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Journal of Environmental Management

DOI:
https://doi.org/10.1016/j.jenvman.2021.113613

Published: 15/12/2021

Peer reviewed version

Pitfalls in international benchmarking of energy intensity across wastewater treatment utilities

Nathan L Walker[a], A. Prysor Williams[a] and David Styles[b]

[a]*School of Natural Sciences, College of Environmental Sciences and Engineering, Bangor University, Gwynedd, UK*

[b]*School of Engineering, University of Limerick, Limerick, Ireland*

Abstract

The collection, treatment and disposal of wastewater is estimated to consume more than 2% of the world's electrical energy, whilst some wastewater treatment plants (WWTPs) can account for over 20% of electrical consumption within municipalities. To investigate areas to improve wastewater treatment, international benchmarking on energy (electrical) intensity was conducted with the indicator kWh/m^3 and a quality control of secondary treatment or better for ≥95% of treated volume. The core sample included 321 companies from 31 countries, however, to analyse regional differences, 11 countries from an external sample made up of various studies of WWTPs was also used in places. The sample displayed a weak-negative size effect with energy intensity, although Kruskal-Wallace analyses showed there was a significant difference between the size of groups (p-value of 0.015), suggesting that as companies get larger; they consume less electricity per cubic metre of wastewater treated. This relationship was not completely linear, as mid to large companies (10,001-100,000 customers) had the largest average consumption of 0.99 kWh/m^3. In the regional analysis, EU states had the largest average kWh/m^3 with 1.18, which appeared a result of the higher wastewater effluent standards of the region. This was supported by Denmark being the second largest average consuming country (1.35 kWh/m^3), since it has some of strictest effluent standards in the world. Along with energy intensity, the associated greenhouse gas (GHG) emissions were calculated enabling the targeting of regions for improvement in response to climate change. Poland had the highest carbon footprint (0.91 kgCO_2e/m^3) arising from an energy intensity of 0.89 kWh/m^3; conversely, a clean electricity grid can affectively mitigate wastewater treatment inefficiencies, exemplified by Norway who emit just 0.013 kgCO_2e per

cubic meter treated, despite consuming 0.60 kWh/m^3. Finally, limitations to available data and the analysis were highlighted from which, it is advised that influent vs. effluent and net energy, as opposed to gross, data be used in future analyses. The large international sample size, energy data with a quality control, GHG analysis, and specific benchmarking recommendations give this study a novelty which could be of use to water industry operators, benchmarking organisations, and regulators.

Key words: Wastewater benchmarking; global wastewater energy efficiency; performance analysis, wastewater quality; benchmarking deficiencies

List of Abbreviations

BOD5	Biological Oxygen Demand in 5-day period
COD	Chemical Oxygen Demand
CO_2e	Carbon Dioxide equivalent
EBC	European Benchmarking Co-operation
GHG	Greenhouse Gas
IBNET	International Benchmarking Network for Water and Sanitation Utilities
kWh	Kilowatt hour
SEAWUN	South East Asian Water Utilities Network
WUP	Water Utility Partnership for Capacity Building in Africa
WWTP	Wastewater Treatment Plants
UWWTD	Urban Waste Water Treatment Directive
TSS	Total Suspended Solids
SD	Standard Deviation
PE	Population Equivalent

1. Introduction

The collection, treatment and disposal of wastewater is a significant consumer of energy, with estimates suggesting that more than 2% of the world's electrical energy is used for water supply and wastewater treatment (Plappally & Lienhard 2012; Olsson, 2015). The EU (2017) state that energy requirements in wastewater treatment plants (WWTPs) account for more than 1% of consumption in Europe, whilst Means (2004) and Kenway *et al*. (2019) report that WWTPs can consume over 20% of electrical consumption within municipalities. Reducing the energy consumption of wastewater management is integral to efficient resource use within a circular economy and to reduce greenhouse gas (GHG) emissions. This task is more difficult considering WWTP electricity demand within developed countries is expected to increase by over 20% in the next 15 years as controls on wastewater become more stringent (Wang *et al*., 2012; Hao *et al*., 2015); with the same trend expected in developing countries as wastewater quality becomes a greater priority (Lopes *et al*., 2020). The importance of improving the sustainability of wastewater treatment is highlighted by its inclusion in the United Nations Sustainability Development Goal 6 (2021a) that seeks to secure safe drinking water and sanitation, focussing on the sustainable management of wastewater, water resources and ecosystems.

Electric energy consumption accounts for approximately 90% of the total energy consumption of WWTPs (Mizuta and Shimada, 2010; Singh *et al.,* 2012). The energy used at each stage of treatment depends on the technologies utilised and the sizes of the plants. Preliminary and primary treatment are estimated to consume between 5-25%, secondary treatment 45-80%, tertiary 10-40%, and sludge 4-14% (Longo *et al*., 2016; Smith and Liu, 2017; Soares *et al*., 2017). Longo *et al*. (2016) detailed the electricity consumption of the different stages of wastewater using data from 21 academic sources, which spanned 1-93 case studies per source and covered all sizes of WWTP. Pre-treatment includes the pumping of wastewater, screening, and grit removal and grinding. During this stage, pumping is the only significant energy consumer, at 0.002-0.042 kWh/m^3, depending on the structure and location of the

