



Understanding water-energy nexus in drinking water provision: An eco-efficiency assessment of water companies

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ABSTRACT

Understanding water-energy nexus in the provision of drinking water services is a challenge which has outstanding relevance in the current climatic emergency. Environmental efficiency and eco-efficiency assessment of water companies are two useful tools to address this challenge. In this study, we estimated hyperbolic and enhanced hyperbolic distance functions to compute the potential reduction in greenhouse gas (GHG) emissions and energy costs in the provision of drinking water. The empirical application focused on the English and Welsh water companies over 2011-2019. Average environmental efficiency and eco-efficiency scores were 0.920 and 0.962, respectively which indicates that water companies performed well but there is room for improvement. Moreover, due to the economies of scale, the cost of reducing GHG emissions was higher for water and sewerage companies than for water only companies. The results and conclusions of this study allow better understanding of the relationship between the provision of drinking water, energy costs and GHG emissions.

1. Introduction

There has been growing interest from policy makers and researchers to understand the relationship between water and energy, i.e., water-energy nexus, as they are two primary sources for life, environment and economy (Emrouznejad and Yang, 2016). The energy used by the water companies, in many cases, is derived from traditional fossil fuel sources and therefore, involves indirect greenhouse gas (GHG) emissions. Moreover, water utilities produce a significant amount of direct GHG emissions (Ananda and Hampf, 2015; Saidan et al., 2019). Wakeel et al. (2018), Chen et al. (2018) and Liao et al. (2020) showed that energy demand will increase in the urban water cycle at country and city level due to climate change and population growth. These previous studies focused on assessing the “energy intensity” of water utilities which is defined as the level of energy required per unit of drinking water supplied (kWh/m³). Therefore, they did not consider either the cost of abstracting, treating and distributing water or the GHG emissions produced in these activities. By contrast, the concept of “efficiency” is a broader metric which integrates additional variables to energy use and water supplied. It is a synthetic index that integrates multiple inputs and

outputs (Molinos-Senante and Sala-Garrido, 2018). In this context, Ananda (2019) evidenced that operational and maintenance costs and operational characteristics had a significant role in water companies’ GHG emissions levels and efficiency.

Understanding, energy costs and GHG performance in the urban water cycle would be of great importance to policy makers to provide water services in a sustainable manner. This can be done by evaluating the economic and environmental efficiency, i.e., eco-efficiency, of water companies. To improve eco-efficiency, water companies should reduce costs and GHG emissions in the provision of drinking water services (Ananda, 2018; Mocholi-Arce et al., 2021). This issue is even more relevant for the English and Welsh water companies because the United Kingdom Government is committed that the water industry should cut down its GHG emissions by 80% by 2050 (Parliament of the UK, 2008). For this reason, the English and Welsh water companies monitor and report their GHG emissions according to the United Kingdom Government Environmental Reporting Guidelines (HM Government, 2019). GHG emissions are categorized in four groups: i) scope 1 which are direct emissions; ii) scope 2 which correspond to indirect emissions; iii) regulated scope 3 (indirect emissions accounted) and iv) non-regulated

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scope 3 (indirect emissions not regulated) (Ofwat, 2010a).

Given the relevance of better understanding of the water-energy nexus, there were several studies in the past devoted to assessing eco-efficiency of water companies and their facilities, i.e., wastewater treatment plants (WWTPs) and drinking water treatment plants (DWTPs). In doing so, the most widely methodological approach employed is Data Envelopment Analysis (DEA) which compares each company's performance relative to the best industry's frontier (Ananda, 2019; Mocholi-Arce et al., 2020; 2021; Sala-Garrido et al., 2021a; 2021b). This method has also been applied to estimate eco-efficiency of WWTPs (Dong et al., 2017; Gómez et al., 2018; Ramirez-Melgarejo et al., 2021). However, the main limitation of DEA is its deterministic nature which means that any deviations from the efficient frontier are due to inefficiency only. Thus, it does not take into account the measurement of error. Moreover, being non-parametric (linear programming) it does not assume a functional form for the underlying technology so the statistical significance of parameters cannot be evaluated. To overcome this limitation, Cuesta and Zofio (2005) and Cuesta et al. (2009) proposed a hyperbolic distance function for the underlying technology which is both parametric and stochastic. In particular, the authors measured environmental efficiency by estimating a translog hyperbolic distance function using Stochastic Frontier Analysis (SFA) techniques. This is an econometric technique that allows us to take into account both noise and inefficiency in performance assessment (Lv et al., 2021). In other words, the authors developed an alternative approach to DEA and SFA which is both parametric and stochastic overcoming the limitations of both methods. This approach has been used in assessing GHG performance in the energy sector at regional and country level (see for instance, Cuesta et al., 2009; Zhang et al., 2015; Duman and Kasman, 2018). However, to the best of our knowledge, it has not been used to study the water-energy-GHG nexus in the water industry. Our study aims to fill this gap in literature.

The objective of this study is to assess the environmental efficiency and eco-efficiency of water companies using advanced techniques which provide reliable and robust estimations avoiding biased results. Moreover, the estimation of both hyperbolic and enhanced hyperbolic distance functions allows us to discuss interesting technological characteristics of the water industry which could have affected environmental performance and eco-efficiency. These included economies of scale, substitutability between inputs and the opportunity cost of reducing GHG emissions. Taking into account the goal of the English and Welsh water industry of reducing GHG emissions by 80% by 2050 (Parliament of the UK, 2008), environmental efficiency refers to simultaneously minimize GHG emissions and maximize the volume of drinking water delivered with the current economic costs, whereas eco-efficiency involves the reduction of GHG emissions and energy and other costs and expanding drinking water delivered at the same time. Both indexes could be part of a more holistic sustainability assessment of water companies since they are SMART (e.g., specific, measurable, achievable, relevant and time bound) which is a basic requirement about the quality of an indicator (Chambers et al., 2022).

