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Research Article

Carbon Accounting, Industrial Water Conservation, and Equipment Reliability in High-Pollution and Highly Corrosive Enterprises Under Carbon Neutrality Mandates

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Abstract: Achieving strict carbon neutrality targets presents systemic friction for high-pollution, highly corrosive industrial entities, where the optimization of process-level carbon accounting metrics and aggressive closed-loop water-saving protocols remains fundamentally constrained by the physical degradation boundaries of localized hardware infrastructure. This study establishes an empirical tri-sector evaluation framework that couples a newly derived enterprise-level carbon emission accounting model with grey correlation-based industrial water conservation algorithms, specifically analyzing their joint operational impact on downstream measurement equipment reliability. During the implementation phase in an active chemical facility, our initial linear predictive flows were severely disrupted by unexpected non-linear spikes in recycled electrolyte concentrations, which induced rapid electrochemical failure of standard instrumentation seals and necessitated an iterative structural redesign utilizing an innovative single-flange transmitter configuration equipped with dual-layer PTFE-V-ring assemblies. Statistical data from subsequent multi-objective optimization simulations indicate that while maximizing water reuse efficiency nominally minimizes indirect carbon footprints, the resulting aggressive chemical media simultaneously intensifies localized stress concentrations, a paradox that might be partially explained by microscopic biofilm-induced pitting or localized galvanic couplings. Considering these entangled dynamics, our multidimensional synthesis offers a possible methodology for heavy industries to navigate environmental compliance without inducing premature asset failure; however, further long-term research is needed to fully quantify the non-linear aging mechanisms of synthetic seals under fluctuating thermo-chemical stresses.

Keywords: Carbon Accounting; Water-Saving Potential; Equipment Reliability; Corrosive Operating Conditions; Multi-Objective Optimization;

1. Introduction

The global imperative to transition toward a low-carbon, resource-efficient industrial paradigm under dual-carbon mandates forces heavy chemical processing, textile dyeing, and pulp-manufacturing sectors to navigate an increasingly convoluted trilemma characterized by stringent regulatory compliance, diminishing freshwater availability, and premature structural degradation of hardware assets. Historically, national environmental policies and corporate engineering strategies have largely treated these industrial pressures as independent variables, creating decentralized optimization pathways that focus primarily on isolated operational gains. Environmental economists, operating within macroeconomic domains, have spent considerable effort refining enterprise-level carbon emission accounting matrices to capture direct and indirect greenhouse gas trajectories across complex supply chains. Simultaneously, water resource engineers have independently developed sophisticated closed-loop industrial water conservation protocols and wastewater purification technologies, driving manufacturing facilities to maximize internal water recycling rates.

However, this compartmentalized approach to industrial sustainability overlooks a critical physicochemical feedback loop that fundamentally limits the viability of decoupled environmental strategies. When a highly corrosive chemical facility or a paper mill aggressively increases its wastewater reuse ratio to minimize its external hydrological footprint, the rapid concentration of non-filterable dissolved solids, residual process electrolytes, and volatile compounds alters the foundational thermodynamic equilibrium of the process fluid. This closed-loop chemical accumulation leads us to further thinking regarding its structural

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externalities: the resulting hyper-electrolyte fluid environments exponentially accelerate the electrochemical corrosion and stress-cracking kinetics of downstream hardware components. Consequently, an overly ambitious carbon-reduction or water-saving protocol might inadvertently compromise the operational reliability of critical inline measurement equipment, such as single-flange transmitters and digital sensory arrays, which are indispensable for maintaining safe process control boundaries.

Furthermore, establishing a seamless carbon-accounting matrix within heavy industries is frequently hindered by organizational and infrastructural limitations within the broader corporate ecosystem. The complete quantification of indirect Scope 3 carbon trajectories remains problematic because the upstream micro and small logistics enterprises that feed raw materials into heavy manufacturing plants typically lack integrated multi-format management systems [14] and long-term digital transformation mechanisms [16]. When these essential supply chain partners operate without automated data infrastructure, the core manufacturing facility is forced to manage fragmented supply data. This data silo effect is worsened by low cross-departmental data collaboration between production, procurement, and environmental compliance sectors, which severely limits tracking efficiency and increases operational friction [6]. Thus, the systemic friction between macro-level carbon-water optimization algorithms and micro-level mechanical failure mechanisms remains, to a significant extent, insufficiently theorized. High-pollution enterprises are currently forced to implement aggressive environmental targets without an integrated analytical framework capable of quantifying how fluid-chemical alterations trade off against physical asset longevity, though further empirical validation across varying industrial baselines is deeply needed.

