Applied Energy, Volume 242, 15 May 2019, pp. 897-910
DOI:10.1016/j.apenergy.2019.03.130

ENERWATER - A standard method for assessing and improving the energy efficiency of wastewater treatment plants

Longo S.[a*], *Mauricio-Iglesias M.*[a], *Soares A.*[b], *Campo P.*[b], *Fatone F.*[c], *Eusebi A. L.*[c], *Akkersdijk E.*[d], *Stefani L.*[e], *Hospido A.*[a]

[a] *Department of Chemical Engineering, Institute of Technology, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Spain*

[b] *Cranfield Water Science Institute, Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK*

[c] *Department of Materials, Environmental and City Planning Science and Engineering, Faculty of Engineering, Polytechnic University of Marche, Ancona, Italy*

[d] *Aggerverband, FB Abwasserbehandlung Sonnenstraße 40, 51645 Gummersbach, Germany*

[e] *ETRA, via del Telarolo 9, 35013 Cittadella, Italy*

[*] *Corresponding author (e-mail:* stefano.longo@usc.es*)*

Abstract This paper describes the first methodology specifically tailored to estimate energy efficiency at wastewater treatment plants (WWTPs). Inspired by the cycle of continuous improvement, the method i) precisely defines the concept of energy efficiency in WWTPs, ii) proposes systematic and comparable ways to measure it, and iii) allows benchmarking and diagnosing energy hotspots. The methodology delivers an aggregated measure of the WWTP energy efficiency defined as the Water Treatment Energy Index, a single energy label that uses universally known illustrations enabling wide communication of standardized information on the WWTP energy status. The accuracy, reproducibility and generality of the methodology were validated by a widespread energy benchmarking method, and a case study is presented to show its capabilities. By promoting dialogue towards the creation of a specific European Standard, the actions accomplished by the H2020 Coordination Support Action ENERWATER should positively contribute to improving the exchange of information on energy saving actions and results between wastewater utilities and towards other stakeholders.

Keywords WWTP; key performance indicators (KPI); benchmarking; label; diagnosis

Nomenclature

BOD	Biochemical oxygen demand
CED	Cumulative energy demand
CFU	Colony-forming unit
COD	Chemical oxygen demand
DEA	Data envelopment analysis
DS	Decision support
EPI	Energy performance indicators
EU	European Union
GPP	Green public procurement
KPI	Key performance indicator
kW	Kilowatt
N	Nitrogen
PE	Person equivalent
P	Phosphorus
RA	Rapid audit
TN	Total nitrogen
TP	Total phosphorus
TSS	Total suspended solids

UV	Ultraviolet
WWTP	Wastewater treatment plant
WTEI	Water treatment energy index

1. Introduction

Water and energy are highly interconnected. Water is needed for most stages of energy production and transmission, and energy is crucial for the provision and treatment of water. This fundamental resource relationship is called the water-energy nexus [1]. The higher the water use by end users, the higher the energy use, and then the higher the water use for energy production, resulting in a feedback loop and ultimately in higher carbon emissions. The increase in carbon emissions contributes to climate change [2], which negatively impacts the availability of water and energy, and shortages in one resource can directly affect the availability of the other. With both water and energy needs set to increase [3], it has become ever more important to understand the linkages between the two, to anticipate future stress points and implement policies, technologies and practices that soundly address the associated risks.

Of the energy consumed along the urban water cycle, the largest amount is used for wastewater treatment, in the form of electricity, in developed countries [4]. To counterbalance the increasing trend in energy intensity of wastewater treatment processes, energy efficiency improvement is the only option as effluent quality needs to be ensured [5]. Any energy policy in the wastewater sector should lead to reduced energy consumption without compromising public health and environment. In practise, such a policy implies i) using less energy to treat the same amount of wastewater or ii) treating more wastewater (or more thoroughly) with the same amount of energy. Both cases require wastewater treatment to become more energy efficient.

With the transposition of the Energy Efficiency Directive 2012/27/EU [6], carrying out energy audit at wastewater treatment plants (WWTPs) has evolved from convenient to an obligation for a significant part of European water utilities, i.e. those with more than 250 employees and with annual trading volume greater than €50 million or whose annual balance sheet exceeds €43 million. However, the Directive as well as its transposition into national legislation by the Member States lacks sufficient detail for a clear and consistent implementation [7]. First, the concept of energy efficiency for WWTPs is not clearly defined: although the Directive defines energy efficiency as "the relationship between the production of service, good or energy and energy demand", the service provided by WWTPs, i.e. "cleaning wastewater", must be specified in quantitative objectives/functions such as "eliminate organic carbon", "eliminate nitrogen", "eliminate solids" or "eliminate pathogens", etc., depending on, e.g., the quality of the effluent wastewater and the location of the discharging point [8]. Second, WWTPs are intrinsically characterized by having heterogeneous layouts, which makes comparisons not trivial. Indeed, the treatment processes are organized in different unit operations grouped together to provide various levels of treatment known as preliminary, primary, secondary, tertiary and sludge treatment [9]. Depending on economic and environmental criteria, WWTPs are composed by different combinations of treatment levels. This heterogeneity has led some scholars to think that WWTPs benchmarking is unfeasible, given that each plant is different [10]. Measurement is however the first step that leads to information gathering, control and eventually improvement. Therefore, any successful WWTPs energy benchmarking system should be capable to adapt to the different WWTPs layouts and process schemes commonly used in the wastewater sector.

In a previous publication [11], we revised existing literature on WWTP energy-use performance and of the state-of-the-art methods for WWTP energy benchmarking, eventually identifying the need of a standardised method. This paper intends to fill that gap by presenting a methodology for carrying out energy benchmarking and diagnosis of energy efficiency of WWTPs. Besides, we show how the absence of systematic methodologies for plant wide evaluation of energy efficiency and the lack of a procedure for benchmarking WWTPs energy efficiency represented a major obstacle to improve WWTPs energy performance. While energy efficiency guidelines and measures are sometimes available for specific equipment, such as blowers [12] or pumps [13], there is no clear way to determine how well these components operate at plant-wide level. Furthermore, decision-makers require tailored energy-related metrics in order to communicate the status quo adequately with other stakeholders [14]. To answer to the European normative pressure and avoid economically wasteful energy policies the need for standardization in the evaluation and comparison of WWTPs energy efficiency appears even more necessary. Based on both a solid theoretical foundation and feedback from the wastewater sector stakeholders, we propose here a methodology as an energy efficiency benchmarking framework. This study therefore focuses on the development of a structured and systematic method for assessing and improving the energy efficiency in WWTPs. The key novelty of the ENERWATER methodology lies on its output – the Water Treatment Energy Index (WTEI) - a single energy label that uses universally known illustrations, to widely communicate standardized information on the WWTP energy status. The methodology here presented is relevant to anyone interested in WWTPs energy efficiency as, for the first time, it provides engineers, wastewater operators and decision-makers a method to obtain standardized and comparable efficiency information. In particular by offering guidelines on how to define energy efficiency of WWTPs and identifying the sources of energy misuse, the outcomes of this article are expected to move WWTPs towards increasing energy efficiency.

Section 2 provides theoretical background on energy efficiency benchmarking methods focusing on key challenges. Section 3 includes a description of the methodology, together with a step-by-step demonstration of a selected case study. The robustness of the efficiency estimation process is then validated in Section 4, while the necessity and utility of the methodology as well as current limitations and future outlook are discussed in Section 5. Finally, Section 6 offers concluding observations.

2. Literature review

In the last decade, a number of benchmarking tools have been developed to estimate energy (in)efficiency in industrial systems. A traditional way to overcome some of the difficulties of making comparison is to use Key Performance Indicators (KPIs) [15], which reflect the purpose of the facility under comparison. A KPI is often a ratio of an input and an output and is usually employed and obtained by simply normalizing the energy use based on the unit activity or service provided [16]. KPIs are often used to monitor energy performance in several industrial applications, e.g. from subway stations [17] to compressed air systems [18]. In the wastewater sector, KPIs have been used to give a general overview of the energy performance of WWTPs [19]. Although such simple normalization is relatively inexpensive to apply, is not data intensive and is easy to implement and understand, the downside it its very limited in scope as KPIs involves only partial evaluations, which is an important constraint [11]. So, a single KPI may not fully reflect the purpose of the plant. A WWTP, from a functionality point of view, could have multiple outputs, e.g. removing chemical oxygen demand (COD), nitrogen, phosphorus, and pathogens, or producing energy or material like biogas and fertilizers. In this regard, a proper measure of WWTP energy efficiency should reflect a multidimensional concept (i.e. taking into account for the different functions of the plant). Although benchmarking methods based on multiple KPIs have been discussed, such as by Fraia et al. [20], some sort of weighting between different KPIs would be necessary. Otherwise, it can be difficult to interpret the results of different indicators, since trade-offs exist for WWTPs at different stages of their lifecycles.

In order to overcome the previous limitations, Data Envelopment Analysis (DEA) represents an attractive tool for performance assessment and, focusing on the last 10 years, there are growing number of studies adopted DEA in energy efficiency analysis. Thanks to its ability to handle multiple inputs and outputs, DEA models have been used to evaluate energy and environmental performance of complex systems such as chemical processes [21], industrial gases facilities [22], service sector [23], and including water [24] and wastewater treatment facilities [25]. Although DEA has great potential for energy efficiency evaluation of WWTPs, it is hardly extensible at international level as a standard tool. In effect, including a new WWTP requires solving the DEA model again for the whole set of observations, with potential changes in the established ranking if the new plant in the set moves away the frontier.

