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Evaluating carbon performance in the water industry: A longitudinal analysis of England and Wales

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ABSTRACT

The transition to a zero-carbon water industry presents significant challenges for water companies and regulators. This study conducts both static and longitudinal assessments of carbon performance of water companies in England and Wales from 2008 to 2020. Carbon efficiency (CE) and carbon productivity (CP) metrics were estimated using the stochastic semi non-parametric envelopment of data method, which addresses the limitations of traditional parametric and non-parametric techniques. The average CE in 2020 was 0.628, indicating a 37.2% potential reduction in carbon emissions can be achieved by water companies. Despite regulatory efforts, the dynamic assessment shows negligible improvement in carbon performance, with average CP index value of 1.0009. The lack of technological innovation is identified as a key barrier, as technical change contributed negatively (0.9929) to CP, while efficiency change was positive (1.0091). The results highlight the critical role of raw water quality in achieving net-zero GHG emissions. Some strategies to accelerate the decarbonization of the water industry include prioritizing raw water protection, incentivizing technological advancements, and fostering knowledge sharing among companies.

1. Introduction

The provision of water and sanitation services involves both direct and indirect greenhouse gas (GHG) emissions [1]. According to GWI [2] estimations, water infrastructure represents 845 million tonnes of CO_2 equivalent (CO_{2e}) per year. Nevertheless, the contribution of water utilities to global GHG emissions is notably uncertain, with recent estimates ranging from 3% [3] to 10% [4]. Given the importance of reducing carbon emissions and better understanding the water-energy-carbon nexus, the estimation of the carbon footprint within the urban water cycle has gained significant interest over the last two decades [5]. Various methodologies and tools have been employed in this endeavor, including life cycle assessment [6,7,8] and multi-criteria methods that generate synthetic indexes for carbon performance [9–11]. Studies on carbon footprint estimations have primarily focused on monitoring and/or modelling GHG emissions from drinking water and/or wastewater treatment at the plant level [12].

As the impacts of climate change intensify, various levels of governance are committing to reducing GHG emissions. Currently, in alignment with the Paris Agreement, approximately 100 water utilities are committing to carbon neutrality [2]. Some water companies have voluntarily set net-zero GHG emissions goals through initiatives such as Race to Zero, a global campaign urging non-state actors to take immediate and rigorous action to halve global emissions by 2030 [13]. Moreover, from an institutional perspective, certain regions and countries have pledged to transition to a zero-carbon water industry, including several states in Australia [14] and the complete water industry in England and Wales [15]. These institutional and corporate commitments highlight the importance of analyzing the carbon performance of the water industry from a holistic perspective, going beyond the carbon footprint estimation of specific water treatment facilities.

In the transition towards a carbon-neutral water industry, two key issues must be considered in the carbon performance assessment of water utilities. Firstly, it is essential to integrate all stages involved in the provision of drinking water services [16]. This means that carbon performance assessment should not be limited to the drinking water plant

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level but must encompass all stages of the water cycle, from raw water abstraction to potable water delivery [17]. Secondly, as most water utilities have defined progressive carbon reduction targets, it is crucial to assess changes in their carbon performance over time. This longitudinal assessment enables the analysis of whether water companies are improving their carbon performance [18]. Additionally, this dynamic assessment allows water regulators and utilities to verify the effectiveness of the policies and measures adopted to promote water decarbonization in achieving their ultimate goal of carbon neutrality in the provision of water services [19].

The scientific aim of this work is to assess carbon efficiency (CE) and its changes (carbon productivity - CP) over time for a sample of water companies using a robust methodological approach that addresses the main limitations of DEA and SFA methods. The subject of the research was to estimate CE and CP indexes for each water company evaluated using the Stochastic Semi Non-parametric Envelopment of Data (StoNED) method [20]. StoNED includes the merits of parametric and non-parametric techniques offering robust estimates of CE and CP [21]. This study contributes to the literature in several ways: (i) it provides a longitudinal assessment of the carbon performance of water companies, focusing solely on GHG emissions rather than integrating both carbon and economic variables. This approach yields specific insights into the evolution of carbon performance within the water industry over time; (ii) it proposes and applies the StoNED methodology to assess CE and CP of water companies, thereby overcoming the limitations of previous methods used to estimate CE and eco-productivity changes in water companies. These innovations represent significant contributions to the framework for assessing the carbon performance of water companies as they transition towards a carbon-neutral water industry.

2. Literature review on carbon performance of water industry

Literature assessing the carbon performance of water utilities in the provision of drinking water is still in its early stages, but notable exceptions exist. One research stream focuses on evaluating the eco-efficiency of water companies by integrating GHG emissions as an undesirable output [22,23,11]. These studies employ the Data Envelopment Analysis (DEA) method to provide a synthetic index of water company performance, incorporating carbon emissions as part of the index along with the operational costs of water services. However, eco-efficiency is a static assessment that informs about performance at a specific time but not its dynamic evolution. To address this limitation, some studies have assessed the eco-productivity of water utilities, examining changes in eco-efficiency over time. Ananda and Hampf [14] and Ananda [24] integrated GHG emissions into the productivity change estimation of a sample of Australian water utilities, using the Malmquist-Luenberger productivity index through the DEA technique. A similar approach was employed by Molinos-Senante and Maziotis [19] for English and Welsh water companies. Recently, Ananda and Oh [18] estimated the metafrontier Malmquist-Luenberger productivity index to assess eco-productivity changes in a sample of Australian water companies, considering their carbon emissions and other heterogeneous characteristics. These studies employed DEA, a non-parametric method that, due to its deterministic nature, does not account for statistical noise and environmental variables influencing performance [25]. To overcome DEA's limitations, Molinos-Senante and Maziotis [26] estimated the eco-productivity of English and Welsh water companies using the Stochastic Frontier Analysis (SFA) method. SFA is a parametric approach that includes inefficiency and statistical noise in performance assessment. However, its main limitations are the need to specify a functional form for the production technology and sensitivity to assumptions regarding the distribution of inefficiency [27].

In conclusion, through the literature review of past studies assessing changes in the carbon performance of water utilities in the provision of water services, two main limitations have been identified. Firstly, from a methodological perspective, past research [24,14,18,19,26] employed DEA and SFA methods to estimate eco-productivity change indexes. These methods have the inherent limitations previously discussed that might bias results and conclusions. Secondly, from a conceptual perspective, eco-productivity change is not a specific metric of carbon performance as it also integrates the economics of water service provision. To specifically estimate carbon performance of water companies over the years, an alternative index based solely on GHG emissions should be developed and utilized.

