the variables that were monitored in this study. The first column lists the basic criteria, and, if possible, these variables were recorded. The additional variables allow a more detailed diagnosis of plant machinery or power characteristics.

Table 3.1. List of electrical variables recorded in this study, including basic variables and additional desirable variables

Basic variables
Voltage
Current
Active power
Apparent power
Reactive power
Power factor
Phase angle
Harmonic distortion
Neutral current
Additional variables
Current harmonic distortions
Voltage harmonic distortions
Frequency
Unbalance
Dips and swells
Energy losses

Detailed diagnoses were performed using the Fluke 435 series II power quality analyser (PQA) (Fluke, Norwich, UK), which is a high-specification energy analyser. The PQA was supplemented with three Amprobe PQ 55A energy analysers. These devices are of mid-range cost and specification, and are capable of recording all basic variables. Finally, smaller plant equipment was metered using eight Iso-Tech IPM2005 meters. Although these meters are capable of monitoring all basic variables, this cannot be done simultaneously. Table 3.2 outlines the basic specifications of each metering device in more detail.

The determination of appropriate sampling frequencies was an important consideration that was assessed and developed throughout this study. Sampling at too high a frequency reduced the length of time for which data could be sampled before manual intervention, whereas a low sampling rate was associated with missing energy events. Table 3.3 documents the sampling frequency methodology and outlines the frequencies used for different types of WWTP equipment.

The scope of the energy monitoring was restricted to on-site processes (i.e. external pumping stations were not included).

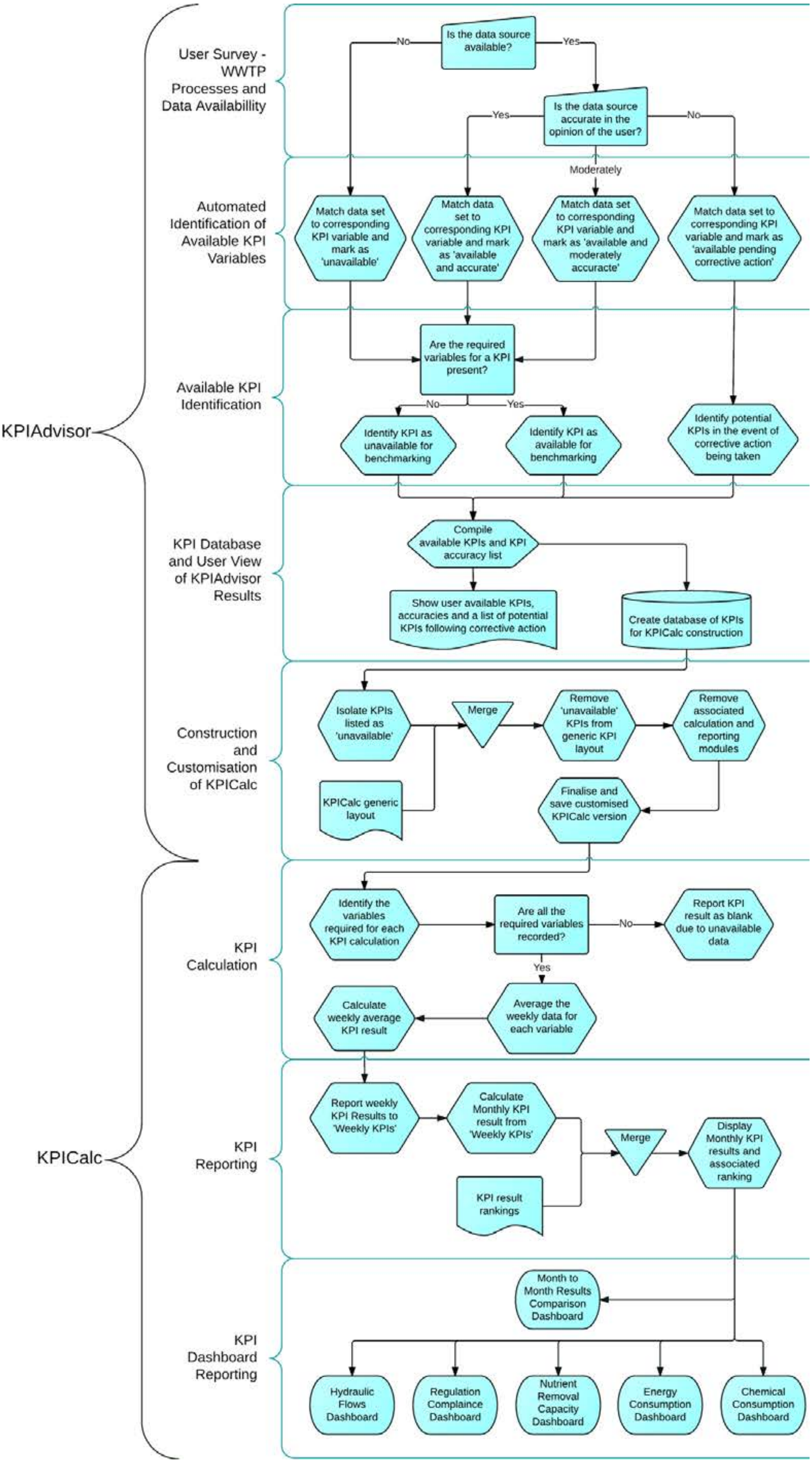


Figure 3.6. Process chart for KPIAdvisor and KPICalc as part of the benchmarking system.

Table 3.2. Basic specifications of the power/energy monitors utilised in plant audits

Monitor	Power	Capability	Logger	Sampling frequency (Hz)	Harmonics (up to)	Coms
Fluke 453 series II	Mains	Single and three phase	SD card (8 GB)	1.3e–4 to 4	50th	USB
Amprobe PQ 55A	Mains	Single and three phase	20,000 records	8.0e–3 to 0.2	31st	RS-232
Iso-Tech IPM2005	Battery	Single and balanced three phase	8000 records	1.6e–3 to 1	N/A	USB optical

Coms, communication device; N/A, not applicable.

Table 3.3. Sampling frequency methodology for WWTP equipment in this study

Sampling frequency	WWTP equipment
High (>2 recordings/minute)	Mains power unit
Moderate (1–2 recordings/minute)	All compressed air blowers Primary grit blowers All sludge centrifuges Influent and effluent pumps
Low (<1 recording/minute)	Recirculation pumps RAS pumps WAS pumps Centrifuge feed pumps

RAS, return activated sludge; WAS, waste activated sludge.

3.5 Exergy Analysis

The data used in the study were a combination of measured, site-specific data, and data obtained from the literature. Table 3.4 lists the site-specific data used in the study for the exergy analyses.

The exergy analysis approach consists of a number of steps:

1. the inputs and outputs for each wastewater treatment process are identified for each plant;
2. the exergy content or work potential of each process stream is determined;
3. the exergy destruction for each process is calculated;
4. a hierarchy of processes/flows, in terms of exergy destruction/exergy losses, is determined;
5. the calculated exergy destruction rates are used as a benchmarking metric for the comparisons of WWTP thermodynamic performances;
6. the exergy losses are determined;
7. the exergetic efficiency of the WWTP is determined.

A number of assumptions and simplifications were made and these are listed below:

- The processes were assumed to be isothermal and isobaric; therefore, thermomechanical exergy was considered negligible.
- Steady state was assumed.
- Heavy metal and chemical input data were not available and were omitted from the analysis.
- The average measured influent and effluent COD data (mg/L), obtained during the testing period, were used in the calculations if available. Inter-process COD data were not available but were estimated using values from the literature.
- Average measured energy values (kWh/day) were used for most processes; return activated sludge (RAS) pumping energy data were available for plant F but not for plant E; grit blower energy

Table 3.4. Site-specific data used for exergy analyses

Parameter	Description
Volume of wastewater treated	The volume (in m^3) of wastewater treated was measured
COD	The quantity of oxygen required to chemically oxidise all organic and inorganic compounds in wastewater was measured
TN	See section 3.2.1; no inter-process data were available (influent and effluent were measured)
TP	See section 3.2.1; no inter-process data were available (influent and effluent were measured)
Energy	
Electricity	Electricity usage was measured

COD, chemical oxygen demand.

data were available for plant E but not for plant F. Because of the similar flows and technologies used in these WWTPs, the energy consumption values of the equipment for which data were missing were assumed to be equivalent for both WWTPs.

- The chemical exergy of the nutrients (kJ/mol) were calculated using the values in Szargut (2005) and were subsequently converted to MJ/day. The molar mass values for NH_4OH (35 g/mol) and H_3PO_4 (98 g/mol) were used for these conversions.
- Data regarding the emissions to air were not available and were omitted from the analyses.
- Inter-process nutrient data were not available, and, therefore, nutrient data were not included in the pre-treatment and secondary treatment process exergy analyses. However, nutrient data were included in the extended boundary exergy analyses.
- Inter-process sludge data were not available. Average WWTP sludge output data were available from operator records; however, RAS and waste activated sludge (WAS) typical concentrations and flow rates were estimated using relevant values from the literature.
- No data were available on the screenings or grit removal quantities; it was assumed that the volumetric flow rate entering the WWTP pre-treatment stage was equal to the flow rate after pre-treatment.

In cases in which COD reduction across specific processes in the WWTPs analysed could not be measured, the estimates reported in Straub (1989) were used, that is, a 5–10% reduction in COD with fine screening and a 50–80% reduction after aeration and sedimentation. If sludge estimation could not be measured on-site, the typical RAS flow rates reported by Metcalf and Eddy (2002), that is 50–75% of the average design flow rate, were used. According to the Irish EPA wastewater treatment manual (EPA, 1997), RAS flow rates of up to 150% for relatively small WWTPs are common. With regard to RAS concentrations, reported values vary widely: from 4000 mg/L to 12,000 mg/L (Metcalf and Eddy, 2002). Values of 4355 mg/L and 9300 mg/L are reported elsewhere in the literature (Khosravi *et al.*, 2013). In this research, midpoint values were used initially to undertake the exergy analyses, that is, values of 7.5%, 8000 mg/L and 90% for percentage of pre-treatment COD reduction, sludge COD concentration and percentage RAS rates, respectively.

3.6 Life-Cycle Assessment Methodology

The main framework for a LCA is laid out by ISO (International Organization for Standardization) 14040 (ISO, 1997). The format follows a systematic step-by-step approach from goal and scope definition, through

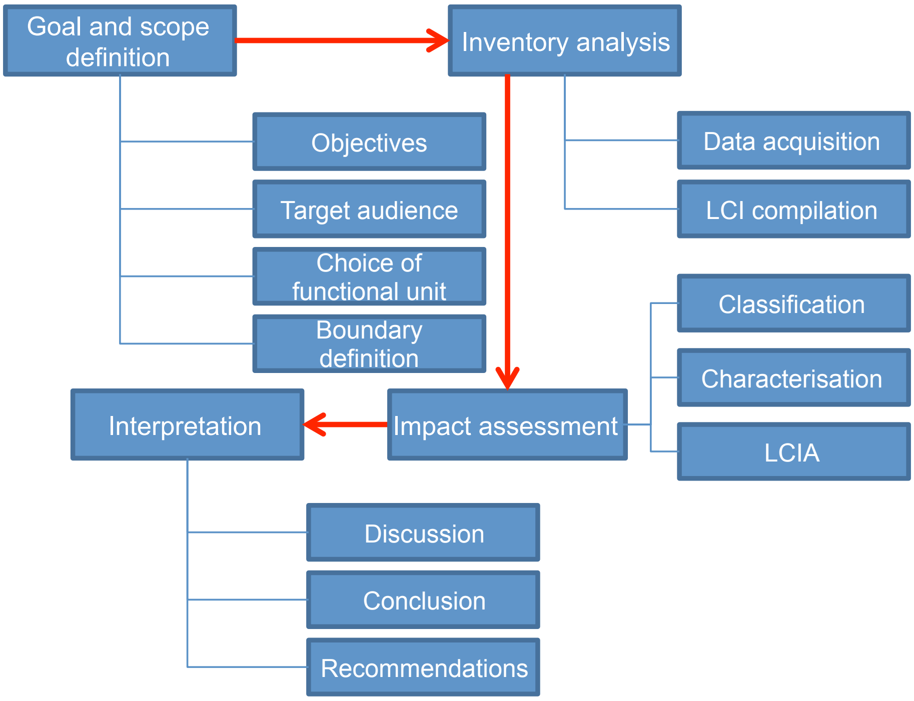


Figure 3.7. LCA format.

to the impact assessment phase (Figure 3.7). The LCA software used in this study was GaBi version 6.0 [Thinkstep (formally PE International); datasets were updated to 2014].

3.6.1 Impact assessment methodology

The CML (Institute of Environmental Sciences, Leiden University) 2001 life-cycle impact assessment (LCIA) methodology was used in this study. This is a *midpoint* impact methodology as opposed to an *endpoint* methodology (Bare *et al.*, 2000). The impact categories are given in Table 3.5.

3.6.2 Data acquisition for LCA

The data used in this study are a mixture of site-specific, aggregated (supplied with the LCA software), estimated and literature data. Table A3 in the appendix lists the site-specific data used in the study.

3.6.3 Assumptions and simplifications

The assumptions and simplifications that were made for this study are listed below:

- plant construction and decommissioning phase were deemed negligible;
- heavy metal concentrations of sludge were based on national averages;
- heavy metal concentrations in final effluent were based on national averages;
- lime quantities used in sludge stabilisation were taken from the literature;
- impacts from landfill use were not included;
- fertiliser production was not included as fertilisers are avoided products;
- transport of influent to WWTPs was not included in analysis;
- emissions from transport used in sludge distribution were not included;
- thickening polymers were not included;
- pickle liquor used for phosphorus precipitation was not included.

Table 3.5. CML 2010: LCIA categories

Impact category	Abbreviation	Units
Global warming potential	GWP 100	kg CO_2 equivalents
Acidification potential	AP	kg SO_2 equivalents
Eutrophication potential	EP	kg PO_4^{3-} equivalents
Ozone depletion potential	ODP, steady state	kg R11 equivalents
Photochemical oxidation potential	PCOP	kg C_2H_6 equivalents
Ecotoxicity		
Freshwater aquatic	FAETP infinite	kg $C_6H_4Cl_2$ equivalents
Terrestrial	TE infinite	kg $C_6H_4Cl_2$ equivalents
Marine aquatic	MAETP infinite	kg $C_6H_4Cl_2$ equivalents
Human toxicity potential	HTP infinite	kg $C_6H_4Cl_2$ equivalents
Abiotic depletion elements	ADP elements	kg Sb equivalents
Abiotic depletion fossil	ADP fossil	MJ

R11, a chlorofluorocarbon used as a refrigerant; Sb, antimony.

