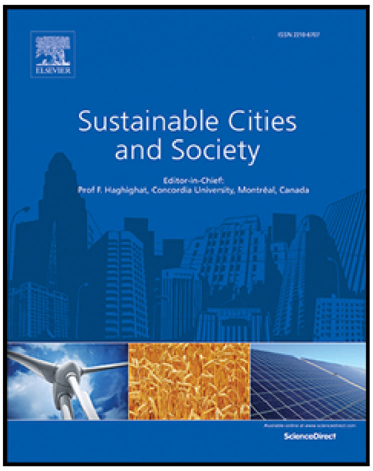
Journal Pre-proof



ESTIMATING ENERGY COSTS AND GREENHOUSE GAS EMISSIONS EFFICIENCY IN THE PROVISION OF DOMESTIC WATER: AN EMPIRICAL APPLICATION FOR ENGLAND AND WALES

Maria Molinos-Senante , Alexandros Maziotis ,
Manuel Mocholi-Arce , Ramón Sala-Garrido

PII: S2210-6707(22)00393-6
DOI: https://doi.org/10.1016/j.scs.2022.104075
Reference: SCS 104075

To appear in: *Sustainable Cities and Society*

Received date: 4 May 2022
Revised date: 6 July 2022
Accepted date: 19 July 2022

Please cite this article as: Maria Molinos-Senante , Alexandros Maziotis , Manuel Mocholi-Arce , Ramón Sala-Garrido , ESTIMATING ENERGY COSTS AND GREENHOUSE GAS EMISSIONS EFFICIENCY IN THE PROVISION OF DOMESTIC WATER: AN EMPIRICAL APPLICATION FOR ENGLAND AND WALES, *Sustainable Cities and Society* (2022), doi: https://doi.org/10.1016/j.scs.2022.104075

HIGHLIGHTS

- Specific efficiency sores for energy costs and greenhouse gas emissions were estimated.
- English and Welsh water companies could save 35.6% of the current energy costs.
- Efficiency on greenhouse gas emissions was estimated at 41.5% level.

ESTIMATING ENERGY COSTS AND GREENHOUSE GAS EMISSIONS EFFICIENCY IN THE PROVISION OF DOMESTIC WATER: AN EMPIRICAL APPLICATION FOR ENGLAND AND WALES

Maria Molinos-Senante,[1,2], Alexandros Maziotis[1], Manuel Mocholi-Arce[2], Ramón Sala-Garrido[2]

[1] Departamento de Ingeniería Hidráulica y Ambiental, Pontificia Universidad Católica de Chile, Avda. Vicuña Mackenna, 4860 Santiago, Chile

[2] Departamento de Matemáticas para la Economía y la Empresa, Universidad de Valencia, Avda. Tarongers S/N, Valencia, Spain.

Abstract:

Reducing greenhouse gas (GHG) emissions and energy costs has been one of the main challenges faced by the water sector. This study provides a quantification of energy costs and GHG emissions efficiency of a sample of the English and the Welsh water companies over the period of 2013-2018. In doing so, the multi-directional data envelopment analysis (DEA) method was employed, which allows the quantification of the potential savings in energy costs and GHG emissions, i.e. defining the targets to be set by the water regulators. In the second stage of the analysis, bootstrap techniques were applied to identify environmental variables influencing the performance of water companies. The results indicate that the efficiency of the English and the Welsh water companies was low since the average efficiency scores for energy costs and GHG emissions were 0.644 and 0.415, respectively. It reveals that the water sector might save 35.6% and 58.6% of the current energy costs and GHG emissions. The study's findings demonstrated that the source of raw water, the treatment required to produce drinking water and population density were the environmental variables influencing the efficiency of these water companies in terms of energy costs and GHG emissions. The evidence provided by this study is of great interest to water regulators and water companies to implement policies and measures towards a low-carbon urban water cycle.

Keywords: Energy efficiency; carbon emissions efficiency; multi-directional efficiency analysis (MEA); environmental variables; data envelopment analysis (DEA).

1. INTRODUCTION

Water utilities are faced with a big challenge in the forthcoming years in light of new climate change events and rapid population growth (Garrido-Baserba et al., 2020). For instance, the need to be resilient in water supplies has led water companies around the world to search for climate-independent solutions, such as desalination and water recycling (Ananda and Hampf, 2015; Arden et al., 2019; Sun et al., 2020). Hence, water services are associated with high energy use and potential high greenhouse gas (GHG) emissions (Zhang et al., 2017; Escrivá-Bou et al., 2018; Kim and Chen, 2018). Loubet et al. (2014) and Lemos et al. (2013), highlighted the large expenditure of energy in the water and wastewater treatment process and the environmental consequences of realising GHG emissions in the atmosphere. Lam et al. (2017), Lee et al. (2017) and Wang et al. (2020) also evidenced that the provision of drinking water services involves energy intensive processes. Thus, in recent decades there has been an increased focus on the water-energy nexus and the reduction of GHG emissions related to the provision of domestic water services (Engström et al., 2017; Ananda, 2018; Fulton and Jin, 2021; Rodriguez-Gutierrez et al., 2022).

The reduction of GHG emissions by the water industry requires the collaboration of regulators, regulated companies, governments and customers. Regulators can promote energy efficiency policies such as financial rewards when the respective companies reduce GHG emissions. Studies suggest that the water companies may benefit heavily from investing in the latest technologies that help them reduce the energy consumed for treating and distributing water, and thereby, the levels of GHG emissions (Stokes et al., 2014; Arenas Urrea et al., 2019). According to Wang and Chermak (2021), there is an urgent need for the water companies to educate the customers regarding the usage of less-energy-intensive and more water-efficient devices at home (Wang and Chermak, 2021). One of the strategies to incentivise the water companies is to introduce policy instruments such as carbon tax or carbon trading scheme (Molinos-Senante and Guzman, 2018, Molinos-Senante et al., 2015). Governments could also set a net-zero carbon target for the overall water industry to be achieved in the future. For instance, currently, the state of Victoria in Australia is working towards net-zero GHG emissions by the water sector by 2050 (Ananda, 2018). Similarly, the government of the United Kingdom is committed to achieve a net-zero GHG target by 2050 by urging all the utilities to become more energy and carbon-efficient (Ofwat, 2010a, 2010b; HM Government, 2018; CCC, 2019). Thus, water utilities have an important role in reducing GHG emissions.

Given the relevance of this topic, several studies in the past have measured GHG productivity in energy and manufacturing sectors in China and Japan (e.g. Krautzberger and Wetzel, 2012; Lee, 2011; Matsushita and Yamane, 2012; Emrouznejad and Yang, 2016), whereas only a few studies exist that estimated GHG efficiency and productivity of the water sector in Australia (Ananda and Hampf, 2015; Ananda, 2018). Similarly, traditional Data Envelopment Analysis (DEA) techniques were used by Wang et al. (2012, 2014) and Hong et al. (2019) to estimate energy and GHG efficiency in several industrial regions of China. The limitations of the above studies were twofold. First, they did not measure energy efficiency, and second, they used traditional non-parametric (linear programming) techniques, such as DEA, to measure GHG productivity. Traditional DEA techniques allow for an expansion of all the desired outputs and contraction of all the undesirable outputs and all inputs, but they do not allow for the measure of variable-specific efficiencies. To overcome the above limitation, Bogetoft and Hougaard (1999) and Asmild et al. (2003) proposed the multi-directional Data Envelopment Analysis (MEA) technique, which provides a specific view of patterns of efficiencies. MEA chooses benchmarks such that the input reductions are proportional to the potential improvements identified by considering the improvement potential of each input separately (Asmid and Mathews, 2012). MEA is suitable for situations where the focus is on the measurement of the efficiency and potential improvement of specific variables (Wang et al., 2013). Given the relevance and the need of reducing energy costs and

GHG emissions of the water industry, the MEA method is very suitable to estimate energy costs efficiency and GHG emissions efficiency of water utilities[1].