In the context of water utilities and other sectors such as electricity distribution and healthcare, past research has highlighted the advantages of the StoNED technique over DEA and SFA. Molinos-Senante et al. [28] assessed and compared the efficiency of 20 Chilean water companies using DEA, SFA, and StoNED methods. Their study highlighted the advantages and disadvantages of each approach, emphasizing the positive attributes of StoNED as a hybrid of DEA and SFA. Similarly, in the context of water utilities, Murwirapachena et al. [29] examined efficiency scores derived from DEA, SFA, and StoNED for South African water utilities, concluding that StoNED is the most consistent technique due to its ability to account for heterogeneity effectively. In the field of energy distribution, Kuosmanen et al. [30] analyzed the impact of using DEA, SFA, and StoNED techniques on cost efficiency for Finnish electricity distribution operators. They found that employing the StoNED cost frontier as a benchmark eliminated certain redundant components in the regulatory model, enhancing transparency. Additionally, in a distinct sector such as healthcare, Cordero et al. [31] evaluated hospital performance using DEA, SFA, and StoNED, further underscoring the limitations of DEA and SFA when compared to StoNED.

3. Material and methods

CE and its change across years, i.e., CP, were estimated using the StoNED method. This method combines the advantages of both parametric and non-parametric approaches. Like SFA, it includes both inefficiency and noise in eco-efficiency assessment. Like DEA, it does not require a priori definition of a functional form for the underlying technology. StoNED maintains the assumptions of convexity, returns to scale, and monotonicity in outputs [32]. Moreover, it allows considering water utilities' heterogeneity by integrating environmental variables in the assessment [33].

Fig. 1 summarizes the main methodological steps followed to estimate both CE and CP for each assessed water company.

3.1. Carbon efficiency estimation

The CE assessment embraces three main steps which are presented as follows:

Step 1: Definition of the production frontier.

The production frontier is defined to relate carbon emissions with the provision of drinking water by water utilities and their operational characteristics:

$$lnC_{i,t} = ln\left(\beta_i + \gamma' y_{i,t}\right) + \delta' z_{i,t} + \varepsilon_{i,t} \tag{1}$$

where ln denotes logarithm; C captures the level of carbon emissions generated from the provision of water services; i and t denote water utilities and year, respectively. Moreover, the constant term is captured by β_i; y is the vector of outputs and z is a set of environmental variables (operating characteristics) that could impact carbon emissions of water utilities. These variables are included to consider utilities' heterogeneity [18]. The Greek letters γ and δ are parameters to be estimated. The error term, ε, includes both inefficiency and noise. In other words, it is a composite term which is defined as $\varepsilon_{i,t} = v_{i,t} + u_{i,t}$, where v is noise and follows the standard normal distribution, $v_{i,t} \sim N(0, \sigma_v^2)$ where σ_v^2 is the variance of noise. On the other hand, $u_{i,t}$ is the inefficiency of each water company i at time t and follows the half-normal distribution, $u_{i,t} \sim$

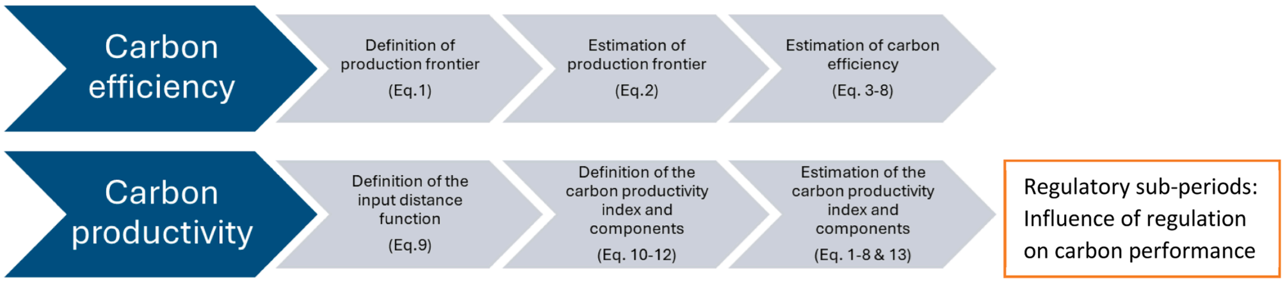

Fig. 1. Main methodological steps for estimating carbon efficiency and carbon productivity of water companies.

$N^{+}(0, \sigma_u^2)$ where σ_u^2 is the variance of inefficiency [20].

Step 2: Estimation of the production frontier:

The production frontier (Eq. (1)) is estimated using the StoNED method. The shape of the production frontier is determined using the convex nonparametric least squares (CNLS) technique, which recovers the estimated parameters of outputs and environmental variables (γ, δ). This involves solving the following non-linear programming model:

$$\min \sum_{i=1}^{I} \sum_{t=1}^{T} \varepsilon_{i,t}^2 \tag{2}$$

subject to :

$$lnC_{i,t} = ln\left(\beta_{i,t} + \gamma_{i,t} y_{i,t}\right) + \delta_{i,t} z_{i,t} + \varepsilon_{i,t} \quad i = 1, .., I; t = 1, ..., T$$

$$\beta_{i,t} + \gamma_{i,t} y_{i,t} \ \geq \beta_{j,\rho} + \gamma_{j,\rho} y_{j,\rho} \quad i,j = 1, ..., I; t, \rho = 1, ..., T$$

$$\gamma_{i,t} \geq 0 \quad i = 1, .., I; t = 1, ..., T$$

The constant term $\beta_{i,t}$ represents the degree of returns to scale. $\beta_{i,t} = 0$ involving that water utilities operate at their most productive scale size. The estimated parameter of outputs, γ, are the coefficients of the tangent hyperplanes to the piece-wise linear production frontier [34]. The first constraint ensures convexity, and the second constraint guarantees monotonicity in outputs [35].

Step 3: Estimation of carbon efficiency for each water company

The CE of each water company is estimated based on the assumptions that inefficiency and noise are distributed according to half-normal and standard normal distributions, respectively. The method of moments is employed to determine the carbon inefficiency and noise parameters [36,34]:

$$\widehat{\sigma}_u = \sqrt[3]{\frac{\widehat{M_3}}{\left(\sqrt{\frac{2}{\pi}}\right)\left[\frac{4}{\pi} - 1\right]}} \tag{3}$$

$$\widehat{\sigma}_v = \sqrt[2]{\widehat{M_2} - \left[\frac{\pi - 2}{\pi}\right](\widehat{\sigma_u})^2} \tag{4}$$

where $\widehat{M_2}$ and $\widehat{M_3}$ are the estimates second and third central moments taken from the composite errors after solving Model (2).

The carbon inefficiency score for each water company is derived by solving Eq. (5):

$$E(u_{i,t}|\varepsilon_{i,t}) = \mu_* + \sigma_* \left[\frac{\phi(-\mu_*/\sigma_*)}{1 - \Phi(-\mu_*/\sigma_*)}\right] \tag{5}$$

where ϕ denotes the standard normal density function and Φ denotes the standard normal cumulative distribution function:

$$\mu_* = -\varepsilon_{i,t}\sigma_u^2 / (\sigma_u^2 + \sigma_v^2) \tag{6}$$

$$\sigma_*^2 = \sigma_u^2 \sigma_v^2 / (\sigma_u^2 + \sigma_v^2) \tag{7}$$

The CE score for each water company is estimated according to Eq. (8):

$$CE_{i,t} = \exp\left(-\widehat{u_{i,t}}\right) \tag{8}$$

The CE score, $CE_{i,t}$, takes a value between zero and one. A value of one means that the water company is on the frontier and therefore is eco-efficient, presenting the best performance among the utilities evaluated. Conversely, a $CE_{i,t}$ value lower than one indicates that the water company is not on the frontier, meaning inefficiency and potential room for improvement to achieve CE.