4 Results and Discussion

An overview of the WWTP energy and water quality audit results is presented in Table 4.1. Eight key performance metrics are presented to facilitate plant comparison across multiple criteria:

- kWh/day;
- kWh/PE.year;
- kWh/m^3;
- kWh/kg NH_4-N removed;
- kWh/kg BOD removed;
- kWh/kg COD removed;
- kWh/kg total suspended solids (TSS) removed;
- kWh/kg TN removed.

The performance of WWTPs is a function of many variables including scale, influent quality and variation, and effluent quality/discharge licence requirements. Therefore, assessing plant performance over a range of metrics provides a fairer comparison among plants, and offers better insights into potential optimisation strategies (Figures 4.1–4.3). Table 4.1 presents the energy and water quality audit results in terms of the key metrics. The first metric, kWh/day, is not an efficiency metric per se, and, therefore, this metric is expected to be primarily related to the scale of the plant. Given that the vertical axis of the graph in Figure 4.1(a) is logarithmic, plant A has the highest daily energy consumption (as expected given it is the largest plant). However, plant B uses significantly less energy per day than plants C, D, E and F, despite being of a similar scale to plants C and D, and being significantly larger than plants E and F. With regard to discharge requirements (see Table A1 in the appendix), plant B has less stringent discharge requirements for BOD, ammonia and orthophosphate than plant C, and thus could be expected to use less energy. For plants B and D, the discharge licence requirements vary for TP, ammonia and orthophosphate: plant D has a 2 mg/L limit for TP, but no discharge requirements for ammonia or orthophosphate. Plant A has the least stringent set of discharge requirements of the plants that are required to have a discharge licence.[2]

Looking at the plants in terms of kWh/m^3 and kWh/PE.year (Figure 4.1(b) and Figure 4.4, respectively) narrows the range of values considerably. Note that these two KPIs are effectively the same metric, where the former is multiplied by a constant.[3]

Based on the literature, it was expected that economies of scale would be apparent, that is, the largest plants would exhibit the highest efficiencies. This is illustrated in Figure 4.5, which shows the energy consumption of several European plants in kWh/PE.year (Tillman *et al.*, 1998; Lundin *et al.*, 2000; Gallego *et al.*, 2008; Hospido *et al.*, 2008; Hospido *et al.*, 2010). However, it should be noted that the European plants selected employ the conventional activated sludge process, and variations in sludge treatment energy usage have not been taken into account.

Plants E and B have the highest and lowest energy consumption values, respectively, in terms of kWh/m^3 of treated wastewater (Figure 4.1(b)), with plant B consuming only 23% of the energy used by plant E. This could potentially be attributed to two significant factors: first, plant B has an almost 30% greater design capacity than plant E, and therefore some economy of scale would be expected; and second, plant B was running at close to 100% (99.31%) of the hydraulic design capacity during the testing period, whereas plant E was running at only 41%. It has been reported that high levels of efficiency can be attained by operating a system at close to its maximum capacity (Dincer and Rosen, 2012).

Plant A is the largest of the plants assessed in the study. However, the anticipated energetic economies of scale are not evident from the KPI results upon comparison with the next largest plant (plant B). Plant B receives less than 24% of the organic loading of plant A, but appears to outperform plant A in almost every KPI. One reason for this is that plant A employs AD which produces energy through biogas production; this study assesses energy efficiency in terms of energy consumed during the treatment process and considers only

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[2] Plant I has a capacity of < 500 PE and is, therefore, required to have only *discharge authorisation*, which does not stipulate discharge requirements.

[3] The kWh/PE.year values are based on the hydraulic definition for PE per year with a value of 150 L. The inclusion of both kWh/m^3 and kWh/PE.year permits comparison with other studies.

Table 4.1. Average energy efficiencies, based on the KPIs, with maximum and minimum values

Plant	Average	Maximum	Minimum
kWh/day			
A	12,524	15,277.53	10,953.97
B	1273	1519.80	878.00
C	1473	1919.69	681.72
D	1868	1994.65	1706.38
E	1705	1780.84	1668.17
F	1451	1562.65	1387.24
G	585	654.00	363.30
H	115	119.71	104.16
I	21	26.05	6.66
J	230	234.27	213.31
kWh/PE.year			
A	26.28	33.19	18.41
B	11.75	21.25	7.59
C	20.03	82.71	3.53
D	16.35	22.61	13.20
E	50.37	52.09	48.92
F	41.06	49.45	28.13
G	20.29	36.80	7.91
H	37.23	43.05	32.75
I	15.02	29.58	4.43
J	32.85	25.00	16.40
kWh/m^3			
A	0.48	0.69	0.38
B	0.21	0.39	0.14
C	0.37	2.98	0.06
D	0.30	0.41	0.24
E	0.92	0.95	0.89
F	0.75	0.90	0.51
G	0.37	0.67	0.14
H	0.68	0.79	0.60
I	0.27	0.54	0.08
J	0.60	1.04	0.30
kWh/kg NH_4-N removed			
A			
B	11.00	37.77	1.37
C			
D	19.40	39.18	10.9
E			
F			
G	16.74	67.99	2.76
H			
I			
J			

Table 4.1. Continued

Plant	Average	Maximum	Minimum
kWh/kg BOD removed			
A	2.79	6.64	1.20
B	1.09	3.56	0.35
C	1.85	4.89	0.42
D			
E	4.68	5.47	4.00
F	7.30	8.90	5.12
G	2.12	6.96	0.62
H	7.79	11.27	2.73
I	1.78	3.21	0.3
J	5.21	10.05	1.18
kWh/kg COD removed			
A	1.28	1.82	0.86
B	0.51	1.33	0.19
C	0.73	3.17	0.07
D	0.70	2.05	0.30
E	2.93	3.41	2.44
F	4.60	7.44	2.19
G	1.37	6.69	0.26
H	3.92	4.98	2.44
I	1.50	4.00	0.22
J	3.53	6.12	1.41
kWh/kg TSS removed			
A	2.16	5.37	0.78
B	1.03	2.19	0.16
C	1.19	6.72	0.11
D	1.38	3.84	0.61
E	10.27	11.80	9.28
F	8.48	10.01	6.05
G	5.03	17.73	0.45
H	6.03	14.56	2.98
I	3.10	6.86	0.99
J	8.19	19.79	5.65
kWh/kg TN removed			
A			
B	21.16	64.27	3.05
C	12.41	30.72	2.18
D	44.38	146.42	6.83
E			
F	76.67	137.04	32.47
G			
H			
I			
J			

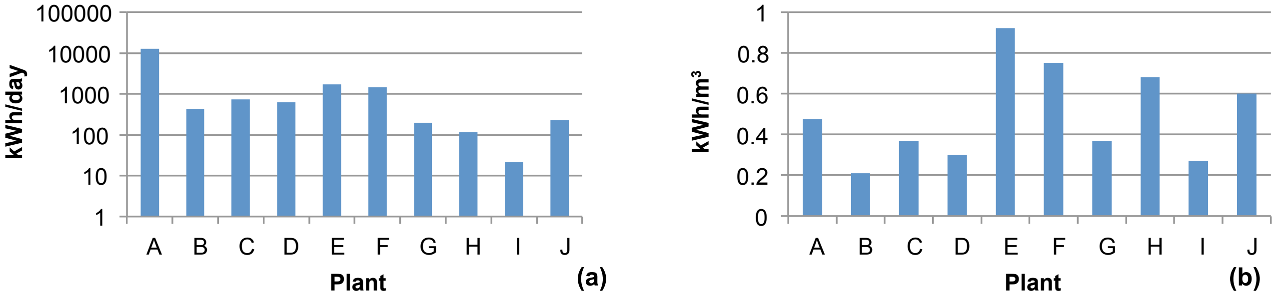


Figure 4.1. WWTP performance metrics: (a) kWh/day and (b) kWh/m³.

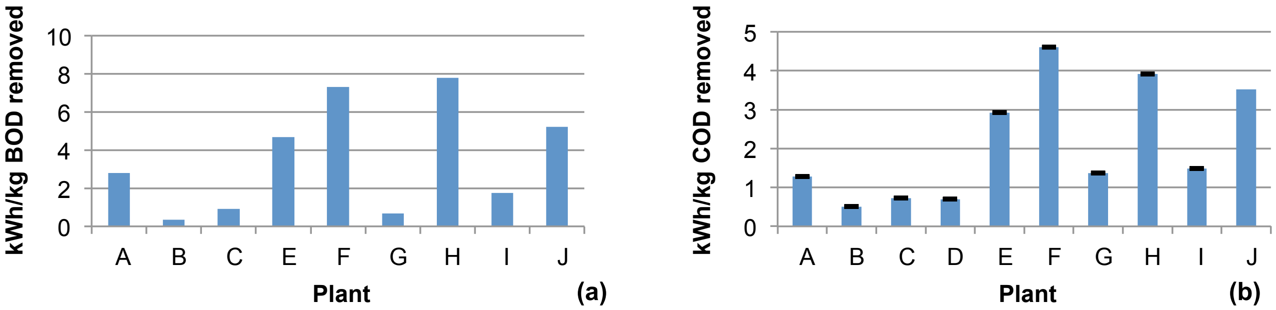


Figure 4.2. WWTP performance metrics: (a) kWh/kg BOD$_5$ removed and (b) kWh/kg COD removed.

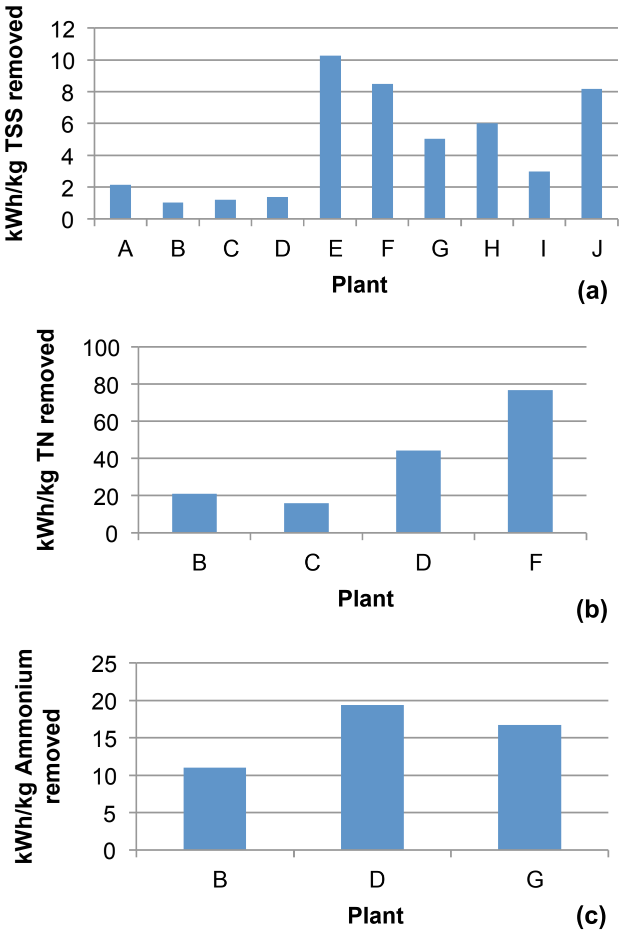


Figure 4.3. WWTP performance metrics: (a) kWh/kg TSS removed, (b) kWh/kg TN removed and (c) kWh/kg NH$_4$-N removed.

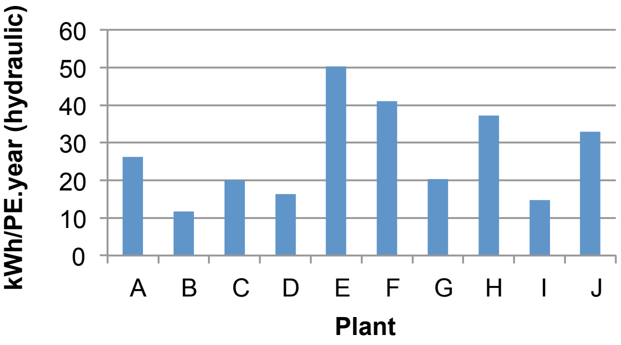


Figure 4.4. kWh/PE.year.

gross energy use, and not the source of energy (this aspect of plant A's energy efficiency is dealt with further in the LCA discussion in section 5.3). Consequently, the energy produced from biogas production is not included. Notwithstanding this, AD can use a significant amount energy to maintain digester reactor temperature, and this should be considered when weighing up the results. It is also noteworthy that plant A is situated close to a residential area and must adhere to strict odour restriction controls. The energy required to operate an odour reduction system for a plant of this size could be substantial. No specific data for odour reduction energy could be gathered as its components are integrated into other subsystems of the plant.

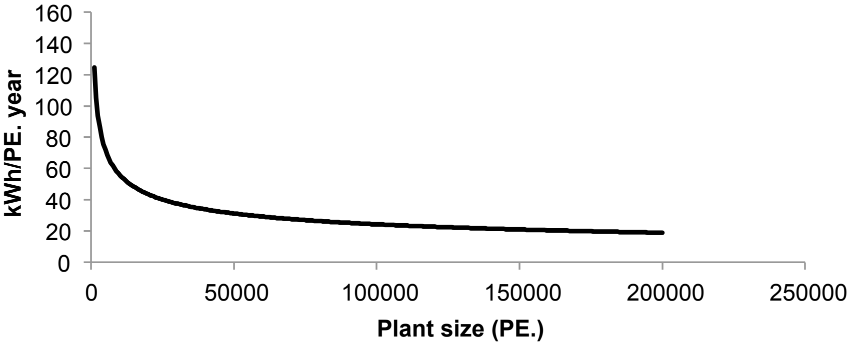


Figure 4.5. Energy efficiency of WWTPs from a selection of other European countries.

Plants E and F are similar in design capacities and technologies (see appendix Tables A1 and A2). However, there are notable differences in performance across all metrics (see Figures 4.1, 4.2, 4.3 and 4.4). Plant F has stricter discharge requirements for BOD, TSS, TP and TN, but lower organic loading. Plant E consumes 1705 kWh/day on average, whereas plant F consumes 1451 kWh/day. On further examination it was found that the average influent BOD was considerably lower for plant F than for plant E (99.2 mg/L vs 209.4 mg/L). Lower organic loading and BOD levels appear to reduce the energy load in terms of kWh/m^3 of treated wastewater, in spite of plant F's stricter effluent discharge limits. However, the reduced influent BOD levels mean that if the KPI is kWh/kg of BOD removed, plant F must treat a much greater volume of influent to extract the same quantity of BOD, thus giving the impression of a lower energy efficiency for the latter metric. Plants G and J have the lowest BOD discharge limits at 10 mg/L. Plant G appears to have a lower energy consumption (2.12 kWh/kg BOD removed) than plant J (5.21 kWh/kg BOD removed). However, as with plants E and F, there were considerable differences in organic loading between plants G and J. During testing, plant G influent BOD was much greater (249 mg/L) than plant J influent BOD (134 mg/L). Plant B had the lowest energy consumption (1.09 kWh/kg BOD removed) and plant H had the highest (7.79 kWh/kg BOD removed). Influent BOD concentrations for plant B were almost 2.5-fold higher than those for plant H. Plant B operated at just over 100% of its organic loading design capacity during the period analysed. The COD KPI values largely reflect those of the BOD KPI, with only small percentage variations across plants.