A third category of benchmarking methods is based on regression analysis and it is called parametric approach. Regression models describe the relationship between energy use of a system and predictor variables influencing energy use, including characteristics and external factors. A consequence of using parametric approaches is that the residuals (i.e. the difference between the energy use predicted by the model and the actual energy use) are treated as a measure of efficiency [26]. The parametric approach is widely used in building energy efficiency applications [27], and it is especially employed for exploring the effects of influencing factors on energy efficiency [28] and identifying its determinants [29]. Furthermore, using specific Stochastic Frontier Analysis models and panel data it is possible to distinguish between persistent and transient inefficiency [30], which is particularly useful in the wastewater sector to complete appropriate energy efficiency diagnosis of WWTPs [31]. However, it is not straightforward and an important source of debate to decide which factors are legitimate uncontrollable influences on performance, and hence to be included in the regression model, and which are within the control of the management. For example, structural differences such as plant size and load factor are compensated in the Energy Star method for WWTPs developed by the US Environmental Protection Agency [32], while they may originate from inefficient plant design. This discussion suggests that controversies may arise from the use of parametric approaches when it comes to standardization applications, while any standard method should be universally applied independently of the stakeholder who is employing it.

In the last decade, efforts in the industry have been targeted to achieve energy efficiency at WWTPs and energy benchmarking systems at WWTPs have become common practice in some countries. Good examples are the detailed energy management systems developed in Germany and Austria [5]. Those approaches are however hardly extensible at international level due to the fact that, using load-specific energy use stated as kWh/PE·y, where PE stands for the Person Equivalent, they assume that concentrations in the influent and effluent (e.g. solids, organic matter, nitrogen, phosphorus etc.) do not vary significantly between WWTPs, hence restricting the application of these approaches to homogenous geographical area with similar effluent quality requirements.

The review of pertinent literature reveals that both academia and industry still lack standard approaches and tools to quantify energy efficiency, able to accurately define WWTPs energy efficiency, to adapt to different plant layouts, possibility of including energy produced onsite, having good geographical coverage at European level, and being of easy communication by an aggregated indicator that reflects the complexity of a WWTP. Based on the previous discussed limitations of existing energy efficiency benchmarking approaches, the main goal of the ENERWATER methodology is to contribute to development of the standardised EU energy methodology and labelling in WWTPs. This study is built upon the results of the ENERWATER[1] project, a three-year Coordinated Support Action within the Horizon 2020 program.

3. The ENERWATER methodology

The methodology developed in the framework of the ENERWATER project[2] aims to systematically determine the energy efficiency of a particular WWTP expressed by the WTEI. The methodology includes the definition of WWTPs typologies, the classification of facilities accordingly, the identification of levels of treatment (stages), the identification of the correspondent KPIs, their aggregation into a composite index (i.e. WTEI), and its labelling for an easy and straightforward communication.

3.1 General considerations

3.1.1 Rapid Audit and Decision Support versions

The methodology can be applied in two different ways according to the following goals:

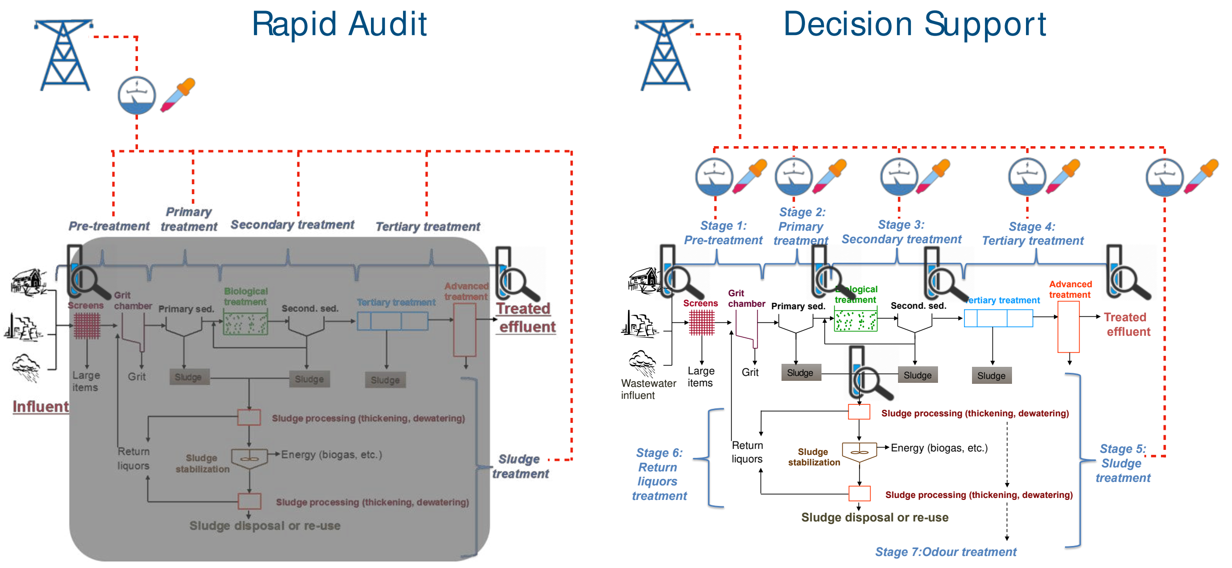
---

[1] The reader is referred to www.enerwater.eu for further information.

[2] All public deliverables are available in the project website at the following link www.enerwater.eu/download-documentation.

- The **Rapid Audit (RA)** method leads to quick estimation of the WTEI based on existing information, such as historical energy use data along with influent and effluent quality values obtained by routine analyses. By doing so, the aim is to obtain a WWTP energy benchmark, a rapid tool to compare a given WWTP performance with other plants and ascertain the need for a detailed monitoring campaign.
- The **Decision Support (DS)** method requires intensive monitoring of energy use and water quality parameters to provide an accurate and detailed calculation of the WTEI for each WWTP stage as well as its overall value for the plant. By doing so, the aim is to serve as a diagnosis of the functions/equipment in order to individuate the origin of inefficiency and develop targeted energy saving strategies.

Both methodologies are structured in a similar way but require inputs with a different level of detail (Fig. 1). In both cases, all measured data can be reported as daily, monthly or yearly averages, being 3 years the recommended time period for data gathering to account for seasonal variability associated with the human activities and the seasonal rainfall. Due to the variable influent behaviour, the pollution load to be treated is continuously changing, and consequently, so are the energy and chemical requirements for the treatment [33]. To sum up the procedures, first the type of WWTP is established according to its functions; then, energy consumption and other measurements (flowrate, pollutant concentrations, etc.) are combined to obtain the relevant KPIs, which are then normalised and weighted to obtain the WTEI. Finally, the WTEI is presented as an energy label to provide all stakeholders with standardized information and facilitate dissemination of WWTPs' the energy efficiency.



	Rapid Audit	Decision Support
Energy consumption data	- Aggregated energy consumption from energy bills and chemicals consumption	- Disaggregated online data from energy meters on site and chemicals consumption
Operational data	- Routine influent/effluent analyses	- Per section influent/effluent analyses
Objective of the analysis	- Energy benchmarking	- Energy benchmarking - Diagnosis

Legend:

Energy sources

Addition of chemicals

Sampling + analysis

Figure 1. Schematic comparison of Rapid Audit (RA) and Decision Support (DS) ENERWATER methodologies. The grey square indicates that in the RA both the energy consumption and the operation data refer to the entire plant observed as black box, as opposed to DS where the data refer to the individual sections of the plant. Note: Energy consumption refers to all sources of energy including electricity, gas, diesel etc.

3.1.2 Definition of plant typology

WWTPs can have various objectives depending on the type of pollutants removed [34]. The need to remove different types of pollutants is linked with the regulatory framework in Europe and the type/water quality of the receiving water body [8]. Based on key European Directives, and to take into account the complexity of the WWTPs, the following typologies are identified linked to wastewater effluent discharges:

- Type 1: Discharge to a non-sensitive area. This includes WWTPs focused on the removal total suspended solids (TSS), biochemical oxygen demand (BOD), COD and NH_4.
- Type 2: Discharge to a sensitive area. This includes WWTPs focused on removing TSS, BOD, COD, total nitrogen (TN) and total phosphorus (TP).
- Type 3: Discharge for re-use. This includes WWTPs focused on removing TSS, BOD, COD, TN, TP and pathogens removal (e.g. coliforms log reduction).

3.1.3 Identification of plant functions, stages and operational parameters

Based on the level of treatment, WWTPs can carry out different functions, e.g. pumping wastewater, producing an effluent free of contaminants such as solids, COD, nitrogen (N), phosphorus (P) and pathogens, processing the sludge produced during treatment, recovering of energy and materials. Independently of the processes implemented at the WWTPs, these facilities are normally organised in 5 main stages according to their respective functions. A complete description of WWTP boundaries and stages is given in Section 1 of Supplementary Material. The suggested operational parameters for the evaluation of the treatment efficiency are reported in Table 1.

Table 1. Identification of plant functions, stages and operational parameters.

Plant function	Stage	Parameter	Type 1 and 2 [a]	Type 3 [a]
Pumping	Stage 1	Flow	Requires measurement of the real flow wastewater treated through online flow meters or similar	
Removal of suspended solids [b]	Stage 2	TSS	Requires measurement of TSS before and after primary treatment and calculation of kg $TSS_{removed}$/day	
Removal of organic matter	Stage 3	COD	Requires measurements of COD in influent and effluent and calculation of kg $COD_{removed}$/day	
Removal of	Stage 3	TN	Requires measurements of N in influent and effluent and	

nitrogen				calculation of kg $TN_{removed}$/day
Removal of phosphorus	Stage 3	TP	-	Requires measurements of P in influent and effluent and calculation of kg $TP_{removed}$/day
Removal of pathogens	Stage 4	E. coli Colony-forming Unit (CFU)	-	Requires measurements of coliforms in the influent and effluent as well as measurement of the real flow wastewater treated, and calculation coliforms log reduction/day
Removal of produced sludge [c]	Stage 5	TS	Requires measurement of $TS_{processed}$ in the sludge line and leaving the plant, and calculation of $TS_{removed}$/day	
Sludge dewatering	Stage 5	TS	Requires measurement of $TS_{processed}$ in the dewatering unit	

[a] For RA pollutants removal are calculated considering the influent and effluent of the plant (i.e. routine analysis), while in DS the influent and effluent of each stage (i.e. detained sampling is needed).

[b] Apply only to DS methodology. In RA this function is reflected by total COD removal given that COD removal is a proxy of total organic matter removal.

[c] Apply only to DS methodology given that normally only the sludge produced/dewatered data are reported in routine analysis.

