

# **A critical comparison of methods for benchmarking energy performance in WWTPs**

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**Abstract:** The energy efficiency of wastewater treatment plants (WWTPs) is a subject of growing interests by water utility and WWTPs operators. As consequence, benchmarking in recent years has become an important tool to assess the performance of these facilities and help identify best practices. This study compares various benchmarking methodology employed for the assessment of the energy efficiency in WWTPs. The literature review revealed three main benchmarking approaches: normalization, statistical techniques and programming techniques. Advantages and disadvantages were identified for each one. It was found additionally that no single Key Performance Indicators (KPIs) used to characterize the energy performance could be used universally. In general, while these methods can be used for comparison, the diagnosis of the energy performance remains an unsolved issue.

**Keywords:** Wastewater treatment; energy efficiency; benchmarking methods

## **Introduction**

Water and energy are intrinsically linked and forms a reinforcing feedback loop: when water use increases, energy associated with water services will also increase, which will further increase water consumed for energy production. In wastewater treatment, it becomes increasingly important to improve the environmental sustainability of wastewater treatment plants (WWTPs) by reducing the consumption of resources and energy.

To prevent environmental threats and increasing operation costs, the wastewater treatment industry has been subjected to public policies aimed at improving its energy performance. In this context, water agencies and WWTPs operators are manifesting a growing interest in the use of tools and methodologies to evaluate the energy consumption, link the energy performance with the operation of the WWTP and save energy through correcting actions. Benchmarking procedures are suitable tools for diagnosing the energy performance of WWTPs, provided that the right indicators are defined.

Literature on WWTP energy performance has been revised in order to classify and analyze the methods for benchmarking. This is the first step in the development of a systematic methodology for evaluation and improvement of energy performance in WWTP operation.

## **Methodology of the literature review**

The literature review aimed at answering the following questions: i) what methods are used for the assessment of energy efficiency in WWTPs? ii) Are these methodologies able to detect accurately energy inefficiency of a WWTP? iii) Do these methodologies properly represent the variety of WWTP technologies?

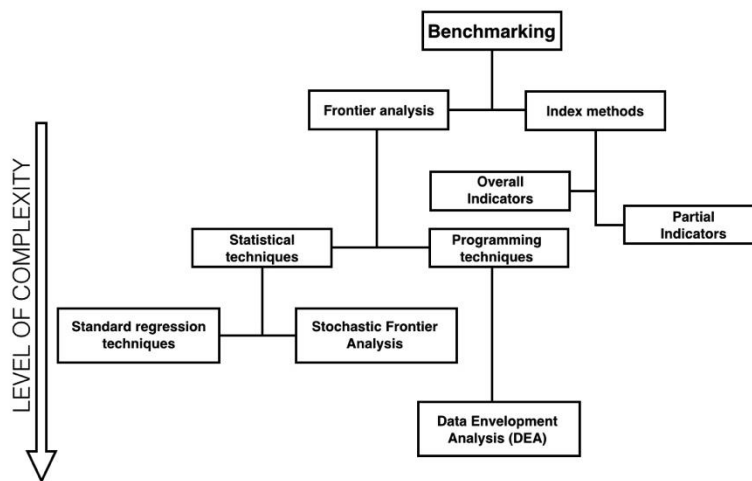
The literature review focus on WWTPs energy-use performance and the benchmarking systems. Peer-reviewed journal articles served as the primary source

for this study, using WWTP energy performance, WWTP energy efficiency assessment, WWTP energy benchmarking as the main keywords for searching.

## Results and Conclusions

There exists a wide range of methods to measure the relative efficiency of plants in relation to a sample. These include simple performance indicators (Balmér et al., 2012), statistical techniques (Carlson et al., 2007) and programming methods (Sala-Garrido et al., 2012). The choice of the benchmarking techniques used by individual utilities depends at least partly on the data available and purpose of the benchmarking exercises and can have impact on the determination of efficiency score.

A possible taxonomy of benchmark techniques in the field of wastewater treatment is illustrated in Fig. 1.



**Figure 1** Benchmarking approaches according to the methods used

*Index methods.* Normalization, for its simplicity in the implementation and interpretation, is the most widely used benchmark system in the field of wastewater system. The normalization approach consists in using ratios of relative key performance indicators (KPIs). KPIs, such as energy-efficiency indicators are usually employed and obtained by simply dividing the energy use based on a given level of output or activity (e.g. volume of wastewater treated, kg of COD/BOD removed, ext.). This approach is a fast and simple way to conduct a preliminary comparison of WWTPs of similar size and characteristics. However, the method is too simplistic when applied to different kinds of plants (e.g. with their different type, size, and location) if only one metric is used. As an example, most authors consider the volume of treated wastewater ( $\text{kWh}/\text{m}^3$ ) or the loads of pollutants entering WWTPs expressed as PE served ( $\text{kWh}/\text{PE}\cdot\text{year}$ ) as a variables when measuring energy efficiency. These two KPIs are only partially valid since they do not account for pollutant elimination rates (which is the actual function of a WWTP). On the contrary, relating energy consumption per unit of pollution-removed load of a certain pollutant (e.g.  $\text{kWh}/\text{kg COD}_{\text{removed}}$ ) is more useful, though it is not valid only when comparing WWTPs with different function (e.g. WWTP for only organic matter removal vs WWTP for organic

matter and nutrient removal). An overview of the most used KPIs in the literature is reported in Table 1.

