Sustainable Development

WILEY

RESEARCH ARTICLE

The Influence of Environmental Variables on the Carbon Performance of Water Companies Across Time

Maria Molinos-Senante[1,2] | Alexandros Maziotis[3]

[1]Institute of Sustainable Processes, University of Valladolid, Valladolid, Spain | [2]Department of Chemical Engineering and Environmental Technologies, University of Valladolid, Valladolid, Spain | [3]Department of Business, New York College, Athina, Greece

Correspondence: Maria Molinos-Senante (maria.molinos@uva.es)

Received: 17 May 2024 | **Revised:** 15 January 2025 | **Accepted:** 20 January 2025

Funding: This study was supported by Agencia Estatal de Investigación (Spain), CNS2022-135573, TED-130807A-100; Junta de Castilla y León, CL-EI-2021-07.

Keywords: carbon productivity change | greenhouse gas emissions | metafrontier Malmquist productivity index | stochastic frontier analysis (SFA) | water utilities

ABSTRACT

One of the main challenges that water companies face is to reduce carbon footprint in their transition to carbon neutrality. Past research assessing carbon performance of water companies has mostly ignored heterogeneity among the water companies evaluated. To overcome this limitation, this study employed a parametric metafrontier approach to assess and compare carbon performance of a sample of English and Welsh water companies, embracing water and sewerage companies (WaSCs) and water-only companies (WoCs). This method allows for a comparison of the carbon performance of these two types of companies and analyses the impact of environmental variables on their performance. It was evidenced that water treatment complexity, main source of raw water, and population density significantly influence carbon performance of water companies. The average carbon efficiency for WaSCs was 0.816, indicating marginally superior performance compared to WoSCs, which had an average carbon efficiency of 0.803. Regarding carbon productivity between 2011 and 2020, WoSCs demonstrated an annual improvement in carbon performance of 2.9%, while WaSCs showed an annual decrease in carbon productivity of 4.2%. The insights gained from this study are highly significant for policymakers focused on transitioning the water industry toward net-zero carbon emissions.

1 | Introduction

Within the framework of sustainable development goals, the water industry faces multiple challenges arising from globalization, climate change, urbanization, and population growth (Lechevallier 2014; Wang, Wang, and Li 2024). Extreme weather events, such as intense rainfall or droughts, pose significant risks to water resources and infrastructure. Concurrently, the escalating water demand due to population growth threatens the sustainability of existing water resources (Sukanya and Sabu 2023). Furthermore, the entire process of water provision, from extraction and treatment to distribution to end-users, demands substantial energy use (Yan et al. 2024). This energy consumption results in the emission of greenhouse gases (GHGs), an undesirable byproduct of water production. Therefore, understanding the factors that influence both economic and environmental performance is crucial for ensuring the sustainable and efficient delivery of water services (Ananda 2018; Sowby and Hopkins 2023).

In recent decades, researchers and policymakers have undertaken initiatives to transition the water industry toward net-zero carbon emissions. For example, several Australian states have declared their intention to establish a net-zero carbon water industry by 2050 (Ananda and Hampf 2015). Similarly, the UK government has set a target to achieve net-zero carbon across industries by

2030 (Ofwat 2010; HM Government 2018; CCC 2019). Numerous studies have examined the link between production factors and GHG emissions in the water cycle (e.g., Yan et al. 2024; Wang, Wang, and Li 2024; Maziotis et al. 2023). A key discovery from these studies is that production factors, particularly energy consumption in water and sewerage treatment, are likely to rise with increasing water demand, potentially leading to higher GHG emissions. In this context, it has been evidenced the positive impact of environmental knowledge and environmental policy regulations on attitudes toward water management programs (Kherazi et al. 2024). Consequently, understanding the factors that drive production costs and carbon emissions in water service provision is crucial. This necessity underscores the importance of evaluating carbon efficiency and productivity in the water industry. The use of composite indicators estimated through multicriteria decision analysis represents a valuable approach for managing the complexity inherent in decision-making within the water industry (D'Adamo et al. 2024).

To better understand the nexus water-energy-carbon in the urban water sector, the objectives of this study are twofold. The first objective was to evaluate and compare the carbon efficiency and carbon productivity of two types of water companies, such as WaSCs and WoCs, accounting for group heterogeneity. The second objective was to quantify the influence of environmental variables on the carbon performance of assessed water companies.

The contributions of this study to existing literature are threefold: First, the study is pioneering as it introduces a parametric metafrontier approach to assess and compare the carbon performance among a sample of water companies. Unlike traditional models, this innovative methodological framework allows for the integration of group heterogeneity and the influence of external variables into the evaluation process. This approach enables a more nuanced understanding of how internal and external factors impact carbon efficiency. Second, the research facilitates the first comparative analysis of the carbon performance between English WaSCs and WoCs. By employing the metafrontier model, this comparison acknowledges the intrinsic differences and operational variations between these groups, thus providing a more context-sensitive evaluation. This aspect of the study is crucial, as it highlights the diverse challenges and opportunities faced by different types of water companies in managing their carbon emissions. Lastly, the study contributes new insights into the role of environmental variables in shaping the carbon performance of water companies. Through a detailed analysis, it identifies specific external factors that are most influential, offering evidence-based recommendations for policy and operational adjustments. These insights are particularly valuable for policymakers and company managers aiming to design targeted strategies to reduce carbon emissions within the sector.

2 | Literature Review

Research on the carbon performance measurement of water companies is relatively limited. Notable exceptions include the studies of Walker et al. (2019) and Sala-Garrido et al. (2021, 2023) who incorporated GHG emissions in efficiency assessments for water companies in England and Wales. These studies utilized data envelopment analysis (DEA) models, a nonparametric method. In the context of Australian water utilities, Ananda and Hampf (2015) and Ananda (2018) explored the impact of GHG emissions on the productivity of water companies. They employed the Malmquist-Luenberger productivity indicator, also using DEA techniques for their estimation. Following a similar approach, Molinos-Senante and Maziotis (2022) applied this framework to evaluate the influence of GHG emissions on the productivity of various water companies in England and Wales.

Despite the notable contributions of past research on this topic, the above-mentioned studies suffer from two main limitations. The first one is that linear programming techniques such as DEA are deterministic which means that statistical noise is not included in the analysis and any deviations from the efficient frontier is due to inefficiency only (Wojcik, Dyckhoff, and Clermont 2019). Moreover, DEA models cannot directly accommodate the impact of several environmental variables on carbon performance of water utilities[1]. The second limitation refers to the heterogeneity among the water companies evaluated. Thus, water companies in England and Wales embrace two types of utilities namely: (i) water and sewerage companies (WaSCs) and (ii) water-only companies (WoCs) (Walker, Williams, and Styles 2020). WaSCs provide both water and sewerage services, while WoCs offer solely water services. Overlooking this distinction implies an assumption that all water companies share access to identical production technology (Oh 2010; Ananda and Oh 2023). However, comparing units (water companies) with heterogeneous production technology can lead to biased results (Jin et al. 2024).

To deal with group heterogeneity issue in efficiency and productivity assessment, the metafrontier concept was introduced. The metafrontier approach was first proposed by Hayami (1969) and was further developed by Battese and Rao (2002), Battese, Rao, and O'Donnell (2004) and O'Donnell, Rao, and Battese (2008) and Huang, Huang, and Liu (2014). The metafrontier is defined as the envelope of producible input–output combinations across all feasible technology groups (Barra and Falcone 2024). The application of the metafrontier framework includes a two-step approach. In the first step, the efficiency of each group (group frontier) is estimated. In the second step, the metafrontier is calculated by assuming that all companies in each group have possible access to the same technologies (Ho, Hung, and Tien 2023). Thus, the efficiencies evaluated under the metafrontier are comparable across different groups (Jin et al. 2024).

Applications of metafrontier approach in the drinking water sector are rare. De Witte and Marques (2009) were pioneered in applying the metafrontier to compare the efficiency of water utilities from five countries. Its analysis was extended to eleven countries by Molinos-Senante and Sala-Garrido. Subsequently, the assessment was extended to examine the dynamic productivity changes (Molinos-Senante, Maziotis, and Sala-Garrido 2017). However, their focus was on economic performance of water companies as they did not integrate GHG emissions on efficiency and productivity estimations. Ananda and Oh (2023) was the only study to assess carbon performance of water companies employing the metafrontier concept. Its assessment focused on a sample of 49 water utilities in Australian embracing four groups according to its size (major, large, medium, and small). However, one limitation of the study was that carbon productivity was estimated using the DEA method whose pitfalls have been previously described.