3.1.4 Gross and Net energy consumption

In facilities where (at least part of the) energy consumed is produced on site, e.g. electricity from anaerobic digestion of sludge, two different values of the WWTP total energy consumption may be identified:

- A plant's *gross energy consumption* is defined as the total amount of energy that is consumed by the plant regardless of its source.
- A plant's *net energy consumption* is defined as the amount of energy that is consumed by the plant excluding the amount of renewable energy produced on site.[3]

---

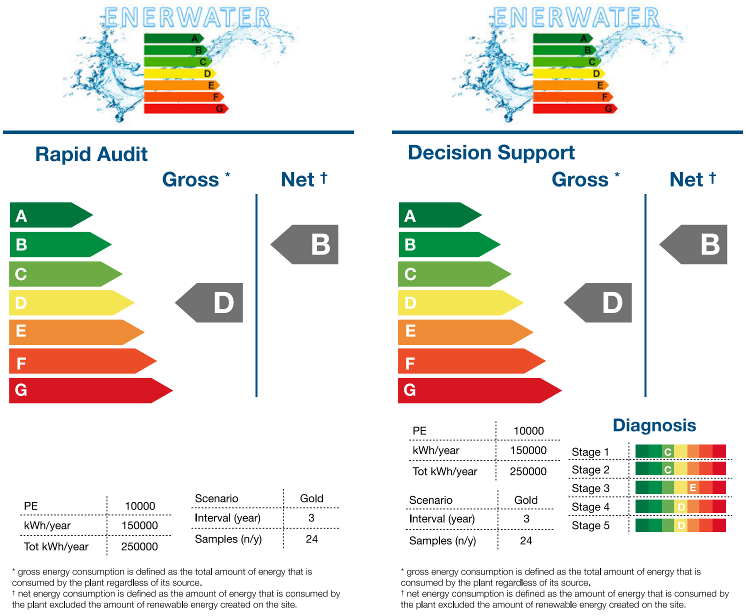
[3] A similar concept was approved and implemented by the European Union and other agreeing countries for the residential sector, i.e. the net-zero energy building: www.ec.europa.eu/energy/en/topics/energy-efficiency/buildings/nearly-zero-energy-buildings

Reporting both gross and net values is important as they convey different information: while gross energy efficiency reflects the plant energy efficiency, the net energy efficiency reflects the plant energy self-sufficiency.

3.1.5 Energy efficiency labelling

In the early 1990s the European Union (EU) introduced energy labelling with a double objective: to inform consumers about the energy performance of energy consuming devices and to promote energy savings and energy efficiency. Following the success of its application to domestic appliances, energy labelling was extended to buildings a decade later [14].

Information and dissemination of WWTPs energy efficiency plays a key role in the water sector for engineers, researchers and water utilities, and it is therefore necessary to introduce a uniform label for WWTPs (Fig. 2), to provide all involved stakeholders with standardized information on WWTPs energy efficiency.



PE	10000
kWh/year	150000
Tot kWh/year	250000

Scenario	Gold
Interval (year)	3
Samples (n/y)	24

* gross energy consumption is defined as the total amount of energy that is consumed by the plant regardless of its source.
† net energy consumption is defined as the amount of energy that is consumed by the plant excluded the amount of renewable energy created on the site.

PE	10000
kWh/year	150000
Tot kWh/year	250000

Scenario	Gold
Interval (year)	3
Samples (n/y)	24

* gross energy consumption is defined as the total amount of energy that is consumed by the plant regardless of its source.
† net energy consumption is defined as the amount of energy that is consumed by the plant excluded the amount of renewable energy created on the site.

Figure 2. General representation of a WWTP energy label. RA (left) and DS (right).

Energy labelling, consisting of assigning an energy performance class or label to the WWTP, requires the development of a scale related to a labelling index, the WTEI. On an ideal scenario the WTEI should be based on the KPIs identified by on-line or frequent monitoring of the KPIs through composite or grab samples to account for the key pollutants removed at the different stages of the process as well as the process efficiency. Nevertheless, these data might not be available in the required detail or resources might be limited preventing the estimation of the WTEI. To respond to this pressure a number of scenarios is proposed when calculating the WTEI, e.g. Platinum, Gold and Bronze, being Platinum scenario benefiting from most numerous detailed data and consequently high levels of confidence and Bronze scenario based on widely accepted text book information and general assumptions, and hence providing the lowest WTEI confidence values [35].

3.1.6 ENERWATER WWTPs database

In order to cover the maximum range of the most widely used wastewater treatment processes, a database was created using 50 WWTPs [36]. To increase the coverage of the dataset, additional data collected from literature of 48 WWTPs were also included in the final dataset thereby accounting for the disaggregated energy consumption data of 98 WWTPs [37].

Different types of preliminary treatment for grease and sand removal were considered while the primary treatment was characterized by the presence or the absence of primary sedimentation. Considering its large impact on energy consumption, particular attention was given to secondary treatment. A wide range of chemical and biological processes was selected. Additionally, various aeration systems for activated sludge process were selected (large, medium and fine bubble diffusers rather than mechanical aeration system). For tertiary treatment, chemical disinfection and ultraviolet (UV) were selected. Moreover, wide ranges of sludge stabilization, whether aerobic or anaerobic, and thickening/dewatering system were considered.

Summary statistics of the ENERWATER database used are given in Table 2.

Table 2. Descriptive statistics for the dataset used.

	Obs.	Mean	SD	Min	Max
Energy and chemical demand					
Total electricity consumption (kWh/d)	98	12,946	26,658	63	149,614
Total chemical consumption (kWh/d)	98	5,020	9,879	0.0	39,917
Plant characteristics					
Served PE	98	169,311	353,843	947	1,325,156
Influent flowrate (m^3/d)	98	55,923	110,474	474	378,616
Influent COD (mgCOD/L)	98	398	120	152	638
Influent N (mgN/L)	98	43.9	12.4	12.2	77.1
Influent P (mgP/L)	98	5.0	1.5	0.7	10.6
Influent E. Coli (UCF/100mL)	53	$7.24 \cdot 10^6$	$1.61 \cdot 10^7$	$3.75 \cdot 10^6$	$1.28 \cdot 10^8$
Effluent COD (mgCOD/L)	98	63.1	67.9	7.0	300
Effluent N (mgN/L)	98	22.3	16.8	2.2	47.5
Effluent P (mgP/L)	98	1.6	2.1	0.2	17.1
Effluent E. Coli (UCF/100mL)	53	24,960	54,588	3.8	375,000

3.2 Calculation of the Water Treatment Energy Index

WTEI was defined as a composite indicator for a particular WWTP. A composite indicator measures multidimensional concepts (e.g. energy consumption for different functions of the WWTP) that could not be expressed by a single indicator. For this purpose, relevant individual indicators were identified, combined and weighted in a way that captured the dimension or structure of the measured concept [38]. The procedure for the WTEI calculation is drawn in Fig. 3 and summarised in detail in the next sub-sections.

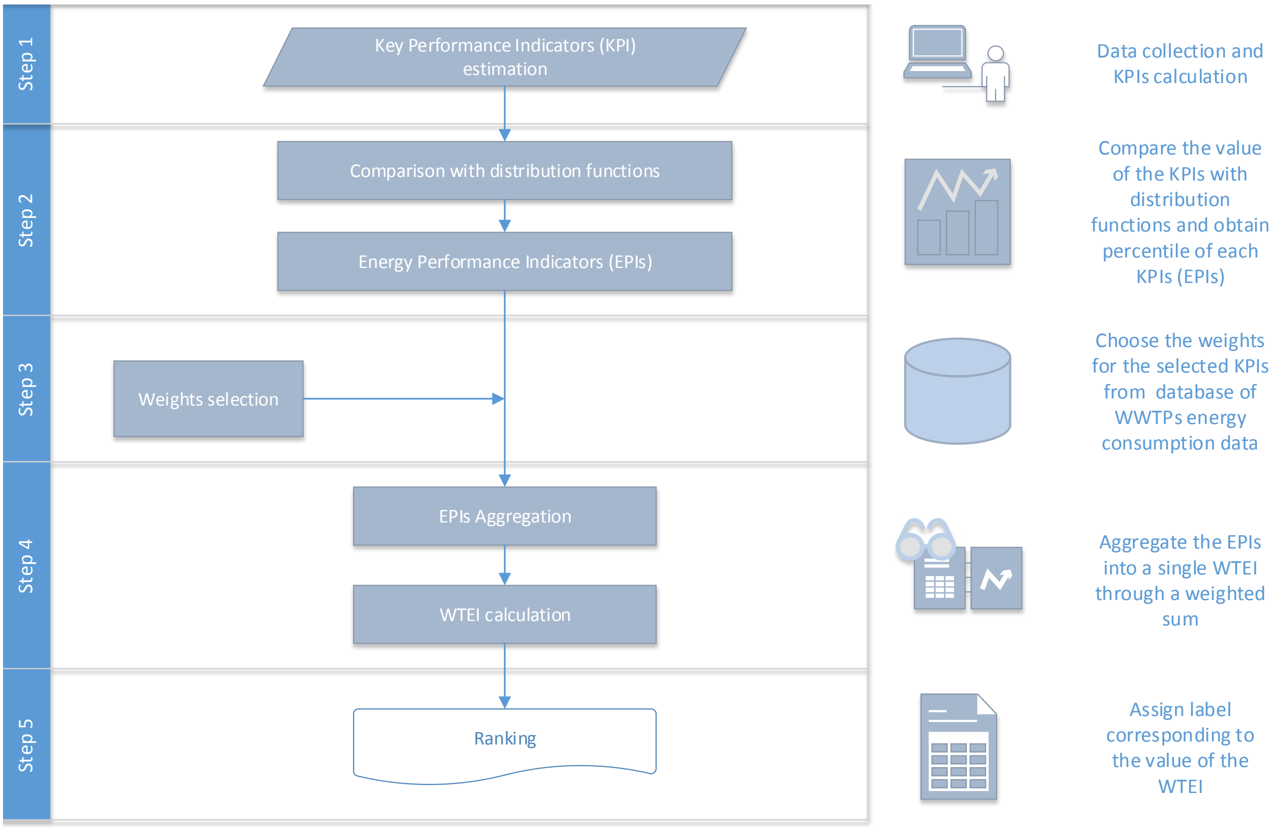


Figure 3. Workflow for the Water Treatment Energy Index calculation.