We contribute to the existing trend of literature in the following ways. First, the environmental efficiency and eco-efficiency of water companies, embracing direct and indirect GHG emissions has not been estimated before using parametric and stochastic methods. Second, we used, for the first time, hyperbolic and enhanced hyperbolic distance functions to evaluate the performance of water companies which allows analyzing the substitutability between inputs and estimating the opportunity cost of reducing GHG emissions. The empirical application focused on the English and Welsh water industry because it is one of the few industries where data on GHG emissions at water company level is available. Hence, the findings of this study can help researchers and policy makers to get a better understanding on the water-energy-GHG emissions nexus in the provision of drinking water services.

2. Materials and methods

2.1. Methodology

To assess environmental efficiency, the hyperbolic distance function was used where water companies simultaneously expand desirable outputs (water delivered) and contract undesirable outputs (GHG emissions) for a given level of inputs (costs). To integrate inputs (costs) in the assessment, i.e., to evaluate eco-efficiency, an enhanced hyperbolic distance function was employed where companies reduce GHG, energy and other costs and expand drinking water delivered at the same time (Adenuga et al., 2020). Hyperbolic and enhanced hyperbolic distance functions were estimated using SFA techniques which allows us to distinguish between noise and inefficiency.

The hyperbolic distance functions were introduced by Fare et al. (1985; 1989) and further developed by Cuesta and Zofio (2005) and Cuesta et al. (2009). These distance functions allow for the simultaneous proportional expansion of desirable outputs and contraction of undesirable outputs and inputs. We first describe how we used these distance functions to represent the production technology and then, the techniques to estimate the underlying technology. We assumed that there are j total water companies in our study that use a set of inputs m to generate a set of r desirable outputs and a set of undesirable outputs. The production technology T is defined as follows:

$$T = \{ (x, y_g, y_b) \in K_+^{M+S+P} \mid x \text{ can produce } y_g \text{ and } y_b \} \quad (1)$$

where $x \equiv (x_1, \dots, x_M) \in K_+^M$, $y_g \equiv (y_{g1}, \dots, y_{gR}) \in K_+^R$, $y_b \equiv (y_{b1}, \dots, y_{bS}) \in K_+^S$ denote the vector of total inputs, desirable and undesirable outputs, respectively that belong to the input set K which shows the different combinations of inputs used for a given level of desirable and undesirable outputs.

The production technology can be represented by the hyperbolic distance function which measures the proportion by which desirable outputs can be expanded and undesirable outputs can be contracted at the same time for a given level of inputs. The hyperbolic distance function is defined as follows:

$$D_H(x, y_g, y_b) = \inf \{ \omega > 0 : (x, y_g / \omega, y_b \omega) \} \in T \quad (2)$$

where ω denotes the scalar, the proportion by which desirable outputs need to be expanded and undesirable outputs to be reduced at the same time. The hyperbolic distance function fulfils the properties of homogeneity, non-decreasing in desirable outputs and non-increasing in undesirable outputs and inputs (Cuesta et al., 2009).

An alternative representation of the production technology is with the use of an enhanced hyperbolic distance function in which inputs and undesirable outputs are contracted and desirable outputs are expanded at the same time. The enhanced hyperbolic distance function is defined as follows:

$$D_{EH}(x, y_g, y_b) = \inf \{ \theta > 0 : (x\theta, y_g / \theta, y_b\theta) \} \in T \quad (3)$$

where θ is the scalar, the proportion by which inputs and undesirable outputs are contracted and desirable outputs are expanded at the same time. The enhanced hyperbolic distance function also fulfils the properties of homogeneity, non-decreasing in desirable outputs and non-increasing in undesirable outputs and inputs (Pham and Zelenyuk, 2018).

The estimation of the hyperbolic and enhanced hyperbolic distance functions using parametric (econometric) techniques requires the specification of a functional form for the underlying production technology. We used a translog specification because it allows for estimating changes in economies of scale over time. It is also flexible, easy to estimate, appropriate for the imposition of homogeneity and widely applied in the literature of efficiency analysis (Morrison-Paul et al., 2000; Saal et al., 2007; Molinos-Senante et al., 2017). After imposing the

homogeneity assumption in desirable outputs and symmetry conditions, the translog hyperbolic output distance takes the following form:

$$\ln(D_H/y_{gRjt}) = a_j + \sum_{m=1}^M a_m \ln x_{mjt} + \sum_{r=1}^{R-1} \beta_r \ln y_{grjt}^* + \frac{1}{2} \sum_{s=1}^{S-1} \beta_s \ln y_{bsjt}^* + \frac{1}{2} \sum_{m=1}^M \sum_{l=1}^M a_{lm} \ln x_{ljt} \ln x_{mjt} + \frac{1}{2} \sum_{r=1}^{R-1} \sum_{p=1}^{R-1} \beta_{rp} \ln y_{grjt}^* \ln y_{gpjt}^* + \frac{1}{2} \sum_{q=1}^{S-1} \sum_{s=1}^{S-1} \beta_{qs} \ln y_{bqjt}^* \ln y_{bsjt}^* + \sum_{m=1}^M \sum_{r=1}^{R-1} \gamma_{mr} \ln x_{mjt} \ln y_{grjt}^* + \sum_{m=1}^M \sum_{s=1}^{S-1} \gamma_{ms} \ln x_{mjt} \ln y_{bsjt}^* + \sum_{m=1}^M \delta_m \ln x_{mjt} t + \sum_{r=1}^{R-1} \mu_r \ln y_{grjt}^* t + \sum_{s=1}^{S-1} \mu_s \ln y_{bsjt}^* t + \pi_1 t + \frac{1}{2} \pi_2 t^2 + \sum_{z=1}^Z \eta_z z_{jt} + \varepsilon_{jt} - u_{jt} \quad (4)$$

where $y_{grjt}^* = y_{grjt}/y_{gRjt}$, $y_{bsjt}^* = y_{bsjt}/y_{gRjt}$ and R^{th} is the desirable output for normalizing purposes as part of the homogeneity condition (Cuesta et al., 2009). In Eq. (4), j denotes water company, t is time, ε_{jt} is the standard error term that follows the normal distribution. The term u_{jt} is the technical inefficiency of each water company j at any time t and follows the half-normal distribution. Moreover, the term z_{jt} denotes the set of operational characteristics that might impact water companies' efficiency and are related to source of raw water, treatment complexity and population density (Sala-Garrido et al., 2021b). The intercept a_j captures unobserved water company heterogeneity which is fixed, time invariant and separated from inefficiency. This is based on the true fixed effects model proposed by Greene (2005) and is estimated using maximum likelihood estimation techniques (Saal et al., 2007; Molinos-Senante et al., 2017; 2018).

