Life Cycle Assessment of Waste Water Treatment Plants in Ireland

Greg McNamara
School of Mechanical Engineering
Dublin City University, Glasnevin, Dublin 9, Ireland
e-mail: greg.mcnamara5@mail.dcu.ie

Matthew Horrigan, Thomas Phelan, Lorna Fitzsimons[1], Yan Delaure, Brian Corcoran
School of Mechanical Engineering
Dublin City University, Glasnevin, Dublin 9, Ireland
e-mail: lorna.fitzsimons@dcu.ie

Edelle Doherty, Eoghan Clifford
Civil Engineering, College of Engineering and Informatics
National University of Ireland Galway
University Road, Galway, Ireland

ABSTRACT

The European Water Act 91/271/EEC introduced a series of measures for the purpose of protecting the environment from the adverse effects of effluent discharge from Waste Water Treatment Plants (WWTP). There are environmental costs associated with attaining the required level of water quality set out in the act such as, emissions from energy production, ecotoxicity from sludge application to land. The goal of this study is to assess these costs. Life Cycle Assessment (LCA) has been the analytical tool used to evaluate the environmental loadings. The CML 2001 Life Cycle Impact Assessment (LCIA) methodology has been adopted and implemented using GaBi 6.0 LCA software. Two plants of varying size and location were chosen for the study. The study found that energy consumption and sludge application to land are the largest contributors to the environmental impact associated with waste water treatment.

KEYWORDS: Wastewater treatment, life cycle assessment, energy, sludge disposal, anaerobic digestion

INTRODUCTION

On the 21st of May 1991 the then European Economic Community (EEC) issued the 91/271 directive that would set in motion a series of reforms to protect the environment from the adverse effects of effluent being discharged from WWTPs [1]. The directive made recommendations on the collection, treatment, and discharge of urban waste water. One of its

[1] Corresponding author

key aspects is that agglomerations greater than 2,000 p.e.[2] discharging final effluent into freshwater and estuaries, and all other agglomerations greater than 10,000 p.e. are to employ secondary treatment[3]. This requirement presents local and national authorities with the challenge of firstly assessing the current state of their respective sewage systems, before bringing standards to required levels.

In Ireland it is the responsibility of the Environmental Protection Agency (EPA) to enforce the measures outlined in 91/271/EEC. In 2013 the EPA initiated a research project to benchmark the energy and resource efficiency of WWTPs in Ireland. So often the metric used to assess the performance of a WWTP is the percentage reduction of influent pollutants such as BOD, COD (chemical oxygen demand) and TSS (total suspended solids). While control of these parameters is necessary for compliance with the regulations, there are other factors involved that must be taken into account. When assessing WWTP efficiency, the environmental cost of attaining the required level of effluent quality must also be considered.

Life Cycle Assessment allows for a holistic approach to the problem of assessing the environmental performance of a product or system, and has been widely accepted as a decision support tool for government bodies, local authorities, and areas of the industrial sector [3-5]. The application of LCA to examine the performance of WWTP is particularly suitable due to the nature of the relationship between a plant's technosphere and the surrounding ecosphere. Indeed there has already been a variety of LCA studies carried out on WWTP, each with their own unique set of objectives but with the common underlying theme of seeking to quantitatively and qualitatively assess environmental impact [6-9].

This paper examines the environmental loadings from two WWTPs in Ireland. The plants vary in size and location. The variation in location is specifically to assess the difference in environmental loading between plants with sensitive and non-sensitive receiving waters. Flow data were collected directly from both sites. Upstream and downstream data were supplied by PE International. The CML (Centre of Environmental Science) 2001 LCIA methodology is used in this study.

GOAL AND SCOPE DEFINITION

This study is part of a larger project that aims to assess the energy and resource efficiency of WWTPs in Ireland. The main goal of the LCA component of the project is to quantify the environmental loading that results from reaching the effluent quality standards set out in 91/271/EEC. The specific goal of this paper looks to assess the environmental costs or gains associated with variations in plant size and location. It has been reported in previous studies by Tillman et al [6] and Lundin et al. [10] that there are economies of scale to be achieved in terms of environmental impact, but this claim has never been investigated from an Irish perspective. The variation in plant location focuses mainly on differences in receiving waters – sensitive versus non-sensitive. The water act requires that there is nutrient reduction of final

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

[3] *"Secondary treatment means treatment of urban waste water by a process generally involving biological treatment with a secondary settlement."* [1]

effluent being discharged into sensitive waters which involves a greater degree of treatment and can result in an increase of sludge volume.

Functional unit

There are a number of options available for the choice of functional unit in a WWTP LCA, such as volume of sludge produced or quantity of removed pollutants. Suh and Rousseaux [11] have recommended using (x) m^3 of treated effluent for one year as it is clear and easy to establish inventory. The functional unit used in this study is the influent generated by one person equivalent (p.e.). It is a popular choice among LCA practioners when direct volumetric flow data are not available and also allows for comparison with other studies of a similar nature [12].