sewer system. Primary treatment involves separating circular settling tanks with mechanical scrapers, using very little electricity ($4.3 \cdot 10^{-5}$ - $7.1 \cdot 10^{-5}$ kWh/m^3). The secondary treatment stage is responsible for a significant proportion of the total electrical consumption, whist the aeration system is the process that consumes most electricity (0.18 and 0.8 kWh/m^3), accounting for 45%-75% of total plant energy consumption (Longo *et al.,* 2016; Gandiglio *et al.*, 2017). Longo *et al*. (2016) comments further that between $8.4 \cdot 10^{-3}$ and 0.012 kWh/m^3 is used by mechanical scrapers in gravity settling to separate sludge. Secondary sludge recirculation requires more pumping, consuming an additional 0.047 to 0.01 kWh/m^3, whilst mixing for anoxic reactors ranges between 0.053 and 0.12 kWh/m^3. Tertiary treatment further increases electricity consumption, the degree to which depends on the technology. Tertiary filtration consumes from $7.4 \cdot 10^{-3}$ to $2.7 \cdot 10^{-3}$ kWh/m^3, UV disinfection uses between 0.045 - 0.11 kWh/m^3, and mechanical utilisation for the dosage of chemicals (e.g., chlorinated reagents, aluminium or iron salts) expends $9.0 \cdot 10^{-3}$ - 0.015 kWh/m^3. Finally, the processing of sludge throughout different stages can represent considerable energy consumption, for example, aerobic sludge stabilisation, which is the most consuming procedure within sludge treatment, can use between 0.024 – 0.53 kWh/m^3.

Efficiency improvements at plant and company level could reduce the energy demand of wastewater treatment. Various methods could enhance overall system intensity, including process-energy reduction and energy recovery from waste, which can be conducted to such an extent that WWTPs can become energy neutral or even energy positive (Maktabifard *et al*., 2018). An effective way to improve efficiency is the use of control engineering techniques (Vrecko *et al.,* 2011). To reduce the complexity of application, costliness, and difficulty of access of these techniques, studies such as Nopens *et al*. (2010), Luca *et al*. (2015), and Santin *et al*. (2015) have implemented benchmarking models for the design and testing of control strategies. Process optimisation techniques such as installing smart meters and control systems for optimal aeration and pumping conditions have proved affective techniques, with the Electric Power Research Institute estimating that 10-20% of energy savings can be

achieved this way (Copeland and Carter, 2014). Approximately 50% of the total energy consumption of a WWTP can be provided by biogas from anaerobic digestion (Hao *et al*., 2015), with sludge pre-treatments enhancing the biomethane yield further. This is also possible by altering fuel cells and optimising thermal conditions (Gandiglio *et al.,* 2017). Furthermore, re-using the nitrogen and phosphorus from WWTPs for crop fertilisation can offset the considerable energy consumption of producing synthetic fertilisers (Danuta, 2018).

A valuable tool for improving wastewater energy intensity amongst water companies is benchmarking. By utilising key performance indicators, it is possible to find the optimal performers and evaluate companies against similar entities or standardised values (Krampe 2013; Torregrossa *et al.,* 2016). By doing this, companies can identify and prioritise areas for improvement and learn from best practices (Walker *et al.,* 2019; Walker *et al*., 2021). Vaccari *et al*. (2018) evaluated energy consumption within Italian WWTPs and documented that energy benchmarks had not been extensively investigated, which appears to still be the case. They highlighted only the USA (WEF 2009; WERF 2011; Wang *et al*., 2016), Australia (Krampe 2013; de Haas *et al.,* 2015), Japan (Mizuta and Shimada, 2010; Hosomi, 2016), Austria (Lindtner *et al.,* 2008; Haslinger *et al.*, 2016), Germany (Wang *et al*., 2016), Sweden (Lingsten *et al.* 2011), Denmark, Norway and Finland (Gustavsson & Tumlin, 2013) as the areas where energy benchmarks had been previously studied. In addition to these studies though, alternative research has been conducted in Portugal (Vieira *et al*., 2019), Finland (Gurung *et al*., 2018), Mexico (Valek *et al*., 2017), Brazil (SNIS, 2014), India (Soares *et al*., 2017), Singapore (Hernández-Sancho *et al.*, 2011), South Korea (Chae and Kang, 2013), China, and South Africa (Wang *et al*., 2016). Most of these studies, although offering value, have limited sample sizes and offer little insight into performance across countries or regions effectively. There are international benchmarking organisations such as the International Benchmarking Network for Water and Sanitation Utilities (IBNET), European Benchmarking Co-operation (EBC), Water Utility Partnership for Capacity Building in Africa (WUP), South East Asian Water Utilities Network (SEAWUN), which collate and provide an expanse of

valuable information. However, energy metrics and samples are often limited and dated, particularly for wastewater, reducing the extent of research outputs.

This study had several objectives. 1) to explore the energy intensity of wastewater treatment on an international scale with the most up-to-date data available and an effluent quality control to ensure credible comparison, an exploration not conducted at this scale previously; 2) to investigate reasons for varying performance, including regional, legislative, and size differences; 3) to assess the carbon impacts of wastewater treatment energy intensity relative to each country, which has not been conducted hitherto; 4) to evaluate areas for improvement in international benchmarking practices. The international scope of the study helps address many of the knowledge gaps highlighted earlier, and the novelty of the work can be of use to the water industry, benchmarking organisations, energy efficiency analysts, and regulators, by providing recent results of wastewater energy intensity and associated carbon from many countries across the world, along with suggestions on improving future data collection, reporting and analysis.

2. Methodology

2.1. Data description

The core indicator used was kWh/m^3 of wastewater treated, kWh being gross electricity consumed. Since the level of wastewater treatment impacts on energy consumption (see Section 1), a control on water quality was deemed necessary. There were limited possibilities with available data; however, wastewater receiving secondary treatment or better at volumes of 95% and above was incorporated. Secondary treatment can vary in processes undertaken and thus energy consumed, e.g., there can be considerable energetic differences between conventional activated sludge and granular activated sludge (Bengtsson *et al*., 2018), and many processes outlined in Section 1 however, without more detailed data, using secondary treatment or better as the quality control was the best option.

