Life Cycle Assessment of Water-Sourcing Strategies for Data Centres Under a Decarbonizing UK Grid

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***Abstract*—The rapid growth of ICT workloads and large-scale data centres is intensifying demand on electricity and water systems. This study applies life-cycle assessment (LCA) to compare three cooling-water configurations under a decarbonizing UK grid: a base case relying on potable water with limited condensate reuse; a policy case that replaces 25% of potable supply with on-site reuse; and a future-state case in which centralized supply from a wastewater treatment plant (WWTP) provides the majority of cooling demand. Carbon impacts are quantified using current grid-carbon intensities. Although the base case is the lowest-energy option, it yields the highest carbon emissions due to significant blue-water demand. The policy configuration reduces emissions, while full WWTP sourcing achieves the lowest overall carbon footprint despite highest energy use. A sensitivity analysis on grid-carbon intensity in the UK further shows that future decarbonization trends increasingly favour the full-WWTP scenario. These results illustrate how grid decarbonization reshapes the environmental hierarchy of water-sourcing strategies, emphasizing the need for integrated energy–water planning to deliver low-carbon, water-resilient data centres.**

***Index Terms*—Data centre, Energy and Water Footprint, Life Cycle Assessment, GHG Emission**

I. Introduction

The accelerating deployment of AI workloads and digital services has led to unprecedented expansion in data-centre capacity worldwide. As a result, data centres have become one of the fastest-growing electricity end-use sectors, with global consumption projected to exceed 1,000 TWh per year by 2030 [1]. In the UK, national decarbonization policies are significantly transforming the power mix. In line with the UK Government's 2025 Greenhouse Gas Report, the carbon intensity of grid electricity decreased by approximately 15% in the past year alone as renewable energy generation rises and fossil fuel reliance declines [2]. Beyond energy and carbon metrics, the water footprint of data centres is increasingly recognized as a critical sustainability indicator. Recent studies highlight that water-usage effectiveness (WUE) and ISO 14046–based water-footprint assessments can reveal substantial direct and indirect water dependencies, particularly for AI-intensive workloads. According to the UK Compute Roadmap [3], the national computing strategy targets approximately 6 GW of installed data-centre capacity to support the growing demand for artificial intelligence (AI) and high-performance computing. The UK's National Framework for Water Resources 2025 highlights a projected multi-billion-litre daily water deficit by mid-century and calls for demand reduction, industrial water reuse, and tighter integration between siting decisions and regional water-resources planning [4]. Together, these developments present both the opportunities and imminent challenge in scaling compute infrastructure sustainably within a rapidly decarbonizing energy ecosystem. While this trend improves the carbon performance of electricity-intensive operations, it also heightens the importance of water sustainability, as further gains in power-use efficiency alone offer diminishing environmental returns. Consequently, attention is shifting toward the coupled energy and water demands of data centre infrastructure, where achieving net-zero emissions must be balanced with responsible water management to ensure sustainable progress in the next phase of AI-driven digital development. Outcomes in [5] demonstrates that AI workloads tightly couple energy use with water demand, as training large-scale models like GPT-3 and GPT-4 indirectly consumes significant freshwater through both data-centre cooling and electricity generation. The research emphasizes the need for coordinated strategies in siting, cooling-water sourcing, and workload scheduling to mitigate regional water stress. Multiple studies [6], [7] consistently show that water reuse reduces freshwater withdrawal but introduces energy penalties from treatment and pumping, reinforcing the need for integrated life-cycle modeling. Similarly, Manganelli et al. [8] emphasize that data-centre sustainability depends on an integrated approach combining renewable-energy adoption, energy-efficiency improvements, and circular-energy utilization. Despite increasing policy guidance encouraging non-potable water use, "the majority of data centres were using the public water supply rather than alternative sources" [9].