In relation to the smallest plants, namely plants H, I and J, it is evident that plant J far exceeds the others with regard to its daily energy consumption. Again, there are several important mitigating factors. First, although plant J is the smallest of the three plants in terms of design scale, it has the highest organic loading (and, in fact, the organic loading exceeded the plant's design capacity during the period monitored). Second, plant J has significantly more stringent discharge requirements than plant H. Plant I has by far the lowest daily energy consumption of all the plants. Putting this result in context, plant I has the lowest organic loading and does not have current discharge requirements. Furthermore, in contrast to the other small plants, plant I uses pump flow biofilm reactor (PFBR) technology as opposed to activated sludge. It should also be noted that the three small plants do not have sludge treatment energy costs.

Plant F has the most lenient discharge limits of the plants with nitrogen restrictions at 20 mg/L, whereas the others have nitrogen restrictions of 15 mg/L. Plant F also had the second highest influent concentration of TN (29.6 mg/L). Plant B had the highest concentration of TN (37 mg/L). Plant C had a lower energy consumption, with regard to kWh/kg of TN removed, than plant F (12.4 kWh/kg vs 76.7 kWh/kg of TN removed).

4.1 Benchmarking

Implementing KPIAdvisor in any WWTP provides the user with useful information and can identify (1) the data streams that are accurate and available, and (2) the data streams that need attention. This information allows the user to evaluate and improve the status of the plant data; for example, it informs users with regard to whether or not it is necessary to improve the accuracy of an existing data stream or make an existing data stream available, and it can recommend which data streams should be collected in order to achieve effective WWTP benchmarking and management.

As part of the benchmarking tool's testing phase, five of the WWTPs used in this study underwent KPIAdvisor testing. The survey element of KPIAdvisor was populated with information that resulted in KPIs being identified. The key results are presented in Table 4.2.

A rating accompanies each KPI to indicate to the user how reliable each KPI is likely to be based on the user-defined or known accuracy of the input data. The accuracy rating of each KPI is portrayed using a traffic light system (see Table 4.2): green markers identify KPIs that were calculated from accurate and reliable data sources; orange markers indicate KPIs which may present discrepancies due to, for example, data accuracy issues; and red markers identify KPIs that could not be calculated because of unreliable data sources.

The methodology behind KPIAdvisor allows the benchmarking system to remove KPIs that are seen as inaccurate. It also allows users to identify areas in which improvements can be made with regard to data acquisition, and how this might enable more comprehensive benchmarking. This is clearly evident for plant I, compared with the other WWTPs included in Table 4.2. Plant I has 100% KPI accuracy in comparison with the other WWTPs, which have many KPIs that are

Table 4.2. KPIAdvisor testing results

KPI	Units	WWTP B	WWTP C	WWTP D	WWTP G	WWTP I
Design capacity utilised	%	🟥 ✓	🟩 ✓	🟩 ✓	🟥 ✓	🟩 ✓
Wastewater volume treated in WWTP	%	🟥 ✓	🟩 ✓	🟧 ✓	🟥 ✓	
Volume of storm overflow	%	🟩 ✓	🟩 ✓	🟩 ✓	🟧 ✓	🟩 ✓
Sludge production in WWTP	kg/m^3	🟥 ✓	🟩 ✓	🟧 ✓	🟥 ✓	
Overall compliance with discharge requirements	% samples	🟩 ✓	🟩 ✓	🟩 ✓	🟩 ✓	
COD samples compliant	% samples	🟩 ✓	🟩 ✓	🟩 ✓	🟩 ✓	
BOD samples compliant	% samples	🟩 ✓	🟩 ✓	🟩 ✓	🟩 ✓	
Ammonium samples compliant	% samples	🟩 ✓	🟩 ✓		🟩 ✓	
Total nitrogen samples compliant	% samples	🟩 ✓	🟩 ✓	🟩 ✓	🟩 ✓	
Orthophosphate samples compliant	% samples	🟩 ✓	🟩 ✓		🟩 ✓	
Total phosphorus samples compliant	%		🟩 ✓	🟩 ✓	🟩 ✓	
Total suspended solids samples compliant	%	🟩 ✓	🟩 ✓	🟩 ✓	🟩 ✓	
BOD removal	%	🟥 ✓	🟩 ✓	🟧 ✓	🟥 ✓	
Nitrogen removal	%	🟥 ✓	🟩 ✓	🟧 ✓	🟥 ✓	
Phosphorus removal	%		🟩 ✓	🟧 ✓		
Volume mains water consumed	L/m^3	🟥 ✓	🟩 ✓	🟩 ✓	🟥 ✓	🟩 ✓
Wastewater reuse	%	🟥 ✓				
Ferric sulphate utilised	kg/m^3	🟧 ✓	🟧 ✓			
WWTP energy consumption per PE	kWh/PE.year	🟥 ✓	🟩 ✓	🟧 ✓	🟥 ✓	🟩 ✓
WWTP energy consumption per unit volume WW treated	kWh/m^3	🟥 ✓	🟩 ✓	🟧 ✓	🟥 ✓	🟩 ✓
WWTP energy consumption per unit mass BOD removed	kWh/kg BOD	🟥 ✓	🟩 ✓	🟧 ✓	🟥 ✓	
WWTP energy consumption per unit mass nitrogen removed	kWh/kg N	🟥 ✓	🟩 ✓	🟧 ✓	🟥 ✓	
WWTP energy consumption per unit mass ammonium removed	kWh/kg NH_4-N	🟥 ✓	🟩 ✓		🟥 ✓	
WWTP energy consumption per unit mass phosphorus removed	kWh/kg P		🟩 ✓	🟧 ✓	🟥 ✓	
Pump house energy consumption per unit volume Influent WW	kWh/m^3	🟥 ✓	🟩 ✓	🟩 ✓	🟥 ✓	🟩 ✓

The KPIs identified as "available" are indicated with a "✓" symbol. The accuracy rating of each KPI is portrayed using a traffic light system: green indicates KPIs that were calculated from accurate and reliable data sources; orange indicates KPIs which may present discrepancies due to, for example, data accuracy issues; and red indicates KPIs that could not be calculated because of unreliable data sources.

unlikely to be accurate (for plants B, D and G this is mostly as a result of flow monitoring issues). Thus, for these WWTPs, KPIs that rely on flow measurement are either automatically excluded from the analysis or flagged as potentially unreliable.

4.2 Flow Monitoring Results

4.2.1 Influent and effluent flow monitoring

Of the five WWTPs used for benchmarking tool testing, only two (plant C and plant I) proved to have accurate flow monitoring (influent, effluent and storm overflow) in place (as determined both by flow analysis and conversation with operators). Flow data is critical for WWTP benchmarking and for the majority of methods used to quantify WWTP performance. For example, WWTP capacity utilisation (the ratio of current loading to design capacity) must be calculated from influent flow data, and this information is critical for identifying whether or not a WWTP is challenged with meeting stringent discharge requirements while operating over capacity at the time of benchmarking.

On a broader scale, only 13 of the 44 KPIs present in the benchmarking system developed in this project do not require flow data. All of these KPIs fall under the regulatory compliance category for which only nutrient analysis results (mg/L) are required. In addition, many WWTPs are not required to comply with all of the regulatory compliance requirements (depending on their discharge licence) and, as a result, would not be subject to the equivalent compliance KPI.

4.2.2 Mains water consumption and water reuse

In many parts of the world in which water is scarce, wastewater is not seen as a waste to be disposed of but rather as a resource to be reused (Metcalf and Eddy, 2002). In Ireland, where water appears to be plentiful and inexpensive, little consideration is given to wastewater reuse. This is also the case for many Irish WWTPs; however, wastewater reuse should be a prominent goal for the future. Water consumption is unmonitored in many Irish WWTPs, including 7 of the 10 WWTPs considered in this study.

The level of water usage in a WWTP can be difficult to appreciate as most of the attention is focused on treating the influent to achieve the desired effluent requirements. However, water is used in many wastewater treatment processes, including, but not limited to:

- chemical dilution (e.g. polyaluminium chloride dilution for sludge bulking);
- tank cleaning and wash down;
- belt-filter press cleaning (e.g. wash water used to clean the belts).

Only one of the WWTPs considered in this study reuses wastewater; in this plant, wastewater is reused as wash water for the belt-filter press. The volume of wastewater reused is recorded using a flow meter and logged by the WWTP’s SCADA system. In contrast, however, this WWTP has never recorded mains water consumption because the meter is located outside of the WWTP grounds. As a result, it was not possible to calculate the water reuse KPI presented in the benchmarking toolkit. This basic issue could be easily corrected by reading the meter on a regular basis.

4.3 Energy Monitoring/Energy Auditing

Energy monitoring/auditing has become increasingly prominent in many business sectors in recent years. Effective energy monitoring and audits require accurate, detailed and frequent energy data; however, the level of energy data collection in Irish WWTPs is often limited. Only 3 of the 10 WWTPs considered in this study operate any level of energy monitoring. This monitoring ranged from limited (total energy used per day) to detailed energy consumption and power quality data for the entire WWTP, the pumping house and the largest energy consumers within the plant (aeration equipment, pumping, etc.). In most of these WWTPs, the energy data collected was potentially erroneous because of a number of factors, including infrequent meter calibration and daily faults from both the energy meters and the SCADA systems.

A number of Ireland’s leading energy providers, including Electric Ireland, Energia and Bord Gáis Electricity, offer medium- to large-scale business users a means of tracking and reporting their energy usage over time by using an online tool at no extra cost (Electric Ireland, 2015; Energia, 2015). These data are provided as daily totals or for 15-minute intervals. In some cases, energy providers also offer additional information regarding maximum demand usage and power quality data, two parameters that can incur monetary penalties/fines if users fail to meet the standards set out by their energy provider (Electric Ireland, 2015; Energia, 2015). These services also offer historical data collection in certain cases, which is invaluable in terms of energy benchmarking. However, many of the WWTP managers, operators and engineers consulted during this study were unaware of these services, which are readily available to them by registering online or by contacting their energy provider.

Installing energy monitoring equipment in a WWTP can be expensive, especially when the collected data needs to be linked to a SCADA system. Although installing specific energy monitoring equipment may offer a more detailed level of energy data than the energy provider is able to supply, the maintenance, calibration and supervision required to ensure that the data collected is accurate and reliable may be underestimated, causing many energy monitoring plans to become marginalised. On the other hand, if a WWTP collects energy data from their energy provider, they are able to partake in energy monitoring and auditing, however limited it may be (because of a lack of process-specific data), in a manner that leads to reliable and accurate results, without the need for any capital expenditure on energy monitoring equipment.

To gather the detailed energy data required for this project, energy monitoring equipment was installed on both the mains incomers, to monitor the amount of energy used by the entire plants, and the equipment involved in the various energy intensive processes. These handheld-type energy and power quality meters can be used to locate energy intensive equipment in a plant in a relatively simple manner once installed by a certified electrician.

4.4 Energy Audit Methodology Results

Detailed energy audits, using high specification PQAs, were carried out in several plants [plants E, F, H and J (see Table 1.1)] to help develop an energy auditing methodology and to determine the usefulness of detailed energy and power quality monitoring. An additional medium- to large-scale WWTP (plant X) was audited early in the study and was analysed using only the Fluke PQA. Because of a lack of data, this plant was not assessed in detail in terms of water quality and, as such, was omitted from Table 1.1. Figure 4.6 shows the power usage over a 1-week period, with an average power usage of approximately 200 kW. The power demand fluctuates daily and lower power demands were observed at the weekend (15–16 December 2013). Local rainfall data were obtained from Met Éireann and were included in the detailed power graphs to help identify unexpected events.

The energy distribution across plant X is highlighted in Figure 4.7. The blowers contributed 42% of the total plant energy, with 17% consumed by the primary treatment facility.

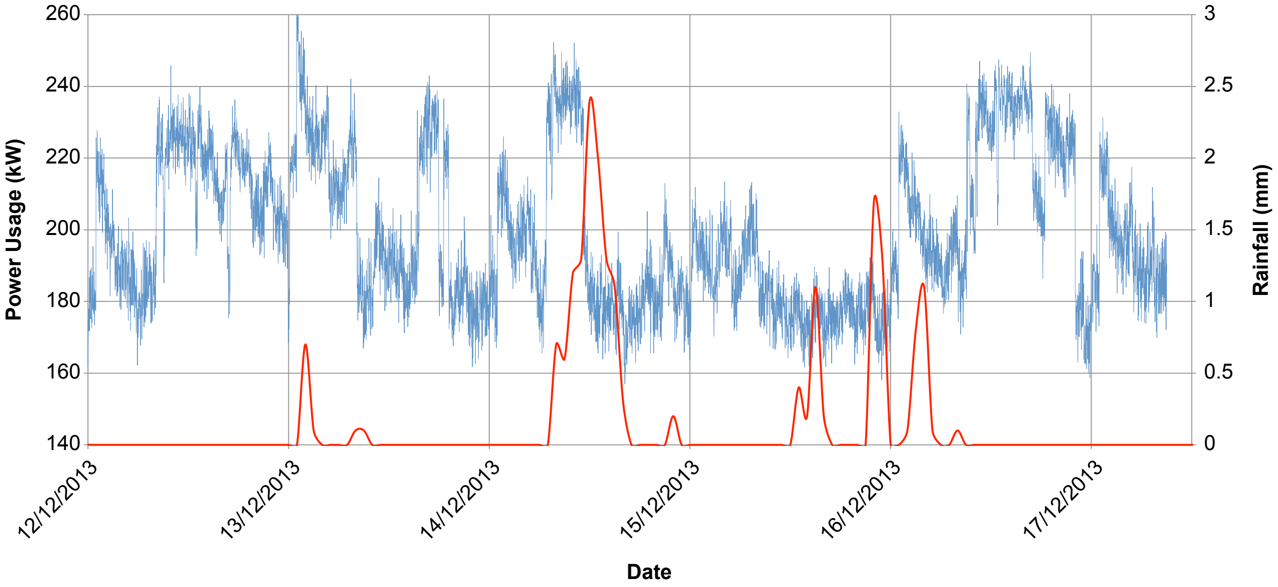


Figure 4.6. Plant X power usage and hourly rainfall.