The main source of data was the International Benchmarking Network for Water and Sanitation Utilities (IBNET, 2021) database, this was supplemented by company reports and

other national benchmarking schemes, which collectively covered Greece, Italy, Spain, Sweden, Canada, United States, UK, Australia, New Zealand, Denmark, and Netherlands. The sample years were 2014-18, with only one year of data being required to be valid in the study to maximise the sample size. It is possible that by using one entry within the five-year range, an abnormal year of heavy rainfall and increased wastewater treatment could be used; however, the indicator kWh/m^3 should negate this. Companies with multiple data points throughout those years had their values averaged. Extra data from the IBNET database were utilised to conduct part of the analysis comparing energy intensity of primary only treatment (>95% of total volume treated) and the core sample data. This extra primary treatment data had 29 companies from nine countries, the comparison with core sample was undertaken with only the same nine countries for the fairest results.

External data to this from journal articles were used in Section 3.3 to enable a better understanding of regional differences, covering Portugal, Germany, Finland, Brazil, Mexico, India, South Korea, China, Japan, Singapore, and South Africa. This external data did not have the same treatment quality controls that the core data had and was based largely on samples of WWTPs, not companies, and therefore was not incorporated into the core sample. Summary statistics for the sample are available in Table 1, with a full data table and data sources available in the Supplementary Information.

Table 1. *Summary data for the core, external and primary treatment samples.*

Sample	Indicator	Countries	Companies	Average	Min	Max	SD
Core sample	kWh/m^3	31	321	0.89	0.04	3.11	0.49
External sample	kWh/m^3	11	N/A*	0.40	0.08	1.15	0.25
Primary treatment only	kWh/m^3	9	29	0.36	0.01	1.25	0.29

***External sample made up of myriad data including WWTPs and tertiary average data from other studies.

When evaluating regional differences in energy intensity (Section 3.1.2), wastewater effluent standards are presented (Table 3) to ascertain the reason behind regional variation, which include the quality parameters Chemical Oxygen Demand (COD), Biological Oxygen Demand

in a 5-day period (BOD5), Total Nitrogen, Total Phosphorus, and Total Suspended Solids (TSS). COD and BOD5 are important parameters because they provide an index to estimate the effect of wastewater discharge. COD is the amount of oxygen required to chemically oxidise pollutants, while BOD indicates the amount of oxygen required to breakdown organic pollutants biologically with microorganisms (Abdullahi *et al*., 2021). Levels too high of these parameters along with Total Nitrogen and Phosphorus and TSS can cause de-oxidised and potentially anoxic environments which compromise aquatic ecosystems; therefore, it is integral they are kept at appropriate standards in wastewater effluent (Shete and Shinkar, 2013).

2.2. Data Analysis

2.2.1. Spearman's rank correlation coefficient

To assess the relationship between a) the size of companies and their energy intensity, and b) the percentage of tertiary treatment received in each country and energy intensity, in Section 3.1, Spearman's rank correlation coefficient (r_s) was utilised. This non-parametric approach was chosen due to the sample being non-normally distributed and has the advantage of being relatively insensitive to outliers. r_s is calculated according to the following equation:

$$r_s = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \qquad (1)$$

where d_i is the difference between ranks for each variable data pair and n is the number of data pairs. When r_s = 1 the data pairs have a perfect positive correlation (d = 0) and when r_s = -1, the pairs have a perfect negative correlation.

2.2.2. Kruskal-Wallis test

To test if there was a significant energy intensity difference between the size groups in Section 3.1, a Kruskal-Wallis H test was used. This non-parametric approach was chosen, as there was not a particular distribution of the energy intensity data. The H statistic is calculated with:

$$H = \left[\frac{12}{n(n+1)} \sum_{j=1}^{c} \frac{T_j^2}{n_j}\right] - 3(n+1) \qquad (2)$$

where n is the sum of sample sizes for all groups, c is the number of groups, T_j is the sum of the ranks in the jth sample, and n_j is the size of the jth sample. To decipher whether the medians of the groups are differing, the H value is compared to the critical chi-square value at an alpha level of 0.05 in this instance (degrees of freedom = 3). If the critical chi-square value is < the H statistic, there is significant difference between the groups, whereas if the chi-square value is ≥H, there is not enough evidence to suggest that the medians are unequal. The limitation of this approach is that the specific groups that display differences between them are not known however, for the purposes of what the K-W test is being used for in this study, this is an accepted condition.

3. Results and Discussion

3.1.1. Size and energy intensity

Typically, the expectation is that larger WWTPs and companies are more efficient due to economies of scale (Molinos-Senante *et al*., 2018). However, this is not always the case. At certain scales, diseconomies can occur, and within rural environments where treatment plants cover large areas, water conveyance can affect energy and financial efficiency (Saal *et al*., 2013; Walker *et al*., 2020).

The international sample utilised here is displayed in Figure 1, with each company and their energy intensity being plotted against their size, measured in population served. The range of data (0.04 to 3.11 kWh/m^3 and 500-15,000,000 in population served) meant that outliers and non-normal distribution could affect inferences from analysis. To negate this, Spearman's rank was utilised, and size categorisation was undertaken to group similar sized companies together, results of which are in Table 2 with their associated mean average electricity intensity.