Boundaries

It has been well documented by many LCA practitioners that the construction phase of a WWTP's life cycle is negligible compared to the operation and maintenance phase [6, 10], and as such has been omitted from the analysis. The collection and delivery of influent has not been included in the analysis as delivery systems can vary greatly, thus leading to unfair comparisons. It is also worth reverting back to the goal and scope of the study, where the focus is on plant efficiency and not the entire waste water system. It is for this reason that the "gate-to-grave" practice has been adopted for the delivery of the influent, whereby the 'gate' is deemed to begin where the influent physically enters the WWTP domain. Upstream processes such as electricity, natural gas and chemical production have been included. Many LCA studies extend the boundaries of their systems to include the production of mineral fertilizers so as to include nitrogen and phosphorus in the sludge applied to land as avoided products. However, in a study carried out by Renou et al. [13], it is stated that mineral fertilizers are spread on growing crops, and that due to safety concerns sludge is applied to the land before crop growth. Therefore, the sludge cannot be deemed to have the same fertilizing effect. Consequently, nitrogen and phosphorous in sludge outputs have not been included as avoided products.

Plant Descriptions

Plant A has a design capacity of over 100,000 p.e. and an average dry weather flow of 35,000 m^3/day. The plant is situated on the coast and discharges the final effluent into the sea. These are not sensitive waters and the plant operators are not compelled to reduce nutrient levels in the final effluent. The plant does however have an anoxic zone equipped for nitrification/denitrification should legislation ever change regarding nutrient reduction requirements. The treated water flow line for plant A (Figure 1) is much the same as that of plant B, with only scale of the processes separating the two plants. The influent entering plant A comes from several catchment areas and is fully domestic. There are no industrial waste waters included.

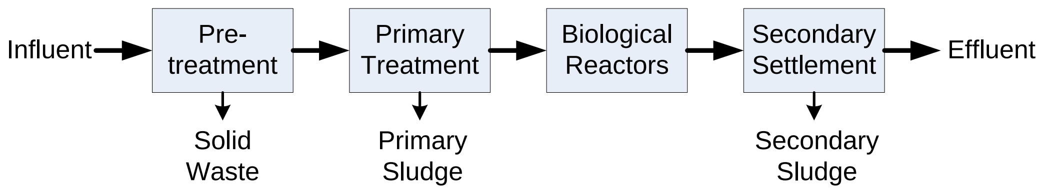

Figure 1. Treated water flow line for both plants A and B.

The sludge line in plant A is in two stages. Firstly the primary sludge goes through a strain press, a drum thickener and then to a mixed sludge tank. The waste activated sludge (WAS) goes through a thickening centrifuge and then to the mixed sludge tank. The mixed sludge then goes to the anaerobic digesters where biogas is produced and sent to the CHP hub. The biogas produced provides > 10% of the total energy used by the plant. The digested sludge with a dry solid concentration of 22% is sent to a holding tank before being sent off site to a composting company. The solid waste that is collected at the inlet works is compressed before being sent to landfill.

The plant is situated in close proximity to residential housing and as such, is subject to very strict odour controls. The odour control system is a very significant aspect of the overall operation of the plant. All process lines are covered by GRP (glass reinforced plastic) covers. Odorous processes have double cover – direct extraction from processes and ambient extraction from building. The collected gas is sent to three deodorisation towers situated around the plant that employ a range of carbon filters and chemical scrubbing agents such as sodium hypochlorite and sodium hydroxide. Hydrogen sulphide (H_2S) and VOC monitors are situated strategically around the perimeter of the plant and there are also H_2S monitors inside each of the deodorising towers.

Plant B has a design capacity of 50,000 p.e. and serves a current agglomeration of 38,000 p.e. The plant is situated inland and discharges its final effluent into a river. These are sensitive waters and therefore nutrient reduction is necessary. As mentioned previously, the treated water flow line is similar to that of plant A (Figure 1) but with the addition of a nitrification/denitrification zone that occupies 25% of the total volume of the aeration basins. Plant B accepts additional waste waters from a waste service company that is classified as grey/dirty water, and from a meat factory that consists mainly of blood and brine. These additional waste waters are introduced at the inlet works of the plant and account for a negligible percentage of the total plant influent.

Plant B has a sludge treatment hub that consists of Picket Fence Thickeners (PFT) for thickening of primary sludge and a Rotary Drum Thickener (RDT) for thickening WAS. There are two Anaerobic Digesters (AD) and storage for biogas. However, during the period of research on the plant these sludge treatment processes were not functioning and sludge treatment was limited to belt filtration and lime stabilisation. The result of this process is an estimated dry solids concentration of 8% [14]. The sludge is then taken from the plant for application to the land.