3.2.1 Step 1: Estimation

Energy consumption data

Historical data on the energy consumed at the WWTP need to be available, including electricity and other fuels such as diesel, natural gas etc. Total WWTPs electricity consumption can be obtained by consulting electricity bills (only for RA), meter readings or existing on-line meters. Likewise, the disaggregated electricity consumption (required for DS) can be measured or estimated, combining the rated power of the electrical motor in kilowatt (kW) and the working hours in a year to provide an estimation of kWh used in each stage per unit of time.

If other energy sources are used, for example to drive generators to produce electricity, they need to be quantified and converted into kWh per unit of time (Table 3) to calculate the total energy consumption (Eq. 1).

$$E_1: Energy\ consumed\ = Ep_{V1} + Ep_{V2} + Ep_{V3} + Ep_{V4} \quad \left[\frac{kWh}{year}\right] \tag{1}$$

Where, Ep_{Vi} is energy consumed as electric energy (V1), diesel (V2), natural gas (V3) and biogas (V4).

Table 3. Energy carriers and associated conversion factors applied by the ENERWATER methodology.

Energy carrier	Conversion factors	Abbr.	Equations to estimate specific power consumption
Electric energy in kWh	$1\ (\mathrm{kWh}/_{\mathrm{kWh}})$	V1	$Ep_{V1} = P \times T \times Use\ Factor$
Diesel in kg	$11.87\ \left(\mathrm{kWh}/_{\mathrm{kg}}\right)$	V2	$Ep_{V2} = equipment\ usage /year\ x\ usage\ time\ (h) \times 11.87 \times diesel\ used\ [kg/h] \times \beta_{el}{}^{*}$
Natural gas in Ncm‡	$9.94\ (\mathrm{kWh}/_{\mathrm{Ncm}})$	V3	I) $Ep_{V3} = Gas\ in\ combined\ heat\ and\ power\ engine$ $kWh_{el} = (Ncm/y) \times 9.94 \times \beta_{el}{}^{*}$ $kWh_{th} = (Ncm/y) \times 9.94 \times (1 - \beta_{el})) \times \beta_{th}{}^{\dagger}$ II) $Ep_{V3} = Gas\ used\ for\ heating\ only$ $kWh_{th} = Ncm/y \times 9.94 \times \beta_{th}{}^{\dagger}$
Biogas in Ncm‡	$9.94\ x\ NGC\ (\mathrm{kWh}/_{\mathrm{Ncm}})$ where NGC is the natural gas content in the biogas (vol/vol)	V4	I) $Ep_{V4} = biogas\ in\ combined\ heat\ and\ power\ engine$ $kWh_{el} = \left(\frac{Ncm}{y}\right) \times 9.94 \times NGC\ x\ \beta_{el}{}^{*}$ $kWh_{th} = \left(\frac{Ncm}{y}\right) \times 9.94 \times NGC\ x\ (1 - \beta_{el})) \times \beta_{th}{}^{\dagger}$ II) $Ep_{V3} = Biogas\ used\ for\ heating\ only$ $kWh_{th} = Ncm/y \times 9.94 \times \beta_{th}{}^{\dagger}$

* Typical efficiency = 0.40 for electricity generation; † typical efficiency = 0.85 for heat production and recovery

‡ Ncm = normal cubic meters. Normal conditions (0°C, atmospheric pressure)

Chemical energy consumption

In some WWTPs chemicals such as iron sulphate or iron chloride are added to the wastewater to remove pollutants such as phosphorus. Other chemicals that are frequently used in WWTPs include alum, polyelectrolyte, acetate, methanol etc. Hence, the use of chemicals and their specific dosage can impact the pollutants' removal efficiency of WWTPs and replace, to a certain extent, the use of energy. The trade-off between energy and chemicals use was tackled in the ENERWATER methodology by using the Cumulative Energy Demand (CED) method developed by Frischknecht et al. [39], which is a widely used indicator for environmental impact evaluations [40]. It reports the direct and indirect consumption of energy necessary to obtain a product or service by computing the equivalent of primary energy consumption in the product chain or the energy consumed in a certain system over its entire lifecycle. Chemical energy consumptions for the main chemicals used during wastewater treatment are given in Table S1 of Supplementary Material. Equation 2 represents the formula used for estimating the chemical energy consumption due to the chemicals.

$$E_2\text{: } Chemical\ energy\ consumption = \sum_{i=A}^{L} cec_i \times M_i \qquad \left[\frac{kWh}{year}\right] \tag{2}$$

Where, A to L are the chemicals used in the WWTP, M_i is the mass (in kg) consumed of each chemical and cec_i is the specific chemical energy consumption (in kWh/kg) for all chemicals used in the WWTP from A to L: A - Acetic acid; B - Aluminium sulphate; C - Iron(III) chloride; D - Iron(III) sulphate; E - Iron(II) sulphate, F - Methanol; G - Peracetic acid; H - Poly-Aluminium-Chloride; I - Polyelectrolyte; L - Sodium hypochlorite.

WWTPs producing energy producing and sludge imports

Wastewater treatment plants can have a range of technologies that produce energy/electricity on site, such as anaerobic digestion (of sludge, imported sludge, other wastes, etc.), hydraulic-power, wind turbines, solar panels, fuel-cells, etc. The generation of electricity in the WWTP can (partially) offset the energy demand of the facilities and should be accounted by using Equation 3.

$$E_3 : Energy\ \ produced\ at\ WWTP \ = \sum_{i=A}^{L} i \quad \left[\frac{kWh}{year}\right] \tag{3}$$

Where, A to L are the types of energy produced in the WWTP: A – biogas (kWh/year); B - hydraulic-power (kWh/year); C - wind turbines (kWh/year); D - solar panels (kWh/year); E – fuel-cells (kWh/year); F-L – other (kWh/year).

When considering anaerobic digestion, many WWTPs act as sludge treatment centres receiving sludge from nearby sites. This imported sludge is often mixed with the sludge produced at the WWTP for further treatment such as dewatering, anaerobic digestion etc., raising significant shares in some WWTPs (up to 2-fold the sludge produced on site). As a result, the volume of sludge imports, respective total suspended solids as well as an estimation of the energy consumed and produced for its treatment, needs to be taken into consideration (Equation 4).

$$\begin{aligned} &E_4\text{: } Energy\ produced\ and\ consumed\ by\ sludge\ imports \\ &= \ Energy\ produced \\ &- \ Energy\ conumed\ (by\ sludge\ imports) \left[\frac{kWh}{year}\right]^{4} \end{aligned} \tag{4}$$

Total gross and net energy consumption estimation

The gross and net energy consumed can be estimated by combining the results from Equations 1-4 as well as sludge imports (Equation 5 and 6, respectively). Gross and net energy consumptions are used as input to estimate each KPI.

---

[4] It can be assumed that energy produced and consumed by sludge imports = E_3 x (sludge imports/total amount of sludge). In case E_4 would be negative (i.e. the energy consumed by sludge imports is higher than the energy that it produces) it should be considered equal to zero given that sludge deriving from other plants is out of the boundaries of the plant and it is not considered a plant function.

$$Gross\ energy\ consumption\ = E_1 + E_2 \quad \left[\frac{kWh}{year}\right] \tag{5}$$

$$Net\ energy\ consumption\ = E_1 + E_2 - E_3 + E_4 \quad \left[\frac{kWh}{year}\right] \tag{6}$$

Identification of KPIs and calculation of its reference values

For the RA methodology it is recommended that different KPIs are considered taking in consideration influent and effluent data (i.e. routine analysis normal available). This information can be obtained from the flowrate measurements taken through online flow meters or similar, or the information taken from the WWTP design sheets. For the DS methodology it is recommended that different KPIs are considered by means of composite or grab samples to account for the key pollutants removed at the different stages of the process (i.e. by detailed sampling campaign is required). Suggested KPIs for application of RA and DS methodology are given in Table 4.

Table 4. Identification of KPIs.

Plant function	Stage	Parameter	Rapid Audit	Decision Support
Pumping	S1	Flow	kWh/m^3	kWh/m^3
Removal of suspended solids*	S2	Total Suspended Solids (TSS)	-	kWh/kg TSS$_{rem}$
Removal of organic matter	S3	Chemical Oxygen Demand (COD)	kWh/kg TPE$_{rem}$[5]	kWh/kg TPE$_{rem}$[5]
Removal of nitrogen	S3	Total Nitrogen (TN)		
Removal of phosphorus	S3	Total Phosphorus (TP)		
Removal of pathogens	S4	E. coli Colony-forming Unit (UCF)	kWh/LogRed*m^3	kWh/LogRed*m^3

---

[5] $Total\ Pollution\ Equivalent\ (TPE) = COD\ (kg_{COD}) + 20\ TN\ (kg_{TN}) + 100\ TP\ (kg_{TP})$ [35].

Removal of produced sludge*	S5	Total Solids (TS)	kWh/kg TS_{proc}	kWh/kg TSE[6]
Sludge dewatering	S5	Total Solids (TS)		

*It applies only to RA methodology

For the RA, KPIs relate the overall energy consumption (e.g. gross energy consumption). In the DS, KPIs are directly associated with the appropriate stage. In this case, the KPIs are calculated using the specific portion of energy consumption related to its function. Summary statics of database of KPIs for RA and DS methodologies are given in Table 5 and 6, respectively.

Table 5. Database of KPIs for overall plant and Rapid Audit methodology.

KPI	KPI units	Average	St. Dev.	P_{90}	P_{10}	Obs.
S1	kWh/m^3	0.348	0.445	0.901	0.161	97
S3	kWh/kg TPE_{rem}	0.488	0.292	0.731	0.171	87
S4	kWh/(Log_{Red}·m^3)	0.058	0.076	0.137	0.030	53
S5	kWh/kg TS_{proc}	2.074	2.165	5.231	0.824	89

Table 6. Database of KPIs for Decision Support methodology.

