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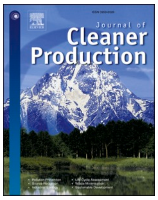

Assessing energy efficiency and its dynamic changes in the water sector integrating heterogeneity and carbon emissions

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ABSTRACT

Enhancing the energy performance of water utilities is a critical step towards achieving a net-zero carbon industry. Traditional energy performance assessments in the water industry often overlook heterogeneity among water companies and fail to account for changes in energy efficiency (EE) over time. To address these shortcomings, this research employs Stochastic Frontier Analysis (SFA) techniques to assess energy performance of two types of water companies such as Water and Sewerage Companies (WaSCs) and Water-only Companies (WoCs) within a single energy frontier model. Empirical analysis of water companies in England and Wales reveals an average EE score of 0.940 over the 2010–2020 period, suggesting a 6% energy-saving potential. English and Welsh water industry exhibited an overall 0.3% annual improvement in energy productivity change (EPC). This improvement was primarily attributed to efficiency changes (average 1.005), which offset the negative shift in technology change (average 0.998), while the scale effect remained negligible (average 1.000). WaSCs experienced a slight increase in EPC, with an average value of 1.018, indicating an improvement in energy productivity. In contrast, WoCs exhibited a decrease in EPC, with an average value of 0.989, suggesting a decline in energy productivity. These disparities were due to opposite shifts in the efficient production frontier; WaSCs had a positive shift (average 1.012), while WoCs had a negative shift (average 0.984). The study also highlights the impact of regulatory policies on energy performance. The 2009 price review involved modest improvements (average EPC = 1.013), while the 2014 price review yielded unfavorable results (average EPC = 0.993), emphasizing the need for long-term policies to facilitate sector-wide transformation towards carbon neutrality.

1. Introduction

The intricate relationship between energy and water has been studied from two perspectives: analyzing water consumption in energy production and the energy utilization in water services (Zib et al., 2021). Concentrating on energy consumption within the urban water sector, the United Nations report that about 8% of the world's total primary energy is expended in the processes of water delivery and treatment (UN Water, 2014; UNESCO, 2014). In light of climate change and population growth, one of the challenges that water utilities are faced with is the need to reduce greenhouse gas emissions (GHG) from the provision of water and sanitation services (Han et al., 2023). Life cycle assessments across various global cities indicate that the activities of extracting, distributing, and treating urban water generate approximately 0.5–2.5 kg of CO_2 equivalent (CO_{2e}) per cubic meter of water supplied (Mo et al., 2014; Meron et al., 2020). In this context, policy makers and researchers are interested in understanding the water-energy-carbon nexus[1] as it would allow them to identify strategies to improve economic and environmental performance and move to a net zero carbon industry (Emrouznejad and Yang, 2016). This ambition is mirrored in the commitments by several Australian states and the United Kingdom (UK), which have set targets to achieve a net-zero carbon water industry by 2050 and 2030, respectively (Ananda and Hampf, 2015; HM Government, 2019; CCC, 2019).

Enhancing energy efficiency (EE) is essential towards carbon neutrality of cities (Xu and Zhang, 2023; Jin and Xu, 2024). Within the

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[1] Water–energy–carbon nexus is a general term that refers to the interrelationships between water, energy, and carbon sources (Ghodrati et al., 2023).

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provision of drinking water services holds the potential for significant benefits, both economically and environmentally. These improvements can lead to reduced operational costs and a decrease in carbon emissions (Walker et al., 2020). However, it is important to acknowledge that water utilities operate as natural monopolies, which can create limited incentives for them to pursue innovation and efficiency enhancements (Marques et al., 2011). In this context, benchmarking emerges as a crucial mechanism for driving efficiency improvements by systematically analyzing performance and making comparisons (Ananda, 2018). Over the past two decades, research in the field of benchmarking analysis within the water industry has significantly expanded, with production frontier analysis being the most prevalent method used to benchmark the performance of water utilities (Berg and Marques, 2011; Carvalho et al., 2012; Worthington, 2014; Cetrulo et al., 2019; Goh and See, 2021).

Although it is crucial to assess the EE of water utilities providing drinking water services, there is a notable scarcity of literature on this subject, with only two noteworthy exceptions. In their study, Walker et al. (2020) evaluated the EE of seventeen water companies operating in England and Wales during the 2017–18 period. They employed data envelopment analysis (DEA), a deterministic parametric method for estimating the production frontier. It is worth noting that DEA is sensitive to outliers (Longo et al., 2023), which is a relevant shortcoming of this methodology. The assessment conducted by Walker et al. (2020) focused on conventional EE without considering the adverse environmental impacts, such as GHG emissions associated with drinking water provision (Ananda and Oh, 2023). Given the increasing importance of reducing GHG emissions for achieving a net-zero carbon water industry, Molinos-Senante et al. (2022) took a different approach by integrating GHG emissions as a significant variable in the production function to estimate EE. Additionally, in contrast to Walker et al. (2020), Molinos-Senante et al. (2022) employed stochastic frontier analysis (SFA), a parametric method that allows for modeling the influence of operational characteristics on water company performance. Their empirical study also focused on a sample of water companies in England and Wales.

While Molinos-Senante et al. (2022) successfully address a significant limitation of conventional efficiency assessments, namely the omission of externalities, their approach is still subject to another challenge inherent to traditional benchmarking. It is the inability to compare heterogenous units (O'Donell et al., 2008; Oh, 2010; Jin et al., 2020). In England and Wales, as in many other countries, drinking water services are provided by two distinct types of water companies: water and sewerage companies (WaSCs) and water-only companies (WoCs). Several studies in the past (e.g., Saal and Parker, 2006; Molinos-Senante and Maziotis, 2017, 2018) highlighted that WoCs and WaSCs might operate under different production technologies. Failing to account for this technological heterogeneity in efficiency estimates can introduce bias, as these units may operate with varying input sets and within different production environments (Huang et al., 2015; O'Donnell et al., 2008).

EE offers a snapshot evaluation of the energy performance of analyzed water companies, assessing their performance at a specific point in time without accounting for potential changes over time (Demiral and Saglam, 2023). In contrast, productivity change expands the concept of efficiency to a temporal context (Lo Storto, 2021). Therefore, the assessment of energy productivity change (EPC) enables us to determine whether water companies have improved or worsened their energy performance over a defined time period. Additionally, in many countries, including England and Wales, Colombia, and certain Australian states, water tariffs are adjusted based on benchmarking their productivity change (Ananda and Oh, 2023). This underscores the importance of evaluating both EE and EPC from a regulatory standpoint. However, to the best of our knowledge, there are no previous studies that assess changes in the energetic performance of water companies over time.