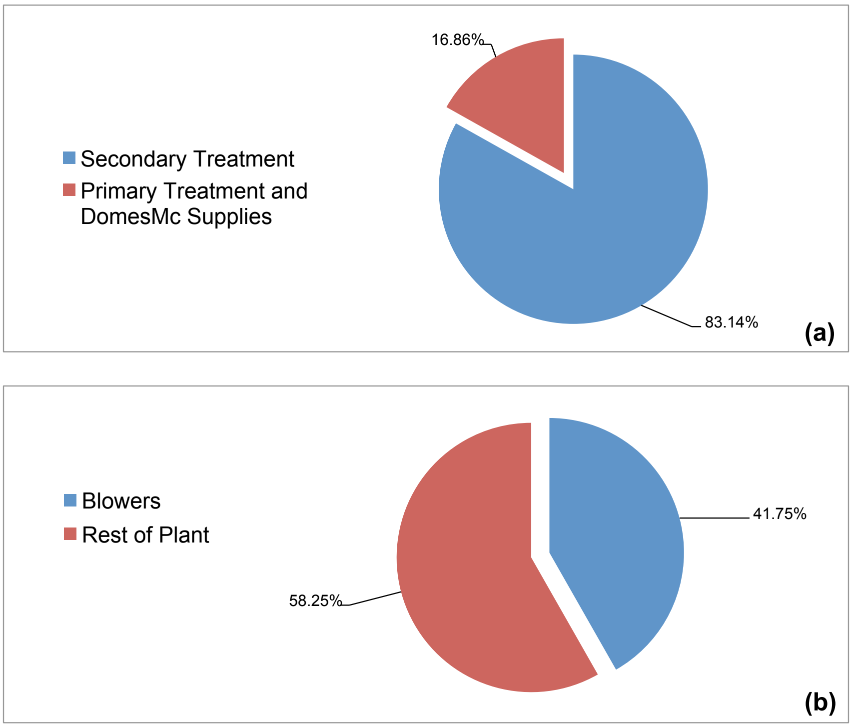


Figure 4.7. Plant X energy distribution. (a) Plant X primary and secondary treatment. (b) Plant X blowers usage.

Plants E and F have similar technologies and design capacities. Figure 4.8 shows the power usage for plant E over a 2-week period and shows distinct variations from night to day. During the night, plant E's power usage can dip to as low as 51 kW, while during the day the power averages approximately 100 kW. The graph in Figure 4.8 shows five sustained spikes in power usage. These spikes represent an increase in energy consumption of as much as 40 kW and they coincide with the running of the sludge dewater centrifuge system. Increased rainfall appears to disturb the normal night–day pattern of plant power usage, but the peak power consumption does not increase beyond normal daily levels.

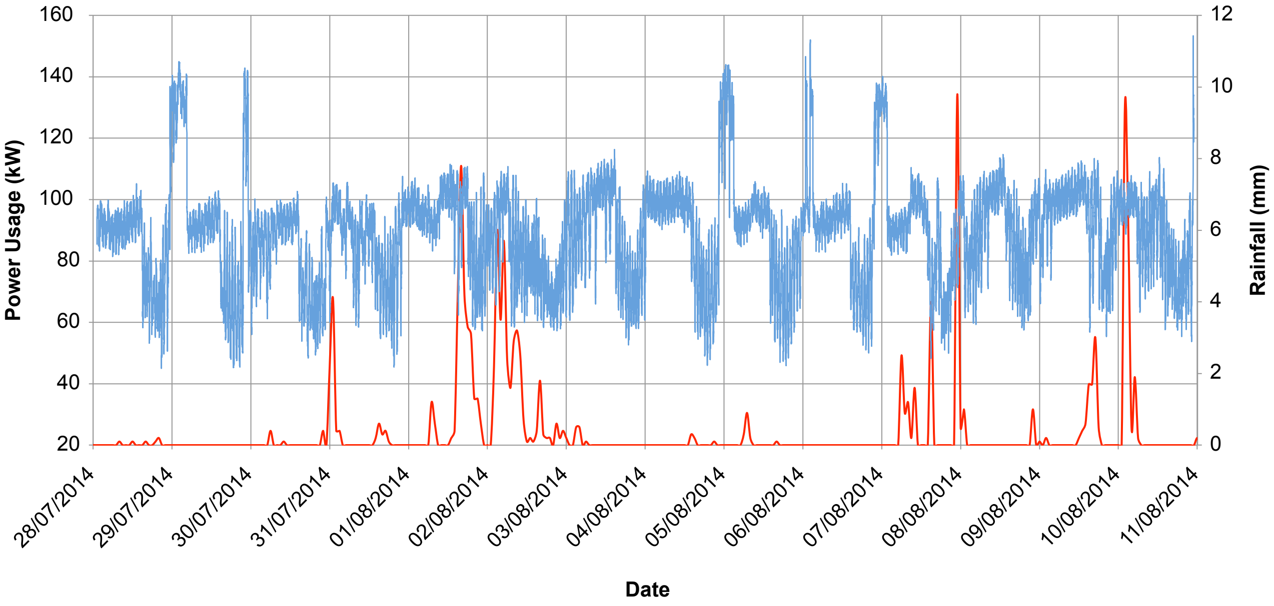


Figure 4.8. Plant E power usage and hourly rainfall.

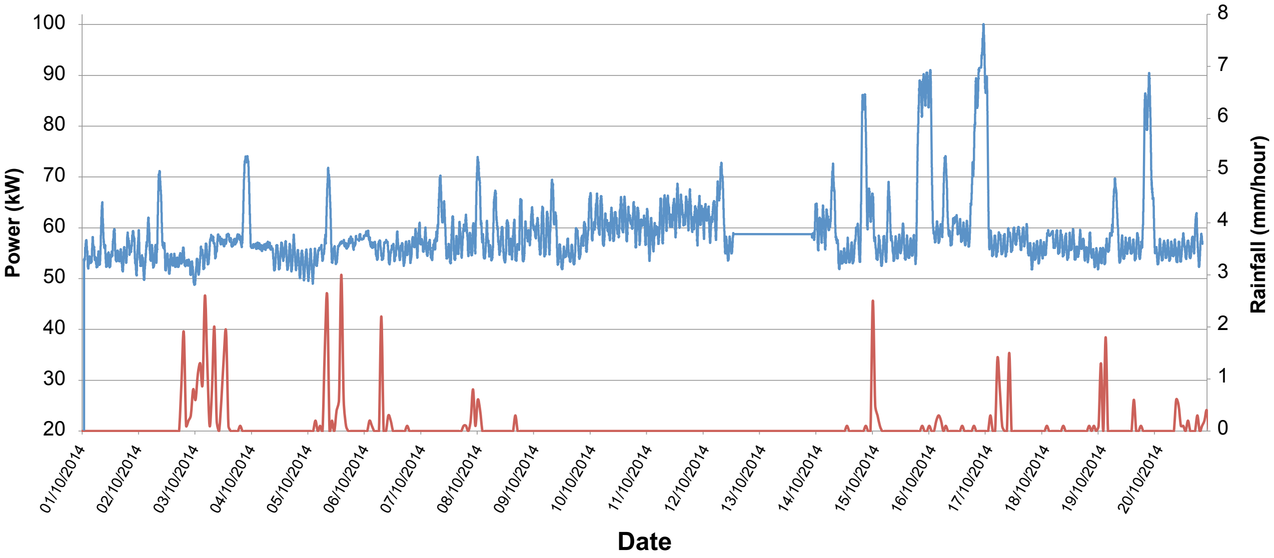


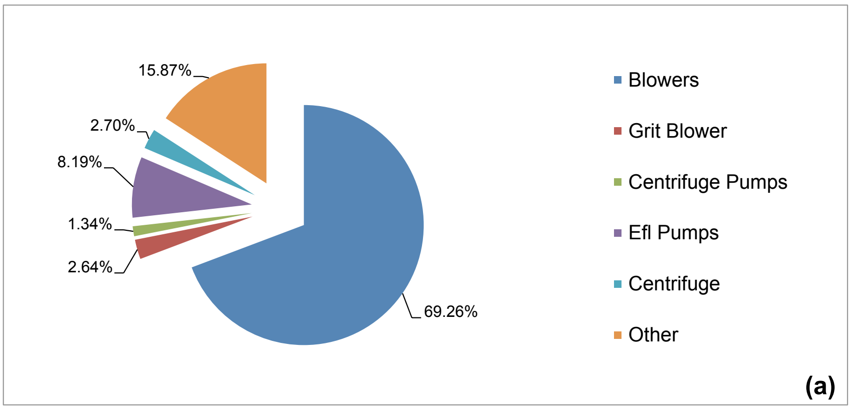
Figure 4.9. Plant F power usage and hourly rainfall.

Figure 4.9 shows the same data for plant F over a 3-week period. The average power usage (≈60 kW) is lower than in plant E. The power consumption for plant F does not display the same night to day fluctuations. After an investigation, issues were identified with the control system that governs plant F's compressed air blowers. During this trial, the control system was set to manual mode rather than automatic, which meant that the blowers were not being adjusted based on DO concentration in the aeration tank. The system was switched to manual as a result of frequent power cuts at the plant. These cuts caused the plant to go without power for just a few seconds, which, although was not long enough to trigger the backup generator, did cause the control systems to crash and not start up again after the power returned. It should be noted that the differences in energy consumption between plants E and F may also relate to the differences in incoming influent concentrations. For example, during the monitoring periods, plant E had an average influent COD concentration of 426.1 mg/L, whereas plant F had an average influent COD concentration of 245.3 mg/L. A further mitigating factor is that plant E pumps effluent downstream of the WWTP, which also adds to the energy burden. The rainfall during this trial period was not significant enough to cause disturbances in the peak power usage. The four spikes in power towards the end of the trial, as before, were caused by the sludge dewatering system.

The energy distribution also varied for these plants (Figure 4.10). The energy used by the compressed air blowers in plant E was responsible for 69% of the total energy consumption. In comparison, only 28% of total energy consumption was due to these blowers in plant F. These significant differences in energy distribution are partly as a result of the plant loadings. The magnitudes of BOD and COD removed are greater for plant E than for plant F, meaning that the blowers have to work harder to maintain the necessary DO concentrations in plant E. Consequently, plant E was running all three available blowers at peak hours to meet the DO concentration demands. In addition, as previously discussed, plant E uses high efficiency pumps with variable frequency drives (VFDs) to transfer the final effluent to the receiving waters; these pumps consume 8% of the total plant energy.

Plant J and plant H are small-scale WWTPs that have comparable technologies and design capacities. Figure 4.11 shows the power usage for plant J over 2 weeks. One interesting part of the graph in Figure 4.11 is the rise in power usage after 2 days of the trial. This was due to the breakdown of one of the compressed air blowers, which was fixed and brought back online on 31 October 2014, resulting in an increase in daytime power consumption from approximately 7 kW to more than 11 kW.

Plant H has a lower power consumption than plant J (Figure 4.12). Plant J serves a greater population and it operates at close to double the design capacity (in terms of PE). As a result, the plant runs both available blowers at their limits with no backup blower. The power usage in plant H is highly variable throughout the day, which is partly because of the type of control system in use. The blowers operate using on/off control. If the DO



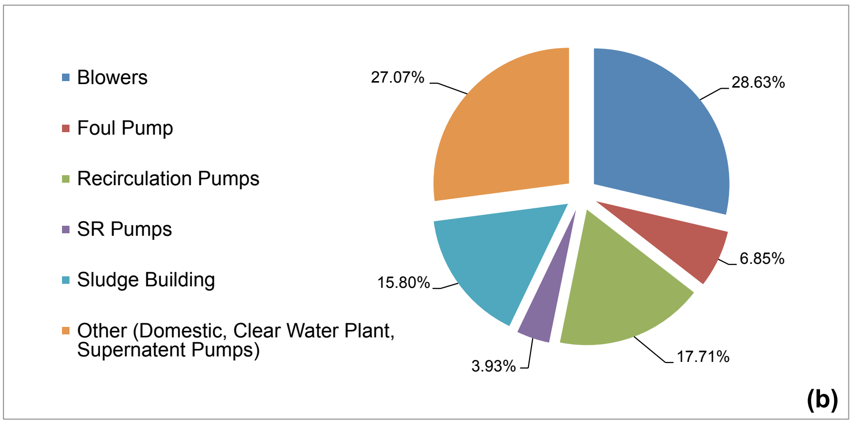


Figure 4.10. Plant E (a) and plant F (b) energy distributions.

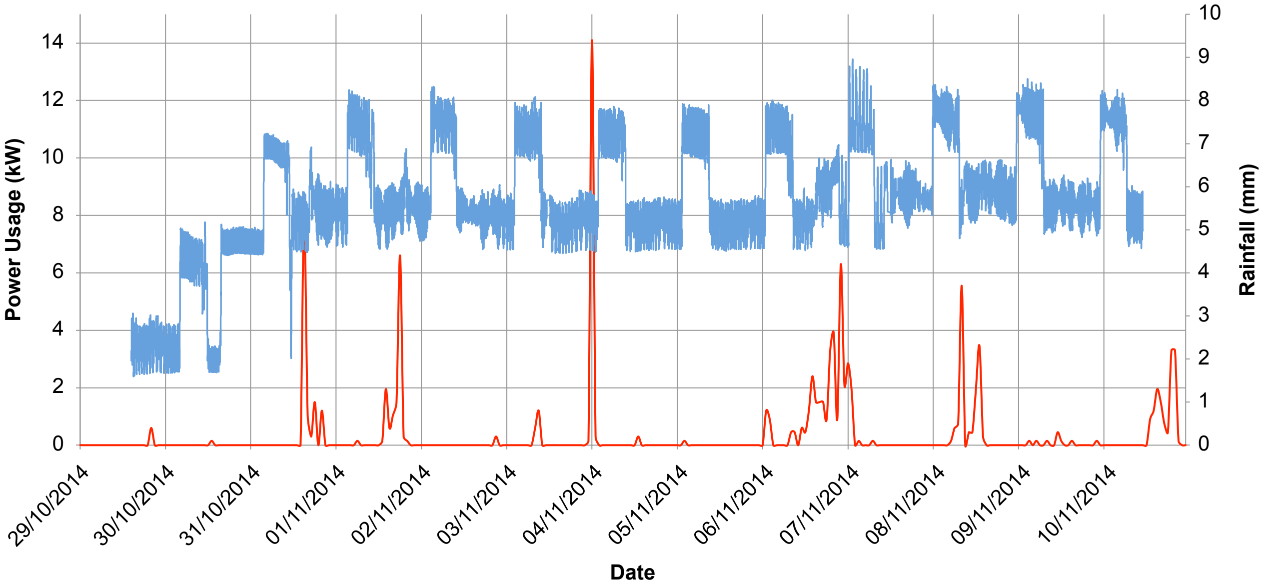


Figure 4.11. Plant J power usage and hourly rainfall.

levels in the aeration tank fall below a certain level, the blowers switch on. This increases the DO concentration and, once this reaches a certain level, the blowers switch off again. It is, therefore, much harder to see a distinct pattern from night to day.

