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Energy Efficiency Drivers in Wastewater Treatment Plants: A Double Bootstrap DEA Analysis

Andrea Guerrini [1,*], Giulia Romano [2] and Alessandro Indipendenza [1]

[1] Department of Business Administration, University of Verona, Via Cantarane, 24, 37129 Verona, Italy; alessandro.indipendenza@studenti.univr.it
[2] Department of Economics and Management, University of Pisa, Via Ridolfi, 10, 56124 Pisa, Italy; giulia.romano@unipi.it
* Correspondence: andrea.guerrini@univr.it; Tel.: +39-334-310-6454

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Abstract: The relevance of wastewater treatment service has increased in recent years, since it has a significant impact on the natural environment. A treatment plant facilitates energy generation, the recovery of products from waste, and the reuse of wastewater for industrial and irrigation purposes. An indirect environmental effect is the high energy consumption for pumping water and for tank aeration. The objective of this research is to develop a tool for measuring the energy costs of wastewater treatment plants and identifying how they can be reduced. The method adopted is double-bootstrap data envelopment analysis. The results show that the variables with a significant influence on efficiency are the chemical oxygen demand concentration; plant capacity; rate of used capacity, which positively affects efficiency; weight of industrial customers, which exerts a negative impact; and aeration system, with a negative impact for turbines. This paper suggests the adoption of an effective control tool to monitor the costs drivers and energy expenditure of water utilities.

Keywords: water utilities; wastewater treatment; energy cost; performance; efficiency; treatment plant

1. Introduction

In Europe, the implementation of the European Union's (EU's) Directive 91/271/EEC provided new rules for the discharge of sewerage and for its treatment, in order to avoid environmental pollution and damage to the ecosystems. Compliance with EU directives and with possible future standards for the treatment of other contaminants, such as pharmaceuticals and veterinary drugs, might require the significant effort of utilities in terms of investment in wastewater treatment plants (WWTPs) and of the higher operating expenditures incurred when treating wastewater [1]. For this reason, the most recent studies have aimed to find new processes for water and sludge treatment that improve the pollutant removal rate, but, at the same time, determine an affordable cost increase or, more preferably, allow a cost savings. Considering that the cost of energy consumption represents a substantial cost to wastewater utilities [2]; since energy is usually consumed from the primary treatment to the digestion of sludge products, it is essential to periodically conduct energy audits and realize some changes in operations and infrastructure that can lead to energy savings [3].

The cost of energy can vary, ranging from 2% to 60% of total operating costs; thus, it can represent the main item of operating expenditures in a WWTP [4,5]. The electrical energy consumption per m^3 of wastewater treated can vary, ranging from approximately 0.26–0.84 kWh/m^3 [2,6,7] depending on several operational and environmental characteristics, such as pollutant loads, plant size and age, and type of WWTP [1,6,7]. The average energy consumption for Germany, the United Kingdom, and United States is 0.67, 0.64, and 0.45 kWh/m^3, respectively, and for Italy, consumption between 0.40 and 0.70 kWh/m^3 was measured, depending on the type of plant [8–10].

As reported by some authors, the higher consumption of electric energy is required by pumps (79%) to pump and treat wastewater [11]. The active sludge treatment, with the biological oxidation of pollutants, absorbs approximately 50% to 65% of the total consumption energy, in addition to the 11% required for the primary treatment, for grit, sand, and oil removal as well as sedimentation [12]. However, plant managers have the opportunity to significantly reduce energy costs through preliminary energy audits followed by process modifications. As described in [13], only an optimization of the aeration and pumping activities allows for annual savings ranging from 547 to 1057 million kWh, reducing the energy consumption by 6%.