The present study aims to overcome two key shortcomings of conventional energetic performance assessment of the water industry. These limitations include the presence of heterogeneity among the water companies being analyzed and the static evaluation that does not account for changes in performance over time. Within this context, the objectives of this study are twofold. The first objective of this study is to evaluate the energetic performance of the water supply process and its changes over time by quantifying both EE and EPC metrics. Unlike previous studies, this evaluation will take into consideration the inherent heterogeneity among water companies and their in carbon emissions. The second objective is to examine the impact of the regulatory cycle on the energetic performance, encompassing both EE and EPC, of the water industry in England and Wales. The current research provides a twofold contribution that significantly enhances the understanding of energy performance in water companies irrespective of the methodological approach such as SFA or DEA. This study pioneers the integration of group heterogeneities into the energy performance assessments of water companies, providing insights that remain robust across both parametric and non-parametric methods. Our innovative approach introduces an econometric model that is capable of simultaneously estimating diverse technologies employed by different types of water companies. This model is designed to mitigate potential biases in efficiency and productivity evaluations, which is critical for accurate performance assessments. To our knowledge, this represents the first attempt to explicitly incorporate the diversity of group characteristics within the water sector into the estimation of performance using these approaches. This methodological advancement is crucial as it mitigates potential biases in efficiency and productivity evaluations (Badunenko and Kumbhakar, 2017). Moreover, our study conducts a longitudinal analysis of energy performance dynamics spanning several years among water utilities in England and Wales. This exploration is pivotal as it dissects the components of energy productivity evolution, categorizing the changes into improvements in energy efficiency, advancements in technology, and alterations in scale. By doing so, it provides a nuanced understanding of how these factors interrelate with the regulatory frameworks in place. The analysis extends to examine the impact of regulatory policies on energy performance, offering empirical insights into the effectiveness of these interventions in fostering enhancements in the energy dynamics of the water sector. This comprehensive examination not only fills a critical gap in the existing literature but also serves as a valuable resource for policymakers and industry stakeholders aiming to optimize energy practices and policy approaches within the water industry.

This article is structured into four additional sections to achieve the proposed objectives. In Section 2, the methodological approach used to estimate EE and EPC is presented in detail. Section 3 introduces the case study. In Section 4, the results on EE and EPC for the English and Welsh water companies are presented and discussed. Finally, the article concludes in Section 5, which provides final remarks and considerations for future research.

2. Methodology

EE and its changes over time, i.e., EPC, can be estimated using non-parametric methods such as DEA (Walker et al., 2020) and parametric methods such as SFA (Molinos-Senante et al., 2022). DEA, as a deterministic approach, is sensitive to outliers and does not allow for the integration of environmental variables in performance assessments. This limitation is particularly relevant for water companies, as environmental variables are known to significantly influence their performance (Pinto et al., 2017; Amaral et al., 2023; Molinos-Senante et al., 2023). To address this issue and incorporate random errors in the assessment, Fried et al. (2022) proposed a three-stage DEA model. However, the initial stage of this model involves estimating efficiency scores using a traditional DEA approach, which can be influenced by extreme values or anomalous data. Additionally, when the sample size is small relative to the number of predictors, the results can be biased, and the model may be overfitted (Moons et al., 2009; Anouze and Bou-Hamad, 2021), a consequence of the sample size rather than the model's behavior. On the other hand, parametric methods, i.e., SFA, also have limitations, mainly due to the variety of production functions available, the choice of which can lead to systematic errors (Zhang and Chen, 2022). Nevertheless, considering the number of water companies to be assessed, the potential variability in data, and previous research, this study opted for the SFA approach to estimate EE and EPC for English and Welsh water companies. Nevertheless, future research could estimate EE and EPC using the three-stage DEA approach to analyze how methodological choices influence the results. The assessment of water companies' energetic performance is conducted using a production economy framework and the distance function approach whose fundamentals are outlined below. Let's assume that the water company, uses a set of inputs $x = x_1, \ldots, x_K$ to generate a set of outputs $y = y_1, \ldots, y_L$. In our case, the inputs are energy (E) and other costs (OC), and the output is the volume of drinking water delivered (y). As part of the process, carbon emissions (c) are produced as well. Water companies want to minimize carbon emissions in addition to their inputs so carbon emissions are treated as another input (Zhou et al., 2010, 2012; Lin and Du, 2015; Tan et al., 2020; Molinos-Senante and Maziotis, 2021).

The production technology is defined as follows:

$$PT = \{(E, OC, y, c) \,|\, E \text{ and } OC \text{ can produce } y \text{ and } c\} \tag{1}$$

Based on the concept of the Shephard distance functions (Shephard, 1957), the energy distance function is defined as follows:

$$D(E, OC, y, c) = sup\left\{\theta : \left(\frac{E}{\theta}, OC, y, c\right) \in PT\right\} \tag{2}$$

where θ measures the distance by which the energy input can be reduced to generate the same level of output. When $D(E, OC, c, y)$ takes a value which is equal to one, it means that the water utility is on the energy frontier, whereas $D(E, OC, c, y) > 1$ denotes inefficiency and therefore, potential room to reduce energy use (Zhou et al., 2012; Lin and Du, 2015).

Based on the energy distance function, energy efficiency (EE) of each water company is computed as follows:

$$EE = \frac{1}{D(E, OC, y, c)} \tag{3}$$

An EE score of 1 signifies that the water company is operating at full energy efficiency, while any score below 1 denotes a measure of inefficiency.

The energy distance function (Eq. (2)) is estimated using parametric techniques and as a result, a specification of its functional form is required. This study uses a translog functional form because we want to keep the presentation of the production technology as much flexible as possible and to allow for the size of companies to vary over time (Faust and Baranzini, 2014; Tourinho et al., 2022; Ben Amor and Mellah, 2023). The generic form of the translog energy distance function is written as follows:

$$\begin{aligned} ln\frac{1}{E_{j,t}} = {} & a_o + \sum_{l=1}^{L} a_l \, ln\, y_{l,j,t} + \sum_{k=1}^{K} \beta_k \, ln\, x_{k,j,t} + \frac{1}{2}\sum_{l=1}^{L}\sum_{m=1}^{L} \alpha_{lm} \, ln\, y_{l,j,t} \, ln\, y_{m,j,t} \\ & + \frac{1}{2}\sum_{k=1}^{K}\sum_{n=1}^{K} \beta_{kn} \, ln\, x_{k,j,t} \, ln\, x_{n,j,t} + \sum_{l=1}^{L}\sum_{k=1}^{K} \gamma_{lk} \, ln\, y_{l,j,t} \, ln\, x_{k,j,t} + \psi_1 t + \frac{1}{2}\psi_2 t^2 \\ & + \sum_{k=1}^{K} \delta_k \, ln\, x_{k,j,t} t + \sum_{l=1}^{L} \delta_l \, ln\, y_{l,j,t} t + \sum_{z=1}^{Z} \mu_z z_{j,t} + v_{j,t} - u_{j,t} \end{aligned} \tag{4}$$

where j denotes any water company, t is the time period covered, x includes other costs and carbon emissions, z is a set of environmental variables such as water treatment complexity, which could have an impact on efficiency (Pinto et al., 2017). Moreover, a_o denotes the constant term, $v_{j,t}$ is the standard error term which follows the normal distribution and $u_{j,t}$ measures inefficiency and follows the exponential distribution.

Thus, EE of any water company j and any time t can be derived as:

$$EE_{j,t} = \exp(-u_{j,t}) \tag{5}$$

Because water utilities providing drinking water in England and Wales embrace WaSCs and WoCs, production technologies (Eq. (1)) are collectively modeled by integrating both types of companies into a unified analysis (Badunenko and Kumbhakar, 2017). This is done by using dummy variables (Triebs et al., 2016; Molinos-Senante et al., 2017). Specifically, we used D^{WASC} as a dummy for WaSCs and D^{WOC} as a dummy for WoCs. Thus, the energy input distance function is modified accordingly:

$$\begin{aligned} ln\frac{1}{E_{j,t}} = D^{WASC} \times \Bigg\{ & a_o + \sum_{l=1}^{L} a_l \, ln\, y_{l,j,t} + \sum_{k=1}^{K} \beta_k \, ln\, x_{k,j,t} + \frac{1}{2}\sum_{l=1}^{L}\sum_{m=1}^{L} \alpha_{lm} \, ln\, y_{l,j,t} \, ln\, y_{m,j,t} + \frac{1}{2}\sum_{k=1}^{K}\sum_{n=1}^{K} \beta_{kn} \, ln\, x_{k,j,t} \, ln\, x_{n,j,t} + \sum_{l=1}^{L} \\ & \times \sum_{k=1}^{K} \gamma_{lk} \, ln\, y_{l,j,t} \, ln\, x_{k,j,t} + \psi_1 t + \frac{1}{2}\psi_2 t^2 + \sum_{k=1}^{K} \delta_k \, ln\, x_{k,j,t} t + \sum_{l=1}^{L} \delta_l \, ln\, y_{l,j,t} t + \sum_{z=1}^{Z} \mu_z z_{j,t} + v_{j,t} - u_{j,t} \Bigg\} + D^{WOC} \times \Bigg\{ a_o + \sum_{l=1}^{L} a_l \, ln\, y_{l,j,t} + \sum_{k=1}^{K} \beta_k \, ln\, x_{k,j,t} + \frac{1}{2}\sum_{l=1}^{L} \\ & \times \sum_{m=1}^{L} \alpha_{lm} \, ln\, y_{l,j,t} \, ln\, y_{m,j,t} + \frac{1}{2}\sum_{k=1}^{K}\sum_{n=1}^{K} \beta_{kn} \, ln\, x_{k,j,t} \, ln\, x_{n,j,t} + \sum_{l=1}^{L}\sum_{k=1}^{K} \gamma_{lk} \, ln\, y_{l,j,t} \, ln\, x_{k,j,t} + \psi_1 t + \frac{1}{2}\psi_2 t^2 + \sum_{k=1}^{K} \delta_k \, ln\, x_{k,j,t} t + \sum_{l=1}^{L} \delta_l \, ln\, y_{l,j,t} t + \sum_{z=1}^{Z} \mu_z z_{j,t} + v_{j,t} - u_{j,t} \Bigg\} \end{aligned} \tag{5}$$

The energy input distance function in Eq. (5) is company-type flexible because it allows water companies of different type to function on their frontier. Moreover, each term in Eq. (5) is activated when the firm-type dummy takes a value of 1 (Molinos-Senante and Maziotis, 2017). Finally, it allows both the variables and related parameters to vary between the two types of water utilities.

The estimated parameters of the energy distance function in Equation (5) enable the evaluation of energy productivity within a flexible technology framework. This means that they allow to assess the EPC of water companies, i.e., changes in the EE of water companies over time. To achieve this, the method for estimating productivity change proposed by Orea (2002) is modified to include considerations for flexible technology types. Thus, we define the EPC between two time period t and $t+1$ under flexible type technology as follows:

$$EPC = ln\left(EP_{j,t+1} \,/\, EP_{j,t}\right) = D^{WASC} \times \left\{ ln\left(EE_{j,t+1} \,/\, EE_{j,t}\right) + \frac{1}{2}\left(\vartheta\, ln\frac{1}{E_{j,t+1}} \Big/ \vartheta t + \vartheta\, ln\frac{1}{E_{j,t}} \Big/ \vartheta t\right) + \left\{ + \frac{1}{2}\sum_{k=1}^{K}\left[\left(1 + \vartheta\, ln\frac{1}{E_{j,t+1}} \Big/ \vartheta lny_{j,t}\right) + \left(1 + \vartheta\, ln\frac{1}{E_{j,t}} \Big/ \vartheta lny_{j,t}\right)\right]\left(lny_{j,t+1} - lny_{j,t}\right) \right\}\right\} + D^{WOC} \times \left\{ ln\left(EE_{j,t+1} \,/\, EE_{j,t}\right) + \frac{1}{2}\left(\vartheta\, ln\frac{1}{E_{j,t+1}} \Big/ \vartheta t + \vartheta\, ln\frac{1}{E_{j,t}} \Big/ \vartheta t\right) + \left\{\frac{1}{2}\sum_{k=1}^{K}\left[\left(1 + \vartheta\, ln\frac{1}{E_{j,t+1}} \Big/ \vartheta lny_{j,t}\right) + \left(1 + \vartheta\, ln\frac{1}{E_{j,t}} \Big/ \vartheta lny_{j,t}\right)\right]\left(lny_{j,t+1} - lny_{j,t}\right) \right\}\right\} \tag{6}$$

A EPC value exceeding one indicates an enhancement in energy performance, while a value below one suggests a decline. The EPC index is composed of three distinct elements, each corresponding to changes in efficiency, technology, and scale, respectively (Ananda, 2018). The first term is defined as energy efficiency change (EEC) and measures the change in energy efficiency from one time period to another, $ln\left(EE_{j,t+1} / EE_{j,t}\right)$. If $EEC > 1$ then it means that the company has improved its efficiency relative to the most energy efficient company, whereas a value lower than one indicates energy efficiency losses. The second component, $\left(\frac{1}{2}\left(\vartheta\, ln\frac{1}{E_{j,t+1}}/\vartheta t + \vartheta\, ln\frac{1}{E_{j,t}}/\vartheta t\right)\right)$, captures energy related technical change (ETC) and measures how the rate of technical progress or deterioration in adopting energy efficient technologies. If $ETC > 1$ then it means that the company achieved technical progress whereas values lower than 1 indicate technical regress. The last component in the EPC index captures the energy related scale effect (ESC). It shows the impact on energy input and inefficiency when the company changes its scale of operations, for example, by delivering more water to its customers. If $ESC > 1$, then it means that an increase in the size of the company might have decrease the energy input requirements as larger companies might have ended up in using more energy efficient methods to treat and deliver water and thus, reduced inefficiency.

The EPC index for any given water utility is calculated by considering the three components (EEC, ETC and ESC) along with the company type dummies. In analogous manner, the two dummy variables are assigned a value of zero or one depending on whether the water utility is a WaSC or a WoC and therefore, they act as a switch (Molinos-Senante and Maziotis, 2018).

Table 1
Average values of the variables for assessing energy efficiency and productivity for English and Welsh water companies (2010–2020).

Variables	Unit of measurement	All water companies	Water only companies (WoCs)	Water and sewerage companies (WaSCs)
Energy expenditure	£m/year	18.78	8.40	27.37
Other expenditure	£m/year	89.73	35.93	134.23
GHG	ton CO_{2eq}/year	75,333	36,847	107,173
Volumes of water delivered	Ml/year	243,098	97,653	363,420
Average pumping head	nr	137.84	145.57	131.46
Water taken from rivers	%	27.0	23.8	29.5
Water taken from boreholes	%	41.9	54.9	31.2
Water receiving high levels of treatment	%	58.0	63.7	53.4
Observations		201	91	110

Operating expenditure is expressed in 2020 prices.

3. Case study description

The empirical application is associated with the water services that WaSCs and WoCs provided to their customers in England and Wales during the years 2010–2020. Operating as natural monopolies, these companies are overseen by the Water Services Regulation Authority (Ofwat), which is tasked with assessing and tracking the economic performance and service quality within the industry. Ofwat conducts a comprehensive review every five years, during which it endorses the business plans of water companies and establishes a permitted expenditure level. This expenditure limit is then converted into a revenue allowance, ultimately shaping the revenue (or price) ceilings (Bottasso and Conti, 2009).

Drawing from prior research on the efficiency of water utilities globally (e.g., Berg and Marques, 2011; See, 2015; Cetrulo et al., 2019; Goh and See, 2021), considering data availability and the primary aim of our study, we selected certain variables to evaluate EE and EPC, including their underlying factors (see Table 1 which presents descriptive statistics of the variables). Our analysis incorporates three input factors. The first is the annual energy expenditure associated with providing water services, quantified in millions of pounds per year. The second input factor is other operational expenditures, calculated by subtracting energy costs from the total operating expenses for water services, also denominated in millions of pounds per year. The third input factor is the GHG emissions from water service operations, reported in tons of CO_{2e} per year. The GHG emissions data are annually disclosed by the water companies in England and Wales, adhering to the UK Government Environmental Reporting Guidelines (HM Government, 2019).[2] As far as the choice of output is concerned, we use the volume of drinking water delivered per year measured in megalitres per year.