KPI	KPI units	Average	St. Dev.	P_{90}	P_{10}	Obs.
S1	kWh/m^3	0.048	0.039	0.101	0.009	97
S2	kWh/kg TSS_{rem}	0.028	0.030	0.055	0.007	64
S3	kWh/kg TPE_{rem}	0.289	0.246	0.519	0.108	87
S4	kWh/(Log_{Red}·m^3)	0.030	0.047	0.054	0.010	53
S5	kWh/kg TSE	0.308	0.400	0.577	0.055	89

---

[6] $Total\ Solid\ Equivalent\ (TSE) = TS_{removed}\ (kg_{TS}) + 2\ TS_{dewatered}\ (kg_{TS})$. Weights are estimated based on own calculations using the ENERWATER dataset [37].

3.2.2 Step 2: Normalization

The KPIs are expressed in a variety of units. Hence, there is need to express them on a common basis. Normalization is done here by comparison with a distribution function, so that the percentiles for each KPI are normalised indicators of performance, here called energy performance indicators (EPI). By comparing the value of the KPIs with the database distribution function a percentile for each KPI is obtained. The percentile is a normalized manner to express the performance of the plant for a given KPI. Each KPI can be normalized by using Eq. 7, which corresponds to Gumbel's cumulative distribution function with parameters estimated for the population of WWTPs in the benchmark database (Table S2 of Supplementary Material).

$$\mathrm{EPI_i} = \mathrm{Percentile}(\%) = \exp\left(-\exp\left(-\left(\frac{\mathrm{KPI_i} - \mu_i}{\sigma_i}\right)\right)\right) \mathrm{x}100 \qquad (7)$$

3.2.3 Step 3: Weights selection

Weighting emphasizes the contribution of a given KPI over others in terms of energy consumption. The particular weights to be applied at ENERWTATER methodology (Table 7) have been estimated based on the average relative contribution of each function/section of the WWTP to the overall energy consumption based on the ENERWATER database (Section 3.1.6), i.e. pumping (stage 1) accounts for almost 12% of the overall energy consumption and the secondary treatment (stage 3) accounts for 54%. The proportions of energy consumption associated with different plant sections (from which the weights have been extrapolated) are in agreement with those available in the literature. As an example, in an energy analysis on 104 Austrian WWTPs, Haslinger et al. [41] found that for plant with design capacity lower than 100,000 PE the pretreatment impact for 12%, secondary treatment for 67% and sludge treatment for 15% of the total energy consumption, while for plants with design capacity higher than 100,000 PE the same plant sections the distribution of energy use relative to the total was respectively 11, 60 and 23%. Similar results are reported in other sources [42].

Table 7. Weights of different KPIs to the overall energy consumption of a WWTP.

	Stage	**S1**	**S2**	**S3**	**S4**	**S5**
Rapid Audit	Value (w_i)	0.119	-	0.535[*]	0.121	0.225
Decision Support	Value (w_i)	0.119	0.015	0.519	0.121	0.225

[*] In the RA, the function solid removal has been considered in stage 3 instead of stage 2 (as in DS) through COD removal, which like TS is a proxy of organic matter. As a result, the weight of stage 3 in RA is equal to the sum of the weight of stage 2 and stage 3 of the DS.

If not all the KPIs are applicable, i.e. in the absence of one stage, weights should be normalised by the weights to sum unity such as described in Equation 8.

$$w_{norm,i} = \frac{w_i}{\sum_1^k w_i} \tag{8}$$

Where k is the number of applicable KPIs.

3.2.4 Step 4: Aggregation

Finally, aggregation consists in the combination of the weighted KPIs at either the stage or the whole plant level so that the corresponding WTEI can be computed and results compared based on a ranking. Aggregate the EPI into a single WTEI through a weighted sum (Eq. 9).

$$WTEI = \sum_{i=1}^{k} w_{norm,i}\, EPI_i \tag{9}$$

3.2.5 Step 5: Rank and label assignation

Using the cumulative frequency distribution curve of WTEI values allows the use of the percentile as an indicator of the energy efficiency performance. At this point, labelling is equivalent to assigning percentile intervals (bands) to energy classes. The scale is defined by fixing the transition values between classes. The boundaries between labels (Table 7) have been decided according to the following criterion, common in EU efficiency labelling standards [43]: the median performance index is the upper boundary of class D. This labelling strategy allows good discrimination power at high efficiency, serving as an incentive for innovation.

Table 7. Label definition according to the WTEI value, with A being the most energy efficient and G the least energy efficient.

Label	WTEI	EPI_1	EPI_2	EPI_3	EPI_4	EPI_5
A	$X<0.110$	$X<0.110$	$X<0.140$	$X<0.110$	$X<0.060$	$X<0.160$
B	$0.110\leq X<0.220$	$0.110\leq X<0.220$	$0.140\leq X<0.280$	$0.110\leq X<0.220$	$0.060\leq X<0.120$	$0.160\leq X<0.320$
C	$0.220\leq X<0.330$	$0.220\leq X<0.330$	$0.280\leq X<0.430$	$0.220\leq X<0.330$	$0.120\leq X<0.180$	$0.320\leq X<0.480$
D	$0.330\leq X<0.440$	$0.330\leq X<0.440$	$0.430\leq X<0.560$	$0.330\leq X<0.440$	$0.180\leq EPI_4<0.240$	$0.480\leq X<0.640$
E	$0.440\leq X<0.550$	$0.440\leq X<0.550$	$0.560\leq X<0.700$	$0.440\leq X<0.550$	$0.240\leq X<0.300$	$0.640\leq X<0.800$
F	$0.550\leq X<0.775$	$0.550\leq X<0.775$	$0.700\leq X<0.850$	$0.550\leq X<0.775$	$0.300\leq X<0.650$	$0.800\leq X<0.900$
G	$X\geq0.775$	$X\geq0.775$	$X\geq0.850$	$X\geq0.775$	$X\geq0.650$	$X\geq0.900$

3.3 Application of the ENERWATER methodology

In this Section, the usefulness of the ENERWATER methodology is demonstrated step-by-step (Fig. 4) by using a real WWTP as an example, having a capacity of 35,800 Person Equivalent (PE) that removed N and P on top of COD, i.e. Type 2. The plant, which is further described in Section 4 of Supplementary Material, consumed a total of 3,575 kWh/d of energy (gross consumption), of which about 25% was due to the chemicals mainly used for P removal. Additionally, 1,409 kWh/d of the plant electricity demand was balanced by biogas production, so its net energy consumption was 2,166 kWh/d.

		Rapid Audit			Decision Support		
	Plant typology	Type 2			Type 2		
Step 1	**- Measure electricity consumption (kWh/d)**	*Whole plant*	2815		*Stage 1*	664	
					Stage 2	14	
					Stage 3	1495	
					Stage 4	-	
					Stage 5	319	
	- Measure electricity production (kWh/d)	*From biogas*	1409		*From biogas*	1409	
	- Compute chemical energy consumption (kWh/d)	*Whole plant (alum. sulfate + poly)*	953		*Stage 1*	0	
					Stage 2	0	
					Stage 3 (alum. sulfate)	925	
					Stage 4	-	
					Stage 5 (poly)	28	
	- Measure other sources of energy (kWh/d)	*Whole plant (oil)*	30		*Stage 1*	0	
					Stage 2	0	
					Stage 3	0	
					Stage 4	-	
					Stage 5 (oil)	30	
			Gross	**Net**		**Gross**	**Net**
	- Compute total energy consumption (kWh/d)	*Whole plant*	3798	2389	*Stage 1*	664	418
					Stage 2	14.0	8.8
					Stage 3	2420	1522
					Stage 4	-	-
					Stage 5	377	237
	- Identify plant function(s)	*Pumping (m^3/d)*	12423		*Pumping (m^3/d)*	12423	
		Pollutant removal (kgTPE_rem/d)	13797		*Solid removal (kgTSS_rem/d)*	1614	
		Pathogens removal (Log_red·m^3)	-		*Pollutant removal (kgTPE_rem/d)*	15928	
		Sludge handling (kgTS_proc)	1770		*Pathogens removal (Log_red·m^3)*	-	
					Sludge handling (kgTSE)	6299	
	- Compute Key Perfomance Indicators (KPIs)	*KPI 1 (kWh/m^3)*	0.306	0.192	*KPI 1 (kWh/m^3)*	0.053	0.034
		KPI 2 (kWh/kg TPE_rem)	0.275	0.173	*KPI 2 (kWh/kg TSS_rem)*	0.009	0.005
		KPI 3 (kWh/(Log_red·m^3)	-	-	*KPI 3 (kWh/kg TPE_rem)*	0.152	0.096
		KPI 4 (kWh/(kg TS_proc)	2.145	1.350	*KPI 4 (kWh/(Log_red·m^3)*	-	-
					KPI 5 (kWh/(kg TSE)	0.060	0.038
Step 2	**- Normalize KPIs and compute Energy Performance Indicators (EPIs)**	*EPI 1*	0.336	0.175	*EPI 1*	0.600	0.387
		EPI 2	0.274	0.108	*EPI 2*	0.186	0.133
		EPI 3	-	-	*EPI 3*	0.281	0.186
		EPI 4	0.409	0.197	*EPI 4*	-	-
					EPI 5	0.148	0.116
Step 3	**- Select weights**	*Weight 1*	0.136		*Weight 1*	0.136	
		Weight 2	0.608		*Weight 2*	0.017	
		Weight 3	-		*Weight 3*	0.591	
		Weight 4	0.256		*Weight 4*	-	
					Weight 5	0.256	
Step 4	**- Aggregate EPIs**	*WTEI*	**0.317**	**0.140**	*WTEI*	**0.289**	**0.194**
Step 5	**- Estimate energy label**	*Global Label*	C	B	*Label stage 1*	F	
					Label stage 2	B	
					Label stage 3	C	
					Label stage 4	-	
					Label stage 5	A	
					Global Label	C	B

Figure 4. Results of the application of the RA and DS methodology to a case study.