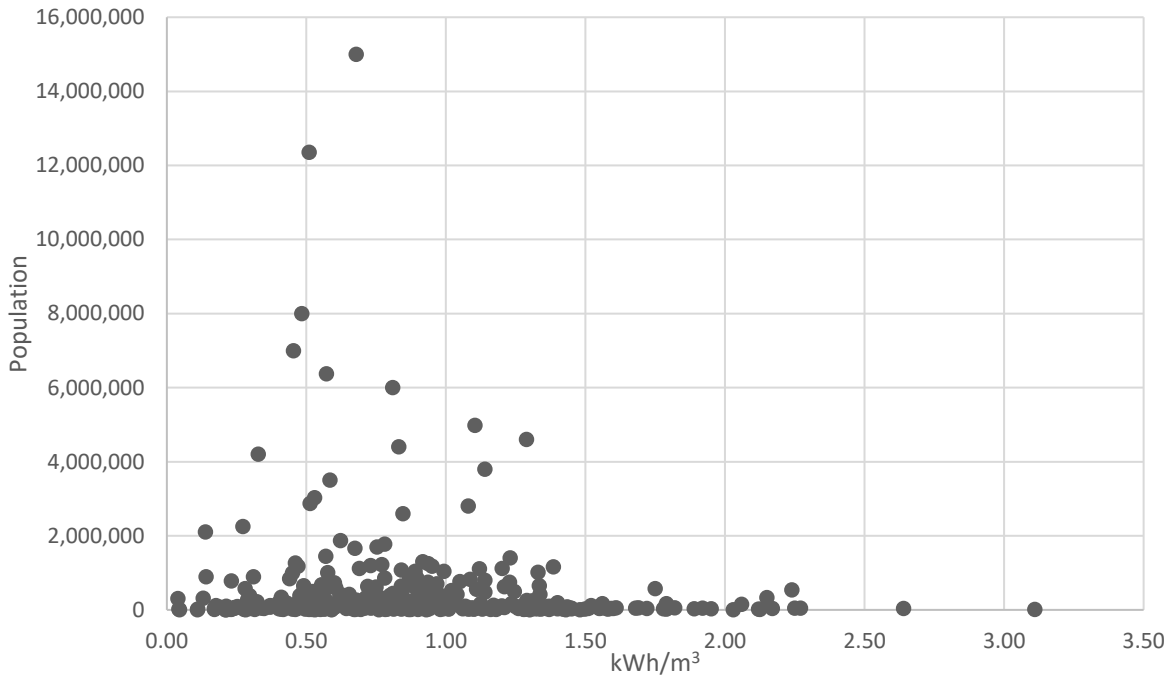

Figure 1. *Electrical intensity of 321 companies plotted against their size (measured in population served*).

The whole sample has a r_s value of -0.108, suggesting, as companies get larger, they consume less electricity per cubic metre of wastewater treated; however, it is a weak relationship and displayed a non-significant p-value. A Kruskal-Wallace test revealed there was a significant difference between the four applicable groups (p-value of 0.015); implying utility size does influence energy intensity, which concurs with much of the literature (Venkatesh *et al*., 2014; Young, 2015). Furthermore, the group of companies serving over 1,000,000 people had a slightly lower average kWh/m^3 compared to the rest of the sample, with the r_s value showing a weak negative relationship to a significant degree (p-value of 0.024), supporting inferences that larger companies have slightly lower energy intensity. This appears to be a non-lineal relationship since the highest average energy intensity is from the 10,001-100,000 group, which with the 100,001-1,000,000 group show very weak positive relationships, whilst the smallest applicable category of 1001-10,000 shows a very weak negative result. These results indicate that the extreme companies on the size spectrum are not necessarily handicapped in their pursuit for efficiency, and therefore should actively seek to learn from the top performers, regardless of their size.

Table 2. *The company size categories based on population served, their average electricity consumption, Spearman's rank correlation coefficient, and associated p-value.*

Size category	n	Average kWh/m^3	Spearman's rank correlation coefficient r_s	P-value
0-1000	1	1.30	N/A	N/A
1001-10,000	21	0.86	-0.07315	0.753
10,001-100,000	141	0.99	0.05516	0.516
100,001-1,000,000	118	0.82	0.01702	0.855
1,000,001+	40	0.78	-0.35685	0.024
All	321	0.89	-0.10778	0.054

It is possible that economies of scale for wastewater treatment companies are only present at the very large size (>1,000,000) as Table 2 hints towards, which could be the case in reality; alternatively, there may be other influencing factors not captured within the available data. For example, the economies of scale relationship could be strong between WWTPs, which is impaired when evaluating the overview of companies and here we only have size of companies that does not necessarily represent the size of their treatment plants. Another factor often heavily linked with energy intensity is the level of treatment the wastewater receives (as discussed in Section 1), which is at least partially dependent on regulatory standards that differ from region to region. The data used ensured that at least 95% of the wastewater from each company received at least secondary treatment. This was an important effluent quality control as data collected, available in the Supplementary Information, showed companies that treated ≥95% wastewater to only a primary level only consumed 0.36 kWh/m^3 compared to 0.76 kWh/m^3 for companies that treated ≥95% wastewater to at least a secondary level in the same countries. Even within secondary wastewater treatment though, there can be variances with the technologies utilised and therefore differing levels of energy consumption; for example, aeration can be conducted with turbines, diffusers and in some cases, not at all (Guerrini *et al*., 2017). Having a quality control in the data was important however, without more granular data on how much of that wastewater was treated to a tertiary extent; relationships within the results could be misrepresented. As Figure 2 shows, secondary treatment or better actually represents mostly tertiary treatment in many EU member states.

Spearman's rank correlation coefficient was conducted with the tertiary treatment percentage data from Figure 2 and the matching countries in the energy intensity sample collected. The relationship was positive but non-significant for all valid data (r_s 0.36, p-value 0.2) and when using countries in the energy data sample that had over 15% of population represented in the data (r_s 0.49, p-value 0.33). Although the results showed tertiary treatment did not cause significant increases in energy consumption, more tertiary treatment will clearly increase energy consumption (Plakas *et al*., 2016) as the technologies in Section 1 showed. This increase, even if not statistically significant, can obscure results when data is only available as secondary treatment or better.