Prior research on energy efficiency in WWTPs shows that several variables should be constantly monitored by the plant manager because they exert an influence on efficiency trends. According to [14], large variations in the quality of wastewater inflows, measured in terms of the five-day biochemical oxygen demand/nitrate as nitrogen (BOD5/NO3-N) ratio, reduce the efficiency achieved in biological denitrification. This result successfully illustrates the trade-off related to the high BOD5 concentration: this pollutant feeds microorganisms and allows the digestion of nitrogen, but, at the same time, it contributes to generating sludge through the fast growth of bacteria. The extant technical literature provides an optimal value of this ratio, which should be around 100:17–100:19 [15]. Recently, the use of a bootstrap approach found that if the value of the chemical oxygen demand (COD)/BOD5 ratio does not respect the standard of scientific literature, normally, the plant managers add more carbon elements and begin other chemical treatment processes, despite the incremental costs per m^3 of wastewater treated of these alternatives and, consequently, this reduces the level of efficiency [16]. Further, it has been demonstrated how seasonality actually influences the energy efficiency of WWTPs, especially for activated sludge technology [17]; similarly, it has been shown that the consumption of energy in a sample of 177 Spanish WWTPs, using extended aeration technology, is 0.82 kWh/m^3, with better efficiency recorded for non-seasonal plants [17,18]. Further, in terms of the technology used to aerate the oxidation tanks, it has been shown that diffusers are more efficient than turbines, since they allow for a higher removal rate of COD, but, at the same time, they require greater energy consumption per m^3 of wastewater treated [18].

Plant size is another key performance driver of energy costs in wastewater treatment. Several studies [18–20] have shown that cost savings are achieved by larger plants in terms of population equivalent (PE), while the m^3 is not a relevant factor to capture increasing return to scale. Moreover, it has been demonstrated that the consumption of energy per kg of COD removed significantly decreases from plants with a capacity of less than 2000 PE (3.21 kWh/kg COD) to those with a capacity of more than 100,000 PE (0.85 kWh/kg COD) [20]. Conversely, [21] show that diseconomies of scale can significantly affect wastewater treatment if an efficiency measure that includes greenhouse gas emissions is considered [21]. In addition, energy consumption is related to the load factor, the ratio between the load of wastewater inflows received to the design value of the plant. Further, two particular studies have confirmed that undersized plants work better than do oversized plants, and energy savings increase when the load factor approaches 100% [22,23].

In light of this scarce and quite recent literature, the current article aims to provide further insights into the energy efficiency of WWTP, observing the effect exerted by several previously examined variables as well as by new environmental factors, such as the rate of wastewater coming from non-domestic customers, rate of production capacity used, and rate of sludge disposed in agriculture. Different from other researches, this article studies the energy efficiency of the whole treatment process, including wastewater and sludge handling, of 127 WWTPs. The prior literature adopts several measurements for energy efficiency. Traditionally, energy consumption is reported in terms of kwh/m^3 or per unit of population (kwh/PE). This measure can have some drawbacks for benchmarking purposes when COD concentration varies among plants [22]; thus, the ratio of kWh to kg of COD removed (or other pollutants) is estimated [24]. Considering that the COD concentrations of inflows are quite similar for the plants observed, this article examines two measures of energy efficiency: (i) the cost of energy per m^3 of wastewater treated and (ii) DEA score, based on a set on inputs and outputs.

The replication of these kinds of analyses offers some guidelines for the decision-making process of plant managers.

2. Materials and Methods

2.1. Case Studied

The WWTPs studied in this article were located in Tuscany, a central region of Italy, and controlled by Acque SpA, a public-private utility entrusted in 2002 with water services in the so-called 'Basso Valdarno' river basin in the province of Pisa.

The data grid for this study was constructed with the support of the Tuscan water authority staff and of the technical staff of Acque SpA. The data for the year 2014 were gathered by a team of engineers from the water utility databases, and their consistency was double-checked by Acque management and researchers. Starting from the 139 WWTPs controlled by the utility, 12 were excluded, since they carry out only the primary treatment through Imhoff tanks without any energy consumption. Table 1 shows that among the remaining 127 plants, 123 are based on a secondary treatment with activated sludge, while four also have a tertiary process, such as denitrification, dephosphorization, and chlorination. Then, 21 plants have additional plants for sludge treatment. The population observed is characterized by small plants, with 85 WWTPs operating with a capacity lower than 2000 PE, 29 plants between 2000 and 10,000 PE, and 13 large plants between 10,000 and 90,000 PE. The aeration devices are mainly turbines, while diffusers are applied in only 23% of cases.

Table 1. Main features of wastewater treatment plants observed.