The selection of environmental potentially affecting the energy efficiency of water utilities was informed by previous studies on the subject (Villegas et al., 2019; Walker et al., 2019; Sala-Garrido et al., 2021a, 2021b). The initial variable selected is the average pumping head, which captures the energy requirements to take water from different sources, move it to the treatment plants and then deliver it to final users. Other environmental variables related to source of raw water were the percentage of water taken from boreholes and rivers. The complexity of water treatment processes was represented by the percentage of water undergoing extensive treatment (Ofwat, 2019; Walker et al., 2020,

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[2] GHG considered in this study involve: i) Scope 1 emissions, i.e., GHG emissions from owned or leased transportation and internal utilization of fossil fuel; ii) Scope 2 emissions, i.e., GHG emissions arising from the computation of grid electricity for several activities including water pumping, treatment and distribution, as well as electricity use within owned buildings and; iii) Scope 3 emissions, i.e., GHG emissions associated with contracted and outsourced services, as well as business-related transportation (Ofwat, 2010).

Table 2
Coefficients of the parameters corresponding to the energy distance functions (Equations (4) and (5)).

Variables	Coeff.	St. Err.	T-stat	p-value
Constant$_{WoC}$	3.822	0.369	**10.366**	0.000
Water delivered$_{WoC}$	−1.109	0.045	**−24.913**	0.000
CO_{2WoC}	0.294	0.097	**3.034**	0.002
Other expenditure$_{WoC}$	0.175	0.096	***1.819***	0.069
Time$_{WoC}$	−0.011	0.004	**−2.747**	0.006
Water delivered$^2_{WoC}$	−0.035	0.035	−1.003	0.316
$CO^2_{2\ WoC}$	0.249	0.142	***1.751***	0.080
Other expenditure $^2_{WoC}$	−0.106	0.050	**−2.124**	0.034
CO_{2WoC}*Other expenditure$_{WoC}$	0.258	0.180	1.433	0.152
Water delivered$_{WoC}$*CO_{2WoC}	0.057	0.056	1.027	0.304
Water delivered$_{WoC}$*Other expenditure$_{WoC}$	0.055	0.050	1.090	0.276
Water delivered$_{WoC}$*Time$_{WoC}$	0.000	0.007	0.064	0.949
CO_{2WoC}*Time$_{WoC}$	−0.011	0.002	**−4.648**	0.000
Other expenditure$_{WoC}$*Time$_{WoC}$	0.012	0.004	**2.999**	0.003
Time $^2_{WoC}$	−0.002	0.004	−0.576	0.564
Average pumping head$_{WoC}$	−0.720	0.053	**−13.691**	0.000
Water treatment complexity$_{WoC}$	−0.322	0.098	**−3.290**	0.000
Water taken from boreholes$_{WoC}$	−0.071	0.054	−1.301	0.193
Water taken from rivers$_{WoC}$	−0.179	0.059	**−3.063**	0.000
Constant$_{WaSC}$	3.420	0.463	**7.385**	0.000
Water delivered$_{WaSC}$	−0.894	0.026	**−33.883**	0.000
CO_{2WaSC}	0.118	0.048	**2.446**	0.014
Other expenditure$_{WaSC}$	0.247	0.042	**5.912**	0.000
Time$_{WaSC}$	0.023	0.005	**4.922**	0.000
Water delivered$^2_{WaSC}$	−0.358	0.075	**−4.753**	0.000
$CO^2_{2\ WaSC}$	0.138	0.055	**2.507**	0.012
Other expenditure $^2_{WaSC}$	0.170	0.083	**2.057**	0.041
CO_{2WaSC}*Other expenditure$_{WaSC}$	0.037	0.053	0.703	0.482
Water delivered$_{WaSC}$*CO_{2WaSC}	−0.062	0.037	−***1.677***	0.094
Water delivered$_{WaSC}$*Other expenditure$_{WaSC}$	0.160	0.072	**2.229**	0.026
Water delivered$_{WaSC}$*Time$_{WaSC}$	0.007	0.007	1.032	0.302
CO_{2WaSC}*Time$_{WaSC}$	0.015	0.005	**2.845**	0.004
Other costs$_{WaSC}$*Time$_{WaSC}$	−0.040	0.015	**−2.682**	0.007
Time $^2_{WaSC}$	−0.001	0.002	−0.524	0.601
Average pumping head$_{WaSC}$	−0.662	0.065	**−10.116**	0.000
Water treatment complexity$_{WaSC}$	−0.257	0.087	**−2.935**	0.000
Water taken from boreholes $_{WaSC}$	−0.114	0.051	**−2.260**	0.024
Water taken from rivers $_{WaSC}$	−0.156	0.089	−***1.748***	0.081
Theta	15.625	3.173	**4.924**	0.000
Sigma	0.065	0.009	**7.600**	0.000
Log-likelihood	203.563			

Energy expenditure is the dependent variable.
Bold statistics are statistically significant at 5% significance level.
Bold and italic statistics are statistically significant at 10% significance level.

2021).

4. Results and discusssion

The first stage to assess the EE and EPC of the water companies estimated the energy distance function whose estimated parameters are shown in Table 2. For both types of water companies (WaSCs and WoCs), the elasticity of energy with respect to water delivered, which is represented by the term "Coeff" in Tables 2 and is negative and statistically significant from zero. Similarly, the elasticities for carbon emissions and other expenditures are positive and also statistically significant from zero. These results indicate that the distance function decreases with increased outputs and increases with heightened inputs, implying that the distance function has been appropriately specified (Ferro and Mercadier, 2016).

Results for WoCs evidence the existence of small diseconomies of scale as on average one percentage increase in the volume of water delivered could lead to an increase in energy by 1.109%. Volumes of water delivered, carbon emissions and other costs have a significant impact on WoCs' energy input on average. The time variable which captures technical change is negative and statistically significant from zero. This suggests the existence of technical regress. The rate of technical regress for an average WoC was 1.1% on average over the period of study. Carbon emissions had been increasing at a decreasing rate as shown by the square term. In contrast, the rate of increase for the other costs was 10.6% over time as indicated by the magnitude of its squared term. As for the environmental variables, it is found that average pumping head, high levels of water treatment and water taken from rivers had a significant impact on average WoCs' energy requirements. In particular, higher pumping requirements to abstract, treat and deliver water to customers the higher the use of energy could be. This might also lead to higher levels of carbon emissions released to the atmosphere. This was the variable that had the major impact on WoCs' energy input as indicated by the magnitude of its estimated coefficient.

In the case of WaSCs, results of the energy frontier model (Table 2) illustrate that a 1% increase in the volumes of water delivered could lead in an increase in energy cost by 0.894% on average. This finding implies the existence of small economies of scale for an average WaSC. The time variable is positive and statistically significant from zero. This means that average WaSC experienced technical progress at a rate of 2.3% per annum. Volumes of water delivered had been increasing at an increasing rate as shown by its squared term. In contrast, the rate of increase for carbon emissions and other costs had been increasing at a decreasing rate which was 13.8% and 17.0% on average, respectively as indicated by the squared terms of these variables. As far as the environmental variables are concerned, it is found that all of them had a significant impact on energy input. Average pumping head and high levels of water treatment were the ones that had the major influence on energy use and costs.

