Energy audit and benchmarking procedure in textile effluent treatment plants (ETPs)

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Abstract

Since energy consumption is one of the most important expenses in textile effluent treatment plants, with a proper design and a careful management model, there is a possibility to achieve significant savings. Energy audit and benchmarking procedures are required for the evaluation of the energy performance. Panta Rei has developed its own energy audit and benchmarking procedures, in order to inform its customers about the possible costs and energy saving actions and the final energy star score.
In this report, an audit in one textile ETP was carried out, where the overall and disaggregated energy consumption were predicted by the energy model and compared to the energy bill. The sensitivity and uncertainty analysis showed that, in this case study, the different stage treatments were not sensitive, which meant that no saving actions were required. The final weighted ordinary least square regression, showed that the energy star score for this case study was 64.

1. Introduction

Energy consumption is one of the highest expenses in wastewater services. Data collected from different European countries shows that the energy consumption for wastewater treatment corresponds to about 1% of the total consumption of the country (Cao et al., 2011). The electricity demand for domestic and industrial water cycle in Spain is about 2-3% of the total energy consumption (Fundación OPTI. 2012). In the UK, the energy consumption in wastewater cycle system accounts for about 3% of the overall energy consumption (Bodík and Kubaská, 2013). In the United States, it has been estimated that roughly 4% of the electricity demand is employed in distribution/collection and potabilization/treatment of water and wastewater, by public and private stakeholders (Goldstein et al., 2002). Although the textile and apparel industry is not considered as an energy-intensive industry, it comprises a large number of plants that, together, consume a significant amount of energy, which results in substantial greenhouse gas (GHG) emissions (Hasanbeigi et al., 2015). Electricity is the most dominant energy use source, especially for textile wet processing (Hasanbeigi et al., 2012). The textile apparel industry accounts for about 4% of the total manufacturing final energy use in China. but less than 2% in the U.S. (Hasanbeigi, 2013).
As energy costs continue to rise, knowledge of energy-efficient technologies and best practices is becoming more valuable. As these practices have slowly gained acceptance within the wastewater industry, increasingly strained budgets, coupled with aging infrastructure, make energy efficiency a feasible option to save money. Energy consumption represents a significant part of the operative cost, but with a correct design and a careful management model, there are significant possibilities for its limitation (Panepinto et al., 2016). An energy audit can vary in complexity from very simple – such as operating process equipment on a different schedule, to complex – changing the type of treatment system or replacing critical process equipment regardless of complexity, the benefits are numerous and typically include cost saving, improved treatment and increased system reliability.
Energy audit and benchmarking procedures are required for the evaluation of the energy performance (Parena et al., 2012). Using benchmarking methodologies, the best operational practices can be identified (Molins-Senante et al., 2014). The energy audit procedure was developed starting from the guideline proposed by ENEA (Italian company for new technologies, energy and sustainable economic actions). The benchmark for textile effluent treatment plants (ETP's) was developed by a statistical linear regression, following the instruction proposed by the U.S.E.P.A. (United States Environmental Protection Agency) and the Energy Star Portfolio Manager methodology. The aim of this technical report is to highlight the importance of checks, control and management of the the energy consumption in textile ETP's, compare the results of the audit with the benchmark and identify the possible cost and energy saving actions.

2. Methods

2.1 Energy audit and Normative framework

Energy audit is the general term used for a systematic procedure used to obtain adequate knowledge of the energy consumption profile of an industrial plant. One of the aims of an energy audit is the determination of energy baseline regarding the reference consumption of individual devices and installation (Longo et al., 2016). Carrying out an energy audit is important for:

- The identification of the most consuming area;
- The identification of the different energy carriers;
- The evaluation of the best solutions to increase the energy performance;
- The identification of most suitable specific energy parameters to reduce the consumption.

The most important outputs are:

- Money saving actions;
- Energy saving actions;
- Greenhouse gas reduction.

Energy audit is the most important tool to analyze the framework of energy management of an activity. It highlights the level of management efficiency, based on an analysis of the significant energy flows to identify the most energy consuming process or device. The energy audit guidelines delivered by ENEA can be represented by an energy scheme consisting of four different levels. The energy scheme is the description of the uses of each energy carrier within specific boundaries in reference to the object of the energy audit. The impact of each utility must be calculated in relation to the total energy consumption.