The energy distribution in both plants is similar, as shown in Figure 4.13. Because of the compact nature of the electrical panels in these smaller plants, it was difficult to monitor all equipment and, because of this, over 30% of the plant equipment was not monitored.

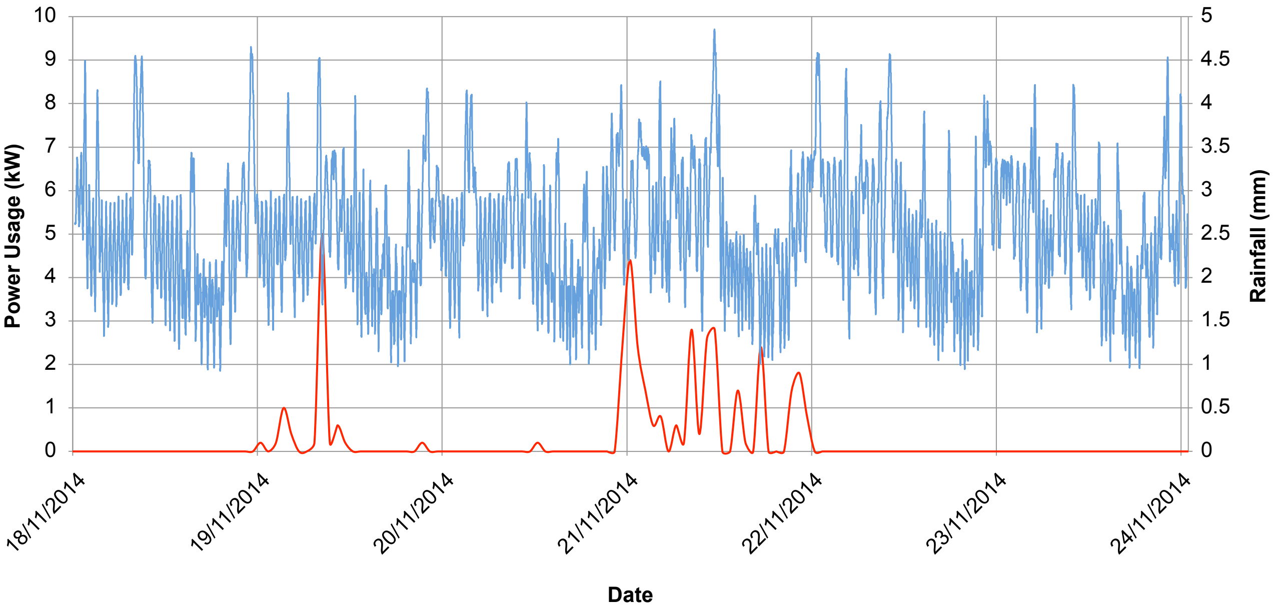


Figure 4.12. Plant H power usage and hourly rainfall.

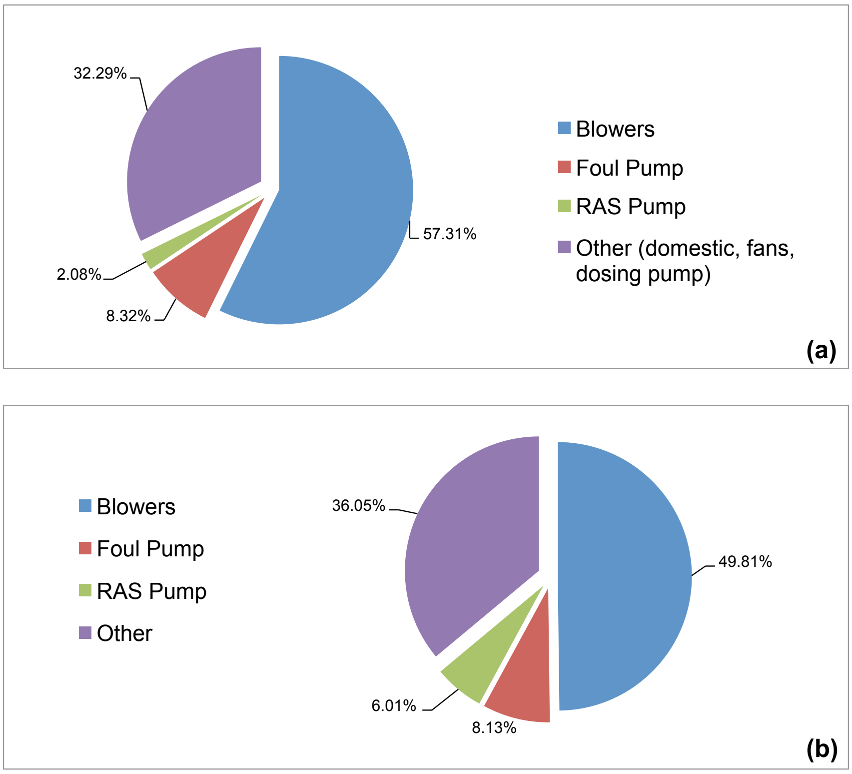


Figure 4.13. Plant H (a) and plant J (b) energy distributions.

All five plants audited and analysed utilise variable frequency drives to reduce the energy consumption of their pumps and blowers. Alongside the energy efficiency benefits, there are a number of drawbacks associated with these devices. The increased harmonic distortion caused by the pulse rectifier in variable frequency drives can have detrimental effects on plant equipment. The Institute of Electrical and Electronics Engineers (IEEE)-519 standards (Hoevenaars *et al.*, 2003) for voltage total harmonic distortion (THD) are shown in Table 4.3.

The treatment plants analysed do not exceed the appropriate plant limits of 5% voltage THD (Table 4.4); however, many plants have high levels of current THD and voltage harmonics. Plant J in particular has high levels of third- and fifth-order harmonics. Third-order harmonics can cause heating in neutral line wires while fifth-order harmonics create negative torque in three-phase motors. This negative torque causes inefficiency in motors and can lead to reduced lifespan.

A number of other issues arose during the completion of these detailed energy audits. As a result of conducting plant walkthroughs and staff interviews, areas of energy waste were identified. Many of the plants had poorly designed pipe routing. Unnecessary pipe bends across plants can cause increased energy consumption as a result of increased pumping requirements. In plants with sludge dewatering facilities, sludge was often pumped from ground level vertically up to the roof across the room and back down again, increasing the pump work and energy consumption. Poor power factor is another issue that was found in a number of plants. Plant F pays fines to the electricity supplier for power factor levels below the allowable limits. The root cause of this problem was found after connecting the power monitors and discovering that the power factor correction unit was turned off and that the capacitors were not suitable for the size of the plant.

It is important to note that the level of detail in the plant audit conducted for plant X differs from the other four plants. The reason for this is the lack of flow and energy monitoring equipment. This study shows the merits of recording and analysing energy data across a whole plant. With more equipment monitored, the analysis became more detailed and plant inefficiencies were identified. One of the biggest problems identified in this study was the amount of equipment breakdowns and reliability issues experienced. The plants studied experienced issues with harmonic distortion, poor power factor, capacity overload and equipment overuse. All of these issues can lead to the deterioration of plant equipment. Without a rigorous preventative maintenance (PM) schedule in WWTPs, the service life of pumps, blowers and dewatering systems can be reduced. This study also highlights the differences between plants operating with and without DO control systems. Plant E used DO control and this reduced the power usage during off-peak times by almost 50%. Plant F, which operated temporarily without DO control, maintained a steady power use across peak and off-peak hours irrespective of the DO concentrations in the aeration tanks.

4.5 Life-Cycle Analysis Results

Life-cycle assessments were carried out for 5 of the 10 plants examined in the study: plants A, E, F, H and J. However, analyses of plants H and J were limited to eutrophication and global warming because of the lack of site-specific data in key areas such as sludge management and chemical usage. The primary functional unit for this discussion is "m^3 of treated wastewater". However, comparisons have also been made using "kg of BOD removed" as the functional unit in cases

Table 4.3. Voltage THD limits, based on IEEE-519 standards (adapted from Hoevenaars *et al.*, 2003)

Bus voltage at PCC	Individual voltage distortion (%)	Total voltage distortion (THD) (%)
69 kV and below	3	5
69.001–161 kV	1.5	2.5
161.001 kV and above	1	1.5

PCC, point of common coupling.

Table 4.4. Voltage and current THD for four audited plants

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

for which large variations in output were considered to exist.

In general, the main contributions of a WWTP life cycle to environmental impacts come from three areas: final effluent discharge, energy use and sludge management.

4.5.1 Final effluent

The eutrophication potential of each plant corresponds largely with the assigned discharge limits, that is, in part, the lower the limits, the lower the eutrophication potential. More than 80% of the eutrophication loading comes from the final effluent discharge with only minor contributions from sludge disposal and electricity use (Figure 4.14).

Plant A has the largest output (0.01 kg phosphate equivalent/m^3 of treated wastewater). The plant discharges its final effluent into the sea and has the least stringent set of discharge limitations and no requirements for nutrient removal. It should be noted that the CML methodology does not differentiate between the eutrophication potential for seawater and freshwater. Plants E and H have similar limits, which are more stringent than those of plant A. Phosphorus inputs to plant E were 65% greater than the inputs to plant H. This is significant as phosphorus is the dominant contributor in this category. Plant J has the lowest discharge limits of all five plants, but exceeded its limits during the testing period. The size of the agglomeration that plant J serves exceeds the design capacity by almost 40%, and during the testing period it experienced an average hydraulic load almost 3.5-fold greater than its capacity and an organic load 1.4-fold more than its capacity.

4.5.2 Energy and global warming

The energy used in the treatment process was found to be the single largest contributor to the environmental impact of each plant in terms of the magnitude of both the loading in an impact category and the range of categories to which it contributes. Global warming potential (GWP) is heavily influenced by energy use (Figure 4.15). The large difference in the GWP output between plant A and plant E can be attributed to a number of factors. First, there is evidence of energetic economies of scale, as published by previous LCA studies of WWTPs (Lundin *et al.*, 2000). The organic design capacity of plant A is almost 16-fold higher than that of plant E. Second, plant A employs AD, which reclaims approximately 10% of the plant's overall energy usage. Finally, as mentioned previously, plant A has the least stringent discharge limits, thus lowering aeration energy requirements.

Other sources of GWP are the on-site gaseous emissions of CO_2, CH_4 and N_2O that are released during the

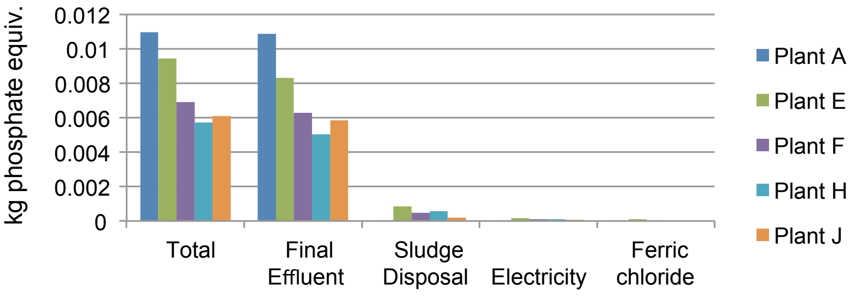


Figure 4.14. Eutrophication potential loading.

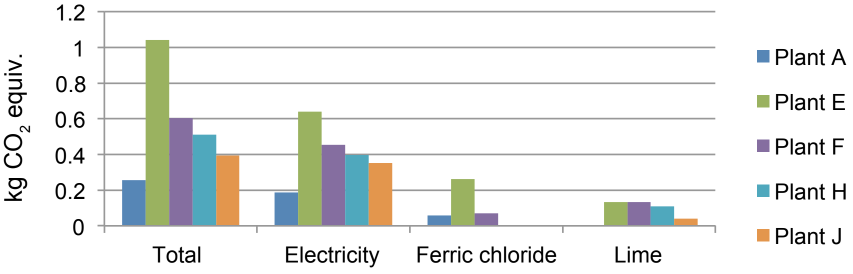


Figure 4.15. Global warming potential.

treatment process itself. The equivalency factors for methane (CH_4) and nitrous oxide (N_2O) are 25 and 289, respectively (i.e. 1 g of N_2O equates to 289 g of CO_2), and, thus, are significant. These compounds were not measured during the testing period. However, other studies have estimated that CH_4 and N_2O could account for 5% and 0.07%, respectively, of the total GWP of a plant (Gupta and Singh, 2012); however, these percentage values are dependent on a number of factors, such as process type, scale and mode of energy generation. The CO_2 generated during the treatment process is not included in the total GWP output because the influent carbon is biogenic and part of the natural carbon cycle.

Plants E and F have similar design capacities, process technologies and system configurations. The difference in GWP values can be attributed, in part, to the compositions of the influent wastewaters. Lower organic loading can reduce the amount of aeration energy required for the activated sludge process. The chemical requirements are reduced with lower TP loading. During the testing period, the TP loading in plant E was over twice that of plant F. Plant E removed 6.7 kg TP/m^3, whereas plant F removed 2.7 kg TP/m^3. Figure 4.16 (a) and (b) show that plant E appears to perform more efficiently if the functional unit considered is “kg BOD removed”, with electricity use being the main source of the variation for this output. There is a small contribution to the variation in outputs from the lime that is used downstream by the sludge stabilisation company

4.5.3 Sludge management

Sludge stabilisation and disposal affects a broad range of impact categories. Two common methods of stabilisation include AD and lime stabilisation. Plants E and F send dewatered sludge (≈18% dry solid concentration) off site to a company that uses lime for sludge stabilisation. The stabilised sludge is then sent for application to farmland. Plant A employs AD to stabilise the sludge. It is then dewatered (≈22% dry solid concentration) before it is sent to a composting company. This avoids the significant environmental loading associated with lime production and transport. AD can reclaim energy, thus reducing loading in energy-generation dominated categories, such as GWP and acidification potential (AP). There is also a significant reduction (>40%) in the volume of sludge if it is digested, which in turn reduces fuel consumption and transport emissions. However, there is a trade-off between the reduction of the organic fraction and the generation of ammonium ions. Increasing sludge retention time in the digesters increases solid degradation, but several studies have shown that there is a direct correlation between increased sludge retention time and increased ammonium ion concentrations in supernatants returning to the plant headworks (Cacho Rivero, 2005). Apart from the associated increase in aeration costs, an increase in ammonium ion concentrations can have adverse effects on the biological processes further downstream.

