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Estimating the impact of carbon inefficiency and overuse of energy on the economics of water companies: A case study for England and Wales

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Abstract

In the face of climate change, it becomes crucial to motivate action and policies within water companies towards achieving carbon neutrality. Estimating the economic consequences of inaction can be a compelling catalyst for change. In this study, the carbon inefficiency and overuse of energy among a selection of English and Welsh water companies were assessed, along with their impact on the operational costs of producing and delivering drinking water over the period from 2010 to 2019. In doing so, a stochastic frontier analysis primal system was employed. The findings revealed that, on average, water companies exhibited a carbon inefficiency of 0.699. The overuse of energy relative to other inputs was estimated to be 71.4%. Consequently, water companies incurred a production cost increase of 0.089 £/m^3. This research demonstrates that transitioning towards a low-carbon urban water cycle is not merely an environmental beneficial endeavor; it also involves significant economic advantages.

KEYWORDS
allocative inefficiency, carbon inefficiency, stochastic frontier analysis, water companies, water supply process, water-energy nexus

1 | INTRODUCTION

In the face of climate change, it is essential to encourage countries to take action and implement policies aimed at carbon neutrality. The primary achievements of the 2021 Conference of Parties (COP26) in Glasgow were the signing of the Glasgow Climate Pact and agreeing the Paris Rulebook. Additionally, COP27, conducted in Egypt in 2022, represented a modest advance in the direction of climate justice by opening a new chapter on financing loss and damage, thereby establishing a framework for cooperation between those requiring assistance and those able to provide it (European Commission, 2022). In this regard, Akram et al. (2023) have empirically demonstrated that the adoption of green energy, the imposition of a carbon tax, and the support for environmental policies contribute to the progression towards carbon neutrality by diminishing CO_2 emissions.

The provision of urban water and wastewater services contributes to greenhouse gas (GHG) emissions (Lam & van der Hoek, 2020). It is estimated that water utilities account for approximately 2% of GHG emissions (Water UK, 2021). Numerous water utilities globally are adopting targets to curtail GHG emissions or achieve carbon neutrality as part of their efforts to combat climate change (Ballard et al., 2018). To illustrate, both the United Kingdom and Australian governments have declared their intentions to attain net zero GHG emissions within their water industries by 2030 and 2050, respectively (CCC, 2019; HM Government, 2018; Ofwat, 2010a, 2010b). Considerable research has been dedicated to developing technologies and management

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alternatives for water utilities to operate with reduced carbon footprint or achieve carbon-neutrality (Alix et al., 2022; Zhang et al., 2017).

To date, however, there is a lack of clarity regarding the relationship between water companies' efforts to reduce GHG emissions and the impact on their operational costs. Moreover, businesses may be disincentivized to invest in low-carbon technologies due to the uncertainty surrounding government policies and regulatory frameworks (Liu et al., 2023). Nevertheless, the existing body of research has made some progress in estimating the marginal abatement costs associated with various technological alternatives aimed at GHG emissions reduction in the provision of water services (Fagan et al., 2010; Lam et al., 2017; Lam & van der Hoek, 2020). However, this previous literature primarily concentrated on isolated opportunities for reducing GHG emissions without taking into consideration the existing carbon performance of water companies. In essence, prior research on this topic did not consider the intrinsic connection between GHG emissions and the production function of water companies. This connection encompasses the utilization of different inputs in the process of providing water services (Trinks et al., 2020). Therefore, there is a gap in comprehending how the existing carbon inefficiencies within the production process of water companies influence the broader picture of GHG emissions reduction and its economic implications.

To address this deficiency, the objectives of this study encompass three key aspects. The initial objective is to undertake a comprehensive analysis of both carbon and allocative inefficiencies within water utilities operating in the water production and supply process. The second objective pertains to discerning potential relationships between any identified carbon and allocative efficiencies and shifts in the demand for various inputs. Lastly, the third objective revolves around quantifying the influence of carbon and allocative inefficiencies on the overall costs of producing and delivering drinking water.

The contributions of this study to the existing body of literature are multifaceted. We introduce a model that simultaneously assesses the allocative and carbon inefficiencies of water utilities, offering significant advancements over conventional analyses focused solely on carbon emissions or carbon intensity within urban water services (refer to the literature review section for more details). First, our carbon efficiency metric provides a more nuanced understanding of how effectively water utilities are reducing carbon emissions throughout their production processes. Second, our integrated framework for carbon and allocative efficiency makes it possible to calculate the additional costs associated with each type of inefficiency. Put differently, the methodological approach outlined in this research (detailed in the materials and methods section) enables the quantification of the economic impact of carbon and allocative inefficiencies on the production costs of water utilities.

To the best of our knowledge, the proposed approach is pioneering as it represents the inaugural attempt to amalgamate the concurrent assessment of carbon and allocative inefficiencies within water utilities. The empirical methodology we employ centers on the examination of water services offered by multiple water utilities in England and Wales throughout the period spanning 2010 to 2019. It is noteworthy that the proposed methodological framework holds the potential to be adapted for gauging the efficiency of other environmental impacts within the water industry as well.

The structure of the paper is organized as follows. Section 2 delves into the methodology that has been utilized, followed by the introduction of the variables that form the foundation of this study. Moving forward, Section 3 presents a comprehensive discussion of the primary findings obtained from the analysis. Ultimately, the concluding section provides a summary of the study's outcomes and implications.