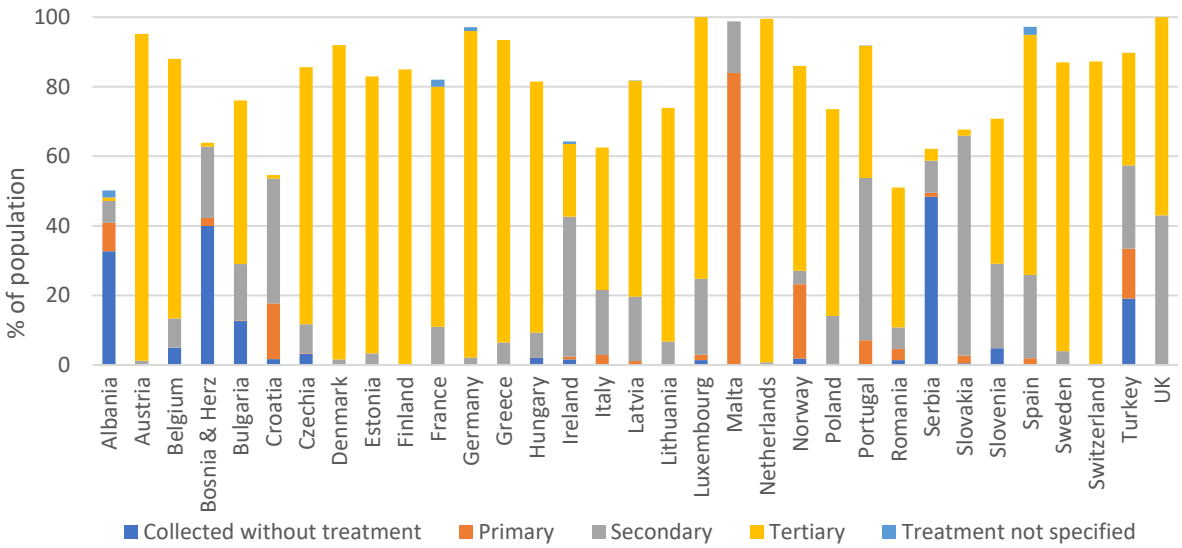

Figure 2. *The proportion of urban wastewater collected, and the level of treatment applied as a percentage of the population in 2017 for EU states (European Environment Agency, 2020).*

3.1.2. Regional differences

To assess regional variances and further investigate the effect of wastewater effluent quality standards on energy consumption, grouping of companies was completed based on their legislation and United Nations (2021b) Sustainable Development Goal regional groupings. A selection of countries and their summarised wastewater parameters is presented in Table 3, however; a more detailed version is available in the Supplementary Information. The EU Urban Wastewater Treatment Directive (1991) regulates the level of treatment by implementing

required removal efficiencies for pollutants within the wastewater that is discharged into water bodies to protect aquatic ecosystems. Non-EU states are often characterised by differing approaches to establishing the legal regulations regarding wastewater discharge into surface waters (Preisner *et al*., 2020). In countries that were formerly part of the Soviet Union, a materially different method is in place, which is based on the assumption that the level of wastewater treatment must ensure the normative water quality in the control cross-sections of individual water bodies (Neverova-Dziopak, 2018). This means the maximum allowable load discharged from each WWTP is defined based on the category of the receiving water, its specific characteristics, and the construction of the wastewater outlet. These different approaches exemplify the difficulty in directly comparing regions, however, the major effluent maximum standards give a reasonable guide, albeit whilst mindful of distinct contexts.

Table 3. *Summarised wastewater effluent standards for a selection of the total sample, a fuller version is within the Supplementary Information.*

Region	WWTP category	COD (mg/l)	BOD_5 (mg/l)	Total N (mg/l)	Total P (mg/l)	TSS (mg/l)
EU	<2000 PE	125	25	n/n[a]	n/n	35
	2000-10,000 PE	125	25	n/n	n/n	35
	10,000-100,000 PE	125	25	15	2	35
	>100,000 PE	125	25	10	1	35
HELCOM	300-2000 PE	n/n	25	35	2	35
	2000-10,000 PE	125	15	30	1	35
	10,000-100,000	125	15	15	0.5	35
	>100,000 PE	125	15	10	0.5	35
Denmark	General	75	10	8	0.4	20
Moldova	General	125	25	15	2	35
Australia (Tasmania)	Fresh	n/n	15	15	3	n/n
	Marine	n/n	20	15	5	n/n
Australia (Queensland)	Surface	n/n	30	15	6	45
Nigeria	Varied	60-90	30-50	10	2	25
India	General	250	30	10	5	50-100
Fiji	General	n/n	40	25	5	60

[a]n/n not normalized parameter

Table 4 shows that the EU companies had the largest average energy intensity at 1.18 kWh/m^3, whilst all other regions averaged much lower, ranging between 0.58-0.64 kWh/m^3, apart from Russia and the former states of the Soviet Union who averaged 0.82 kWh/m^3. The

EU UWWTD directive is widely appreciated to have some of the strictest effluent standards in the world (Morris *et al*., 2018), so it was anticipated for those countries to have a higher energy intensity due to higher levels of treatment requiring more energy (Capodaglio and Olsson, 2020). Despite this, it is still a little surprising that it is so high compared to others, considering many EU countries utilise some of the most efficient treatment techniques and technologies (United Nations, 2017; Preisner *et al*., 2020), such as those discussed in Section 1. It is expected then, that as regions with lower effluent standards improve to similar levels of advanced economies, their energy consumption will increase too.

Table 4. *Regional data description displaying average energy consumption.*

	EU UWWTD	Transition to UWWTD	Russia & former Soviet Union states	Developed Oceania	Developing Oceania	Central & South America	North America	Sub-Saharan Africa
No. Countries	12	3	5	2	5	1	2	1
No. Companies	112	31	126	43	5	1	2	1
Average kWh/m^3	1.18	0.62	0.82	0.65	0.64	0.64	0.57	0.58
S.D	0.43	0.58	0.41	0.42	0.40	N/A	0.05	N/A

In addition to compliance with relevant wastewater effluent legislation, there are alternative possibilities for the variance between the regions. For example, some countries may require different technologies relative to their environmental circumstances, such as areas with water demand higher than consistent supply. An effective solution is to re-use wastewater for non-potable requirements, as is the case in many countries throughout the globe including China who had the most wastewater reuse by volume (14.8 million m^3/day), and Qatar which has the most reuse per capita (170,323 m^3/day per million capita) (Jimenez and Asano, 2008). Though necessary, the processes for reusing wastewater are often energy intense compared to typical wastewater treatment. Ozonation, a common wastewater reuse treatment, consumes approximately 0.27 kWh/m^3 (Meneses *et al*., 2010), however, often a collection of treatment technologies is utilised and can add significant energy consumption on top of the baseline, exemplified by San Diego and Los Angeles utilities who consumed an extra 0.93 kWh/m^3 and 0.49 kWh/m^3, respectively (National Research Council, 2012). This can be even more

substantial as water scarcity increases, for example, in Australia, energy use for enhanced effluent is projected to grow between 130% and 200% by 2030 (Capodaglio and Olsson, 2020).

