REVIEW OF ENERGY AUDIT AND BENCHMARKING TOOLS TO STUDY ENERGY EFFICIENCY THROUGH REDUCING CONSUMPTION IN WASTEWATER TREATMENT SYSTEMS

Francisco Esteves
University of Trás-os-Montes and Alto Douro, UTAD
Vila Real, Portugal
francisco.esteves@cieifm.com

José Carlos Cardoso
University of Trás-os-Montes and Alto Douro, UTAD
Vila Real, Portugal
jcardoso@utad.pt

Sérgio Leitão
University of Trás-os-Montes and Alto Douro, UTAD
Vila Real, Portugal
sleitao@utad.pt

E. J. Solteiro Pires
University of Trás-os-Montes and Alto Douro, UTAD
Vila Real, Portugal
epires@utad.pt

José Baptista
University of Trás-os-Montes and Alto Douro, UTAD
Vila Real, Portugal
baptista@utad.pt

Abstract. Wastewater treatment systems are major consumers of electricity being responsible for 3 to 5% of global energy consumption, and 56% of greenhouse gas emissions into the atmosphere in the water treatment sector. Climate change currently imposes the definition of a new pattern of human behavior in the defense and sharing of a common space that is the planet, so the optimization of water treatment models plays a crucial role in the definition of sustainability strategies as part of the challenges for decarbonization by 2050. The physical-chemical characteristics of the influent, the treatment techniques and associated technologies and the unpredictability of external phenomena of inefficiency transform wastewater treatment plants (WWTPs) into complex systems, sometimes difficult to understand. The study of energy efficiency plays an important role in the emergence of a standard behavior model, which allows the correction of unbalanced situations in the expected energy consumption. Given the importance of the topic, the present review aims to study energy auditing techniques and benchmarking tools developed for the wastewater treatment sector to reduce the current electricity consumption, which could represent up to 90% of total energy consumption. The result of the research was organized according to the criteria defined for the characterization of auditing techniques and benchmarking tools. A review was conducted from 51 scientific papers from different reference research platforms published in the last 20 years according to the keywords. This literature review has shown that there are, in the classification of consumption reduction, energy auditing and benchmarking tools; energy management techniques and methods directed to the energy efficiency of the treatment stages and specific equipment; and, finally, decision support tools. According to the methodology followed, it was possible to conclude that although the concern is not recent, there are techniques and tools for assessing energy performance more suitable for the wastewater sector. However, the authors recognize that associated with the complexity of wastewater treatment systems, inefficiency phenomena still strongly impact energy efficiency assessment, so the contributions for their identification and quantification may represent an added value for data analysis, systematization, and optimization methodologies.

Keywords: wastewater treatment plants; energy efficiency; energy consumption reduction; energy audits; energy benchmarking tools.

INTRODUCTION

Gradually more global and unprecedented climate change is increasing the variability of the water cycle by inducing a rise in the number of extreme weather events, reducing the predictability of water availability, and affecting water quality. In turn, this sequence of events threatens sustainable development, biodiversity, and the human right to water and sanitation across the planet. Water supply and distribution and wastewater treatment account for about 50% each of the total energy demand of the urban water sector in Europe, for a total of about 70-80 TWh in 2014 (Magagna et al., 2019).

As an essential public service, wastewater treatment has a significant impact on the electricity consumption of the urban water cycle. The water-energy nexus has been an emerging concern for responsible politicians. According to projections from the European Union (EU), there will be an increase in energy consumption in the water supply sector in the coming years of approximately 2.6% of the total electricity consumption in the EU[1].

[1] http://op.europa.eu/en/publication-detail/-/publication/3efed15a-9c73-11e9-9d01-01aa75ed71a1/language-en

The WWTPs are large consumers of electric energy, 3 to 5% of global consumption, and indirectly responsible for 56% of greenhouse gas emissions into the atmosphere in the water treatment sector (Chen & Chen, 2013; Environment Agency, 2010). According to the International Energy Agency (IEA), worldwide electricity consumption in the wastewater sector will increase by about 80% by 2040, according to Figure 1. However, there is significant potential for energy savings if all possible energy efficiency scenarios are explored[1].

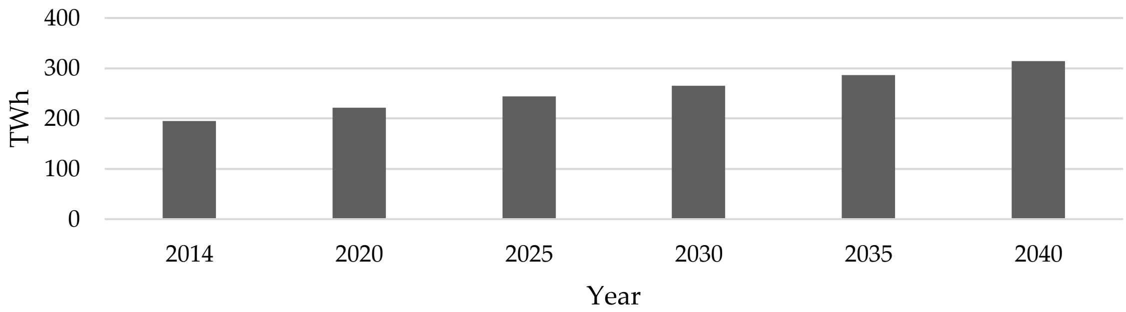

Figure 1 – Electricity consumption in the wastewater treatment sector[2]

The study of energy efficiency in wastewater treatment systems is of utmost importance for the systematization and standardization of procedures and project techniques, operation management and maintenance actions for the revision of public energy policies.

In view of the above, the study of energy efficiency in wastewater treatment infrastructures requires special attention, which has motivated various specialists to develop methodologies to analyze and optimize electricity energy consumption to better understand the phenomena related to energy performance, according to a standard behavior approach.

Following the literature review conducted, several papers were found on energy efficiency in WWTPs (Vrecko, Hvala, & Kocijan, 2002; Torregrossa, et al., 2016; Panepinto, et al., 2016). Using energy consumption modeling tools, the authors present different approaches for identification, analysis and understanding of the causes and consequences of the inefficiency. However, there is a common aspect: the complexity of treatment models. WWTPs are complex systems and, therefore, non-linear (García Nieto, et al., 2013; Longo et al., 2016; Filipe et al., 2019) being infrastructures with intensive consumption of electric energy.

To better understand a complex system, it is essential to comprehend and identify its elements and interrelations[3]. The emergence of an assessment pattern for energy performance of a wastewater treatment system requires a complete and truly holistic knowledge within all the competencies involved (Long & Cudney, 2012).

This paper carries out a reflection on the different approaches of investigation related to the theme of energetic efficiency in wastewater treatment systems, supported by audit and benchmarking techniques focusing on the reduction of electricity energy consumption. The methodology followed for the development of this revision study will be presented in section 2. Section 3 includes a description of the main wastewater treatment model and corresponding electricity energy consumption. Section 4 will carry out a literary revision according to the methodology presented in section 2. Finally, in section 5, a brief discussion on the theme and the respective conclusions will be presented.

METHODOLOGICAL APPROACH

Based on auditing techniques and benchmarking tools to reduce energy consumption in WWTPs, the research was conducted using different combinations of keywords: wastewater treatment plants, energy efficiency, energy consumption reduction, energy audits and energy benchmarking tools.

---

[2] https://www.iea.org/topics/energy-and-water
[3] http://home.iscte-iul.pt/~jmal/mcc/MGM99.pdf

A VIEW OF WASTEWATER TREATMENT AND THE RESPECTIVE ELECTRICITY CONSUMPTION

A wastewater treatment system composed of Pumping Stations incorporated in the sewer network and the WWTP has, as its main goal, the protection of public health and the environment and, whenever possible, reduce water shortage by promoting its reuse (Massoud, Tarhini, & Nasr, 2009). According to some authors (Tchobanoglou et al., 2006), we can group the WWTPs in four or more categories according to the Population Equivalent (PE): PE≤2k; 2k<PE≤10k; 10k<PE≤50k; 50k<PE≤100k; PE>100k where k=1000 equivalent inhabitants.

Regarding the analysis of energy consumption, the bibliographic sources studied provide different approaches. According to Figure 2, most of the studies analyzed refer to the aggregated consumption, either in relation to electricity energy consumption by volume of treated water (kWh/m³) or the total value in kWh. One of the reasons this happens is due to the format of the monthly energy consumption information provided by the electric energy supplier. Regarding the value of electricity energy consumption per treatment stage, in kWh, the availability decreases significantly, declining in the case of the kWh/m³ indicator (Longo et al., 2016; Belloir, Stanford, & Soares, 2015).