Against this background, the objectives of this study are threefold. The first objective is to measure the energy cost and GHG emissions efficiency of the water sector. To do this, we apply, for the first time, the MEA approach which permits the investigation of the specific patterns of efficiencies. This technique also allows us to quantify the savings in energy costs and GHG emissions that the water companies could potentially achieve over time, which is the second objective of this study. The third objective is to evaluate the impact of several environmental variables on the energy cost and GHG emissions of water companies. This is a novel approach, as to the best of our knowledge, there have not been any previous studies on the water sector that specifically measured the energy costs and GHG emissions efficiency. Moreover, the identification of factors that might influence water companies' efficiency can aid policymakers in understanding what drives the energy costs and GHG emissions in the provision of water services and make informed decisions.

The empirical application conducted focuses on several English and Welsh water and sewerage companies (WaSCs) and water only companies (WoCs) that provided water services over the period 2013-2018. We also linked our results with the regulatory cycle and several policy implications were discussed based on the analysis of our results. The English and the Welsh water industry is a prominent case study because the United Kingdom is committed to achieve net-zero GHG emissions by 2050 (CCC,

[1] The MEA method was used in fields such as transportation (Holvad et al., 2004; Bi et al., 2014), banking (Asmild and Matthews, 2012; Zhu et al., 2019; 2020), farm (Asmid et al., 2016), and industrial sectors (Wang et al., 2013). However, to the best of our knowledge, there are not any studies that measured energy and carbon emissions efficiency in the water industry.

2019). Moreover, the water companies in England and Wales are highly regulated by the water services regulation authority (Ofwat). Thus, although the present study focuses on the English and Welsh water industry, it also provides knowledge and methods on issues that are relevant to the water industry in several other countries across the world.

In this paper, our contribution to existing literature is twofold. First, motivated by improving the understanding of the water-energy-GHG nexus from a sustainability perspective, we evaluated the performance of a sample of water companies focusing on energy costs and GHG emissions. Second, unlike past research, we employed a novel non-radial DEA model which allowed us to compute a specific efficiency score for energy costs and GHG emissions. This further allowed us to quantify their potential savings based on an efficiency target and ideal reference point specifically estimated for each water company. To the best of our knowledge, there are no previous studies estimating specific efficiency scores for energy costs and GHG emissions in the provision of domestic water.

2. METHODOLOGY

This section describes the methodological approach used to estimate the energy cost and GHG emissions efficiency of several water companies in England and Wales. To do this, we employed the MEA approach that is designed to directly estimate specific-variable efficiency scores (Zhu et al., 2020). The main reason for using MEA approach in this study, instead of traditional radial DEA models is that while traditional DEA models use a radial, i.e., proportional change of all variables, MEA selects bechmarks such that the input reductions and output expansions are proportional to the potential improvements identified by considering the improvement potential in each variable separately (Asmild and Matthews, 2012). The MEA approach is ideally suited for assessing the performance of water companies focusing on specific variables (energy costs and GHG emissions) as required to achieve the main aim of this study. Figure 1 shows the main methodological steps employed in this study.

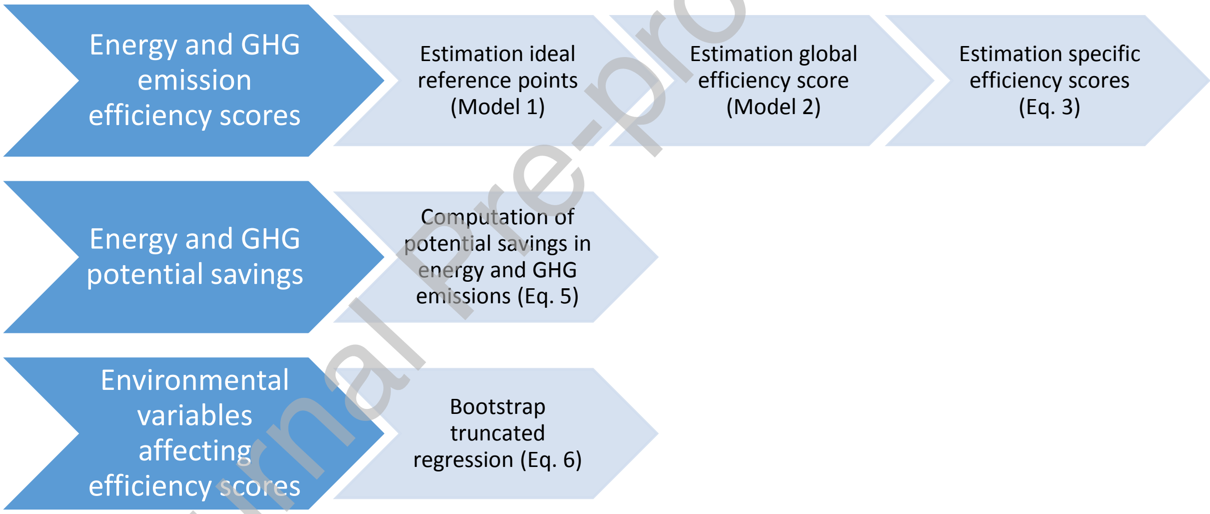


Figure 1. Methodological approach followed.

Considering that in this study, we are focussed on estimating the potential reduction in energy cost and GHG emissions while maintaining some of the inputs and outputs fixed, we used an input-oriented MEA model where both discretionary and non-discretionary variables were employed (Wang et al., 2013). Let’s assume that a water company j at any period t uses a set of inputs $x_{i,j}^{t}$, $i = 1, \ldots, n$ to generate a set of outputs $y_{r,j}^{t}$, $r = 1, \dots, m$. As it is illustrated on Figure 1, the first step to derive the potential improvements on the inefficiency index for each water company j, is to derive the ideal reference point for each observation $\left(x_{i,j_0}^{t}, y_{r,j_0}^{t}\right)$. The ideal reference point corresponds to the largest possible reduction in each input variable taken separately. In doing so, the linear programming model (1) was solved n time (one for each input) (Asmild and Matthews, 2012; Asmild et al., 2016):

$$\min \theta_{i,j_0}^{t} \tag{1}$$

$s.t.$

$\sum_j \lambda_j x_{i,j}^{t} \leq \theta_{i,j_0}^{t},$

$\sum_j \lambda_j \, x_{-i,j}^{t} \leq x_{-i,j_0}^{t}, -i = 1, \dots, i-1, i+1, \dots, l$

$\sum_j \lambda_j \, x_{i,j}^{t} \leq x_{i,j_0}^{t}, i = l+1, \dots, n$

$\sum_j \lambda_j \, y_{r,j}^{t} \geq y_{r,j_0}^{t}, r = l+1, \dots, m$

$\lambda_j \geq 0$

In the linear programming model (1), $x_{i,j}^{t}$ are discretionary inputs, whereas $x_{-i,j}^{t}$ denote non-discretionary inputs, λ_j are intensity variables that are used to construct the efficient frontier (Sala-Garrido et al., 2019). θ_{i,j_0}^{t} is the target value for the ith input reduction, i.e., the potential improvement in the use of this input. We can then define the ideal reference point with a particular observation $\left(x_{i,j_0}^{t}, y_{r,j_0}^{t}\right)$ as $\left(\theta_{i,j_0}^{t*}, y_{r,j_0}^{t}\right)$, where θ_{i,j_0}^{t*}denotes the optimal solution of linear programming model (1).