Data that are more detailed would clearly enable higher quality inferences from the analysis, which is epitomised in what having influent and effluent quality information could facilitate. It would permit accurate pollutant removal efficiencies to be assessed; currently without this data, some regions are perhaps being misrepresented. For example, it is probable that countries adhering to the EU UWWTD are removing more pollutants on average than those countries transitioning to the Directive (Sanfey and Milatovic, 2018), which would at least partially explain the energy consumption deficit of 0.56 kWh/m^3. The lack of influent and effluent data can be paramount if the sampling has captured areas within a region that treat significant volumes of industrial wastewater. The removal of metals from industrial wastewater can be energy intensive with techniques such as chemical precipitation, ion exchange, and electrochemical removal, although there are less utilised technologies with lower energy consumption like polymer-supported ultrafiltration and complexation–filtration as Barakat (2011) discusses in detail. Guerrini *et al*. (2017) showed in their study of 127 Tuscan WWTPs that a 1% increase of inflows from industry will decrease energy efficiency by 28%. If the sample has areas that treat high volumes of industrial effluent, then they would have performed poorly in this analysis.

The regional and global perspective could look very different depending on the data available. For example, the average energy intensity for the whole sample in this study was 0.89 kWh/m^3, within the wide range of global average estimates reported by Wakeel *et al*. (2016) of 0.38-1.12 kWh/m^3 based on different studies. The disparity between these results is likely due to differences in the context of various data. Some may be temporally divergent or have representativeness issues where a few WWTPs may represent a company, a few companies may represent a country, and a few countries may represent a whole region. Table 4 for example, shows how Central and South America, North America, and Sub-Saharan Africa

have very few countries within them and those countries only have one company representing them, although this is possible when a quality control (≥ secondary treatment for ≥ 95% of volume) reduces sample size. Having representativeness issues is not ideal; however, the practice is carried out by international benchmarking organisations such as the EU Benchmarking Co-operation (2020), when more data is unavailable. In addition, there may be biases in reporting where companies who may already be performing well or actively trying to improve are more likely to actively share their wastewater energy data, whereas poorer performers may not disclose the data or just not have the means to collect it thus, undermining benchmarking efforts. Although there are potential issues around the sampling parameters, data representativeness, and potential reporting biases, this is a common theme when attempting to collect sufficient data for comparison (Singh *et al*., 2012). The results presented here however are the best current indication of reality, which is discussed further in Section 3.1.4.

3.1.3. Country-level analysis

To further evaluate possible influences of energy intensity and the practicality of the data, the scope was narrowed to country-level analysis. The global coverage of the dataset was patchy despite extensive efforts to collect wide-ranging data, therefore some partially mismatching data in terms of company-level and known WWTP-level data was used from other studies to further inspect differences in electrical intensity between countries (Figure 3). Due to the expansive sample, many countries and companies that have not been evaluated previously are included in this study.

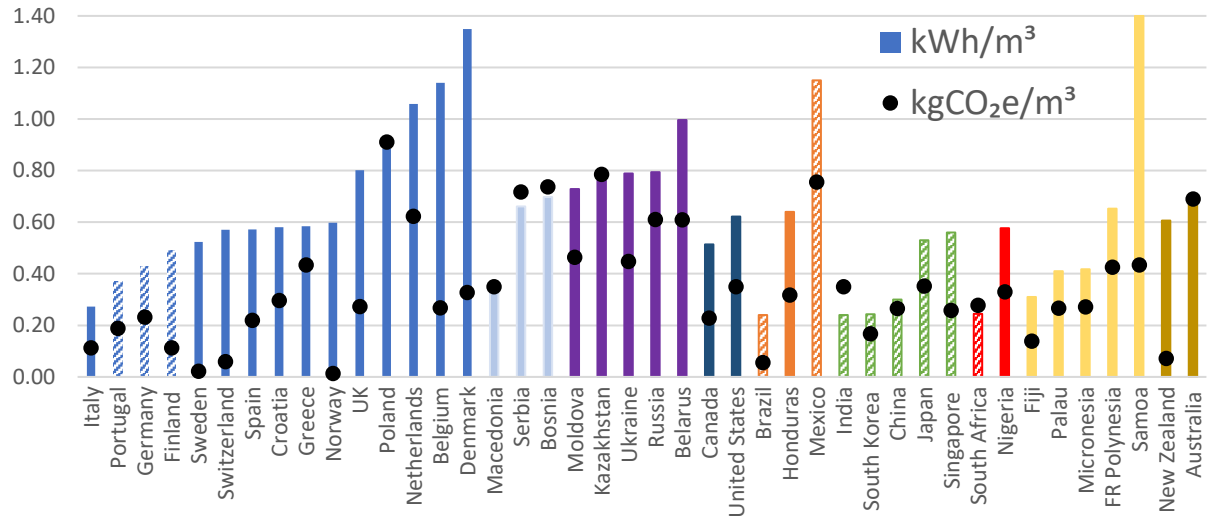

Figure 3. *Energy intensity (kWh/m³) and associated greenhouse gas emissions (kgCO₂e/m³) for all countries in the core sample, supplemented by external WWTP data, represented by striped columns (42 countries in total). The colours represent regional separation.*