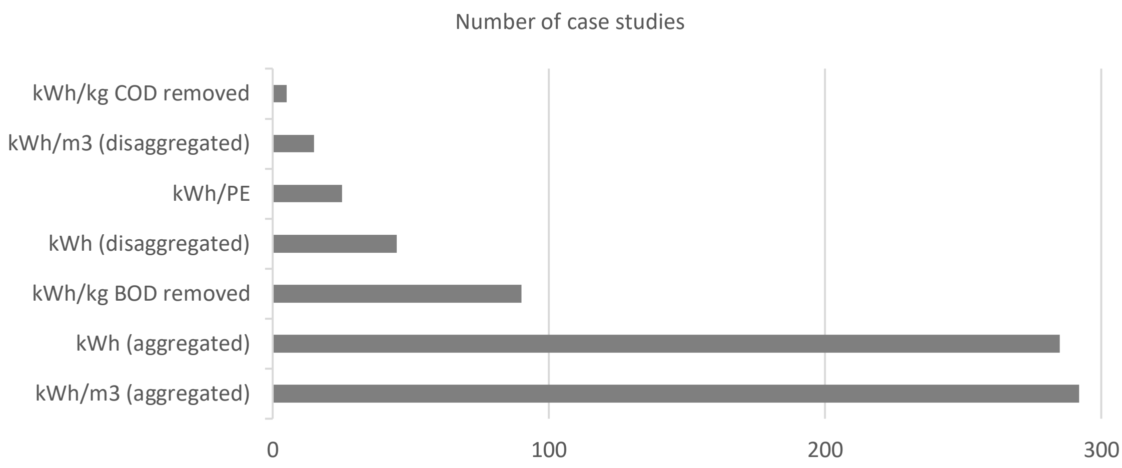

Figure 2 – Statistics frequencies of how energy data are reported in literature
Source: Longo et al. (2016)

Throughout the wastewater treatment process, it is frequent to find different stages: pretreatment, primary treatment, secondary or biological treatment, tertiary treatment, disinfection, sludge treatment and deodorization. According to the data presented in this section, these treatment stages present different consumption rates.

According to the literature review, most of the consumption data is presented in kWh/m³, so the Key Performance Indicator (KPI) will be the most used to describe the consumption for each treatment stage.

The diversity of electricity consumption throughout the WWTP results from each of the stages specificity and treatment requirements. Usually, in medium and large treatment plants, the equipment installed in the biological reactor and in the sludge dewatering stage is known for its high electricity consumption.

In the pretreatment stage, when there is a wastewater pumping system, the electric energy consumption varies between 2.2×10^{-2} and 4.2×10^{-2} kWh/m³, which represents between 5 to 18% of the total energy consumed, according to the size of the plant and intensity of the treatment. The consumption associated with the screening requires about 2.9×10^{-5} and 1.3×10^{-2} kWh/m³, which represents 1.3 to 2.7% of the total energy consumed (Longo et al., 2016).

The primary treatment is, mostly, a simple separation step in circular settling tanks equipped with mechanized scrapers and requires about 4.3×10^{-5} and 7.1×10^{-5} kWh/m³ (Longo et al., 2016).

Then secondary, or biological, treatment is applied for the removal of about 90% of Total Suspended Solids (TSS), a considerable part of the nutrients, Phosphorus (P) and Nitrogen (N), Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD) (EUROSTAT, 2019). This is a structure where the alternating aeration system, aerobic, anoxic, and anaerobic cycle occur, using high consumption power equipment. For this reason, electricity energy consumption presents values between 45 to 75% of the overall consumption of the WWTP, with an efficiency between 0.18 and 0.8 kWh/m³ (Longo et al., 2016).

During tertiary treatment, wastewater undergoes disinfection (bacteria, viruses, and fungi), removal of suspended solids and emerging pollutants. The values depend on the associated technology and range from 4.5×10^{-2} to 0.11 kWh/m^3 for ultraviolet (UV) disinfection (Longo et al., 2016).

Finally, there is the sludge stabilization and dewatering process responsible for 6 to 34% of the total energy consumption, which corresponds to an indicator that can vary between 1.8×10^{-2} and 2.7×10^{-2} kWh/m^3 (Longo et al., 2016).

The energy consumption of a WWTP is sensitive to several factors. Figure 3 shows the connection between energy consumption depending on the WWTP capacity and the respective treatment stage.

According to the data presented, it is possible to perceive that consumption increases with the number of stages, specifically with secondary treatment found in larger infrastructures. It is also evident that the energy intensity per cubic meter of treated wastewater decreases with the capacity of the WWTP due to the scale effect.

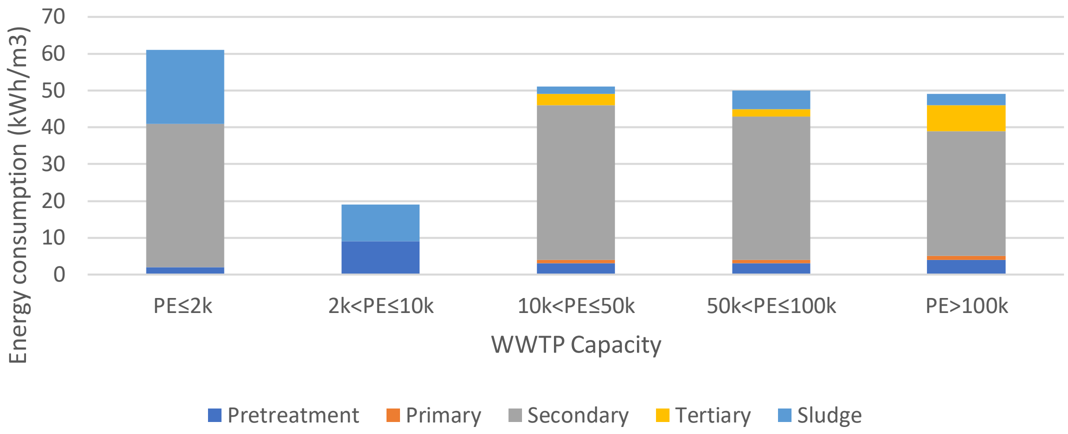

Figure 3 – Average energy consumption of the WWTP according to the capacity and treatment stage
Source: Longo et al. (2016)

Several authors have focused on analyzing energy consumption in WWTPs. The authors Ganora et al. (2019), in their paper on energy efficiency in urban wastewater treatment on a European scale, present a relation between the electricity energy consumption of 19074 WWTPs, with the number of the population equivalent, per infrastructure, never below 2000 inhabitants.

According to Table 1, the total consumption of 24747 GWh/year represents 0.8% of the energy produced in the European Union in 2015 (Magagna et al., 2019). Highlighting that the WWTPs up to 50000 equivalent inhabitants (32% of the study's target population), although they represent 88% of the infrastructures of the study, they correspond to only 43% of electricity consumption.

Regarding the WWTPs above 50000 equivalent inhabitants (12%), they cover 68% of the population and correspond to 57% of the consumption. This means that larger capacity WWTPs, usually close to large centers, despite their higher consumption, have a greater population coverage, which allows a more efficient cost/inhabitant ratio (Yang & Chen, 2021). Aggravating this situation, with significant contributions in terms of energy efficiency, is the depopulation of low-density territories.

Table 1 – Characterization and electricity consumptions of the WWTP.

Capacity	Population	N. º WWTPs	GWh/year
2k<PE≤10k	51827664	11 046	3812
10k<PE≤50k	130862477	5824	6754
50k<PE≤100k	83228712	1180	3399
100k<PE≤500k	174421062	899	6358
500k<PE	128847853	125	4424
TOTAL	569187768	19074	24747

Source: Ganora et al. (2019)

As a reference for this study, some data of electric energy consumption in WWTPs belonging to Águas de Portugal Group (AdP), will be presented. The national reality follows the European panorama and has been the target of several interventions. In 2015, AdP represented 1.4% of the country's total energy consumption, with electricity consumption of around 680 GWh, corresponding to an annual cost of 68 M€[4].

According to the annual water report and waste services in Portugal (RASARP2020), the total energy consumption for pumping on high was 44724686 kWh/year and on low was 16093828 kWh/year. As shown in figure 4, data from the same report show that the energy efficiency of pumping facilities in mainland Portugal is average in both high and low service, indicating a potential for improvement with the adoption of operational and monitoring methodologies that allow a more efficient management.