Type of Treatment		**Presence of Sludge Treatment on Site**		**Plant Size**		**Aeration Type**	
Secondary	123	No	106	Small	85	Turbines	88
Tertiary	4	Yes	21	Medium	29	Diffusers	29
				Large	13	No Aeration	10

2.2. Input and Output Measures

Considering the 127 plants, the cost of energy was measured and used as input, while the amount of COD removed and the percentage of dry matter represented the main outputs of the wastewater and sludge treatments. Next, to estimate the energy unit cost, the data on the total amount of cubic wastewater inflows were collected for every plant. As shown in Table 2, the average size is quite small if measured in terms of kg of pollutants removed; then, the small entity of energy consumed and dry matter obtained is the effect both of size and of a not too complex treatment process, which is only rarely based on a tertiary stage and on sludge treatment.

Table 2. Descriptive statistics for input and output variables.

Input and Output Variables	**Output**		**Input**
	COD Removed	**Dry Matter**	**Energy Costs**
Mean	142,829 kg	3.9%	€35,347
Max	2,444,406 kg	36.9%	€492,139
Min	48 kg	0.0%	€367
Standard Deviation	378,829 kg	6.5%	€76,351

Notes: COD = chemical oxygen demand.

2.3. Exogenous Variables

The set of operational variables was defined considering the following issues [16]: (1) wastewater features, (2) WWTP technology, (3) other features of WWTPs, and (4) methods of sludge disposal. The following wastewater features were included: (1) wastewater from non-domestic customers, (2) per cent dilution of wastewater inflow, and (3) average concentration of COD. The WWTP technology considered in this article is the type of aeration system in the biological oxidation activity, which could be mechanical or made with diffusers. The former is based on the use of turbines, which vigorously mix wastewater, creating turbulence and allowing air to be introduced, while the latter produce bubbles which rise slowly from the floor of a tank. Both methods provide the quantity of oxygen required by microorganisms to produce the enzymes that allow the flocculation process, but they show different productivity and effectiveness; in Acque, 29 of the 127 WWTPs have a mechanical aeration process that uses turbines, 88 adopt diffusers, and 10 work without an aeration system [18].

Among the other WWTP features, three variables were observed: (1) plant capacity (PE), (2) year of building, and (3) percent of production capacity used. Finally, the method used for sludge disposal was observed, measuring the percentage of sludge disposed in agriculture.

The eight operational variables are shown in Table 3.

Table 3. Measures for exogenous variables.

Operational Variable	**Measure Adopted**
Wastewater Features	
Wastewater from Non-domestic Customers	m^3 of wastewater from non-domestic customer/total m^3 of inflow
Dilution of Wastewater Inflow	m^3 of wastewater treated/estimated m^3 of wastewater in dry weather
Average Concentration of COD	gr. of COD per m^3 of wastewater treated
WWTP Technologies	
Type of Aeration System	Turbines–Diffusers
Other Features of WWTPs	
Plant Capacity	Persons equivalent
Year of Building	Year
Percentage of Production Capacity Used	(PE of working capacity/PE potential capacity)*100
Sludge Disposal in Agriculture	(Tons of sludge disposed in agriculture/total tons of sludge produced)

Notes: COD = chemical oxygen demand; WWTP = wastewater treatment plant; PE = population equivalent.

The 127 selected plants show different characteristics for every exogenous variable observed, as shown in Table 4. The average inflows from non-domestic customers is very low (3.2%), even if few plants, operating in the area of lather manufacturers, have a relevant amount of wastewater produced by these industries (75%). Moreover, the wastewater features are different when the dilution rate and pollutant concentration are measured. The effects of permeation of storm water in the sewerage networks, especially in the older ones, increase the dilution rate, which varies from 0.16 to 68.81. This rate is obviously lower when the WWTP is served by a sewerage network that keeps the mains of wastewater separate from those used to collect storm water. In terms of COD concentration, the average value is approximately equivalent to the threshold assigned by law 152/2006 for the discharge of effluent produced by domestic customers; however, the maximum value recorded (1601 gr/m^3) is abundantly over this limit and associated with the presence of many households and industries in the area served by the WWTP.

Table 4. Different characteristics of input and output variables.

	Mean	**Max.**	**Min.**	**Standard Deviation**
Wastewater from Non-domestic Customers	3.2%	75.0%	0.0%	10.3%
Dilution of Wastewater	4.02	68.81	0.16	7.03
COD Concentration (gr/mc)	496	1601	33	338
Plant Capacity	5618	90,000	50	14,145
Year of Building	1987	2009	1962	9
Percentage of Working Capacity	95.2%	280.5%	8.8%	47.3%
Percentage of Sludge in Agriculture	4.1%	44.9%	0.0%	10.2%

Notes: COD = chemical oxygen demand.