METHODOLOGY

The software chosen for the project was GaBi 6.0. The GaBi data base provided by PE International contains many of the upstream processes such as energy production and diesel refinement. Further datasets that were supplied by PE International were waste water treatment and chemical production data. The life cycle impact assessment (LCIA) methodology used in the study is CML 2001 (Nov.10) which is largely compliant with the ISO 14040 series[4]. There are nine impact categories used in the analysis, the choices of which are consistent with many other LCA studies of WWTPs [7, 12, 15] The impact categories consist of:

- Global Warming Potential (GWP)
- Eutrophication (EP)
- Acidification Potential (AP)
- Ozone Layer Depletion Potential (ODP)
- Ecotoxicity Potential
    - Marine Aquatic (MAETP)
    - Freshwater Aquatic (FAETP)
    - Terrestrial (TETP)
- Human Toxicity Potential (HTP)
- Abiotic Depletion fossil (ADP)

DATA QUALITY

The data quality in an LCA will ultimately determine the level of meaningfulness and transparency in the study. Direct collection and analysis of data is always the most preferred level of quality but not always the most practical or even possible. In this project a selection of data has had to be collected from the literature and a number of estimations have had to be made where gaps in direct, on-site data existed. Table 1 outlines the data sources used in the study. In general, the data for Plant A is of a higher quality than that of plant B. Plant A in its current form is only 2 years old. It has a bespoke, state-of-the-art SCADA system that monitors almost all aspects of plant operation. Sampling of influent, primary effluent and final effluent for BOD, COD and TSS are carried out daily. Sludge outputs are recorded as well as biogas produced from AD. Electricity consumption is recorded and can also be quantified at a subsystem level – inlet works, biological reactors, sludge treatment, outfall pumping and utilities have individual metering. Ammonia emissions resulting from sludge storage had to be estimated. All of the upstream data such as electricity and chemical production is supplied by PE International. Electricity and natural gas production reflects Ireland’s electricity grid and natural gas mix respectively, but chemical production is based on European averages. Downstream data – energy and resource consumption data, emissions data - for the composting company used by plant A were not available; therefore the main pollutants in the sludge leaving the plant (nitrogen, phosphorus, heavy metals) were considered to end up in soil regardless of dilution post composting. The author recognises that this is a broad assumption, but a full LCA of the composting company is outside the scope of this stage of the project.

The flow data for plant B are supplied mainly from the data collection carried out by the EPA as part of its compliance with 91/271 for the year 2012. This data includes; levels of BOD,

[4] ISO 14040 is the international standard that describes the principles and framework for life cycle assessment.

COD, TSS, total nitrogen and total phosphorus, as well as heavy metal concentrations in influent and effluent. It also includes details of sampling frequency and quality. Other data for the plant has had to be estimated or taken from the literature. As with plant A, all of the upstream and downstream data such as electricity and chemical production is supplied by PE International. Both plants employ solid waste compressors to reduce volume, but neither plant could provide meaningful data for quantities of solid waste disposal.

Table 1. Sources of data used in the LCA

Site specific data	Plant A	Plant B
Influent flow	Plant Operators - measured	Based on plant agglomeration
Effluent flow	Plant Operators - measured	EPA data - measured
BOD, COD, TSS	Plant Operators - measured	EPA data - measured
Total N, Total P	EPA data - average	EPA data - measured
Influent heavy metals	EPA data - average	EPA data - measured
Sludge output volume	Plant Operators - measured	EPA data - average
Sludge dry solid concentration	Plant Operators - measured	Estimated – based on plant technology [14]
Sludge heavy metals	Literature [16]	
Electricity consumption	Plant Operators - measured	Plant Operators - measured
Biogas production	Plant Operators - measured	N/A
Natural gas consumption	Plant Operators - measured	N/A
Chemical consumption	Plant Operators - measured	Estimated [14]
Upstream/downstream data		
Electricity production	PE International	PE International
Chemical production	PE International	PE International
Natural gas production	PE International	PE International
Diesel refinement	PE International	PE International

RESULTS

Energy

Plant A consumes 37 kWh/p.e. year, 60% of which is supplied by the national electrical grid and 40% is generated by the CHP plant. Of the 40% of power produced by the CHP plant, 75% of the energy comes from natural gas and the remaining 25% is generated from biogas produced from anaerobic digestion of the sludge. Plant B consumes 52 kWh/p.e. year, all of which comes from the national grid. Figure 2 shows the percentage consumption per process of both plants. Data for plant B were limited to metering of the biological reactors and the total plant consumption. The biological reactors at plant B account for 75% of the total plant energy consumption. The biological reactors at plant A account for just 30% of energy consumption. Sludge treatment was the largest consumer of energy at plant A at 37%. However sludge treatment at plant A consists of an extensive series of thickening and dewatering processes, a vast odour extraction system, as well as two anaerobic digesters that return > 10% of the total plant energy. The inlet works which includes pre-screening, grit removal and primary sedimentation account for 26% of the total energy.