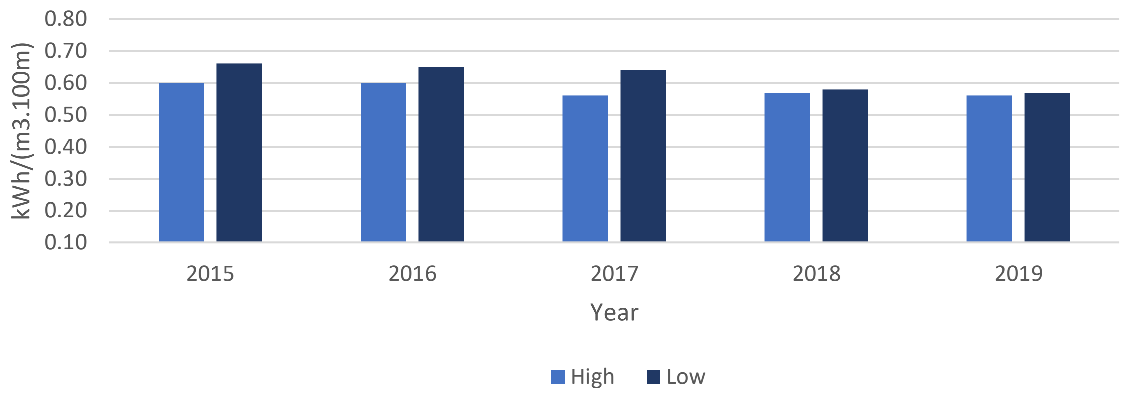

Figure 4 – Energy efficiency of installations are on high and low levels [kWh/ (m3.100m)] – average improvement of the indicator between 2015-2019

When the service is on high levels, the indicator's average value oscillated in the last five years between 0.56 and 0.60 kWh/ (m3.100m), registering a slightly favorable evolution in 2019. Regarding the indicator on the low service, it shows a favorable evolution in the analyzed period.

Energy costs represent a significant portion of the total operating costs of managing entities, so the optimization of electricity consumption plays a strategic role in the financial and environmental sustainability of the sector (Eggink, 2020).

The characterization of wastewater treatment infrastructures, as well as the review and evaluation studies of the sector's electric consumption, demonstrate, by their accuracy and comprehensiveness, the complexity of treatment models and the importance of studying energy efficiency, in addition to inefficiency phenomena, given the demonstrated energy potential.

ENERGY EFFICIENCY IN WASTEWATER TREATMENT SYSTEMS: AUDITING TECHNIQUES AND ENERGY BENCHMARKING TOOLS

Most wastewater treatment systems were designed and built when energy costs were not a concern. Managing entities were focused on pollution levels in water lines and the difficulty in obtaining potable water. The availability of community funds and the time allotted for the construction of the treatment infrastructures conditioned environmental aspects and concerns (Pato, 2016).

Nowadays, the circumstances and concerns are different. The significant increase in energy consumption and the consequent climate change force a deep reflection on the need to mitigate and reduce consumption, making wastewater treatment models more efficient, with less greenhouse gas emissions into the atmosphere, without compromising the water quality standards to which they are subjected to (Fawzy et al., 2020).

Energy efficiency

The most common definition for calculating energy efficiency is evaluated based on three performance indicators: Energy Intensity (EI), Specific Energy Consumption (SEC) and Carbon Intensity (CI) (Lawrence et al., 2019).

---

[4] https://www.adp.pt/downloads/file333_pt.pdf

In the water treatment sector, one of the most widely used indicators is kWh/m^3, which translates the energy consumed by electrical equipment to perform the corresponding tasks throughout the whole treatment process.

However, the energy efficiency calculation obeys an analysis and systematization of input and output data, properly contextualized to the legal sector requirements, in the definition of selected criteria for the best energy practices. It is necessary to introduce new indicators and methodologies for evaluation and decision support.

Given the complexity of wastewater treatment systems, understanding the causes and consequences of inefficiency phenomena is relevant in the framework of public energy policies, given the commitment for decarbonization by 2050 (Environment Agency, 2010) and the definition of procedures and configuration techniques, management, and regulation of treatment systems, specific to the sector.

The Urban Wastewater Directive, adopted in 1991[5], in order to protect the environment from the adverse effects of urban and industrial wastewater discharges, the Water Framework Directive 2000/60 / EU[6], the Energy Efficiency Directive 2012/27 / EU, implemented in the national legal system by Decree-Law No. 68-A/2015[7] and ISO 50001 are examples of important legislative contributions, which associated with research methodologies and energy benchmarking tools represent a set of measures and strategies relevant to optimizing of wastewater treatment systems.

The incorporation of energy efficiency techniques in wastewater treatment systems and infrastructures, although not recent, has been gaining the interest of several researchers, from different areas of intervention, to optimize energy consumption through the identification of a pattern of WWTP operation and behavior concerning inefficiency phenomena.

Figure 5 represents the number of papers published between 2003 and 2020 on energy efficiency in WWTPs, with the aim to reduce electricity consumption in the main consumers of electrical installed in the various treatment stages.

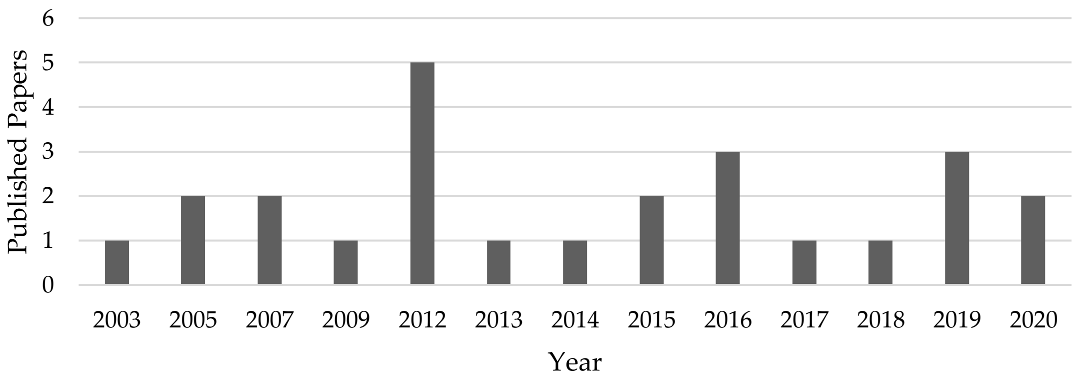

Figure 5 – Papers published on energetic efficiency in the wastewater sector between 2003 -2020

The increase of studies has accompanied the legal and regulatory framework, with special focus on 2012, the date corresponding to the Energy Efficiency Directive 2012/27.

Since system complexity is the characteristic that most concerns researchers, it is important to identify the incidence of studies throughout the various treatment stages.

As shown in Figure 6, there is an incidence of studies on the biological reactor, corresponding to the secondary treatment and the stage with the highest electric energy consumption. Assuming a prominent place in the hierarchical chain of the complex system.

---

[5] https://eur-lex.europa.eu/legal-content/PT/TXT/HTML/?uri=LEGISSUM:l28008
[6] https://apambiente.pt/dqa/assets/01-2000_60_ce---directiva-quadro-da-%c3%a1gua.pdf
[7] https://dre.pt/application/conteudo/67123272

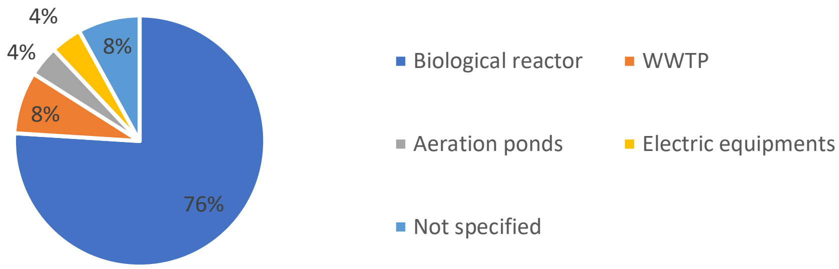

Figure 6 – Number of studies by treatment stage

The reduction of energy consumption using energy auditing and benchmarking techniques has been the subject of research by several authors (Longo et al., 2016; Nakkasunchi et al., 2021; Zhao et al, 2020). Thus, it is important to understand the work done in order to better understand the state--of-the-art, the goal of the present paper.

Energy audits

An energy audit is one of the initial steps to assess the energy consumption and carbon emissions of wastewater treatment systems (Poladori, Vaccari, & Vitali, 2015). The continuous improvement methodology allows companies to establish the structures and processes required for better performance of energy management systems by identifying the most significant energy consumers pertreatment stage or per equipment (Daw et al., 2012).