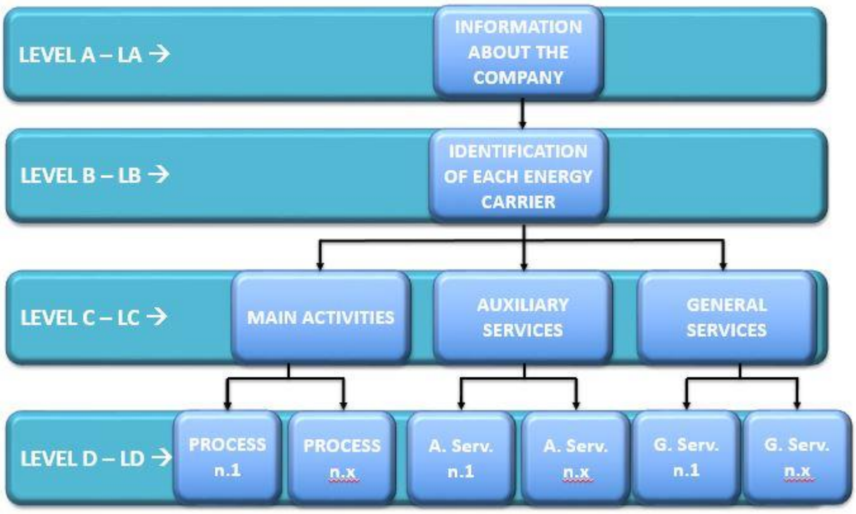

Figure 1: Schematic representation of the required tasks to complete an energy audit

- Level A (LA) is characterized by the description of the general data of the ETP;
- Level B (LB) is the point of extreme synthesis of the energy structure for each energy carrier;
- Level C (LC) is the part that identifies the functional areas;
- Level D (LD) is a schematic structure of the energy mapping.

2.1.1 *Energy audit methodology*

The ENEA guidelines were adopted to develop the audit procedure as described below:

A- Pre-audit survey - data collection

Before the on-site survey, a proper check-list document is forwarded to the customers. The main documents required are:

- Process scheme;
- Layouts;
- Equipment inventory;
- Name plates;
- Equipment working hours;
- Electrical bills;
- Flowrate;
- Influent and effluent characteristics.

The documentation will be analyzed in order to plan in detail the on-site survey and collect eventual missing information.

B- On-site survey

The objective of the on-site survey is to properly understand the different processes within the ETP and identify possible technological and management weak points. The presence of energy meters will be checked in order to get the amperometric values.

C- Mathematical energy modelling

The mathematical energy modelling allows for the detailed description of the energy consumption as a function of the availability of on-site measures and name plates. Starting from the information taken in the previous steps, a detailed energy consumption table will be created, using measured or estimated values of each equipment involved in the process.

D- Energy saving actions

Through the obtained information of the energy model, possible weak points and suitable solutions and alternatives will be identified in order to improve the energy efficiency, taking into account the Best Available Technologies.

E- Cost-benefit analysis

The proposed alternatives will be compared and arranged in function of their affordability, evaluated through the cost benefit analysis.

F- Benchmarking comparison

Using a statistical analysis described in the USEPA energy star portfolio manager, the benchmark for textile ETP's was developed. After the energy audit of the ETP, the result obtained will be compared with the benchmark in order to give an energy score.

G- Energy star score

The energy stare score generates an energy consumption score by comparing predicted values with actual data to obtain a 1 to 100 percentile ranking of performance: the lower the energy use intensity, the higher the score.

H- Energy report

The energy report shows in detail the audit procedure, energy and cost saving actions and the energy score obtained.

2.2 *Data collection: reference data for statistical population*

100 designed ETP's were taken into account to develop the current benchmark for textile ETP's. Energy consumption was gathered along with data related to the process, influent and effluent characteristics, biological oxygen demand (BOD), influent flow-rate, chemical oxygen demand (COD) and oxygen transfer rate (OTR). Table 1 shows a descriptive statistic summary for the ETP's studied.

Table 1: Statistic description of the ETP's studied.