Once the ideal reference points are estimated, the following linear programming model was solved to estimate the global efficiency of each observation (considering all inputs and outputs):

$$\max \beta_{j_0}^{t} \tag{2}$$

$$s.t.$$

$$\sum_j \lambda_j x_{i,j}^{t} \leq x_{i,j_0}^{t} - \beta_{j_0}^{t}\left(x_{i,j_0}^{t} - \theta_{i,j_0}^{t*}\right), \quad i = 1, \dots, l$$

$$\sum_j \lambda_j \, x_{i,j}^{t} \leq x_{i,j_0}^{t}, i = l+1, \dots, n$$

$$\sum_j \lambda_j \, y_{r,j}^{t} \geq y_{r,j_0}^{t}, r = l+1, \dots, m$$

$$\lambda_j \geq 0$$

The solution $\left(\lambda_j, \beta_{j_0}^{t}\right)$ from the linear programming model in (2) is employed to define the variable (individual) specific MEA efficiency score ($\vartheta_{i,jo}^{t}$) for the input x_{i,j_0}^{t}, and therefore, is defined as follows (Wang et al., 2013):

$$\vartheta_{i,jo}^{t} = \frac{x_{i,j_0}^{t} - \beta_{j_0}^{t*}\left(x_{i,j_0}^{t} - \theta_{i,j_0}^{t*}\right)}{x_{i,j_0}^{t}} \tag{3}$$

From the specific individual MEA efficiency scores estimated using Eq. (3), the aggregate MEA efficiency score is derived for the observation $\left(x_{i,j_0}^{t}, y_{r,j_0}^{t}\right)$ as follows (Wang et al., 2013):

$$\varphi_{j_0}^{t} = 1 - \frac{1}{l}\left[\sum_{i=1}^{l} \frac{\beta_{j_0}^{t*}\left(x_{i,j_0}^{t} - \theta_{i,j_0}^{t*}\right)}{x_{i,j_0}^{t}}\right] \tag{4}$$

Based on the specific individual target efficiency score estimated in Eq. (2) ($\beta_{j_0}^{t*}$), the ideal reference point (θ_{i,j_0}^{t*}) and the current use of input (x_{i,j_0}^{t}), we estimated the potential savings for each input as follows:

$$S_{i,jo}^{t} = \beta_{j_0}^{t*}\,(x_{i,j_0}^{t} - \theta_{i,j_0}^{t*}) \tag{5}$$

Finally, the last step of the methodology involved understanding the factors that may impact the energy cost and GHG emissions efficiency of water utilities. To do this, we regressed the aggregate MEA efficiency score obtained from Eq. (4), $\varphi_{j_0}^{t}$, in a set of environmental variables. As the dependent variable, the aggregate efficiency score, takes a value between zero and one, estimating the regression model using Ordinary Least Squares (OLS) techniques may lead to biased estimates (Garcia-Sanchez, 2006; Renzetti and Dupont, 2009). Thus, the specification of the truncated regression is considered to be more appropriate (Guerrini et al., 2015; Wang et al., 2016). Simar and Wilson (2007) demonstrated that efficiency scores might be serially correlated with the error term and the explanatory variables. As a result, the use of the traditional Tobit regression might lead to biased estimates. To deal with this limitation, Simar and Wilson (2007) developed the bootstrap truncated regression. The regression model is expressed as follows:

$$\varphi_{j_0}^{t} = \alpha z_j^{t} + \varepsilon_j^{t}, \varepsilon_j^{t} \sim N(0, \sigma^2) \tag{6}$$

where z_j^t is a set of environmental variables for each water company j at any period t, ε_j^t denotes the noise that follows the normal distribution and $\varphi_{j_0}^{t}$ denotes the MEA aggregate efficiency score that takes values ranging from zero to one. The truncated maximum likelihood is maximised concerning the estimated parameters and the variance of the error (Badunenko and Tauchmann, 2019). A parametric bootstrap of the truncated regression is then employed to obtain unbiased beta coefficients and valid confidence intervals (Simar and Wilson, 2007).

3. DATA SAMPLE AND SELECTION

Our empirical study focused on several WaSCs and WoCs that provide water services to the customers in England and Wales over the period 2013-2018. Being privatised as natural monopolies, the economic regulator, Ofwat was set up to protect customers from monopoly abuse (Molinos-Senante et al., 2017). Ofwat monitors water companies' economic and environmental performance by approving water companies' business plans every five years. These plans are part of the price review process to set tariffs by promoting quality service, technical and environmental efficiency at a low cost (Villegas et al., 2019; Walker et al., 2021). The data used in this study were retrieved from Ofwat's website and the company's annual performance reports.

The selection of desirable and undesirable outputs and inputs was based on past research on this topic and data availability. The desirable output was the volume of domestic water supplied measured in cubic metres per year (Cetrulo et al., 2019). The undesirable output was defined as the emissions of GHG into the atmosphere from the provision of water services involving various stages of treatment and the subsequent distribution of domestic water to the customers (Ofwat, 2009; 2010a; Ananda and Hampf, 2015; Molinos-Senante et al., 2015; Ananda, 2018). GHG emissions were expressed in tons of CO_{2eq} per year and were measured following the United Kingdom Government Environmental Reporting Guidelines[2] (HM Goverment, 2019).

[2] According to Ofwat (2010b), GHG emissions in the water industry are categorized in four groups: i) scope 1 (direct emissions); ii) scope 2 (indirect emissions); iii) regulated scope 3: indirect emissions which are accounted for and iv) non-regulated scope 3: indirect emissions not taken into accounted.

Two inputs were selected. The first one was defined as the total energy cost (expenditure) used for the provision of water services and is expressed in millions of ₤ per year (Stone and Webster consultants, 2004). The second input was the other costs (expenditure) in millions of ₤ per year (Saal et al., 2007; Molinos-Senante et al., 2017; Molinos-Senante and Maziotis, 2018). Other costs were computed as the difference between the total operating costs and the energy costs of water services.

Finally, based on past research (Brea-Solis et al., 2017; CEPA, 2018; Molinos-Senante and Maziotis, 2018; Ofwat 2019a; 2019b), several environmental variables were selected to assess their impact on the energy cost and carbon efficiency scores. These included the following: i) the percentage of water extracted from boreholes; ii) the percentage of water taken from reservoirs; iii) average pumping head to capture the energy requirements to abstract, treat and deliver water to customers; iv) the number of treatment works for water that comes from surface water resources; v) the number of treatments of water that comes from groundwater resources; vi) the percentage of water receiving extensive treatment to capture the complexity of treatment works[3]; and vii) water population density measured as the number of water population divided by the water area. Table 1 reports the descriptive statistics for the variables used in the model.

Table 1. Descriptive variables for English and Welsh water companies

Variables	**Unit of**	**Mean**	**Std. Dev.**	**Minimum**	**Maximum**

Based on this definition, scope 1, scope 2, and regulated scope 3 GHG emissions were considered in this study.

[3] Ofwat groups the water treatment works in several levels. For instance, the first and second treatment levels incorporate simple treatment works such as slow sand filtration, whereas the next treatment levels involve more complex or advanced treatment techniques such as activated carbon/ pesticide removal (Ofwat, 2019c). We used the percentage of water treated at water treatment works with a complexity level more than 3 as a factor that might influence energy cost and CO_{2eq} (Ofwat, 2018, 2019a; 2019b).

		measurement				
Output (Eqs. 1-5)	Volume of water delivered	000s m^3/year	712.86	554.73	56.17	2168.81
Inputs (Eqs. 1-5)	Greenhouse gas emissions	Ton CO_{2eq} / year	82845	69062	4542	275900
	Energy costs	£m /year	20.38	15.03	1.72	59.99
	Other costs	£m /year	93.39	78.89	7.56	331.65
Environmental variables (Eq. 6)	Water taken from boreholes	%	40.0	31.0	3.0	92.0
	Water taken from reservoirs	%	37.0	26.0	0.0	95.0
	Surface water treatment works	nr	16.18	15.32	1.00	54.00
	Groundwater treatment works	nr	50.83	40.34	2.00	127.00
	Water receiving high levels of treatment	%	93.0	5.0	81.0	100.0
	Average pumping head	nr	147.45	43.96	64.82	256.48
	Population density	000s/km^2	0.47	0.29	0.15	1.25

Observations: 102

Energy and other costs were expressed in 2018 prices

4. RESULTS AND DISCUSSION

4.1 Efficiency and potential savings estimation

Figure 2 shows the energy cost efficiency, the GHG emissions efficiency and the aggregate efficiency for English and Welsh WaSCs and WoCs over the years 2013-2018. It was found that on average WaSCs were more energy cost and GHG emissions efficient than WoCs. However, both types of companies did not report high specific efficiency scores. In particular, the average energy cost and GHG efficiency of WaSCs were at the level of 0.678 and 0.426, respectively. This means that WaSCs should reduce energy costs in their daily operations by 32.2% and GHG emissions by 57.4%, respectively. As far as the WoCs' efficiency scores are concerned, it is shown that, on average, WoCs need to reduce their energy costs and GHG emissions by 40% and 60%, respectively. The aggregate efficiency measure suggests that on average WaSCs and WoCs need to reduce both energy costs and GHG emissions by 44.8% and 50.3%, respectively.