The energy audit is a simple methodology but essential in studying the consumption of the various electrical equipment, the respective electrical inefficiency phenomena, and the definition of the payback period of the investment, according to technical recommendations[8].

An effective energetic efficiency program needs to adopt a structural approach in the energy management process. The ISO 50001, developed by the International Organization for Standardization, represents an international energy management standard for industrial plants energy efficiency.

Intended for companies with more than two hundred and fifty employees and with an annual turnover greater than 50M€, or whose annual balance sheet exceeds 43M€, they are required to conduct audits every four years, starting in December 2015, as established by the EU Directive 2012/27/EU.

The technical guide for efficient energy use in water services of ADENE - Agency for Energy in Portugal is based on this methodology[7] and the Decree-Law No. 71/2008 that regulates the Intensive Energy Consumption Management System (SGCIE) within the National Strategy for Energy. This program foresees that energy-intensive installations (≥ 500 toe/year) promote energy audits, which focus on the conditions of energy use and promote the increase of energy efficiency, including the use of renewable energy sources.

The energy saving potential of a WWTP does not only depend on the efficiency of the equipment or the use of technologies for reuse or introduction of renewable energy. It also depends on the knowledge that energy managers have of the consumption pattern of the installed equipment and the appropriate use of KPI indicators in the systematization of data for decision support.

According to the reviewed literature (Lawrence et al., 2019; Longo et al., 2016) on energy audits, there are six indica-tors, three of which are the main performance indicators applicable to the water treatment sector (Energy Intensity - EI; Specific Energy Consumption - SEC; Carbon Intensity - CI).

$$KPI1 = EI = \frac{total\ energy\ consumption\ (toe) *}{gross\ added\ value\ (€)}$$

[8]http://www.ersar.pt/pt/site-comunicacao/site-noticias/documents/gt24-eficiencia-energetica.pdf

$$KPI2 = SEC = \frac{total\ energy\ consumption\ (toe) *}{production}$$

$$KPI3 = CI = \frac{GHG\ emissions\ (kgCO2e)}{total\ energy\ consumption(teo)}$$

$$\text{KPI4} = \frac{\text{electric energy } consumption}{\text{volume of treated wastewater}}$$

$$\text{KPI5} = \frac{\text{electric energy consumption}}{served\ PE}$$

$$KPI6 = \frac{electric\ energy\ consumption}{COD\ load\ removed}$$

(*) If there is energy consumption resulting from endogenous waste and other renewable fossil fuels, only 50% of that portion is considered for the calculation of total energy consumption.

The comparison between wastewater management entities or treatment facilities through the indicators provided should consider the standardization of factors to eliminate or mitigate the influence of many different aspects (equipment characteristics, geographical location, etc.)[8].

In order to improve the energy performance of the plant, a data collection and analysis procedure should be carried out, as well as an energy assessment of the WWTP management methods. The regulations also include establishing action plans, objectives, targets, and indicators for measuring results and management techniques evaluation.

In view of the results, ISO 50001 is based on the Plan-Do-Check-Act continuous improvement methodology, according to table 2.

Table 2 – ISO 50001 standard energy efficiency indicators

	ISO 50001
Plan	▪ Energy assessment ▪ Establishment of energy performance indicators ▪ Definition of the action plan
Do	▪ Action plan implementation
Check	▪ Monitoring and Measurement
Act	▪ Management review and continuous improvement

As the energy audit typically uses indicators to evaluate the process efficiency, proper measurement and treatment of operating data are essential to ensure the reliability of the audit conclusions. Therefore, it is recommended that in the process preparation of an audit's, the auditor establishes contact with all those responsible for the functioning of the WWTP, allowing a complete view of its behavior and the relationship between the different stages of treatment, according to a truly holistic view of the entire treatment system (Longo et al., 2016; Long & Cudney, 2012).

While this approach is straightforward and can easily provide calculated energy consumption indicators, it has significant limitations regarding to energy reference exercises and standardization methodologies (Longo et al., 2016).

As the number of WWTPs increases around the world and effluent quality requirements become stricter, the issue of energy efficiency is becoming more and more demanding in environmental and economic terms (Molinos-Senante, Hanley, & Sala-Garrido, 2015), so researchers are turning to new methodologies of data analysis and systematization in the study of energy efficiency in WWTP.

Energy benchmarking tools

The energy benchmarking tool is defined as a continuous and systematic process of comparing energy efficiency indicators of different WWTPs, according to a performance benchmark, to identify the most efficient units and the best management practices (Jamasb & Pollitt, 2000). Any WWTP energy benchmarking system, to be successful, must be able to adapt to different layouts and treatment models used in wastewater treatment.

The use of this type of data analysis and optimization methodology allows wastewater treatment system managers to determine the performance of each infrastructure or set of infrastructures, as well as highlight the best and worst practices in energy management, based on a significant number of indicators.

As mentioned in section 3, the electric energy consumption in WWTPs is usually calculated according to the volume of wastewater treated kWh/m^3 depending on the pollution load (Mizuta & Shimada, 2010; Yang et al., 2010). Although this is a simple and indicative approach to evaluate energy consumption, this indicator has significant variations when influenced by the degree of wastewater dilution. According to the authors, a WWTP where there is an influent dilution due to storm water is more efficient (Campanelli, Foladori, & Vaccari, 2013).

In view of the above, the studies support that the calculation of energy efficiency based on the inflow pollutant load (kWh/PE) gives more accurate results, but in this case, nitrogen must be considered for the calculation of PE, instead of BOD and COD (Benedetti et al., 2008).

Vanrolleghem et al. (1996) proposes for the first time, in 1996, the idea of presenting the energy consumption by pollutant removed per unit, in other words, concerning TSS, BOD, COD, N and/or $P_{removed}$, depending on the aim of the study and the treatment model of the WWTP. The great advantage of this concept is that the tasks of removing organic matter and nutrients is part of the treatment steps with the highest electricity consumption.

Some authors used other indicators: kWh/kg $TSS_{removed}$, kWh/kg $BOD_{removed}$ and kWh/$COD_{removed}$ (Campanelli, Foladori, & Vaccari, 2013; Pan, Zhu, & Ye, 2011), kWh/$N_{removed}$, in case of annual nitrogen removal processes (Lackner et al., 2014) or a combination of these indicators where organic matter and nutrients (N and P) are added together and converted to a reference unit, such as equivalent Phosphate (PO_4^{3-}) (Rodriguez-Garcia et al., 2011). Although current European legislation imposes requirements only on N and P reduction, for effluents treated and returned to sensitive areas (Rodriguez-Garcia et al., 2011), an increase in the number of quality requirements as well as other obligations in the scope of wastewater reuse and, consequently, performance indicators, are to be expected. Concerning the Nitrogen case, the removal is done through the nitrification and denitrification processes, and in the case of Phosphorus, through the recirculation of sludge to the anaerobic tank. Removing these two nutrients requires more electrical equipment (submersible pumps and agitators) and, consequently, higher energy consumption. For this reason, the removal of these two nutrients is considered a relevant KPI. Table 3 lists the main indicators and their importance for each treatment stage.

Table 3 – Comparison of most used KPIs, according to the treatment steps. Legend: Universally Suitable (US), Not Universally Suitable (NUS), Not Suitable (NS)

KPI	Overall	Preliminary	Primary	Secundary	Tertiary	Sludge
kWh/m^3	NS	US	NS	NS	NUS	NS
kWh/PE year	NS	NS	NS	NS	NS	NS
kWh/kg CODremoved	NUS	NS	NUS	NUS	NS	NS
kWh/kg TSSremoved	NS	NS	US	NS	NS	US
kWh/kg Nremoved	NUS	NS	NS	NUS	NS	NS
kWh/kg TPUSremoved	US	NS	NS	US	US	NS

Source: Longo et al. (2016)

The different approaches of benchmarking

The inherent complexity of wastewater treatment systems, combined with the increasing number of quality requirements and external phenomena of inefficiency, involve robust data analysis and evaluation tools in decision support (Aljerf, 2018). The benchmarking results can help wastewater treatment system managers determine the performance of each infrastructure during the analysis process and performance control.

According to Figure 7, there are three main benchmarking approaches: normalization, statistical techniques (OLS and SFA) and programming (DEA and SDEA).

