

Energy Recovery and Clean Water: Techno-Economic and Environmental Assessment

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1. Introduction

Significant energy resources are required to harness, treat, and distribute water for drinking, agriculture, and industry. Energy consumers in the water sector range from large-scale recycling facilities to decentralized, fuel-powered groundwater extraction systems. As climate change intensifies, the interdependence between water and energy systems is becoming increasingly important [1]. Addressing these challenges requires phasing out fossil fuels, reducing CO₂ emissions, and adopting sustainable, low-carbon water and energy technologies [2].

Innovative technologies and appropriate policies that focus on energy recovery are required to optimize water use and improve energy efficiency, important steps for advancing the sustainability of water systems. However, implementing energy recovery involves complex tradeoffs between technology costs, economic efficiency, and environmental impacts.

This Special Issue, “Energy Recovery and Clean Water: Techno-Economic and Environmental Assessment,” addresses these interconnected challenges. The contributions advance our knowledge and propose innovative solutions to support policymakers and planners in developing energy-, climate-, and water-smart systems for a resilient future.

2. Contributions Included in This Special Issue

This Special Issue includes eight peer-reviewed articles that encompass a diverse, yet complementing array of topics, ranging from dynamic wastewater modeling to the broader water–energy–carbon nexus. The contributions are summarized below.

2.1. The Water–Energy–Food–Carbon Nexus and Climate Resilience

A central theme of this issue is the interconnectedness of essential resources under the pressures of climate change.

- Climate impacts on the WEF nexus: Zwane et al. [Contribution 4] demonstrated the cross-sectoral impacts of climate change on the water, energy, and food (WEF) nexus in Narok County, Kenya, and Vhembe District, South Africa. Utilizing nine dynamically downscaled Global Climate Models (GCMs) under RCP 4.5 and RCP 8.5 scenarios, their framework confirms that future climate change will have noticeable interlinked impacts on vulnerable communities, necessitating transformative, multi-stakeholder WEF nexus solutions.
- Integrated energy–water–carbon modeling: Highlighting the socio-economic dependencies among energy, water, and carbon, Rozali et al. [Contribution 5] developed a



Received: 29 March 2026

Accepted: 23 July 2026

Published: 29 July 2026

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novel Automated Targeting Modeling (ATM) framework. By combining the insight-based Pinch method with mathematical programming, the ATM framework successfully established minimum targets for power and water while constraining carbon emissions. Their industrial case study demonstrated that shifting to greener fuels could lead to a 45% reduction in carbon discharge with a meagre 0.45% increase in overall costs.

- Hydropower and environmental flow: Maroufpoor and Qin [Contribution 3] assessed the energy potential of run-of-river hydropower plants (RHPs) across 199 hydrometric stations in Mainland Southeast Asia. Utilizing the HBV hydrological model and climate projections, they balanced the need for renewable energy against environmental flow constraints, concluding that optimal RHP development in the region could avoid 32.5 Mt of CO₂ emissions.

2.2. Decarbonization and Innovative Treatment Technologies

Achieving net-zero emissions requires comprehensive transformation of water infrastructure alongside the deployment of innovative treatment technologies.

- Strategies for a net-zero water industry: Silva [Contribution 8] conducted a systematic literature review (PRISMA) to identify sustainable water resource management (SWRM) strategies that can decarbonize utility value chains. The findings indicate that the water industry, responsible for 3% of global greenhouse gas emissions, could reduce its footprint by over 45% through electrifying transport fleets, transitioning to renewable energy, and implementing advanced oxidation processes (AOPs).
- Ozonation for small-scale resource recovery: Addressing decentralized water reuse, Díaz et al. [Contribution 7] reviewed and experimentally validated the use of aqueous ozone (O₃) for low-load domestic greywater treatment. As a standalone treatment, ozonation, with an oxidation potential nearly twice that of chlorine, achieved significant reductions in BOD₅, turbidity, and total suspended solids while ensuring a 1 Log disinfection level for fecal coliforms in handwashing sink wastewater.

2.3. Advanced Modeling for Water Quality and Operational Efficiency

Digital implementation and statistical forecasting play a critical role in optimizing treatment systems and monitoring surface water quality.

- Dynamic wastewater modeling: El Hawary et al. [Contribution 1] developed a comprehensive model of the Khorshed Wastewater Treatment Plant in Alexandria, Egypt, using GPS-X and the Activated Sludge Model No. 1 (ASM1). Calibrated over 18 months of operational data, the dynamic state model accurately predicted nutrient removal efficiency (TSS, COD, BOD₅, and N-NO₃⁻), providing a validated foundation for future scenario analysis and operational decision support in arid regions.
- Time-series surface-water forecasting: Kovács et al. [Contribution 6] evaluated autoregressive moving-average models for predicting the temporal evolution of water quality parameters in the Kis-Balaton Water Protection System in Hungary. Application of ARIMA models enabled accurate forecasting of oxygen saturation, pH, electrical conductivity, and redox potential, providing a reliable tool for continuous online water management.

2.4. Groundwater Assessment and Agricultural Demand

Sustainable agricultural practices depend on effective management of groundwater quality to prevent soil degradation.

- GIS-based hydrochemical assessment: Badraoui et al. [Contribution 2] investigated the suitability of groundwater for irrigation in the Hennaya region of Northwest

Algeria. Utilizing spatial analysis, hierarchical clustering, and the Water Quality Index (WQI), they categorized the local groundwater as “Good” for irrigation. However, the presence of slight salinity and elevated total dissolved solids (TDS) levels underscores the need for continuous monitoring and proactive management to protect these vital resources.

3. Concluding Remarks

The research presented in this Special Issue demonstrates that securing a clean-water future requires holistic, interdisciplinary strategies. Approaches such as automated targeting models for the energy–water–carbon nexus, climate-resilient hydropower, and decentralized wastewater reuse highlight the need to prioritize both techno-economic feasibility and environmental protection in the transition toward sustainability.

The guest editors express their sincere appreciation to all the authors for their invaluable contributions and the reviewers for upholding the high scientific standards of the published papers. We hope that the methodologies, governance models, and technological applications presented in this Special Issue will inspire continued innovation in energy recovery and global water security.

Conflicts of Interest: The authors declare there are no conflicts of interest.

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