Despite the valuable contributions of existing studies previously discussed, a significant gap remains in the comprehensive assessment of carbon performance in water companies, particularly in addressing group heterogeneity and the influence of environmental factors. Most prior research has relied on deterministic models, such as DEA, which do not account for statistical noise or the impact of external variables, potentially leading to biased performance evaluations. Additionally, these studies often assume uniform production technologies across all companies, overlooking the technological and operational differences between WaSCs and WoCs. This assumption fails to capture the diverse operational environments within the water sector.

To address these limitations, this article applies a parametric metafrontier approach—a pioneering methodology in this context—that provides a more nuanced analysis. Unlike traditional methods, this approach accounts for heterogeneity among water companies and quantifies the influence of external environmental variables on carbon performance. By adopting this methodology, the study offers new insights into how varying operational and contextual factors impact the carbon efficiency of WaSCs and WoCs. Furthermore, this research makes a novel contribution to the literature by providing a comprehensive comparative analysis of carbon performance across these two distinct groups of water companies. The findings have practical implications for policymakers, highlighting the importance of tailored strategies to enhance carbon productivity within the water sector.

3 | Methodology

Carbon efficiency and carbon productivity of English and Welsh WaSCs and WoCs was estimated and compared based on the metafrontier concept which involves estimating the production technology for each group of water companies, that is, WaSCs and WoCs, and the production technology that encompasses all observations from all groups, that is, the metafrontier.

Figure 1 shows the main methodological steps to estimate both carbon efficiency and carbon productivity of WaSCs and WoCs.

3.1 | Carbon Efficiency Estimation

Step 1. Definition of the carbon Shephard distance function.

Let's suppose that each water company employs a vector of inputs such as operating expenses to produce a set of outputs such as drinking water delivered. As part of the water production and distribution process, carbon emissions (c) are also produced. Considering the environmental objective of minimizing carbon

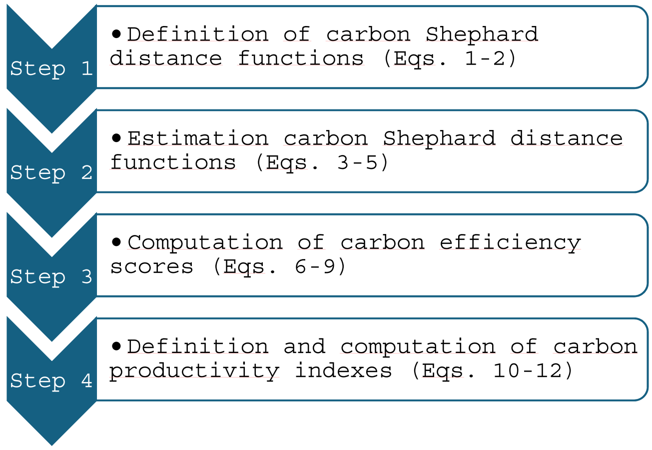

FIGURE 1 | Main methodological steps to estimate carbon efficiency and carbon productivity of water companies.

emissions, this variable was treated as input as well (Zhou, Ang, and Han 2010; Zhou, Ang, and Wang 2012; Lin and Du 2015; Tan et al. 2020; Molinos-Senante and Maziotis 2022). The vector of inputs is denoted as $x = (x_1, \ldots, x_K)$ and the vector of outputs as $y = (y_1, \ldots, y_L)$.

Carbon efficiency for each group of water companies and for the whole sample was estimated using the concept of the Shephard distance function (Tan et al. 2020; Molinos-Senante and Maziotis 2022). The carbon Shephard distance function with respect to the group frontier and metafrontier technology is defined as follows:

$$D_I^j(x, c, y) = \max\left\{\delta : \delta > 0\left(\frac{c}{\delta}\right), y \in \mathrm{PPT}^j\right\} \quad (1)$$

$$D_I^*(x, c, y) = \max\left\{\delta : \delta > 0\left(\frac{c}{\delta}\right), y \in \mathrm{PPT}^*\right\} \quad (2)$$

where δ denotes the distance by which carbon emissions can go down (Molinos-Senante and Maziotis 2022). If the analyzed water company is on the frontier, then $D_I^j(x, c, y) = 1$ or $D_I^*(x, c, y) = 1$ which means that the company is carbon efficiency, and therefore, in comparison to its peers, it has no room to reduce carbon emissions.

Step 2. Estimation of the carbon Shephard distance function.

The carbon Shephard distance function is estimated using the stochastic frontier analysis (SFA) method. A parametric approach such as SFA is chosen because of its advantage to include both statistical noise and inefficiency (Huang, Huang, and Liu 2014; Horncastle et al. 2022). The functional form selected for the underlying production technology is the translog input distance function because of its flexible form as it includes interactions between inputs and outputs (Susaeta et al. 2024). Moreover, the use of an input distance function allows us to accommodate multiple inputs and outputs without the requirement of using prices for inputs and outputs (Rita et al. 2023).

Focusing on group frontier, for any group j for any water company i and period t, the translog carbon Shephard distance function is as follows:

$$\ln \frac{1}{c_{jt}} = a_j + \sum_{l=1}^{L} a_l \ln y_{ljt} + \sum_{k=1}^{K} \beta_k \ln x_{kjt} + \frac{1}{2}\sum_{l=1}^{L}\sum_{m=1}^{L} \alpha_{lm} \ln y_{ljt} \ln y_{mjt} + \frac{1}{2}\sum_{k=1}^{K}\sum_{n=1}^{K} \beta_{kn} \ln x_{kjt} \ln x_{njt} + \sum_{l=1}^{L}\sum_{k=1}^{K} \gamma_{lk} \ln y_{ljt} \ln x_{kjt} + \psi_1 t + \frac{1}{2}\psi_2 t^2 + \sum_{k=1}^{K} \delta_k \ln x_{kjt} t + \sum_{l=1}^{L} \zeta_l \ln y_{ljt} t + \sum_{z=1}^{Z} \mu_z z_{jt} + v_{jt} + u_{jt} \quad (3)$$

where z denotes a set of environmental variables that could influence carbon efficiency, a_j captures unobserved heterogeneity, v is the statistical noise that follows the normal distribution, and u captures inefficiency which follows the half-normal distribution.

In the case of the metafrontier, following the approach of Huang, Huang, and Liu (2014) and Cao, Qi, and Ren (2017), we first derive the optimal carbon emissions $\left(c^*_{i,t}\right)$ for any water company i at any time t as:

$$c^*_{i,t} = c_{i,t} \times \text{GCEI}_{jt} \quad (4)$$

where $c_{i,t}$ is the current carbon emission of the water company i at time t, and $GCEI_{jt}$ is the group carbon efficiency index of the group of water companies j at time t.

Then, the second stage SFA regression for any water company i at any time t becomes:

$$ln \frac{1}{c^*_{i,t}} = a_j + \sum_{l=1}^{L} a_l \ln y_{l,i,t} + \sum_{k=1}^{K} \beta_k \ln x_{k,i,t} + \frac{1}{2}\sum_{l=1}^{L}\sum_{m=1}^{L} \alpha_{lm} \ln y_{l,i,t} \ln y_{m,i,t} + \frac{1}{2}\sum_{k=1}^{K}\sum_{n=1}^{K} \beta_{kn} \ln x_{k,i,t} \ln x_{n,i,t} + \sum_{l=1}^{L}\sum_{k=1}^{K} \gamma_{lk} \ln y_{l,i,t} \ln x_{k,i,t} + \psi_1 t + \frac{1}{2}\psi_2 t^2 + \sum_{k=1}^{K} \delta_k \ln x_{k,i,t} t + \sum_{l=1}^{L} \zeta_l \ln y_{l,i,t} t + \sum_{z=1}^{Z} \mu_z z_{i,t} + v^*_{i,t} + u^*_{i,t} \quad (5)$$

where the meaning of the parameters is the same as in Equation (3) and * denotes optimal values.

Step 3. Computation of carbon efficiency scores and technological gap ratio (TGR).

Carbon efficiency of water companies based on the group frontier and metafrontier technology are defined as follows:

$$\text{GCEI} = \frac{1}{D_I^j(x, c, y)} \quad (6)$$

$$\text{MCEI} = \frac{1}{D_I^*(x, c, y)} \quad (7)$$

where GCEI and MCEI denote the group carbon efficiency index and metafrontier carbon efficiency index, respectively. These indices take a value between zero and one, with a value of one meaning that the water company under assessment is fully carbon efficient. Values lower than one indicate carbon inefficiency and, therefore, the potential to reduce carbon emissions. The TGR measures the distance in the carbon efficiency of a water company between the group and metafrontier technology (Battese and Rao 2002; O'Donnell, Rao, and Battese 2008).

$$\text{TGR}(x, y) = \frac{D_I^j(x, c, y)}{D_I^*(x, c, y)} = \frac{\text{MCEI}}{\text{GCEI}} \quad (8)$$

Equation (8) can be written as follows:

$$\text{MCEI} = \text{TGR} \times \text{PCEI} \quad (9)$$

Equation (9) evidences that the MCEI is influenced by two key factors, namely GCEI and TGR. Consequently, a water company can enhance its carbon efficiency concerning the metafrontier technology by pursuing one or more of the following strategies: (i) improving efficiency within its own group while keeping the distance between the group frontier and metafrontier technology constant; (ii) enhancing its potential efficiency, which is equivalent to reducing the gap between the group frontier and metafrontier technology, assuming that internal efficiency within the group remains unchanged and; and (iii) simultaneously working on both improving group efficiency and potential efficiency.