	Flow-rate (m^3/d)	BOD_5 (mg/L)	COD (mg/L)	O.T.R. (kg/h)
Average	3,058	556	1,274	179
Minimum	300	200	500	13
Maximum	12,000	1,800	3,000	825
Standard Deviation	2,287	256	547	146

2.3 *Benchmarking procedure for textile ETP's*

Once the reference data to establish the statistical population was processed, the benchmarking procedure for textile ETP's was developed through an existing standard proposed by the U.S.E.P.A., the Energy Star Portfolio Manager (U.S.E.P.A., 2014).

2.3.1 *Analyzed variables*

The reference data were analyzed using a weighted ordinary least squares regression, which evaluates energy use relative to plant activity. The linear regression yields an equation that is used to compute energy use (also called the dependent variable) based on a series of characteristics that describe the business activity (also called independent variables).

2.3.2 *Dependent variable*

The dependent variable is what we try to predict with the regression equation. For the ETP's analysis, the dependent variable is the energy consumption expressed as source of energy use intensity (source EUI). For ETP's, this is defined as the total energy source use of the property divided by the average influent flow-rate (in cubic meters per day). The regressions analyze the key drivers of the source EUI – the factors that explain the variation in source of energy use per unit flow through the treatment plant.

2.3.3 *Independent variable*

The survey data includes extensive information on plant operation, including influent and effluent water quality. Based on the regression analysis, three key explanatory variables were identified. which can be used to estimate the expected average source EUI (kWh/m^3) of ETP's:

- Natural log of average influent flow (m^3/d);
- Natural log of average influent BOD_5 load (kg/d);
- Natural log of oxygen transfer rate (kg/d).

2.4 *Energy Star score*

The energy star score, generates an energy consumption score by comparing predicted values with actual data to obtain 1 to 100 percentiles ranking of performance: a lower intensity user earns a higher score.

3. Results and discussions

3.1 *Regression equation results*

The final regression is a weighted ordinary least square regression across the filtered data set of 100 observations. The dependent variable is the source EUI (kWh/m^3). Each independent variable was centered relative to the mean values, presented in table 2.

Table 2: Mean. min and max across the variables of the 100 ETP's studied.

Variable	Mean	Min	Max
EUI	1.000	0.527	2.451
Ln Flow rate	7.762	5.704	9.393
Ln influent BOD_5	7.089	4.787	8.882
Ln O.T.R	8.041	5.751	9.893

To perform the regression, the actual EUI, of each ETP, was kept as dependent variable, while the centered values (actual Ln value – mean Ln value) were used as independent variables of the model. The output of the regression is the predicted values of the EUI obtained through the statistical identification of the Unstandardized Coefficients.
The regression equation has a coefficient of determination (R^2) value of 0.736, which indicates how much of the total variation in the dependent variables can be explained by the independent variable, in this case 73.6% can be explained, which is a large number. Table 3 indicates that the ANOVA results of the regression model predict the dependent variable fairly well. The significant values (p-level) are less than 0.05, and indicate that the regression model predicts the outcome variable properly from the statistical point of view. The Unstandardized coefficients calculated by the regression were used to identify the predicted source EUI starting from the centered independent variables.

Table 3: Mean. min and max across the variables of the 100 ETP's studied.

Dependent variable	Actual source EUI (kWh/m^3)			
Number of observations	100			
R^2 value	0.744			
Adjusted R^2 value	0.736			
F statistic	93.156			
Significant (p-level)	0.000			
	Unstandardized Coeff.	Standard error	T value	P - level
Constant	1.000	0.017	58.189	0.000
Centered Ln flow rate	-0.925	0.058	-15.714	0.000
Centered Ln influent BOD_5 load	0.175	0.070	2.521	0.013
Centered Ln OTR	0.677	0.080	8.340	0.000

3.2 *Energy star score gamma distribution*

The final regression equation yields a prediction of source EUI based on the ETP's operating characteristics. Some ETP's in the reference data sample use more energy than predicted by the regression equation, while other use less. The actual source EUI of each reference data observation was divided by its predicted source EUI in order to calculate an energy efficiency ratio:

$$Energy\ Efficiency\ Ratio = \frac{Actual\ source\ EUI}{Predicted\ Source\ EUI} \quad \text{Equation 1}$$

A lower efficiency ratio indicates that a ETP uses less energy than predicted, and consequently is more efficient. A higher efficiency ratio indicates the opposite. The efficiency ratios were sorted form smallest to largest and the cumulative percent of the population at each ratio was computed using the individual weights from the reference data set. Figure 2 shows a plot of this cumulative distribution. A smooth curve was fitted to the data using a two-parameter gamma distribution. The fit was performed in order to minimize the sum of squared differences between each ETP actual rank in the population and each ETP percent rank with the gamma solution. The final fit for the gamma curve yielded a shape parameter (alpha) of 8.927 and a scale parameter (beta) of 8.927.