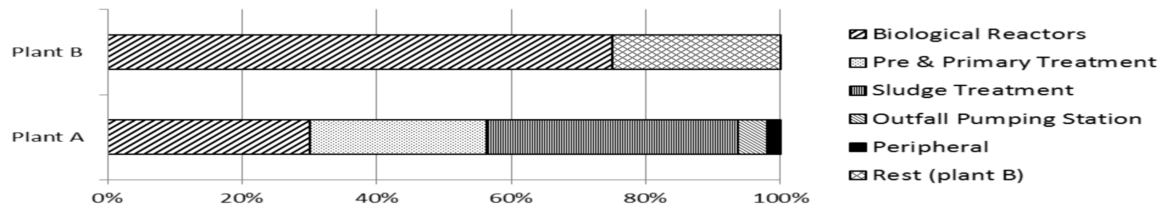

Figure 2. Process breakdown of energy expenditure. The biological reactors in plant B account for 75% of total energy consumed. Sludge treatment consumes the most energy at plant A with 37% of the total.

Life Cycle Impact Assessment

Figure 3 outlines the differences in environmental loading between both plants. It should be noted that the y axis is in logarithmic scale and therefore differences in outputs of some categories can be significant. Table 2 lists the full list of impact category values as well as the percentage difference between plants. Individual analysis of each category will follow.

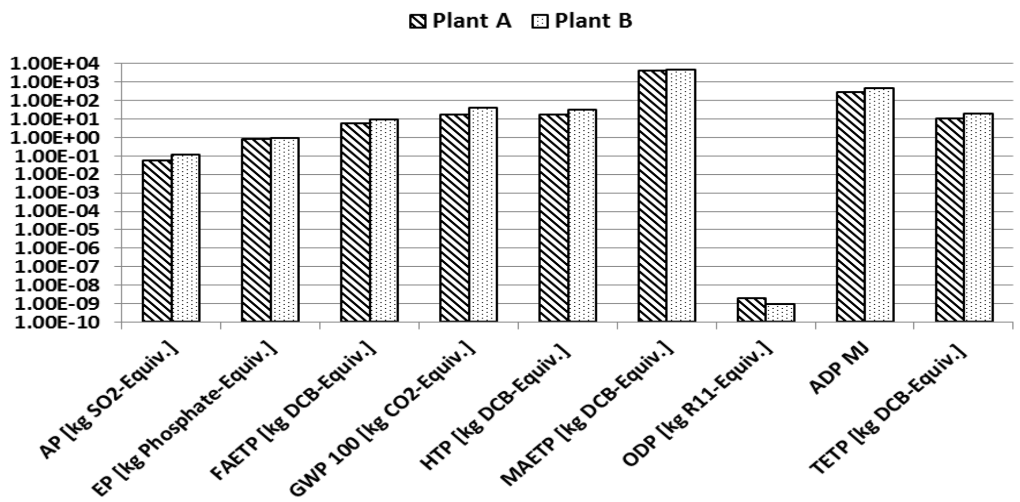

Figure 3. Comparison of the environmental loading of both plants across all impact categories.

Table 2. Impact category values and percentage difference between plants (plant B used as reference)

Impact category and unit		*Plant A*	*Plant B*	*Percentage difference in impact loading (%)*
ADP	[MJ]	2.81E+02	4.79E+02	41.34
AP	[kg SO_2 - equiv.]	6.14E-02	1.14E-01	45.95
EP	[kg phosphate - equiv.]	8.02E-01	9.29E-01	13.72
FAETP	[kg DCB – equiv.][5]	6.15E+00	9.45E+00	34.96
GWP 100	[kg CO_2 - equiv.]	1.87E+01	3.95E+01	52.72
HTP	[kg DCB – equiv.]	1.67E+01	3.33E+01	49.78
MAETP	[kg DCB – equiv.]	4.15E+03	4.86E+03	14.55
ODP	[kg R11- equiv.]	2.01E-09	9.88E-10	50.85
TETP	[kg DCB – equiv.]	1.09E+01	2.10E+01	48.03

[5] DCB refers to 1,4 - dichlorobenzene

Eutrophication

The eutrophication impact from plant A is dominated by the output of the final effluent (Figure 4). As plant A discharges its final effluent into coastal waters it does not have the nutrient restriction requirements of plant B. Phosphorus contribution to eutrophication is 140 times that of COD [4], thus small differences in phosphorus levels in final effluent will have a large effect on eutrophication, when compared with changes in BOD/COD levels. For plant B this variation in nutrient reduction requirement can also increase the production of WAS. When this is coupled with the lack of AD, the total sludge output volume per p.e. increases significantly. Despite the large percentage difference in the contributing sources to eutrophication, the overall difference between the plants is < 14% (Figure 2).