The digestion of the volatile solids fraction results in a reduction in sludge volume; however, the heavy metal content remains untouched. The heavy metal content of the sludge is the main contributor to aquatic, terrestrial and human toxicity levels. It should be noted that the environmental harm that results from toxicity is as much a function of the receiving environment as it is of the substance being emitted. The methodology used in these assessments measures the *potential* of a substance to do environmental harm, and does not try to predict what the actual harm will be.

The impact from energy consumption comprises two major areas: (1) the amount of energy that is used and (2) the mode of energy generation. In relation to the latter, Ireland is heavily dependent on fossil fuels for energy generation (>80% of electrical grid mix). This weighs heavily on global impact categories such as GWP, AP and marine aquatic ecotoxicity potential. However, this is not an aspect of wastewater treatment

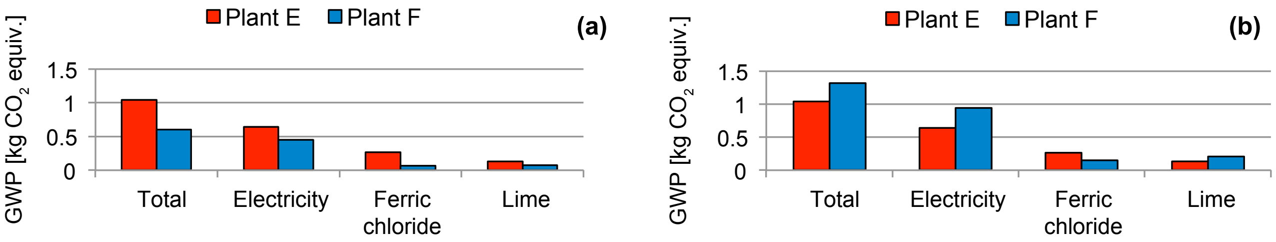


Figure 4.16. (a) GWP using m^3 of wastewater treated as the functional unit. (b) GWP using 200 mg of BOD removed as the functional unit.

over which the plant operators have any control. The focus must therefore shift towards reducing the amount of energy that is used by WWTPs.

AD would seem to be an attractive solution to deal with both an increase in demand for greater energy efficiency and an increase in national sludge volume. However, AD requires large start-up capital, skilled operators, a large feed stock and may not be ideally suited to Ireland's rural sprawl (i.e. small WWTPs dominate the landscape). A possible solution is centralised anaerobic digestion (CAD), which can accept feed stock not only from WWTPs, but also from agriculture. An LCA could be carried out to assess the long-term feasibility of such a venture. In general, there is no "one-size-fits-all" solution to sludge control, and its management should be dealt with on a case-by-case basis.

4.6 Exergy Analysis Results

Exergy analyses were carried out for plants E and F. The reason for selecting these two specific plants was primarily their similar scales, technologies and COD discharge requirements, thereby, in theory, facilitating thermodynamic performance comparisons.

Plant E comprises screening equipment, grit removal equipment, three aeration tanks (a diffused aeration system), two clarifiers, and phosphorus removal, sludge thickening and sludge dewatering equipment. Storm water storage tanks and a picket fence thickener are also included as part of the wastewater treatment works. The clarified effluent is discharged to a river. Plant F inlet works use mechanical and manual screens together with a compaction unit, an overflow unit and grit traps. The influent is then passed to anoxic tanks in which it is mixed with RAS. The effluent from each tank is spilt between the two aeration basins. The secondary treatment process is a single-stage anoxic zone aeration process followed by clarification. The clarified effluent is discharged to a river (Figure 4.17).

The boundary definitions for the plant exergy analyses are shown in Figure A1 of the appendix and were largely driven by data availability. The relevant inputs and outputs for the exergy analyses are shown in Boxes A1 and A2 of the appendix. Estimated values for RAS flow rates and concentrations were used. For the results presented here, mid-range values for pre-treatment COD reduction, RAS COD concentration and RAS return rate were chosen (i.e. 7.5% COD reduction, 8000 mg/L COD and 90% RAS rate, respectively; see section 3.5). Exergy analyses were undertaken for the pre-treatment processes, the secondary treatment processes and for an extended boundary incorporating both processes. The main reason for carrying out the extended boundary analysis was to include influent and effluent TN and TP concentrations in the exergy analyses; it was difficult to find reasonable estimates in the

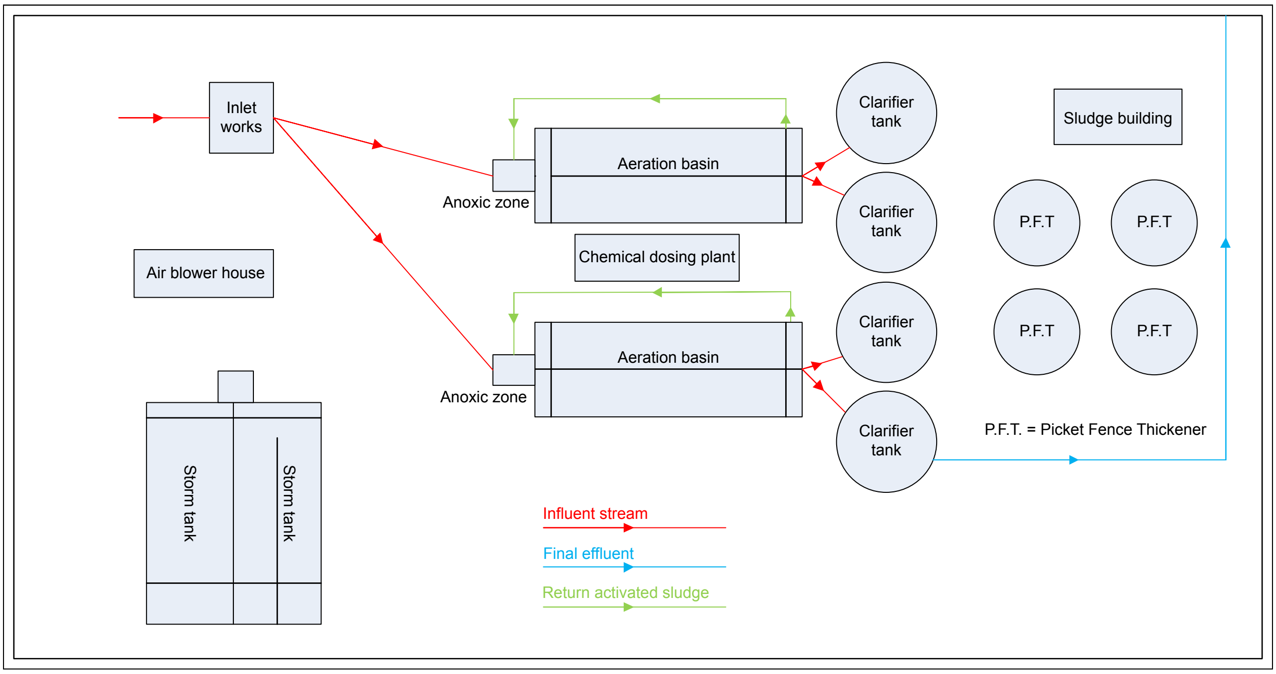


Figure 4.17. Schematic representation of the treatment process in plant F.

literature for TN and TP reduction across pre-treatment processes.

Table 4.5 collates the key results of the WWTP exergy analysis. The presented results include, for each WWTP, (1) the exergy destruction in each of the treatment stages, (2) the exergy losses to the environment, and (3) the rational exergetic efficiency (REE).

The REE of the extended boundary was calculated for both WWTPs. There are a number of exergetic efficiency definitions in the literature, which have been discussed in depth in previous publications (Kotas, 1995; Cornelissen, 1997; Fitzsimons, 2011). This research uses the REE definition from Kotas (1995), that is, the REE is defined as the exergy of the desired output divided by the exergy of the required inputs, which include the electrical exergy flows and any changes in exergy flows required to produce the desired output. Mathematically, for the WWTPs under consideration, this can be defined as shown in Equation (4.1):

$$\text{REE} = \frac{\text{Exergy}_{\text{effluent}}}{\text{Exergy}_{\text{electrical}} + \text{Exergy}_{\text{influent}} + \text{Exergy}_{\text{TN, TP, in}} - \text{Exergy}_{\text{sludge}} - \text{Exergy}_{\text{TN, TP, out}}} \tag{4.1}$$

Table 4.5. Exergy analysis results

WWTP	Exergy destruction (MJ/day)			Exergy losses (MJ/day)	Exergetic efficiency (%)
	Pre-treatment	Secondary treatment	Extended boundary		
Plant E	983.2	4920.7	6354.9	8278.5	27.5
Plant F	675.4	1619.9	2556	4682.7	40.2
Difference (%)	31.3	67.1	59.8	43.4	–46.2

At the pre-treatment stage, the magnitude of exergy destruction in plant E is 31.3% greater than in plant F. This is because of the difference in the incoming COD concentrations and the estimated changes in concentration that take place (note that the pre-treatment electrical energy inputs are assumed to be equivalent and it is primarily the difference in COD concentrations that causes these differences). The exergy due to the measured pre-treatment electrical energy requirements in both WWTPs is 180 MJ/day, whereas the exergy flows due to the influent COD concentrations are 10,709 MJ/day and 6605.4 MJ/day in plants E and F, respectively. Accordingly, the pre-treatment energy requirements are not a major factor in the pre-treatment exergy balance relative to the organic matter.

At the secondary treatment stage, the magnitudes of exergy destruction are 4920.7 MJ/day for plant E and 1619.9 MJ/day for plant F, giving a percentage difference of 67%. Putting this in context, the COD exergy flows are 9905.9 MJ/day for plant E and 6110 MJ/day for plant F. Measured COD values were used for the effluent streams, resulting in exergy flows of 2411 MJ/day and 1715.9 MJ/day for plants E and F, respectively. The exergy flows due to the aeration and RAS pumping energy inputs were 4920.7 MJ/day for plant E versus 1619.9 MJ/day for plant F. Therefore, from Table 4.5, it is evident that the exergy destruction that takes place in the secondary treatment process is equivalent to the exergy flows due to the electricity inputs. This is an interesting finding and is essentially a function of how the exergy of the wastewater is calculated. That is, it is a function of the COD concentration but may not effectively take into account the changes in the wastewater streams that take place in the aeration basin. The exergy losses, which are due to the WAS and the TN and TP outputs, are again notably different for both WWTPs: 8278.5 MJ/day for plant E versus 4682.7 MJ/day for plant F. The main reason for this is the difference in output COD concentrations in the WAS.

The hierarchy of exergy destruction across WWTP processes is important with regard to focusing improvement efforts. For both WWTPs, the majority of exergy destruction takes place at the secondary treatment stages; however, the proportion of total exergy destruction (i.e. the sum of pre-treatment and secondary treatment exergy destruction) attributable to the pre-treatment and secondary treatment processes is quite different. That is, the pre-treatment process in plant E is responsible for 16.7% of the total exergy destruction, whereas it is responsible for 29.4% in plant F.

The REE was found to be 27.5% for plant E and 40.2% for plant F. The differences in performance between the two WWTPs were notable across exergy destruction, exergy losses and exergetic efficiency. However, there is one important mitigating factor, and that is the differences between the influent COD concentrations. Plant E had an influent concentration of 426.1 mg/L COD, whereas plant F had an influent concentration of 245.3 mg/L COD. Although the measured effluent COD was lower for plant F (64.9 mg/L COD vs 104.5 mg/L COD for plant E), the electrical energy inputs for the extended boundary analysis were different for both WWTPs (1416.9 kWh/day for WWTP E vs 500 kWh/day for WWTP F). The end result was different exergetic efficiency profiles. As mentioned previously, the WWTP operator has little or no control over the quality of the water that arrives at the WWTP, and, therefore, the efficiency metrics generally considered in exergy analyses may not be sufficient to offer a fair comparison of WWTP performances. The use of exergy analysis without the corresponding consideration of water quality may lead to unfair comparisons between WWTPs and an additional, novel metric is proposed to capture these variations, namely exergy destruction per kg COD removed. Should data quality improve, future work will re-analyse the WWTPs to assess the implications of the assumptions made.

5 Conclusions

The main objective of this research was to assess and improve the efficiency of Irish WWTPs using a number of synergistic approaches, which included water quality and energy auditing, benchmarking, and environmental and thermodynamic performance assessment. There were several key challenges associated with undertaking this work: representative plant selection; the development of an appropriate auditing methodology; access to plant data, equipment and water quality samples; the identification of essential data requirements for each of the individual approaches followed by the development and implementation of data acquisition strategies; and the determination of metrics to provide fair comparisons across WWTPs, despite the many variables, such as influent quality, discharge requirements, scale and nutrient removal requirements, that exist. It was vital to build good working relationships and trust with the plant managers and operators to access the requisite data and information, and to discuss and understand any anomalies or issues that arose. Their contributions are gratefully acknowledged; without their help and process knowledge, this project would not have been feasible.

The principal outputs of this research project include the following:

- 10 representative Irish WWTPs have been audited (with regard to detailed energy breakdown and water quality);
- an energy auditing methodology for WWTPs has been developed;
- KPI benchmarking software tools/methodologies have been developed and tested;
- life-cycle models of WWTPs have been developed and LCAs of several Irish WWTP have been undertaken;
- exergy analyses of several Irish WWTPs were conducted.

5.1 Wastewater Treatment Plant Audits

The detailed energy and water quality audits that were undertaken informed the development of linked auditing and benchmarking methodology/toolkits (KPIAdvisor and KPICalc).

A detailed energy audit methodology was developed, including the consideration of sampling frequencies for various pieces of WWTP equipment. While it was found that energy monitoring equipment can be expensive and does require calibration and maintenance, detailed energy audits can provide accurate baselines for energy management and optimisation. Furthermore, they can highlight and pinpoint specific issues that may otherwise go unnoticed. Importantly, such detailed energy audits revealed several WWTP issues, such as poor power factors, blower control issues (e.g. switching from automatic to manual, which results in increased and unnecessary energy consumption), equipment breakdowns and poor equipment reliability.