2. Literature Review

To properly contextualize the operational boundaries of sustainable engineering within high-pollution industrial sectors, it is necessary to critically examine the methodology and structural limitations inherent in previous carbon tracking and resource conservation paradigms. Early attempts to quantify water-saving capacity inside heavy manufacturing clusters relied heavily on aggregated input-output assessments and macro-level static data. A foundational example is found in the work of Lu L. et al. [1], who utilized historical macroeconomic input-output tables to analyze industrial water conservation potentials across major manufacturing regions. While their macro-scale methodology successfully identified large-scale target sectors for policy intervention, their model treated industrial complexes as isolated systems, failing to account for seasonal variations and the ongoing temporal water quality degradation that occurs within the urban-industrial river networks that receive wastewater discharges [12]. By overlooking the real-time dynamic flux of pollutants, such macro-scale methodology remains ill-suited for factories requiring precision intra-day parameter adjustments.

Subsequent environmental engineering research attempted to address these spatial-temporal variations by introducing correlation modeling to interpret fluctuating aqueous environments. For instance, Liu et al. [2] adapted grey correlation modeling to evaluate water quality dynamics in urban-industrial river matrices, providing a mathematical pathway to weigh interdependent chemical variables under conditions of partial data uncertainty. However, the limitation of this method lies in its reliance on static boundary assumptions; the grey correlation coefficients were calculated using fixed environmental snapshots. Consequently, when applied to closed-loop industrial water recycling systems—where electrolyte concentrations, chemical oxygen demand, and corrosive chloride ions build up non-linearly over prolonged operational cycles—the predictive accuracy of these linear models degrades significantly. This mismatch indicates that water conservation potentials cannot be calculated independently of the cumulative chemical evolution of the recycled fluid.

This operational volatility has led contemporary researchers to explore digital, data-driven regulation frameworks to manage complex manufacturing environments. Liu, X. [5] addressed this need by proposing an intelligent response system powered by structured knowledge graphs designed to streamline environmental compliance audits for chemical production facilities.

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Furthermore, Liu, X. [9] utilized multi-objective optimization algorithms to dynamically balance coupled process parameters within transnational electrolyte factories, aiming to optimize both energy efficiency and throughput. While these algorithmic frameworks represent a major advancement in process automation, they manifest a shared structural vulnerability: they proceed under the idealized assumption of pristine, uninterrupted sensor reliability. In hostile processing conditions—such as those involving wet chlorine gas, high-salinity brines, or volatile organic solvents—the physical instruments feeding data into the knowledge graphs are subject to severe chemical attack.

The real-world consequences of ignoring hardware vulnerability are regularly exposed by empirical mechanical engineering literature. Experimental structural studies, such as the investigation by Zhang, Y. [4] into single-flange transmitters operating under highly corrosive media, demonstrate that the interaction between severe chemical attack and mechanical stress produces unexpected structural failures. Specifically, Zhang, Y. [4] showed that innovative sealing structures designed with conventional materials often suffer from localized stress concentrations and micro-pitting along the sealing lip when exposed to fluctuating process pressures, violating established technical testing standards for corrosive media measurement [11]. Furthermore, these internal degradation vectors are frequently exacerbated by external environmental shifts. Recent advancements in meteorological modeling by Chang et al. [23] demonstrate that boundary layer wind fields during tropical cyclones introduce intense low-frequency structural vibrations to coastal industrial facilities. When these external physical loads are coupled with high-resolution climate projections that predict increased building thermal energy simulations [10], the combined thermal-mechanical stresses accelerate the mechanical failure of inline instruments long before the process automation algorithm signals that the macro-system has reached its computed environmental equilibrium.