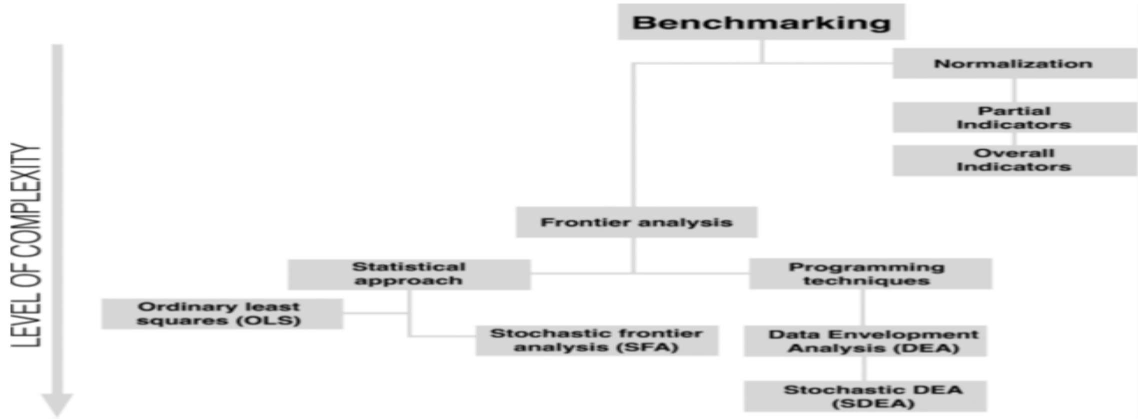

Figure 7 – Benchmarking Approaches. Source: Longo et al. (2016)

According to the degree of complexity, the method of normalized performance consists of comparing indicators and classifying their performance based on a benchmark or according to the best result (Mizuta & Shimada, 2010; Yang et al., 2010; Krampe, 2013; Xie & Chengwen, 2012). This approach assumes that the entire WWTP population is universally comparable with only one metric (Longo et al., 2016). Despite the easiness of understanding the results, the method lacks a large number of infrastructures and indicators to obtain reliable results.

As for frontier analysis, methods define a representative space of an average or best outcome according to the input data. Concerning this method, it is possible to use statistical techniques, OLS or SFA, to describe or infer the energy performance through a sample (Carlson & Walburger, 2007) or through DEA programming techniques (Hernández-Sancho, Molinos-Senante, & Sala-Garrido, 2011; Sala-Garrido, Molinos-Senante, & Hernández-Sancho, 2011; Sala-Garrido, Hernández-Sancho, & Molinos-Senante, 2012), or SDEA, which represents a more robust version of DEA (Kavousian & Rajagopal, 2014).

The approximation using the OLS boundary method allows to estimate the average tendency of the entire infrastructure population and then compare the consumption behavior of each WWTP with the average total value. All WWTPs with above-average ratings can be considered inefficient, while those with below-average ratings are considered efficient (Chung, 2011). The residual resulting from the difference between the real and predicted energy consumption is treated as a measure of inefficiency. Therefore, a negative residual means that the WWTP consumes less energy than another with the same characteristics (Longo et al., 2016). The dependency on a large number of data and the sensitivity of the results of the functional form is presented as two negative aspects of this method (Longo et al., 2016).

Regarding to Stochastic Frontier Analysis (SFA), it is another statistical approach that estimates the efficiency frontier and the efficiency score of the management entities (Blank, 2020). Unlike the OLS method, SFA considers the deviation from the efficiency frontier as two distinct terms since it separates the error from the inefficiency component (Chung, 2011). The random error term allows to cover the random effect of the measurement error on the output (Perttunen, 1989). However, the estimation results are sensitive to distributional assumptions on the error terms and the robustness of the model requires large samples (Longo et al., 2016).

Multicriteria problems have more than one objective. Therefore, it is not straightforward to identify the decision variables that must be adjusted to improve the objectives. In this class of problems, the objectives are conflicting, i.e., when one objective is improved, at least one of the others worsen. Therefore, it is essential to identify the efficiency frontier that identifies these Decision Making Units (DMUs). Several parametric and nonparametric methods have been used to estimate these frontiers (Murillo-Zamorano, 2004). However, nonparametric approaches are preferable since they make no assumptions on the production function distribution, e.g., the DEA method. The DEA methodology allows, among a set of comparable DMUs, to determine which are efficient and which are inefficient, to estimate an efficiency frontier across a set of efficient units, and to identify the efficient units that serve as a reference for the inefficient ones (Sueyoshi & Goto, 2011). Characterized as a production process with multiple inputs and outputs, it easily reproduces the operating model of a wastewater treatment plant. This deterministic approach provides only information on the efficiency of the total energy consumption. The non-radial DEA model (Hernández-Sancho, Molinos-Senante, & Sala-Garrido, 2011) was used to access information on the efficiency of a specific consumption. Being a highly adaptive model to data, efficiency estimation based on single measurements is not considered reliable (DEA, 2021). The literature consulted presents an extension of the DEA model that combines the flexible structure of the nonparametric model and considers the influence of statistical noise (Kavousian & Rajagopal, 2014).

The different benchmarking approaches show large differences between them, and therefore the results on the energy performance of treatment infrastructures will necessarily differ (Longo et al., 2016). On the other hand, the specification of the model and the selection of the technique depend on the benchmarking objectives, the data availability, and the user's willingness to accept the technical specifications (Longo et al., 2016). This means that the result should not be viewed as conclusive.

Literature revision on energy benchmarking tools

In view of the increasing energy costs and demand to reduce greenhouse gas emissions, the optimization of electricity energy consumption in wastewater treatment plants is an issue of growing importance for management entities, as well as for those responsible for public energy policies (Christoforidou et al., 2020).

The difficulty in evaluating energy efficiency is related to a set of external factors, not always predictable and easy to control, which sometimes complicate data analysis and the optimization of energy consumption. Therefore, to overcome these limits, it is necessary to compare energy efficiency with a statistically relevant base to identify deficiencies and optimize results.

Figure 8 presents the number of papers published between 2000 and 2021 on energy benchmarking tools to reduce electricity consumption.

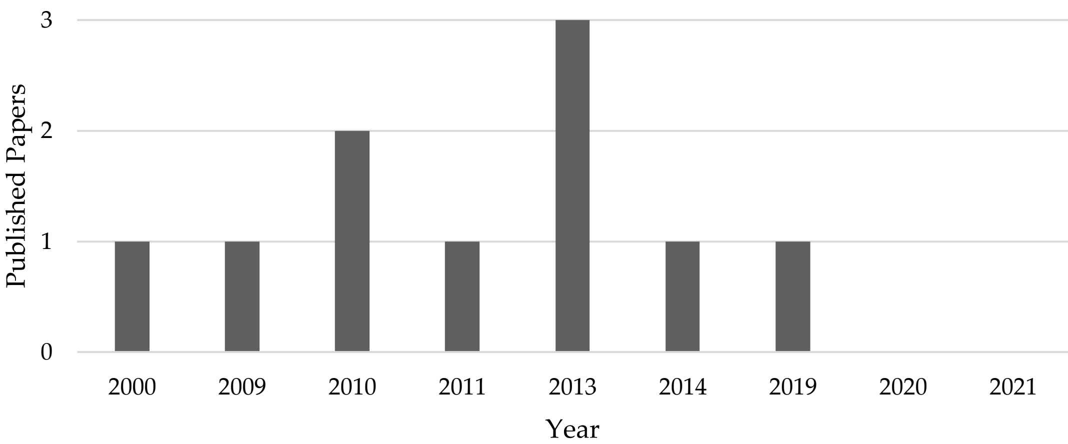

Figure 8 – Published papers on energy benchmarking tools, between 2000-2021

This section provides a literature overview on the energy performance of WWTPs, using different energy benchmarking methodologies: standardization, statistical approximation, and programming techniques.

Balmér (2000) present a study on operating costs and resource consumption in WWTPs with nutrient removal in Northern Europe. Following the expansion of most of the infrastructures, to remove nutrients, a study was developed to compare the costs of energy, reagents, and labor. After collecting data from 5 WWTPs, with different treatment models, the author concluded that the energy consumption ranges between 31 and 47 kWh/PE/year, together with the labor costs, totals a net operational cost between 6 and 14 €/PE/year. Energy costs represent about 25% of total net costs. The classification presented using the normalization method is very dependent on the criteria used.