One of the main challenges associated with assessing the performance of a WWTP lies in determining the most relevant metrics. Many of the plants examined in the study exhibited varying performance depending on the choice of KPI. This variance can be attributed to a number of factors, including influent composition, treatment technology, the level of treatment required, the type of control system (i.e. automated or manual), the plant discharge limits, the design capacity and the relationship between the current plant loading and the design capacity. It is therefore prudent to consider all of these factors when assessing plant performance.

It was also noted that a lack of reliable data (particularly flow and water quality data) can greatly hinder any benchmarking or auditing process. In some cases, such data were available but were found not to be accurate when checked against expected flows from the area being serviced.

Energetic economies of scale were apparent to some degree. There were some exceptional results that warrant further investigation. However, in general, the largest plants exhibited the best all-round efficiencies. It should also be considered that a larger sample size may have produced closer correlations with scale-efficiency predictions.

5.2 Benchmarking and Key Performance Indicators

There is a need for best management practices for WWTP benchmarking to focus on the identification of WWTPs capable of conducting accurate and detailed KPI analysis. The survey element (KPIAdvisor) of the benchmarking system, developed during this research, offers a viable solution to this problem in a concise and effective manner. Assessing and validating available data is key to effective benchmarking, as nothing can be gained from benchmarking with, or against, incorrect data.

Accurate flow data, along with regular compliance monitoring, are key requirements for any benchmarking scheme that aims to detail either operational performance or resource consumption in WWTPs. To accompany these datasets, high-resolution energy and chemical consumption data further increase the ability of a WWTP to achieve successful benchmarking.

The resource benchmarking methodology (KPIAdvisor and KPICalc) developed in this research is:

- easily accessible, highly automated and suitable for implementation in WWTPs with varying treatment processes, PE capacities, staffing numbers and resource consumption levels;
- adept at assisting stakeholders with the identification of faults in data acquisition methods in WWTPs prior to the initiation of WWTP resource consumption benchmarking; this feature can save WWTP managers and operators from spending time implementing a benchmarking system that is destined to fail because of poor data reliability;
- designed to offer toolkit users an incentive for improving data acquisition methods by displaying any additional KPIs to the user that could be adopted in their WWTP, provided that the corresponding data source inaccuracies are corrected;
- flexible in terms of the frequency of data collection it can handle, allowing WWTP managers to adopt periods of intensive monitoring in order to achieve continuous commissioning of a WWTP if desired.

5.2.1 Benchmarking results

The study shows that influent composition can have a large effect on the interpretation of the results and the defined plant performance. Influent composition is not a factor over which a plant operator has any control, and this aspect must be considered before making any comparative judgements. Of the plants that employ the conventional activated sludge system, those with higher concentrations of organic carbon loading may have comparatively lower energy usage if measured as kWh consumed/kg of BOD removed, whereas those with lower organic loadings and higher hydraulic loads may have comparatively lower energy usage if measured as kWh consumed/m^3 of treated wastewater. Lower organic loading results in less aeration energy consumption during secondary treatment, and a reduction in sludge treatment energy. This is offset by the energy efficiency that could be achieved by operating the secondary treatment process close to organic loading design capacity. Plants operating close to both organic and hydraulic design capacity perform better in most KPIs. This is most evident with the outputs from plant B, which operated at close to 100% capacity during the testing period.

The variance in discharge limits between plants adds to the difficulty in making a useful comparison between WWTPs. Tighter discharge requirements can result in a higher energy demand depending on the KPI to which the limit applies. The rate of change in the energy cost of treating wastewater to ever higher standards can result in significant (and non-linear) increases in energy demand. As well as the energy costs, more stringent discharge limits can also increase other resource costs related to, for example, the chemicals required to reduce phosphorus, ammonia and nitrogen levels.

5.3 Life-Cycle Assessment and Exergy Analysis

Life-cycle and exergy analyses can be useful tools for benchmarking current plant performance and to determine the impact of process changes on overall plant environmental and thermodynamic performances. In order to carry out these analyses, basic information is required, for example data on flow, energy, sludge, water and chemical usage. Acquiring these data, particularly inter-process and emissions data, presented challenges, on occasion, throughout this project.

The LCA studies resulted in some very interesting findings. Two important environmental considerations that are often overlooked when considering WWTP performance are the energy required to operate WWTPs and the management of the sludge produced by plants. With regard to plant energy consumption, the Irish electricity mix contributes greatly to the environmental impact of Irish WWTPs and, since this is unlikely to change in the near future, improved energy efficiency appears to be the best option in the short term.

Sludge management should be approached on a case-by-case basis, as there is no one-size-fits-all solution. Direct application of sludge to farmland may not be an option in the near future and provisions should be made to deal with the likely increase in sludge volume. Plants that serve large agglomerations have the option of employing AD, which can reclaim energy through biogas production, reduce sludge volume and transport costs, and mitigate the environmental and financial costs associated with lime stabilisation. For small rural plants, the practice of transporting sludge to larger plants with a sludge treatment hub already exists and should continue until the technology improves to the point at which small-scale sludge treatment becomes economically viable. Alternatively, CAD centres that include inputs from agriculture and other feedstock could be considered.

Exergy analyses were carried out for two Irish WWTPs that are of a similar scale and use similar technologies. The magnitude of exergy destruction and the REE differed significantly between these two plants. Although the two plants were similar in scale, there was over a two-fold difference in exergy destruction across the plants: the plant with the lower organic loading exhibited significantly less exergy destruction and increased exergetic efficiency. Again, the influent concentration was an important mitigating factor. A novel exergy-based metric was proposed to account for the organic loading variations. Some potential limitations were identified with regard to the current approaches used to calculate WWTP exergy values; coupled with data limitations, it is currently difficult to draw well-supported conclusions and make exergy-based decisions. Notwithstanding this, the thermodynamic performance trends are very interesting. Further work is required to tease out the existing shortcomings and a repeat of this analysis is planned if more data become available.

6 Recommendations

6.1 Assess Plant Performance using Multiple Criteria and KPIs

This study showed that the performance of WWTPs is a function of many variables, including some, such as influent concentrations and discharge requirements, over which a plant manager has little control. Therefore, common, simple benchmarking metrics, such as kWh/m^3 or kWh/PE, are unlikely to allow fair comparisons across plants. Similarly, energy audits or water quality testing alone are not sufficient to comprehensively audit and benchmark plant performance.

6.2 Design for Efficiency at the Outset

Effectiveness and efficiency should not be considered separately, and the ultimate goal should be to operate WWTPs that are both effective and efficient. In general, this is best achieved at the design phase, during which the longer term life-cycle costs and performance of the WWTP can be anticipated and optimised, rather than by solely focusing on the initial capital costs. An integrated engineering design (civil, mechanical and electrical) should be applied to both the immediate plant design and layout, and local networks, if possible. Piping and pumping networks should be optimised to minimise life-cycle costs and long-term energy consumption.

6.3 Specify and Provide Adequate Monitoring, Monitoring Instrumentation and Equipment

The specification and provision of adequate monitoring instrumentation can facilitate monitoring, management, control and optimisation of plant performance. Such instrumentation includes:

- influent and effluent flow meters;
- water consumption meters;
- energy monitoring equipment/methodologies.

Whole-life costs should be considered when investing in such equipment.

6.3.1 Flow monitoring

Prior to WWTP benchmarking, it should be ensured that flow monitoring equipment appropriate for the plant size is present, fully functional and accurate. In order to achieve this, it is necessary to inspect flow monitors on a regular basis in order to ensure that:

- flow monitors are installed at the correct locations within the WWTPs (influent monitor incorrectly installed post-RAS return feed in plant G and effluent monitor incorrectly positioned in plant D);
- flow monitors that involve flumes and ultrasonic level sensors are not impeded by any upstream or downstream elements, such as manual screens, etc., and that the channel is kept clear (incorrect flow monitoring occurred in plant B because of this issue);
- flow monitors are calibrated as required (infrequent flow monitor calibration identified in plant D).

The collection of mains water data provides information on water consumed on site as a result of tank cleaning, etc. These data, in most cases, are readily available because of the presence of a water meter on the mains supply; however, they are often overlooked. Water consumption data provides a more holistic view of the quantity of the various resources consumed in order to treat wastewater in an effective manner.

6.3.2 Energy monitoring

If a WWTP manager is planning to develop an energy monitoring/auditing scheme, based on this report, it is recommended that energy data are initially collected from the energy provider (if available) prior to the purchase and installation of perhaps expensive energy monitoring equipment. This is recommended as a starting point to ensure that, once an energy monitoring/auditing scheme is adopted, it can be maintained over time by WWTP staff, who already fulfil expansive roles.

On the other hand, there is no substitute for detailed energy monitoring in order to baseline and optimise

WWTP and plant equipment performances. This study identified several specific plant issues, which would otherwise have gone unnoticed, by undertaking comprehensive plant energy audits.

6.3.3 Chemical and other consumable usage monitoring

It is recommended that detailed records of the usage of chemicals and other consumables (e.g. membranes) should be kept.

6.3.4 Sludge monitoring

It is recommended that detailed sludge management records should be kept.

6.4 Adopt a Holistic Approach to the Evaluation of Environmental Performance

Effluent discharge is not the sole indicator of plant environmental performance. A good level of control over eutrophication loading was exhibited by the plants and was achieved via the imposition and meeting of discharge limits on the final effluent quality. Energy and chemical consumption and sludge management have their own, often significant, environmental impacts, and it is crucial not to lose sight of this when operational changes or indeed policy decisions are made.

6.5 Plant Loadings Must Match Plant Capacity

It is evident that, ideally, plant loadings should match plant capacity. Equipment should be selected so that it is efficient for the current plant loading, but also so that it can facilitate flexibility and efficiency for predicted future loadings. Blowers and frequently used pumps should have duty and standby units that are rotated regularly to avoid overuse of individual plant items.

6.6 Use Energy-Efficient Equipment

There are opportunities to improve the efficiency of existing plants. However, in order to achieve this, a good understanding of current WWTP performance, and the potential for improved performance, is required. Pump energy calculators, including simple payback calculations, are available from the Sustainable Energy Authority of Ireland[4] and could be effective.

Old pumps and blowers should be upgraded to energy-efficient pumping systems based on appropriate payback periods. If possible, pumps and blowers with appropriate variable frequency drives should be retrofitted (choosing a VFD with a higher number of pulse converters creates a signal with less harmonic distortion).

6.7 Introduce and Implement Preventative Maintenance Schedules

PM reduces equipment wear, increases service life and potentially increases energy efficiency across the plant. PM can be as simple as weekly visual inspections, or more complex, involving, for example, monthly or yearly equipment audits that include detailed equipment monitoring and/or thermographic analyses.

6.8 Review Plant Power Factors and Control Strategies Regularly

Plant power factor correction units should be reviewed regularly to ensure that they are correctly specified for the plant size. Retrofitting passive or active filters can remove unwanted harmonic distortion and therefore increase the life of plant equipment. Blower control strategies should be reviewed and optimised regularly if possible (DO control/ammonium–DO cascade control). Switching from automatic to manual control can occur and this leads to unnecessary and expensive energy consumption.

6.9 Identify Data Requirements Prior to Managing, Benchmarking and Optimising WWTP Performance

Data requirements should be highlighted prior to commencing management or benchmarking schemes in any WWTP to ensure that the required data are available, accurate and of sufficient frequency. A means of identifying data requirements is included in the benchmarking system developed in this research (KPIAdvisor).

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[4] Adapted from http://www.seai.ie/energymap/Resources_tools/Template_Energy_Use_Cost_Savings_/Pump_Energy_Efficiency_Calculation_Tool/

Publications Arising from this Research

Articles

Doherty, E., Fitzsimons, L., Corcoran, B. *et al.,* 2014. A resource consumption benchmarking system for WWTPs. *Asian Water* 11: 11–16.

McNamara, G., Fitzsimons, L., Phelan, T. *et al*., 2016. Life cycle assessment of wastewater treatment plants in Ireland. *Journal of Sustainable Development of Energy, Water and Environment Systems* (in press).

Fitzsimons, L., Horrigan, M., McNamara, G. e*t al.* Benchmarking the thermodynamic performance of Irish municipal wastewater treatment plants using exergy analysis. *Journal of Cleaner Production* (submitted, under review).

Peer-reviewed Conference Papers

Doherty, E., McNamara, G., Phelan, T. *et al*., 2015. *Benchmarking Resource Efficiency in Wastewater Treatment Plants: Developing Best Practices*. IWA International Conference on Water Efficiency and Performance Assessment of Water Services, 20–24 April 2015, Cincinnati, OH, USA.

McNamara, G., Fitzsimons, L., Doherty, E. *et al*., 2015. *Performance Metrics in Life Cycle Assessments of Wastewater Treatment Plants*. 10th Conference on Sustainable Development of Energy, Water and Environment Systems, 27 September–2 October 2015, Dubrovnik, Croatia.

Doherty, E., Fitzsimons, L., Corcoran, B. *et al*., 2014. *Design and Implementation of a Resource Consumption Benchmarking System for Wastewater Treatment Plants*. The IWA Water, Energy and Climate Conference 2014, 21–23 May 2014, Mexico City, Mexico.

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Fitzsimons, L., McNamara, G., Phelan, T. *et al*., 2014. *Energy and Water: Wastewater Treatment.* Water: the Greatest Global Challenge – 2nd Annual Conference, 27–28 November 2014, DCU Water Institute, Dublin.