Focusing on the EE of assessed water companies, Fig. 1 reveals that the English and Welsh water industry has achieved commendably high energy performance levels, with average EE scores for WoCs, WaSCs, and the industry as a whole being 0.942, 0.938, and 0.940, respectively. This indicates that there is a potential for water utilities to achieve energy savings of about 6% while maintaining the same drinking water delivery volume. WoCs, on average exhibited marginally higher energy efficiency than WaSCs, with potential energy input reductions of 5.8% for WoCs and 6.2% for WaSCs without altering water delivery volumes.

Previous studies in this field have yielded widely varying conclusions. On one hand, Walker et al. (2020) estimated an average EE of 0.083 using the DEA method, suggesting that English and Welsh water companies could potentially save, on average, 91.7% of their energy usage. The authors themselves acknowledged that this result is unusual and likely influenced by the small number of water companies evaluated ($n = 17$) relative to the number of variables used, which was three.[3] Notably, this study did not incorporate GHG emissions or the operational characteristics of water companies into their EE estimations. On the other hand, Molinos-Senante et al. (2022) employed SFA methods and estimated an average EE of 0.962, indicating that potential energy savings for English and Welsh water companies amount to approximately 3.8%. This result aligns with our own estimations, where the average EE for all companies is estimated at 0.940. These findings underscore the importance of using robust methods when assessing the energy efficiency of water companies.

Fig. 1 also shows the evaluation of EE across years. EE variation for both company types may be linked to fluctuations in the costs. From 2010 to 2013, WaSCs, on average outperformed WoCs in terms of EE, and both company types saw significant improvements in this period. For example, the average EE of WoCs rose from 0.903 in 2010 to 0.945 in 2012. Despite a drop in energy efficiency in 2013 for both types of companies, they maintained high efficiency levels of 0.933 for WoCs and

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[3] A basic premise to apply DEA method is to meet the thumb rule which indicates that the number of units must be equal to or greater than $max\{m\,x\,s; 3\,x\,(m+s)\}$ where m and s are the inputs and outputs variables, respectively (Cooper et al., 2007).

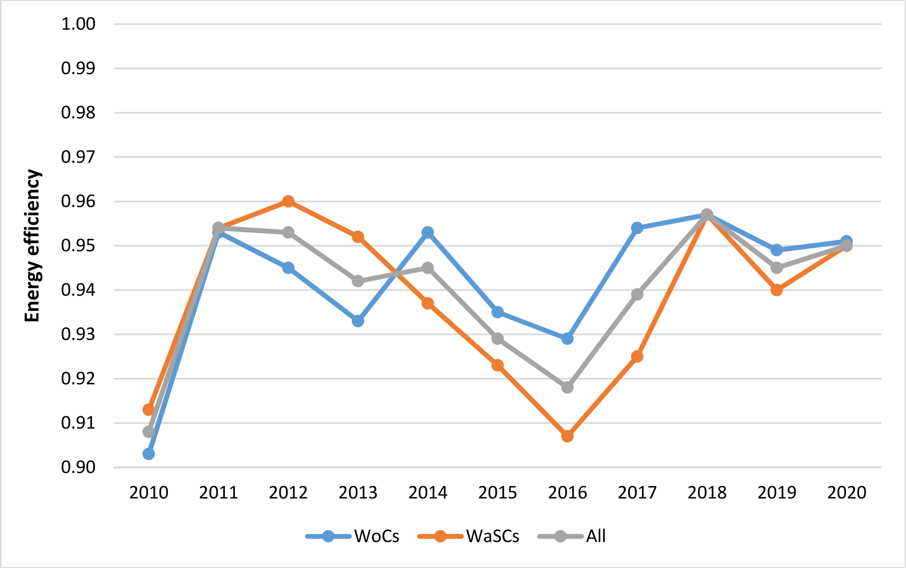

Fig. 1. Evolution of average energy efficiency of English and Welsh water only companies (WoCs) and water and sewerage companies (WaSCs).

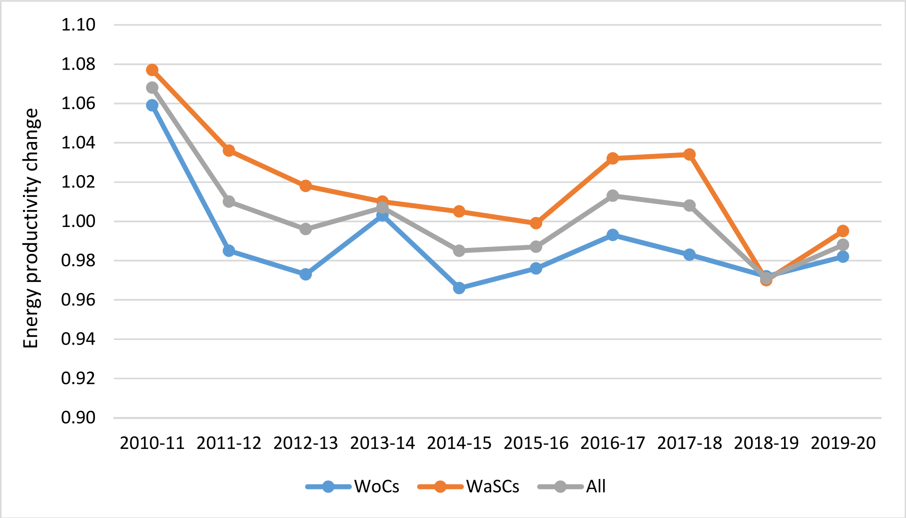

Fig. 2. Evolution of average energy productivity change of English and Welsh water only companies (WoCs) and water and sewerage companies (WaSCs).

0.952 for WaSCs. In subsequent years, WoCs typically surpassed WaSCs in EE, possibly due to WoCs' enhanced management of daily operational costs, leading to greater efficiency. Between 2014 and 2017, a significant decrease in average EE for WaSCs was observed, primarily due to increasing energy costs. By 2017, both WaSCs and WoCs had the capacity to further reduce their energy consumption by 7.5% and 4.6%, respectively. In the later years of the study (2018–2020), both WoCs and WaSCs achieved substantial reductions in energy costs and carbon emissions, which contributed to an improvement in EE. By the end of the study period, the industry had the potential to increase its EE by an additional 5%.

Fig. 2 presents a comparison of the average EPC for WaSCs, WoCs, and the entire water industry in England and Wales spanning from 2010 to 2020. The data indicates that, on average, the energy productivity of the English and Welsh water sector experienced a slight annual increase of 0.3% (average EPC = 1.003). There were moderate discrepancies observed between WaSCs and WoCs. On one side, the average energy productivity for WaSCs improved annually by 1.8% (average EPC = 1.018), suggesting a positive trend in their energy performance over time. In contrast, with an average EPC of 0.989, WoCs displayed an annual decline in energy performance by 1.1%.

Examining the EPC trend, WaSCs reported values above one from 2010 to 2016, indicating enhanced energy performance throughout this period. However, a downturn in EPC was noted for WaSCs in the final two years covered by the study. Conversely, WoCs experienced more fluctuation in energy performance, with EPC improvements only in the years 2010-11 and 2013–14, implying that they experienced a decline in energy performance in most of the years assessed. Considering the overall trend for the English and Welsh water industry, periods of improvement and decline in EPC alternated, making it difficult to discern a definitive pattern. This outcome is particularly notable given that in 2011, the UK committed to reduce by 80% its GHG emissions by 2050 through its Carbon Plan (UK, 2011). It recognizes the need of dramatically increase in the EE across all sectors. Hence, in 2012 it was launched the UK EE Strategy to "to maximise existing policy and realise the wider energy efficiency potential that is available in the UK economy" (UK, 2012). However, it is important to recognize that the English and Welsh water industry had a relatively strong starting position in terms of EE (as shown in Fig. 1), which meant that the scope for further enhancements was somewhat limited compared to other sectors.