3.2 | Carbon Productivity Assessment

Step 4. Definition and estimation of the carbon productivity index.

Carbon productivity measures changes in carbon performance of each water company i between two time periods, t and $t+1$. This assessment is done using the traditional Malmquist productivity index framework, which comprises two integral components: technical change and efficiency change (Fare, Grosskopf, and Zhang 1994):

$$\text{GCPI}_{i,t,t+1} = \frac{1/D_I^{j,t+1}(x_{i,t+1}, c_{i,t+1}, y_{i,t+1})}{1/D_I^{j,t}(x_{i,t}, c_{i,t}, y_{i,t})} \times \left[\frac{D_I^{j,t+1}(x_{i,t+1}, c_{i,t+1}, y_{i,t+1})}{D_I^{j,t}(x_{i,t+1}, c_{i,t+1}, y_{i,t+1})} \times \frac{D_I^{j,t+1}(x_{i,t}, c_{i,t}, y_{i,t})}{D_I^{j,t}(x_{i,t}, c_{i,t}, y_{i,t})}\right]^{0.5} = \text{GCECI}_{i,t,t+1} \times \text{GCTCI}_{i,t,t+1} \quad (10)$$

$$\text{MCPI}_{i,t,t+1} = \frac{1/D_I^{*,t+1}(x_{i,t+1}, c_{i,t+1}, y_{i,t+1})}{1/D_I^{*,t}(x_{i,t}, c_{i,t}, y_{i,t})} \times \left[\frac{D_I^{*,t+1}(x_{i,t+1}, c_{i,t+1}, y_{i,t+1})}{D_I^{*,t}(x_{i,t+1}, c_{i,t+1}, y_{i,t+1})} \times \frac{D_I^{*,t+1}(x_{i,t}, c_{i,t}, y_{i,t})}{D_I^{*,t}(x_{i,t}, c_{i,t}, y_{i,t})}\right]^{0.5} = \text{MCECI}_{i,t,t+1} \times \text{MCTCI}_{i,t,t+1} \quad (11)$$

where $GCPI_{i,t,t+1}$ denotes the group frontier carbon productivity index which could improve, deteriorate, or remain constant between two time periods, respectively, if $GCPI_{i,t,t+1} > < = 1$. It is decomposed into group frontier carbon efficiency change ($GCECI_{i,t,t+1}$) and group frontier carbon technical change ($GCTCI_{i,t,t+1}$). Analogously, in Equation (10), $MCPI_{i,t,t+1}$ denotes the metafrontier carbon productivity index between two time periods. It consists of two components, the metafrontier carbon efficiency change, $MCECI_{i,t,t+1}$, and the metafrontier carbon technical change, $MCTCI_{i,t,t+1}$. Both with respect to the group frontier and the metafrontier, efficiency change component measures changes to the efficiency of carbon emissions input from time period t to time period $t+1$. It is interpreted as a measure of the catching-up effect (Ananda and Oh 2023). In our case study, it involves the capacity of the water companies to be managed in accordance with the best operational practices. The second component, that is, technical change measures the improvement or retardation in carbon efficient (group and metafrontier) technologies. It measures the changes in frontiers between two periods. It is related to long-term strategic planning and timely capital investment.

$MCPI_{i,t,t+1}$ is the product of two terms namely, group carbon productivity (GCPI) index ($GCPI_{i,t,t+1}$) and TGR ($TGR_{i,t,t+1}$) (Equation (9)).

$$MCPI_{i,t,t+1} = GCPI_{i,t,t+1} \times TGR_{i,t,t+1} \tag{12}$$

This means that metafrontier carbon productivity ($MCPI_{i,t,t+1}$) can be influenced by group frontier and TGR. It suggests that using the metafrontier technology carbon productivity could be affected by the performance within each group and whether group productivity moved closer or away from metafrontier productivity.

4 | Case Study Description

The evaluation of carbon efficiency and carbon productivity refers to the water services provided by WaSCs and WoCs in England and Wales over the period 2011–2020. The monopolistic nature of the private water industry required the establishment of a regulator, the Water Services Regulation Authority (Ofwat) who monitors the economic and environmental sustainability of the industry. Every five years the regulator approves water companies' business plans and determines a future revenue allowance for each company (price review process), which is then used by the companies to set tariffs (Molinos-Senante, Maziotis, and Sala-Garrido 2017).

To calculate carbon efficiency and productivity over time, we selected inputs and outputs based on available data and past literature reviews (e.g., See 2015; Walker et al. 2019; Walker, Williams, and Styles 2020; Cetrulo, Marques, and Malheiros 2019; Goh and See 2021). As output, we used the volume of water delivered measured in megaliters per year. We used two inputs in our analysis. The first input was defined as the annual operating expenditure of water services expressed in millions of ₤. The second input was the carbon emissions from the supply of water services. They were expressed in kg of CO_2 equivalent (CO_{2eq}) and are associated with the operation of water services. Carbon emissions are reported by water companies based on the UK Government Environmental Reporting Guidelines (HM Government 2019)[2].

Several studies in the past (e.g., Zhou, Ang, and Wang 2012; Lin and Du 2015; Tan et al. 2020) showed that environmental variables could influence carbon performance and therefore, they were included in the modeling approach. The first environmental variables were associated with the geographic conditions from which raw water is abstracted. These included the percentage of water taken from two different water sources, rivers, and boreholes. We also incorporated the average pumping head as a proxy for the energy required to take, treat, and deliver water to users (Walker et al. 2021). The subsequent environmental variable captured the treatment quality of water. This was defined as the percentage of water receiving high levels of water treatment (Ofwat 2010). We finally included in the analysis population density which was defined as the ratio of population and water area.

The descriptive statistics of the variables used in the study are displayed in Table 1 and were collected from Ofwat and water companies´ annual reports.

TABLE 1 | Descriptive variables of water companies to assess its carbon performance. Values from 2011 to 2020.

Variables	Unit of measurement	Mean	Std. Dev.	Minimum	Maximum
Operating expenditure[a]	₤m/year	110.86	96.87	8.33	422.84
Carbon emissions	$kgCO_{2e}$/year	74,667,299	67,258,171	3,122,940	275,900,000
Volume of water delivered	Ml/year	246,301	203,783	8924	791,616
Water taken from rivers	%	27.2	24.8	0.0	86.1
Water taken from boreholes	%	41.2	31.2	0.0	100.0
Average pumping head	nr	139	36	65	224
Water receiving high levels of treatment	%	58.1	22.4	22.3	99.0
Population density	$000 s/km^2$	0.469	0.280	0.146	1.263

Note: Total observations are 180 being 100 WaSCs and 80 WoCs.
[a]Operating expenditure is expressed in 2020 prices.

TABLE 2 | Estimates of parameters of the carbon distance function for group and metafrontier models.

	Group of WaSCs		Group of WoCs		Metafrontier WaSCs and WoCs	
Variables	**Coeff.**	**S.Err.**	**Coeff.**	**S.Err.**	**Coeff.**	**S.Err.**
Water delivered	−0.827***	0.073	−0.989***	0.065	−0.975***	0.059
Opex	0.626***	0.056	0.581***	0.062	0.804***	0.063
Time	−0.003	0.006	0.009***	0.003	−0.024***	0.006
Water delivered^2	−0.401***	0.145	−0.301***	0.105	−0.102***	0.016
Opex^2	0.403***	0.062	0.549***	0.073	0.272***	0.043
Water delivered*opex	−0.126***	0.031	0.274***	0.037	0.029	0.024
Opex*time	−0.041***	0.009	0.021*	0.011	−0.017**	0.007
Water delivered*time	0.0141*	0.008	−0.044***	0.005	−0.035***	0.005
Time^2	0.007*	0.004	−0.008***	0.003	−0.003	0.004
Average pumping head	−0.251***	0.057	−0.582***	0.021	−0.293***	0.027
% of water taken from rivers	0.298***	0.084	0.0205	0.048	0.307***	0.057
Population density	0.154***	0.039	−0.205***	0.020	0.072***	0.019
% of water taken from boreholes	0.032	0.088	0.138***	0.043	0.082	0.050
Water treatment complexity	−2.584***	0.437	0.186***	0.172	−0.672***	0.162
Sigma	0.175***	0.012	0.147***	0.009	0.242***	0.014
Lambda	1.005***	0.216	2.251***	0.319	0.726***	0.235
Log-likelihood	66.97		59.77		87.001	

***, **, and *: 1%, 5%, and 10% leves of significance, respectively.

5 | Results and Discussion

5.1 | Estimation of the Carbon Shephard Distance Function

In the proposed methodology for assessing carbon efficiency and carbon productivity, the initial step involves calculating the carbon Shephard distance function for each group of water companies, that is, WaSCs and WoCs, as well as for the metafrontier. The findings from this stage of the analysis are presented in Table 2[3].