1.1 | Literature review on carbon efficiency of water utilities

The water-energy-GHG nexus is at the forefront towards sustainable cities (Shemelev and Shemeleva, 2018). Focusing on water utilities, different methodological approaches have been using to quantify GHG emissions associated with the provision of drinking water services (Nair et al., 2014) such as life cycle analysis (Chini et al., 2020; Gani et al., 2023; Ortiz-Rodriguez et al., 2022; Wiener et al., 2016; Zib et al., 2021); input–output models (Fang and Chen, 2017; Zhang et al., 2017) and mixed models (Lam et al., 2022; Liu and Mauter, 2022). These previous studies estimated the carbon footprint or carbon intensity of water utilities in delivering drinking water. In other words, they estimated the amount of CO_2 equivalent (CO_{2eq}) emitted by cubic meter (m^3) of drinking water delivered. Hence, they focused on the environmental dimension of the provision of drinking water ignoring the economics of the process.

The eco-efficiency concept has been used to jointly assess the economic and environmental (carbon) performance of water utilities in the provision of drinking water (Maziotis et al., 2023). At its most fundamental level, eco-efficiency encompasses the production of a greater quantity of goods and services while using fewer resources and causing a reduced environmental impact (Gómez et al., 2018). Enhancing the eco-efficiency of water utilities—meaning both their environmental and economic performance—is crucial in the shift towards a low-carbon urban water cycle (Lam et al., 2022). Past research on this topic (Amaral et al., 2022; Ananda, 2018, 2019; Ananda & Hampf, 2015; Li et al., 2023; Walker et al., 2021) estimated the eco-efficiency of water utilities by computing a synthetic index which integrates operational costs, volume of drinking water and carbon emissions of water utilities. Nevertheless, this synthetic index does not allow for the evaluation of the specific carbon efficiency of water utilities. Carbon efficiency refers to how effectively a given level of output is generated with the least possible carbon emissions compared to direct peers within the sector (Trinks et al., 2020). Achieving economic (or allocative) efficiency within a supply process does not imply the same level of environmental (carbon) efficiency, and the reverse is also true.

Within the context of production theory, a scarcity of prior research exits that has examined the carbon efficiency of water utilities in delivering water services. On one side, Molinos-Senante et al. (2022) adopted Data Envelopment Analysis (DEA), a non-parametric methodology, to evaluate the carbon efficiency of a subset of water companies operating in England and Wales during the period spanning 2013–2018. In an effort to surmount the constraints inherent in non-parametric approaches, Molinos-Senante and Maziotis (2022) employed stochastic frontier analysis (SFA), a parametric technique, on the same set of water companies. This application aimed to gauge alterations over time in the carbon performance of these utilities. An additional advancement was introduced by Maziotis et al. (2023) who, through the utilization of an efficiency analysis tree method, not only gauged carbon efficiency but also estimated the optimal level of GHG emissions required for the provision of potable water. As such, prior research concentrated on evaluating the carbon efficiency of water companies, without considering its potential repercussions on allocative inefficiency and the increase in production costs attributed to carbon and allocative inefficiencies.

2 | MATERIALS AND METHODS

2.1 | Methodology to assess carbon and allocative inefficiencies

The methodological approach utilized in this study is rooted in the SFA primal system framework established by Kumbhakar and Wang (2006). Adopting the SFA concept allows us to include the simultaneous impact of both carbon and allocative inefficiencies in the production process. Given that both these forms of inefficiency could potentially lead to elevated production costs, the utilization of this methodology further enables us to quantify the increment in production costs associated with each specific type of inefficiency. The SFA econometric model gauges the extent of output disparities from the frontier. In the context of our study, utilizing carbon emissions as an undesirable output implies that the greater the distance from the frontier line a utility is, the more environmentally efficient it becomes (Jin & Kim, 2019).

This approach comprises three key sequential steps, which are outlined as follows:

Step 1: Estimation of the production function and the first order conditions (FOCs).

The study commences by formulating a Cobb–Douglas production frontier. This choice is grounded in the fact that the Cobb–Douglas model represents the simplest and most straightforward first-order approximation of the actual production function (Hu, 2014). This selection is driven by the aim to achieve a balance between capturing the essential relationships within the production process while minimizing the complexity of the model. The Cobb–Douglas production function is characterized by its inherent parsimony and linearity, which makes it a suitable initial approximation. This approach aligns with the goal of maintaining a reasonable number of degrees of freedom, promoting model tractability, and simplifying the estimation process (Zhang et al., 2019).

The Cobb–Douglas production function is defined as follows:

$$lny = a_0 + \sum_j a_j lnx_j + \sum_j \gamma_j lnz_j + \nu - u = f(x) + \nu - u, \tag{1}$$

where a_0 is the constant term,y denotes the level of carbon emissions, x_j denotes the set of inputs used in the production process that is, energy input and other inputs in our case study $(j = 2)$, and z is a set of operating characteristics (Brea-Solis et al., 2017) that could influence the level of carbon emissions. In our case study, and according to past research (Lin & Du, 2015; Tan et al., 2020), these characteristics include: (i) percentage of water from reservoirs; (ii) population density and; (iii) percentage of water receiving high levels of treatment (see for more details in the next section). Depending on the specifics of the case study, other variables may be integrated into the model. Moreover, ν is the standard noise error term to capture any uncertainty in the data and is distributed as $\nu \sim N(0, \sigma_\nu^2)$, u is the inefficiency[1] of the water company and is assumed to follow the truncated at zero distribution and is distributed as $u \sim N(0, \sigma_u^2)$.

The first order conditions are defined below:

$$\frac{f_j}{f_1} = \frac{w_j}{w_1} e^{\xi_j} \Rightarrow \frac{\frac{\vartheta lnf}{\vartheta lnx_j}}{\frac{\vartheta lnf}{\vartheta lnx_1}} \equiv \frac{s_j}{s_1} = \frac{w_j x_j}{w_1 x_1} e^{\xi_j} \Rightarrow \ln s_j - \ln s_1 - \ln(w_j x_j) + \ln(w_1 x_1) = \xi_j. \tag{2}$$

In Equation (2), f_j is the first derivative of the production function with respect to input j. It provides information of the contribution of the input j to the production of outputs (carbon emissions in this study); w_j is the price of input j; s_j is the cost share of input j and ξ_j is the allocative inefficiency for the input pair $(j, 1)$where x_1 is the numeraire. ξ_j is independent of ν and u and is distributed as $\xi_j \sim MVN(0, \Sigma)$ (Kumbhakar & Wang, 2006; Zhang et al., 2019). In other words, allocative inefficiency does not depend on carbon inefficiency of water utilities.