As previously mentioned, the plant sizes are quite small, but they are completely used (the average rate of working capacity is 95.2%), while in other cases, they are overused, with a volume of wastewater treated that is more than two times plant capacity. This occurs, especially, in those areas affected by a wide process of urbanization in recent years that was not followed by a renewal of the water infrastructure, as testified by the average age of the buildings (almost 30 years old).

Finally, the quantity of sludge disposed in agriculture must have specific characteristics that allow its discharge in the natural environment, as established by Directive 86/278/CEE, applied in Italy through Law 99/1992. The parameters provided by the law refer to a maximum amount of heavy metals, carbon, nitrogen, and phosphorus contained by the sludge. The reduced amount disposed in agriculture, on average, by Acque (4.1%) could mean that the sludge does not comply with the law provisions, since only 21 of the 127 WWTPs carry out a proper sludge treatment process.

2.4. Method Adopted

There are several methods for the measurement of efficiency, based on parametric and non-parametric approaches. The former estimates a cost function by adopting a multivariate regression analysis of a specific dataset, formed by the inputs and outputs of production (i.e., cost of labour, cost of capital, and water delivered). The efficiency is measured by the distance between the observed data and maximum production represented by the frontier. This kind of model was developed in the 1970s [25] and is based on assumptions about the parameters of the population distribution from which data are drawn. On the other hand, the parametric approach includes deterministic and stochastic frontiers, depending on the assumptions regarding the disturbance terms.

Non-parametric analysis does not require the specification of any particular functional form to describe the efficient frontier. One non-parametric method is data envelopment analysis (DEA), which compares each producer with its related virtual 'best' producer, identified through a linear programming approach, which enquires whether it is possible for a real operative unit to obtain more output with the same input or to obtain the same output with less input [26]. The first version of this linear programming method was adopted to build a production frontier, in which decision-making units (DMUs) could linearly scale inputs and outputs without any variation in efficiency. However, this implies operation under the assumption that all units have an optimal scale. Therefore, this assumption of constant return to scale was removed and the efficiency score was split into a scale effect and pure technical efficiency, assuming variable return to scale [27]. Specifically, the latter measures the real capacity of a company to purchase, mix, and consume inputs, while its scale effect indicates the effectiveness of the decision to operate at a certain production scale.

The advantages of frontier methods, if compared with other techniques, such as key performance indicator analysis [28], are their high quality and objectivity, since they are based on a mathematical approach. These methods are often applied to detect the effects of environmental and contextual factors on efficiency, following a two-stage approach. As a result, the efficiency scores estimated are subjected to a second-stage regression analysis. The study of these effects can help managers to improve their decision-making processes, allowing a valuation of cost and benefits for each choice that can be made.

However, this second stage has some flows when applied with DEA, since (1) the estimated efficiency scores are biased and serially correlated, and (2) the environmental variables affect output and input [29,30]. Moreover, [30] proposed a procedure based on a double bootstrap that allows consistent inference within models, explaining efficiency scores as well as estimating standard errors and confidence intervals for them. Then, the adoption of a maximum likelihood estimation and bootstrapped resampling procedure avoids the limits of multicollinearity among efficiency scores and provides robust results.

In recent years, several papers on public services have adopted this approach (e.g., [31–33]), which is also suitable for the research purposes of the current paper, following the variable return to scale assumption. In short, if the non-parametric DEA method overcome its flaws (referring to the outlying sensitivity in the first stage and serial correlation in the second stage), it shows some interesting advantages when compared with stochastic frontier analysis or with other parametric methods, such as the lack of any hypothesis on the functional form of the frontier.