The estimated parameters indicate that the distance function behaves as expected: it is nonincreasing in outputs and nondecreasing in inputs. For WaSCs, the analysis reveals that a 1% increase in the volume of water delivered or in operating expenses could lead to an increase in carbon emissions by approximately 0.828% and 0.627%, respectively. Similarly, for WoCs, a 1% increase in the same factors might result in carbon emissions rising by 0.990% for water delivery and 0.581% for operating expenses. This pattern involves both types of companies which could potentially reduce their carbon footprint by increasing their scale of operation. The same trend is observed in the metafrontier model, where, on average a 1% increase in water delivery could lead to a 0.975% increase in carbon emissions across the water industry, and a 1% rise in operating expenses might result in a 0.804% increase in carbon emissions, all else being equal. Table 2 further confirms that the volume of water delivered and operating expenses are statistically significant factors driving carbon emissions in both WaSCs and WoCs. This finding emphasizes the importance of these variables in managing and strategizing for better carbon efficiency in the water industry.

In the metafrontier model, the time variable, representing technical change, showed a negative and statistically significant deviation from zero. This indicates that, on average, the water industry experienced a technical regression at a rate of 2.4%. However, the impact of this regression appears to be relatively minor, as suggested by the insignificance of the squared term of the time variable. When examining the different types of water companies separately, technical change was found to be insignificant among WaSCs. In contrast, a small technical progress was observed among WoCs. This difference suggests that while overall the industry faced challenges in advancing its technical capabilities, the extent and impact of these challenges varied between different types of companies. This finding highlights the nuanced nature of technical change within the water industry and underscores the importance of differentiating between various types of companies when assessing industry-wide trends and developments. It also points to the need for targeted strategies to address the specific challenges and leverage the opportunities for technical advancement in different segments of the industry.

The analysis of environmental variables in relation to carbon emissions, using the metafrontier technology, yielded several insightful conclusions. Most environmental factors, except for the percentage of water drawn from boreholes, significantly influenced carbon emissions. Notably, two factors—average pumping head and water treatment quality—were found to potentially increase carbon emissions. This suggests that the processes involved in the abstraction, treatment, and delivery of water could lead to increased energy use and, consequently, higher carbon emissions. The impact of water treatment on carbon emissions was particularly pronounced, as indicated by the magnitude of its coefficient. This implies that more complex water treatment processes, which require greater input, can result in elevated carbon emissions.

Conversely, the study found that the percentage of water sourced from rivers and the population density could reduce carbon emissions. This might be attributed to the lower energy intensity of extracting water from rivers compared to other sources. The results indicate a nuanced relationship between different water sources and treatment methods and their respective carbon emission impacts. Understanding these dynamics is crucial for developing strategies to reduce the carbon footprint of the water industry, particularly in areas where environmental factors significantly influence energy consumption and carbon emissions.

The analysis of environmental variables among WaSCs yielded findings consistent with those observed using the metafrontier technology. Specifically, the complexity of water treatment emerged as having the most significant impact on carbon emissions among WaSCs, as indicated by the size of the estimated coefficient. This underlines the substantial influence of water treatment processes on the carbon footprint of these companies. However, when the analysis focused solely on WoCs using their specific frontier model technology, some differences emerged. The results suggested that for WoCs, average pumping head and population density could potentially increase their average carbon emissions. On the other hand, the percentage of water sourced from boreholes appeared to decrease carbon emissions in this group. Notably, among WoCs, the average pumping head was identified as having the most significant effect on carbon emissions, as evidenced by the size of its estimated coefficient.

These findings highlight the varying impacts of different environmental variables on carbon emissions across WaSCs and WoCs. They reveal the importance of considering the specific operational characteristics and environmental contexts of different types of water companies when assessing their carbon emissions and formulating strategies to mitigate their environmental impact.

Results highlighted the necessity for customized policies and interventions that take into account the unique characteristics and challenges of the two evaluated types of water companies. It is essential that policymakers utilize these findings to craft regulations and support initiatives that cater to the particular requirements of WaSCs and WoCs. This conclusion was reached by acknowledging the diversity in carbon performance among water companies. Without this consideration, traditional analyses would fail to distinguish the varying carbon performance between WaSCs and WoCs. From a theoretical viewpoint, this research underscores the significance of integrating environmental variables when setting carbon performance benchmarks for the urban water sector. By exploring the link between operational factors and carbon emissions, the study validates the critical role of environmental factors in shaping carbon performance objectives.

TABLE 3 | Summary of group carbon efficiency, metafrontier carbon efficiency, and TGR for English and Welsh water companies (2011–2020).

	Mean	St.Dev.	Min	Max
WoCs				
Group CE	0.894	0.065	0.691	0.979
Meta CE	0.803	0.066	0.620	0.905
TGR	0.898	0.012	0.872	0.926
WaSCs				
Group CE	0.909	0.029	0.762	0.966
Meta CE	0.816	0.039	0.662	0.909
TGR	0.897	0.018	0.833	0.942
WoCs and WaSCs				
Group CE	0.902	0.049	0.691	0.979
Meta CE	0.810	0.053	0.620	0.909
TGR	0.898	0.016	0.833	0.942

5.2 | Estimation of Carbon Efficiency of Water Companies

Table 3 reports a summary of the statistics of the group and meta carbon efficiency scores for the water industry over the years 2011–2020. The results indicate that on average the water industry showed considerable levels of carbon efficiency using the group and metafrontier technologies. However, there is room for further reductions in carbon emissions. The mean group carbon efficiency score for both WaSCs and WoCs was 0.902 which means that the industry could reduce carbon emissions by 9.8% to produce the same level of output when using group technologies. However, there is potential for higher savings in carbon emissions if the industry's best available technologies are adopted. As shown by the metafrontier carbon efficiency score, the industry could further cut down carbon emissions by 19% on average if the metafrontier technology is employed.

The analysis of carbon efficiency between WaSCs and WoCs revealed that on average WaSCs tend to be slightly more carbon efficient than WoCs (Table 3). Specifically, on average WoCs could reduce their carbon emissions by 10.6% (average CE score of 0.894) whereas WaSCs by 9.1% (average CE score of 0.909) to deliver the same amount of water. Within WoSCs, the least carbon efficient water company had a CE score of 0.856 (Figure 2), indicating that the worst-performing firm could potentially reduce its carbon emissions by an average

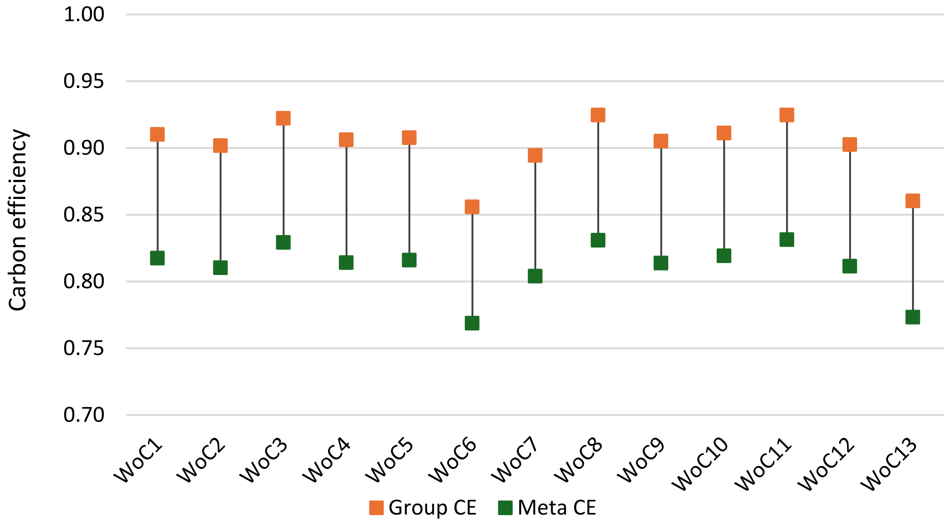

FIGURE 2 | Average carbon efficiency (Group CE), potential carbon efficiency, and meta carbon efficiency for English and Welsh water-only companies (WoCs) (2011–2020).