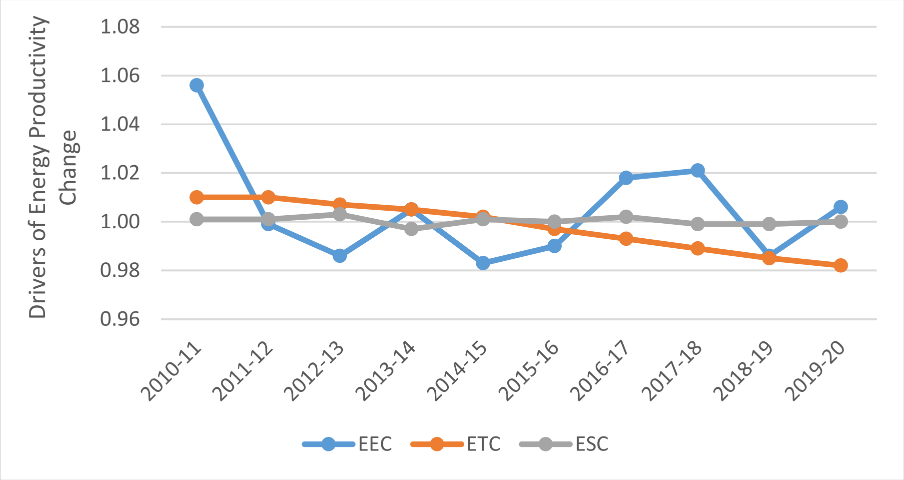

Fig. 3. Drivers of the energy productivity change (EPC) of the English and Welsh water companies: Energy efficiency change (EEC), Energy technical change (ETC) and Energy scale change (ESC).

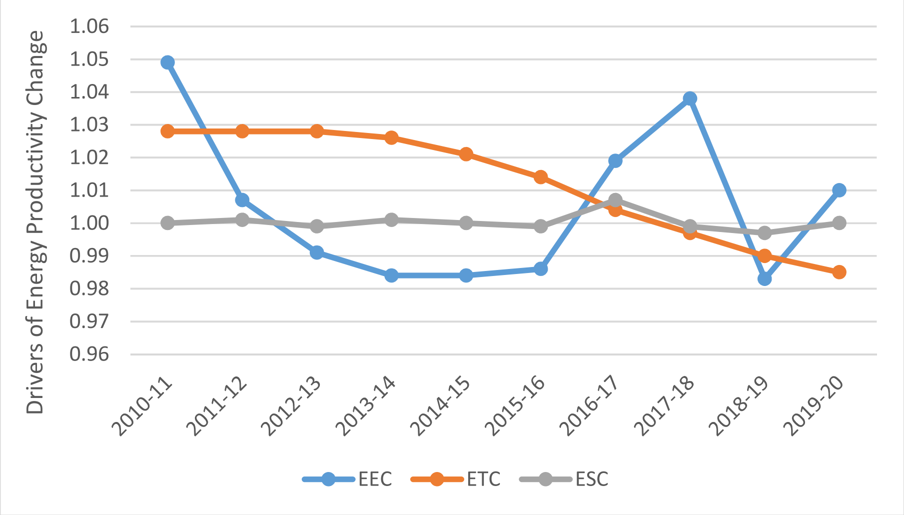

Fig. 4. Drivers of the energy productivity change (EPC) of the Water and Sewerage Companies (WaSCs): Energy efficiency change (EEC), Energy technical change (ETC) and Energy scale change (ESC).

To further understand the evolution of the energy performance of English and Welsh water industry, Figs. 3–5 show the drivers of EPC for the entire sector, as well as separately for WaSCs and WoCs. For the entire water industry (Fig. 3), the marginal improvement in energy performance (average EPC = 1.003) is ascribed to advancements in energy efficiency change, which have mitigated the effects of any technical regression. The influence of scale-related energy effects on productivity appears to be negligible. This outcome implies that the less energy-efficient utilities have elevated their performance, moving closer to the benchmark set by the most efficient entities within the sector. The average annual increase in energy efficiency stood at 0.5% (average EEC = 1.005). Nonetheless, this progress was counteracted by a technical change that regressed at a rate of 0.2% per year (ETC = 0.998), indicating the industry's hesitance to embrace new energy-saving technologies, thereby leading to a slowdown in energy productivity. Furthermore, expansions in the scale of operations among water utilities did not significantly impact energy costs or EPC (average ESC = 1.000). The evolution of the drivers of EPC across years (Fig. 3) suggests that although the companies showed some leadership in advancing their energy related technologies, they did not manage to control their costs and levels of carbon emissions. The last two time periods (2018–2020) of our sample are characterized by a considerable retardation in EPC which is explained by technical regress and losses in energy efficiency. This finding suggests that industry needs to adopt new energy efficient technologies and improve their managerial practices to become more energy efficient and productive.

In the case of WaSCs, the energy productivity improvement (average EPC = 1.018) was due to both gains in energy efficiency and improvements in technical change (Fig. 4). Energy efficiency improved at a rate of 0.5% per year on average whereas the rate of technical progress was at the level of 1.2% per year on average (average EEC = 1.005 and average ETC = 1.012). In contrast, average WoC showed a decrease in its energy productivity (average EPC = 0.989) which is attributed to technical regress (Fig. 5). Any small gains in WoC's energy efficiency (average EEC = 1.005) were lost to a deterioration in technology which was at the level of 1.6% per year (average ETC = 0.984). These findings suggest that both WaSCs and WoCs showed small gains in energy efficiency over time, i.e., improvements in the way daily operations are managed. However, there was a diversion in the level of technical change each type of company experienced during the period of study. Average WaSCs appeared to have adopted energy efficient technologies in the water production and delivery process. However, this was not the

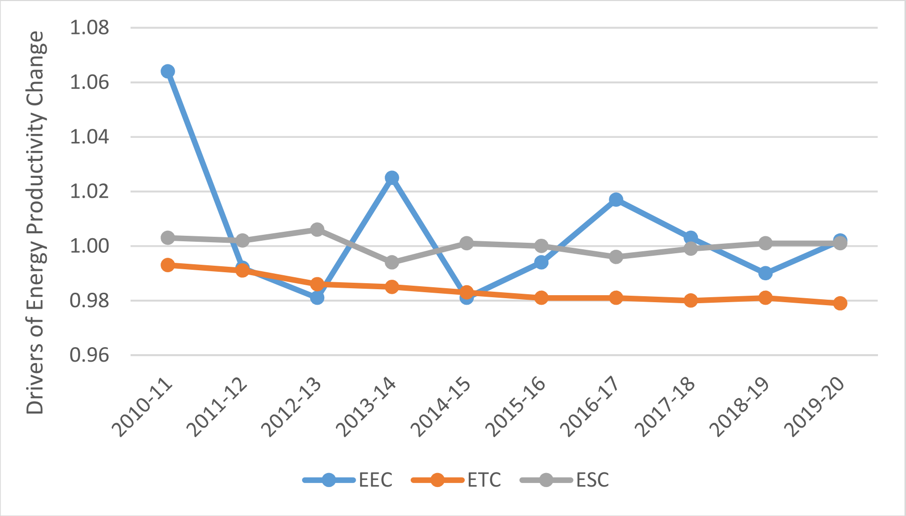

Fig. 5. Drivers of the energy productivity change (EPC) of the Water only Companies (WoCs): Energy efficiency change (EEC), Energy technical change (ETC) and Energy scale change (ESC).