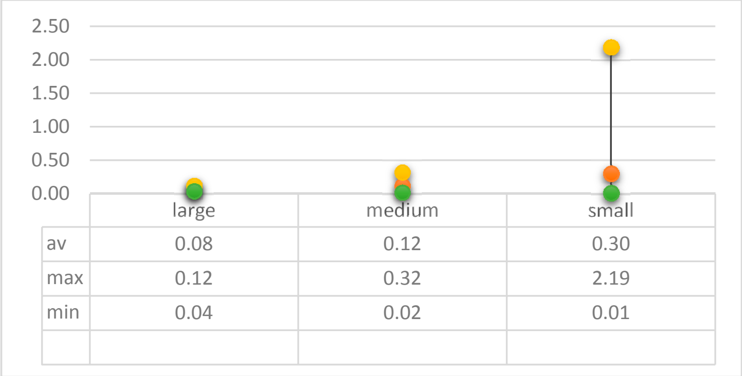
This paper adopted Algorithm 1 of [30], which improves inference, without the bias correction provided by Algorithm 2. This choice was due to the additional noise that could be created with the latter procedure [32].

First, an efficiency score was estimated solving an output orientation problem with the variable return to scale assumption. This choice is consistent with the operations of a WWTP, which should aim to improve the quality of wastewater and sludge treatment, with a higher removal rate and percentage of dry matter, keeping costs as a constraint. Variable return to scale was assumed, since the business of wastewater treatment is affected by relevant economies of scale, as demonstrated by the previous literature [34–37]. Then, the Algorithm 1 was applied with (i) the development of a truncated regression analysis, (ii) resampling procedure to generate virtual efficiency scores and re-estimation of the model, and (iii) calculation procedure of standard errors and confidence intervals from the re-estimated model.

3. Results and Discussion

The results obtained refer to the energy cost per m^3 and efficiency score estimated using the DEA approach. This double perspective of analysis allows for the identification of those WWTPs with the lowest costs and those that achieve the best overall performance, considering not only energy costs, but also the rates of pollutant removal from wastewater and of dry matter achieved in sludge treatment.

The average energy cost is 0.24 €/m^3, which is abundantly below the average values recorded in other studies for Europe and Italy, in particular, and discussed in the literature section. This cost varies for different sizes of plants, as shown by Figure 1; the average energy expenditure is 0.08 €/m^3 in plants serving more than 10,000 PE; 0.12 in medium plants; and 0.30 in those with a capacity lower than 2000 PE.



	large	medium	small
av	0.08	0.12	0.30
max	0.12	0.32	2.19
min	0.04	0.02	0.01

Figure 1. Cost of energy per m^3 of wastewater treated.

In addition, other plant features affect energy costs, such as the type of aeration and faculty to derogate to the effluent discharges rules, admitted by the environmental authority (see Table 5). The results on aeration systems confirm those of the previous research [18]. The aeration provided with diffusers is more expensive than that realized with turbines; the latter shows a cost of 0.13 €/m^3, less than half of that incurred with diffusers. Moreover, the faculty to derogate to the environmental law represents a significant driver of cost performance, since those plants who achieve it record a lower cost of energy. This evidence is explained considering that the reduced compliance with environmental law determines poor treatment, with low operating expenditure.

Table 5. Effects of two exogenous variables on energy costs.

Type of Aeration	Energy Cost
Diffusers	0.29 €/m^3
Turbines	0.13 €/m^3
No Aeration	0.08 €/m^3
Bartlett's test prob > chi^2	*0.000*
Derogation with environmental law	
No	0.26 €/m^3
Yes	0.09 €/m^3
Mann Whitney test prob > $\mid z \mid$	*0.0005*

Then, energy costs per m^3 were inferred, including several exogenous variables in a linear regression model. Table 6 shows that only the rate of used capacity and type of aeration affect costs. A more intense use of the plant capacity decreases energy costs per m^3, since with this operational condition, energy can be consumed more efficiently and the fixed component of energy costs is decreased with a large production volume. Furthermore, the lack of any kind of aeration has a positive impact on energy costs, since this activity requires the highest energy-consumption rate among those included in the treatment process.

Table 6. Estimators for energy-cost linear regression model.

127 Plants	
Energy costs	Estimators
Capacity (PE)	−0.000
Rate of used capacity	−0.247 ***
Dilution of waste water	0.000
Wastewater from industry	0.019
Year of building	0.003
Aeration	
−Turbines	−0.059
−No Aeration	−0.178 **
COD concentration	0.000
Sludge to agriculture	−0.251

Notes: PE = population equivalent; COD = chemical oxygen demand. ** $p < 0.05$; *** $p < 0.01$.