We note that the production function is an output-oriented model so the output oriented SFA estimates how much output deficits from the frontier (Jin & Kim, 2019). Since carbon emissions are undesirable products, the farther from the frontier a water company is, then the more carbon efficient it is (Jin & Kim, 2019).

Equation (2) allows determining if there is over or under use of an input j relative to the numeraire input by looking at the sign of the allocative inefficiency which can take positive or negative values. For instance, if $\xi_2 < 0 \Rightarrow w_2 e^{\xi_2} < w_2$ then input x_2 is overused relative to input x_1 (Kumbhakar & Wang, 2006). Then the allocative inefficiency associated with an input pair is used to estimate the increase in production costs (step 2). The allocative inefficiencies obtained from term ξ^j show if an input is over or under used relative to another one based on the sign. These inefficiencies are then expressed as percentages of over and underuse of the input factors; that is $100 \times (e^{\xi_2} - 1)$ per cent (Hu, 2014; Kumbhakar et al., 2015).

After estimating the parameters of the above model (Equation 1), we can calculate the water company-specific carbon and allocative inefficiencies. The carbon inefficiency of each water company $(INE(u|(\nu - u)))$ is calculated following the formula suggested by Jondrow et al. (1982):

$$INE(u|(\nu - u)) = \mu^* + \sigma^* \frac{\phi\left(\frac{\mu^*}{\sigma^*}\right)}{\Phi\left(\frac{\mu^*}{\sigma^*}\right)}, \tag{3}$$

where ϕ is the standard normal density function and Φ is the standard normal cumulative distribution function, $\mu^* = -(\nu - u)\sigma_u^2/\sigma^2$ and $\sigma^* = \sigma_u \sigma_\nu / \sigma$ (Kumbhakar et al., 2015). Alternatively, carbon inefficiency of each water company can be converted into carbon efficiency as $\mathrm{Eff} = \exp(-INE)$. In this case, carbon efficiency scores can take a value between zero and one. When the carbon efficiency score takes a value equal to one, it means that the water company is carbon efficient, whereas a value lower than one implies that it is not carbon efficient.

Step 2: Impact of carbon and allocative inefficiency on production costs.

Equations (1), (2) are used to quantify the role of carbon and allocative inefficiencies in the production process (Zhang et al., 2019). This is done by deriving the following input demand functions:

$$lnx_j = a_j + \frac{1}{r}\sum_{i=1}^{J} a_i lnw_i - lnw_j + \frac{1}{r}lny + \frac{1}{r}\sum_{i=2}^{J} a_i\xi_i - \xi_j - \frac{1}{r}(\nu - u), \quad (4)$$

$$j = 2, \ldots J$$

$$\ln x_1 = a_1 + \frac{1}{r}\sum_{i=1}^{J} a_i \ln w_i - \ln w_1 + \frac{1}{r}\ln y + \frac{1}{r}\sum_{i=2}^{J} a_i\xi_i - \frac{1}{r}(\nu - u), \quad (5)$$

where $r = \sum_{i=1}^{J} a_i$ denote returns to scale and $a_j = lna_j - \frac{1}{r}\left[a_0 + \sum_{i=1}^{J} a_i lna_i\right], j = 1 \ldots, J$.

The input demand function is impacted by all error components such as carbon inefficiency, allocative inefficiency and error term in addition to returns to scale, the price of inputs and the error term (Kumbhakar & Wang, 2006). In particular, carbon inefficiency results in an increase in the use of all inputs by $\left(\frac{1}{r}u_{i,t}\right)$ 100%. Allocative inefficiencies are unconstrained so they can result in an increase or decrease in the use of inputs (Lai & Kumbhakar, 2019). However, the existence of allocative inefficiencies will always result in an increase in the production costs.

Based on the input demand of x_j, we can calculate the input demand for x_j when carbon efficiency is present only, x_{jTI} and the input demand for x_j when allocative inefficiency is present only, x_{jAI} (Kumbhakar & Wang, 2006). Then we can derive the corresponding costs c_{CI} and c_{AI} by multiplying the price of each input by the input demands with different inefficiency conditions (Zhang et al., 2019). As a result, we can compute the increase in production cost due to carbon and allocative inefficiency, c_{carbon} and $c_{\mathrm{allocative}}$.

Considering that our assessment involves several water companies and years, we introduce the subscripts *m* and *t* for firm and time, respectively, on Equation (1) (Kumbhakar et al., 2015; Kumbhakar & Wang, 2006):

$$\ln y_{mt} = a_0 + \sum_j a_j \ln x_{jmt} + \sum_j \gamma_j z_{jmt} + a_t t + \nu_{mt} - u_{mt} = f(x) + \nu_{mt} - u_{mt}. \quad (6)$$

The corresponding FOCs are defined as follows:

$$\ln s_{jmt} - \ln s_{1mt} - \ln(w_{jmt}x_{jmt}) + \ln(w_{1mt}x_{1mt}) = \xi_{jmt}. \quad (7)$$

Thus, Equation (7) allows the measurement of the allocative inefficiency associated with the input pair $(j,1)$ at any time *t* for any water company *m* (Lai & Kumbhakar, 2019).