3.2. Carbon productivity estimation

CP estimation involves extending CE to a temporal setting by assessing how water companies have changed their performance over time. The methodological approach applied involved 3 steps defined as follows:

Step 1. Definition of the carbon distance function:

According to Lin and Du [37] and Tan et al. [38] the carbon distance function is as follows:

$$CD_t(C_t, y_t) = min\{\theta : (\theta \cdot C_t) \in PT_t(y_t), \theta > 0\} \tag{9}$$

where θ the contraction in carbon emissions required for a given level of output y using the underlying production technology, PT.

Step 2. Definition of the carbon productivity index (CPI) and its components:

Similar to the Malmquist Productivity Index [39], the CPI between time period t and $t+1$ was defined as follows:

$$CPI_{t,t+1} = \left(\frac{CD_t(C_t,\ y_t)}{CD_t(C_{t+1}, y_{t+1})} \times \frac{CD_{t+1}(C_t,\ y_t)}{CD_{t+1}(C_{t+1}, y_{t+1})}\right)^{1/2} \tag{10}$$

If $CPI_{t,t+1}$ is larger than one, it indicates that carbon performance improved. Conversely, a value lower than one indicates deterioration in CP.

The CPI in Eq. (10) ($CPI_{t,t+1}$) is decomposed into two drivers: carbon efficiency change ($CEC_{t,t+1}$) and carbon technical change ($CTC_{t,t+1}$)

$$CEC_{t,t+1} = \left(\frac{CD_{t+1}(C_{t+1},\ y_{t+1})}{CD_t(C_t, y_t)}\right) \tag{11}$$

$$CTC_{t,t+1} = \left(\frac{CD_t(C_{t+1},\ y_{t+1})}{CD_{t+1}(C_{t+1}, y_{t+1})} \times \frac{CD_t(C_t,\ y_t)}{CD_{t+1}(C_t, y_t)}\right)^{1/2} \tag{12}$$

$CEC_{t,t+1}$ measures the change in CE from one period to another. It assesses whether less efficient utilities have moved closer to or further away from the efficient frontier, representing the catch-up factor. If $CEC_{t,t+1} > 1$, it indicates that CE gains were achieved over time. Conversely, if $CEC_{t,t+1} < 1$, it signifies losses in CE. $CTC_{t,t+1}$ captures the existence of technical progress or regress, indicating the positive or negative shift of the efficient frontier. If $CTC_{t,t+1} > 1$, it denotes technical progress. In contrast, if $CTC_{t,t+1} < 1$, it indicates a lack of adoption of technological advancements to control carbon emissions.

Step 3. Estimation of the CPI and its components.

The StoNED method is employed to estimate the CPI defined in Eq. (10). Inspired by Kuosmanen [30], Cheng et al. [36], Zhou [40] and Maziotis et al. [41] and considering Eqs. (1)–(8), it is defined as follows:

$$CPI_{t,t+1} = \exp\left(Trend + \varepsilon(i, t+1) - \varepsilon(i,t)\right) \tag{13}$$

where exp (Trend) and $\exp(\varepsilon(i,t+1) - \varepsilon(i,t))$ represent carbon technical change (CTC) and carbon efficiency change (CEC), respectively. CTC is estimated though the estimation of the coefficients in Model (2), whereas CEC estimation involves solving Eqs. (2)–(8).

3.3. Case study and data description

CE and CP were estimated for a sample of English and Welsh water companies during the years 2008-2020. The water industry in England and Wales is paradigmatic as it one of the first to formally commit to carbon neutrality. The provision of drinking water in England and Wales is carried out by water and sewerage companies (WaSCs) and water only companies (WoCs). Both types of water utilities are private natural monopolies regulated by the Water Services Regulation Authority (Ofwat). Ofwat monitors the economic and environmental sustainability of the sector. From an economic perspective, as part of the price review process, every five years the regulator determines the future revenue that each water company is allowed to recover from its customer base [42]. From the environmental perspective, water companies monitor carbon emissions and report them annually to Ofwat [43]. Carbon emissions regulated by Ofwat in the provision of drinking water and therefore considered in this study as input, are the following [44]:

Scope 1: GHG emissions from transport owned or leased and emissions from companies' own fossil fuel use.

Scope 2: GHG emissions from grid electricity used for pumping, treatment and distributing water and grid electricity used in owned buildings.

Scope 3[1]: GHG emissions from contractors and outsourced services and business-associated transport, on public transport or in private vehicles.

Following the United Kingdom Government Environmental Reporting Guidelines [45], carbon emissions are expressed in tons of CO_{2e} per year. Two outputs, reflecting the main function of water companies, are considered. The first output is the annual volume of drinking water delivered, measured in megalitres per year [46,17]. The second output is the annual number of water-connected properties, measured in thousands [47,48].

In the assessment of water utility performance, environmental variables are factors beyond the control of the utilities that can influence their performance. Given that these environmental variables can affect performance, it is essential to account for them when estimating CE and CP scores. Considering evidence from previous studies [49,50,51,52] and available statistical data, the following environmental variables are integrated into CE and CP assessment: (i) Percentage of water taken from rivers and boreholes; (ii) average pumping head; (iii) number of treatment works required to clean water from groundwater resources; (iv) percentage of water that receives high level of treatment and; (v) population density defined as the ratio of the number population and length of water mains. Both output and environmental variables are published annually by Ofwat, which is the source of data for this study. The main descriptive statistics of the variables employed in the study are reported in Table 1.

4. Results

In this section, the estimations for CE and CP are presented. As a static indicator, CE is discussed on an annual basis. On the other hand, CP is grouped according to the price review sub-periods of the English and Welsh water industry to explore the potential impact of regulatory approaches on the carbon performance of water companies.

4.1. Carbon efficiency assessment

According to the methodological approach, the analysis begins by presenting and interpreting the parameters of the production frontier function (Table 2). Subsequently, the CE scores estimated for each water company are presented.

Results from the estimation of the production frontier (Table 2) indicate that carbon emissions associated with the provision of water services are not directly proportional to either the volume of water delivered or the number of water-connected properties. Specifically, a 1% increase in the volume of water delivered and connected properties would result in an increase in carbon emissions by 0.634% and 0.299%, respectively. This finding suggests that a potential policy to reduce carbon emissions could involve increasing the operational scale of the water utilities. Increasing scale may lead to greater efficiency and lower carbon emissions per unit of water delivered or per property served, underlining the importance of considering scale enhancements in strategic planning for emission reductions.