It is quite interesting to observe that energy costs are not affected by plant size; the capacity measured in terms of PE shows an estimator that is not statistically significant. This evidence contradicts that which is reported in Figure 1, and that from the previous literature [35]. The estimators could be affected by the high variance recorded for the cluster '<2000 PE' plants, which includes the highest and smallest values in terms of energy cost, 2.19 €/m^3 and 0.01 €/m^3, respectively. To avoid this potential noise, some outliers were removed from the populations, excluding those small plants that provide a sketchy wastewater treatment; however, the retrieved statistical model provides results for plants capacity that are very similar to those shown in Table 6.

Then, the energy efficiency was estimated using the DEA approach. For the 127 WWTP of Acque, an average value of 0.458 was observed, which means that the plants should increase the rate of COD removed and that of dry matter by 54.2%, along with the actual expenditure of energy consumption. If compared with those of other studies, this value is far more appropriate, even if, with a different DEA model, [18] showed a score of 0.310 for 177 Spanish plants. Considering the actual value of input and output, the observed plants show an average value of energy cost equal to 0.25 €/kg COD. This assumes that all plants are on the frontier with full efficiency, and that the cost is reduced to 0.21 €/kg COD, with a decrease of approximately €874,000 in energy expenditures (−19.5% if compared with the actual costs of the 127 WWTPs). This target value could be achieved by Acque, handling several exogenous variables, as described hereafter.

Figure 2 shows that the energy efficiency scores decrease from large to small plants, with the average values of medium and small clusters being approximately half of the 0.84 achieved by the largest WWTPs. This trend is confirmed when the percentage of plant efficiency is observed; while the WWTPs with a capacity higher than 10,000 includes 38.5% of efficient units, the medium and small WWTPs achieve a percentage of 6.9% and 3.5%, respectively. These results are confirmed by the double-bootstrap DEA model described at the end of this section.

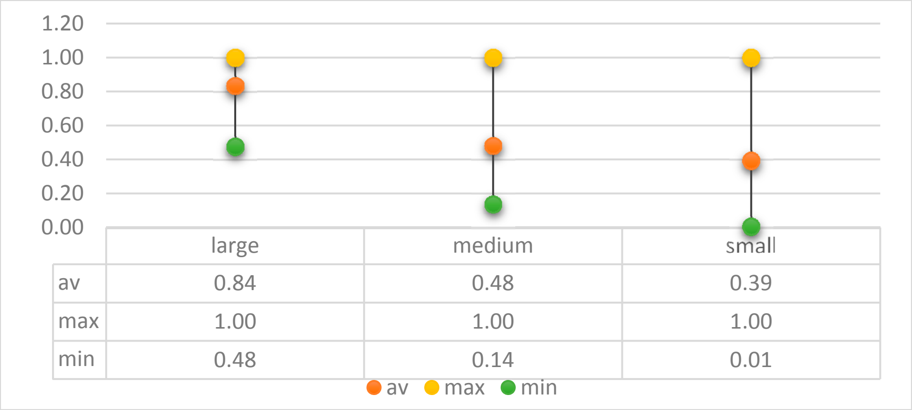


Figure 2. Energy efficiency from data envelopment analysis.

The type of aeration seems to have no effect on the efficiency score, which means that, despite turbines determining a lower cost of energy, they also generate a lower amount of output than do diffusers. Both effects have opposite influences on efficiency scores; thus, their global impact is not statistically relevant, as shown by Bartlett's test (see Table 7). This evidence will be partially contradicted by the double-bootstrap DEA procedure. The same discussion should be made for the derogation with environmental law; a WWTP with a derogation receives higher cost savings than do other plants, but it achieves a lower rate of pollutant removal. Despite the DEA score for plants "with derogation" being 0.71, higher than the 0.42 achieved by others plants, the difference is not statistically significant according to a Mann Whitney test.

Table 7. Effects of two exogenous variables on energy efficiency score.