The parameters of the model in Equations (6)–(7) are estimated by maximizing the concentrated log-likelihood function (Kumbhakar et al., 2015). Based on the estimated parameters we can further calculate the returns to scale (RTS) and technical change (TCH) of each water company.

$$RTS_{mt} = \sum_j \frac{\vartheta lny_{mt}}{\vartheta lnx_{jmt}} = \sum_j a_j, \quad (8)$$

$$\mathrm{TCH}_{mt} = \frac{\vartheta lny_{mt}}{\vartheta t} = a_t. \quad (9)$$

A RTS_{mt} value greater than 1 implies decreasing RTS which means that a 1% increase in outputs may lead to a more than 1% increase in all inputs. By contrast, a RTS_{mt} value lower than 1 implies increasing RTS whereas a RTS_{mt} value equal to 1 implies constant returns to scale. In the case of TCH, a positive value for TCH_{mt} implies technical progress whereas a negative value for TCH_{mt} implies technical regress.

2.2 | Data and sample selection

The empirical analysis conducted in this study is centered around water companies that offer water services to all customers across England and Wales. The study's focus spans the duration from 2010 to 2019. These companies, originally established as natural monopolies, underwent privatization in 1989. Subsequently, the Water Services Regulation Authority (Ofwat) was established to ensure customer protection against monopolistic practices, oversee the economic and environmental performance of water companies, and safeguard environmental interests (Williams et al., 2020).

The regulatory framework, overseen by Ofwat, is structured around a periodic review process that spans five-year intervals. During each review, Ofwat determines the permissible future revenues or prices that these companies can charge their customers. These assessments are based on the rigorous evaluation of the companies' business plans, intended to enhance service quality, technical and environmental efficiency, and affordability (Brea-Solis et al., 2017).

To estimate the production frontier as described in Equation (1), the study employed the following set of outputs and inputs. Consistent with established precedent (Ananda, 2018; Ananda & Hampf, 2015; Goh & See, 2021; Molinos-Senante et al., 2015), the study selected GHG emissions stemming from the provision of water services as the single undesirable output. The measurement unit for GHG emissions is expressed in kilograms of CO_2 equivalent (CO_{2eq}) per year, reflecting the carbon footprint of companies' routine activities (Ofwat, 2009; Sala-Garrido, Mocholi-Arce, Molinos-Senante, & Maziotis, 2021). The quantification of GHG emissions in relation to water services aligns with the UK Government Environmental Reporting Guidelines (HM Government, 2019).

Ofwat is responsible for overseeing the measurement of three distinct categories of GHG emissions: (i) Scope 1 which encompass emissions originating from owned or leased transportation, emissions linked to the company's internal utilization of fossil fuels, as well as methane and nitrous oxide emissions stemming from sewage treatment; (ii) Scope 2 that involves GHG emissions arising from the consumption of grid electricity for activities such as water and sewage pumping and treatment, as well as electricity use within owned buildings and; (iii) Regulated scope 3 which are associated with contracted and outsourced services, as well as business-related transportation, both involving public transport and private vehicles (Ofwat, 2010a). As such, the empirical application of our study encompasses GHG emissions originating from the sources mentioned above. It is important to note that GHG emissions stemming from chemical manufacturing, embedded emissions arising from construction and manufacturing operations, customers' energy use for water heating, and the release of methane and nitrous oxide from sludge disposed of in landfills and agricultural activities are classified as non-regulated emissions according to Ofwat's guidelines. Consequently, these emissions have not been taken into consideration in the study.

The study incorporated two inputs along with their associated prices, which were defined as follows: (i) Energy consumption: This input quantifies the energy used to provide water services, measured in Megawatt-hours (MWh) per year. The energy expenditure was sourced from relevant data (Molinos-Senante & Maziotis, 2021; Walker et al., 2019). The price of energy was computed by dividing the cost of energy expenditure (expressed in millions of British Pounds) for water services by the corresponding annual energy consumption. This calculation yielded the price of energy, denominated in £/MWh; (ii) Other inputs: it was calculated as the disparity between water operating costs and energy costs, both expressed in millions of British Pounds per year (Sala-Garrido, Mocholi-Arce, Molinos-Senante, Smyrnakis, & Maziotis, 2021). The price of other inputs was established using the Office of National Statistics producer price index specifically for inputs associated with water collection, treatment, and supply. This price of other inputs was adjusted using deflation techniques. Consequently, the price of other inputs was defined in terms of its relationship with the producer price index.

In the analysis, the price of other inputs and the other inputs themselves were utilized as the numeraire input price and input, respectively. This approach is in line with the methodology employed in prior studies (Abbott et al., 2012; Berg & Marques, 2011; De Witte & Marques, 2011; Molinos-Senante et al., 2015), ensuring consistency and comparability across analyses.

In order to comprehensively assess the influence of operating characteristics on the carbon efficiency associated with water services, the study drew upon insights from prior research in this field (e.g., Lin & Du, 2015; Tan et al., 2020; Zhou et al., 2012). The specific variables chosen as potential influencing factors on carbon emissions included: (i) Percentage of water from reservoirs: This variable captures the proportion of water sourced from reservoirs. The transportation of water from the source to treatment centers can elevate energy consumption and production costs (Brea-Solis et al., 2017; Molinos-Senante & Maziotis, 2018); (ii) Population density: Expressed as the ratio of water population to water area, this metric characterizes the density of the population in a given area (Walker et al., 2020, 2021); (iii) Percentage of water receiving high levels of treatment: This variable encapsulates the extent of treatment applied to water before it is distributed to consumers. Greater treatment complexity can be linked to higher carbon emissions (Ofwat, 2019).

Table 1 reports the descriptive statistics from the variables used in this study. The source of data comes from Ofwat's website.