Before discussing the results of the case study, it is important to mention some differences in the application of the RA and DS versions of the methodology: first, the total gross energy consumption in RA did not correspond exactly to the sum of the energy consumption of the different stages in DS. In effect, the total electricity consumption in RA derived from the electrical bill and included also electricity consumption for odour treatment and general services (e.g. remote control, compressor room, illumination and office) that were not measured in the DS.[7] Secondly, the detailed sampling campaign carried out for the DS has also highlighted that the total amount of pollutants removed (as calculated in TPE) in the secondary treatment in the DS was higher than estimated for RA. This is due to the fact that in RA, the additional N and P load deriving from the reject water resulting from dewatering of anaerobic digested sludge (about 20% and 10% of N and P entering the plant) were excluded when comparing plant influent and effluent wastewater.

From the comparison of the RA and DS WTEIs, it can be seen that they are slightly different, given different input energy and operational data deriving from two different sampling campaigns (the correspondence between RA and DS is assessed in Section 4). As a result, different values of KPIs were calculated, which were then compared against different KPIs Gumbel's distributions. However, for this particular plant, this small difference was not transferred to the label allocation and both approaches reach a C gross label, which was improved in term of net energy label (B) when accounting for the partial auto-sufficiency of its energy demand. These results suggest that the plant has a sufficient level of energy efficiency but in comparison with best practices some room from improvement may be present, i.e. to pass from C to A label, ceteris paribus, a reduction of about 47% of the energy consumption would be necessary.

The results of the RA analysis can be used to estimate the level of energy efficiency and allows the user to answer the question "How is the energy performance of my plant in comparison to others in the

---

[7] According to legislation, at least 85% of total consumption must be monitored to apply the DS methodology.

industry?", but the RA method itself does not provide any suggestion of what the source(s) of the inefficiency may be. Having the possibility to assign a label to each stage, the DS methodology provides a way to compare energy performance and a diagnosis tool in order to single out which stages have lower efficiency. The result of this case study shows that inefficiency is not generalized but instead is concentrated in two stages: stage 3 and especially stage 1, having a label C and F, respectively. Therefore, taking in consideration that being the pumping station and the aeration system were the most important equipment of, respectively, stage 1 and 3, these are good candidates to complete further analysis to understand the reason of the inefficiencies and put into practice actions to decrease it.

4. Validation of ENERWATER methodology

Depending on the method and the rigour in the application, benchmarking procedures based on composite indicators may be subjective, selective and prejudicial (i.e. rely on unjustified preferences) [38]. The comparison of such approaches with other methods would eventually give rise to inconsistent efficiency estimates. Therefore, before pushing up the here presented benchmarking methodology as a standard procedure an important question needs to be addressed: how accurate and consistent is the ENERWATER methodology in terms of efficiency ranking and ability to identify best and worst-practices?

To do so, a cross-examination approach, using internal and external validation, was chosen as the procedure to investigate the robustness of the ENERWATER methodology in efficiency analysis. In both cases, the cross-examination consisted in checking if different approaches rank the WWTPs in approximately the same order. This consistency condition was tested using Spearman's rank order correlation coefficients for the efficiency scores generated by different methods. Spearman's ρ is defined in Eq. 10.

$$\rho = 1 - \frac{6 \cdot \sum d^2}{n \cdot (n^2 - 1)} \tag{10}$$

Where *n* is the number of rank pairs, and *d* is the difference between paired ranks. Correlation equal to 1 indicates that two methods rank WWTPs in identical way and correlation equal to 0 indicates that two methods rank WWTPs with a completely different order.

While for the internal validation the efficiency results applied to the dataset of 98 plants described on Section 3.1.6 are used, the external validation was carried out using a different dataset of 60 WWTPs not employed in the development of the ENERWATER methodology.

4.1 Internal validation

The comparison between the efficiency ranking obtained with RA and DS methodologies is reported in Fig. 5.

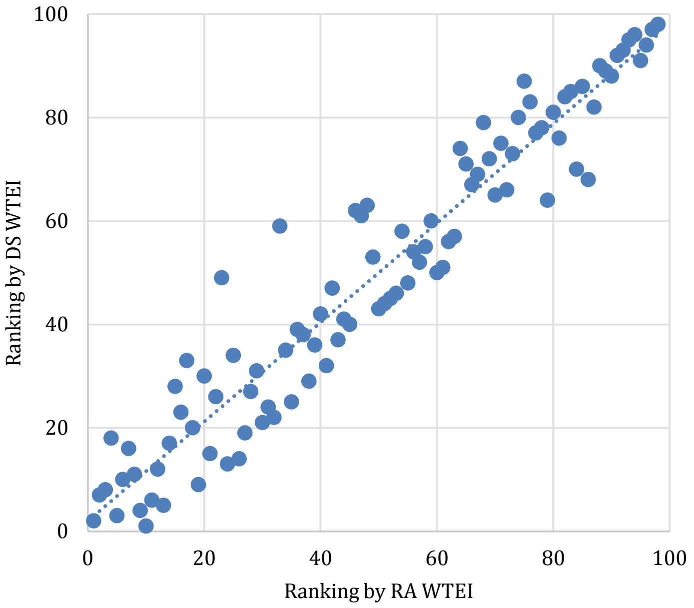


Figure 5. Internal validation. RA and DS ranking comparison.

As expected, and as already happened with the plant described on Section 4.4, WTEI values were slightly different when applying RA or DS due to the different data requirement of the methodologies. In any case, RA and DS gave highly consistent rankings with each other, with an average rank-order correlation equal to 0.96. This coefficient captured the similarity in the efficiency rankings across the various methods used, suggesting that both the RA and DS ENERWATER were able to rank WWTPs energy efficiency in a consistent way. The differences between both methodologies can be explained by the fact that in the RA methodology inefficiencies are spread over the whole plant, while in the DS inefficiencies refer to each stage and then are weighted using specific weights for each stage, which contribute differently to the whole plant efficiency. Moreover, the two methodologies make different evaluations for the sludge treatment. The RA methodology takes into account only the dewatering function, while the DS methodology also considers the sludge elimination function. Consequently, the RA methodology is expected to underestimate the efficiency of those plants that have a more complex sludge treatment chain (i.e. thickening, dewatering and anaerobic digestion), and overestimate the efficiency of those plants that have a simpler sludge line (i.e. only thickening).

4.2 External validation

Different benchmarking methods may assign efficiency scores differently, but robust methodologies should be consistent in ranking WWTPs efficiency. DEA, a linear-programming tool [44] widely used for energy efficiency estimation in various fields [45] including the wastewater sector [46], has been selected as the external validator of the ENERWATER methodology. DEA is used here since it allows the use of multiple inputs and outputs [47], and the efficiency quantification is based on identification of efficient relationships between energy consumption and plant's functions [25]. One major benefit of DEA is that the composite weights for each indicator and plant are endogenously determined to reveal the maximum overall efficiency for each observation and thus are not subject to specific normative preference [47], which is otherwise a concern when constructing a composite indicator. In other words, the weights in DEA are the most favourable ones for each plant and are not imposed a priori.

The comparison of ranking order between ENERWATER and DEA is presented in Fig. 6.

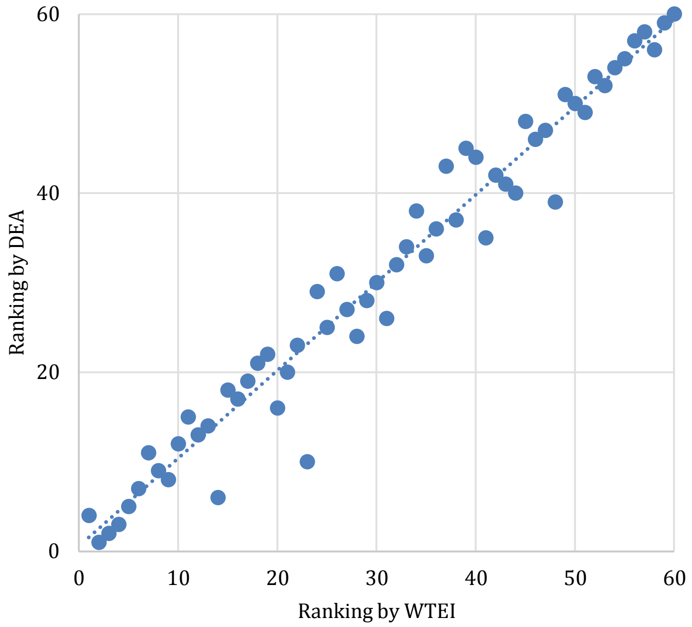


Figure 6. External validation. ENERWATER and DEA ranking comparison.

Apart from few points where the ranking position is slightly different, both methodologies rank the 60 plants in a similar way. The average rank-order correlation between WTEI and DEA scores was 0.98. As a result, if both methodologies individuate a plant as inefficient it can be concluded with sufficient confidence that in this plant a waste of energy is present, and vice versa. Some differences in ranking are however present, which can be attributable to the different type of weighting employed by DEA and ENERWATER. While in ENERWATER all individual functions contribute to the value of the efficiency index (proportionally to their importance), a benefit of doubt approach is used in DEA [48]. Consequently, DEA weights more the functions that a given WWTP performs best. For a few

WWTPs, overall efficiency is dictated by the performance in a single function and disregards the information of the other functions. By doing so, few plants that are particularly efficient in one single function, e.g. pumping but not in removing contaminants in secondary treatment, will be labelled as more efficient by DEA than in ENERWATER.

Composite indicators such as the WTEI offer some important benefits, for example by providing a comprehensive assessment of system efficiency and promoting accountability for the whole plant. Yet they are also often criticized for their lack of transparency in weighting. The use of DEA for validation of the process of constructing the WTEI helps to address some of these issues.

5. Discussion

In the next sections, the necessity and utility of the methodology as well as its current limitations and future outlook are discussed.