The environmental efficiency of any water company j at any time t is calculated as follows:

$$EE_{jt} = \exp\left(\ln D_{Hjt}(x_{mjt}, y_{grjt}^*, y_{bsjt}^*)\right) = \exp(-u_{jt}) \quad (5)$$

In analogous manner, the translog enhanced hyperbolic output distance function is defined as follows:

$$\ln(D_{EH}/y_{gRjt}) = a_j + \sum_{m=1}^M a_m \ln x_{mjt} + \sum_{r=1}^{R-1} \beta_r \ln y_{grjt}^* + \sum_{s=1}^{S-1} \beta_s \ln y_{bsjt}^* + \frac{1}{2} \sum_{l=1}^M \sum_{m=1}^M a_{lm} \ln x_{ljt} \ln x_{mjt} + \frac{1}{2} \sum_{r=1}^{R-1} \sum_{p=1}^{R-1} \beta_{rp} \ln y_{grjt}^* \ln y_{gpjt}^* + \frac{1}{2} \sum_{q=1}^{S-1} \sum_{s=1}^{S-1} \beta_{qs} \ln y_{bqjt}^* \ln y_{bsjt}^* + \sum_{m=1}^M \sum_{r=1}^{R-1} \gamma_{mr} \ln x_{mjt} \ln y_{grjt}^* + \sum_{m=1}^M \sum_{s=1}^{S-1} \gamma_{ms} \ln x_{mjt} \ln y_{bsjt}^* + \sum_{m=1}^M \delta_m \ln x_{mjt} t + \sum_{r=1}^{R-1} \mu_r \ln y_{grjt}^* t + \sum_{s=1}^{S-1} \mu_s \ln y_{bsjt}^* t + \pi_1 t + \frac{1}{2} \pi_2 t^2 + \sum_{z=1}^Z \eta_z z_{jt} + \varepsilon_{jt} - u_{jt} \quad (6)$$

where $x_{mjt}^* = x_{mjt}/y_{gRjt}$ and R^{th} is the desirable output which is used for normalizing purposes based on the homogeneity condition (Cuesta et al., 2009). Like Eq. (4), the enhanced hyperbolic model includes operational characteristics that might influence water companies' efficiency and firm-specific fixed unobserved heterogeneity.

The eco-efficiency of any water company j at any time t from the enhanced hyperbolic model is calculated as follows:

$$TE_{jt} = \exp\left(\ln D_{EHjt}(x_{mjt}^*, y_{grjt}^*, y_{bsjt}^*)\right) = \exp(-u_{jt}) \quad (7)$$

The estimated parameters of the distance functions in Eqs. (4) and (6) allowed us to measure several characteristics of the underlying technology. These include the following: i) the elasticity of desirable output regarding inputs; ii) the degree of substitutability or

complementarity among inputs and; iii) the rate of transformation between desirable and undesirable outputs (Grosskopf et al., 1995; Morrison-Paul et al., 2000). In particular, the elasticities for each input m for the hyperbolic and enhanced hyperbolic distance functions can be derived as follows, respectively:

$$\varepsilon_{y_g, x_m}^H = \partial \ln y_g / \partial \ln x_m = a_m + \sum_{m=1}^M a_{lm} \ln x_{ljt} + \sum_{s=1}^S \gamma_{ms} \ln y_{bsjt}^* + \sum_{m=1}^M \delta_m t \quad (8)$$

$$\varepsilon_{y_g, x_m}^{EH} = \partial \ln y_g / \partial \ln x_m^* = a_m + \sum_{m=1}^M a_{lm} \ln x_{ljt}^* + \sum_{s=1}^S \gamma_{ms} \ln y_{bsjt}^* + \sum_{m=1}^M \delta_m t \quad (9)$$

The elasticity of the output distance with respect to an input m shows the percentage increase in the desirable output when there is an increase in input m . We note that the negative of the sum of the input elasticities gives a measure of scale elasticity (Cuesta and Zofio, 2005). If scale elasticity takes a value greater than 1, then increasing returns to scale prevail. This means that on average costs increase less than an expansion in outputs. If scale elasticity is lower than 1, then decreasing economies of scale exist. If scale elasticity is equal to one, then constant returns to scale are present.

In Eqs. (8) and (9) input elasticities have a second order term between inputs, a_{lm} , which indicates if inputs are substitutes or complements (Morrison-Paul et al., 2000). For instance, in the case of the hyperbolic distance function, let's denote $A_{lm} = a_{lm} \ln x_{ljt}$. Then, if A_{lm} is negative (positive) the contribution of x_l to production expands (contracts) when x_m increases, suggesting that both inputs are complements (substitutes) (Cuesta et al., 2009).

The rate of transformation between desirable outputs and undesirable outputs for each distance function can be derived from the output elasticities. The undesirable output elasticity for each distance function are derived as follows:

$$\varepsilon_{y_g, y_b}^H = \partial \ln y_g / \partial \ln y_b^* = \beta_s + \sum_{q=1}^{S-1} \beta_{qs} \ln y_{bqjt}^* + \sum_{m=1}^M \gamma_{ms} \ln x_{mjt} + \sum_{s=1}^{S-1} \mu_s t \quad (10)$$

$$\varepsilon_{y_g, y_b}^{EH} = \partial \ln y_g / \partial \ln y_b^* = \beta_s + \sum_{q=1}^{S-1} \beta_{qs} \ln y_{bqjt}^* + \sum_{m=1}^M \gamma_{ms} \ln x_{mjt}^* + \sum_{s=1}^{S-1} \mu_s t \quad (11)$$

The desirable output elasticity for each distance function is derived through the homogeneity condition as follows (Cuesta et al., 2009):

$$\varepsilon_{y_g}^H = 1 + \varepsilon_{y_g, y_b}^H \quad (12)$$

$$\varepsilon_{y_g}^{EH} = 1 + \varepsilon_{y_g, y_b}^{EH} \quad (13)$$

The ratio of these output elasticities give a degree of substitutability between desirable and undesirable output which is denoted as follows:

$$Subs_{y_g, y_b}^H = \frac{\varepsilon_{y_g}^H}{\varepsilon_{y_g, y_b}^H} \quad (14)$$

$$Subs_{y_g, y_b}^{EH} = \frac{\epsilon_{y_g}^{EH}}{\epsilon_{y_b}^{EH}} \quad (15)$$

If negative values of $Subs_{y_g, y_b}$ are greater than unity, then it means that the opportunity cost of desirable output in terms of undesirable output is high. This suggests that the cost of reducing undesirable output is high. Moreover, there is a high degree of complementarity between these outputs which suggests that in order to reduce the undesirable output requires a reduction in the production of desirable output (Cuesta et al., 2009).