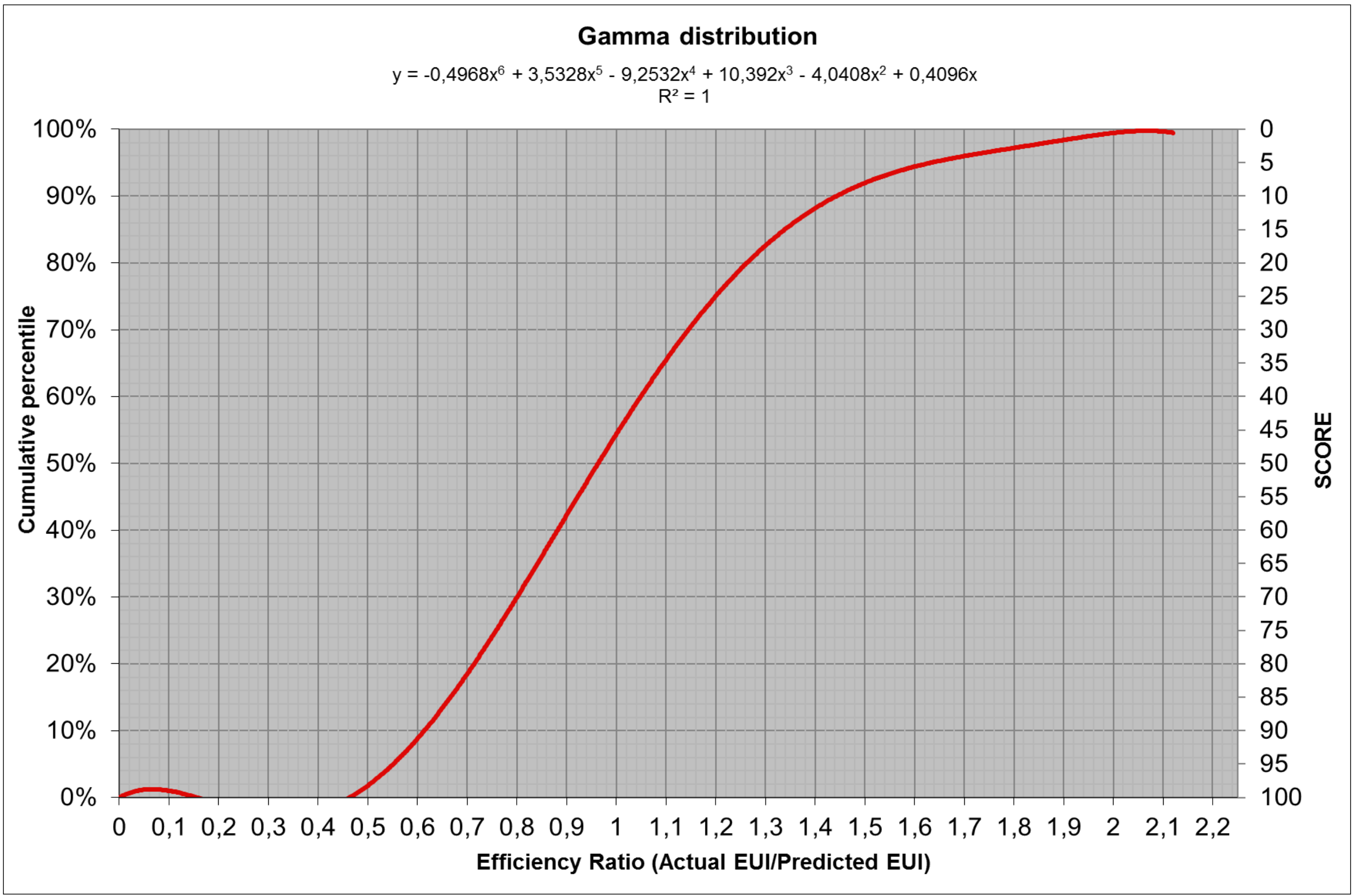

Figure 2: Gamma cumulative distribution

The final gamma shape and scale parameters were used to calculate the efficiency ratio at each percentile (1 to 100) along the curve. For example, the ratio on gamma curve at 1% corresponds to a score of 99; only 1% of the population has a ratio like this or smaller. The ratio on gamma curve at the value of 25% will correspond to a score of 75; only 25% of the population has the ratio like this or smaller.