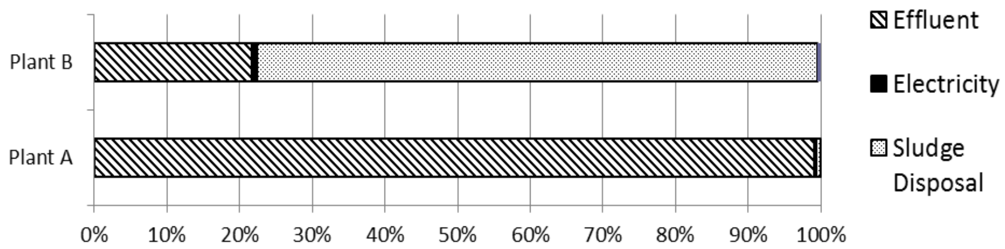

Figure 4. The contribution to eutrophication by plant A is dominated by the final effluent discharge while almost 80% of the contribution of plant B comes from sludge disposal.

Global Warming Potential 100 years

GWP is calculated over a particular time period, generally 20, 100 or 500 years. The 100 year time period is the most commonly chosen and is used in the CML 2001 LCIA methodology. The contribution to GWP from both plants is dominated by electrical energy production (Figure 5). 73% of the GWP loading at plant A can be attributed to electricity consumption while ferric chloride production accounts for 22%. The remainder of the loading comes from natural gas production and an aggregated total for sludge and chemical transport. Plant B electricity consumption accounts for 82% of the contribution to GWP. Lime production is the second largest contributor at 9% while the remainder is made up from ferric chloride production and transportation of chemicals and sludge.

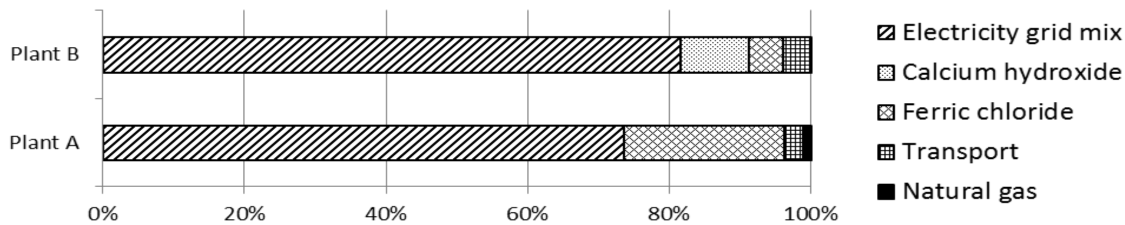

Figure 5: GWP 100 impact for both plants are dominated by electricity production.

The energy usage accounts in both cases for > 75% of the overall contribution to the GWP impact. This can be attributed to the heavy dependence on fossil fuel in the Irish electrical grid mix (Figure 6). Natural gas, hard coal, peat and heavy fuel oil make up almost 82% of the electrical grid mix in Ireland [17].

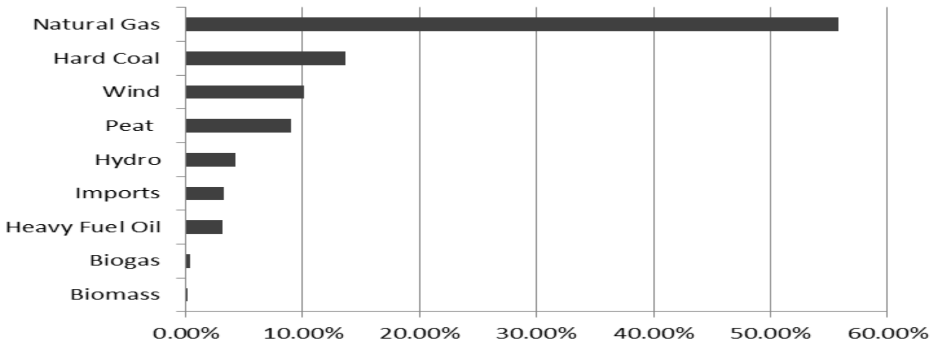

Figure 6. Ireland's electricity grid mix. Almost 82 % of the electricity grid mix in Ireland is fossil fuel based. It is for this reason that the energy consumption at both WWTPs is the main contributor to GWP.

Acidification Potential (AP)

Much like GWP, acidification potential is dominated by the impact of energy production, accounting for > 60% of the contribution for plant A and 78% for plant B (Figure 7). Ferric chloride production accounts for 28% of AP at plant A, while transport of sludge and chemicals was the next largest contributor at plant B.