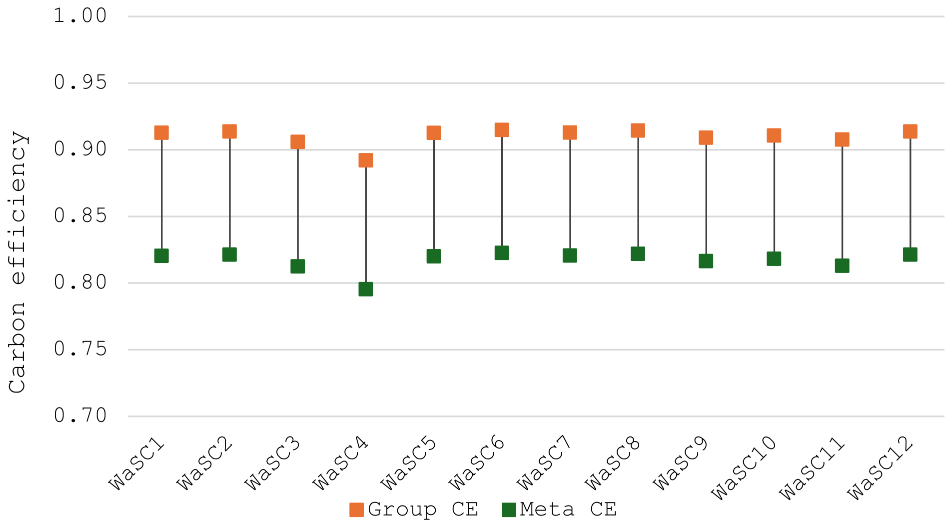

FIGURE 3 | Average carbon efficiency (Group CE), potential carbon efficiency, and meta carbon efficiency for English and Welsh water and sewerage companies (WaSCs) (2011–2020).

of 14.4%. On the other hand, the most carbon efficient WoC achieved a mean efficiency of 0.925, suggesting a possible reduction in carbon emissions by 7.5%. These findings highlight that different WoCs need to put varying levels of effort into becoming more carbon efficient. When considering the mean meta carbon efficiency for an average WoC, it was found to be 0.803. The average TGR is 0.898, which is close to 1. This proximity to 1 indicates that group and metafrontier carbon efficiency scores are moving in the same direction. However, there is still potential for WoCs to become more carbon efficient by adopting the industry's available technologies, suggesting room for improvement through technological adaptation and operational optimizations.

Delving into the results for WaSCs it is found that the potential savings in carbon emissions was at the level of 9.1% to generate the same level of output when the group technology is used. The less efficient company within this group reported a carbon efficiency score of 0.892, whereas the most carbon efficient utility showed an efficiency score of 0.915 (Figure 3). This means that the savings in carbon emissions among WaSCs could vary between 8.5% and 10.8% on average. The mean meta CE was at the level of 0.816 and the average TGR was 0.897 which means that the companies in this group could additionally reduce carbon emissions by 10.3% based on the available technology to the industry as a whole.

By identifying the most and least carbon efficient water companies (Figures 2 and 3), areas for targeted efforts become evident. Water companies with lower carbon efficiency scores should adopt specific strategies to enhance their performance, drawing insights from their more efficient counterparts. The observed differences between WaSCs and WoCs validate the application of the metafrontier approach in assessing carbon efficiency within the water industry. This contributes to the theoretical understanding of how diverse efficiency models can be employed to measure and compare carbon performance effectively.

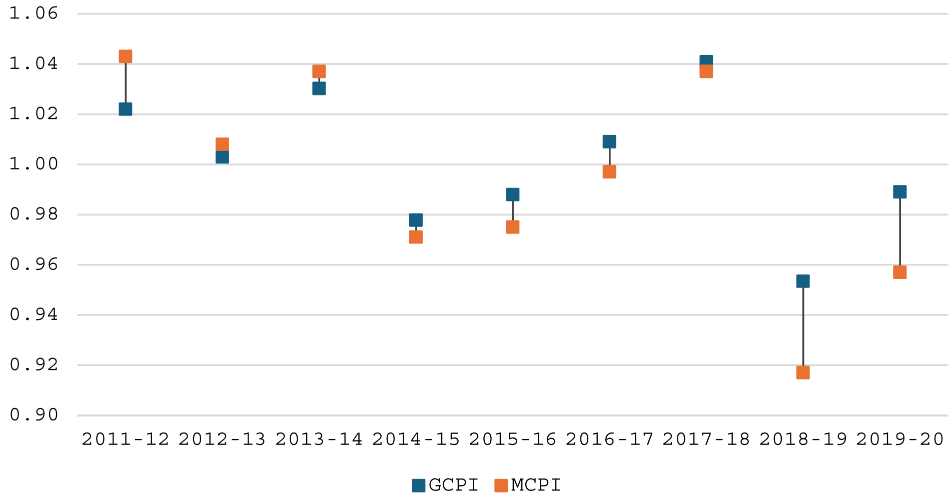

FIGURE 4 | Average group carbon productivity (GCPI) and metafrontier carbon productivity (MCPI) for English and Welsh water and sewerage companies and water-only companies.

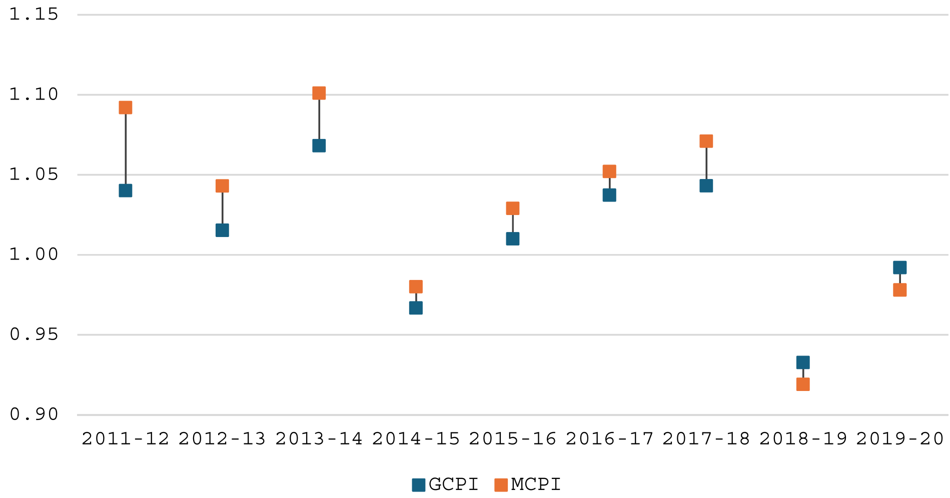

FIGURE 5 | Average group carbon productivity (GCPI) and metafrontier carbon productivity (MCPI) for English and Welsh water-only companies.

5.3 | Estimation of Carbon Productivity Change of Water Companies

Figure 4 shows the average estimates of the GCPI and metafrontier carbon productivity change during the years 2011–2020. The results indicated that based on both group and metafrontier estimations, carbon productivity remained almost constant for the period 2011–2020 since average GCPI was 1.00 and average MCPI was 0.99. However, carbon productivity was not constant over years. Figure 3 illustrates that carbon productivity improved during the years 2011–2014 and 2016–2018 whereas for the remaining years evaluated suffered a retardation. These results can be linked with the regulatory cycle of English and Welsh water companies. The 2009 price review refers to the years 2011–2015. As part of the 2009 price review, the water regulator, Ofwat, adopted several incentive schemes to encourage performance. For instance, it strengthened cost reduction targets and allowed companies to hold any savings in costs no matter the year these happened. Moreover, it introduced the Service Incentive Mechanism (SIM) to reward/penalize water companies for outperformance/underperformance, respectively, regarding quality of service. The results indicate that the industry made considerable improvements in their carbon productivity which increased at a rate of 1.5% per annum.

As part of the 2014 price review, the regulator replaced SIM with a set of common and company-specific indicators to monitor industry's economic and environmental sustainability. Water companies received financial rewards/penalties when they deliver/do not deliver the outcomes they set in their business plans. Some performance indicators such as water leakage and bursts in pipes are associated with financial rewards and penalties, whereas other indicators such as GHG emissions and production of renewable energy are related to reputational rewards. Thus, the 2014 price review appeared to have stimulated less efficient WoCs to improve their carbon efficiency, while continuing to be industry leaders in terms of technological advancements. In contrast, WaSCs reported lower rates of carbon productivity on average. This was attributed to the lack of adoption of group-specific and industry carbon efficient technologies (See Figures 5 and 6).