All environmental variables were found to have a positive sign and were statistically significant from zero. It was determined that the higher the percentage of water extracted from rivers and boreholes, the higher the carbon emissions released into the atmosphere. Similarly, the average pumping head contributed to this effect; an increase in the requirements to pump water from various sources and then transport it to treatment facilities tends to increase energy costs, thereby leading to higher carbon emissions. Furthermore, the complexity of the water treatment process was also linked to higher carbon emissions. It was observed that if the percentage of water that receives high-quality treatment increases by one unit, carbon emissions could rise by an average of 0.117%. Additionally, an increase in the number of treatment works by one unit could result in an average increase in carbon emissions by 0.107%. These results highlight the significant impact of raw water quality on the carbon emissions associated with the provision of water services. Consequently, policies aimed at reducing carbon emissions in the provision of drinking water should extend beyond water utilities domain. It is crucial to enhance the quality of raw water by implementing various strategies such as payment for ecosystem services [53], controlling non-point source pollution [54], and reducing misconnections in urban areas [55].

CE scores were estimated for all water utilities, including both WaSCs and WoCs for the 2008-2020 period. The average results displayed in Fig. 2 indicate that the English and Welsh water industry made concerted efforts to improve CE over time. In 2008, the mean CE was 0.550, and by 2020, it had increased to 0.623. This reflects an average improvement in CE of 13%. Generally, it was observed that the CE of water utilities remained almost stable from 2009 to 2016, with average CE scores for those years being 0.547 and 0.566, respectively. However, from 2016 to 2020, there was a notable improvement in CE, from 0.566 to 0.628. Despite this improvement, an average CE of 0.628 still implies that water utilities could reduce carbon emissions by an average of 37.2%.

When analyzing the CE scores by type of water company (Fig. 2) it is evidenced that both WoCs and WaSCs improved their CE over time, following a similar upward trend. It should be noted that the improvement in WoCs has been more substantial than in WaSCs. Specifically, the

[1] Not regulated Scope 3 emissions and therefore, not considered in this study are those related to chemical manufacture, embedded emissions from construction and manufacturing activity and customers' energy use to heat water.

Table 1
Descriptive statistics of the variables used to estimate carbon efficiency and carbon productivity.

	Input	Outputs		Environmental variables					
Year	Total carbon emissions (Ton CO_{2e}/year)	Total water connected properties (10^3)	Total volumen of water delivered (Ml/year)	Average density (10^3/km)	Average water from river (%)	Average water from boreholes (%)	Average pumping head (nr)	Average groundwater treatment works (nr)	Average water receiving high levels of treatment (%)
2008	1,687,810	23,271	12,020	0.461	34.9%	37.8%	136.7	47.6	58.1%
2009	1,725,080	24,309	12,265	0.458	29.6%	40.3%	132.3	49.4	59.6%
2010	1,684,596	24,405	12,280	0.461	31.2%	40.6%	134.9	49.4	59.4%
2011	1,690,377	24,496	12,333	0.464	31.4%	40.8%	137.6	49.3	59.5%
2012	1,633,664	24,624	12,259	0.466	31.9%	40.3%	140.4	49.7	59.8%
2013	1,567,481	25,026	11,889	0.453	33.2%	40.4%	135.2	49.3	58.9%
2014	1,470,706	25,162	12,097	0.459	29.4%	38.6%	142.2	48.8	59.9%
2015	1,563,348	25,392	12,038	0.466	28.8%	39.5%	142.0	48.9	59.8%
2016	1,414,081	25,586	12,118	0.467	28.8%	40.2%	139.7	50.2	60.1%
2017	1,448,523	25,750	12,231	0.474	24.4%	39.5%	143.3	50.4	59.0%
2018	986,076	25,980	12,339	0.480	21.8%	31.2%	143.0	48.2	56.7%
2019	830,604	26,215	11,978	0.498	23.0%	42.0%	138.5	50.8	54.8%
2020	801,009	26,428	11,926	0.503	23.1%	42.0%	138.5	50.8	54.8%

Table 2
Estimates of the production frontier function.

Variables	Coeff.	St. err.	T-stat	p-value
Volume of water delivered	0.634	0.060	**10.625**	0.000
Water connected properties	0.299	0.065	**4.624**	0.000
Population density	0.299	0.020	**14.905**	0.000
% water taken from rivers	0.325	0.023	**14.080**	0.000
% water taken from boreholes	0.303	0.019	**16.033**	0.000
Average pumping head	0.107	0.016	**6.609**	0.000
Number of groundwater treatment works	0.107	0.014	**7.659**	0.000
% water receiving high treatment quality	0.117	0.025	**4.695**	0.000
Year	-0.003	0.002	***-1.655***	0.099

$R^2 = 0.994$; Observations: 227
Carbon emissions is the dependent variable.
Bold statistics are statistically significant at 5% significance level
Bold and italic statistics are statistically significant at 10% significance level

average CE for WoCs increased by 37% over the period, from 0.474 in 2008 to 0.649 in 2020. In contrast, the average CE for WaSCs also increased but to a lesser extent, showing a 9% rise over the same period, from 0.556 in 2008 to 0.608 in 2020. The CE results further reveal that during the initial years of the study period, up to 2012, WaSCs were more carbon efficient than WoCs on average. However, the less efficient WoCs managed to make significant improvements and effectively caught up with their more efficient counterparts in the industry. Consequently, from 2013 onwards, WoCs have consistently outperformed WaSCs in terms of average CE. This shift underscores the dynamic nature of performance improvements within the English and Welsh water industry.

To better understand the differences in CE among water companies, Figs. 3 and 4 provide detailed statistics of CE scores estimated for all evaluated companies (Fig. 3) and split on WaSCs and WoCs (Fig. 4). Fig. 3 shows that from 2008 to 2012, the CE scores across water companies were relatively consistent, characterized by a narrow interquartile range. This indicates a relatively uniform performance in CE across the industry during the initial years. However, from 2013 to 2016, the variability in CE among water companies increased, signifying a divergence in performance levels. Notably, between 2008 and 2016, two companies stood out by achieving higher CE scores, with one reaching a peak score of 0.77 in 2016. This suggests that certain companies were early adopters of effective carbon reduction strategies, resulting in comparatively superior performance. During the 2017–2020 period, water companies generally exhibited higher CE scores, yet with increased variability among companies. This variability implies that companies are pursuing different approaches to carbon reduction and implementing these strategies at varying rates, reflecting a diverse