Type of Aeration	DEA
Diffusers	0.42
Turbines	0.50
No Aeration	0.63
Bartlett's Test Prob $> chi^2$	*0.675*
Derogation with Environmental Law	DEA
No	0.42
Yes	0.71
Mann Whitney test prob $> \lvert z \rvert$	*0.0002*

The double-bootstrap DEA procedure provides some interesting results with regard to energy efficiency. Observing Table 8, several variables affect the efficiency scores, such as wastewater coming from non-domestic customers, COD concentration among wastewater features, capacity (PE), and its used rate among the features of the WWTP. Plant size exerts a favorable impact on energy efficiency, implying that the largest plant achieves the highest performance in the wastewater and sludge treatment among the population observed, with an increasing return to scale in the consumption of energy. The same effect is exerted by an increase in the rate of used capacity. Then, considering the wastewater features, the presence of factories among the customers of a WWTP damages its efficiency, through the higher consumption of energy required for the treatment of industrial wastewater. Furthermore, a high COD concentration in wastewater inflows improves efficiency, since the target rate of pollutant removal is obtained when processing less volume of wastewater and achieving energy-cost savings. Note that the COD concentration depends on the amount of rainfall that dilutes the wastewater to treat.

Table 8. Effects of exogenous variables on scores of data envelopment analysis.

127 Plants	
Double Bootstrap DEA	Estimators
Capacity (PE)	0.000 ***
Rate of Used Capacity	0.110 ***
Dilution of Wastewater	−0.000
Wastewater from Industry	−0.284 *
Year of Building	−0.001
Aeration	
−Turbines	0.006
−No Aeration	0.243
COD Concentration	0.000 ***
Sludge to Agriculture	0.159

Notes: PE = population equivalent; COD = chemical oxygen demand; DEA = data envelopment analysis. * $p < 0.10$; *** $p < 0.01$.

In order to confirm the results obtained observing the 127 WWTPs, the double-bootstrap DEA procedure was applied again to a restricted sample of plants. The 21 plants observed show similar characteristics in terms of the treatment process carried out; all of them are based on a secondary treatment with activated sludge, and are vertically integrated, since the sludge treatment is made 'on site', immediately after the wastewater treatment.

The results shown in Table 9 are similar to those of Table 8: plant capacity, its used rate, and the weight of wastewater delivered by non-domestic customers exert an influence on energy efficiency. However, different from the analysis made on the 127 WWTPs, the COD concentration is not a more relevant variable, while the aeration system becomes a driver to improve performance. The use of turbines damages performance, despite their lower consumption of energy than diffusers; this means that diffusers can better aerate wastewater, facilitating its oxidization and sludge production.

Table 9. Effects of exogenous variables on scores of data envelopment analysis for subsample of WWTPs.

21 Plants	
Double bootstrap DEA	Estimators
Capacity (PE)	0.000 ***
Used capacity rate	0.254 ***
Dilution of wastewater	0.119
Wastewater from industry	−0.809 **
Year of building	−0.009
Aeration	
−Turbines	−0.156 ***
COD concentration	−0.000
Sludge to agriculture	−0.390

Notes: PE = population equivalent; COD = chemical oxygen demand; DEA = data envelopment analysis. ** $p < 0.05$; *** $p < 0.01$.

Considering all of the results obtained with both samples (127 and 21 WWTPs), some interesting insights are found. The observed wastewater features exert opposite effects on performance. The negative effect associated with a high weight of industrial customers can be explained by considering the higher amount of energy consumed and number of technology devices adopted to treat this type of wastewater. Furthermore, high concentrations of toxic chemicals dissolved in sewage from manufacturing industries can kill bacteria; if this shock occurs, the removal rate drops down and the plant could discharge effluent into the environment. The marginal effect of industrial wastewater on energy efficiency is approximately -0.28 for the 127 plants observed, which means that a 1% increase of inflows from industry will decrease efficiency by 28%. The tariffs set by water utility authorities, as well as their differences among residential and non-residential customers, should take into account the marginal effect to comply with the 'polluters pay principle' and avoid any extra costs for households.

A low dilution of wastewater, measured by the COD concentration, facilitates the treatment process, since a plant has to process lower volumes. The extant literature is not in agreement on this issue; the result obtained is consistent with those of [22,38], which demonstrate the negative effect of rainfall on WWTP efficiency. The investments in a completely separate sewerage system would help to reduce rainwater inflows, improve COD concentration, and boost energy-efficiency savings.