3. Methodology and Field Operations

The development of an integrated empirical framework for dual-carbon heavy industries requires a methodology that moves away from laboratory-scale isolation to confront the unbuffered fluctuations of active industrial streams. Our research design initially mapped a linear analytical path: integrating a sector-specific carbon accounting matrix with a dynamic wastewater reuse scheduling protocol, followed by a standard finite element verification of sensory sealing structures. To test this programmatic setup under real operational loads, we initiated a six-month pilot deployment within a chemical and paper-making facility complex, targeting the processing nodes where high-salinity process fluid and volatile organic compounds create the most severe operational friction. The baseline operational boundaries of the testing environment, representing the macro-environmental tracking parameters of the facility before our optimization interventions, are documented in Table 1.

Table 1. Baseline Facility Operational and Environmental Parameters

Parameter Description	Baseline Value	Measurement Unit	Spatial/Temporal Source Node
Annual Paper-making Throughput	240,000	Metric Tons / Year	Production Management System
Fresh Water Intake Rate	18.5	m^3 / Ton of Paper	Main Hydrological Intake Meter
Scope 1 Direct Emissions	142,500	tCO_2e / Year	Facility Gate-to-Gate Log
Scope 2 Indirect Emissions	89,400	tCO_2e/ Year	Power Grid Substation Interface

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Parameter Description	Baseline Value	Measurement Unit	Spatial/Temporal Source Node
Average Process Fluid Temperature	65.0	°C	Downstream Clarifier Outflow

However, transitioning our predictive models into the physical plant immediately revealed substantial field anomalies that exposed the limitations of idealized environmental algorithms. During the initial data acquisition phase, our cross-departmental carbon tracking framework suffered from high data volatility; missing multimodal covariates in material gate-to-gate inventories made direct carbon accounting highly uncertain. To mitigate this without introducing artificial imputation bias, we adapted a regularized multi-response regression approach designed specifically for block-missing multi-modal data profiles [3], which allowed the model to maintain statistical integrity despite missing inventory segments. Furthermore, to handle the continuous influx of real-time operational metrics under severe network constraints, we integrated an adaptive supervised learning method optimized for sparse data streams in reproducing kernel Hilbert spaces [21], which successfully prevented data saturation during rapid process transitions.

A more severe disruption occurred during the industrial water sampling phase. As the factory increased its water reuse ratio to simulate peak water-saving capacity, the rapid accumulation of closed-loop chemicals caused a non-linear spike in chloride ions and total dissolved solids. This hyper-electrolyte environment exceeded our initial chemical simulations by a factor of three. Within the first 72 hours of peak recycling operations, the aggressive chemical fluid induced severe pitting corrosion and hydrogen embrittlement in the standard AISI 316L stainless steel diaphragms of our online pressure sensors, causing a catastrophic loss of calibration and subsequent data gaps.

This major technical setback forced us to halt the operational run, reconsider our instrumentation boundaries, and perform an iterative hardware adjustment. To resolve the sensor degradation without reverting to unsustainable freshwater dilution, we redesigned the inline physical interface by replacing the baseline instruments with an innovative single-flange transmitter assembly utilizing a pure tantalum diaphragm and a dual-layer, prestressed polytetrafluoroethylene (PTFE) V-ring sealing configuration [4]. This custom structural configuration was engineered specifically to redistribute mechanical clamping stress and establish a chemical isolation barrier against aggressive organic media. Following this hardware substitution, we re-calibrated our environmental multi-objective optimization algorithms, allowing the system parameters to dynamically adjust to the empirical degradation thresholds of the newly introduced sealing materials, as systematically detailed in Table 2.

Table 2. Modified Sealing Material and Structural Testing Configurations

Structural Assembly Component	Material Specification	Clamping Torque (Nm)	Design Corrosion Limit (mm/yr)
Baseline Diaphragm Assembly	AISI 316L Stainless Steel	25.0	0.150
Advanced Diaphragm Replacement	Pure Tantalum	28.5	0.002
Standard Sealing Element	Nitrile Butadiene Rubber	12.0	N/A (Rapid Swelling)
Redesigned Sealing	Dual-Layer Prestressed	18.5	N/A (Chemically Inert)

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Structural Assembly Component	Material Specification	Clamping Torque (Nm)	Design Corrosion Limit (mm/yr)
Assembly	PTFE		

4. Results and Discussion

The empirical data collected from the optimized pilot runs present a multifaceted behavioral spectrum that strongly resists simplistic, unidirectional interpretations. Upon achieving the calculated steady-state water reuse configuration, the enterprise-level environmental monitoring array documented a noticeable reduction in both freshwater extraction and macro-level greenhouse gas expenditures, driven primarily by the lowered thermal and pumping energy demands of the closed-loop system. The quantified shifts in environmental performance metrics over the final 90-day stable evaluation period are detailed in Table 3.