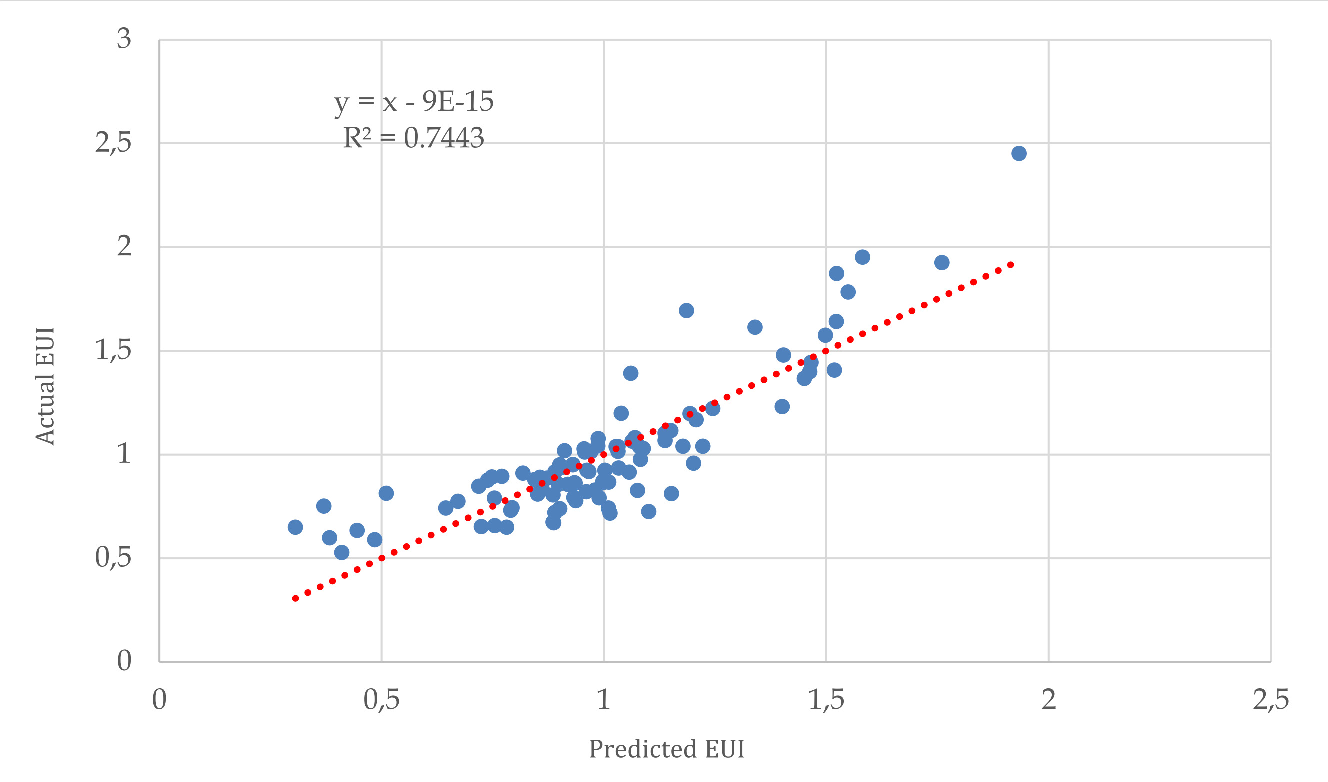

Figure 3: Correlation between actual and predicted EUI

3.3 ***Calculation example***

One textile ETP, with the characteristics shown in table 4, was the object of the audit. By the application of the developed audit methodology and the benchmarking comparison, the energy consumption, possible costs and energy savings as well as the energy score were evaluated.