Using the same energy benchmarking method, (Xie & Chengwen, 2012) present an analysis of the electricity energy consumption of 1856 WWTPs, as well as the impact of different influencing factors on energy performance. The results analysis showed that in 2009, the average power consumption was 0.254 kWh/m^3, which decreases with increasing the WWTP capacity and operating conditions. A WWTP was also selected to analyze the energy consumption in the different treatment stages, concluding that the aeration phase consumed more than half of the total energy consumption. This situation leads the COD indicator to assume a relevant role in analyzing energy efficiency. Based on the consumption presented, the authors recognize the importance of studying energy efficiency throughout the different stages towards creating new models and treatment techniques that are more energy and environmentally efficient. The study presented can serve as a guideline for those responsible for the WWTP operations in achieving lower energy consumption.

Yang et al., (2010) established in 2006 an integrated operational energy performance assessment system in 599 Chinese municipal wastewater treatment plants. This system consists of 7 energy performance indicators in the secondary treatment stage (with oxidation pond, anoxic tank, and sequencing batch reactor) divided into three levels: total energy consumption, energy consumption per unit (pumping, aeration, and sludge treatment) and energy recovery. Using the standardization benchmarking method, the authors identified the main factors in evaluating energy efficiency, the treatment technology chosen, the flow rate of wastewater treated, and the amount of pollutant load removed. The authors concluded that energy benchmarking is applicable and useful in recognizing the energy efficiency potential of WWTPs, especially when the aeration stage exists. It was also demonstrated through statistical analysis of the data that the average electricity consumption in the secondary treatment was 0.290 kWh/m^3.

Focused on reducing of greenhouse gas emissions by 985 Japanese municipal WWTPs, Mizuta and Shimada (2010) present an energy benchmarking analysis using the normalization method. The WWTPs were classified according to their capacity, the existence of oxidation ditch, the existence of activated sludge process (with and without incineration) and advanced wastewater treatment. The electricity energy consumption of each WWTP was estimated from statistical data of the year 2004 and the results of the study showed a specific energy consumption between 0.44 and 2.07 kWh/m^3 for WWTP with an oxidation ditch and 0.30 and 1.89 kWh/m^3 for conventional activated sludge WWTP, without incineration. In a WWTP with gas utilization, the anaerobic digestion, is electricity energy consumption is 0.32 kWh/m^3, with an estimated reduction of 0.17 kWh/m^3. According to the authors, the consumption differences are mainly due to the WWTPs capacity and not the different treatment models. In conclusion, the centralization and capacity of the WWTPs represent two essential factors in reducing electricity consumption.

Taking into consideration the results and contributions of some of the energy benchmarking systems developed in Europe and applied to WWTPs, the Australian company SA WATER decided to conduct an energy performance study on 24 wastewater treatment infrastructures to identify opportunities to optimize consumption and support decision making within the framework of capital investment in energy efficiency. The experiment results are presented by Krampe (2013). Given the wide range of treatment plant sizes and technologies, the authors use kWh/PE/year as the main comparison indicator. The specific energy consumption showed great variability in the various categories, and only a few WWTPs achieved results close to the reference values. According to the author, the stage responsible for reuse (water reuse pump station, ultraviolet disinfection, etc.) is the main reason for the differences in the consumption presented. In this research, as there is no reference to this step in the chosen energy benchmarking tool, it was decided to perform a consumption measurement of the equipment installed in the reuse, being this an important future contribution. Not being an exclusive characteristic of the tools used in the study, one of the problems encountered is the lack or uncertainty of some data. Despite some limitations, the results presented allowed the identification of some deficiencies in the infrastructures, a better understanding of the flow of energy consumption and, finally, the improvement of the energy performance of the WWTPs.

Bodík and Kubaská (2013), in their study on energy and sustainability in WWTPs using the normalization method, summarize the energy consumptions obtained in 51 large and 17 small rural WWTPs in Slovakia. After comparison in technological and energy terms, the average energy consumption in the larger WWTPs is 0.485 kWh/m^3 and 0.915 kWh/m^3 in rural WWTPs. The average energy demand related to the Biochemical Oxygen Demand load (BOD_5) is 2.27 kWh/kg. The specific energy production is relatively low, in the order of 1.2 kWh_{el}/m^3 of biogas produced and 0.1 kWh_{el}/m^3 of treated wastewater. In the present case, the energy benchmarking reported data according to the capacity of the WWTP.

Campanelli, Foladori and Vaccari (2013) present a study of 289 wastewater treatment plants in Italy using a normalization benchmarking approach, to be an operational tool for data treatment, analysis methods and decision support in the development of a standard knowledge on energy efficiency. The research has shown, as in previous studies, that the size of the WWTP and the treatment system have a significant impact on the plant's energy efficiency.

In the study presented by Belloir, Stanford and Soares (2015), the authors focus on the importance of various aspects, particularly the layout and location of the WWTP, in the use of energy benchmarking tools. The study involved a comparison of 2 WWTPs, located at different sites (1 and 2) in the UK and both consisting of primary, secondary, and tertiary treatment stages. The results indicated that sites 1 and 2 presented a consumption of 2.32 kWh/m^3 and 0.98 kWh/m^3, respectively. In the 2 WWTPs, the aeration stage presented the highest consumptions with 2.08 kWh/m^3 at location 1 and 0.91 kWh/m^3 at location 2. This study has shown that the effectiveness of the energy benchmarking exercise in identifying the main energy consumers lacks a holistic view of the treatment model and the need to include parameters such as effluent quality, WWTP operation and layout.

The paper under review by Carlson and Walburger (2007) represents a benchmarking tool for frontier analysis, by statistical approximation, Ordinary Least Squares (OLS). This study aimed to develop metrics to compare energy use between wastewater treatment plants and wastewater management entities. This comparison allowed the normalization of factors and produced a scoring method according to the established goal.

Another benchmarking approach, called non-radial DEA, was used by the authors Hernández-Sancho et al. (2011) in calculating the energy efficiency indices of 99 WWTPs, located in Spain. After an analysis of the operational variables that impact the difference in energy behavior of the WWTPs, the authors found that efficiency levels were low, with only 10% of the WWTPs being efficient. They also showed that the size of the WWTP, the amount of pollutant load removed, and the aeration stage in the reactor have a significant bearing on the difference in results. Contrary to expectations, the authors consider that the WWTP age is not determinant in the energy consumption calculation. Finally, they quantified the savings, both in economic terms and CO_2 emissions. It was acknowledged that there is a considerable potential for reducing consumption, greenhouse gas emissions and operational costs related to the WWTP.

In order to determine the operational efficiency, or eco-efficiency, of each of the 113 Spanish WWTPs, Lorenzo-Toja et al. (2015) developed a study methodology that combines Life Cycle Assessment (LCA) and the DEA method. They recognized the WWTPs as complex systems with multiple input and output variables, the authors identified with this study several factors that impact efficiency, such as the size of the treatment infrastructure, the level of technology complexity used, climatic influences, the pollutant load of the influent, and the type of operational management, among others. It also showed with this research, as with others, that efficiency levels are directly proportional to the WWTP capacity, which means lower reduction potential. Despite the relevance of the research presented, as well as the contributions to the understanding of the differences between the WWTPs and the characterization of an integrated environmental profile, the authors suggest in the paper, as future work, monitoring for annual periods, which allows the study of the regularity of a pattern or the relationship of the respective variations with the changes in the parameters analyzed.

The authors Longo et al. (2019) present a specific standard methodology for energy efficiency assessment and optimization of energy consumption in WWTPs, based on the DEA benchmarking method called ENERWATER. Inspired by the continuous improvement cycle, the method defines the concept of energy efficiency and proposes a systematic, aggregated, and comparable measurement of data at 98 WWTPs, defined as the Water Treatment Energy Index (WTEI). This indicator, translated into an energy tag, allows access to information about the energy status of the WWTP, according to defined consumption patterns. A limitation of the method is the difficulty in accessing the data, which makes it difficult to calculate the KPI efficiency indicators and consequently the composite energy index (WTEI). Even though they are not used in determining the index, the indicators will be used in extensions of the ENERWATER methodology in decision support. This benchmarking tool, considered to be the first dedicated tool to study the efficiency of WWTPs, aims to contribute to the development of a standard energy methodology in the context of EU energy policies accessible to managers and operators of water treatment plants.

CONCLUSION

Based on electricity consumption data, resulting from the reviewed papers on energetic efficiency in wastewater treatment systems, it is now acknowledged that WWTPs are intensive electricity consumers, with a negative impact on greenhouse gases emissions into the atmosphere and on the operational treatment costs. The number of WWTPs and the number of quality requirements can be expected to increase significantly, so it is important to continue studying and developing analysis methodologies and optimization, as well as treatment technologies, focusing on the inefficiency phenomena. The evidence of some studies on the potential of energy consumption reduction is enough motivation for the goal to be achieved.