Table 3. Quantified Environmental Performance Shifts Post-Optimization

Evaluated Environmental Metric	Pre-Optimization	Post-Optimization	Absolute Shift (%)	Observed Operational Variances
Freshwater Intensity (m3/t)	18.5	11.2	-39.46%	Constrained by Slurry Consistency
Direct Carbon Intensity (kg/t)	593.7	572.1	-3.64%	Tied to Biogenic Fuel Substitutions
Indirect Electricity Carbon (kg/t)	372.5	311.4	-16.40%	Heavily Dependent on Pump VFDs
Wastewater Discharge Volume (m^3/d)	4,200	1,650	-60.71%	Resulted in Non-linear TDS Build-up
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A standard structural interpretation would attribute the significant reduction in sensor drift and von Mises stress for the redesigned element solely to the superior mechanical elasticity and lower friction coefficient of the prestressed PTFE material. However, alternative biochemical and metallurgical explanations must be considered to fully account for these operational variances. The high density of micro-pitting observed on the standard nitrile assembly, for example, cannot be explained purely by chemical dissolution; it is highly possible that trace anaerobic sulfate-reducing bacteria, thriving within the high-temperature recycled process water, formed resilient localized biofilms under the flange sealing lip. These biological matrices create localized micro-environments where the pH drops far below the macro-fluid baseline, accelerating galvanic corrosion cells that skew standard mechanical wear models.

Furthermore, to successfully operationalize these multi-objective optimization algorithms under real-time field variations without causing network overload, the computation must be managed via local computing architectures. Relying on remote cloud servers introduces prohibitive transmission latency, which compromises the system's ability to respond to sudden pressure spikes. Therefore, managing real-time AI workloads requires low-overhead scheduling models implemented directly on multi-core edge chips [13]. By executing dynamic task prioritization for edge AI nodes, the system effectively balances computational latency against edge-node energy consumption [17], ensuring that the infrastructure provides fault-tolerant, real-time scheduling capabilities even when operating within critical, high-stress industrial environments [24]. Potential biases may still exist in our calculated Mean Time Between Failures for the redesigned components because our active field testing window was bounded by the six-month limits of the pilot project, meaning long-term synergistic aging mechanisms could not be fully manifested in the empirical data. To some extent, the optimization algorithm achieves a highly contingent equilibrium; a minor shift in the upstream chemical composition or a sudden variation in processing temperatures could push the localized stress concentrations past the newly established material yield boundaries.

5. Conclusions

Considering the interconnected environmental and mechanical dynamics detailed throughout this investigation, this research moves beyond the conventional practice of presenting isolated resource-saving metrics to establish a more profound theoretical framework: the sustainable transition of high-pollution, highly corrosive industrial sectors cannot be decoupled from the physical and metallurgical limits of the hardware infrastructure that enables it. By revealing the hidden materials-degradation costs of closed-loop water conservation, this study provides clear evidence against "siloed sustainability targets," proving that aggressive corporate carbon or hydrological optimization protocols without integrated real-time mechanical reliability constraints can induce premature structural failures, thereby causing secondary resource consumption and unexpected carbon penalties during infrastructure remanufacturing. While our multi-objective algorithm demonstrates that a precarious operational equilibrium between energy-water reduction and instrument longevity is possible to some extent, the observed sensitivity of synthetic seals to non-linear chemical accumulation points to an urgent academic need. This leads us to further thinking regarding future strategic horizons, where further research is critically needed to focus on the molecular design of smart, self-healing sealing polymers capable of dynamically adjusting cross-linking densities in response to shifting fluid chemistries, as well as the integration of decentralized lifecycle carbon-wear tracking chains across heavy manufacturing ecosystems.

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Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The author(s) declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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