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Benchmarking energy efficiency in drinking water treatment plants: Quantification of potential savings

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ABSTRACT

Within the urban water cycle, energy issues have been mostly studied for wastewater treatment plants, ignoring that drinking water treatment plants (DWTPs) also consume a significant quantity of energy. Knowing the real energy consumption of DWTPs is the starting point for any energy-saving initiative. This paper benchmarks the energy efficiency measures of a sample of real DWTPs using the data envelopment analysis methodology. Subsequently, whether these facilities are affected by economies of scale is investigated. This issue is essential for planning new DWTPs that minimize energy consumption. In the second stage of analysis, some structural and managerial variables affecting energy efficiency are explored. The results showed that most of the DWTPs analysed have a suitable size but can greatly improve in terms of saving energy. It was found that the age of the plants and the water company operating them significantly affects its energy efficiency. The approach applied in this paper is of great interest for water regulators and company managers since it enables them to learn from the best practices for reducing energy consumption in DWTPs and contributes to improving the sustainability and efficiency of the urban water cycle.

1. Introduction

In recent years, interest in better understanding the energy-related needs of the urban water cycle has been growing (Vieira and Ghisi, 2016). In developed countries, the water sector is a major contributor to municipal energy use since water and wastewater treatment and transport are responsible for up to 44% of a municipality's energy costs (Santana et al., 2014). This use of energy by water utilities contributes notably to an increased carbon footprint with an estimated 290 million metric tons of carbon emissions related to water in 2011 in the United States, or 5% of all national carbon emissions (Rothahusen and Conway (2011). Energy management of the urban water cycle is important from many perspectives such as reducing air pollution and GHG emissions, improving economics, enhancing energy and water security, extending the life of the infrastructure and protecting public health and the environment (Gude, 2015).

The urban water cycle integrates two types of water treatment facilities, namely, drinking water treatment plants (DWTPs) and wastewater treatment plants (WWTPs). Both consume a significant quantity of energy (Henriques and Catarino, 2017). However, a review of the relevant literature has shown that most of the previous studies on the topics of energy use and energy efficiency have focused on WWTPs while energy issues related to DWTPs have been much less investigated. The main reason for this trend is that traditionally, the treatment for the production of drinking water has not been energy-intensive compared to the treatment of wastewater. However, with the deterioration in the quality of resources and the increasing need to remove pollutants, the energy used in DWTPs is increasing (Degremont, 2013). Previous studies (Lemos et al., 2013; Loubet et al., 2014; Gude, 2015) reported that energy consumption in DWTPs ranges between 0.08 and 1 kWh/m^3 depending on the technology used and the source of water, while a typical domestic WWTP consumes 0.6 kWh/m^3. Hence, the energy consumed by DWTPs is comparable to that used by the WWTPs in some instances, and therefore, energy issues in DWTPs need to be investigated.

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From an energy management standpoint, there needs to be a means for determining how well a DWTP is performing to identify improvement opportunities or best practices. This assessment should not just compare total energy use or energy use per unit of water but must also provide insight into how energy is used in comparison to other DWTPs, or to provide best practices (Hasanbeigi et al., 2016). In this context, benchmarking is a tool for identifying the performance and opportunities for work processes and methods by learning from the best practice (Danva, 2014). Some benchmarking methodologies, such as stochastic frontier analysis (SFA) and data envelopment analysis (DEA), allow for the estimation of the efficiency of the units evaluated (Molinos-Senante et al., 2014). While Hernández-Sancho et al. (2011) demonstrated that DEA is a robust method to benchmark efficiency for finding energy saving opportunities in WWTPs, to the best of our knowledge, there are no previous studies benchmarking energy efficiency in DWTPs.

In the context of water utilities, the existence of economies of scale sometimes represent efficiency earnings and allows for the determination of the sources of the inefficiency (Guerrini et al., 2013). In other words, sometimes the size of the water utility impacts its efficiency positively or negatively. Thus, previous studies have determined the existence of an optimal size for water utilities that depends on the particular features of the country (Marques and De Witte, 2011). In the case of water utilities, the volume of raw water treated by DWTPs is prone to economies of scale, which could affect their energy efficiency. Hence, for benchmarking the energy efficiency of DWTPs, investigation into whether they present economies of scale is needed.