3 | RESULTS AND DISCUSSION

3.1 | Estimation of carbon and allocative inefficiencies

According to the methodology applied in this study, the initial step involved estimating a production function, with the associated coefficient parameters presented in Table 2. The presence of a negative sign for the parameter associated with technical change that is, σ_v^2, indicates that the water companies in England and Wales underwent a period of technical regression. The statistical significance of the estimated parameter σ_u^2 being different from zero indicates that the application of a stochastic production frontier was warranted. This highlights the validity of utilizing this approach to model and analyze the production process as it acknowledges the inherent variability and uncertainties in the data.

Notably, most parameters of the production function, excluding the one pertaining to population density, were found to be statistically significant. Of particular significance were the positive coefficients attributed to “other inputs” and “energy”. These findings indicated that, while holding other variables constant, a 1% increase in “other inputs” and “energy” would correspond to a 0.501% and 0.533% increase in CO_{2eq} emissions, respectively. This suggests that both “other inputs” and energy played substantial roles in driving carbon emissions.

Results on Table 2 also revealed a correlation between the complexity of water treatment processes and heightened levels of CO_{2eq} emissions. This observation suggests that more intricate water treatment procedures are associated with increased atmospheric carbon emissions. Conversely, the study indicated that a higher percentage of water drawn from reservoirs corresponded to lower levels of CO_{2eq} emissions. This insight implies that a greater reliance on reservoir-sourced water contributes to reduced carbon emissions.

The average RTS was 1.034, a value close to 1, which means that on average the English and Welsh water companies operated at their efficient scale. On average the water industry experienced a technical regress at a rate of 4.7% per year. This implies that the lack of adoption carbon-efficient technologies might have led to higher production costs and consequently, higher levels of carbon emissions. This result is slightly higher than the one reported by Molinos-Senante and Maziotis (2022) who based on conventional SFA models, estimated a technical regression of 1.4% per year.

Figure 1 provides an overview of the key statistics pertaining to the estimations of carbon and allocative inefficiencies. The outcomes

TABLE 1 Descriptive variables of the English and Welsh water companies.

Variables	Unit of measurement	Mean	Std. dev.	Min.	Max.
GHG	$kgCO_{2eq}$/year	27,131,661	24,308,731	1,233,015	96,565,000
Energy	MWh/year	201,942	154,592	16,317	561,564
Other inputs	£m/year	102.29	86.81	8.20	358.49
Price for energy	£/Mwh	0.0017	0.0002	0.0010	0.0026
Price for other inputs	Index	0.91	0.05	0.81	1.00
Population density	000 s/km^2	0.48	0.28	0.15	1.25
Water taken from reservoirs	%	34.0	25.0	0.0	83.1
Water receiving high levels of treatment	%	57.0	23.0	22.0	99.0

Note: Observations: 166. Input prices are expressed in 2019 prices.

TABLE 2 Estimated parameter of the production function.

Variables	Parameter	Coef.	Std. err.	z	$p > z$
Constant	α_0	0.336	0.112	**2.990**	0.003
Other inputs	α_1	0.501	0.016	**32.030**	0.000
Energy	α_2	0.533	0.017	**32.140**	0.000
Time	α_t	−0.047	0.010	**−4.820**	0.000
Population density	γ_1	0.000	0.000	−0.470	0.642
Water receiving high levels of treatment	γ_2	0.344	0.155	**2.210**	0.027
Water taken from reservoirs	γ_3	−0.181	0.084	**−2.150**	0.032
σ_u^2		−5.575	0.693	**−8.050**	0.000
σ_ν^2		−1.127	0.134	**−8.400**	0.000
Log likelihood	−161.12				

Note: Observations: 166. Carbon emissions is the dependent variable. Bold statistics are statistically significant from zero at the 5% level.

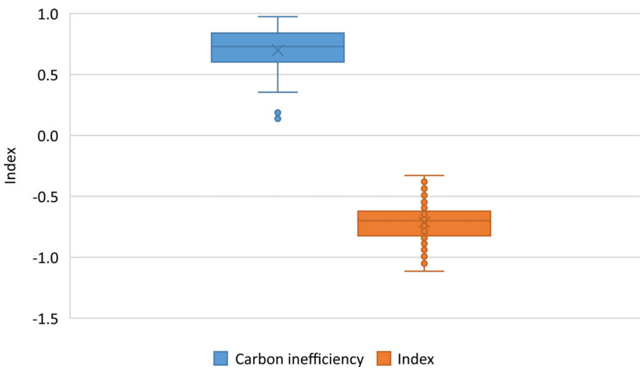


FIGURE 1 Statistics of carbon inefficiency and allocative inefficiency of English and Welsh water companies (2010–2019).

of the analysis revealed that, during the period from 2010 to 2019, the average carbon inefficiency within the English and Welsh water industry stood at 0.699 or alternatively, the average carbon efficiency score was 0.497. This means that water companies could potentially curtail their GHG emissions by 51.3% on average. This outcome underscores the existence of substantial potential for enhancing the carbon efficiency levels within the industry. Our results align with those obtained by Maziotis et al. (2023), who for a set of 20 water companies in England and Wales over 2011–2020, calculated an average carbon efficiency of 0.632. The carbon efficiency figures put forward by Molinos-Senante and Maziotis (2022) are significantly higher, with an average of 0.925, suggesting that water companies in England and Wales could potentially reduce their GHG emissions by only 7.5%. It is important to note that their analysis was limited to GHG emissions falling within Scope 1 and Scope 2, whereas our study also encompasses Regulated Scope 3 emissions, underscoring the necessity of including all categories of GHG emissions when measuring carbon efficiency. Conversely, Molinos-Senante et al. (2022) reported a lower average carbon efficiency of 0.415. Their study utilized the DEA method which did not take into account contextual variables—that is, operational factors that affect carbon efficiency. The discrepancy between the studies assessing carbon efficiency of English and Welsh water companies, attributable to the methodologies used and the range of GHG emissions included, highlight the necessity for Ofwat, the regulatory body, to establish a uniform method that incorporates carbon efficiency as a key factor in regulating water companies. Additionally, the findings suggest the need for policy development that accounts for contextual factors influencing carbon efficiency. This would ensure that water companies are assessed and motivated equitably, in line with their unique operational conditions.