To the best of our knowledge, most existing assessments of digital-infrastructure sustainability focus on either energy performance (e.g., PUE, waste-heat reuse) or water use (e.g., WUE, water-scarcity footprint), and only a few recent studies evaluate both dimensions within a unified life-cycle assessment framework. However, very few analyses explicitly compare alternative water-reuse sourcing strategies while jointly modeling water and energy impacts under a dynamically decarbonizing power grid, which is the focus of this work. Therefore, this study examines three cooling-water supply configurations for data centres: a status quo *Base* case de-

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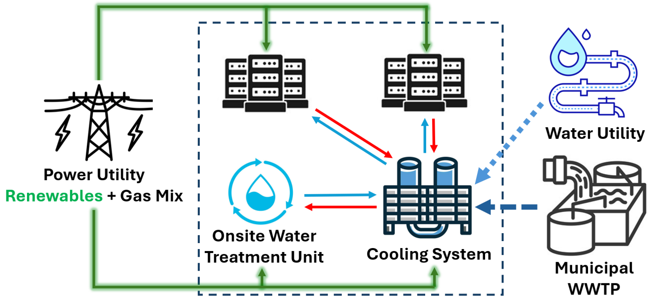

Fig. 1. Resource and energy flow schematic for a data centre. The proportions of different water sources for cooling (utility supply, on-site polish and treatment, and WWTP reclaimed water) can vary from 0% to 100%, depending on the specific system configuration. The energy mix is evolving due to the increasing penetration of renewable resources.

pendent on potable utility water with minimal on-site reuse; a *Policy*case that replaces a portion potable supply with on-site water reuse to align with emerging circular-economy policies and water-reuse standards and a future-state *Full WWTP* case in which most make-up water is supplied from a centralized wastewater treatment plant. Together, these scenarios provide a structured basis for comparing the technical feasibility, environmental performance, and siting implications of increased water circularity. The contributions of this paper are as follows:

- Integrated energy–water assessment: A coupled modeling framework is developed to quantify the links between water footprint, treatment pathways, cooling energy demand, and life-cycle greenhouse gas emissions, enabling system-level evaluation of energy–water trade-offs.
- Grid decarbonization sensitivity analysis: The analysis incorporates the UK's evolving low-carbon grid mix, revealing how the carbon impacts of alternative water reuse strategies shift under progressive decarbonization.
- Treatment technology LCA: Life-cycle impacts are quantified for high-TRL water treatment options including condensate recovery, ultrafiltration (UF), membrane bioreactors (MBR), and Ultraviolet (UV) as applied across the three modeled scenarios.
- Policy and regulation implications: The results highlight the conditions under which circular water management reduces operational emissions and potable water dependence, providing evidence to support emerging data centre water reuse standards and net-zero policies.

II. Methodology

A coupled power–water modeling framework is developed and integrated with a time-resolved life-cycle assessment to evaluate the energy demand, freshwater withdrawal, and greenhouse-gas (GHG) emissions of alternative cooling-water supply configurations in data centre operation. The model resolves daily electricity and water flows across the cooling, and treatment subsystems. By computing corresponding life-cycle carbon emissions using temporally explicit emission factors that reflect current and projected UK grid decarbonization. Three cooling-water sourcing scenarios are defined to represent progressively higher levels of water circularity and infrastructural integration.

TABLE I
Cooling-Water Supply Scenarios

Case	Make-Up Water Sources	Treatment
Base	W_{utility} + $W_{\text{condensate}}$	UV
Policy	W_{onsite} + $W_{\text{condensate}}$ + W_{utility}	UF + UV
Full WWTP	$W_{\text{WWTP,direct}}$ + $W_{\text{condensate}}$	MBR + UV

A. Coupled Power–Water Modeling Framework

Figure. 1 illustrates the system boundary and resource flows represented in the coupled power–water model. The framework isolates the effect of cooling-water sourcing by holding IT load, cooling configuration, and electricity demand constant across all scenarios, while accounting for the evolving carbon intensity of UK grid electricity required to operate the system. The model explicitly captures interactions between the three water-supply pathways and the decarbonizing electricity mix, enabling comparative assessment of freshwater withdrawal, treatment energy, and life-cycle GHG emissions. Within the coupled framework (Figure 1), all subsystems draw electricity from the UK grid, whose carbon intensity varies over time according to the projected renewable–fossil generation mix. The three cooling-water supply configurations differ only in their sourcing and treatment pathways:

- Potable utility supply: conventional mains water (on-site polish) with limited on-site reuse (baseline case).
- On-site reuse: Condensate recovery and/or on-site process applied to internally captured or reclaimed water.
- Cooling-grade reclaimed water delivered directly from a centralized municipal wastewater treatment plant.