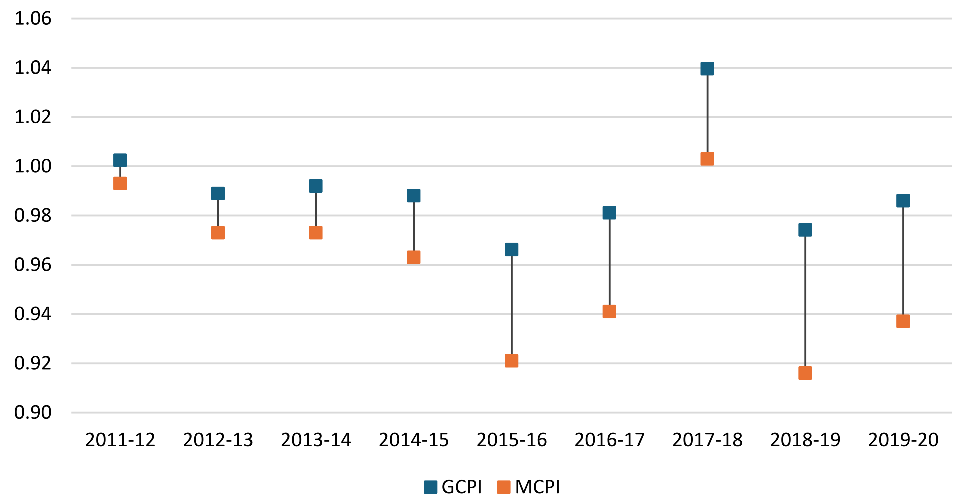

FIGURE 6 | Average group carbon productivity (GCPI) and metafrontier carbon productivity (MCPI) for English and Welsh water and sewerage companies.

The comparison between GCPI and metafrontier carbon productivity (MCPI) estimations for the English and Welsh water industry, as illustrated in Figure 3, reveals significant variations across different years. In some years, such as 2012–2013 and 2017–2018, the average values of GCPI and MCPI are quite similar, indicating a close alignment between the group and metafrontier productivity measurements. However, in other years, notably 2018–2019 and 2019–2020, there are more substantial differences between these metrics. This variability in the TGR from year to year suggests that the potential for carbon efficiency improvement in the industry is not consistent over time. Factors contributing to these fluctuations could include changes in technology, regulatory policies, environmental conditions, and operational practices among the water companies. This finding underscores the importance of a dynamic approach to managing and enhancing carbon efficiency, recognizing that the pathways and potential for improvement may vary significantly from 1 year to the next. Adapting strategies to these changing conditions and opportunities is crucial for continuous improvement in carbon efficiency within the water industry.

The separate analysis of carbon productivity for WoCs and WaSCs, as depicted in Figures 5 and 6, reveals that WoCs have generally been more carbon productive than WaSCs over time. The comparison of average GCPI and MCPI between WoCs and WaSCs reveals notable differences in carbon productivity trends between 2011 and 2020. Specifically: The average GCPI for WoCs was 1.011, indicating an improvement in carbon productivity during this period. In contrast, the average GCPI for WaSCs was 0.991, suggesting a slight decrease in carbon productivity. Furthermore, these trends are consistent when carbon productivity is assessed using the metafrontier approach. The average MCPI for WoCs was higher at 1.029, further confirming their improvement in carbon productivity. For WaSCs, the average MCPI was 0.958, again indicating a decrease in carbon productivity. These results demonstrate that WoCs, on average, have been more successful in enhancing their carbon productivity compared to WaSCs during this timeframe. The higher MCPI values for WoCs suggest that they have been more effective in adopting or benefiting from the industry's best available technologies and practices to reduce carbon emissions relative to their outputs. Conversely, the lower productivity indices for WaSCs highlight challenges or slower progress in carbon efficiency improvements in this group. This difference could be due to various factors, including the scale of operations, the nature of the services provided, investment in technology, or other operational strategies.

A key factor behind this trend is the technological advancements among WoCs, which have accelerated the convergence rate between group and metafrontier technologies. Specifically, during the years 2011–2020, the metafrontier carbon productivity for WoCs improved at an annual rate of 2.9%, as shown in Figure 5. Similar to the overall trend observed in the English and Welsh water industry, carbon productivity change among WoCs was not constant over the years. Notable divergences are observed across different time periods. This fluctuation in carbon productivity for WoCs mirrors the pattern seen in the wider industry, which is often influenced by the regulatory cycle.

While average WoC reported an improvement in carbon productivity, this was not the case for an average WaSC. This group of water companies showed a considerable retardation in their productivity over time showing negatives rates of productivity for most of the period of study (Figure 6). This was due to the lack of adoption of group-specific and metafrontier technologies. Mean carbon productivity deteriorated at a rate of 4.2%. There was a divergence between group and metafrontier technologies at an annual rate of 3.5% on average. This finding means that although WaSCs did not show a substantial leadership in adopting new carbon efficient technologies, small efficiencies in the allocation of resources might have led to lower carbon emissions contributing therefore positively to productivity growth.

The results depicted in Figures 3–6 highlight the influence of regulatory changes on the carbon productivity of water companies. This underscores the connection between policy modifications and operational outcomes, a critical insight for strategic planning directed toward achieving a carbon-neutral water industry. The fluctuating nature of carbon productivity over the years indicates that both water companies and regulators must maintain flexibility, adapting their strategies to align with current conditions and technological progress. This adaptability is crucial for effectively managing carbon efficiency in the face of evolving environmental and regulatory landscapes. From a theoretical perspective, this underscores the importance of evaluating carbon performance longitudinally, that is, assessing carbon productivity over multiple years, rather than just within a single year. This approach allows for a more comprehensive understanding of trends and the effectiveness of various strategies over time, reflecting the dynamic nature of carbon management in the water industry.

Enhancing the carbon performance of water utilities is essential for improving the sustainability of drinking water services. However, other approaches may also contribute significantly to achieving this goal. In this context, the circular economy represents a powerful framework for addressing a range of sustainability challenges within the urban water cycle (Castellet-Viciano, Hernández-Chover, and Hernández-Sancho 2022). Several conceptual frameworks have been proposed to advance circular economy principles in water and sanitation services. For instance, Delgado et al. (2024) developed a framework that jointly assesses circular economy and resilience by integrating nature-based functions into the drinking water supply. Similarly, Carrard et al. (2024) proposed a framework based on eight "R strategies," with three focused on practical applications of circular economy principles in the design of water and sanitation systems, while the remaining five address critical dimensions such as purpose, process, and inclusion. Moreover, the food-energy-water nexus has been identified as an effective approach to improve sustainability within the urban water cycle by alleviating conflicts and enhancing synergies across these interconnected sectors (Verma et al. 2024). This methodological approach has been used to propose and apply water circularity indicators that measure, monitor, and promote urban water circularity. For example, Kakwani and Kalbar (2024) developed a 5Rs index to evaluate water circularity in India and propose policies for its improvement. Similarly, Peydayesh and Mezzenga (2024) introduced a water circular economy index based on the targets of Sustainable Development Goal 6. Their application of this index across 132 countries identified critical bottlenecks and challenges in the sustainable use of water resources across six continents. Adopting circular economy principles in the water sector presents multidimensional challenges, encompassing economic, governance, social, environmental, political, and technological aspects (Vinayagam et al. 2024; Smol, Szołdrowska, and Duda 2024). Addressing these challenges requires an integrative and collaborative approach that promotes circular economy practices within the urban water sector, ultimately enhancing its overall sustainability.

6 | Conclusions

In the quest for efficient and sustainable water services, it is crucial to assess both economic efficiency and environmental performance. A sustainable water cycle demands reducing not only the production costs but also the carbon emissions resulting from the provision of water services. This study specifically addresses the carbon efficiency and productivity of various English and Welsh water companies, utilizing the metafrontier concept. This approach is particularly beneficial due to its ability to accommodate heterogeneous technologies within the industry. The metafrontier framework is well-suited for the analysis of English and Welsh water companies, which consist of both WaSCs and WoCs. These different types of companies often operate using varied technologies and under distinct conditions, which necessitates a method of evaluation that can capture these discrepancies. By employing the metafrontier concept, the study can effectively compare and measure the performance of these diverse entities in terms of carbon efficiency and productivity. This method provides a more comprehensive understanding of how different technologies and operational models impact the environmental footprint of water service provision, guiding the industry toward more sustainable and environmentally responsible practices.