In spite of the positive features of the methodological approach applied to compute environmental efficiency and eco-efficiency scores, it has two potential shortfalls. First, it provides a static performance assessment since efficiency scores are estimated for a given time, i.e., year. This is not an issue if we are generally interested in comparing the efficiency among water companies. However, we could evaluate GHG productivity change by conducting dynamic efficiency analysis. Second, it does not distinguish between persistent and transient efficiency. The distinction between persistent and transient efficiency is of great interest from a policy point of view because they have different policy implications (Minviel and Sipiläinen, 2021).

2.2. Case study

Our empirical study focuses on the water services that are provided by several water utilities in England and Wales over the 2011-2019 period. Water and Sewerage companies (WaSCs) and Water only companies (WoCs) are the two types of companies that were formed after the privatization of the water industry in 1989. WaSCs provide water and sanitation services whereas WoCs only provide water services, i.e., both types of water companies provide water services. According to the Net Zero 2030 Roadmap (Water UK, 2022), English and Welsh water companies monitor and report GHG emissions separately for water and sanitation services. Considering the objectives of this study, environmental efficiency and eco-efficiency scores in the provision of water services for both WaSCs and WoCs were computed. The Water Services Regulation Authority (Ofwat) monitors the economic and environmental performance of the water companies by approving their business plans every five years. In these business plans the allowed tariffs that the companies would recover in the future is determined (price reviews). More information about the regulation model applied is provided by Ofwat (2022a).

Inputs, desirable outputs and undesirable outputs were selected based on data availability and studies that evaluated companies' performance in water industry (e.g., Berg and Marques, 2011; Pinto et al., 2017; Cetrulo et al., 2019; Walker et al., 2019; Goh and See, 2021). The first input was the energy expenditure (cost) of water services measured in millions of pounds every year. The second input was the other expenditure (cost) which is defined as the difference between operating expenditure and energy expenditure. Other expenditure was also expressed in millions of pounds every year. The desirable output was defined as the volume of drinking water delivered measured in cubic metres per year. The undesirable output was defined as the GHG emissions from the provision of drinking water which is expressed in tonnes of CO₂ equivalent (CO_{2eq}) per year (Molinos-Senante et al., 2015; Ananda and Hampf, 2015; Molinos-Senante and Guzman, 2018; Sala-Garrido et al., 2021a). GHG emissions are associated with companies' activities to abstract, treat and supply water to its customers (Ofwat, 2010a; 2010b) and were measured based on the United Kingdom Government Environmental Reporting Guidelines (HM Government, 2019).

According to Ofwat (2010a), GHG emissions are categorized in four groups: i) scope 1; ii) scope 2; iii) regulated scope 3 and iv) non-regulated scope 3. Scope 1 involves emissions from transport owned or leased, emissions from the companies' own fossil fuel use and methane and nitrous oxide from sewage treatment. Scope 2 involves grid

electricity used for pumping and treatment of water and sewage and grid electricity used in owned buildings. Regulated scope 3 involves emissions from contractors and outsource services and business associated transport, on public transport or in private vehicles. Finally, nonregulated scope 3 involves chemical manufacture, embedded emissions –from construction and manufacturing activity, customers' energy use to heat water and release of methane and nitrous oxide from sludge disposed to landfill and agriculture (Ofwat, 2010a). Thus, our study involves scope 1, scope 2, and regulated scope 3 emissions related to water services and does not include scope 3 emissions that are not regulated by Ofwat and GHG emissions associated to sanitation (wastewater collection and treatment) activities. The adoption of renewable energy by water companies in England and Wales is heterogeneous which means that the contribution of scope 2 emissions to the total GHG emissions of water companies varies (Environment Agency, 2009) and therefore GHG emissions and energy costs are not related variables for English and Welsh water companies.

The selection of operational characteristics was also based on data availability and past research on this topic (Ofwat, 2019; Dinverno et al., 2021). In particular, we included several operational characteristics to reflect the raw water abstraction process and treatment complexity of water production process. The raw water abstraction process was captured by the percentage of water taken from rivers and average pumping head. It is expected that the abstraction of more water requiring high pumping could lead to higher carbon emissions and therefore, impacting on the eco-efficiency of water companies. The water treatment complexity was captured by the number of treatment works for water coming from groundwater and surface water resources. We also used the percentage of water that receives advanced level of water treatment (for more details please see Ofwat, 2018). It is expected that when the water requires high levels of treatment before it is distributed to customers, the higher the level of GHG emissions and inefficiency could be.

Data about input, desirable outputs, undesirable outputs and operational characteristics were collected from Ofwat and water companies' webpages and therefore, variables are at water company level. No specific procedures were applied to the data before computing the equations described in Section 2.1 Methodology. The descriptive statistics of the variables used in the study are reported in Table 1.

3. Results and discussion

3.1. Water-energy nexus through environmental efficiency and eco-efficiency assessment

According to the methodology previously discussed, to estimate environmental efficiency and eco-efficiency scores for each water company, the hyperbolic and enhanced hyperbolic distance functions were estimated (Table 2). Before the estimation of the distance functions, all variables were normalized around the mean and therefore, the estimated coefficients are interpreted as elasticities (Molinos-Senante et al., 2017). We first look at the coefficients of hyperbolic distance function which were negative and statistically significant from zero for both the undesirable output and inputs. This means that the distance function is non-increasing in undesirable outputs and inputs and the monotonicity condition is fulfilled. Results indicate that an increase in GHG emissions would increase the distance to the frontier. The coefficients of each parameter embracing Eq. (4) are shown in Table 2 and allow concluding that technically speaking and keeping other variables equal, a 1% increase in GHG emissions would increase drinking water supplied by 0.36%. Both energy costs and other costs played a major role in the production of water output. It is found that ceteris paribus a 1% increase in energy costs and other costs could lead to an increase in drinking water by 0.492% and 0.445%, respectively. Summing up the negative of these input elasticities gives a measure of scale elasticity of 0.937, which means that on average the industry operates under

Table 1
Descriptive variables to estimate environmental efficiency and eco-efficiency scores of English and Welsh water companies.