Energy and carbon emissions performance of water companies could be associated with other factors beyond topography, treatment complexity and density. These factors could be the regulatory environment the water companies operate. For instance, incentive schemes that the regulator introduced as part of the price review process, might not have stimulated companies to achieve savings in production process. Other factors that could impact water companies' performance could be related to changes in climate and population. For instance, extreme climatic events such as heavy rainfall might have pushed up operational costs such as energy costs leading therefore to a deterioration in efficiency in terms of reducing energy and carbon emissions. Moreover, poor managerial decisions such as the lack of investment in new technologies to produce renewable energy from waste might not have led to cost savings.

A similar pattern in the efficiency scores of WaSCs and WoCs was observed. During the years of 2013-16, there was a decreasing trend in energy costs efficiency, which might have attributed to an increase in energy costs and has impacted GHG emissions, and thus, the GHG efficiency scores. It is noted that during that period energy costs increased by almost 20%, while they decreased by almost 4% during the subsequent years 2017-18. Thus, during that period water companies became more energy-efficient, which led to lower GHG emissions into the atmosphere from the treatment of water and therefore, higher GHG efficiency scores.

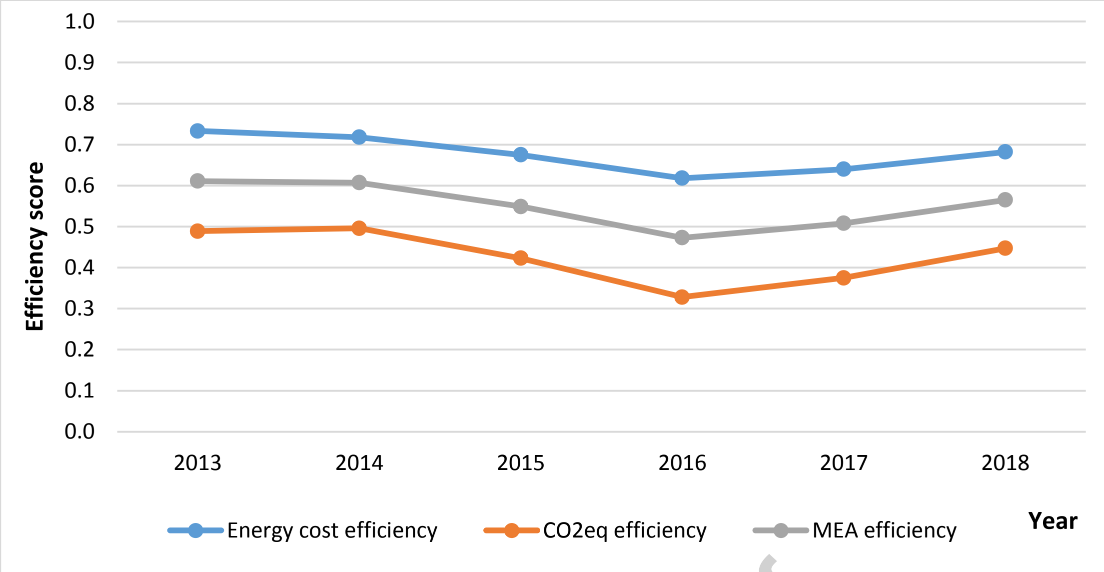


Figure 2. Evolution of average energy cost efficiency, GHG efficiency and aggregate efficiency scores for English and Welsh water and sewerage companies (WaSCs) and water only companies (WoCs).

The efficiency scores from this study cannot be compared directly with the results of past research due to several reasons. First, the geographical focus is dissimilar. Second, the study periods being analyzed are different. Third, the model and variables employed are also divergent. However, it is worth considering the findings of previous studies to contextualize the performance of the English and Welsh water companies. Ananda and Hampf (2015) found that the global productivity of Australian water companies decreased annually by 3.65% during the period 2006-2011 when performance assessment integrated GHG emissions. This negative trend was confirmed by Ananda (2018) who also evidenced that in the following years (2011-2014) productivity declined. The retardation in the productivity was mainly attributed to the extreme drought conditions that Australia experience at that time. This involved an increase in the volume of recycled water consuming more energy for its treatment. As in our case study, another contributing factor to changes on efficiency could have been the rising energy prices. The heavily reliance on high-energy water supply sources and process combined with larger electricity prices might have contributed to a significant increase in the operational costs of water companies. In this context, the cost of energy has achieved unprecedent levels never experienced across European Union and therefore, water companies´ operational costs are also being considerably impacted (Wareg, 2022).

Figures 3 and 4 quantify the potential savings in energy cost and GHG emissions that the water companies could achieve during the years 2013-18. It is shown that on average WaSCs could potentially achieve a 32.34% reduction in their energy cost and 57.35% reduction in their GHG emissions, whereas the potential savings in energy cost and GHG emissions for WoCs were 40% and 60%, respectively. This finding is consistent with the specific efficiencies reported in Figure 2. We analysed the trend in energy cost and GHG emissions by looking at two sub-periods of our sample. The first sub-period (2013-15) covers the 2009 price review, whereas the second sub-period (2016-18) refers to the 2014 price review. During the years 2013-15, Ofwat introduced financial rewards when companies improved economic and environmental performance (Villegas et al., 2019). However, it appeared that WaSC's total energy cost considerably increased from £247.7 million to £286.0 million, whereas the average annual potential savings in energy costs that could have been achieved were at £70.5 million, which was equivalent to a 26.1% reduction in energy costs. Similarly, GHG emissions slightly fluctuated in the years 2013 and 2015 reporting a value of around 1,200,000 tons of CO_{2eq}/year. It was estimated that on average WaSC's GHG emissions could be reduced by 56.8% during the years 2013-15. As far as the potential reductions in energy cost and GHG emissions of WoCs are concerned, it is found that there was a considerable increase in both energy cost and GHG emissions over time. On average, energy costs could be reduced by 50.7%, which was equivalent to a reduction in energy cost of the level of £33 million per year. On the other hand, the potential savings in CO_{2eq} were at the level of 81.4% which is equivalent to 252,706 tons of CO_{2eq}/year. The findings suggest that during the years 2013-15, the water companies did not perform well in terms of energy management and did not adopt any energy and carbon-efficient technologies when abstracting, treating and distributing water to customers.

By contrast, during the second sub-period of our sample (2016-18), this situation appeared to have changed. We note that during that period, Ofwat introduced a set of common indicators to reward/penalise water companies' economic and environmental performance when targets were met/not met. This set of performance indicators was associated with the quality of service and protection of the environment such as water leakage, mains bursts, or sewage collapses (Villegas et al., 2019). Thus, the results showed that during the years 2016-18 average WaSCs' actual energy costs slightly reduced, however, the potential reduction in energy cost in 2018 could still be at the level of £91.6 million per year which was equivalent to a reduction by 31.8%. Over time GHG emissions reduced as well, however, they could additionally be reduced by 68.6% on average during that period of study. A similar pattern is observed for potential savings in energy cost and GHG emissions for WoCs. Although WoCs' actual energy costs and CO_{2eq} considerably reduced during the years 2016-18, companies could still save £36.3 million per year in energy cost and CO_{2eq} by 79.1%. This finding implies that although water companies made some improvements in their energy and CO_{2eq} during the years 2016-18, there is still room for reducing energy and carbon emissions redundancies. It appears that the regulator needs to pay greater attention to the implementations of their energy (carbon-zero) efficiency policies and incentivise water companies to adopt new technologies when treating and distributing water. It also indicates that the potential savings in energy and GHG, in percentage terms, were considerably higher for WoCs than WaSCs suggesting that WoCs need to catch up with the high-efficiency benchmark companies.