One of the conclusions of this study is that it is difficult to define the concept of energy efficiency in WWTPs. The system's complexity requires a set of variables and inefficient phenomena that are difficult to predict and sometimes difficult to explain due to the non-linearity of the treatment models. ENERWATER, considered the first energy benchmarking tool specific to wastewater treatment systems, presents a definition of energy efficiency based on a specific composite indicator for wastewater, according to a multidimensional concept, to capture the dimension of the values measured throughout the treatment process.

Throughout this review study it was possible to understand the differences between the energy audit methodologies and the energy benchmarking tool, as well as the importance of the complementarity between the two in achieving the intended goals. The importance of a holistic view in approaching the study of energy efficiency in wastewater treatment sector was also demonstrated. The geographical characteristics of the area where the infrastructure is located, climatic conditions, the pollution load of the influent, the cost of electricity, as well as human behavior represent a significant number of factors without a correspondence in existing benchmarking tools.

Another conclusion of this review work is related to the importance of the objective, and the extent of the analysis in the benchmarking tool selection process since its range of applicability and validity is different. Of the main methods targeted for study, DEA is the one that best fits the complexity of WWTPs, since it allows the identification of reference values in multivariable systems, which makes this method very dependent on the selection of variables.

Although the methods presented can be used for analysis and comparison according to their characteristics, it is unanimous that the diagnosis of energy performance in wastewater treatment systems lacks dedicated optimization methodologies suited to the reality of the systems. Most benchmarking methods are merely diagnostic tools, with shortcomings prescribing optimization strategies.

It was based on this assumption, after evaluating a representative data sample, that the ENERWATER project decided to present a methodology capable of quantifying the energy efficiency in WWTPs through an energy label and identifying energy inefficiencies, in compliance with the requirements of the EU Energy Efficiency Directive by wastewater system operators. Despite the benefits resulting from the use of this energy benchmarking tool, the reviewed works considered the existence of some limitations: the availability of data, the correspondence between some performance indicators and the WTEI composite indicator, the quantification of inefficiency phenomena in the evaluation of WWTP energy efficiency, etc.

There is clearly a common denominator in all revised papers on the study of energy efficiency in WWTPs. Whether through a quick audit or using an energy benchmarking tool using normalization or frontier analysis methods, the complexity of the treatment system makes it difficult to analyze and correlate performance indicators, as well as to identify and characterize inefficiency phenomena in a timely manner. While these methods can be used for comparison, energy performance diagnosis is far from conclusive. A complex system needs, throughout the evaluation stages, characterization and optimization, a thorough understanding of the inefficiency phenomena in each of its constituent elements and the dependency relationships between them.

This paper concludes that the identification and quantification of these inefficiency phenomena play a key role in identifying a pattern of emergence behavior, throughout the treatment system, according to a truly holistic vision of competencies.

REFERENCES

ADENE_Eficiência Energética (2020, april). Retrieved: http://www.ersar.pt/pt/site-comunicacao/site-noticias/documents/gt24-eficiencia-energetica.pdf

Aljerf, L. (2018). High-efficiency extraction of bromocresol purple dye and heavy metals as chromium from industrial effluent by adsorption onto a modified surface of zeolite: Kinetics and equilibrium study. *J. Environ. Manage.*, 225, 120–132. doi: 10.1016/j.jenvman.2018.07.048

Balmér, P. (2000). Operation costs and consumption of resources at Nordic nutrient removal plants. *Water Sci. Technol.*, 41(9), 273–279. doi: 10.2166/wst.2000.0224

Belloir, C., Stanford, C., & Soares, A. (2015). Energy benchmarking in wastewater treatment plants: the importance of site operation and layout. *Environ. Technol.*, 36(2), 260–269. doi: 10.1080/09593330.2014.951403

Benedetti, L., Dirckx, G., Bixio, D., Thoeye, C., & Vanrolleghem, P. A. (2008). Environmental and economic performance assessment of the integrated urban wastewater system. *J. Environ. Manage.*, 88(4), 1262–1272. doi: 10.1016/j.jenvman.2007.06.020

Blank, J. L. T. (2020). The use of the scaling property in a frontier analysis of a system of equations: An application to Dutch secondary education. *Appl. Econ.*, 52(49), 5364–5374. doi: 10.1080/00036846.2020.1763246

Bodík, I., & Kubaská, M. (2013). Energy and sustainability of operation of a wastewater treatment plant. *Environ. Prot. Eng.*, 39(2), 15–24. doi: 10.5277/EPE130202

Campanelli, M., Foladori, P., & Vaccari, M. (2013). *Consumi elettrici ed efficienza energetica del trattamento delle acque reflue*. Maggioli Editore.

Carlson, S., & Walburger, A. (2007). *Energy index development for benchmarking water and wastewater utilities*. American Water Works Association.

Christoforidou, P., Bariamis, G., Iosifidou, M., Nikolaidou, E., & Samaras, P. (2020). Energy Benchmarking and Optimization of Wastewater Treatment Plants in GreecE. *Environ. Sci. Proc.*, 2(1), 36. doi: 10.3390/environsciproc2020002036

Chung. W. (2011). Review of building energy-use performance benchmarking methodologies. *Appl. Energy*, 88(5), 1470–1479. doi: 10.1016/j.apenergy.2010.11.022

Daw, J., Hallett, K., DeWolfe, J., & Venner. I. (2012). *Energy Efficiency Strategies for Municipal Wastewater Treatment Facilities*. National Renewable Energy Lab. (NREL), Golden, CO (United States), NREL/TP-7A20-53341. doi: https://dx.doi.org/10.2172/1036045

Decreto-Lei 68-A/2015. (2015). Retrieved: https://dre.pt/application/conteudo/67123272

Diretiva 2012/27/EU (2012). Parlamento Europeu e do Conselho, de 25 de outubro de 2012, relativa à eficiência energética, que altera as Diretivas 2009/125/CE e 2010/30/UE e revoga as Diretivas 2004/8/CE e 2006/32/CETexto relevante para efeitos do EEE (p. 56).

Eggink, J. (2020). *Managing Energy Costs: A Behavioral and Non-Technical Approach*. River Publishers. doi: 10.1201/9781003151227

Energy and water – Topics (2021, april). IEA. Retrieved: https://www.iea.org/topics/energy-and-water

Environment Agency (2010). *A low carbon water industry in 2050*. Bristol: Environment Agency.

Environmental and Energy Efficiency Evaluation Based on Data Envelopment Analysis (DEA). MDPI, 2021. doi: 10.3390/books978-3-0365-0573-2

EUROSTAT (2019). Union européenne, e Commission européenne, Energy, transport and environment statistics.

Fawzy, S., Osman, A. I., Doran, J., & Rooney, D. W. (2020). Strategies for mitigation of climate change: a review. *Environ. Chem. Lett.*, 18(6), 2069–2094. doi: 10.1007/s10311-020-01059-w

Filipe, J., Bessa, R. J., Reis, M., Alves, R., & Póvoa, P. (2019). Data-driven predictive energy optimization in a wastewater pumping station. *Appl. Energy*, 252, 113423. doi: 10.1016/j.apenergy.2019.113423

Foladori, P., Vaccari, M., & Vitali, F. (2015). Energy audit in small wastewater treatment plants: Methodology, energy consumption indicators, and lessons learned. *Water Sci. Technol. J. Int. Assoc. Water Pollut. Res.*, 72, 1007–1015. doi: 10.2166/wst.2015.306

Ganora, D. et al. (2019). Opportunities to improve energy use in urban wastewater treatment: a European-scale analysis. *Environ. Res. Lett.*, 14(4), 044028. doi: 10.1088/1748-9326/ab0b54

García Nieto, P. J., Alonso Fernández, J. R., Cos Juez, F. J., Sánchez Lasheras, F., & C. Díaz Muñiz, C. (2013). Hybrid modelling based on support vector regression with genetic algorithms in forecasting the cyanotoxins presence in the Trasona reservoir (Northern Spain). *Environ. Res.*, 122, 1–10. doi: 10.1016/j.envres.2013.01.001

Gell-Mann, M. (1988). Simplicity and complexity in the description of nature. *Engenieering & Science*, 3-9. Retrieved: http://home.iscte-iul.pt/~jmal/mcc/MGM99.pdf

Hernández-Sancho, F., Molinos-Senante, M., & Sala-Garrido, R. (2011). Energy efficiency in Spanish wastewater treatment plants: A non-radial DEA approach. *Sci. Total Environ.*, 409(14), 2693–2699. doi: 10.1016/j.scitotenv.2011.04.018