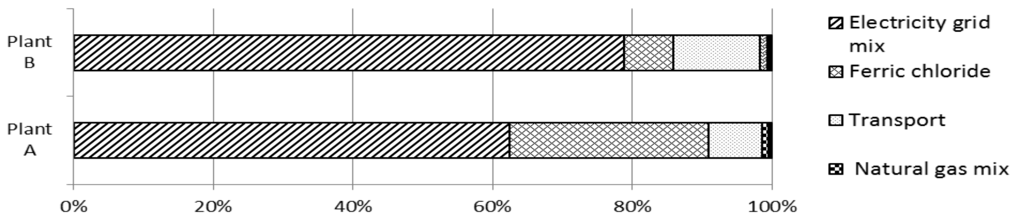

Figure 7. Acidification Potential for both plants is dominated be energy generation.

Ecotoxicity Potentials

The FWAETP categories for both plant A and plant B are dominated by sludge application to land (Figure 8). The effluent discharge from plant B contributes 12% of the overall loading in this category.

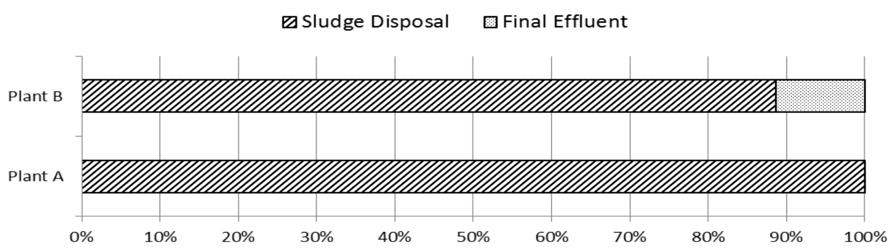

Figure 8. Freshwater Aquatic Ecotoxicity Potential

Over 40% of the MAETP output of plant A comes from final effluent discharge, > 33% is due to sludge disposal. Sludge disposal accounts for > 55% of the loading in plant B. Electricity production is the second largest contributor to this category with almost 30% of the total impact (Figure 9).

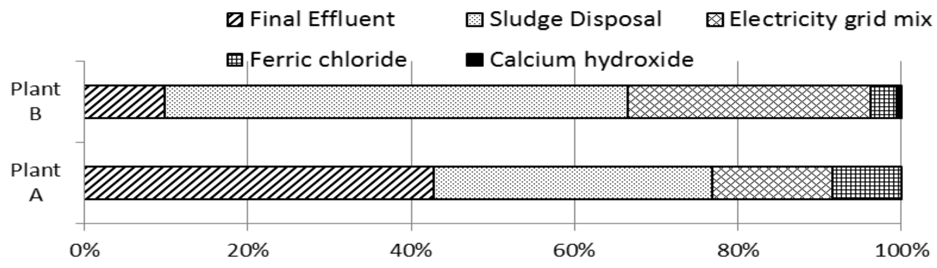

Figure 9. Marine Aquatic Ecotoxicity Potential

HTP is dominated in both plants by sludge disposal with only small contributions from other processes such as electrical and chemical production (Figure 10).

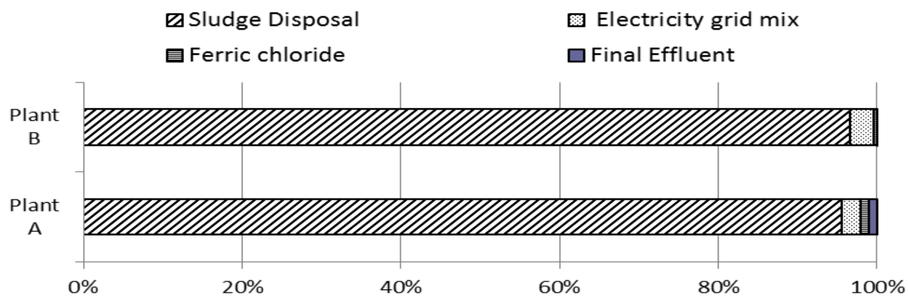

Figure 10. Human Toxicity Potential

Sludge disposal accounts for almost 100% of the TETP impact in both plants (Figure 11). The digested sludge output from plant A is 9.7 kgds/p.e. year (kilogrammes of dry solids per person equivalence year) at a solid concentration of 22%. The sludge is sent to a composting company 175 km from the plant where it is further treated. The undigested sludge output from plant B is 18.6 kgds/p.e. year at a solid concentration of 8%. The sludge is estimated to travel an average distance of 50 km from the plant for direct application to farmland. Direct application to farmland has been found to be the least favourable option of sludge disposal in several LCA studies carried out to examine the environmental loading for several disposal methods [18, 19].