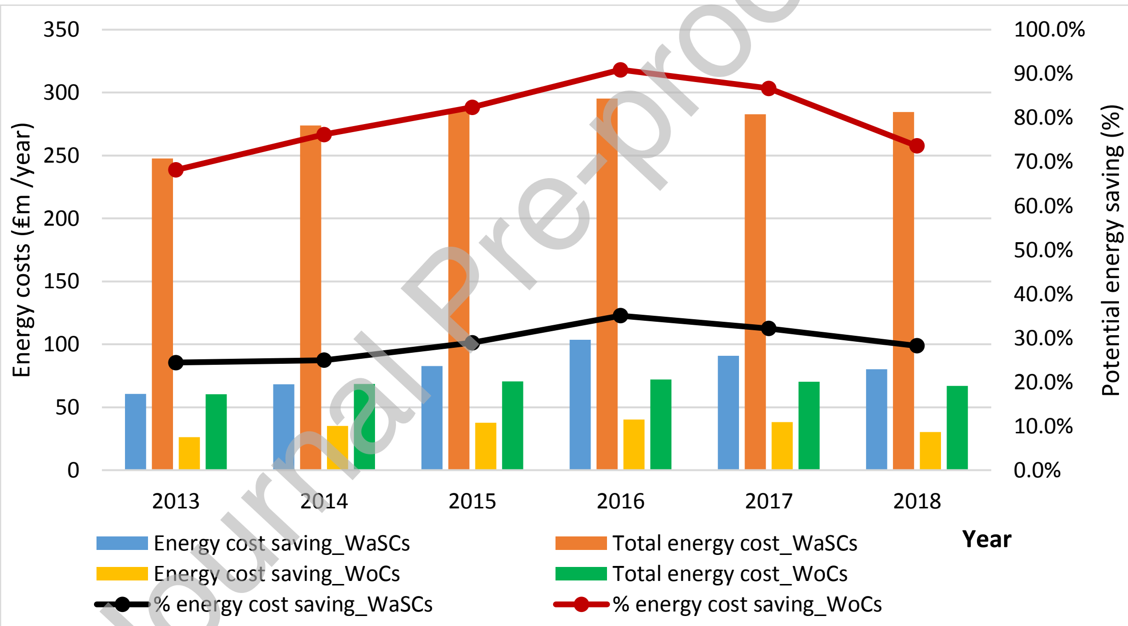


Figure 3. Evolution of the current and potential savings in energy costs for English and Welsh water and sewerage companies (WaSCs) and water only companies (WoCs)

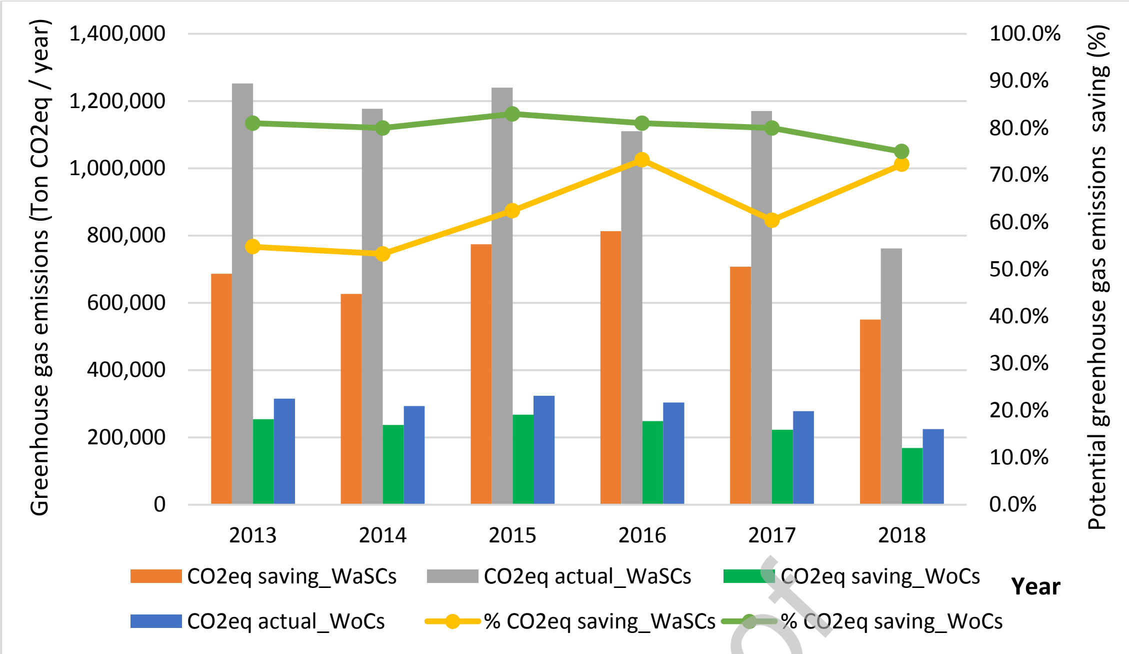


Figure 4. Evolution of the current and potential savings in greenhouse gas emissions for English and Welsh water and sewerage companies (WaSCs) and water only companies (WoCs)

We next discuss the average potential savings in energy costs and GHG emissions that could be achieved at a water company level during the years 2013-18. The results shown in Figure 5 indicate that among WaSCs the potential savings in energy costs ranged from 1.8% to 55.3%. There were five water companies (2 WoCs and 3 WaSCs) whose energy cost savings varied between 1.8% and 6% whereas the rest of the companies reported savings higher than 20%. Considerable higher energy cost savings could be achieved by WoCs. On average, two WoCs could potentially reduce their energy costs by 1.5% whereas the rest of the companies could potentially have energy cost savings between 50% and 61.8%. As far as the GHG savings are concerned, among WaSCs there were three companies whose savings in carbon emissions could vary between 5% and 18.4%. The rest of the companies needed to achieve substantial CO_{2eq} savings ranging from 34% to 88%. Higher GHG savings could be achieved by WoCs. It is found that two WoCs could achieve savings up to 2.1%, whereas for the rest of the companies the savings in CO_{2eq} could be up to 89.4%. The findings demonstrate that WoCs were less energy and carbon-efficient than WaSCs and most of them needed to adopt energy and carbon-efficient technologies in the provision of water services to catch up with the most efficient companies.