Variable	Unit of measurement	Mean	Std. Dev.	Minimum	Maximum
Desirable output	Volume of water delivered m ³ /year	209123599	176341350	8924250	563096450
Undesirable output	Greenhouse gas emissions ton CO _{2eq} /year	65524	66000	3523	255179
Inputs	Energy costs £m /year	15.90	13.31	0.53	54.50
	Other costs £m /year	75.30	72.76	7.56	281.73
Operational characteristics	Water taken from rivers %	29	25	0	86
	Water receiving high treatment %	93	5	81	100
	Number of surface water treatment works nr	11.61	13.79	1.00	54.00
	Number of groundwater treatment works nr	51.85	42.27	2.00	127.00
	Average pumping head nr	140.40	40.99	64.82	224.21

Observations: 164

Energy and other costs are expressed in 2019 prices

Table 2
Estimated coefficients of stochastic frontier analysis models.

Variables	Hyperbolic distance function				Enhanced hyperbolic distance function			
	Coeff.	Std.Err.	T-stat	p-value	Coeff.	Std.Err.	T-stat	p-value
GHG	-0.360	0.052	-6.882	0.000	-0.039	0.013	-2.985	0.003
Energy cost	-0.492	0.052	-9.529	0.000	-0.384	0.023	-16.690	0.000
Other cost	-0.445	0.043	-10.409	0.001	-0.399	0.014	-27.799	0.000
Time	-0.006	0.006	-1.099	0.272	0.014	0.002	7.515	0.000
Energy cost ²	-2.263	0.299	-7.560	0.000	-0.047	0.051	-0.931	0.352
Other cost ²	-0.349	0.157	-2.218	0.027	-0.006	0.044	-0.142	0.887
Energy cost*Other cost	0.444	0.145	3.054	0.002	0.013	0.041	0.317	0.751
GHG*Energy cost	0.811	0.090	9.044	0.000	0.048	0.020	2.394	0.017
GHG*Other cost	-0.081	0.054	-1.490	0.136	-0.017	0.020	-0.856	0.392
GHG ²	-0.311	0.046	-6.706	0.000	-0.041	0.013	-3.261	0.001
Energy cost*Time	0.096	0.015	6.614	0.000	0.013	0.004	3.293	0.001
Other cost*Time	-0.023	0.015	-1.526	0.127	-0.011	0.004	-2.659	0.008
GHG*Time	-0.028	0.007	-3.929	0.000	-0.001	0.002	-0.536	0.592
Time ²	-0.014	0.004	-3.794	0.000	-0.003	0.001	-2.344	0.019
Groundwater treatment works	0.000	0.000	1.699	0.089	0.001	0.000	7.117	0.000
High water treatment levels	0.386	0.136	2.829	0.005	0.255	0.065	3.950	0.000
Surfacewater treatment works	0.006	0.001	6.391	0.000	0.002	0.000	6.143	0.000
Water taken from rivers	0.198	0.038	5.257	0.000	0.020	0.012	1.723	0.085
Average pumping head	0.140	0.018	7.638	0.000	0.351	0.013	26.855	0.000
Sigma	0.165	0.013	12.985	0.000	0.067	0.003	25.383	0.000
Lambda	0.918	0.298	3.083	0.002	1.224	0.155	7.883	0.000
Log-likelihood	145.06				287.60			

Observations: 164

Volume of drinking water delivered is the dependent variable

Bold statistics are statistically significant from zero at the 5% level

Bold italics statistics are statistically significant from zero at the 10% level

decreasing economies of scale. Thus, an increase in costs by 1% leads to an increase in drinking water supplied by less than 1%, i.e., 0.937%. Focusing on performance change over time, the negative sign of time and time squared indicates that there was upward shift in the production frontier which means that the English and Welsh water industry experienced technical progress at a rate of 1.4% over the period of study. The statistically significant and positive coefficient of the interaction term between energy costs and other costs suggests that they could be complementary (Adhikari and Bjorndal, 2012).

The results from the operational characteristics reveal that all variables are statistically significant from zero and have a positive coefficient. It is found that advanced levels of water treatment, water taken from rivers and average pumping head had the major contribution to eco-efficiency. The more advanced the level of water treatment is the higher the inefficiency as it might increase energy costs and GHG emissions. Keeping other variables constant, a 1% increase in water treatment complexity might increase inefficiency by 0.386%. As it is shown in Table 2, higher pumping requirements to abstract, treat and distribute water to customers might lead to higher GHG emissions and lower inefficiency as well.

We next discuss the results from the enhanced hyperbolic model which are similar to the ones obtained with the hyperbolic model. However, the values of the coefficients of the Eq. (6) and shown in

Table 2 are smaller because the enhanced hyperbolic model expands the desirable output (volume of water supplied) and contracts GHG emissions and inputs (costs). More particularly, it is shown that a 1% increase in GHG emissions increased water output by 0.039% keeping other variables the same. Lower values for energy costs and other costs are reported as well. Both types of costs are significant contributors to output expansion. A 1% increase in energy costs and other costs could increase the volume of water delivered by 0.384% and 0.399%, respectively. Like the hyperbolic model, this model showed that at the sample mean decreasing returns to scale for the industry prevail. The need to simultaneously expand output and contract GHG emissions and costs made it difficult for the production frontier to shift upwards. The rate of technical change was immaterial and at the level of 0.1% which was considerably lower than the hyperbolic model. All operational characteristics were statistically significant from zero. Treatment complexity and average pumping head had the major impact on eco-efficiency. Technically speaking and other variables being equal, a 1% increase in water treatment complexity and average pumping head could reduce eco-efficiency by 0.255% and 0.355%, respectively. This is attributed to the fact that higher energy costs are involved to pump water into treatment plants and then treat water before delivered to customers. This could lead to higher GHG emissions and lower eco-efficiency. This is also evident when higher treatment works are