**Table 1** Comparison of most used KPIs

KPIs	Overall	Preliminary treatment	Primary treatment	Secondary treatment	Tertiary treatment	Sludge treatment	Comments
kWh/m <sup>3</sup> *m	✗	✓	✗	✗	✗	✗	Only suitable for pumping
kWh/m <sup>3</sup>	✓	✓	✗	✗	✗	✗	Does not take into account influent dilution; Does not represent the removal of pollutants
kWh/PE*year	✓	✗	✗	✗	✗	✗	Does not represent the removal of pollutants
kWh/kg COD <sub>removed</sub>	✓	✗	✓	✓	✗	✓	Limited to plants with same function
kWh/kg TSS <sub>removed</sub>	✗	✗	✓	✗	✗	✓	Limited to primary and/or sludge treatment
kWh/kg TPUS <sub>removed</sub> *	✓	✗	✗	✓	✗	✗	Weights factors are uncertain

*Regression models.* The most commonly used statistical approach is regression models, such as ordinary least squares (OLS). An example of such application is ENERGY STAR method (Carlson et al., 2007). Using a large sample of WWTP operation data, OLS calculates the expected average energy use for the variables with a largest influence on the energy consumption of a particular plant, namely average influent flow rate, influent and effluent BOD, plant load factor and whether the plant presents filtration or nutrient removal. For a given WWTP and using as input the aforementioned variables, the OLS regression model returns the expected (average) energy consumption. Dividing the actual energy use by the expected value allows a comparison versus the population of plants used to develop the model. Furthermore, a distribution of energy use is available, providing for a given WWTP in which percentile of energy performance is located. The major criticism of this approach are i) that a limited amount of variables are considered as an input leaving other important variables as unexplained variability and ii) that as all the indicators are merged into a single one, it is possible to offset the inefficiency in one variable by another, e.g. high BOD removal can compensate not removing nutrients.

The third approach involves Data Envelopment Analysis (DEA) methodology. Basically, DEA is a mathematical programming technique that allows building an envelopment surface or efficient production frontier to assess the efficiency of a set of units Decision Making Units (DMUs), which are WWTPs in our case. Thus, those DMUs that establish the surface of the envelopment are considered efficient units and those that do not rest on the surface are considered inefficient. A unit is considered to be efficient if and only if it is not possible to improve its outputs while its inputs are fixed, and it is not possible to do change its inputs without altering the resulting outputs. DEA does not need to employ an assumption for the functional form of the frontier. Consequently, there is no danger of wrong model specification for the frontier. Moreover, it can incorporate uncontrollable (or unpredictable) factors (e.g. environmental). In this context, DEA approach has recently attracted special interest for the task of assessing the technical, economic and environmental efficiency of WWTPs. However, taking into account that a WWTP is viewed as a multiple input and outputs unit, the shortcoming of DEA models is that they do not provide information on the efficiency of specific inputs. Like the OLS, another limitation of

studies that applied DEA to energy efficiency is the assumption of deterministic energy efficiency scores.

Regarding the end-user of the benchmarking system, methods are best adapted to public (or “user friendly”) or internal benchmarking. For DEA, a new public user cannot use the model without solving it again for new rankings of all observations. Therefore, the benchmarking system developed by DEA is not suitable for public use. On the other hand, new observations can be benchmarked directly with the benchmarking table generated by OLS and normalization approaches. In effect, it is not necessary to solve the model to obtain the benchmarking score. These methods then become suitable for public users.

Energy consumption has a significant stochastic component, affected by weather, seasonality and human factors. For that reason a good benchmark system should be able to discern actual inefficiency from energy use due to those factors or data errors. Further efforts have to be addressed for the development of a methodology able, on the one hand to quantify WWTPs energy efficiency, and on the other hand to indicate where in the plant a possible inefficiency originates.

**Table 2** Comparison of various benchmarking approaches

Benchmarking Approaches	System	Method	Approach	Model	Key characteristics	Pros	Cons
Normalization	Public	Non-Frontier	Deterministic	-	Based on relative simple performance indicators, and ratios of single input and output	Relative inexpensive; Easy to implement and interpret	It assume that the entire population of plants is comparable universally and with only one metric
Regression models	Public	Frontier	Deterministic	Parametric	Estimates the average trend over the entire population, and then compare each plant with that overall trend.	Computationally easy and straightforward; Suitable for public users	Residuals are treated as measures of inefficiency, even if they actual reflect a combination of different factors; Sensitive to outliers; Difficult to implement on small samples
Data Envelopment Analysis	Internal	Frontier	Deterministic	Non-Parametric	Non-parametric approach that calculates, rather than estimates, the frontier using programming techniques	No assumption or specification of energy function is required; Can incorporate uncontrollable (or unpredictable) factors (e.g. environmental)	Sensitive to choice of input and output variables; No allowance for stochastic factors and measurement errors

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