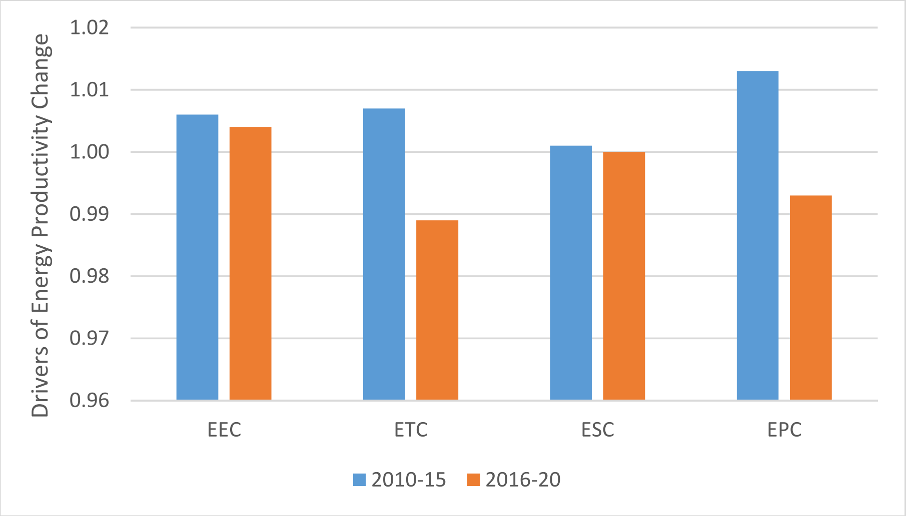

Fig. 6. Energy productivity change (EPC) of the English and Welsh water companies and its drivers: Energy efficiency change (EEC), Energy technical change (ETC) and Energy scale change (ESC) grouped by regulatory cycle.

case for the average WoCs. For both types of water companies (WaSCs and WoCs), the impact of energy related scale effect although was positive for most of the years of study was immaterial (average ESC = 1.000). This finding suggests that increases in the size of water utilities might not have affected their energy productivity.

Overall, the findings reveal that while WaSCs generally demonstrated greater energy productivity than WoCs over the analyzed period, a significant decline in productivity was observed in the final two-time intervals, driven by technical regression and a reduction in energy efficiency. Conversely, the productivity of WoCs was consistently hampered by technical regression. Consequently, both WaSCs and WoCs need to channel investments into energy-efficient technologies to bolster their economic and environmental performance. Utilities that lag in energy efficiency should intensify their efforts to use their resources more judiciously, manage their production costs effectively, and strive to reach the efficiency levels of the leading companies within the sector.

As a key element of its regulatory framework, Ofwat carries out a pricing review for all water companies in England and Wales every five years. During this review, water companies present their business proposals to Ofwat, outlining their projected expenditures for service provision over the coming five years, along with the revenue they believe they need to generate from customer water and wastewater bills. Ofwat's responsibility includes ensuring that water companies have adequate funding to efficiently fulfill their commitments to customers and the environment (Ofwat, 2023). Consequently, Ofwat could implement various policies to promote energy efficiency during each pricing review cycle. To investigate the impact of Ofwat's pricing review policies on the energy performance of water companies, we split the period of study into sub-periods according to price reviews (Figs. 6–8).

The first period (2010–15) is covered by the 2009 price review. During this period, OFWAT did not introduce measures and policies directly focused on energy performance. By contrast, the framework created strong financial incentives for water companies to improve their overall operational efficiency, which included energy use. As part of this price review, the regulator introduced several incentive schemes to boost performance in industry. Water utilities were allowed to keep any savings in operational costs regardless of the years they were saved (Villegas et al., 2019). Any cost outperformance was shared with customers as well. To improve the service quality, the regulator introduced a financial scheme called Service Incentive Scheme (SIM) where

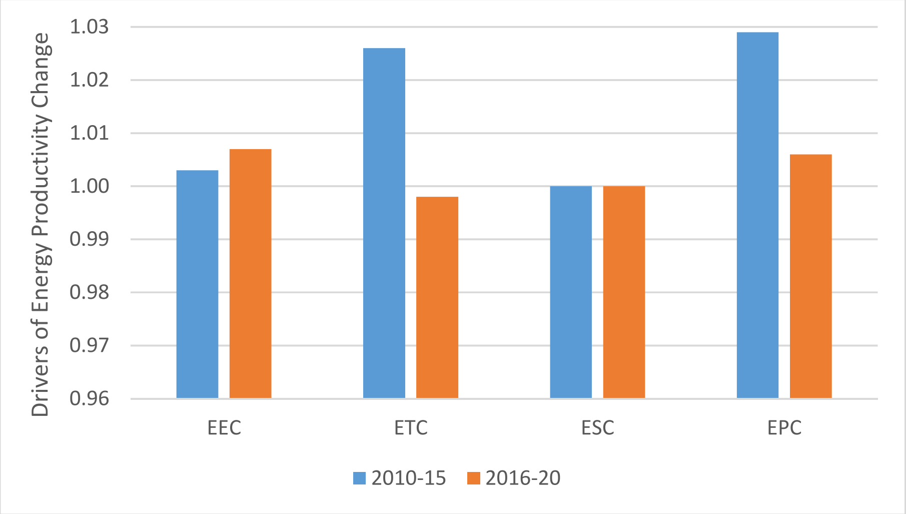

Fig. 7. Energy productivity change (EPC) of the Water and Sewerage Companies (WaSCs) and its drivers: Energy efficiency change (EEC), Energy technical change (ETC) and Energy scale change (ESC) grouped by regulatory cycle.

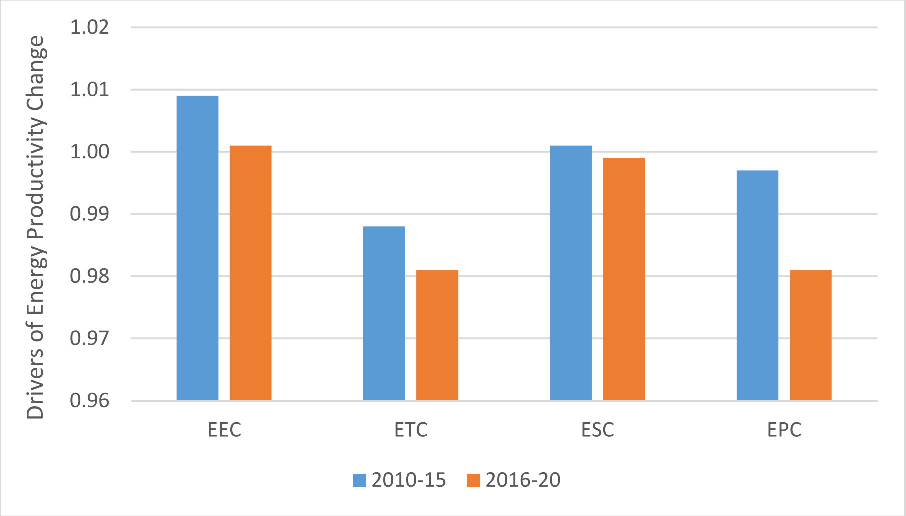

Fig. 8. Energy productivity change (EPC) of the Water only Companies (WoCs) and its drivers: Energy efficiency change (EEC), Energy technical change (ETC) and Energy scale change (ESC) grouped by regulatory cycle.

companies were rewarded/penalized for any out-performance/underperformance regarding service quality variables such as water leakage or unplanned water supply interruptions.

