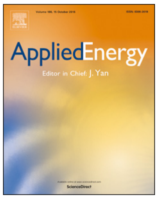
Applied Energy 229 (2018) 1095–1102

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy



Evaluation of energy performance of drinking water treatment plants: Use of energy intensity and energy efficiency metrics

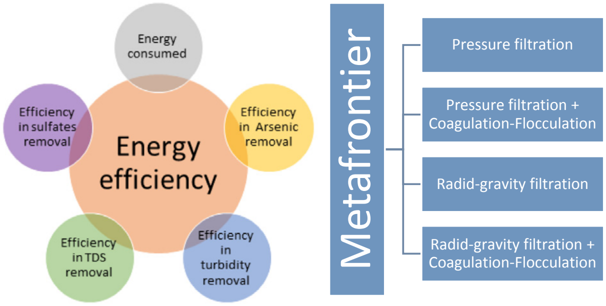
María Molinos-Senante[a,b,*], Ramón Sala-Garrido[c]

[a] Departamento de Ingeniería Hidráulica y Ambiental, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Santiago, Chile
[b] Centro de Desarrollo Urbano Sustentable CONICYT/FONDAP/15110020, Av. Vicuña Mackenna 4860, Santiago, Chile
[c] Departamento de Economía para la Empresa, Universitat de Valencia, Avda. Tarongers S/N, Valencia, Spain

HIGHLIGHTS

- Energy efficiency metric is proposed to evaluate energy performance of drinking water treatment plants.
- Energy efficiency integrates in a synthetic index the energy consumed, the volume of water treated and its quality.
- Energy efficiency of four technologies for treating water is compared.
- Energy intensity and energy efficiency estimates lead to opposite results.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Energy intensity
Energy efficiency
Drinking water treatment
Performance
Data envelopment analysis
Metafrontier

ABSTRACT

One of the United Nations Sustainable Development Goals is to provide access to safe and clean drinking water. However, treating raw water in facilities currently involves using a non-negligible amount of energy, and the fossil fuels used are both expensive and emit greenhouse gases when combusted. Previous studies have evaluated the energy performance of drinking water treatment plants by estimating the amount of energy consumed per volume of water. However, such studies have not accounted for differences between treatment technologies and have assumed a common standard water treatment technology. To overcome these limitations, this study employed metafrontier data envelopment analysis to evaluate and compare the energy performance of four types of treatment technologies. This approach integrates energy intensity with pollutant removal efficiency into a single, synthetic index to deliver an energy-efficiency score. A comparison of the four treatment technologies showed that facilities using rapid-gravity filtration and coagulation-flocculation processes provided the highest energy efficiencies. However, energy intensity and energy efficiency metrics delivered contradictory results, which thus illustrates the importance of including pollutant removal efficiency data in performance assessments. This study provides valuable information for policy-makers when planning and developing new drinking water treatment plants and for water utility managers when identifying energy reduction opportunities in plants.

---

[*] Corresponding author at: Departamento de Ingeniería Hidráulica y Ambiental, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Santiago, Chile.

E-mail address: mmolinos@uc.cl (M. Molinos-Senante).

https://doi.org/10.1016/j.apenergy.2018.08.102
Received 11 June 2018; Received in revised form 3 August 2018; Accepted 17 August 2018

Acronym list

CF	Coagulation-flocculation
CRS	Constant returns-to scale
DEA	Data Envelopment Analysis
DMUs	Decision making units
DWTPs	Drinking water treatment plants
PF	Pressure filtering
QAOs	Quality-adjusted outputs
RGF	Rapid-gravity filtering
TGR	Technological gap ratio
VRS	Variable returns-to scale

1. Introduction

Urban water supply utility plants use energy to extract, convey, treat, and distribute drinking water, and this produces a considerable amount of greenhouse gas emissions. In addition, energy costs currently account for up to 40% of the operating budget of a utility plant, and this percentage is expected to rise as water supplies become increasingly scarce and stricter water quality standards are imposed [1]. Chen et al. [2] reported that approximately 7% of the energy produced worldwide is currently used to enable the anthropogenic water cycle, which includes providing a drinking water supply and treating wastewater.

Dai et al. [3] conducted a literature review and determined an increase in the number of scientific and policy-related studies focusing on the topic of water-energy nexus. It is clear that future efforts will be required to adapt water systems to meeting the increasing demand for water, in addition to ensuring conformity with associated regulatory requirements and mitigating the effects of climate change, and such adaptations will impose additional economic, environmental, and social challenges to water utility companies. In this context, Parkinson et al. [4] proposed a multicriteria model to integrate several objectives when planning energy and water supply infrastructure.