5.1 Necessity

Energy benchmarking is a critical step in managing energy usage more effectively at WWTPs and assessing the current state of efficiency. Wastewater treatment plants, however, are complex systems involving several processes to treat wastewater at different stages having distinctive functions. There are many successful examples showing the enormous potential of increasing energy efficiency. So, in Central Europe, after more than ten years of effort spent on energy auditing and benchmarking, energy consumption has been reduced by an average of 38% in Switzerland, 50% in 344 WWTPs in Germany, and about 30% in Austria [49]. These experiences based on similar benchmarking systems are not easily exportable at European scale however. While providing an overview of the status quo, aggregated measures like kWh/PE·y do not reflect the plant function (i.e. the removal of contaminants from wastewater) since it is assumed that pollutant concentrations in the influent and effluent (e.g. solids, organic matter, nitrogen, phosphorus etc.) do not vary significantly between WWTPs, hence restricting the application of these approaches in large geographical areas characterized by a wide heterogeneity in influent and effluent characteristics. As a result, there are not universal energy efficiency indicators that can be applied in every situation. Although the claim that "every plant is different" is shown to be correct, the methodology presented here represents a successful attempt to take into account this complexity by defining plant's functions and corresponding energy efficiency indicators for each function. In this way plant energy performance is better represented and allows WWTPs saving energy while providing the desired level of wastewater treatment services; in other words, being more energy efficient.

The methodology here presented allows for the first time the different stakeholders involved in the water sector to obtain and share standardized and comparable WWTP energy efficiency information, which has been previously identified as a major obstacle to reduced energy use at WWTPs. In particular by using this method engineers can test and compare energy saving strategies from different studies or plants, wastewater operators can properly evaluate the performance change after the implementation of any energy saving measure and decision-makers can employ a single energy label that uses universally known illustrations, to widely communicate information on the WWTP energy status.

5.2 Utility

As far as the different stakeholders involved in the wastewater sector are concerned, it is likely that for the decision-making process easy and simple way to communicate energy efficiency level is necessary. A continuous exchange of experience at international level is in fact crucial to achieve the target of the Energy Efficiency Directive [7]. In doing so, countries may learn from each other's experience and try to adopt best practices or at least avoid bad ones. The WTEI described in this paper represents a determined attempt to create a composite index, the WTEI, able to measure the multidimensional concept of energy efficiency at WWTPs. Composite indexes are in fact easier to interpret than a battery of many separate indicators and facilitate communication among different stakeholders [38]. Having this object in mind, an energy label system has been developed taking into account that energy labelling is accepted and normalized at the present time in the private consumer sector and begins also to spread in the public sector. With the advent of Green Public Procurement (GPP), public administrations integrate environmental criteria at all stages of the purchasing process, encouraging the diffusion of sustainable technologies and the development of environmentally valid products, through research and choice of results and solutions that have the lowest possible impact on the environment throughout the entire life cycle [50]. Following the successful introduction of EU energy labelling for energy consuming devices and buildings, we argue that extending energy labelling to WWTPs would positively contribute to improving the exchange of information on energy saving actions and results between wastewater utilities and towards other stakeholders, thus supporting the concept of GPP.

Any successful energy saving project must be based on a decision support framework able to identify sources of inefficiency and to assist plant operators in the decision-making process by suggesting energy saving actions. Nevertheless, tools limited to energy efficiency benchmarking cannot be considered diagnostic tools because they fail at prescribing any improvement strategy. The developed ENERWATER DS methodology is proposed to address this gap by intending to identify where inefficiencies come from in the plant. In fact, when diagnostic tools are reported in literature are in general too complex to be applied on a large scale due to the large amount of data and time required, as well as specific for some equipment. On the contrary, the RA ENERWATER methodology just requires parameters regularly measured in the plant. This quick assessment can facilitate the process of energy diagnosis, at least at the initial phase of inefficiency identification, by providing plant operators with case-based suggestions for energy efficiency.

5.3 Limitations

One limitation of the developed method is the availability of data. The 50 ENERWATER case studies were selected in order to cover the maximum range of the most widely used wastewater treatment techniques and reflecting the actual size distribution of European plants, whose majority are of medium-small size (i.e. less than 2,000 PE). Even if additional 48 WWTPs, whose data were retrieved from literature, were included in the final database, reaching a final dataset of 98 WWTPs, the number of observations is relatively small to be representative of all European WWTPs. Furthermore, for the sake of completeness and with the aim of designing a methodology that can be applied in the future as the complexity of WWTPs increases, the division into stages and the definition of KPIs has been done comprehensively, i.e. by defining additional stage 6 and 7 (respectively for return liquor and odour treatment) or by identifying KPIs for micropollutants [35]. However, not all the KPIs and stages can be, at the current state of development, combined into the WTEI. The lack of actual data on the contribution of each of these functions to the overall energy efficiency of the plants prevents from using them in the determination of WTEI. These indicators are kept, nonetheless, for future extensions of the DS ENERWATER methodology.

5.4 Future outlook

The study of the standardization landscape at European and at international level confirms the absence of specific normative documents in the framework of energy efficiency in wastewater treatment plants. Therefore, there is a good opportunity to fill this gap by raising a proposal based on the results of the presented work to the standardization organizations. To impulse dialogue towards the creation of a specific European Standard, the corresponding standardization bodies were contacted (CEN/TC 165 at European level, CTN 149 at national level (Spanish)) so that the ENERWATER methodology could be the basis for a standardization document. As a result of a very favourable reception by CEN/TC 165, the ENERWATER methodology is being adapted to the European Technical Report format that will be submitted for consultation and voting by the CEN national members. If finally approved, this

Technical Report could be the first step for a future European standard on energy efficiency in WWTPs.

The European as well as national evaluation and monitoring process indicated by the Energy Efficiency Directive (Article 8) offers a window of opportunity for data collection purposes [7], which once being in a standardized form will favour the future design of policy instruments. These actions should also bring to European water industry a competitive advantage in new products development and a faster access to markets by facilitating evidence of energy reduction therefore fostering adoption on new technologies.

6. Conclusions

This paper describes the first methodology specifically tailored to estimate energy efficiency at wastewater treatment plants. Starting from a clear definition of energy efficiency, the proposed methodology illustrates an innovative way to measure such energy efficiency by developing a tool for benchmarking and diagnosing the use of energy and formulating improvement actions based on previous analyses. The ENERWATER methodology was built up following a transparent procedure (public deliverables, stakeholder events, national and internal conference participations) that involved various stakeholders (universities, water utilities, standardisation bodies, SMEs and engineered product manufacturers), thus achieving a high-shared consensus in the industry.

The main contributions of ENERWATER as a standard energy efficiency methodology for WWTPs are: i) accurate definition of WWTPs functions by identification of KPIs that reflect the operational efficiency of each function, ii) ability to adapt to different plant layouts, iii) consideration of energy produced onsite; iv) good geographical coverage at European level, and v) easy communication by an aggregated indicator that reflect the complexity of a WWTP, the Water Treatment Energy Index.

The case study illustrates the procedure to carry out an energy analysis and the usefulness of the proposed methodology for estimate the energy label of a WWTP. Additionally, the efficiency estimates obtained with the proposed methodology have been successfully validated with other techniques commonly employed in the literature, therefore suggesting a high level of robustness of the efficiency estimates produced by the ENERWATER methodology.

Finally, it is interesting to remark that the proposed methodology can be easily applied by operators in existing WWTPs given that requires the measurement of common parameters generally measured in the plant, therefore it is expected that its application will facilitate the process of energy diagnosis, at least at the initial phase of inefficiency identification, by providing plant operators with case-based suggestions for energy efficiency. Moreover, we argue that extending energy labelling to WWTPs would positively contribute to improving the exchange of information on energy saving actions and results between wastewater utilities and towards other stakeholders, which is seen as crucial to achieve the target of the Energy Efficiency Directive.

Acknowledgments

We thank Benedetto Mirko d'Antoni and Diego Cingolani for their contribution to the development of the ENERWATER methodology. Stefano Longo, Miguel Mauricio-Iglesias and Almudena Hospido belong to the Galician Competitive Research Group (ED431C 2017/029) and the CRETUS strategic partnership (AGRUP2017/01), co-funded by FEDER (EU). Besides, they are supported by 'ENERWATER' Coordination Support Action (www.enerwater.eu) that has received founding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 649819.

References

[1] Gu, Y., Li, Y., Li, X., Luo, P., Wang, H., Robinson, Z.P., Wang, X., Wu, J., and Li, F. (2017). *The feasibility and challenges of energy self-sufficient wastewater treatment plants*. Appl. Energy 204, 1463-1475. https://doi.org/10.1016/j.apenergy.2017.02.069.

[2] Wang, H., Yang, Y., Keller, A.A., Li, X., Feng, S., Dong, Y., and Li, F. (2016). *Comparative analysis of energy intensity and carbon emissions in wastewater treatment in USA, Germany, China and South Africa.* Appl. Energy 184, 873-881. https://doi.org/10.1016/j.apenergy.2016.07.061.

[3] Cohen-Shacham, E., Walters, G., Janzen, C., and Maginnis, S. (2016). *Nature-based solutions to address global societal challenges*. Gland: IUCN. Retrieved from www.portals.iucn.org/library/sites/library/files/documents/2016-036.pdf

[4] Wakeel, M., Chen, B., Hayat, T., Alsaedi, A., and Ahmad, B. (2016). *Energy consumption for water use cycles in different countries: A review*. Appl. Energy 178, 868-885. https://doi.org/10.1016/j.apenergy.2016.06.114.

[5] Krampe, J. (2013). *Energy benchmarking of south Australian WWTPs*. Water Sci. Technol. 67(9), 2059-2066. https://doi.org/10.2166/wst.2013.090.

[6] EC (2012). *Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC*. Brussels: European Council. Retrieved from www.eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012L0027&from=en.

[7] Nabitz, L., and Hirzel, S. (In Press). *Transposing the requirements of the energy efficiency directive on mandatory energy audits for large companies: A Policy-Cycle-based review of the national implementation in the EU-28 member states*. Energy Policy. https://doi.org/10.1016/j.enpol.2017.12.016.

[8] EC (2000). *Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy.* Brussels: European Council. Retrieved from www.eur-lex.europa.eu/resource.html?uri=cellar:5c835afb-2ec6-4577-bdf8-756d3d694eeb.0004.02/DOC_1&format=PDF.