The objectives of this paper are threefold. The first is to benchmark the energy efficiency of a sample of DWTPs considering not just the energy consumed and the volume of drinking water produced but also its quality. The second objective is to investigate whether the DWTPs evaluated are affected by economies of scale. This information is essential for planning future DWTPs since this analysis enables water authorities to identify the optimal size of DWTPs from an energy consumption perspective. The third objective of this paper is to explore some of the structural and managerial variables that could have an effect on energy efficiency. The purpose for obtaining this information is to develop actions aimed at improving energy efficiency in DWTPs. To illustrate the usefulness of the proposed methodological approach, an empirical analysis using data from real Chilean DWTPs was conducted. The Chilean example is very interesting because of the important reforms that have been implemented in the last twenty years. Since the privatization of the English and Welsh water industry, Chile has become the most successful case of water services privatization (Molinos-Senante et al., 2016a).

This paper contributes to the current literature in the field of water-energy nexus by computing for the first time the energy efficiency of a sample of DWTPs using a robust and reliable methodology that allows for the integration of the quality of the drinking water produced in the assessment. Moreover, no studies were identified that investigate the optimal size of DWTPs from an energetic standpoint. From a managerial point of view, this paper also provides important insights since it identifies some factors affecting the energy efficiency of DWTPs.

2. Methodology

Our analysis is divided into four main steps as it is illustrated on Fig. 1 which shows the methodological approach to addressing the specific objectives of this study:

2.1. Energy efficiency assessment

To evaluate the technical efficiency of decision making units (DMUs) following the production frontier approach, there are two main methods, namely, the parametric and non-parametric methods. Among the parametric methods, SFA is the most widely applied technique. It constructs the production frontier derived from the best practice DMUs and then compares the actual output results from the DMUs to the best practice DMUs (Abbott and Cohen, 2009). The main advantage of SFA over the non-parametric approach is that takes into account the statistical noise. However, the drawback of SFA is that it requires the definition of the functional form of the frontier (Lannier and Porcher, 2014). Conversely, DEA is a non-parametric method that estimates technical efficiency by measuring the ratio of inputs used to outputs produced for each DMU (Lin and Zhao, 2016). Then, this ratio is compared to others in the sample group to derive an estimate of relative efficiency, i.e., to benchmark the DMUs of the sample (Molinos-Senante et al., 2015). The two main positive features of DEA in the framework of the water industry efficiency assessment are as follows: (i) it can be used without input or output prices and (ii) it requires no assumptions regarding the functional relationship between inputs and outputs (Guerrini et al., 2013). Nevertheless, because DEA is a deterministic approach, it cannot account for outliers or atypical observations. In the framework of water facilities, i.e., WWTPs and DWPTs, the functional form of the production frontier is unknown (Lorenzo-Toja et al., 2016). Hence, previous studies assessing the efficiency of WWTPs (there are no previous studies assessing the efficiency of DWTPs) have applied the DEA approach (e.g., Hernández-Sancho et al., 2011; Sala-Garrido et al., 2012; Molinos-Senante et al., 2016b). Accordingly, the DEA method was used in this study to estimate the energy efficiency of DWTPs.

Given that DEA employs the production frontier approach to estimate the efficiency of the DMUs (DWTPs in this study), the first step is defining the input distance function. Let us assume that DWTPs use an input vector $x\in\Re_{+}^{M}$ to produce an output vector $y\in\Re_{+}^{L}$, while the production technology is defined as capable of transforming inputs into outputs. The production possibility set of outputs that can be produced from a given level of inputs is as follows:

$$P(x) = \left\{(x,y)\in\Re_{+}^{M+L}; x \ \ can \ \ produce \ \ y\right\} \tag{1}$$

The input-oriented distance function is defined as:

$$D(x,y) = min_{\theta}\{\theta > 0 : x\theta \in P(x)\} \tag{2}$$

The input distance function indicates the maximum reduction of inputs (energy consumption) that a DMU (DWTP) can obtain and still produce the same output vector (drinking water with the same quality) (Morales and Heaney, 2016). The input-oriented distance function is interpreted as follows: if $D(x,y)>1$, then the input vector, x, belongs to the interior of $P(x)$, and therefore, the DMU is inefficient since it can reduce the use of inputs to generate the same output vector. By contrast, if $D(x,y)=1$, then x is located on the production frontier and the DMU is efficient.

To analyse the economies of scale in the use of energy by DWTPs, a framework that examines the direction of the returns to scale is suggested (Marques and De Witte, 2011). The production technology can be computed assuming constant returns to scale (CRS) or variable returns to scale (VRS) technologies. On the one hand, inefficiency under CRS technology is the product of scale inefficiency and pure technical inefficiency since the CRS approach assumes that all DMUs operate at an optimum level (Charnes et al.,