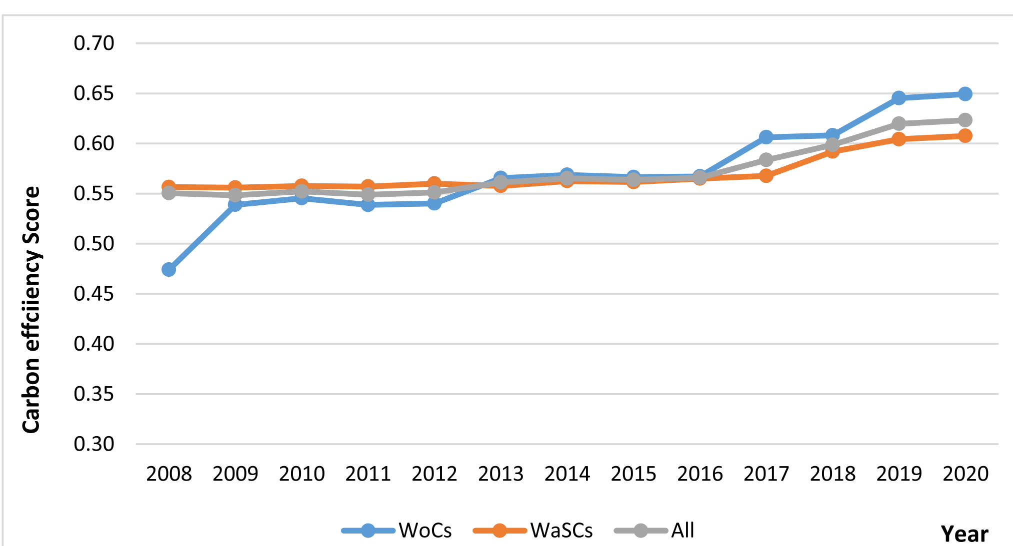

Fig. 2. Average carbon efficiency scores over time for all water companies, water only companies (WoCs) and water and sewerage companies (WaSCs).

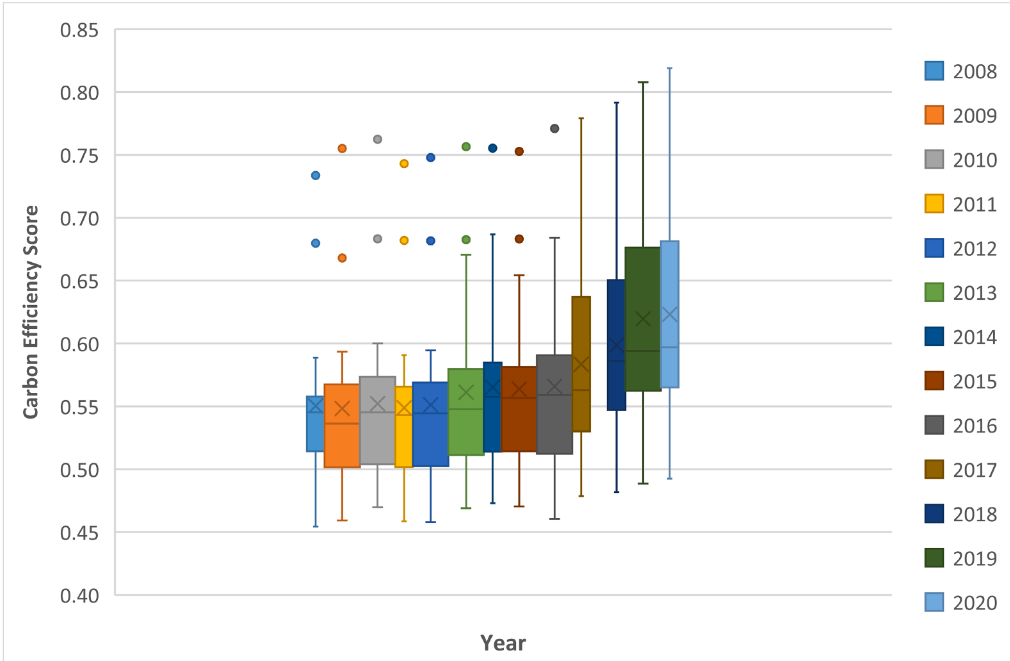

Fig. 3. Statistics of the carbon efficiency across years for all English and Welsh water companies.

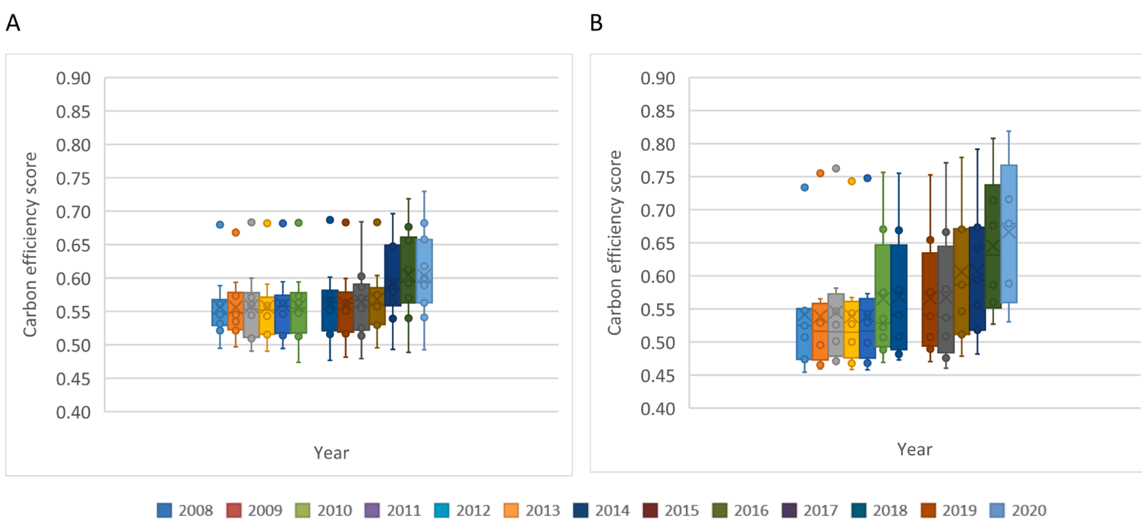

Fig. 4. Statistics of the carbon efficiency across years for water and sewerage companies (4A) and water only companies (4B).

response to carbon efficiency improvement across the industry. This period likely reflects a phase where industry began to more aggressively pursue carbon reduction initiatives, influenced by external pressures such as regulatory requirements and societal expectations for more sustainable practices [43].

The comparison of Fig. 4A and B distinctly illustrates that WaSCs and WoCs exhibited different behaviors in terms of carbon performance. Initially, from 2008 to 2012, both WaSCs and WoCs were characterized by very small variability in CE scores among water companies, indicating a relatively uniform performance within each group during this period. However, this pattern diverged significantly after 2012. For WaSCs, the small variability in CE scores was maintained up to 2017. In contrast, for WoCs, the variability among companies notably increased starting in 2013. This increase in variability continued, with not only the interquartile range but also the differences between the minimum and maximum CE scores for WoCs becoming notably larger than those for WaSCs. This suggests that some WoCs have made significant advancements in improving their carbon efficiency, setting new benchmarks for performance within this group. The larger range in CE scores among WoCs could indicate a more diverse adoption of innovative technologies or strategies aimed at reducing carbon emissions. It also suggests that within the WoC group, there are leaders and laggards in terms of carbon performance, with some companies achieving substantial improvements that markedly distinguish them from their peers. This divergence could provide valuable insights for stakeholders looking to understand the drivers of successful carbon management strategies and replicate them across the sector.