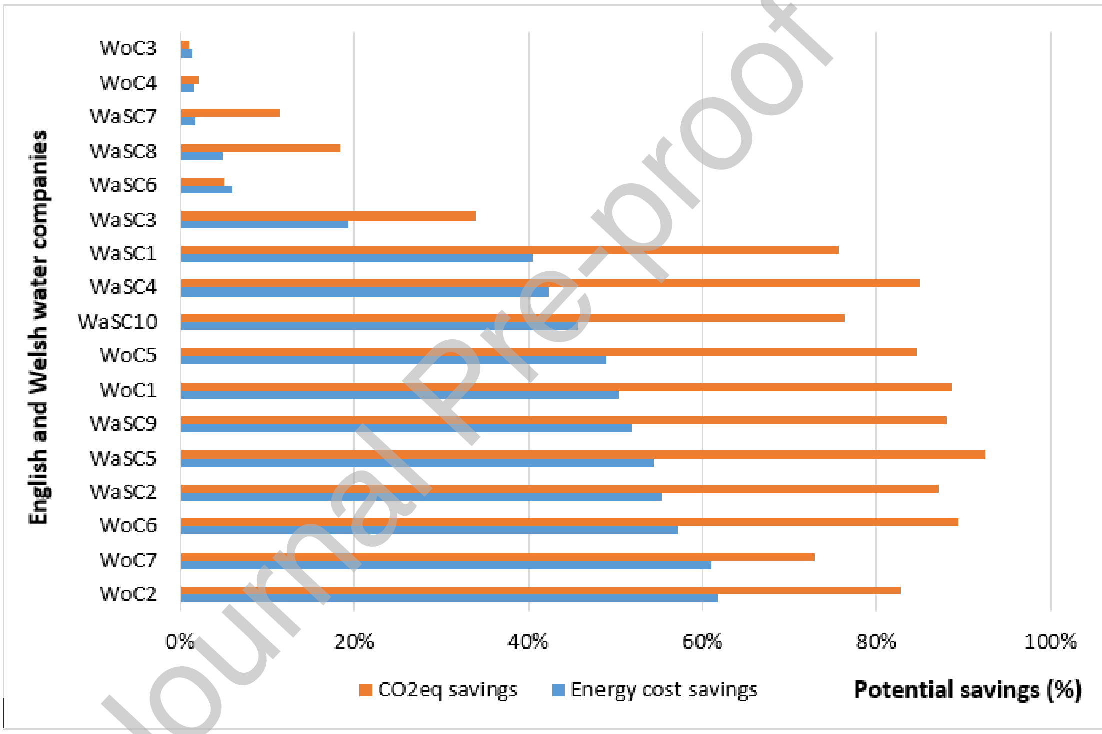


Figure 5. Average potential savings in energy costs and CO_{2eq} for English and Welsh water and sewerage companies (WaSCs) and water only companies (WoCs) over 2013-2018.

The Water Framework Directive (WFD, Directive 2000/60/EC) in the European Union and other national regulations set basic requirements for economic regulation of the water services. In particular, the WFD establishes the principle of full recovery of the costs of water services which involves that water tariffs paid by customers should be in accordance with the costs of the service including environmental and resource costs. This is a basic principle which does not establish any requirement of approach to set water tariffs. The definition of environmental costs in the WFD was vague and therefore, a variety of approaches have been adopted by the different river basin authorities for their estimation. This hinders the proper application of the cost recovery principle (Gomez-Limon and Martin-Ortega, 2013). Taking into account the difficulties of estimating environmental costs, including those for the emission of GHG, an alternative approach might be considering GHG emission efficiency of the water companies when water tariffs are setting. For this purpose, the MEA efficiency scores estimated in this study might be appropriate because they were computed based on ideal reference points specifically derived for each water company. This approach could be implemented by water regulators employing a revenue cap method for setting water tariffs. To set the maximum water tariffs, this regulatory approach not only takes into account the cost of the service but also the efficiency of the water companies (Wareg, 2019). In this context, the potential savings estimated based on energy and GHG emission efficiency scores are an insightful input for the water regulator to improve the process to set water tariffs. This issue is especially relevant in the current energetic context where energy costs are very dynamic and new approaches are needed to integrate energy costs on water tariff setting.

4.2 Influence of environmental variables on aggregate efficiency scores

As the potential savings in energy cost and GHG varied across water companies and over time, it is relevant to assess the impact of several environmental variables on the aggregate efficiency that takes into account both energy cost and GHG emissions efficiency. These results are reported in Table 2. It is found that the percentage of water taken from boreholes, the number of surfaces and groundwater treatment works, the percentage of water receiving high levels of treatment, average pumping head and population density had a statistically significant impact on companies' efficiency. In particular, keeping other things fixed, a one-unit increase in the percentage of water taken from boreholes might lead to a reduction in companies' efficiency by 0.673 units. This reveals that abstracting water from boreholes might require high energy leading therefore to higher energy costs and GHG emissions and consequently, higher inefficiency. This is also evident with the number of treatment works for surface and groundwater but their impact on water companies' efficiency is smaller as indicated by their coefficient. It is also found that the more complex the water treatment process is, the higher the costs of treatment will be and eventually the higher the energy costs and GHG emissions will be, leading therefore to lower efficiency. Ceteris paribus, one unit of increase in the percentage of water receiving high treatment could result in a deterioration in efficiency by 1.874 units. As expected, the higher the energy requirements to abstract, treat and distribute water as captured by the average pumping head, the lower the efficiency of the companies could be. In contrast, as population density increases, the lower the costs of treating and distributing water could be and, subsequently, higher the efficiency of the water company could be, suggesting the existence of economies of density.

Table 2. Environmental variables influencing efficiency score. Estimates of the bootstrap truncated regression

Variables	Coeff.	Bootstr. St.Error	*z*-stat	*p*-value
Constant	3.126	0.724	**4.320**	0.000
Water taken from boreholes	-0.673	0.176	**-3.830**	0.000
Surface water treatment works	-0.006	0.003	***-1.940***	0.055
Groundwater treatment works	-0.001	0.001	***-1.770***	0.080
Water receiving high levels of treatment	-1.874	0.763	**-2.460**	0.016
Average pumping head	-0.003	0.001	**-3.780**	0.000
Population density	0.316	0.137	**2.310**	0.023
Water taken from reservoirs	-0.248	0.155	-1.600	0.113
year				
2014	-0.171	0.037	**-4.594**	0.000
2015	-0.190	0.027	**-7.037**	0.000
2016	-0.131	0.011	**-11.909**	0.000
2017	-0.189	0.023	**-8.217**	0.000
2018	0.108	0.010	**10.800**	0.000
$X^2(12) = 35.85$				
Prob > X^2 = 0.000				

Observations: 102

Bold coefficients are statistically significant from zero at 5% level

Bold italic coefficients are statistically significant from zero at 10% level

As is illustrated in Table 2, several environmental variables influence the efficiency of water companies. According to this finding, water regulators and governments should be cautious in setting GHG emission reduction targets. In other words, due to exogenous factors to water companies, the effort that utilities must make to improve their efficiency in GHG emissions is variable and this should be considered by the regulator.

We note that the period evaluated, i.e. 2013-18, refers to the period covered by the 2009 and 2014 prices. As part of the 2009 price review, the water regulator introduced several incentive schemes to encourage companies to improve performance. For instance, water companies were allowed to keep any savings in operating costs regardless of the year these occurred. Moreover, as part of the 2014 price review, the regulator introduced further incentives to promote economic and environmental efficiency of the water sector. These were related to the imposition of financial penalties and rewards when water companies did not achieve/achieve economic and environmental targets. Our results indicate that these incentives might not have a positive impact on companies' efficiency as average efficiency reduced over time as indicated by the time variable. Moreover, during the regulatory periods, it seems that water companies might have difficulties to control production costs. For instance, high energy prices or the lack of using more renewable energy in the treatment of water could have led to higher energy use and overall costs. Furthermore, extreme climatic events such as heavy rainfall might have caused problems in network performance which could have pushed up production costs. Increases in population growth might have been another reason that could have led to more abstraction of water and therefore high treatment and production costs. The use of energy inefficient technologies to abstract, treat and distribute water to end users could be another factor that increased production costs and deteriorated efficiency. We note that controlling production costs is of great importance from an economic and environmental perspective. Companies could pass cost savings to customers in terms of lower tariffs. At the same time, the use of less energy in the abstraction, treatment and distribution of water could lead to lower carbon emissions and enhance environmental sustainability of water cycle.

5. CONCLUSIONS

According to the environmental standards defined by several countries, one of the main challenges that water utilities are faced with, in the light of climate change and population growth, is the need to reduce energy costs and GHG emissions. To contribute to this relevant issue, in this study, we assessed the energy cost and GHG emissions efficiency of several water companies in England and Wales over the period of 2013-18. We used an MEA approach to compute variable-specific efficiencies, i.e., a separate efficiency score for both energy cost and carbon emissions of the water companies. We then quantified the potential reduction in energy cost and GHG emissions by these companies. Finally, we used econometric techniques to assess the impact of several environmental variables on water companies' energy costs and GHG emissions efficiency.