Shifting the focus to the economic aspect, it is found that the calculated mean allocative inefficiency of energy in relation to other inputs yielded a negative value, −0.714. This implies that on average energy was utilized less efficiently compared to other inputs. In other words, on average energy was overused by 71.4% relative to other inputs over the period of study. Although there are no prior studies specifically on the allocative inefficiency of water companies, Molinos-Senante et al. (2022) calculated an energy efficiency rate of 0.644 for water companies in England and Wales. This indicates a potential for these companies to decrease their energy costs by 35.6%. Even more pronounced reductions were identified by Walker et al. (2020), who for a smaller set of 12 water companies, found an average possible energy usage decrease of 91.7%.Our study spans a decade from 2010 to 2019, and this timeframe can be segmented into two distinct sub-periods: 2010 to 2015 and 2015 to 2019 (Figure 2). This division aligns with the tariff assessments carried out by Ofwat in 2009 and 2014. In 2009, as part of the price review process, Ofwat introduced a range of financial incentives aimed at motivating companies to enhance their efficiency. For instance, water companies were obligated to distribute any cost savings resulting from their daily operations and infrastructure maintenance to customers. However, despite these incentives, the average carbon performance of water companies did not exhibit any improvements during this period. Similarly, there was a lack of observable changes in allocative inefficiency concerning energy usage (Figure 2). Consequently, it becomes evident that the policies implemented by Ofwat to foster efficiency within water companies did not yield discernible effects on their average carbon and allocative efficiency levels.

The subsequent sub-period, spanning from 2015 to 2019, corresponds to the aftermath of the 2014 price review. During this review, Ofwat implemented a standardized set of performance indicators known as Outcome Delivery Incentives (ODIs), aimed at monitoring both service quality and environmental performance of companies (Ofwat, 2015). Consequently, water companies were required to demonstrate annually to both regulatory bodies and customers whether they successfully met their performance targets by the end of the regulatory period. This framework aimed to encourage enhanced economic efficiency alongside improvements in service quality and environmental performance. As illustrated in Figure 2, the results indicate a significant enhancement in carbon efficiency over this time frame. Specifically, the average carbon inefficiency decreased from 0.738 in 2016 to 0.503 in 2019. As the industry transitioned towards greater carbon efficiency, there was a concurrent improvement in allocative efficiency. This observation aligns with the central conclusion drawn by Trinks et al. (2020), whose work demonstrated a positive relationship between carbon efficiency and the short-term profitability of firms.

Given the significant potential for English and Welsh water companies to cut their GHG emissions and enhance their carbon efficiency, the regulator should advocate for the implementation of various eco-friendly policies. These should include: (i) Integrating renewable energy: encouraging the use of clean energy sources such as solar or wind power in water treatment and distribution systems to lessen the carbon footprint; (ii) Advancing energy efficiency: launching initiatives to modernize infrastructure with more energy-efficient technologies, including high-performance pumps and intelligent grid systems; (iii) Providing incentives for adopting low-carbon technologies: offering economic incentives to facilitate the use of low-carbon technologies in the water treatment and distribution processes; (iv) Monitoring carbon emissions: mandating that water utilities regularly measure and report their carbon emissions to pinpoint improvement opportunities and monitor progress and; (v) Setting benchmarks and sharing best practices: creating benchmarks for carbon efficiency and promoting best practices via regulatory standards to drive sector-

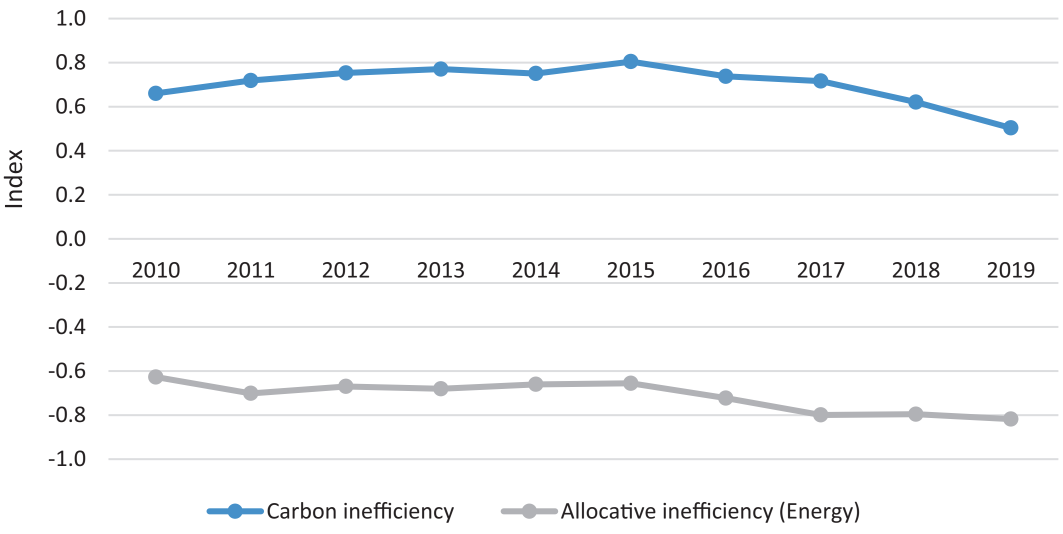


FIGURE 2 Evolution of average carbon inefficiency and allocative inefficiency (energy) for English and Welsh water companies from 2010 to 2019.

wide improvements. Extreme decentralization of water and wastewater treatment services has been proposed as an emerging paradigm towards low-carbon urban water cycle (Garrido-Baserba et al., 2022). However, the success of this paradigm shift hinges on the formation of sustainable communities actively participating in the green transition (Canova et al., 2022). Looking at the photovoltaic energy sector, D'Adamo et al. (2023a) evidenced that the transition related to residential users is connected to a new business model which involves benefits for users. In this context, Rabaey et al. (2020) highlight the importance of drawing lessons from other infrastructural transitions, such as power generation at household level, to foster the implementation of decentralized urban water systems. Moreover, more resilient and sustainable global value chains can be achieved through responsible business conduct (OECD, 2021). Thus, local industrial development of the sector plays a key role in improving the sustainability of firms (D'Adamo et al., 2023b).