[9] Metcalf, L. and Eddy, H. P. (2003). *Wastewater Engineering: Treatment and Reuse.* New York: McGraw Hill.

[10] DWA (2015). *Standard DWA-A 216E: Energy check and energy analysis – instruments to optimise the energy usage of wastewater systems*. Hennef: German Association for Water, Wastewater and Waste (DWA).

[11] Longo, S., d'Antoni, B. M., Bongards, M., Chaparro, A., Cronrath, A., Fatone, F., Lema, J. M, Mauricio-Iglesias, M., Soares, A., and Hospido, A. (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. https://doi.org/10.1016/j.apenergy.2016.07.043.

[12] Torregrossa, D., Hernández-Sancho, F., Hansen, J., Cornelissen, A., Popov, T., and Schutz, G. (2017). *Energy saving in wastewater treatment plants: A plant-generic cooperative decision support system.* J. Clean. Prod. 167, 601-609. https://doi.org/10.1016/j.jclepro.2017.08.181.

[13] Torregrossa, D., Hansen, J., Hernández-Sancho, F., Cornelissen, A., Schutz, G., and Leopold, U. (2017). *A data-driven methodology to support pump performance analysis and energy efficiency optimization in waste water treatment plants.* Appl. Energy 208, 1430-1440. https://doi.org/10.1016/j.apenergy.2017.09.012.

[14] Pérez-Lombard, L., Ortiz, J., González, R., and Maestre, I. R. (2009). *A review of benchmarking, rating and labelling concepts within the framework of building energy certification schemes.* Energy Build. 41(3), 272-278. https://doi.org/10.1016/j.enbuild.2008.10.004.

[15] May, G., Barletta, I., Stahl, B., and Taisch, M. (2015). *Energy management in production: A novel method to develop key performance indicators for improving energy efficiency.* Appl. Energy 149, 46-61. https://doi.org/10.1016/j.apenergy.2015.03.065.

[16] Li, M., and Tao, W. (2017b). *Review of methodologies and polices for evaluation of energy efficiency in high energy-consuming industry.* Appl. Energy 187, 203-215. https://doi.org/10.1016/j.apenergy.2016.11.039.

[17] Ahn, J., Cho, S., and Chung, D.H. (2016). *Development of a statistical analysis model to benchmark the energy use intensity of subway stations.* Appl. Energy 179, 488-496. https://doi.org/10.1016/j.apenergy.2016.06.065.

[18] Salvatori, S., Benedetti, M., Bonfà, F., Introna, V., and Ubertini, S. (2018). *Inter-sectorial benchmarking of compressed air generation energy performance: Methodology based on real data gathering in large and energy-intensive industrial firms.* Appl. Energy 217, 266-280. https://doi.org/10.1016/j.apenergy.2018.02.139.

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

[20] Di Fraia, S., Massarotti, N., and Vanoli, L. (2018). *A novel energy assessment of urban wastewater treatment plants.* Energy Convers Manag. 163, 304-313. https://doi.org/10.1016/j.enconman.2018.02.058.

[21] Geng, Z., Dong, J., Han, Y., and Zhu, Q. (2017). *Energy and environment efficiency analysis based on an improved environment DEA cross-model: Case study of complex chemical processes.* Appl. Energy 205, 465-476. https://doi.org/10.1016/j.apenergy.2017.07.132.

[22] Fernández, D., Pozo, C., Folgado, R., Jiménez, L., and Guillén-Gosálbez, G. (2018). *Productivity and energy efficiency assessment of existing industrial gases facilities via data envelopment analysis and the Malmquist index*. Appl. Energy 212, 1563-1577. https://doi.org/10.1016/j.apenergy.2017.12.008.

[23] Zhang, G., and Lin, B. (2018). *Impact of structure on unified efficiency for Chinese service sector—A two-stage analysis*. Appl. Energy 231, 876-886. https://doi.org/10.1016/j.apenergy.2018.09.033.

[24] Molinos-Senante, M., and Sala-Garrido, R. (2018). *Evaluation of energy performance of drinking water treatment plants: Use of energy intensity and energy efficiency metrics*. Appl. Energy 229, 1095-1102. https://doi.org/10.1016/j.apenergy.2018.08.102.

[25] Longo, S., Hospido, A., Lema, J. M., and Mauricio-Iglesias, M. (2018). *A systematic methodology for the robust quantification of energy efficiency at wastewater treatment plants featuring data envelopment analysis*. Water Res. 141, 317-328. https://doi.org/10.1016/j.watres.2018.04.067.

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

[27] Chitnis, M., and Sorrell, S. (2015). *Living up to expectations: Estimating direct and indirect rebound effects for UK households*. Energy Econ. 52, S116. https://doi.org/10.1016/j.eneco.2015.08.026.

[28] Liao, N., and He, Y. (2018). *Exploring the effects of influencing factors on energy efficiency in industrial sector using cluster analysis and panel regression model*. Energy 158, 782-795. https://doi.org/10.1016/j.energy.2018.06.049.

[29] Broin, E.Ó, Nässén, J., and Johnsson, F. (2015). *Energy efficiency policies for space heating in EU countries: A panel data analysis for the period 1990–2010*. Appl. Energy 150, 211-223. https://doi.org/10.1016/j.apenergy.2015.03.063.

[30] Filippini, M., and Greene, W. (2016). *Persistent and transient productive inefficiency: a maximum simulated likelihood approach*. J. Prod. Anal. 45, 187-196. https://doi.org/10.1007/s11123-015-0446-y.

[31] Longo, S., Chitnis, M., Mauricio-Iglesias, M., and Hospido, A. (2018). *Transient and persistent energy efficiency in the wastewater sector based on economic foundations.* Manuscript submitted for publication.

[32] Carlson, S. W., and Walburger, A. (2007). *Energy index development for benchmarking water and wastewater utilities.* Denver: American Water Works Association (AWWA). Retrieved from www.waterrf.org/PublicReportLibrary/91201.pdf.

[33] Revollar, S., Vega, P., Vilanova, R., and Francisco, M. (2017). *Optimal Control of Wastewater Treatment Plants Using Economic-Oriented Model Predictive Dynamic Strategies.* Appl. Sci.7(8), 813. https://doi.org/10.3390/app7080813.

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

[35] ENERWATER (2017). *ENERWATER methodology.* ENERWATER project, deliverable D3.4. Retrieved from www.enerwater.eu.

[36] ENERWATER (2015). *Study of published energy data.* ENERWATER project, deliverable D2.1. Retrieved from www.enerwater.eu.

[37] ENERWATER (2016). *Benchmarking database.* ENERWATER project, deliverable D2.5. Retrieved from http://www.enerwater.eu/.

[38] Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., Hoffman, A., and Giovannini, E. (2005). *Handbook on Constructing Composite Indicators: Methodology and User Guide.* Paris: OECD.

[39] Frischknecht, R., Jungbluth, N., Althaus, H.J., Hischier, R., Doka, G., Bauer, C., Dones, R., Nemecek, T., Hellweg, S., Humbert, S. and Margni, M., 2007. *Implementation of life cycle impact assessment methods. Ecoinvent Report No. 3. v2.0.* Dübendorf: Swiss Centre for Life Cycle Inventories. Retrieved from www.oecd.org/sdd/42495745.pdf.

[40] Remy, C., Boulestreau, M., and Lesjean, B. (2014). *Proof of concept for a new energy-positive wastewater treatment scheme.* Water Sci. Technol. 70(10), 1709-1716. https://doi.org/10.2166/wst.2014.436.

[41] Haslinger, J., Lindtner, S., and Krampe, J. (2016). *Operating costs and energy demand of wastewater treatment plants in Austria: benchmarking results of the last 10 years.* Water. Sci. Technol. 74(11), 2620-2626. https://doi.org/10.2166/wst.2016.390.

[42] Plappally, A. K. and Lienhard V., J. H. (2012). *Energy requirements for water production, treatment, end use, reclamation, and disposal.*, Renew. Sust. Energ. Rev. 16(7), 4818-4848. https://doi.org/10.1016/j.rser.2012.05.022.

[43] CEN (2007). *EN 15217–Energy performance of Buildings–Methods for expressing energy performance and for energy certification of buildings.* European Committee for Standardization. Brussels: European Standardisation Organisation.

[44] Cooper, W. W., Seiford, L. M., and Zhu, J. (2011). *Handbook on data envelopment analysis.* New York: Springer Science & Business Media.

[45] Mardani, A., Zavadskas, E. K., Streimikiene, D., Jusoh, A., and Khoshnoudi, M. (2017). *A comprehensive review of data envelopment analysis (DEA) approach in energy efficiency.* Renew. Sust. Energ. Rev. 70, 1298-1322. https://doi.org/10.1016/j.rser.2016.12.030.

[46] Guerrini, A., Romano, G., Mancuso, F., and Carosi, L. (2016). *Identifying the performance drivers of wastewater treatment plants through conditional order-m efficiency analysis.* Utilities Policy 42, 20-31. https://doi.org/10.1016/j.jup.2016.08.001.

[47] Charnes, A., Cooper, W. W., Lewin, A. Y., and Seiford, L. M. (2013). *Data envelopment analysis: Theory, methodology, and applications.* New York: Springer Science & Business Media.

[48] Cherchye, L., Moesen, W., Rogge, N., & Van Puyenbroeck, T. (2007). *An introduction to 'benefit of the doubt'composite indicators*. Soc. Indicators Res. 82(1), 111-145. https://doi.org/10.1007/s11205-006-9029-7.

[49] Wett, B., Buchauer, K., and Fimml, C. (2007). *Energy self-sufficiency as a feasible concept for wastewater treatment systems*. IWA Leading Edge Technology Conference. Singapore: Asian Water.

[50] Testa, F., Annunziata, E., Iraldo, F., and Frey, M. (2016). *Drawbacks and opportunities of green public procurement: An effective tool for sustainable production*. J. Clean. Prod. 112, 1893-1900. https://doi.org/10.1016/j.jclepro.2014.09.092.