One of the 17 Sustainable Development Goals adopted by the United Nations in 2015 (Goal 6) is to achieve universal and equitable access to safe and affordable drinking water for all by 2030 [5]. However, according to WHO-UNICEF [6], 844 million people still lack basic drinking water services, and 159 million people still collect drinking water directly from surface water resources. It will thus be necessary to construct many more water treatment facilities in the near future to achieve Goal 6, which will unquestionably increase the amount of energy required for drinking water supplies worldwide, and thus also increase greenhouse gas emissions.

Given the economic and environmental significance of using energy for treating and distributing water, a number of studies have focused on the amount of energy used by urban water systems in supplying drinking water to major cities. In this respect, the study of Gude et al. [7] focused on the benefits of reducing energy use in water and wastewater treatment systems, and reported a range of energy intensity values for water supply systems. In addition, a review by Sowby and Burian [8] focused on the energy requirements for supplying water to 109 cities in the United States. The study of Lee et al. [9] evaluated 25 urban water supply systems in 12 countries, in addition to estimating the energy intensities of urban water systems and their greenhouse gas emissions, and the study of Wakeel et al. [10] also focused on the same topic but evaluated the energy intensity of the urban water cycle at state and/or regional levels. These studies, therefore, focused on estimating the energy intensity of water supplies.

However, to supply reliable and high-quality drinking water, it is necessary to firstly treat raw water in drinking water treatment plants (DWTPs), and this process requires most of the energy used in the water supply chain. In this respect, energy studies relating to DWTPs have also been conducted. For example, Miller et al. [11] compared the energy intensities of several water treatment facilities located in India and the United States. As a previous step to conducting a life cycle assessment, Loubet et al. [12] reported notable differences in the energy usage between a sample of DWTPs. Recently, Lam et al. [13] compared the energy intensity involved in treating raw water in 17 cities, and analyzed influential factors such as climate, topography, water use patterns, and operational efficiencies.

These studies have compared energy use among DWTPs using "energy intensity" as an overarching metric to describe the energy required by a DWPT to treat water, where energy intensity is defined as the energy consumed (kWh) per unit volume (m^3) of drinking water processed (expressed in kWh/m^3) [9]. However, as the amount of energy consumed in processing (treating) water is determined not only by the specific treatment processes applied, but also by the quality of the raw water to be processed [14,15], using the energy intensity metric alone is inadequate when comparing the performances of DWTPs [8]. In other words, energy intensity does not reflect the quality of the raw water being processed, and raw water that has a poorer quality requires more energy per unit volume to meet mandated drinking water quality standards than raw water of a superior quality. Therefore, a broader concept than energy intensity is required: a concept that integrates pollutant removal efficiency rates with the energy required to process the water. We therefore propose the use of "energy efficiency" as a metric for comparing energy performances of DWTPs, which is defined as a synthetic index that incorporates both the quality of the raw water being processed and the energy required to treat it.

Prior studies estimating the energy efficiency of wastewater treatment plants [16–18] have consistently shown that the energy efficiency approach is reliable for benchmarking the energy performance and identifying potential energy-saving opportunities. However, only the study of Molinos-Senante and Guzmán [19] benchmarked energy performances to estimate energy efficiencies of DWTPs (n = 42 plants compared). This was achieved this by computing energy efficiency scores for each facility using a data envelopment analysis (DEA) method. DEA is a well-known, robust, reliable and widely applied method used to estimate efficiency scores for various types of decision-making units (DMUs) [20], and is a mathematical programming technique that allows users to build an efficient production frontier based on inputs (e.g. energy) and outputs (e.g. treated water) for DMUs (e.g. DWTPs) [21]. The recent study conducted by Molinos-Senante and Guzmán [19] is very useful for providing a real-world example of how the performances of DWTPs can be compared relative to their energy efficiencies. However, in their examples, the authors assumed that all treatment technologies used by DWTPs have equally efficient potentials. By ignoring variations in these potential efficiencies between treatment technologies, they also assumed that the type of treatment technology employed would not affect the energy efficiency, and thus, assumed that all DWTPs have the same efficiency production frontier [22]. As treatment technologies differ in their intensity of energy use, this implies that both their assumption and their direct cross-comparison of energy efficiencies across DWTPs are inappropriate.

To appropriately compare energy efficiencies among DWTPs that use different treatment technologies, we applied the metafrontier concept proposed by Hayami (1961). This approach has been used previously to evaluate and compare efficiencies of water utilities in various countries [22,23], among concessionary and private water companies [24] and as a component used in other assessments of urban water systems. The metafrontier approach subsumes all possible efficiency frontiers that may arise due to the technological heterogeneity of DWTPs; therefore, it enables the energy efficiencies of all DWTPs to be simultaneously benchmarked, even when they employ different raw water treatment technologies.

This study has two objectives and an ultimate aim of gaining an