Beyond the average inefficiency for the English and Welsh water industry, Figure 3 shows the average carbon and allocative inefficiencies for each water company between 2010 and 2019. Focusing on carbon inefficiency, notable differences are observed among water companies. Thus, the minimum inefficiency is reported for WC3 whose carbon inefficiency was 0.389 meaning that over the period 2010–2019, it could reduce its GHG emissions by 32.2%. On the other hand, the water company with the largest room to reduce carbon emissions was WC18 whose average carbon inefficiency was estimated to be 0.918. Looking at allocative inefficiency, also notable diverges are evidenced among water companies.

The water company with the highest variation in input misallocation is WC13 because its allocative inefficiency was −0.908. This means that this company overused energy by 90.8% relative to other inputs. On the other hand, the water company with the lowest variation in input misallocation among the set of utilities evaluated is WC17. Its average allocative inefficiency was −0.488 suggesting that over time energy was overused by 48.8% relative to other inputs.

3.2 | Impact of carbon and allocative inefficiencies on production costs

The effects of allocative and carbon inefficiencies on the production costs of water companies in England and Wales are shown in Figure 4. Examining the period spanning from 2010 to 2015, it becomes evident that production costs escalated due to carbon inefficiency. However, post-2015, owing to the enhancement in the carbon performance of water companies (as depicted in Figure 2), production costs attributed to carbon inefficiency commenced a downward trajectory. Conversely, an opposing trend is observed for production costs arising from allocative inefficiency. Notably, these costs exhibited a substantial increase since 2017, which can be attributed to a slowdown in allocative inefficiency improvements and concurrent upticks in energy and input prices. Interestingly, the escalation in production costs attributed to carbon inefficiency outpaced the rise stemming from allocative inefficiency up until 2017, after which the pattern reversed. This finding underscores the substantial efforts made by the English and Welsh water companies, particularly following the 2014 price review, to enhance their carbon efficiency. These endeavors have yielded positive outcomes for water companies, both from an environmental and economic standpoint.

At water company level, Figure 5 illustrates the implications of allocative and carbon inefficiency on the costs of producing and delivering drinking water. On average, the expenses linked to the production and distribution of drinking water experienced an uptick of 0.089 £/m^3 due to the combined influence of water companies' allocative and carbon inefficiencies. Of this total, allocative inefficiency contributed to 37.1% of the increase, while carbon inefficiency accounted for the remaining 62.89%. As anticipated, substantial variations are discernible among the different water companies. The impact of inefficiency (both allocative and carbon) on production costs ranged from 0.049 to 0.127 £/m^3. Furthermore, Figure 5 highlights that, for certain water companies, carbon inefficiency constituted the primary factor driving the rise in production costs, while the opposite held true for others. Consequently, no

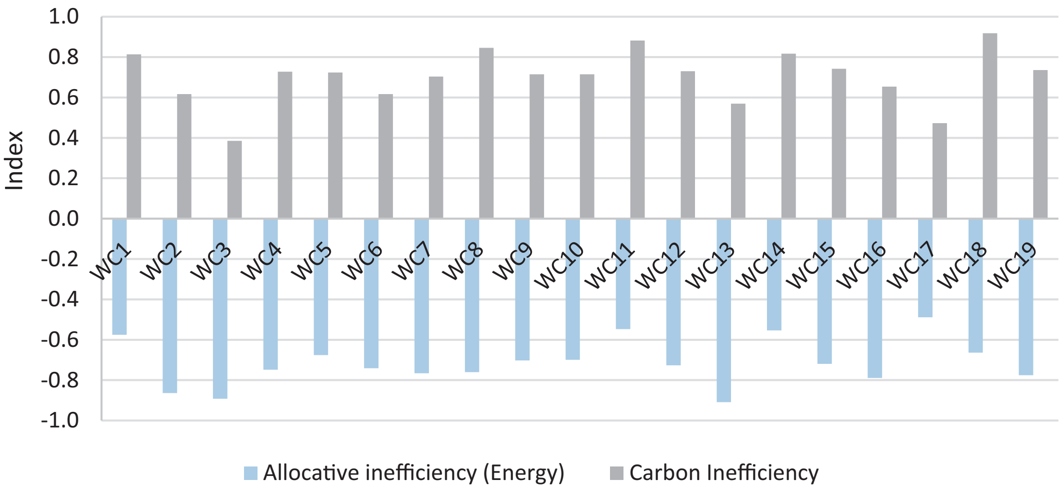


FIGURE 3 Average carbon and allocative inefficiencies (energy) for each water company (WC) from 2010 to 2019.

FIGURE 4 Total costs of English and Welsh water companies due to carbon and allocative inefficiencies (2010–2019).