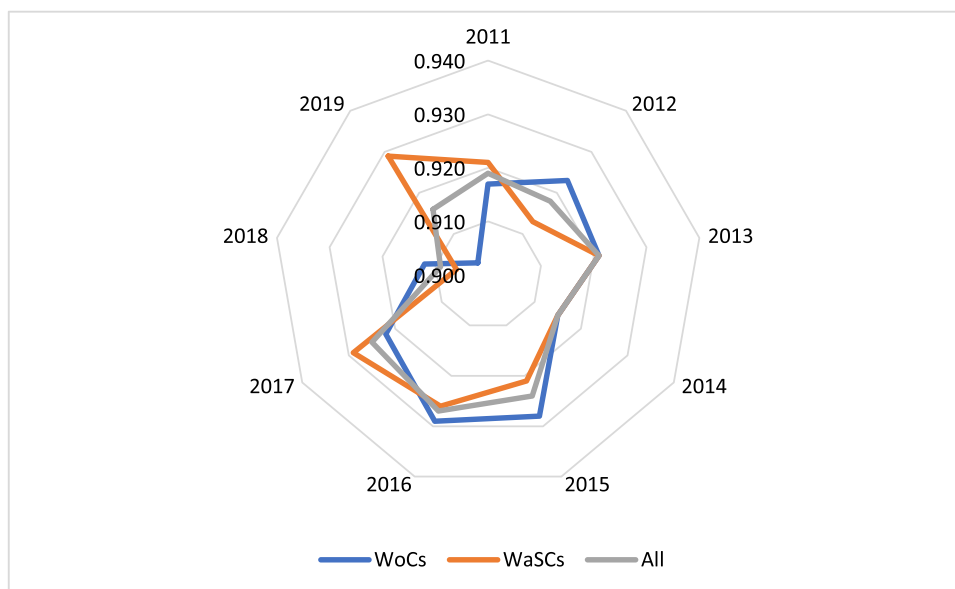


Fig. 1. Average environmental efficiency scores of English and Welsh water companies based on hyperbolic distance function.

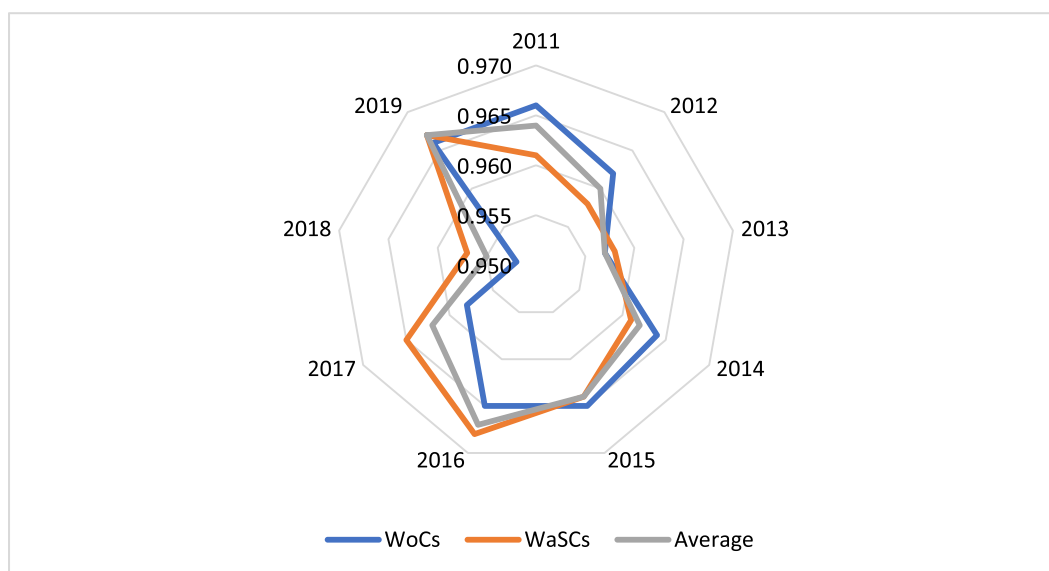


Fig. 2. Average eco-efficiency scores of English and Welsh water companies based on enhanced hyperbolic distance function.

required when water is taken from surface and groundwater resources.

Figs. 1 and 2 present the average environmental efficiency and eco-efficiency scores from the hyperbolic and enhanced hyperbolic models, respectively, which have been estimated by solving Eqs. (5) and (7). In terms of environmental efficiency, the results shown in Fig. 1 suggest that on average the water companies performed well. In particular, it was found that on average, the English and Welsh water companies could increase the volume of drinking water delivered by 8.75% ($1/0.920=1.0875$) and at the same time reduce GHG emissions by 8% ($1-0.920=0.080$). Over the whole period of study, both WaSCs and WoCs reported the same levels of environmental efficiency which was 0.920. When the companies need to reduce costs along with GHG emissions, then they became even more efficient. Therefore, the results from the enhanced hyperbolic distance function (Fig. 2) suggest that on average the companies could increase the volume of water delivered by 3.95% ($1/0.962=1.0395$) and at the same time contract GHG emissions and costs (energy and other costs) by 3.8% ($1-0.962=0.038$). Thus, adopting

energy efficient practices involves cost savings and lower levels of carbon emissions and eventually, lower inefficiency.

In order to discuss the trend in water companies' efficiency over time we split the period of study (2011-19) into two sub-periods. The first sub-period (2011-15) refers to the 2009 price review where the regulator (Ofwat) introduced several schemes to boost companies' efficiency. These included a rolling incentive mechanism where the companies could keep any savings in operating expenditure regardless of the year occurred (Villegas et al., 2019). Moreover, to ensure environmental sustainability such as reduction in water leakage and unplanned interruptions the regulator introduced several financial rewards when the companies met their targets. The results from the hyperbolic model (Fig. 1) indicated that during the period 2011-15, average WoC's environmental efficiency fluctuated but it was increasing at a rate of 0.28% per year. It finally increased from 0.917 in 2011 to 0.928 in 2015. In contrast, average WaSC's environmental efficiency remained stable at the end of the sub-period. This finding suggests that both WoCs and

WaSCs performed well in delivering water to customers and reducing GHG emissions at the same time for a given level of inputs. We note that WaSCs could be more efficient and catch-up with WoCs by further reducing their carbon emissions.