For each scenario, the model computes total electricity demand, freshwater withdrawal, and life-cycle GHG emissions associated with cooling operation and scenario-specific water treatment. All configurations share the same IT load, cooling architecture, and operating assumptions; therefore, differences in results arise solely from the water sourcing strategy.

As shown in Table. I, three cooling-water supply scenarios are defined to represent increasing levels of water circularity and external infrastructure integration. In all scenarios, the total make-up water requirement for the evaporative cooling tower, W_{makeup}, is given by:

$$W_{\text{makeup}} = W_{\text{evap}} + W_{\text{drift}} + W_{\text{blowdown}}, \quad (1)$$

where W_{evap}, W_{drift}, and W_{blowdown} denote evaporative loss, drift loss, and blowdown discharge, respectively.

The sourcing of W_{makeup} varies by scenario as follows:

a) Base Case:

$$W_{\text{makeup}} = W_{\text{utility}} + W_{\text{condensate}} \quad (2)$$

The base case reflects the current situation in the UK, where potable mains water is used as the primary make-up source for most data centres. With limited on-site reuse consisting of chilled-water condensate recovery, $W_{\text{condensate}}$. No external reuse infrastructure is required.

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b) Policy Case:

$$W_{\text{makeup}} = W_{\text{onsite}} + W_{\text{condensate}} + W_{\text{utility}} \tag{3}$$

This scenario reflects a practical near-term pathway in which the data centre supplements potable utility water with on-site reclaimed water streams. On-site reuse is limited to a maximum of 30% of total make-up water, comprising chilled-water condensate recovery and additional internally recycled sources. No external reclaimed-water supply from a WWTP is assumed. On-site treatment includes compact process as UF followed by UV disinfection for polishing.

c) Future-state Case: Full WWTP Supply (High Circularity):

$$W_{\text{makeup}} = W_{\text{WWTP, direct}} + W_{\text{condensate}} \tag{4}$$

This configuration corresponds to a centralized WWTP supply system (i.e. MBR) aligned with long-term industrial water circularity targets. In this case, cooling-grade effluent is delivered directly from a regional WWTP, $W_{\text{WWTP,direct}}$, which performs all necessary treatment prior to distribution. On-site treatment is limited to condensate recovery, thereby reducing on-site energy use and operational complexity. Centralized treatment infrastructure enables scalable service to multiple data centre facilities within the same service area.

Across all scenarios, condensate recovery is implemented to improve water-use efficiency without incurring additional treatment energy. The IT load, cooling configuration, ambient conditions, and grid electricity supply are held constant across the analysis. As a result, variations in freshwater withdrawal, treatment-related energy use, and life-cycle GHG emissions are attributable solely to the cooling-water sourcing pathway.

B. Performance Metrics

The cooling-water supply scenarios are evaluated using a set of performance indicators that quantify water use, energy demand, and life-cycle GHG emissions. These metrics enable comparative assessment of operational and environmental outcomes across scenarios.

1) Total Energy Demand: The total energy demand E_{tot} comprises cooling-system energy and any scenario-specific treatment energy:

$$E_{\text{tot}} = E_{\text{cool}} + E_{\text{treat}}, \tag{5}$$

where E_{cool} represents fan and pumping power, and E_{treat} denotes the energy required for UF, RO, and UV disinfection.

2) Life-Cycle Carbon Intensity: Life-cycle GHG emissions, expressed in kg CO_2e per functional unit, are calculated as:

$$\text{GHG}_{\text{tot}} = E_{\text{tot}} \cdot \text{EF}_{\text{grid}} + W_{\text{treat}} \cdot \text{EF}_W, \tag{6}$$

where EF_{grid} is the grid carbon intensity (kg CO_2e kWh^{-1}) and EF_W is the water-treatment emission factor (kg CO_2e m^{-3}). Carbon impacts from electricity use and water treatment are incorporated on a daily basis.