The lowest energy intensity was observed in Brazil (0.24 kWh/m^3), India (0.24 kWh/m^3), South Korea (0.24 kWh/m^3), South Africa (0.24 kWh/m^3), and China (0.3 kWh/m^3). All five of these countries were from the external data, which were collated through individual studies on WWTPs; therefore, it is probable the countries are not being fully expressed due to limited sample size, as discussed in the previous section. There is also the major influencing factor of the disparity of wastewater effluent quality within the sample as examined above; especially considering the external data could not be filtered by secondary treatment or better as the main sample was. These five countries with the lowest energy intensities have some of the lowest wastewater quality requirements in the sample as Table 3, the Supplementary Information, Choi *et al*. (2015), Edokpayi *et al*. (2017), Never and Stepping (2018), and Wang and Gong (2018) document. This means these countries are more likely to have lower energy consumption out of the 42 countries because they are using less intensive, but less effective, processes. It should be noted though that these countries have large disparities of wastewater services, treatment and compliance, and some cities within these countries have established wastewater infrastructure capable of high levels of treatment.

The counties with the highest specific energy requirements for wastewater treatment were Samoa 1.4 (kWh/m^3), Denmark 1.35 (kWh/m^3), Mexico 1.15 (kWh/m^3), Belgium 1.14 (kWh/m^3), and Netherlands 1.06 (kWh/m^3). These countries contrast to the lower energy consuming performers as this group has mixed wastewater legislation and standards, as opposed to having standards from one end of the spectrum. The three European countries show that it is not only higher levels of wastewater treatment with stricter legislation causing perceived inefficiency. It also highlights another issue with the data, which is that it is based on gross, as opposed to net, consumption. This issue is exemplified by Denmark who not only have among the most stringent legal regulations regarding wastewater discharges in the EU after reducing their allowable pollution more than the UWWTD (Valero *et al.*, 2018), but heavily utilise energy recovery technologies in WWTPs (Grando *et al*., 2017). The Danish water benchmarking 2019 report (DANVA, 2019) showed six companies actively producing energy via their wastewater treatment at various rates; however, their gross consumption classifies them as energy sinks. The most extreme instance was Kalundbord who had 4.27 kWh/m^3 gross energy consumption but produced 7.9 kWh/m^3 in net energy. By only using gross energy data instead of net, it fails to capture the energy produced by wastewater, which can be substantial. The pure energy intensity of operations is still captured however, under a wider sustainability view; the data does not function adequately.

The energy intensity variations within regions and between countries came as a slight surprise, for countries using the UWWTD and within the developing Oceania, they ranged between 0.27-1.35 kWh/m^3 (SD 0.29) and 0.61-1.40 kWh/m^3 (SD 0.40), respectively. A possible explanation is that whilst countries may share effluent standards, they have differing compliance rates. This is supported by the 10th report on the implementation of the UWWTD (European Commission, 2020), which shows that 95% of wastewater in the EU is collected and 88% is biologically treated. The wastewater quality control indicators in this study only covers the degree of treatment as a percentage, not specific compliance. Furthermore, the same legislation can be managed differently in different countries. For example, Preisner *et*

al. (2020) comments that fifteen EU member states including Belgium, Denmark, Netherlands, Poland, Sweden, Finland have identified all their surface water bodies in their territory as sensitive areas, whereas thirteen countries containing Croatia, Germany, Italy, Spain, Portugal, and United Kingdom considered only selected water areas as sensitive (Zaragüeta and Acebes, 2017). The varied identification of water bodies as sensitive and non-sensitive impacts the level at which wastewater needs to be treated and therefore, affects the energy required to treat it.

The importance of energy efficient wastewater treatment is even greater when considering the carbon intensity of fuel mixes powering electricity grids. As Wang *et al*. (2016) commented, there is a general lack of understanding regarding electricity consumption and carbon emissions between countries on the international scale. To evaluate GHG emissions from wastewater energy consumption enabling the targeting of regions for improvement in response to climate change, and deliver further novelty, country conversion factors from the EcoInvent v3.7 database (method: CML 2001 superseded, GWP 100a) were used and multiplied with the electricity intensity indicator (kWh/m^3 * kgCO_2e/kWh = kgCO_2e/m^3). Figure 3 displays the kgCO_2e/m^3 for all 42 countries in the extended sample, showing Poland, Macedonia, Serbia, Bosnia, Kazakhstan, India, South Africa, and Australia all produce more than one kg of CO_2e/kWh, meaning their GHG contribution is particularly substantial relative to the kWh/m^3 figures. This becomes particularly problematic in countries with already high-energy intensity for treating wastewater, as is the case with Poland who consume 0.89 kWh/m^3 and have the highest carbon footprint intensity with 0.91 kgCO_2e/m^3. Conversely, a clean electricity grid can affectively mitigate wastewater treatment inefficiencies, exemplified by Norway who emit just 0.013 kgCO_2e per cubic meter, despite consuming 0.60 kWh/m^3, followed by Sweden and New Zealand, emitting 0.02 and 0.07 kgCO_2e/m^3 whilst consuming 0.52 and 0.61 kWh/m^3, respectively. Sustainability in the context of GHG emissions from wastewater treatment then, depends on influent and effluent water quality, treatment technologies, effluent quality standards and compliance with those standards, and electricity

fuel mix. To reduce GHG emissions, companies require a reduction in energy consumption, in addition to possible self-generated renewable energy generation. To reduce energy consumption, benchmarking and modelling followed by learning from best practice and incorporating applicable processes (some were outlined in Section 1) can be beneficial (Mannina *et al*., 2016), although the importance of investing in new and innovative technologies should not be underestimated either.