Another way to boost energy efficiency is to operate on a larger scale, while also assuring a high used capacity rate. In fact, larger plants achieve higher removal and dry matter rates, since, in this case, it is economically convenient to install innovative technologies, whose costs might be allocated to a large amount of production. This result is consistent with the main results from the previous literature, demonstrating the benefits achieved with a larger-scaled plant [18,19,34,35]. Then, the benefits obtained with an increase of the used capacity rate are due to a characteristic of energy cost: it includes a percentage of fixed expenditures, so that a growth in the used capacity allows to for improved reduction in this constant cost item per m^3 of treated wastewater. Furthermore, under certain limits, a full employment of the plants could allow a better performance in terms of the removal rate. In the design phase, engineers could be oriented to oversize the plant, in order to face the risk of extra volumes, generated by tourists as well as new urban and industrial settlements; however, if an excessive oversize reduces the load factor, the design choice will be paid in terms of higher energy costs.

Finally, as previously mentioned, an air diffuser is an aeration device which is used to transfer air into wastewater, while mechanical aeration is based on low-speed turbines, direct-drive surface aerators, and brush-type surface aerators. Since oxygen is required by microorganisms/bacteria residents in the water to break down the pollutants, an aeration system must provide a higher amount of oxygen per hour of work. According to the technical literature [39], the oxygen transfer rate is 6.5 lb/h for fine bubble diffusers and only 3 lb/h for mechanical aerators; for this reason, the former technology assures the higher removal rate of pollutants, balancing its higher costs for energy. Following this evidence, (i) the complete renovation of the aeration systems represent a policy for improving energy efficiency, which should be adopted with others solutions as: (ii) the application of variable frequency drivers and more efficient pumps, (iii) operation of an aeration system pursuing a match with oxygen demands, (iv) and adoption of Sharon® and Anammox processes to transform ammonium into molecular nitrogen, which does not require high oxygen demand.

4. Conclusions

This study provides some insights on the efficiency of wastewater treatment, observing 127 WWTPs located in Italy, and measuring energy costs, pollutant removal rates, and the weight of dry matter obtained in the sludge treatment process. The study is based on a two-stage analysis in order to identify the exogenous variables exerting an influence on energy efficiency and that should be constantly monitored by plant managers. The factors studied are grouped as follows: (1) wastewater features, (2) WWTP technology, (3) other features of WWTPs, and (4) method of sludge disposal. The results obtained show that the method of sludge disposal is not related to energy efficiency; this implies that energy efficiency is not conditioned by the sludge destination. Furthermore, the same occurs for the year of building among the other features of WWTPs. This could be justified considering that the plant age refers to the tanks and not the technological devices installed; thus, an old plant with renewed technologies can achieve high performance. To better identify the effect of this variable, future research should measure the age not only of buildings, but also of devices installed.

The other variables that were observed to exert a relevant impact on efficiency are wastewater features, such as COD concentration and the weight of industrial customers; WWTP technology, such as aeration systems; and other features of WWTPs, such as plant capacity and the load factor. This paper highlights the negative effects exerted by highly polluted wastewater inflows on energy efficiency. Considering the technology devices, the benefits obtained with diffusers are shown, and they can be quantified with an increase of 15.6% of the energy efficiency score, in comparison with mechanical aeration, made with turbines. Then, the plants size and full absorption of capacity are two features that positively affect efficiency; thus, the DEA score of large plants is two times greater than that of small plants, while the same measure is improved with a growth in the load factor.

This paper provides some suggestions in terms of utility policies and regulatory provisions for promoting energy efficiency. Firms should carefully study the abovementioned drivers when designing a new plants or renewing an existing one and, at this stage, managers should promote the design of properly sized plants, avoiding any oversizing that will reduce the load factor and aiming to fully obtain the benefits of economies of scale. Then, the plant should be equipped with technical devices able to operate aeration according to the effective oxygen demands, and with energy efficient aeration systems, such as diffusers. A plant manager must be assisted by an effective monitoring system that controls the pollutant load of the wastewater inflows in order to properly set the treatment process in terms of reagents and aeration. From the point of view of regulators, water authorities should promote energy-saving practices through effective tariff models. Even if these kinds of practices are expensive, the costs could be completely covered by the savings collected during the plant's useful life, paying a lower cost for energy. However, to date, Italian water regulation has not incentivized investments for energy efficiency improvements, since all cost savings collected are wholly passed to customers with a tariff decrease. Following the results of this study, a necessary reform of the actual regulation should allow firms to hold the energy cost savings earned as profit, at least for an assigned period.

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