Ofwat's 2009 Price Review framework emphasized the importance of sustainable development, which included improving resource efficiency such as water and energy use. Water companies were expected to integrate sustainability into their operations and long-term planning, with energy efficiency being a key element of this broader sustainability focus. In this context, Ofwat required water companies to take into account carbon emissions in their business plans, and it encouraged investments that would reduce the sector's overall carbon footprint. Energy efficiency was seen as a critical component of achieving these targets, particularly in the context of rising energy costs and environmental impact. However, Ofwat's regulatory approach did not mandate specific renewable energy initiatives. By contrast, only encouraged water companies to explore renewable energy sources as part of their efforts to reduce costs and improve sustainability.

Within this framework, the results shown on Fig. 6 indicated that English and Welsh water industry improved its energetic productivity by 1.3% per year (average EPC = 1.013) which was due to a small improvement in EEC (0.6% per year), in ETC (0.7% per year) and in ESC (0.1% per year). This finding suggests that less energy efficient companies made some improvements in their resource allocation whereas the industry adopted energy efficient technologies. This pattern was apparent for an average WaSC whose energy productivity improved by 2.9% per year (Fig. 7). However, this was not the case for an average WoC who displayed a deterioration in its energy productivity by 0.3% per year which was due to technical regress (Fig. 8).

In the second sub-period (2016–20), covered by the 2014 price review, the regulator replaced the SIM scheme with a set of common and bespoke performance indicators, called Outcome Delivery Incentives (ODIs) to monitor economic and environmental sustainability. Unlike the 2009 price review, Ofwat's 2014 price review framework promoted energy efficiency by incentivizing water companies to integrate sustainable practices, optimize operational performance, and invest in innovative, energy-saving technologies. In particular, Ofwat moved from separate capital expenditure (Capex) and operational expenditure (Opex) allowances to a total expenditure (Totex) framework. The idea behind this approach was to incentivize water companies to pursue more cost-effective solutions, including energy-efficient practices. Water companies were required to submit business plans for the 2014 price review, where they needed to demonstrate how they would improve operational efficiency, including energy use. The 2014 price review also supported measures that encouraged companies to invest in renewable energy generation.

The results indicated that this sub-period was challenging for WoCs who reported lower levels of energy productivity (Fig. 8). The rate of energy productivity deterioration was 1.9% per annum which was driven by technical regress. Gains in energy efficiency were immaterial. In contrast, average WaSC's energy productivity remained positive but its rate was lower than the previous sub-period (Fig. 7). It improved by 0.6% per year which was attributed to gains in energy efficiency. During that period average WaSCs experienced a small deterioration in their technology. Overall, energy productivity of the whole water industry suffered a regression of 0.7% per year (Fig. 6) which was attributable to the negative shift of the energy production technology because the average ETC was 0.989 whereas EEC was 1.004 and ESC was 1.000.

The average EPC for English and Welsh water companies during the two sub-periods under review reveals that, although the 2014 price review introduced direct policies aimed at improving the energy performance of water companies, it was less successful than the framework implemented in the 2009 price review. Ofwat itself has acknowledged that since 2011, the productivity growth in the water sector of England and Wales has been weak (Ofwat, 2021). It is important to note that the forthcoming 2024 price review is on the horizon, and one of the critical considerations for Ofwat in setting water prices will be advancements made through efficiency and innovation. Additionally, the guidelines for the 2024 price review stress the importance of boosting water companies' efficiency through the valorization of bioresources, sustainable water resource management, and collaborations with other entities (Ofwat, 2021). Against this backdrop, it is crucial for water companies to orient future business strategies towards investing in new technologies that can help them manage production costs and carbon emissions more effectively, all while maintaining the current standard of water services for their consumers.

5. Conclusions

Enhancing the EE of water utilities represents a critical step towards realizing a net-zero carbon water industry. This study introduces an innovative methodological approach designed to tackle two primary shortcomings prevalent in the conventional assessment of energy performance within the water industry: heterogeneity among water companies and a static evaluation that overlooks changes in performance over time. To address these issues, we adopted a unique approach, modeling the heterogeneous technologies utilized by WaSCs and WoCs together within a single production frontier. This was accomplished through the application of SFA techniques.

The empirical analysis of water companies in England and Wales reveals that, on the whole, these companies demonstrate a commendable level of EE. Over the period from 2010 to 2020, the average EE stood at 0.940, indicating that there is a potential energy saving opportunity of 6%. When examining EPC over the years, the water industry demonstrated an overall improvement in energy performance, growing by 0.3% annually. This improvement is primarily attributed to efficiency changes (average EEC = 1.005), which offset the negative shift in technology change (average ETC = 0.998), while the scale effect remained negligible (average ESC = 1.000). However, it is important to note that there were divergent trends observed for both types of water companies. WaSCs experienced a slight increase in EPC, with an average value of 1.018, indicating an improvement in energy performance. In contrast, WoCs exhibited a decrease in EPC, with an average value of 0.989, suggesting a decline in energy performance. These disparities can be attributed to opposite shifts in the efficient production frontier; WaSCs had a positive shift (average ETC = 1.012), while WoCs had a negative shift (average ETC = 0.984).

When analyzing the EPC results in accordance with the two price reviews conducted during the evaluated period, it becomes evident that alternative policies should be considered by the water regulator to enhance the energy performance within the English and Welsh water industry. Under the SIM framework adopted in the 2009 price review, there was a modest improvement in the energy performance of water companies, with an EPC of 1.013. However, the ODI scheme implemented in the 2014 price review did not yield favorable results for energy performance. In fact, the average EPC for the period from 2016 to 2020 stood at 0.993, indicating a regression of 0.7% per year in energy performance.

Beyond the empirical application conducted for English and Welsh water companies, this study could be of interest to policy makers for the following reasons. First, we provide a method that compares water companies with heterogeneous technologies and provides robust estimates of elasticities, efficiency and productivity. Second, policy makers have the opportunity to identify what drives energy use and costs when providing water services. Our study showed that a combination of several outputs, inputs and environmental variables influence energy requirements of water utilities. Understanding these factors could help managers to make informed decisions to improve economic and environmental performance. In addition, the decomposition of energy productivity allows understanding how gains in energy efficiency, technical and scale of operations affected performance. They can also see how technologically advanced the industry is, i.e., the technological leaders and followers. Our results showed that investing and adopting in energy efficient technologies should be a priority for water utilities in their future business plans.

This study represents a significant advancement in assessing the changes in energy performance of water utilities, yet it presents two limitations that open avenues for future research. Firstly, heterogeneity in our study is confined to the variety of services provided by water companies. In other contexts, water companies may exhibit additional heterogeneities, such as ownership types, regulatory environments, or environmental conditions. Future research could expand on this by exploring different or multiple heterogeneities in assessing both EE and EPC of water companies. Such analyses would be valuable for water managers to formulate targeted actions and policies aimed at enhancing energy performance in the water industry. Secondly, our assessment integrates the three primary stages of drinking water provision: raw water abstraction, water treatment, and water distribution. A more detailed analysis that evaluates each stage independently could provide more nuanced insights, facilitating more effective decision-making. This approach would enable researchers and policymakers to pinpoint specific energy inefficiencies and opportunities for improvement at each stage of water provision.

CRediT authorship contribution statement

Alexandros Maziotis: Writing – original draft, Methodology, Data curation, Conceptualization. **Ramon Sala-Garrido:** Writing – review & editing, Methodology, Formal analysis. **Maria Molinos-Senante:** Writing – review & editing, Visualization, Validation, Funding acquisition.

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.

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Data availability

Data will be made available on request.

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