3.1.4. Learning from limitations

Results presented in this study offer the best view of the state of international wastewater energy intensity with current available data; however, as the sections above have discussed, there are avenues to improving future analysis and reporting, which is particularly pertinent to water managers and analysts. Foremost, there is a need for more data; this sample included 31 countries and 321 companies in the core sample, before expanding it to 42 countries with more sporadic WWTP data from individual studies. Chini and Stillwell (2017) also call for more availability and transparency in water utility data in their study of the United States water sector, highlighting that the only means of acquiring data is through open record requests of individual utilities. Even following data requests from over 200 utilities, only 61% responded. Sato *et al*. (2013) further emphasise the need for global, regional, and country level data, illustrating that only 55 countries have data available on wastewater production, treatment and reuse, with 57 countries having no information available at all. Whilst the study is somewhat dated now, clearly these themes are still valid. A lack of data not only makes it difficult to affectively evaluate energy intensity and conduct benchmarking, but it also causes problems of representativeness. With only limited companies reporting their data, it can lead to biases within the sample. For example, perhaps only the best performers who already partake in benchmarking and external analyses make their data publicly available (Denrell, 2005). In combination alongside general limited coverage within areas, a lack of representation causes analyses to miss the full picture, therefore reducing the quality of recommendations and real-world improvements.

The need for more detailed and granular data alongside additional data is paramount for enhanced assessments of wastewater treatment in the future. A subject at the core of the results in this study is the difference between net and gross energy consumption in reporting. Net energy consumption would enable more meaningful sustainability outcomes as energy production and strain on the electricity grid are encompassed, which are integral elements for modern WWTPs. Additionally, compliance rates with wastewater effluent standards would enhance the accuracy of analysis, as currently regions with similar standards are grouped together, although their compliance rates may differ greatly. These extra and more detailed data would also enable the inclusion of explanatory factor analysis to improve understanding of how exogenous influences can be managed to enhance efficiency. Currently, the data conditions of scarcity and factors already influencing results such as those mentioned above would mean explanatory factor analysis would not currently offer value. Finally, this study used wastewater treated at least to secondary treatment level or better, but more detail on which level of treatment has been used and what volume that was applied to would enable a better understanding of the current state of wastewater treatment in many regions. For the best understanding of treatment levels, having key pollutant removal data or influent vs effluent data would be required. An alternative unified metric to kWh/m^3 that incorporates energy and a quality aspect would be best for optimum intensity benchmarking. An example is energy per unit of organic load removed (kWh/$COD_{removed}$), which is a simple performance indicator that conveys meaningful information. This has been used in other studies (Patziger, 2017) and offers real value however, it is not uniformly applied. Christoforidou *et al.* (2020) exemplified how useful this metric can be in their energy benchmarking of WWTPs in Greece, particularly in combination with other energy key performance indicators that cover volume treated (kWh/m^3) and population equivalent (kWh/PE). An increasing number of studies are implementing and recommending a quality parameter to be included in WWTP analysis as Clos *et al*. (2020) notes. This is a positive development however, the highest levels of treatment where pathogens are being removed using energy intensive methods, e.g., disinfection via UV, chlorination, and ozone treatment (Chuang *et al*., 2019), are still not

captured in these indicators. Using multiple quality indicators or the development of a framework covering all key technologies and pollutants may be the best solution for future analyses. Although there is more demand for quality indicators to be ubiquitous in measuring and reporting, and there are differing approaches in including quality within energy efficiency assessments, it is important that utilities, regulators, and academics unify their metrics, to ease comparisons, analysis, and ultimately, facilitate learning and improvement.

4. Conclusions

The objectives of this study were to investigate the international energy intensity of wastewater treatment, explore variances in performance, evaluate the carbon impact of the energy consumption, and assess how to improve international benchmarking practices. The global average electricity consumption for wastewater treatment was 0.89 kWh/m^3. Larger companies serving over 1 million customers display slightly lower specific consumption, of 0.78 kWh/m^3. When viewing regional groupings, EU companies had the highest average energy intensity at 1.18 kWh/m^3, with three EU countries standing out: the Netherlands (1.06 kWh/m^3), Belgium (1.14 kWh/m^3), and Denmark (1.35 kWh/m^3). Countries with the lowest energy intensity varied from Brazil, though India and South Korea to South Africa (averaging 0.24 kWh/m^3). This appeared to be a symptom of the energy data being gross consumption and there being a disparity between wastewater quality standards, since energy production at WWTPs was not captured and the lowest energy consumers had some of the worst standards, and vice versa. It is expected that as regions with lower effluent standards improve to similar levels of advanced economies, their energy consumption will increase too. The influence of energy consumption on GHG emissions was diverse owing to interaction with widely differing emission intensities of grid electricity; Poland had the highest carbon footprint with 0.91 kgCO_2e/m^3, whilst Norway emitted just 0.013 kgCO_2e per cubic meter of, despite consuming 0.60 kWh/m^3, showing the importance of energy intensity on particular infrastructures. Although this study provided some valuable quantifiable results, the conclusions stemming from the limitations of carrying out the benchmarking exercise are just as crucial. There is a

lack of quantity, quality, and granularity in existing global wastewater data, making it difficult to fully analyse the impact and potential paths to improve wastewater treatment. A lack of data generally leads to a lack of representativeness of certain regions, skewing comparisons with limited sample sizes. The two changes that would have the most significant impact for future analyses are to have influent vs. effluent quality and net energy consumption data, which would increase the accuracy of studies, circumnavigating varying legislative effluent standards and compliance rates. The large international sample size, energy data with a quality control, GHG analysis, and specific benchmarking recommendations provide novel results which could be of use to water industry operators, benchmarking organisations, energy efficiency analysts, and regulators.

Acknowledgments

This research was undertaken within the Dŵr Uisce project, part funded by the European Regional Development Fund (ERDF) through the Ireland Wales Co-operation programme 2014-2020.

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