The results from the enhanced hyperbolic model, i.e., eco-efficiency, (Fig. 2) reveal a different pattern. In particular, average WoC's eco-efficiency followed a downward trend over time which was interrupted in 2014. Its eco-efficiency in 2015 was at the same level with the one reported in 2011. During the sub-period 2011-15 average WoC's eco-efficiency was 0.963 which means that desirable output could be expanded by 3.9% and at the same time carbon emissions and costs could be reduced by 3.7%. In contrast, average WaSC's eco-efficiency was slightly increasing at a rate of 0.06% per year. Eco-efficiency increased from 0.961 in 2011 to 0.964 in 2015. Like the environmental efficiency, during the years 2011-15, average WaSCs were slightly more eco-efficient than WoCs. The findings suggest that both WaSCs and WoCs might have experienced difficulties in achieving further savings in costs over time. However, their efficiency remained at high levels.

We then analyze the efficiency estimates from the second sub-period (2016-19) which refers to the 2014 price review. The regulator introduced further financial incentives to promote economic and environmental efficiency. It introduced a set of common performance indicators for the whole water industry to monitor cost and environmental performance. These indicators such as water leakage, flooding and pollution incidents, carbon emissions had the form of financial or reputation rewards when companies met their targets (Villegas et al., 2019). The results from the hyperbolic model (Fig. 1) suggest that during the years 2016-19 average WoC's environmental efficiency followed a downward and considerably decreased from 0.929 in 2016 to 0.903 in 2019. This is attributed to the fact that the company did not manage to reduce its GHG emissions for a given level of inputs. WoCs are smaller than WaSCs in terms of volume of drinking water delivered and therefore, as small water utilities face other problems and challenges than WaSCs. Although there is no direct scientific evidence, the results from our study suggest that WoCs have not prioritized the reduction of GHG emissions as WaSCs have done. In contrast, during the same period WaSCs seemed to have performed slightly better than WoCs. Their mean environmental efficiency was increasing at rate of 0.22% per year and eventually increased compared to the previous sub-period. In 2019 average WaSCs needed to further reduce their GHG emissions by 7.8% whereas WoCs needed to reduce their carbon emissions by 10%. The findings suggest that during the years 2016-19 WaSCs managed to catch-up and exceed WoC's efficiency levels whereas WoCs did not continue to improve their efficiency. This is attributed to the fact that their GHG emissions performance was not satisfactory. The results from the enhanced hyperbolic model reveal a similar trend. During the second sub-period (2016-19), WoC's eco-efficiency followed a downward trend with the exception being the last year of the sample. In contrast, average WaSC performed slightly better than WoC over that period and its eco-efficiency remained at high levels, 0.965. WaSC could become more environmentally efficient by further reducing costs and GHG emissions by 3.5%. Because of the smaller size of WoCs relative to WaSCs, sometimes it may be difficult to implement innovations to reduce GHG emissions and energetic costs on these small water companies. Previous research (Portela et al., 2011; Molinos-Senante et al., 2015; Molinos-Senante and Maziotis, 2020) also concluded that WaSCs performed slightly better than WoCs from an economic perspective. The authors suggested that WoCs were more affected than WaSCs due to the rise in electricity prices and reduction in the levels of leakage imposed by the 2009 and 2014 price reviews.

In terms of environmental efficiency, WoCs improved their performance during the first period evaluated (2011-15), whereas in the second period the improvement was mainly achieved by WaSCs. In the case of eco-efficiency, the same trend is observed for the two periods evaluated. WoCs suffered a regression on eco-efficiency scores whereas WaSCs improved their performance. Hence, according to the results

shown on Figs. 1 and 2, it can be concluded that the measures adopted by Ofwat during the 2009 and 2014 price reviews favored improvements in the performance of WaSCs. However, negative effects (except for environmental efficiency in the first period) were reported for WoCs.

As part of the strategy to achieve the goal of reducing GHG emissions by 80% by 2050, the English and Welsh water companies have individual strategies to reduce GHG emissions or even achieve net zero emissions. The environmental efficiency and eco-efficiency scores estimated for each water company could be used to feed into and update these plans. It should be noted that both synthetic indicators developed take into account the impact of exogenous variables, (e.g., source of raw water, level of treatment, pumping head, etc.) on the performance of water companies. Hence, in addition to the national policy landscape, the specific results at water company level are useful to identify specific operational requirements and local decarbonization opportunities. Moreover, the approach applied in this study would be also used by the water regulator. In January 2022, Ofwat, published a position paper on the Net Zero 2030 Routemap on carbon by Water UK (Ofwat, 2022b). Among other issues, Ofwat emphasized the importance of integrating the net-zero strategies developed by the water companies with the "PR24 and Beyond: Creating tomorrow, together" which is the framework for price review in 2024 and future price reviews in the English and Welsh water industry. In particular, Ofwat stated that future price controls should support water companies to meet the challenge of net zero. Ofwat recognizes that transition to net zero may increase costs of service. Considering the regulatory approach employed by Ofwat to set water tariffs, i.e., price cap regulation, where tariffs are adjusted considering inflation and expected efficiency improvements, the methodology proposed in our study might be very useful for the regulator to integrate GHG emissions on efficiency assessment. Moreover, it has been evidenced that environmental efficiency and eco-efficiency scores estimated using the hyperbolic and enhanced hyperbolic distance functions are robust avoiding any misleading conclusions.