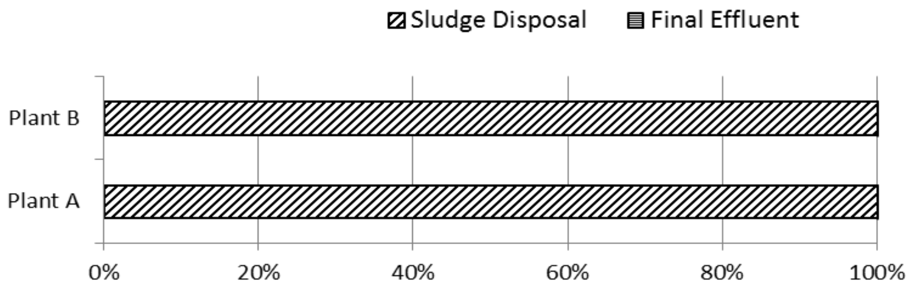

Figure 11. Terrestrial Ecotoxicity

Ozone Depletion Potential

Ferric Chloride production accounts for over 90% of the ODP impact in both plants with minimal contributions from electrical and other chemical production (Figure 12). Plant A outputs 2.01e-9 kg of R11-equiv/p.e. year (kilograms of chlorofluorocarbon equivalent per person equivalence year). Ferric chloride production accounts for over 98% of this total with less than 2% contribution from electricity production. The plant B output to ODP 9.88e-9 kg of R11-equiv/p.e. year. Ferric chloride production accounts for < 92% of this total and the contribution from electricity production increases to 8%. The study carried out by Hospido et al. [8] found that chemical production contributed almost half of the loading to this category with the remainder being attributed to electricity production. The difference here can be attributed mainly to the difference in both countries electricity grid mix. The Spanish electrical grid mix contributes over 100 times more to ODP than the Irish grid, thus decreasing the percentage contribution of chemical production in the Spanish scenario. The difference between the two Irish plants can be attributed in part to the economies of scale in terms of kWh/p.e. Plant B uses 40% more energy per p.e. than plant A, thus increasing the percentage contribution of electricity production to the impact category.

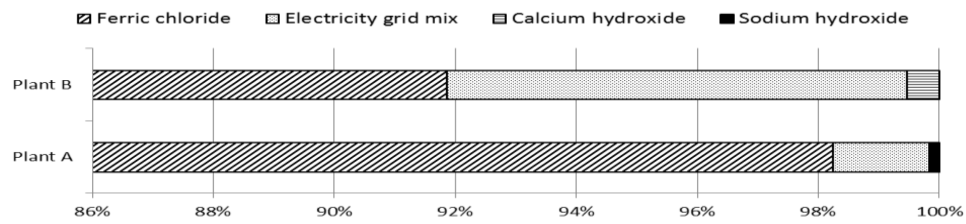

Figure 12. The ozone depletion impact is dominated by ferric chloride production which accounts for over 90% of the loading at both plants

Abiotic Depletion Potential (fossil)

The current CML methodology for ADP distinguishes between ADP fossil and ADP elements. ADP elements describes the depletion of the total natural reserves of the elements without regard for their functionality, while ADP fossil is defined by the energy content of the fossil fuels measured in MJ. As energy consumption and production is central to this study, it has been decided that ADP fossil is the most relevant choice. Electricity production is the main source of resource depletion. It accounts for over 60% of the output for plant A and over 80% of the output for plant B. Ferric chloride production is the next largest contributor for plant A with almost 20%, whilst making up < 5% of the contribution for plant B. The diesel refinery mix accounted for 15% of the plant A output.

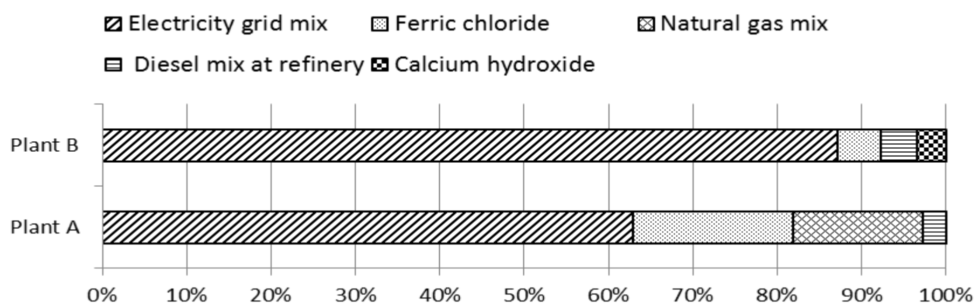

Figure 13: Abiotic depletion potential of both plants

DISCUSSION

When considering the environmental impact associated waste water treatment the main focus is generally on eutrophication caused by the final effluent. However, the 91/271 directive has established a set of acceptable limits for pollutant concentrations in final effluent for both sensitive and non-sensitive receiving waters, limits of BOD, COD and TSS, as well as nutrient limits of phosphorus and nitrogen. If it is understood and accepted by the scientific community that these limits represent a sustainable, non-destructive level of eutrophication, then the primary focus should no longer be on the quality of the final effluent, but more on the impact that results from achieving this effluent quality. This study found that there were two main contributors to environmental loading; the energy that goes into treating the influent, and the sludge disposal. The electricity grid mix in Ireland contributes heavily to aerial emissions such as GWP and AP, whereas sludge disposal contributes mainly to the ecotoxicity categories. There is an intrinsic link between the energy that is consumed during the treatment process and the sludge that is produced. Plant A employes AD in its system and this serves a number of purposes:

- Reclaims a significant amount of energy that can be fed back into the operation of the plant, reducing aerial emissions associated with electricity generation.
- Reduces the volume of sludge leaving the plant which reduces transport emissions and fuel consumption. This can be significant when the sludge has to travel long distances to its final destination as is the case with plant A.
- Stabilises sludge which reduces the emissions associated with lime production, and reduces resource depletion

CONCLUSION

It is without doubt that AD is a key process in wastewater treatment as it reduces the output of two of the main contributors to the overall environmental impact. In terms of what happens after the sludge is digested, there needs to be a definitive solution on how best to dispose of the sludge. The literature is filled with conflicting findings between those promoting one form of disposal over another. However, most studies would agree that direct application to land of untreated sludge is the least favoured option.

The variation in location has several effects on the environmental loading. The difference in contribution to eutrophication between the two plants was due mainly to the requirements of plant B to reduce nitrogen and phosphorus in the final effluent. This has the dual effect of reducing the nutrients in the effluent but also increasing the volume of sludge.

Investigation into economies of scale proved inconclusive as too many variables exist between plants. The lack of AD at plant B has a significant effect on aerial, aquatic and terrestrial emissions, thus a fair comparison cannot be made until both plants employ AD. This particular aspect of the study will be more conclusive when the full complement of plants in the broader study is assessed.

REFERENCES

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

[2] M. Henze., (1997). *Wastewater Treatment: Biological and Chemical Processes,* (2nd ed.)

[3] A. A. Jensen, et al. (1997). "Life Cycle Assessment: a guide to approaches, experiences and information sources," *Environmental Issue Series,* pp. 53 - 56,.

[4] A. M. Tillman and H. Baumann. (2004) *The Hitch Hiker's Guide to LCA* ,1:7 ed., vol. 1, Sweden: Holmsbergs, pp. 543.

[5] S. J. Cowell, R. Fairman and R. E. Lofstedt. (2002 10). Use of risk assessment and life cycle assessment in decision making: A common policy research agenda. *Risk Analysis: An International Journal 22(5),* pp. 879-894.

[6] A. Tillman, M. Svingby and H. Lundstrom. (1998 05/01). Life cycle assessment of municipal waste water systems. *The International Journal of Life Cycle Assessment 3(3),* pp. 145-157.

[7] A. Hospido, et al. (2004 07/01). Environmental performance of a municipal wastewater treatment plant. *The International Journal of Life Cycle Assessment 9(4),* pp. 261-271.

[8] A. Hospido, M. Moreira and G. Feijoo. (2008 01/01). A comparison of municipal wastewater treatment plants for big centres of population in galicia (spain). *The International Journal of Life Cycle Assessment 13(1),* pp. 57-64.

[9] J. C. Pasqualino, et al. (2009 05/01; 2014/03). LCA as a decision support tool for the environmental improvement of the operation of a municipal wastewater treatment plant. *Environ. Sci. Technol. 43(9),* pp. 3300-3307.

[10] M. Lundin, M. Bengtsson and M. Sverker. (2000). "Life Cycle Assessment of Wastewater Systems: Influence of System Boundaries and Scale on Calculated Environmental Loads," vol. 34, pp. 180 -186,.

[11] Y. Suh and P. Rousseaux. Considerations in life cycle inventory analysis of municipal wastewater treatment systems. Presented at Oral Presentation at COST 624 WG Meeting, Bologna, Italy< Http://Www. Ensic. Inpl-Nancy. Fr/COSTWWTP.

[12] P. P. Kalbar, S. Karmakar and S. R. Asolekar. (2013). Assessment of wastewater treatment technologies: Life cycle approach. *Water and Environment Journal 27(2),* pp. 261-268.

[13] S. Renou, et al. (2008 7). Influence of impact assessment methods in wastewater treatment LCA. *J. Clean. Prod. 16(10),* pp. 1098-1105.

[14] M. P. K. Izrail. S.T. (2006). "Wastewater Sludge Processing".

[15] A. Gallego, et al. (2008 4). Environmental performance of wastewater treatment plants for small populations. *Resour. Conserv. Recycling 52(6),* pp. 931-940.

[16] European Commission. (2001)."Pollutants in urban waste water and sewage sludge".

[17] M. Howley, E. Dennehy, M. Holland and B. O Gallachoir. (2012). "Energy in ireland: Key statistics 2012".

[18] M. Lundin, et al. (2004 7). Environmental and economic assessment of sewage sludge handling options. *Resour. Conserv. Recycling 41(4)*, pp. 255-278.

[19] G. Houillon and O. Jolliet. (2005 2). Life cycle assessment of processes for the treatment of wastewater urban sludge: Energy and global warming analysis. *J. Clean. Prod. 13(3)*, pp. 287-299.