The main findings can be summarized as follows. First, it was found that using the metafrontier technology the volumes of water delivered and operating expenses were major determinants of carbon emissions. Additionally, several environmental variables related to topography, water treatment complexity, and density influenced carbon emissions. It was found that average pumping head and high levels of water treatment could increase energy requirements and subsequently, could lead to higher levels of carbon emissions. In contrast, water taken from rivers and densely populated areas had an adverse impact on carbon emissions. Moreover, the results from the carbon efficiency estimates using the group and metafrontier technology showed that the water industry is characterized by high levels of carbon efficiency. WaSCs were found to be more carbon efficient than WoCs on average. Over time, both WoCs and WaSCs showed high levels of convergence in their group and metafrontier carbon efficiency scores.

The results obtained from the metafrontier analysis of carbon productivity indicates that, generally, the carbon productivity in the industry has shown a slight decline. It was observed that WoCs were more efficient in carbon productivity compared to WaSCs. The average carbon productivity of WoCs increased annually by 2.9%, positioning them as technological frontrunners in the industry and leading to a harmonization of group and metafrontier technological standards. In contrast, the average carbon productivity of WaSCs worsened, primarily due to their failure in adopting the most effective group and industry technologies. Additionally, the 2014 price review appeared to significantly boost the carbon productivity of WoCs, while it negatively impacted the carbon productivity of WaSCs.

The findings from this study offer valuable insights for policy formulation in the water industry, especially in the context of pursuing a net-zero carbon goal. The methodology developed and utilized in this research provides several advantages for policymakers: (i) The methodology enables the measurement of carbon efficiency and productivity changes in a context where water companies are heterogeneous. This is particularly important given the varied scales, operational models, and technologies employed by different companies within the industry; (ii) The approach is robust as it accounts for the different technologies that companies may operate. This is crucial in ensuring that the assessment of carbon efficiency and productivity is accurate and reflective of the actual capabilities and practices of each company; (iii) The methodology allows policymakers to identify which companies are the most and least productive over time. This information is critical for understanding where interventions or support may be needed and where best practices can be replicated and; (iv) The insights gained from this study are highly significant for policymakers focused on transitioning the water industry toward net-zero carbon emissions. By identifying the current state of carbon efficiency and productivity across various companies, policymakers can develop more targeted and effective strategies. These strategies could include incentivizing technological adoption, setting performance benchmarks, and fostering industry-wide collaboration to share best practices.

While this study significantly advances the understanding of the water-energy-carbon nexus within the water sector, it presents two limitations that pave the way for potential future research. First, the current research approach aggregates all GHG emissions related to the provision of drinking water without distinguishing between the types of emissions—namely, scope 1 (direct emissions from owned or controlled sources), scope 2 (indirect emissions from the generation of purchased electricity), and scope 3 (all other indirect emissions in a company's value chain). Future studies could enhance the understanding of carbon performance assessments by evaluating each GHG type separately. This differentiated approach would provide a clearer picture of the primary contributors to carbon inefficiency and allow for more targeted interventions. Second, the assessment conducted integrates the three primary stages involved in drinking water provision, that is, raw water abstraction, water treatment, and water distribution. Conducting a detailed analysis that treats each stage independently could yield nuanced insights that support more effective decision-making. This approach would allow researchers and policymakers to identify specific inefficiencies and improvement potentials at each stage of water provision, leading to more precise and impactful strategies to enhance carbon performance in the water sector.

Acknowledgments

This work has been supported by project CL-EI-2021-07 funded by the Regional Government of Castilla y León and the EU-FEDER and projects TED-130807A-100 and CNS2022-135573 funded by MCIN/AEI/10.13039/501100011033 and by the "European Union NextGenerationEU/PRTR".

Endnotes

[1] To overcome this limitation, Molinos-Senante and Maziotis (2021) used parametric (econometric) techniques such as Stochastic Frontier Analysis (SFA) to measure carbon efficiency and productivity of a sample of English and Welsh water companies.

[2] Carbon emissions involve scope 1 which embraces direct emissions, scope 2 which embraces indirect emissions and regulated scope 3 embracing emissions from contractors and outsourced services and business-associated transport, on public transport or in private vehicles. Non-regulated scope 3 emissions embracing chemical manufacture, Embedded emissions—from construction and manufacturing activity, customers' energy use to heat water and release of methane and nitrous oxide from sludge disposed to landfill and agriculture are not considered (CIWEM 2013).

[3] Before analyzing the results we note that we conducted a log-likelihood test (LR test) to determine if the water companies operated under heterogeneous technologies. The LR test took the form of $LR = 2 \times |LR_1 - LR_o|$, where LR_1 is the sum of log-likelihood values of each SFA group model (see Table 2), whereas the LR_o is the value of the log-likelihood function for the model that assumes a common technology (see Table S1). The outcome of the LR supports the use of metafrontier technology and rejects the null hypothesis that water companies operate the same technology.

References

Ananda, J. 2018. "Productivity Implications of the Water-Energy-Emissions Nexus: An Empirical Analysis of the Drinking Water and Wastewater Sector." *Journal of Cleaner Production* 196: 1097–1195.

Ananda, J., and B. Hampf. 2015. "Measuring Environmentally Sensitive Productivity Growth: An Application to the Urban Water Sector." *Ecological Economics* 116: 211–219.

Ananda, J., and D.-H. Oh. 2023. "Assessing Environmentally Sensitive Productivity Growth: Incorporating Externalities and Heterogeneity Into Water Sector Evaluations." *Journal of Productivity Analysis* 59, no. 1: 45–60.

Barra, C., and P. M. Falcone. 2024. "Environmental Performance of Countries. Examining the Effect of Diverse Institutional Factors in a Metafrontier Approach." *Socio-Economic Planning Sciences* 95: 101972.

Battese, G. E., D. P. Rao, and C. J. O'Donnell. 2004. "A Metafrontier Production Function for Estimation of Technical Efficiencies and Technology Gaps for Firms Operating Under Different Technologies." *Journal of Productivity Analysis* 21, no. 1: 91–103.

Battese, G. E., and D. S. P. Rao. 2002. "Technology Gap, Efficiency, and a Stochastic Metafrontier Function." *International Journal of Business and Economics* 1, no. 2: 87–930.

Cao, L., Z. Qi, and J. Ren. 2017. "China's Industrial Total-Factor Energy Productivity Growth at Sub-Industry Level: A Two-Step Stochastic Metafrontier Malmquist Index Approach." *Sustainability* 9: 1384.

Carrard, N., A. Kumar, Đ. Văn, et al. 2024. "8Rs for Circular Water and Sanitation Systems: Leveraging Circular Economy Thinking for Safe, Resilient and Inclusive Services." *Environmental Development* 52: 101093.

Castellet-Viciano, L., V. Hernández-Chover, and F. Hernández-Sancho. 2022. "The Benefits of Circular Economy Strategies in Urban Water Facilities." *Science of the Total Environment* 844: 157172.

CCC. 2019. "Net Zero: The UK's Contribution to Stopping Global Warming." Report Prepared by the Committee on Climate Change. London. UK.

Cetrulo, T. B., R. C. Marques, and T. F. Malheiros. 2019. "An Analytical Review of the Efficiency of Water and Sanitation Utilities in Developing Countries." *Water Research* 161: 372–380.

CIWEM. 2013. "A Blueprint for Carbon Emissions Reduction in the Uk Water Industry." www.ciwem.org/assets/pdf/Policy/Reports/A-Blueprint-for-carbon-emissions-reductions-in-the-water-industry.pdf.

D'Adamo, I., C. Di Carlo, M. Gastaldi, and A. F. Uricchio. 2024. "Equitable and Sustainable Well-Being Indicators: A Study of Italian Regional Disparities Towards Sustainable Development." *Sustainable Development* 32, no. 5: 5538–5549.

De Witte, K., and R. C. Marques. 2009. "Capturing the Environment, a Metafrontier Approach to the Drinking Water Sector." *International Transactions in Operational Research* 16, no. 2: 257–271.

Delgado, A., D. J. Rodriguez, C. A. Amadei, and M. Makino. 2024. "Water in Circular Economy and Resilience (WICER) Framework." *Utilities Policy* 87: 101604.

Fare, R., N. Grosskopf, and Z. Zhang. 1994. "Productivity Growth, Technical Progress, and Efficiency Change in Industrialized Countries." *American Economic Review* 84: 66–83.

Goh, K. H., and K. F. See. 2021. "Twenty Years of Water Utility Benchmarking: A Bibliometric Analysis of Emerging Interest in Water Research and Collaboration." *Journal of Cleaner Production* 284: 124711.