3) Water Footprint (ISO 14046): In accordance with ISO 14046, this study reports the *blue water footprint* associated with operational water consumption, as data-centre activities do not involve green-water use and off-site wastewater treatment lies outside the system boundary. The blue water footprint is calculated as [10]:

$$WF_{\text{blue}} = \sum_i V_i, CF_i, \tag{7}$$

where V_i is the consumptive volume from water source i, and CF_i is the corresponding water-scarcity characterisation factor ($\text{m}^3_{\text{world-eq}}$,$\text{m}^{-3}$). Green and grey water are neglected because in the defined cases, the data centre does not use soil-water rainfall, and pollutant loads are treated off-site at the WWTP system which lies outside the defined system boundary.

C. Life-Cycle Assessment Configuration

The life-cycle assessment quantifies the operational and upstream impacts associated with cooling-water sourcing, treatment, and electricity use across the three scenarios. The analysis follows ISO standards principles and is structured to isolate the effect of the water-sourcing pathway under consistent cooling and IT operation.

1) System Boundary and Functional Unit: The system boundary includes electricity consumed by cooling and water-treatment subsystems, water withdrawal from external sources, and associated emissions from treatment and distribution, as shown in Fig. 1. Embodied emissions from construction of cooling equipment, pipelines, and buildings are excluded due to limited site-specific data and their negligible contribution at the functional scale considered. The functional unit for comparison is defined as *1 day of cooling operation per 50 MW of IT load*. This unit enables temporal evaluation of net freshwater withdrawal, treatment energy use, and life-cycle GHG emissions under UK grid. Shared assumptions for IT load, cooling architecture, site location, and meteorological conditions ensure that scenario differences arise solely from variations in water sourcing and treatment. Note that the model assumes idealized system performance and does not account for losses due to water leakage, electricity transmission, or heat dissipation unless otherwise specified.

TABLE II
BENCHMARK PARAMETERS FOR WATER-REUSE AND UTILITY SUPPLY

Process	**EUI**[a]	**GHG (kg CO_2e/m^3)**[b]	**TRL**
Condensate recovery	Low	0.00	9
Wastewater Treatment	High	0.108 (MBR + UV) [11] 0.072 (UF + UV) [12]	8–9
Portable Water Supply (UK)	High	0.19	9

[a]EUI based on PNNL reuse benchmarks [6]. [b]UK GHG factors per [2].

2) Inputs and Assumptions: The model relies on several key technical and environmental inputs, some of which are based on values derived from the literature:

- Cooling Need and IT Load:

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- Constant 50 MW IT load, representative of a hyper-scale data centre.
  - Based on [13] on cooling water use intensity, $1.8\,\mathrm{m}^3$ of water per $\mathrm{MW}\cdot\mathrm{h}$ of IT load has been defined.
- Energy and Emissions:
  - Electricity supplied by the UK grid, with carbon intensity of $0.18\ \mathrm{kg\,CO_2e\,kWh^{-1}}$ [2].
  - Water-treatment energy intensities: $0.5\ \mathrm{kWh\,m^{-3}}$ for MBR [11], $0.3\ \mathrm{kWh\,m^{-3}}$ for UF and $0.1\ \mathrm{kWh\,m^{-3}}$ for UV alone (polishing) [12].
  - Pumping alone accounts for roughly 25% of total water treatment carbon, a value adopted in the base-case analysis [14].
  - Condensate recovery can supply only a small portion of water demand and can be reused without additional energy input [15].
  - Water source allocation by scenario:
    - ∗ Base: 95% utility water, 5% condensate recovery.
    - ∗ Policy: 25% on site reuse water, 5% condensate recovery, 70% utility water.
    - ∗ Full WWTP: 95% direct reclaimed water, 5% condensate recovery.
  - Municipal utility water and reclaimed WWTP supply assigned GHG factors of $0.19\ \mathrm{kg\,CO_2e\,m^{-3}}$ [2].
- Infrastructure and Siting:
  - Reclaimed-water scenarios assume connection to a municipal WWTP, with distribution pumping included in the treatment energy.
  - Capital and embodied emissions from infrastructure construction are excluded.