3.3.1 Pre-audit survey

During the pre-audit survey, the useful data regarding the process characteristics and the equipment list were collected accordingly to the procedure.

Table 4: Characteristics of the audited ETP

	Characteristics	
Flow-rate (m^3/d)	3,600	
O.T.R (kg/h)	180	
Oxidation volume (m^3)	7,200	
HRT (h)	48	
MLSS (mg/L)	6,667	
MLVSS (mg/L)	5,000	
Energy bill (kWh/y)	1,091,513	
kgTSS_dry/d	1,728	
	influent (mg/L)	outlet (mg/L)
COD	1,200	150
BOD_5	600	50
TSS	120	10

Table 5: Equipment list and stage classification

Energy Use	Stage	Equipment	n° of Equipments	CODE
Pretreatment	Screening	motor	1	**A**
Pumping	Lifting	pump	3	**B**
	Feeding	pump	2	**C**
Storage	Equalization	Blowers - Motor	2	**D**
	Neutralization	Acid dosing pump	2	**E**
		Decolourant dosing pump	2	**F**
		Sodium hypochlorite dosing pump	1	**G**
		Antifoam dosing pump	1	**H**
Biological	Oxidation	Blowers -Motor	3	**I**
		Return sludge pump	2	**L**
	Sedimentation	Scraping bridge	1	**M**
Outlet	Oxygen increase	Blowers -Motor	2	**N**
Sludge	Dehydration	Filterpress	1	**O**

3.3.2 Mathematical energy modelling

Through the gathered data the energy audit was carried out in order to estimate the energy consumption of each equipment and process unit.

Table 6: disaggregated energy consumption

CODE	Efficiency	Power (kW)	Voltage (V)	Nominal Current (A)	Absorbed power (kW)	Working hours (h/y)	Contemporary factor	Load factor	En.Con. (kWh/y)
A	71.0%	0.37	400	1.18	0.22	4,380	1.00	0.43	971
B	82.0%	5.90	400	10.00	3.54	4,380	0.67	0.49	31,010
C	82.0%	5.90	400	10.00	3.54	8,760	0.50	0.49	31,010
D	93.4%	18.50	400	52.10	16.70	8,760	0.50	0.84	146,292
E	70.0%	0.24	400	0.80	0.14	3,650	0.50	0.42	526
F	70.0%	0.24	400	0.80	0.14	3,650	0.50	0.42	526
G	70.0%	0.24	400	0.80	0.14	365	1.00	0.42	53
H	70.0%	0.24	400	0.80	0.14	1,460	1.00	0.42	210
I	94.8%	75.00	400	127.00	44.18	8,760	0.67	0.56	777,888
L	82.0%	5.90	400	10.00	3.54	8,760	0.50	0.49	31,010
M	71.0%	0.18	400	1.18	0.11	8,760	1.00	0.43	945
N	88.2%	4.00	400	7.40	2.40	8,760	0.50	0.53	21,024
O	80.0%	7.50	400	7.32	4.23	4,015	1.00	0.45	16,987

When the energy meters were not present, the absorbed power was calculated as:

$$Absorbed\ power = \frac{Power * Load\ Factor}{Efficiency}$$ Equation 2

The load factor is a variable that describes how the devices are working compared to their nominal power. Starting from the absorbed power, the energy consumption was calculated as:

$$E.c. = n° * P_{ass} * W_h * C_F$$ Equation 3

Where: E.c. is the energy consumption in kWh/y; P_{ass} is the absorbed power; W_h is the working hours in hours/year; C_F is the contemporaneity factor that describe how many equipment are working respecting that one installed.

The total energy consumption resulted from the audit was 1,058,453 kWh/y. The energy audit was carried out successfully since the deviation from the energy bill is lower than 5%.

In order to better understand the energy use of each unitary process end/or equipment, the energy consumption was disaggregated end the key energy indicators identified.