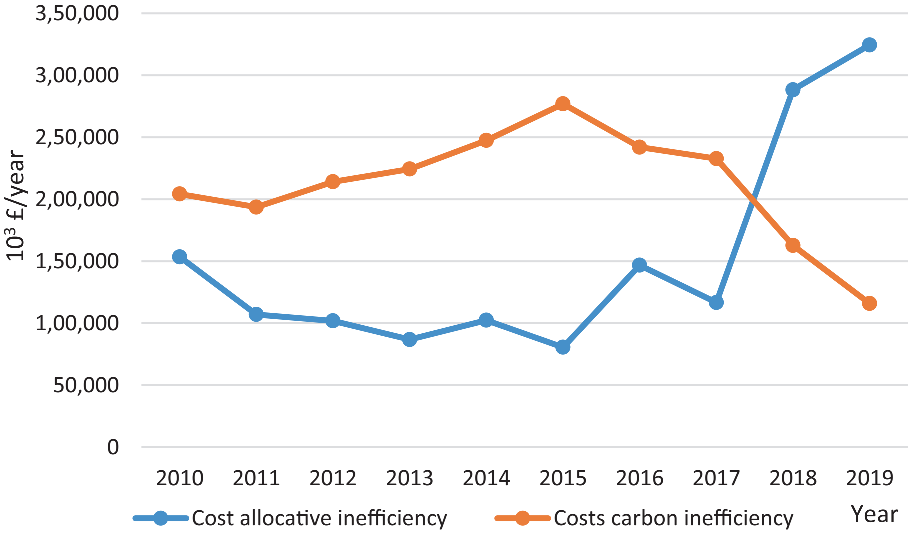
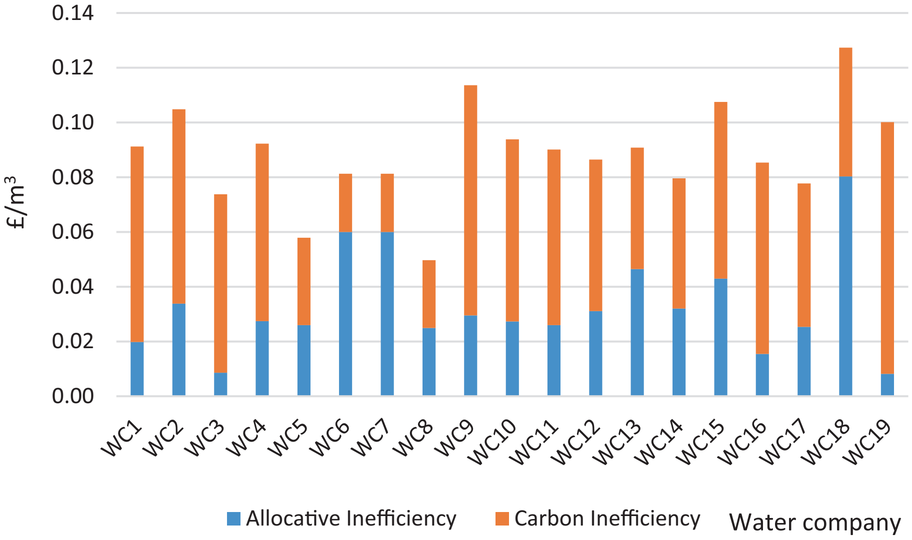


FIGURE 5 Average impact of allocative and carbon inefficiency on production costs of water companies (2010–2019).



discernible overarching trend emerges regarding which form of inefficiency primarily contributes to the escalation in production costs.

4 | CONCLUSIONS

Water industries globally are confronted with the challenge of mitigating GHG emissions as part of the shift towards a more environmentally friendly and carbon-neutral urban water cycle. To showcase the potential advantages of embracing technological and managerial solutions to reduce GHG emissions within water companies, it is crucial to conduct a comprehensive evaluation of the economic consequences associated with current carbon inefficiencies in the provision of urban water services. In this context, this study introduces a methodological approach aimed at quantifying both carbon and allocative inefficiencies exhibited by water companies and assessing their effects on the costs related to the production and distribution of drinking water.

Through a quantitative analysis of the English and Welsh water industry as a case study, this research has empirically demonstrated the adverse economic impact of both carbon and allocative inefficiency in the provision of drinking water services. Specifically, it was found that over the period from 2010 to 2019, the average carbon inefficiency among English and Welsh water companies was 0.699 and a 71.4% excess utilization of energy was estimated. These inefficiencies resulted in higher operational costs for the production and distribution of drinking water, amounting to an average increase of 0.089 £/m^3. At water industry level, allocative inefficiency played a predominant role, contributing to 62.9% of the increased costs, while carbon inefficiency had a more moderate impact, accounting for 37.1%. However, at the individual water company level, diverse patterns and degrees of inefficiency were observed. This underscores the necessity of tailoring specific policies and strategies for each utility as they transition towards a low-carbon water provisioning model.

The findings from this study hold significant relevance for both water regulators and water company managers. From an academic and practitioner perspective, there is a growing trend of monitoring energy use and GHG emissions in physical terms, i.e., monitoring the energy and carbon intensity of water companies in the provision of water services. However, this study introduces another crucial dimension: the quantification of the economic repercussions stemming from excessive energy use and carbon inefficiency on the cost associated with producing and delivering drinking water. This additional dimension not only helps water companies better comprehend the full economic implications of their inefficiencies but also provides a practical basis for implementing improvements. From a practical standpoint, this information is immensely valuable for water regulators. It demonstrates that transitioning towards a low-carbon urban water cycle is not merely an environmentally beneficial endeavor; it also yields significant economic advantages. These benefits can potentially be passed on to citizens in the form of lower water tariffs, generating a positive social impact. In this way, the study underlines the importance of a holistic approach to water management, taking into account both environmental and economic factors, ultimately leading to more sustainable and cost-effective water services for the public.

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ENDNOTE

[1] SFA models are based on the premise that the assessed units (water utilities) follow a common production function, meaning they have the same relationship between inputs and outputs (Equation 1), and that deviations in behavior between units are due to noise errors (v) or inefficiencies (u).

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