3.2. Characteristics of the water industry

We now turn our discussion in the results from the derivation of the average inputs and output elasticities for the whole period of study (Table 3). It is found that in the hyperbolic distance function, a 1% increase in industry's energy costs and other costs could lead to an increase in the volume of drinking water delivered by 0.871%. This result suggests that the industry operated below its optimal scale. However, a different situation is evident when looking at the results for each company type. During the period of study average WoC operated under decreasing economies of scale whereas WaSC seemed to function under small increasing economies of scale. A 1% increase in energy and other costs could result in a higher output expansion by 1.142%. This means that adjustments in WaSC's scale of operations could lead to lower costs and higher efficiency. However, we note that WaSCs could further improve efficiency by reducing energy costs as this factor plays a major role in providing water services. In contrast, WoCs should focus on reducing energy and other costs before producing more output.

The negative sign of $A_{EC,OC}$ and $A_{OC,EC}$ suggest that energy costs and other costs are complements. This exists for both WoCs and WaSCs. This means that the path to eco-efficiency requires reductions in both energy and other costs. The adoption of energy efficient practices when abstracting and treating water could lead to lower levels of GHG emissions and higher environmental efficiency. When companies aim to simultaneously expand output and reduce carbon emissions for a given level of inputs then the opportunity cost of reducing carbon emissions $Subs_{CO_2,y}$ is relatively costly. For WaSCs $Subs_{CO_2,y}$ takes a value which is slightly higher than unity, whereas for WoCs the value of $Subs_{CO_2,y}$ is almost unity. This means that it is not relatively expensive for WoCs to reduce carbon emissions whereas for WaSCs it may be. This is explained by the fact that WaSCs have more customers to serve than WoCs and thus

Table 3
Characteristics of the English and Welsh water industry.

Characteristic	Water only companies (WoCs)		Water and sewerage companies (WaSCs)		All water companies	
	Hyperbolic	Enhanced hyperbolic	Hyperbolic	Enhanced hyperbolic	Hyperbolic	Enhanced hyperbolic
$\epsilon_{WD,EC}$	-0.253	-0.417	-0.703	-0.387	-0.478	-0.402
$\epsilon_{WD,OC}$	-0.348	-0.372	-0.439	-0.402	-0.393	-0.387
Economies of scale	0.601	0.789	1.142	0.789	0.871	0.789
$A_{EC,OC}$	-0.154	-0.005	-0.194	-0.005	-0.174	-0.005
$A_{OC,EC}$	-0.112	-0.005	-0.317	-0.005	-0.215	-0.005
$\epsilon_{WD,CO2eq}$	-0.497	-0.016	-0.268	-0.033	-0.383	-0.025
ϵ_{WD}	0.503	0.984	0.732	0.967	0.617	0.975
$Subs_{CO2eq,WD}$	-1.010	-60.271	-2.735	-29.195	-1.614	-39.454

higher overall costs.

The results from the enhanced hyperbolic model reveal several interesting conclusions. First, during the years 2011-19 both WaSCs and WoCs operated under decreasing economies of scale. A 1% increase in costs would lead to a lower increase in outputs, by 0.789%. Water companies should put efforts into achieving cost savings in water production processes rather than expanding their size by producing more output. Like the hyperbolic model, there is a degree of complementarity between energy costs and other costs. This means that if the companies want to become more environmentally efficient they should reduce both energy costs and other costs. Unlike the hyperbolic model, the opportunity cost of reducing carbon emissions is now considerably high for both WoCs and WaSCs. This is attributed to the fact that the companies need to reduce carbon emissions and inputs and deliver more water at the same time. Considering that GHG emissions involve both direct and indirect emissions associated with electricity use, it appears that for WoCs high energy requirements to abstract, treat and supply water to customers could explain the high cost of reducing carbon emissions. For WaSCs the use of other costs such as labour and chemicals when treating more water might explain the high cost of curtailing carbon emissions. As $Subs_{CO2,y}$ takes a value beyond unit, the reduction of both carbon emissions and water delivered is the right way for a sustainable urban water cycle.

4. Conclusions

Water companies are faced with several challenges in the light of climate change and population growth such as providing enough drinking water and at the same time reducing GHG emissions. In this study we used the hyperbolic and enhanced hyperbolic distance functions to evaluate the environmental efficiency and eco-efficiency of several water companies in England and Wales over the years 2011-2019. Moreover, it was assessed the substitutability between costs, and between water delivered and carbon emissions. The empirical application conducted focused on the English and Welsh water industry because is one of the of the most advanced in the monitoring and reporting of GHG emissions at water company level. In addition, the water regulator considers the need for and importance of reducing GHG emissions in the processes to set water tariffs. However, the methodology proposed in this study could be applied to water companies operating in other countries and could also be extended to wastewater collection and treatment services. We finally note that the methodology of this study could be used to quantify the environmental impact of any other undesirable product in water industry such as water leakage or any other industry such as supply interruptions in energy sector.

The case study evidenced that the English and Welsh water industry performed well in terms of environmental efficiency. On average, it could expand the volume of drinking water delivered by 8.75% and at the same time curtail GHG emissions by 8%. Higher level of performance was reported when eco-efficiency was assessed. In particular, the results showed that water companies could increase their volume of drinking water delivered by 3.95% and at the same time contract GHG emissions and costs (energy costs and other costs) by 3.8%. After splitting the study

period into two sub-periods to reflect the regulator's price reviews, it can be concluded that the measures adopted by Ofwat during the 2009 and 2014 price reviews favored improvements in both environmental efficiency and eco-efficiency of WaSCs. Our study demonstrated that the more complex the treatment of water is, the higher the costs and level of carbon emissions could be. Finally, it is evidenced that both energy costs and other costs need to reduce to improve eco-efficiency as these inputs are complements.

The findings of our study are of great significance for policy makers for the following reasons. First, water managers can evaluate how efficient companies are when expanding the volume of drinking water delivered and curtailing GHG emissions at the same time for a given level of costs. They can also determine how efficiency changes when companies want to reduce costs as well. Moreover, our study showed that both energy costs and other costs are the major cost drivers of companies' efficiency. However, managers could identify additional factors that could impact overall costs and inefficiency such as pumping requirements and complexity of water treatment process. These factors should also be included in the decision making process. Our methodology also showed that the path to an environmentally sustainable industry requires improvements in energy efficiency, reduction in carbon emissions and abstraction of less water. This could be achieved by the constructive collaboration of water managers and regulator via the form of financial rewards when companies adopt practices that help them to become more eco-efficient.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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