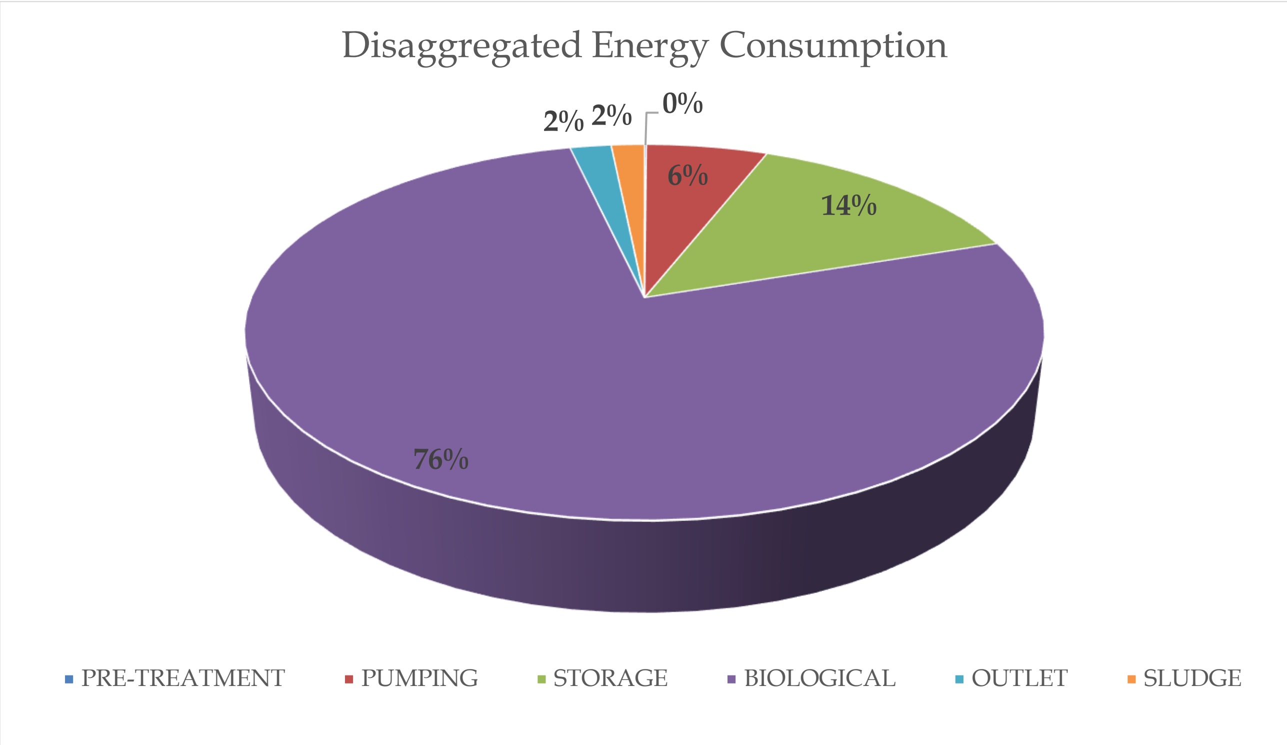

Figure 4: Disaggregated energy consumption per stage treatment

As expected, and in line with the literature data, the biological stage was the most energy consuming among all the stages because the air to be supply in the oxidation reactor. Storage tank and pumping stages account respectively 14% and 6% of the overall consumption.

Table 7: Key Energy Indicators

Energy Use	kWh/y	K.E.I.	Units
Pre-treatment	971	0.001	kWh/m³
Pumping	62,021	0.047	kWh/m³
Storage	147,606	0.112	kWh/m³
Biological	809,844	0.59	kWh/kg COD removed
Outlet	21,024	0.016	kWh/m³
Sludge	16,987	0.03	kWh/kgTSS_dry
Overall	1,058,453	0.81	kWh/m³
		0.77	kWh/kg COD removed

3.3.3 *Energy saving actions: Sensitivity and Uncertainty analysis*

In order to identify the possible energy and cost saving actions, the sensitivity and uncertainty analysis was carried out.

The uncertainty analysis was carried out starting from the energy consumption of each treatment stage compared to the overall consumption of the plant. Table 8 gives the Uncertainty condition 1 starting from the disaggregated energy consumption per treatment stage (Figure 4).

Table 8: Uncertainty conditions 1

0	**1**	**2**	**3**
Weight C1	Consumption <	Consumption<	Consumption >=
	5%	15%	15%
Weight C2	5	10	15

The Uncertainty condition 2 was given using table 9. Analyzing the energy consumption of each equipment, the age and the equipment wear, the values of variable a, b and c were chosen in function of the conditions. The score of the Uncertainty condition 2 is a combination of a chosen values of the different variables.