4.2. Carbon productivity assessment

The English and Welsh water regulator, Ofwat, conducts a price review every five years, where penalties and incentives are established to promote efficiency in the water industry [56]. The time frame analyzed in this study encompasses the 2004, 2009, 2014, and 2019 price reviews. Accordingly, to analyze the potential impact of these price reviews on the carbon performance of water utilities, the CPI and its components have been discussed for three distinct sub-periods aligned with each price review cycle: 2008-2010, 2011-2015, and 2016-2020 (Table 3).

4.2.1. Carbon productivity change between 2008 and 2010

The 2008-2010 period corresponds to the aftermath of the 2004 price review, where Ofwat introduced several incentive schemes aimed at improving the economic and environmental sustainability of the water industry. Notable among these was a rolling incentive mechanism designed to control production costs, allowing utilities to retain any operational cost savings regardless of when these savings were realized. Additionally, a composite measure of utilities' service levels, termed Operational Performance Assessment (OPA), was linked to financial rewards and penalties [52]. Despite such incentives, the results indicate that during the years 2008-2010, on average CP did not show any improvement. While carbon efficiency was positive, suggesting improvements in CP, these gains were offset by negative performance in terms of technical change. The behavior between WoCs and WaSCs was notably different. WoCs experienced a significant improvement in carbon efficiency, which led to improvements in their overall CP. By contrast, in the case of WaSCs, both components of the CPI —CEC and CTC—remained stable, leading to no changes in CP. This divergence between WoCs and WaSCs highlights the variability in how different types of utilities respond to regulatory incentives and challenges.

4.2.2. Carbon productivity change between 2011 and 2015

During the second sub-period, 2011–2015, which follows the 2009 price review, Ofwat continued with the rolling incentive scheme concerning operating costs, which allowed water companies to retain savings from operational efficiencies [57]. Additionally, the 2009 price review introduced a requirement for water companies to share any savings from maintaining and upgrading infrastructure with customers. Furthermore, the Service Incentive Mechanism (SIM) replaced the previous composite indicator used to measure the service quality performance of the sector [58]. Despite these regulatory adjustments, the carbon performance of water companies during this period remained unchanged from the previous sub-period (2008–2010). The exception was the CEC for WoCs, which, while still showing improvement, did so at a less pronounced rate than in the earlier sub-period. This suggests that during 2011–2015, English and Welsh water utilities, on average, did not manage to efficiently allocate their resources, potentially impacting their performance from a carbon perspective negatively. This observation indicates that while regulatory incentives like the SIM and rolling incentive schemes may have been effective in maintaining operational efficiency, they were not sufficiently influential to drive significant improvements in carbon productivity across the board.

4.2.3. Carbon productivity change between 2016 and 2020

The last sub-period evaluated (2015-20) covers the 2014 price review. The regulator introduced a set of common and bespoke performance indicators to boost economic and environmental sustainability of the industry [59]. These indicators were linked with payments rates, called Outcome Delivery Incentives (ODIs) [60]. A financial reward when commitment levels were achieved, whereas a financial penalty was imposed when outcomes were not delivered. This regulatory approach did not lead to an improvement in CP within the English and Welsh water industry. The CPI for all evaluated water companies remained nearly constant (CPI = 1.001). This trend was similar for both WaSCs and WoCs. The average CPI for WaSCs increased at a modest rate of 0.2% per year, while the average CPI for WoCs progressed at an annual rate of 1.5%. For both types of water companies, the carbon efficiency positively impacted CPI, whereas the CTC experienced a slowdown, counteracting the gains in carbon efficiency.

Table 3
Average carbon productivity estimates by regulatory period.

	2008-10	2011-15	2016-20
Carbon efficiency change			
WaSCs	1.001	1.001	1.016
WoCs	1.074	1.008	1.028
All	1.004	1.005	1.019
Carbon technological change			
WaSCs	1.000	0.999	0.987
WoCs	0.994	0.995	0.988
All	0.997	0.997	0.985
Carbon productivity index			
WaSCs	1.001	1.000	1.002
WoCs	1.068	1.002	1.015
All	1.000	1.001	1.001

4.2.4. Components of carbon productivity change

To better understand the changes in carbon performance in the English and Welsh water industry, the CPI and its components, CEC and CTC, were estimated annually (Fig. 5). Analyzing the complete period from 2008 to 2020, the average values for CPI, CEC, and CTC remained relatively stable over time, with average values of 1.0009, 1.0091, and 0.9929, respectively, indicating little overall change in these parameters when a value of 1.0 represents no changes. However, the underlying variability in the drivers of CPI across years is noteworthy. Fig. 5 shows that CPI demonstrated positive rates throughout the entire period studied, suggesting that water companies have consistently managed to avoid declines in terms of CP across the years. The behaviors of CTC and CEC were generally opposite, which explains the relative stability in CPI, as positive and negative trends in CTC and CEC counterbalanced each other, keeping the CPI constant.

CEC exhibited a positive trend in most periods, except for 2010/11 and 2014/15, where the average CEC estimation was negative. This indicates that in most years evaluated, water companies improved their carbon efficiency, moving closer to the efficient carbon frontier. This suggests an adoption of available technologies to enhance carbon performance. The positive trend in CEC was particularly notable in 2016/2019, where it improved by 2.3% annually, partly motivated by the regulatory framework defined by Ofwat in the 2014 price review, which introduced specific incentives and penalties aimed at encouraging companies to focus more on service and efficiency for their customers [61]. Conversely, the average value of CTC was negative for all years assessed except for 2010/11 and 2014/15, where slight improvements (less than 0.5%) were noted. This suggests that the shift in the carbon-efficient frontier has been negative, indicating that the water industry has not developed and applied novel technological approaches to reduce carbon emissions but has been limited to applying existing technologies. Therefore, the improvement in CP from 2008 to 2020 was minimal. This finding underscores that, to meet the English and Welsh water industry's commitment to achieving net-zero emissions by 2030, significant additional efforts in technological development are necessary.

4.2.5. Carbon productivity change by type of water company

Fig. 6 reports the CPI estimates and its determinants by type of water company. It was found that both types of utilities presented positive CP changes over the study period, with WoCs showing higher improvements at an average annual rate of 1.9%, compared to WaSCs, whose productivity gains were minimal. The main driver for CP change in both utilities was CEC. WoCs improved their carbon efficiency by 2.7% annually, while WaSCs saw a smaller improvement of 0.7%. This indicates that less efficient WoCs made significant progress toward efficiency, while WaSCs showed slower gains. Carbon efficiency gains were notable during the years 2016-17 and 2018-19, with increases of 6.9% and 6.1%, respectively. However, the period was marked by technical regression, with an average annual decline of 1.5% in technical efficiency, negatively impacting carbon productivity. From 2012-13 to