Jamasb, T., & Pollitt, M. (2000). Benchmarking and regulation: international electricity experience. *Util. Policy*, 9(3), 107–130. doi: 10.1016/S0957-1787(01)00010-8

Kavousian, A., & Rajagopal, R. (2014). Data-Driven Benchmarking of Building Energy Efficiency Utilizing Statistical Frontier Models. *J. Comput. Civ. Eng.*, 28(1), 79–88. doi: 10.1061/(ASCE)CP.1943-5487.0000327

Krampe, J. (2013). Energy benchmarking of South Australian WWTPs. *Water Sci. Technol.*, 67(9), 2059–2066. doi: 10.2166/wst.2013.090

Lackner, S., Gilbert, E. M., Vlaeminck, S. E., Joss, A., Horn, H., & Van Loosdrecht, M. C. M. (2014). Full-scale partial nitritation/anammox experiences – An application survey. *Water Res.,* 55, 292–303. doi: 10.1016/j.watres.2014.02.032

Lawrence, A., Thollander, P., Andrei, M., & Karlsson, M. (2019). Specific Energy Consumption/Use (SEC) in Energy Management for Improving Energy Efficiency in Industry: Meaning, Usage and Differences. *Energies*, 12(2), 247. doi: 10.3390/en12020247

Long, S., & Cudney, E. (2012). Integration of energy and environmental systems in wastewater treatment plants. *International Journal of Energy, Environment and Economics,* 3(4), 521-530.

Longo, S. et al. (2016). Monitoring and diagnosis of energy consumption in wastewater treatment plants. A state of the art and proposals for improvement. *Appl. Energy*, 179, 1251–1268. doi: 10.1016/j.apenergy.2016.07.043

Longo, S., et al. (2019). ENERWATER – A standard method for assessing and improving the energy efficiency of wastewater treatment plants. *Appl. Energy*, 242, 897–910. doi: 10.1016/j.apenergy.2019.03.130

Lorenzo-Toja, Y., Vázquez-Rowe, I., Chenel, S., Marín-Navarro, D., Moreira, M. T., & Feijoo, G. (2015). Eco-efficiency analysis of Spanish WWTPs using the LCA + DEA method. *Water Res.*, 68, 651–666. doi: 10.1016/j.watres.2014.10.040

Magagna, D., Hidalgo González, I., Bidoglio, G., Peteves, S., Adamovic, M., Bisselink, B., De Felice M., De Roo, A., Dorati, C., Ganora, D., Medarac, H., Pistocchi, A., Van De Bund, W., &Vanham, D. (2019). *Water – Energy Nexus in Europe*. Publications Office of the European Union, Luxembourg. doi: 10.2760/968197, JRC115853

Massoud, M. A., Tarhini, A., &. Nasr, J. A. (2009). Decentralized approaches to wastewater treatment and management: Applicability in developing countries. *J. Environ. Manage.*, 90(1), 652–659. doi: 10.1016/j.jenvman.2008.07.001

Mizuta, K., & Shimada, M. (2010). Benchmarking energy consumption in municipal wastewater treatment plants in Japan. *Water Sci. Technol.*, 62(10), 2256–2262. doi: 10.2166/wst.2010.510

Molinos-Senante, M., Hanley, N., & Sala-Garrido, R. (2015). Measuring the CO2 shadow price for wastewater treatment: A directional distance function approach. *Appl. Energy*, 144, 241–249. doi: 10.1016/j.apenergy.2015.02.034

Murillo-Zamorano, L. R. (2004). Economic Efficiency and Frontier Techniques. *J. Econ. Surv.*, 18(1), 33–77. doi: 10.1111/j.1467-6419.2004.00215.x

Nakkasunchi, S., Hewitt, N. J., Zoppi, C., & Brandoni, C. (2021). A review of energy optimization modelling tools for the decarbonisation of wastewater treatment plants. *J. Clean. Prod.*, 279, 123811. doi: 10.1016/j.jclepro.2020.123811

Pan, T., Zhu, X.-D., & Ye, Y.-P. (2011). Estimate of life-cycle greenhouse gas emissions from a vertical subsurface flow constructed wetland and conventional wastewater treatment plants: A case study in China. *Ecol. Eng.*, 37(2), 248–254. doi: 10.1016/j.ecoleng.2010.11.014

Panepinto, D., Fiore, S., Zappone, M., Genon, G., & Meucci, L. (2016). Evaluation of the energy efficiency of a large wastewater treatment plant in Italy. *Appl. Energy*, 161, 404–411. doi: 10.1016/j.apenergy.2015.10.027

Pato, J. (2016). *História das Políticas Públicas de Abastecimento e Saneamento de Águas em Portugal*. Cronologia e Depoimentos.

Perttunen (1989). Bayesian model parameter estimation of systems subject to random input and output measurement error. *IEEE 1989 International Conference on Systems Engineering*, Aug. 1989, (pp. 227–230). doi: 10.1109/ICSYSE.1989.48660

Rodriguez-Garcia, G., Molinos-Senante, M., Hospido, A., Hernández-Sancho, F., Moreira, M. T., & Feijoo, G. (2011). Environmental and economic profile of six typologies of wastewater treatment plants. *Water Res.*, 45(18), 5997–6010. doi: 10.1016/j.watres.2011.08.053

S. Chen, & B. Chen (2013). Net energy production and emissions mitigation of domestic wastewater treatment system: A comparison of different biogas–sludge use alternatives. *Bioresour. Technol.*, 144, 296–303. doi: 10.1016/j.biortech.2013.06.128.

Sala-Garrido, R., Hernández-Sancho, F., & Molinos-Senante, M. (2012). Assessing the efficiency of wastewater treatment plants in an uncertain context: a DEA with tolerances approach. *Environ. Sci. Policy*, 18, 34–44. doi: 10.1016/j.envsci.2011.12.012

Sala-Garrido, R., Molinos-Senante, M., & Hernández-Sancho, F. (2011). Comparing the efficiency of wastewater treatment technologies through a DEA metafrontier model. *Chem. Eng. J.*, 173(3), 766–772. doi: 10.1016/j.cej.2011.08.047

Sueyoshi, T., & Goto, M. (2011). DEA approach for unified efficiency measurement: Assessment of Japanese fossil fuel power generation. *Energy Econ.*, 33(2), 292–303. doi: 10.1016/j.eneco.2010.07.008

Tchobanoglou, G., Burton, F. L., Stensel, H. D., Eramo, B., & Sirini, P. (2005). *Ingegneria delle acque reflue: Trattamento e riuso*. Milano: McGraw-Hill.

Torregrossa, D., Schutz, G., Cornelissen, A., Hernández-Sancho, F., & Hansen, J. (2016). Energy saving in WWTP: Daily benchmarking under uncertainty and data availability limitations. *Environ. Res.*, 148, 330–337. doi : 10.1016/j.envres.2016.04.010

Vanrolleghem, P. A., Jeppsson, U., Carstensen, J., Carlssont, B., & Olsson, G. (1996). Integration of wastewater treatment plant design and operation — a systematic approach using cost functions. *Water Sci. Technol.*, 34(3), 159–171. doi: 10.1016/0273-1223(96)00568-9

Vrecko, D., Hvala, N., & Kocijan, J. (2002). Wastewater treatment benchmark: What can be achieved with simple control. *Water Sci. Technol. J. Int. Assoc. Water Pollut. Res.*, 45, 127–34. doi: 10.2166/wst.2002.0568

Xie, T., & Chengwen, W. (2012). *Energy Consumption in Wastewater Treatment Plants in China*. doi: 10.13140/2.1.1228.9285

Yang, J., & Chen., B. (2021). Energy efficiency evaluation of wastewater treatment plants (WWTPs) based on data envelopment analysis. *Appl. Energy*, 289, 116680. doi: 10.1016/j.apenergy.2021.116680

Yang, L., Zeng, S., Chen, J., He, M., & Yang, W. (2010). Operational energy performance assessment system of municipal wastewater treatment plants. *Water Sci. Technol.*, 62(6), 1361–1370. doi: 10.2166/wst.2010.394

Zhao, L., Dai, T., Qiao, Z., Sun, P., Hao, J., & Yang, Y. (2020). Application of artificial intelligence to wastewater treatment: A bibliometric analysis and systematic review of technology, economy, management, and wastewater reuse. *Process Saf. Environ. Prot.*, 133, 169–182. doi: 10.1016/j.psep.2019.11.014.