Table 9: Uncertainty conditions 2

How to choose parameters a. b. c			
Variable	Meaning	Value	Condition
a	Actions applicability	0	No actions applicable
		1	Obsolete equipment. Replacement expensive
		2	Obsolete equipment. Replacement acceptable
b	Consumption % of obsolete equipment compared to the overall consumption of the stage	1	Consumption < 20%
		2	20% ≤ consumption < 50%
		3	Consumption ≥ 50%
c	Expected energy saving	1	Saving < 10%
		2	10% ≤ saving < 20%
		3	Saving ≥ 20%

Since the uncertainty analysis was involved, the sensitivity analysis was carried out in order to identify if some possible improvements, by the replacement of some equipment, could be considered. The sensitivity analysis given as a final score is combination of the score obtained during the Uncertainty condition 1 and 2, considering a limit value and a weighted constant.

The results of sensitivity and uncertainty analysis are reported in table 10. As can we observe, since the equipment installed in the plant is new and highly performant, corrective actions were not needed.

Table 10: Uncertainty and sensitivity analysis

Energy Use	En.Cons.	Uncertainity 1		Uncertainity 2					Sensitivity Analysis	
	kWh/y	% Consumption	Score	a	b	c	Score	Possible improvement	Final Score	Sensitivity
Pre-treatment	971	0%	1	1	1	1	1	None	1.0	not sensitive
Pumping	62,021	6%	2	0	1	1	1	None	1.5	not sensitive
Storage	147,606	14%	2	0	1	1	1	None	1.5	not sensitive
Biological	809,844	77%	3	0	1	1	1	None	2.0	not sensitive
Outlet	21,024	2%	1	2	1	1	1	None	1.0	not sensitive
Sludge	16,987	2%	1	0	1	1	1	None	1.0	not sensitive

3.3.4 Benchmarking and energy score

In order to compare the results of the audit and identify the score, there are 5 steps to be followed:

- Step 1: User data information

Table 11: Input data for computing Actual and Predicted Source EUI

Energy data	Value
Audit results (kWh/y)	1,058,453
Property use details	**Value**
Average flow rate (m^3/d)	3,600
Average influent BOD_5 (mg/L)	600
Oxygen transfer rate (kg/h)	180

- Step 2: Computation of the actual source EUI

The energy source is divided by the average influent flow-rate to determine the actual EUI:

$$Actual\ EUI = \frac{kWh/y}{m^3/y} = 0.806 \qquad \text{Equation 4}$$

- Step 3: Computation of the predicted source EUI:
  - Using the property use details form Step 1, the methodology computes each variable value in the regression equation (determining the natural log or density as necessary).
  - The centered values are subtracted to compute the centered variables for each operating parameter.
  - The centered variables are multiplied by the coefficient got through the regression equation to obtain a predicted EUI.

Table 12: Computing Predicted Source EUI

Variable	Actual plant value	Reference centered value (Table 2)	Plant centered variable	Coefficient (Table 3)	Coefficient centered variable
Constant	-	-	-	1.000	1.000
Ln_influent	8.189	7.762	0.427	-0.925	-0.395
Ln_BOD_5 load	7.678	7.089	0.589	0.176	0.104
Ln_OTR	8.317	8.041	0.330	0.678	0.224
Predicted source EUI (kWh/m^3)					**0.933**

- Step 4: Computes the energy efficiency ratio:

Using Equation 1, the efficiency ratio resulted in 0.864

- Step 5: Assigning the score via a gamma distribution:

Entering in figure 2 with the efficiency ratio obtained. the energy score is 64.

4. Conclusions

The energy audit and benchmarking procedures were described in detail. The results of the case study showed that:

1) The predicted energy consumption by the energy model accurately described the actual energy consumption reported on the energy bill.

2) Through the mathematical energy model, the disaggregated energy consumption in each stage treatment was identified, and so were the key energy indicators.

3) Sensitivity and uncertainty analysis showed that no saving actions were required to improve the energy performance of the plant.

4) The results of the audit were compared with the textile ETP's benchmark in order to identify, through the final weighted ordinary least square regression, the final energy star score of the plant.

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