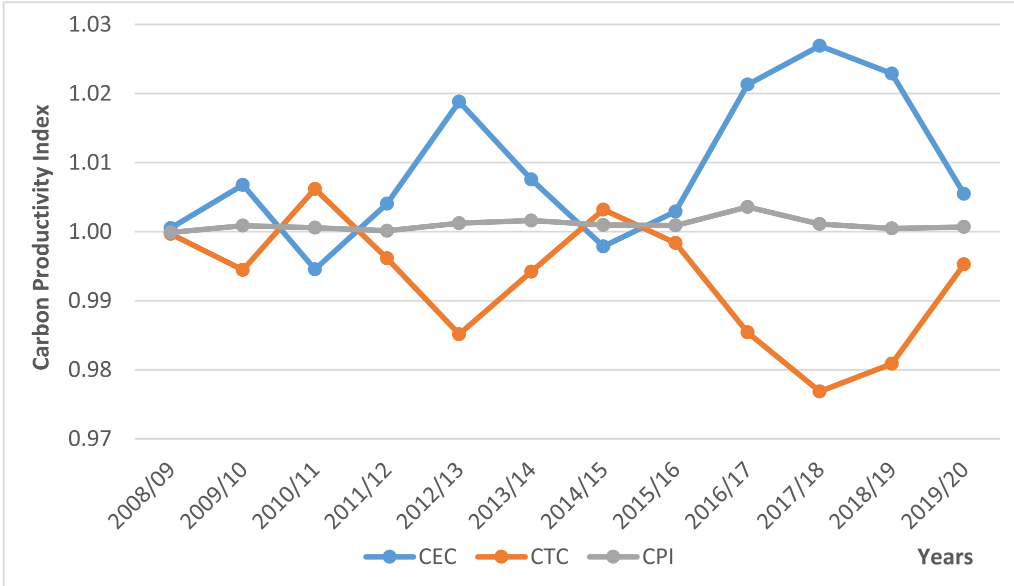

Fig. 5. Average carbon productivity index and its drivers across years.

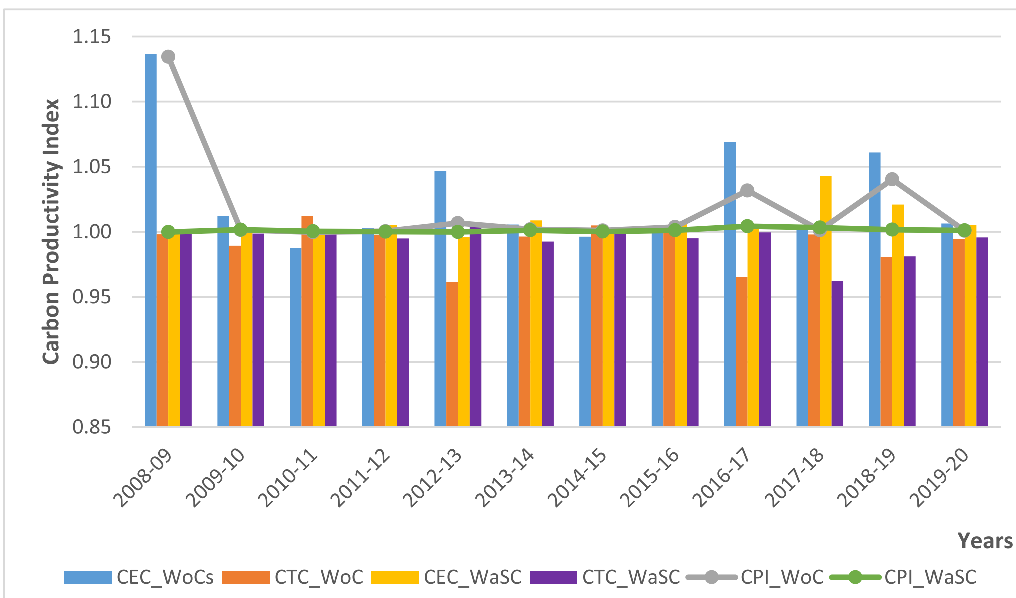

Fig. 6. Average carbon productivity index and its drivers for water and sewerage companies (WaSC) and water only companies (WoC).

2018-19, technical efficiency remained largely unchanged, showing that WaSCs made little effort to enhance environmental performance. Despite managerial improvements leading to some gains in carbon efficiency for WaSCs during 2016-18 (3.2% annual increase), technical changes continued to regress at an average annual rate of 1.2% from 2017-18 onward. Overall, WoCs were more productive than WaSCs, with significant improvements in carbon efficiency observed for WoCs between 2009–2014 and smaller gains for WaSCs from 2015 to 2020. Both types of utilities need to adopt advanced technologies to further enhance CP.

5. Discussion

The CE estimations in this study are significantly lower than those reported by Molinos-Senante and Maziotis [26], who found an average CE of 0.925 for all evaluated water companies in England and Wales from 2010 to 2019. In contrast, this study found an average CE of 0.571 for the period from 2008 to 2020. This lower carbon performance was also evident for both WaSCs and WoCs, with average CE values of 0.567 and 0.571, respectively, compared to 0.928 for WaSCs and 0.923 for WoCs as reported by Molinos-Senante and Maziotis [26]. These differences can be attributed to two main factors. First, the variables used in the assessments differ. This study focused solely on carbon performance, considering carbon emissions as the only input, while Molinos-Senante and Maziotis [26] included two economic variables (energy costs and other costs), indicating that the economic aspects of water companies were also part of their assessment. Second, the methodological approaches differ; StoNED was employed for CE estimation, whereas Molinos-Senante and Maziotis [26] used SFA, a parametric approach where the definition of the production frontier could influence the results.

From a policy perspective, Ofwat, as a regulator, had introduced measures to reduce the carbon footprint of the industry starting in 2010, significant policy impetus came in 2016 when the United Kingdom (UK) ratified the Paris Agreement on Climate Change [62]. To meet the challenges of delivering on the Paris Agreement's goals, the UK developed the National Infrastructure Delivery Plan 2016–2021, which included critical infrastructure such as water services. According to this plan, over £500 billion was planned to be invested in the construction of UK infrastructure and actions for reductions in GHG emissions between 2016 and 2030 [63]. Thus, it is evidenced that this national policy significantly contributed to the improvement of CE in the English and Welsh water industry.

The analysis of the CPI across different regulatory periods shows that changes introduced by the urban water regulator did not result in a significant improvement in the CP of the English and Welsh water industry, as the CPI for all evaluated companies remained almost constant across the three subperiods analyzed (2008-10; 2011-15; 2016-20). However, WoCs exhibited slightly better CP than WaSCs, driven by larger carbon efficiency improvements, which were especially noticeable during the first subperiod (2008-19). In contrast, CTC negatively impacted CP for both types of water companies across all three subperiods. This indicates that water companies need to introduce technological changes to reduce their carbon footprint. For example, using renewable energy could lead to lower carbon emissions and better environmental performance. Regulators could intervene by providing subsidies for renewable resources, enabling utilities to invest in these new technologies. Additionally, the efficient use of pumps when abstracting and transporting water to treatment plants could result in lower energy use and carbon emissions [64]. Another alternative would be adopting technologies to increase water availability. Utilizing technologies that better predict leaks and bursts in mains could improve network performance. Reducing water loss in the network decreases the need for water abstraction, potentially leading to lower treatment requirements and carbon emissions. Customers also have a crucial role to play. Installing water-efficient devices at home could reduce per capita consumption, thereby reducing the amount of water abstracted. This could lead to lower treatment requirements, reduced energy use, and decreased carbon emissions [65].