III. Numerical Results and Analysis across Different Scenarios

This section presents a quantitative assessment of the three cooling-water sourcing scenarios defined in Section II-A, using the performance metrics outlined in Section II-B and the LCA framework described in Section II-C, which also defines the base-case data centre scenario. The evaluation considers a functional unit of one day of operation at a 50 MW IT load, reflecting 2025 UK grid conditions and projected future decarbonization trends. The resulting numerical outcomes provide a holistic view of water use (including potential saving of municipal blue water), energy consumption, and potential future policy compliance simulation, offering insights into the environmental, operational, and regulatory trade-offs associated with each scenario.

A. Water–Energy–Emissions Trade-offs

As shown in Fig. 2, the three scenarios reveal systematic trade-offs between blue-water use, electricity demand, and GHG emissions driven by differing water sourcing and treatment intensities. The *Base* case exhibits the highest water-related emissions (389.9 kg CO_2e/day) but the lowest electricity-related emissions (36.9 kg CO_2e/day), reflecting the low energy intensity of conventional water supply. This results in the highest total emissions (426.8 kg CO_2e/day) and a strong dependence on freshwater resources. In the *Policy* scenario, partial substitution of blue water with on-site reuse reduces water-related emissions to 287.3 kg CO_2e/day, while electricity-related emissions increase to 66.1 kg CO_2e/day. The net effect is a 17.2% reduction in total emissions relative to the *Base* case, indicating that moderate increases in treatment energy can deliver overall environmental benefits. The *WWTP* scenario eliminates blue-water use, yielding the lowest water-related emissions (97.5 kg CO_2e/day) but the highest electricity-related emissions (221.6 kg CO_2e/day). Despite the need for additional treatment infrastructure and higher electricity consumption, total emissions are lowest (319.1 kg CO_2e/day) and the municipal blue water consumption is 0, indicating that the environmental benefits of wastewater reuse can outweigh its energy penalty as grid emissions decline.

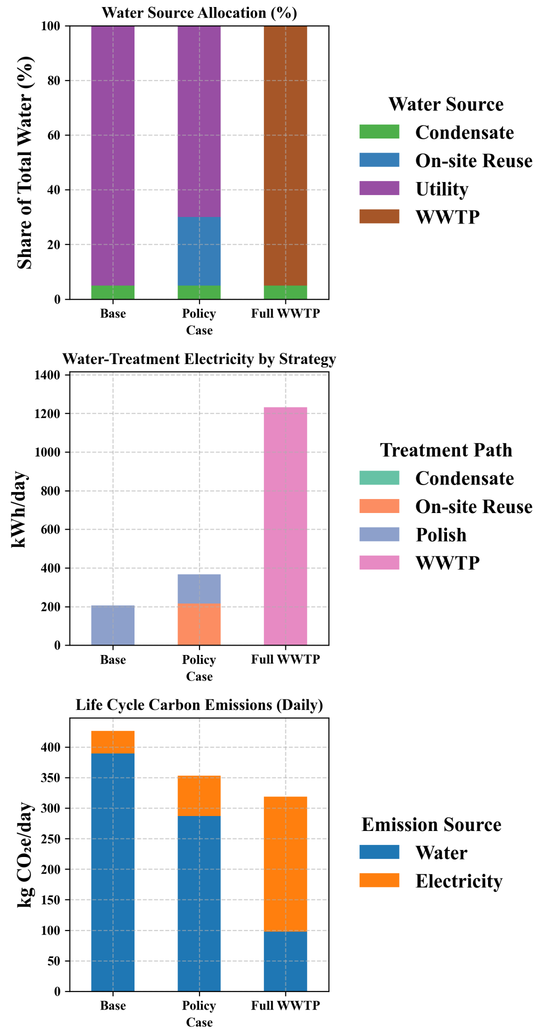

Fig. 2. Visualized comparison of water source allocation, treatment electricity use, and daily life-cycle carbon emissions across the Base, Policy Case, and Full WWTP strategies.