The findings of our study can be summarised as follows. First, it was found that WaSCs were more energy cost and GHG efficient than WoCs. However, both types of companies need to make substantial reductions in their daily energy costs and the level of GHG emissions. In particular, during the years 2013-18, WaSCs and WoCs needed to reduce their energy costs by 32% and 40% on average, respectively, whereas GHG emissions could further be reduced by 57% and 60% on average, respectively. Equivalently, the potential savings in energy costs for WaSCs and WoCs could be at the level of £91.6 and £36.3 million on average per year, respectively. Furthermore, WaSCs and WoC could save 693,097 and 232,913 tons of CO_{2eq} on average per year if they become more carbon efficient. Considering that revenue cap approach is the method used in England and Wales to set water tariffs, the estimated savings should be passed on to citizens to improve water affordability. Moreover, in the current context of exorbitant increases in energy prices, water regulators should introduce effective policies and tools to encourage water companies to reduce energy costs and GHG emissions.

The findings of our study could be of great interest to policymakers for several reasons. First, they show if the water industry is moving towards being an energy and carbon-efficient industry. considering this data, the water companies can observe the potential improvements that they could achieve in both energy and GHG emissions. The methodology applied in this study allows water regulators to design more energy and carbon-efficient policies and promote energy-efficient management. Moreover, it allows the companies to identify the factors that might be influencing their current energy and GHG efficiency such as the high degree of water treatment. Subsequently, water companies could adopt the appropriate strategies and technologies to reduce energy costs and the level of GHG emissions due to the provision of water services. This information is essential in the transition to a low-carbon urban water cycle.

Because this study integrates both WaSCs and WoCs, it focused on water services. However, the urban water cycle also involves the collection and treatment of wastewater. The literature evidences that wastewater treatment in an energy intensive process with notable differences among wastewater treatment technologies. In this context, future research on this topic might focus on estimating energy costs and GHG emission efficiency scores for a large sample of wastewater treatment plants and comparing their performance based on the technology used for wastewater treatment. Another potential extension of this study is the integration of GHG emissions (scope 3) which currently are not regulated by Ofwat. It would provide a more complete assessment of GHG emissions efficiency in the provision of drinking water services. Finally, the proposed methodology could be used to estimate energy costs and GHG emission efficiency scores for water utilities operating in other countries to enable a cross-country comparison of water companies' performance.

Declaration of interests

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.

REFERENCES

Ananda, J. (2018). Productivity implications of the water-energy-emissions nexus: An empirical analysis of the drinking water and wastewater sector. *Journal of Cleaner Production,* 196, 1097-1195.

Ananda, J., Hampf, B. (2015). Measuring environmentally sensitive productivity growth: An application to the urban water sector. *Ecological Economics*, 116, 211-219.

Arden, S., Ma, X.C., Brown, M. (2019). Holistic analysis of urban water systems in the Greater Cincinnati region: (2) resource use profiles by emergy accounting approach. *Water Research X*, 2, 100012.

Arenas Urrea, S., Díaz Reyes, F., Peñate Suárez, B., de la Fuente Bencomo, J.A. (2019). Technical review, evaluation and efficiency of energy recovery devices installed in the Canary Islands desalination plants. *Desalination*, 54-63.

Asmild, M., Baležentis, T., Hougaard, J.L. (2016). Multi-directional productivity change: MEA-Malmquist. *Journal of Productivity Analysis*, 46, 109–119.

Asmild, M., Hougaard, J.L., Kronborg, D., Kvist, H.K. (2003). Measuring inefficiency via potential improvement. *Journal of Productivity Analysis*, 19(1), 59–76.

Asmild, M., Matthews, K. (2012). Multi-directional efficiency analysis of efficiency patterns in Chinese banks 1997–2008. *European Journal of Operational Research*, 219, 434–441.

Badunenko, O and Tauchmann, H. (2019). Simar and Wilson two-stage efficiency analysis for Stata. *The Stata Journal*, 19 (4), 950-988.

Bi, G., Wang, P., Yang, F., Liang, L. (2014). Energy and Environmental Efficiency of China's Transportation Sector: A Multidirectional Analysis Approach. *Mathematical Problems in Engineering*, 2014,539596.

Bogetoft, P., Hougaard, J.L. (1999). Efficiency evaluations based on potential (non proportional) improvements. *Journal of Productivity Analysis*, 12(3), 233–247.

Brea-Solis, H., Perelman, S. Saal, D.S. (2017). Regulatory incentives to water losses reduction: the case of England and Wales. *Journal of Productivity Analysis*, 47 (3), 259-276.

CCC (2019). Net Zero The UK's contribution to stopping global warming. Report prepared by the Committee on Climate Change. London. UK.

CEPA (2018). PR19 Econometric benchmarking models Ofwat. Report prepared by Cambridge Economic Policy Associates Ltd.

Cetrulo, T.B., Marques, R.C., Malheiros, T.F. (2019). An analytical review of the efficiency of water and sanitation utilities in developing countries. *Water Research*, 161, 372-380.

Engström, R.E., Howells, M., Destouni, G., Bhatt, V., Bazilian, M., Rogner, H.-H. (2017). Connecting the resource nexus to basic urban service provision – with a focus on water-energy interactions in New York City. *Sustainable Cities and Society*, 31, 83-94.

Emrouznejad, E., Yang, G-L. (2016). A framework for measuring global Malmquist-Luenberger productivity index with CO2 emissions on Chinese manufacturing industries. *Energy*, 115, 840-856.

Escriva-Bou, A., Lund, J.R., Pulido-Velazquez, M., Hui, R., Medellín-Azuara, J. (2018). Developing a water-energy-GHG emissions modeling framework: Insights from an application to California's water system. *Environmental Modelling and Software*, 109, 54-65.

Fulton, J., Jin, Y. (2021). Visualizing the United States electricity-water-climate nexus. *Environmental Modelling and Software*, 143, 105128.

Garcia-Sanchez, I. (2006). Efficiency measurement in Spanish local government: The case of municipal water services. *Rev. Policy Res.,* 23, 355–371.

Garrido-Baserba, M., Corominas, L., Cortés, U., Rosso, D., Poch, M. (2020). The Fourth-Revolution in the Water Sector Encounters the Digital Revolution. *Environmental Science & Technology,* 54 (8), 4698-4705.

Gómez-limón, J.A., Martin-Ortega, J. (2013). The economic analysis in the implementation of the Water-Framework Directive in Spain. *International Journal of River Basin Management,* 11 (3), 301-310.

Guerrini, A., Romano, G., Leardini, C., and Martini, M. (2015). The Effects of Operational and Environmental Variables on Efficiency of Danish Water and Wastewater Utilities. *Water*, 7, 3263-3282.

HM Government (2018). A Green Future: Our 25 Year Plan to Improve the Environment. London. UK.

HM Government (2019). Environmental Reporting Guidelines: Including streamlined energy and carbon reporting guidance March 2019 (Updated Introduction and Chapters 1 and 2). London, UK.

Holvad, T., Hougaard, J.L., Kronborg, D., Kvist, H.K. (2004). Measuring inefficiency in the Norwegian bus industry using multi-directional efficiency analysis. *Transportation*, 31, 349–369.

Hong, J., Zhong, X., Guo, S., Liu, G., Shen, G.Q., Yu, T. (2019). Water-energy nexus and its efficiency in China's construction industry: Evidence from province-level data. *Sustainable Cities and Society*, 48, 101557.

Kim, H., Chen, W. (2018). Changes in energy and carbon intensity in Seoul's water sector. *Sustainable Cities and Society*, 41, 749-759.

Krautzberger L, Wetzel H. (2012). Transport and CO2: productivity growth and carbon dioxide emissions in the European commercial transport industry. *Environmental Resource & Economics,* 53 (3), 435-54.

Lam, K.L., Kenway, S.J., Lant, P.A. (2017). Energy use for water provision in cities. *Journal of Cleaner Production,* 143, 699-709.

Lee, M. (2011). Potential cost savings from internal/external CO2 emissions trading in the Korean electric power industry. *Energy Policy*, 39 (10), 6162-6167.