Some policies from other countries and sectors that have been effective in enhancing carbon efficiency could be adapted for the English and Welsh water industry. One such policy is Germany's energy transition program, "Energiewende," a long-term strategy aiming for a climate-neutral energy system by 2045. Central to this program is the transformation of the power sector, with strong incentives for renewable energy production, particularly solar and wind, and measures to improve energy efficiency already in effect [66]. Additionally, Canada has introduced a federal carbon pricing policy that imposes a fee on fossil fuel consumption (Government of Canada, 2024). A similar approach in the water sector could encourage the adoption of energy-efficient technologies and processes by making high-carbon options economically less attractive. Lastly, the United States has set strict energy efficiency standards and guidelines for appliances and industrial operations. Since 1987, these standards have prevented approximately 2.3 billion tons of CO_2 emissions, equivalent to the annual emissions from 500 million automobiles [67]. Adopting comparable standards for water pumps, treatment equipment, and operational technologies in the water sector could lead to substantial reductions in energy consumption and associated carbon emissions.

Due to data availability constraints, this study focuses on the period from 2008 to 2020. However, since then, the water regulator Ofwat and water companies have underscored its commitment to decarbonizing the water industry in England and Wales. In 2021, water companies collaborated with Water UK to develop the *Net Zero Routemap* [68] outlining a strategy for the industry to achieve net zero across most of its operational emissions (specifically, all operational emissions excluding those from chemicals) using current and emerging technologies. This industry-wide Routemap has provided a foundation for individual water companies to formulate their own net zero plans. In 2022, Ofwat published the "Net Zero Principles Position Paper," designed to support companies in their planning for net zero. Specifically, it expects water companies to: (i) ensure their net zero plans are clearly linked to national government targets; (ii) action on net zero to encompass both operational and embedded emissions and; (iii) prioritise the elimination and reduction of GHG emissions before the use of offsets [69]. Focusing on the price review 2024, Ofwat has introduced incentives for companies to achieve net zero by implementing a common operational GHG emissions performance commitment.

Regarding the lack of technical innovation, the 2022 baseline report on innovation in the water sector, commissioned by Ofwat to the Centre for Strategy and Evaluation Services (CSES), assessed the state of innovation within water companies in England and Wales and their broader innovation networks. It focuses on two primary aspects: the companies' internal capacity and approaches to innovation and the wider "innovation ecosystem," including collaborative efforts and regulatory impacts on innovation. The findings highlight the varying degrees of commitment to innovation across water companies, as reflected in their PR19 business plans, with significant differences in the structure and focus of innovation activities based on company size and starting points. While some companies treat innovation as a dedicated corporate function, others integrate it across all operations, presenting diverse models for innovation but also distinct risks and challenges in scaling up successful innovations. Several key barriers to broader sectoral innovation are identified. First, there is limited knowledge transfer of successful innovations across companies, hindered by geographic differences and a lack of shared insights on tested solutions. Additionally, the report emphasizes a need for increased engagement with innovation suppliers, which could be facilitated through networks, open events, and pilot projects. Established collaborations between water companies and universities are crucial for innovation but face potential threats due to the loss of EU funding post-Brexit. Furthermore, the education and training sector could better support innovation capacity-building, though current offerings are underutilized. Finally, the sector lacks a structured forum for dialogue with other regulatory bodies, which could facilitate cross-regulatory support for innovation [70].

6. Conclusions

The transition to a zero-carbon water industry is one of the main challenges faced by water companies and regulators. Assessing CE and CP provides relevant information to better understand the water-energy-carbon nexus and evaluate the effectiveness of policies and measures introduced to decarbonize the water industry. However, this assessment must be conducted using robust methodological approaches and specific indices that accurately measure carbon performance. Therefore, this study employs the StoNED method, which overcomes the limitations of traditional DEA and SFA techniques, to assess the CE and CP -and its drivers- of a sample of water companies in England and Wales over the period 2008–2020.

CE estimations highlight the importance of protecting raw water quality in the transition to net-zero GHG emissions, as environmental variables related to the need for high levels of treatment to produce drinking water were identified as determinants of CE. The analysis based on price review periods demonstrates that despite various regulatory incentives adopted by the water regulator, the overall CP of water companies did not improve over time. This stagnation is attributed to the lack of technological innovations by water companies to reduce carbon emissions. Comparing the carbon performance of both types of water companies, WoCs exhibited a larger CPI than WaSCs.

Based on the main results of both CE and CP estimations, some key policy implications are as follows. Water regulatory institutions should prioritize policies that enhance the protection of raw water sources to minimize the need for extensive treatment processes to produce potable water. The water regulator should introduce or expand alternative incentives for water companies to adopt and develop new technologies aimed at reducing carbon emissions. These incentives should be part of a more ambitious regulatory policy to encourage significant carbon reductions in the water industry. Given the differences in carbon performance among water companies, the development of a platform for sharing best practices and knowledge among companies could contribute to the decarbonization of the water industry.

Despite the key contributions of this study to the literature, several areas for future research have been identified. Firstly, with a new regulatory price review scheduled by the English and Welsh regulator in 2024, it would be valuable to extend the analysis period to evaluate its potential impact on the carbon performance of water companies. Secondly, from a technological standpoint, conducting a detailed analysis of the specific approaches adopted by water companies to reduce their carbon footprint could offer deeper insights into the relationship between carbon performance and technological advancements. This would enhance the understanding of how different technologies contribute to carbon efficiency within the water industry.

Acronyms and Nomenclature

Acronym	Meaning
CE	Carbon efficiency
CEC	Carbon efficiency change
CNLS	Convex nonparametric least squares
CP	Carbon productivity
CPI	Carbon productivity index
CTC	Carbon Technological change
CO_{2e}	CO_2 equivalent
DEA	Data Envelopment Analysis
GHG	Greenhouse gas
SFA	Stochastic Frontier Analysis
StoNED	Stochastic Semi Non-parametric Envelopment of Data
WaSCs	Water and Sewerage Companies
WoCs	Water only Companies
Nomenclature	**Meaning**
C	Carbon emissions
i	Water utility
t	Time
β_i	Constant term
y	Vector of outputs
z	Set of environmental variables
γ	Parameter to be estimated
δ	Parameter to be estimated
ε	Error term
ϕ	Standard normal density function
Φ	Standard normal cumulative distribution function
$CD_t(C_t, y_t)$	Carbon distance function
θ	Contraction in carbon emissions
PT	Production technology

CRediT authorship contribution statement

Alexandros Maziotis: Writing – original draft, Software, Data curation, Conceptualization. **Ramon Sala-Garrido:** Writing – review & editing, Validation, Resources, Conceptualization. **Manuel Mocholi-Arce:** Writing – review & editing, Validation, Conceptualization. **Maria Molinos-Senante:** Writing – original draft, Project administration, Data curation, Conceptualization.

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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