B. Sensitivity Analysis to Grid Carbon Intensity

To assess the influence of grid decarbonization, a sensitivity analysis has been conducted to compare GHG emissions

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TABLE III
NUMERICAL COMPARISON ACROSS THREE CASES (DAILY TOTAL)

Case	Blue water (m^3)	Electricity (kwh)	GHG (kg CO_2e/day)
Base	2052	205.2	426.8
Policy	1512	367.2	353.4
WWTP	0	1231.2	319.1

across the water-treatment scenarios. Daily GHG emissions associated with water treatment are calculated as:

$$\mathrm{GHG}_{\mathrm{daily}}^{\mathrm{Total}} = (V_{\mathrm{utility}} \cdot \mathrm{E}_{\mathrm{polish}} + V_{\mathrm{reuse}} \cdot \mathrm{E}_{\mathrm{treatment}}) \cdot \mathrm{C}_{\mathrm{grid}}. \quad (8)$$

As shown in Fig. 3, the *Full WWTP* scenario consistently results in higher water-treatment emissions than the *Policy* case. At a grid carbon intensity of 0.18 kg/kWh, emissions are 222 kg/day versus 66 kg/day, a difference of 156 kg/day. As the grid decarbonizes to 0.05 kg/kWh, emissions drop to 62 kg/day and 16 kg/day, respectively, narrowing the absolute gap to 44 kg/day. This reduction demonstrates that grid decarbonization not only lowers overall water-treatment GHG emissions but also delivers a further significant environmental benefit, suggesting that energy-intensive water reuse becomes increasingly favourable in the context of electricity grid decarbonisation.

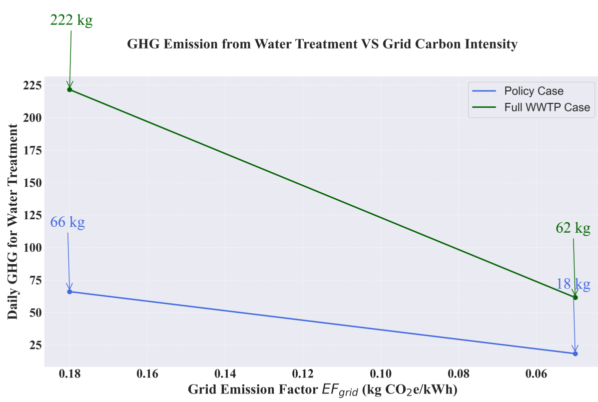

Fig. 3. Sensitivity of water-treatment GHG emissions to grid carbon intensity under different scenarios.

IV. CONCLUSION AND FUTURE WORK

This paper proposes a water–energy synergy framework to analyze the trade-offs among water sourcing strategies for data centers, and the LCA-based analysis framework is transferable to different scales and settings. The comparative analysis highlights a trade-off between near-term implementability and long-term sustainability in data centre cooling water sourcing strategy. The *Policy* scenario represents a future compliance pathway, in which partial on-site reuse and low-energy treatment are adopted in response to tightening water and environmental regulations in the UK. While not reflective of current standard practice, this hybrid configuration offers a realistic intermediate step that balances environmental performance with manageable increases in energy use and cost. In contrast, the *WWTP* scenario reflects a longer-term transition toward fully centralized water reuse. Although it requires additional infrastructure, higher energy input, and greater coordination with utilities, it aligns more closely with anticipated policy directions targeting water circularity, systematic sustainability goal, and deep decarbonisation. As regulatory pressure intensifies and electricity grids continue to decarbonise, such energy-intensive reuse pathways are likely to become increasingly viable. Future work will extend the framework to jointly consider infrastructure costs, IT load variability, and dynamic grid emissions, enabling system-level optimisation of water and energy use under evolving policy and operational conditions.

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