Lee, M., Keller, A. A., Chiang, P.-C., Den, W., Wang, H., Hou, C.-H., Wu, J., Wang, X., Yan, J. (2017). Water-energy nexus for urban water systems: A comparative review on energy intensity and environmental impacts in relation to global water risks. *Applied Energy*, 205, 589-601.

Lemos, D., Dias, A.C., Gabarrell, X., Arroja, L. (2013). Environmental assessment of an urban water system. *Journal of Cleaner Production*, 54, 157–65.

Loubet, P., Roux, P., Loiseau, E., Bellon-Maurel, V. (2014). Life cycle assessments of urban water systems: a comparative analysis of selected peer-reviewed literature. *Water Research*, 67, 187–202.

Molinos-Senante, M., Guzman, C. (2018). Reducing CO_2 emissions from drinking water treatment plants: A shadow price approach. *Applied Energy*, 210, 623-631.

Molinos-Senante, M., Hanley, N., Sala-Garrido, R. (2015). Measuring the CO_2 shadow price for wastewater treatment: A directional distance function approach. *Applied Energy*, 144, 241-249.

Molinos-Senante, M., Maziotis, A. (2018). Flexible versus common technology to estimate economies of scale and scope in the water and sewerage industry: an application to England and Wales. *Environmental Science and Pollution Research*, 25, 14158–14170.

Molinos-Senante, M., S. Porcher, and A. Maziotis. (2017). Impact of Regulation on English and Welsh Water-Only Companies: An Input Distance Function Approach. *Environmental Science and Pollution Research*, 24 (20), 16994–17005.

Ofwat (2009). Levels of service for the water industry in England & Wales 2008-2009 report. The Water Services Regulation Authority, Birmingham, UK.

Ofwat (2010a). Preparing for the future –Ofwat's climate change policy statement. The Water Services Regulation Authority, Birmingham, UK.

Ofwat (2010b). Playing our part – reducing greenhouse gas emissions in the water and sewerage sectors Supporting information, The Water Services Regulation Authority, Birmingham, UK.

Ofwat (2018). Cost assessment for PR19: a consultation on econometric cost modelling. The Water Services Regulation Authority, Birmingham, UK.

Ofwat (2019a). PR19 final determinations: securing cost efficiency technical appendix. The Water Services Regulation Authority, Birmingham, UK.

Ofwat (2019b). PR19 final determinations: Supplementary technical appendix: Econometric approach. The Water Services Regulation Authority, Birmingham, UK.

Ofwat (2019c). RAG 4.08 – Guideline for the table definitions in the annual performance report. The Water Services Regulation Authority, Birmingham, UK.

Renzetti, S., Dupont, D. (2009). Measuring the technical efficiency of municipal water suppliers: The role of environmental factors. *Land Economics*, 85, 627–636.

Rodríguez-Gutiérrez, J.E., Castillo-Molar, A., Fuentes-Cortés, L.F. (2022). A multi-objective assessment for the water-energy-food nexus for rural distributed energy systems. *Sustainable Energy Technologies and Assessments*, 51, 101956.

Saal, D.S., Parker, D., Weyman-Jones, T. (2007). Determining the contribution of technical efficiency, and scale change to productivity growth in the privatized English and Welsh water and sewerage industry: 1985–2000. *Journal of Productivity Analysis*, 28 (1), 127–139.

Sala-Garrido, R., Molinos-Senante, M., Mocholi-Arche, M. (2019). Comparing changes in productivity among private water companies integrating quality of service: a metafrontier approach. *Journal of Cleaner Production,* 216, 597–606.

Simar, L., Wilson, P.W. (2007). Estimation and inference in two-stage, semiparametric models of production processes. *Journal of Econometrics,* 136 (1), 31–64.

Stokes, C.S., Simpson, A.R., Maier, H.R. (2014). The cost–greenhouse gas emission nexus for water distribution systems including the consideration of energy generating infrastructure: an integrated conceptual optimization framework and review of literature. *Earth Perspectives*, 1, 9.

Stone & Webster Consultants. (2004). Investigation into evidence for economies of scale in the water and sewerage industry in England and Wales (Final Report). London: Tennyson House.

Sun, Y., Garrido-Baserba, M., Molinos-Senante, M., Donikian N.A., Poch, M., Rosso, D. (2020). A composite indicator approach to assess the sustainability and resilience of wastewater management alternatives. *Science of the Total Environment*, 725, 138286.

Villegas, A., Molinos-Senante, M., Maziotis, A. (2019). Impact of environmental variables on the efficiency of water companies in England and Wales: a double-bootstrap approach. *Environmental Science and Pollution Research*, 26, 31014–31025.

Walker, N.L., Styles, D., Gallagher, J., Prysor Williams, A. (2021). Aligning efficiency benchmarking with sustainable outcomes in the United Kingdom water sector. *Journal of Environmental Management,* 287, 112317.

Wang, J., Chermak, J.M. (2021). Is less always more? Conservation, efficiency and water education programs. *Ecological Economics*, 184, 106994.

Wang, K., Wei, Y.M., Zhang, X. (2013). Energy and emissions efficiency of Chinese regions: a multidirectional efficiency analysis. *Applied Energy*, 104, 105-16.

Wang, K., Wei, Y.M. (2014). China's regional industrial energy efficiency and carbon emissions abatement costs. *Applied Energy*, 130, 617- 31.

Wang, K., Wei, Y.-M., Zhang, X. (2012). A comparative analysis of China's regional energy and emission performance: Which is the better way to deal with undesirable outputs?. *Energy Policy*, 46, 574-584.

Wang, X., Xan, L., Yin, L. (2016). Environmental Efficiency and Its Determinants for Manufacturing in China. *Sustainability*, 9, 47.

Wang, X.-C., Klemes, J.J., Wang, Y., Dong, X., Wei, H., Xu, Z., Varbanov P.S. (2020). Water-Energy-Carbon Emissions nexus analysis of China: An environmental input-output model-based approach. *Applied Energy*, 261, 114431.

Wareg (European Water Regulators Association) (2019). Tariff regulatory frameworks in WAREG member countries. Available at: https://www.wareg.org/documents/water-tariffs-frameworks-in-europe/

Wareg (European Water Regulators Association) (2022). Energy cost recovery in tariff methodologies in the water sector. Call for proposal. Available at: https://www.wareg.org/call-for-proposals/

Zhang, Q., Nakatani, J., Wang, T., Chai, C., Moriguchi, Y. (2017). Hidden greenhouse gas emissions for water utilities in China's cities. *Journal of Cleaner Production*, 162, 665-677.

Zhu, N., Balezentis, T., Yu, Z., Wu, Y. (2020). Multi-Directional Meta-Frontier DEA Model for Total Factor Productivity Growth in the Chinese Banking Sector: A Disaggregation Approach. *Informatica*, 31 (1), 185–204.

Zhu, N., Wu, Y.R., Wang, B., Yu, Z.Q. (2019). Risk preference and efficiency in Chinese banking. *China Economic Review*, 53, 324–341.

NOMENCLATURE

CO_{2eq}: CO_2 equivalent

DEA: Data Envelopment Analysis

GHG: greenhouse gas

MEA: multi-directional Data Envelopment Analysis

Ofwat: water services regulation authority

OLS: Ordinary Least Squares

WaSCs: water and sewerage companies

WoCs: water only companies

j: water company

t: time

$x_{i,j}^{t}$: set of discretionary inputs

$x_{-i,j}^{t}$: set of non-discretionary inputs

$y_{r,j}^{t}$: set of outputs

$x_{i,j_0}^{t}, y_{r,j_0}^{t}$: ideal reference point for water company j_0

λ_j: intensity variables

θ_{i,j_0}^{t}: target value for the ith input reduction.

θ_{i,j_0}^{t*}: optimal solution model (1)

$\beta_{j_0}^{t}$: optimal solution model (2); global efficiency score

$\varphi_{j_0}^{t}$: aggregate efficiency score

z_j^t: set of environmental variables

ε_j^t: noise of the regression model