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Abbreviations

AD	Anaerobic digestion
AP	Acidification potential
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BOD	Biochemical oxygen demand
BOD_5	5-Day biochemical oxygen demand
CAD	Centralised anaerobic digestion
COD	Chemical oxygen demand
DO	Dissolved oxygen
EPA	Environmental Protection Agency
GWP	Global warming potential
ICA	Instrumentation, control and automation
IEEE	Institute of Electrical and Electronics Engineers
KPI	Key performance indicator
KPIAdvisor	Key Performance Indicator Advisor
KPICalc	Key Performance Indicator Calculator
LCA	Life-cycle analysis
LCI	Life-cycle inventory
LCIA	Life-cycle impact assessment
NH_4-N	Ammonium nitrogen
PE	Population equivalent
PFBR	Pump flow biofilm reactor
PM	Preventative maintenance
PQA	Power quality analyser
RAS	Return activated sludge
REE	Rational exergetic efficiency
SCADA	Supervisory control and data acquisition
THD	Total harmonic distortion
TN	Total nitrogen
TOC	Total organic carbon
TOD	Total oxygen demand
TP	Total phosphorus
TSS	Total suspended solids
VFD	Variable frequency drive
WAS	Waste activated sludge
WWTP	Wastewater treatment plant

Appendix

Table A1. WWTP characteristics

Characteristic	WWTP A	WWTP B	WWTP C	WWTP D	WWTP E	WWTP F	WWTP G	WWTP H	WWTP I	WWTP J
Treatment technology	Activated Sludge	Activated Sludge	Activated sludge with P removal	Activated Sludge	Activated sludge with P removal	Activated sludge with P removal	Activated sludge with P removal	Activated sludge with P removal	PFBR (biofilm)	Activated sludge with P removal
Influent characteristics	Municipal wastewater only	Municipal wastewater and landfill leachate	Wastewater and landfill leachate	Municipal wastewater and landfill leachate	Municipal wastewater only	Municipal wastewater only	Municipal wastewater and landfill leachate	Municipal wastewater only	Municipal wastewater with storm water	Municipal Wastewater only
Tertiary treatment	None	None	Sand filtration	None	None	None	None	None	None	None
Design capacity (BOD)	186,000 PE	25,000 PE	24,834 PE	18,517 PE	12,000 PE	12,000 PE	5000 PE	820 PE	750 PE	600 PE
Organic loading	79,133 PE (2015)	18,659 PE (2013)	22,440 PE (as of 2010)	25,633 (2014)	12,284 PE (2014)	9036 PE (2015)	2500 PE (2014)	590 PE (2015)	422 PE	1024 PE (2015)
Hydraulic capacity (DWF) (m^3/year)	13,140,000	2,253,753	1,847,995	1,420,215	1,642,500	821,250	200,750	36,500		49,275
Hydraulic capacity (peak flow) (m^3/year)	39,420,000	6,761,260	5,543,985	4,260,645	4,927,500	2,463,750	602,250	109,500		147,825
Hydraulic loading (m^3/year)	14,940,180	2,056,410	1,303,780	3,544,150	839,135	1,072,005	570,228	41,245		110,960
Discharges into	Long sea outfall	River	River	River	River	River	River	River	River	River
Test frequency	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	3 times per year	Bi-monthly

Table A1. WWTP characteristics (continued)

Characteristic	WWTP A	WWTP B	WWTP C	WWTP D	WWTP E	WWTP F	WWTP G	WWTP H	WWTP I	WWTP J
Discharge requirements										
pH	–	6–9	7–9	6–9	6–9	6–9	6–9	6–9	–	6–9
Temperature	–	25°C (max)	25°C (max)	25°C (max)	–	–	25°C (max)	–	–	–
BOD	25 mg/L	25 mg/L	15 mg/L	25 mg/L	25 mg/L	20 mg/L	10 mg/L	25 mg/L	–	10 mg/L
COD	125 mg/L	125 mg/L	125 mg/L	125 mg/L	125 mg/L	125 mg/L	125 mg/L	125 mg/L	–	50 mg/L
Suspended solids	35 mg/L	35 mg/L	15 mg/L	35 mg/L	35 mg/L	30 mg/L	35 mg/L	35 mg/L	–	25 mg/L
TN (as N)	–	15 mg/L	15 mg/L	15 mg/L	–	20 mg/L	–	–	–	–
TP (as P)	–	–	2 mg/L	2 mg/L	2 mg/L	1 mg/L	–	–	–	–
Ammonia (as N)	–	10 mg/L	1 mg/L	–	5 mg/L	–	1 mg/L	5 mg/L	–	1 mg/L
Orthophosphate (as P)	–	5 mg/L	0.2 mg/L	–	1 mg/L	–	1 mg/L	2 mg/L	–	0.5 mg/L
Sludge treatment										
Yearly sludge output (kg dry solids)	1,394,395	559,800	2,760	2,197,410	183,600	108,000	14,280	N/A	N/A	N/A
Sludge out per m³ of influent (kg dry solids)	0.09		0.00	0.62	0.22	0.10	0.03	N/A	N/A	N/A
Sludge treatment	Centrifugal dewatering and thickening, chemical stabilisation and AD	Chemical dosing, picket fence thickener and belt press	Primary sludge stabilisation tank, thickening, dewatering and lime stabilisation	Sludge holding tank, picket fence thickener, belt press and lime stabilisation	Picket fence thickeners, centrifugal dewatering and thickening, chemical stabilisation	Picket fence thickeners, centrifugal dewatering and thickening, chemical stabilisation		None (sent for external treatment)	N/A	None (sent for external treatment)
Sludge disposal method	Composting	Exported for nutrient recovery	Composting and land spreading	Land application	Land application	Land application	Land application	Land application	N/A	Land application

N/A, not applicable.

Table A2. WWTP testing methods

Characteristic	WWTP A	WWTP B	WWTP C	WWTP D	WWTP E	WWTP F	WWTP G	WWTP H	WWTP I	WWTP J
Sampling dates	3–7, 10–14, 17–21 and 24–26 November 2013	9–29 September 2014	Ongoing	5–12 December 2014	2–7 September 2014	7–9, 14, 15–16 and 19 October 2015	4 July to 25 August 2014	18–20 and 24 November 2015	9–30 June 2014	6–9 November 2015
Number of days	18 days	21 days	Ongoing	8 days	6 days	7 days	53 days	4 days	22 days	4 days
Flow streams sampled	Influent and effluent	Influent and effluent	Influent and effluent	Influent and effluent	Influent and effluent	Influent and effluent	Influent and effluent	Influent	Influent and effluent	Influent
Number of samples per stream per day	As per plant managers schedule	3	As per plant managers schedule	4	6	6	3	6	3	6
Time between samples	N/A	8 hours	N/A	6 hours	4 hours	4 hours	8 hours	4 hours	8 hours	4 hours
Influent testing location	Influent stream	Screening	Influent stream	Influent stream	Screening	Screening	Screening	Influent stream	Imhoff tank	Influent stream
Influent sampling method	Grab sample (automatic sampler)	Grab sample (automatic sampler)	Grab sample	Grab sample (automatic sampler)	24-hour composite	24-hour composite	Grab sample (automatic sampler)	24-hour composite	Grab sample (automatic sampler)	24-hour composite
Effluent testing location	Outfall channel	Leaving final clarifier	Leaving final clarifier	Effluent channel	Leaving final clarifier	Leaving final clarifier	Effluent sump	Effluent channel	Leaving final clarifier	Leaving final clarifier
Effluent sampling method	Grab sample (automatic sampler)	Grab sample (automatic sampler)	Grab sample	Grab sample (automatic sampler)	24-hour composite	24-hour composite	Grab sample (automatic sampler)	24-hour composite	Grab sample (automatic sampler)	24-hour composite
Energy data	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Data point frequency	Daily totals and process breakdown	25–60 s	As frequent as necessary (historical data)	25–60 s	30–60 s	30–60 s	25–60 s	30–60 s	25–60 s	30–60 s
Influent flow data	Yes	No	Yes	Yes	Yes	Yes	No	Yes	No	Yes
Frequency and type	Daily total	N/A	Daily total	Daily total	Daily total	Daily total	N/A	Daily total	N/A	Daily total
Effluent flow data	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	No
Frequency	Daily total	Daily total	Daily total	N/A	Daily total	Daily total	Daily total	N/A	Daily total	N/A

Table A3. Site-specific data used in LCA

Parameter	Description
Volume of wastewater treated	The volume of wastewater treated in m^3
BOD	The amount of oxygen used by microorganisms while consuming organic matter
COD	A measure of the oxygen required to oxidise the wastewater under aerobic conditions, and determined experimentally by measuring the amount of a chemical oxidising agent needed to fully oxidise a sample
Total suspended solids	The sum of the organic and inorganic solid concentrations in the wastewater
TN	See section 3.2.1
TP	See section 3.2.1
Energy	
Electricity	Electricity used
Natural gas	Natural gas used
Chemicals	
Ferric chloride	Ferric chloride used for phosphorus precipitation
Sodium hypochlorite	Sodium hypochlorite used for deodorisation
Sodium hydroxide	Sodium hydroxide used for deodorisation
Sludge	Monthly average of sludge produced on-site

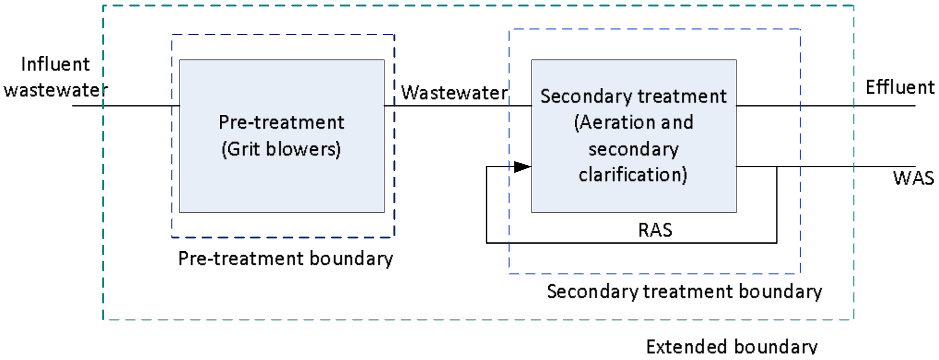

Figure A1. Boundary definition for the plant exergy analyses.

Box A1. Plant E exergy analysis inputs and outputs

Pre-treatment

Inputs:

- Wastewater (COD 426.1 mg/L; flow rate 1848 m^3/day)
- Electricity (grit blowers 50.01 kWh/day)

Outputs:

- Wastewater (COD 394.14 mg/L; flow rate 1848 m^3/day)

Secondary treatment

Inputs:

- Wastewater (COD 394.14 mg/L; flow rate 1848 m^3/day)
- Electricity (aeration blowers and sludge return pumps 1366.9 kWh/day)
- RAS (COD 8000 mg/L; flow rate 1663.2 m^3/day

Outputs:

- Effluent (COD 104.53 mg/L; flow rate 1696 m^3/day)
- WAS (COD 8000 mg/L; flow rate 68.89 m^3/day)

Extended boundary

Inputs:

- Wastewater (COD 426.1 mg/L; flow rate 1848 m^3/day)
- Electricity (grit blower, aeration blowers and sludge return pumps 1416.9 kWh/day)
- TN (71.46 mg/L)
- TP (7.66 mg/L)

Outputs:

- Effluent (COD 104.53 mg/L; flow rate 1696 m^3/day)
- WAS (COD 8000 mg/L; flow rate 68.89 m^3/day)
- TN (50.06 mg/L)
- TP (0.98 mg/L)

Box A2. Plant F exergy analysis inputs and outputs

Pre-treatment

Inputs:

- Wastewater (COD 245.3 mg/L; flow rate 1980 m^3/day)
- Electricity (grit blowers 50.01 kWh/day)

Outputs:

- Wastewater (COD 226.9 mg/L; flow rate 1980 m^3/day)

Secondary treatment

Inputs:

- Wastewater (COD 226.9 mg/L; flow rate 1980 m^3/day)
- Electricity (aeration blowers and sludge return pumps 450 kWh/day)
- RAS (COD 8000 mg/L; flow rate 1782 m^3/day)

Outputs:

- Effluent (COD 64.9 mg/L; flow rate 1944 m^3/day)
- WAS (COD 8000 mg/L; flow rate 40.39 m^3/day)

Extended boundary

Inputs:

- Wastewater (COD 245.3 mg/L; flow rate 1980 m^3/day)
- Electricity (grit blower, aeration blowers and sludge return pumps 500.01 kWh/day)
- TN (29.6 mg/L)
- TP (3.63 mg/L)

Outputs:

- Effluent (COD 64.9 mg/L; flow rate 1944 m^3/day)
- WAS (COD 8000 mg/L; flow rate 40.39 m^3/day)
- TN (16 mg/L)
- TP (0.85 mg/L)

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú

Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:

- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce

- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol

- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn

- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil

- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta

- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas

- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta

- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:

- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- An Oifig um Cosaint Raideolaíoch
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research Report 168

Increasing Resource Efficiency in Wastewater Treatment Plants

Authors: Lorna Fitzsimons, Eoghan Clifford, Greg McNamara, Edelle Doherty, Thomas Phelan, Matthew Horrigan, Yann Delauré and Brian Corcoran

epa Research
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

This research adopted a multi-pronged approach to audit and benchmark the resource efficiency of Irish wastewater treatment plants (WWTPs), including the use of life-cycle analysis (LCA) and exergy analysis. Ten representative Irish WWTPs were audited in detail. The plants varied in scale, with regard to their design capacities, from 600 PE to 186,000 PE. Simultaneous energy and resource consumption and water quality audits were undertaken, resulting in the development of benchmarking tools and auditing methodologies, and the detailed performance evaluation of the plants to support better resource management and to provide baseline data with regard to the holistic performance of the WWTPs. The results of this research should be of interest to Irish Water and other water utilities, the EPA, WWTP managers, researchers, and policy makers inter alia.

Identifying Pressures

Wastewater treatment is a resource intensive process utilising several inputs such as energy, chemicals and water to produce an effluent that meets designated environmental standards. Driven by environmental regulations, the focus of wastewater treatment plants (WWTPs) has traditionally been the quality of the effluent and not necessarily energy or resource efficiency. Regulation and penalties incentivise the meeting of environmental effluent standards; however, to date, there are no such analogous penalties or incentives to expedite the focus on resource efficiency. It is imperative to recognise that resource utilisation and indeed sludge management also have significant environmental consequences, and therefore WWTP performance should be viewed holistically.

Informing Policy

The development of effective environmental wastewater treatment policies is dependent on a holistic understanding of the environmental impacts of wastewater treatment. Knowledge of these impacts in turn relies on accurate data to quantify the resources consumed to treat wastewater to the designated standards, and the impact of this broader consumption on the environment.

Developing Solutions

A suite of software tools to assist WWTP benchmarking and performance management was developed and tested: KPIAdvisor and KPICalc. The tools are easily accessible, highly automated, and suitable for implementation in WWTPs of varying treatment processes, population equivalent, staffing numbers and resource consumption. In addition, the toolkit can assist stakeholders in the identification of faults in data acquisition methods, offers users an incentive for improving data acquisition methods, and is flexible in terms of the frequency of data. Effective and efficient operation of WWTPs is best achieved at the design phase, when the longer term life cycle costs and performance of the WWTP are anticipated and optimised, rather than solely focusing on the initial capital costs. The key recommendations are as follows:

- Assess plant performance using multiple criteria and KPIs
- Specify and provide adequate monitoring, monitoring instrumentation and equipment
- Use energy efficient equipment
- Introduce and implement preventative maintenance schedules for plant process equipment, and ensure plant monitoring equipment is calibrated regularly
- Review plant power factors and control strategies regularly

Comhshaol, Pobal agus Rialtas Áitiúil
Environment, Community and Local Government

EPA Research: McCumiskey House,
Richiew, Clonskeagh, Dublin 14.

Phone: 01 268 0100
Twitter: @EPAResearchNews
Email: research@epa.ie

www.epa.ie

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