Hayami, Y. 1969. "Sources of Agricultural Productivity Gap Among Selected Countries." *American Journal of Agricultural Economics* 51, no. 3: 564–575.

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

HM Government. 2019. "Environmental Reporting Guidelines: Including Streamlined Energy and Carbon Reporting Guidance March 2019 (Updated Introduction and Chapters 1 and 2.") London. UK.

Ho, P. T., P. X. Hung, and N. D. Tien. 2023. "Effects of Varieties and Seasons on Cost Efficiency in Rice Farming: A Stochastic Metafrontier Approach." *Asian Journal of Agriculture and Rural Development* 13, no. 2: 120–129.

Horncastle, A., J. Duffy, C. X. Ng, and P. Krupa. 2022. "Benchmarking in the European Water Sector: Applications of Production Economics." In *Handbook of Production Economics*, 1563–1628. Singapore: Springer Nature Singapore.

Huang, C. J., T. H. Huang, and N. H. Liu. 2014. "A New Approach to Estimating the Metafrontier Production Function Based on a Stochastic Frontier Framework." *Journal of Productivity Analysis* 42: 241–254.

Jin, Q., A. Basso, S. Funari, K. Kerstens, and I. Van de Woestyne. 2024. "Evaluating Different Groups of Mutual Funds Using a Metafrontier Approach: Ethical vs. Non-Ethical Funds." *European Journal of Operational Research* 312, no. 3: 1134–1145.

Kakwani, N. S., and P. P. Kalbar. 2024. "Prioritization of Strategies for Urban Water Circular Economy Using Water Circularity Indicator." *Water Policy* 26, no. 5: 480–505.

Kherazi, F. Z., D. Sun, J. M. Sohu, I. Junedo, H. M. Naveed, and A. Khan. 2024. "The Role of Environmental Knowledge, Policies and Regulations Toward Water Resource Management: A Mediated-Moderation of Attitudes, Perception, and Sustainable Consumption Patterns." *Sustainable Development* 32: 5719–5741.

Lechevallier, M. W. 2014. "The Impact of Climate Change on Water Infrastructure." *Journal of American Water Works Association* 106, no. 4: 79–81.

Lin, B., and K. Du. 2015. "Modeling the Dynamics of Carbon Emission Performance in China: A Parametric Malmquist Index Approach." *Energy Economics* 49: 550–557.

Maziotis, A., R. Sala-Garrido, M. Mocholi-Arce, and M. Molinos-Senante. 2023. "Carbon Efficiency Analysis in the Provision of Drinking Water: Estimation of Optimal Greenhouse Gas Emissions." *Journal of Cleaner Production* 392: 136304.

Molinos-Senante, M., and A. Maziotis. 2021. "The Impact of Greenhouse Gas Emissions on the Performance of Water Companies: A Dynamic Assessment." *Environmental Science and Pollution Research* 28, no. 35: 48284–48297.

Molinos-Senante, M., and A. Maziotis. 2022. "Assessing the Dynamic Carbon Performance of Water Companies: A Parametric Approach." *International Journal of Environmental Science and Technology* 19: 5472–5561.

Molinos-Senante, M., A. Maziotis, and R. Sala-Garrido. 2017. "Assessing the Productivity Change of Water Companies in England and Wales: A Dynamic Metafrontier Approach." *Journal of Environmental Management* 197: 1–9.

O'Donnell, C. J., P. Rao, and G. E. Battese. 2008. "Metafrontier Frameworks for the Study of Firm-Level Efficiencies and Technology Ratios." *Empirical Economics* 34: 231–255.

Ofwat. 2010. "Preparing for the Future –Ofwat's Climate Change Policy Statement." The Water Services Regulation Authority, Birmingham, UK.

Oh, D.-h. 2010. "A Metafrontier Approach for Measuring an Environmentally Sensitive Productivity Growth Index." *Energy Economics* 32, no. 1: 146–157.

Peydayesh, M., and R. Mezzenga. 2024. "The Circular Economy of Water Across the Six Continents." *Chemical Society Reviews* 53, no. 9: 4333–4348.

Rita, R., V. Marques, D. Bárbara, V. Moutinho, and M. Pereira. 2023. "Crossing Non-Parametric and Parametric Techniques for Measuring the Efficiency: Evidence From 65 European Electricity Distribution System Operators." *Energy (Oxford)* 283: 128511.

Sala-Garrido, R., M. Mocholi-Arce, A. Maziotis, and M. Molinos-Senante. 2023. "The Carbon and Production Performance of Water Utilities: Evidence From the English and Welsh Water Industry." *Structural Change and Economic Dynamics* 64: 292–300.

Sala-Garrido, R., M. Mocholi-Arce, M. Molinos-Senante, and A. Maziotis. 2021. "Comparing Operational, Environmental and Eco-Efficiency of Water Companies in England and Wales." *Energies* 14: 3635.

See, K. F. 2015. "Exploring and Analyzing Sources of Technical Efficiency in Water Supply Services: Some Evidence From Southeast Asian Public Water Utilities." *Water Resources and Economics* 9: 23–44.

Smol, M., D. Szołdrowska, and J. Duda. 2024. "Identification of Barriers and Driving Forces for Circular Economy (CE) Implementation in Water and Wastewater Companies." *Business Strategy and the Environment*. https://doi.org/10.1002/bse.4097.

Sowby, R. B., and E. G. Hopkins. 2023. "Energy Management in the Water Sector: A Policy Statement Review." *Water Environment Research* 95, no. 12: e10972.

Sukanya, S., and J. Sabu. 2023. "Chapter 4 - Climate Change Impacts on Water Resources: An Overview." In *Visualization Techniques for Climate Change With Machine Learning and Artificial Intelligence*, 55–76. Amsterdam, The Netherlands: Elsevier. https://www.sciencedirect.com/science/article/pii/B9780323997140000881.

Susaeta, A., B. Sancewich, K. Klizentyte, J. Soto, and O. Joshi. 2024. "Profit Efficiency in the Provision of Ecosystem Services in the Cross Timbers Forests." *Land Use Policy* 136: 106978.

Tan, X., Y. Choi, B. Wang, and X. Huang. 2020. "Does China's Carbon Regulatory Policy Improve Total Factor Carbon Efficiency? A Fixed-Effect Panel Stochastic Frontier Analysis." *Technological Forecasting and Social Change* 160: 120222.

Verma, N., P. Talwar, A. Upadhyay, et al. 2024. "Food-Energy-Water Nexus in Compliance With Sustainable Development Goals for Integrating and Managing the Core Environmental Verticals for Sustainable Energy and Circular Economy." *Science of the Total Environment* 930: 172649.

Vinayagam, V., D. Sikarwar, S. Das, and A. Pugazhendhi. 2024. "Envisioning the Innovative Approaches to Achieve Circular Economy in the Water and Wastewater Sector." *Environmental Research* 241: 117663.

Walker, N. L., A. Norton, I. Harris, A. P. Williams, and D. Styles. 2019. "Economic and Environmental Efficiency of UK and Ireland Water Companies: Influence of Exogenous Factors and Rurality." *Journal of Environmental Management* 241: 363–373.

Walker, N. L., D. Styles, J. Gallagher, and A. P. Williams. 2021. "Aligning Efficiency Benchmarking With Sustainable Outcomes in the United Kingdom Water Sector." *Journal of Environmental Management* 287: 112317.

Walker, N. L., A. P. Williams, and D. Styles. 2020. "Key Performance Indicators to Explain Energy & Economic Efficiency Across Water Utilities, and Identifying Suitable Proxies." *Journal of Environmental Management* 269: 110810.

Wang, Q., X. Wang, and R. Li. 2024. "The Impact of Globalization on the Decoupling of Water Consumption and Economic Growth in BRICS and N11 Countries—Linear and Nonlinear Approaches." *Sustainable Development* 32, no. 1: 755–776.

Wojcik, V., H. Dyckhoff, and M. Clermont. 2019. "Is Data Envelopment Analysis a Suitable Tool for Performance Measurement and Benchmarking in Non-Production Contexts?" *Business Research* 12, no. 2: 559–595.

Yan, G., S. J. Kenway, K. L. Lam, and P. A. Lant. 2024. "Water-Energy Trajectories for Urban Water and Wastewater Reveal the Impact of City Strategies." *Applied Energy* 366: 123292.

Zhou, P., B. W. Ang, and J. Y. Han. 2010. "Total Factor Carbon Emission Performance: A Malmquist Index Analysis." *Energy Economics* 32: 194–201.

Zhou, P., B. W. Ang, and H. Wang. 2012. "Energy and CO2 Emission Performance in Electricity Generation: A Non-Radial Directional Distance Function Approach." *European Journal of Operational Research* 221: 625–635.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.