

**EDITORIAL**

Advances in Integrated Energy–Water–Environment Systems and Energy Storage Systems

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ABSTRACT: The energy transition increasingly requires holistic approaches that integrate electricity, heating and cooling, water management, industrial processes, transport, and environmental considerations within coherent system frameworks. Such integration is essential for achieving deep decarbonisation while maintaining reliability, affordability, and resource efficiency across diverse regional and sectoral contexts. This Special Issue of *Energy Engineering* presents selected contributions from the 2024 Conferences on Sustainable Development of Energy, Water and Environment Systems (SDEWES), reflecting recent advances in modelling, system integration, and technology deployment. The included papers address a broad spectrum of challenges relevant to integrated energy–water–environment systems. These include building-sector decarbonisation through hybrid heat pump configurations, geothermal revitalisation of existing oil and gas wells via deep borehole heat exchangers, and techno-economic comparisons of electrochemical batteries and supercapacitors for island energy systems. Further contributions investigate decentralised micro-hydropower solutions tailored to Amazonian conditions, advanced modelling of seepage characteristics in deep tight reservoirs accounting for creep effects, and multi-physical thermal modelling of lithium iron phosphate batteries for residential applications. In addition, hydrogen storage-supported energy system planning using detailed regional housing datasets and retrofit solutions for load balancing in legacy drilling-rig mud pump drives are explored. Collectively, the papers demonstrate how component-level innovation, data-driven planning, and system-level integration can jointly support flexible, resilient, and sustainable energy transitions. By covering diverse applications and geographical contexts, this Special Issue highlights the breadth of the SDEWES research community and provides insights that are relevant for researchers, system planners, and decision-makers working toward integrated energy–water–environment systems.

KEYWORDS: Household energy storage; stationary energy storage; sustainable development; micro-hydropower systems; hydrogen storage

1 Introduction

The 2024 cycle of the SDEWES conferences included the 4th Latin American SDEWES (Viña del Mar, Chile), the 2nd Asia-Pacific SDEWES (Gold Coast, Australia), and the 19th SDEWES Conference (Rome, Italy), bringing together experts from multiple disciplines to address challenges ranging from sector coupling and flexibility to circularity, digitalisation, and infrastructure resilience.

Recent literature provides a strong contextual foundation for the research directions highlighted in this Special Issue. The integrative vision of sustainable energy–water–environment systems has been clearly

articulated in recent SDEWES editorials, most notably by Pfeifer et al. [1], who synthesised cutting-edge advances in sector coupling, system integration, and holistic energy planning, thereby framing many of the challenges addressed by the present Issue's contributions. Within this broader transition, the growing importance of stationary energy storage has been comprehensively reviewed by Wüllner et al. [2], who analysed application domains, optimal placement, and techno-economic potential of storage technologies, directly underpinning the relevance of comparative and context-specific storage assessments featured in this Special Issue.

At the building scale, Coccato et al. [3] reviewed optimisation strategies for battery energy storage systems in the built environment, highlighting control, sizing, and integration aspects that resonate with the component-level modelling and residential storage analyses presented here. Complementing these perspectives at the system level, Calise et al. [4] applied advanced thermoeconomic modelling to next-generation district energy networks, demonstrating how integrated thermal, electrical, and storage infrastructures can be evaluated within a unified framework—an approach closely aligned with the multi-energy and system-oriented analyses showcased in this Issue.

Recent studies further demonstrate how these concepts translate into deployable solutions. For instance, Schedler et al. [5] proposed a bottom-up methodology for classifying building portfolios to support storage demand analysis, while Knorr et al. [6] investigated the flexible operation and integration of high-temperature heat pumps, highlighting their role in sector coupling and thermal system flexibility. Beyond the building and district scale, Guarino et al. [7] advanced the energy–water nexus through a comprehensive 3E assessment of a solar-driven reverse-osmosis desalination system for small islands, and Wilk et al. [8] contributed to circular-economy pathways by experimentally analysing hydrothermal carbonisation of sewage sludge.

The potential role of hydrogen in decarbonising end-use sectors has also received increasing attention. Vespasiano et al. [9] assessed the energy, environmental, and economic implications of hydrogen blending in natural gas grids for residential applications, providing an important bridge between hydrogen infrastructure planning, building-sector decarbonisation, and the hydrogen-supported energy system analyses discussed in this Issue. In the context of decentralised renewable generation, earlier work by Çelo and Bualoti [10] analysed the impacts of small- and micro-hydropower integration on distribution networks and the associated investment requirements, while the present Issue extends this line of research through an Amazonian case study focusing on the identification and application of suitable micro-hydropower technologies for local deployment.

The present Issue assembles selected contributions aligned with these themes. While the papers span distinct technical domains, they share a common vision: advancing sustainable engineering solutions that integrate technical, environmental, and socio-economic considerations within coherent system perspectives. In the following sections, we summarise each contribution and highlight cross-cutting insights relevant to integrated energy–water–environment systems.

2 Decarbonising Buildings with Hybrid Heat Pumps

Di Matteo et al. [11] evaluate the performance of a hybrid heating system that combines a natural gas boiler with an air-to-water heat pump to support decarbonisation of the buildings sector. By coupling laboratory characterisation with dynamic modelling, the study provides an energetic, environmental, and economic assessment of hybrid configurations and operational strategies. The work contributes practical evidence on near-term retrofit pathways for existing building stock, where electrification constraints, legacy equipment, and cost considerations can favour hybrid solutions during transition periods.

3 Geothermal Heat from Deep Borehole Heat Exchangers and Well Revitalisation

Macenić et al. [12] assess the energy potential of deep borehole heat exchangers (DBHEs) in Croatia and provide an economic analysis for revitalising existing oil and gas wells. The study addresses both the technical feasibility and investment considerations of repurposing legacy wells for geothermal heating applications. In contexts where hydrocarbon production is declining, such repurposing can reduce drilling needs, leverage existing assets, and accelerate geothermal deployment—supporting both decarbonisation and circular use of infrastructure.

4 Energy Storage Considerations: Batteries, Supercapacitors, or Hydrogen Storage

Naves et al. [13] conduct a techno-economic comparison of electrochemical batteries and supercapacitors for photovoltaic energy storage in a Brazilian island application, considering both off-grid and on-grid configurations. By explicitly examining performance, cycling durability, and cost trade-offs, the analysis clarifies where fast-response storage may complement or, in selected cases, substitute conventional batteries. The work is particularly relevant for islanded and remote systems where reliability, maintenance constraints, and high renewable shares make storage design central to system resilience. Costa et al. [14] present a multi-physical numerical model of the thermal behaviour of a residential battery pack based on lithium ferro phosphate (LFP) chemistry. Thermal management is a key barrier to safe and durable residential storage deployment, especially under realistic operating conditions. The modelling framework supports the assessment of temperature evolution, safety margins, and design improvements that can enhance both performance and risk management in distributed storage applications. Schedler et al. [15] apply a regional dataset of the housing sector to support hydrogen storage-enabled energy system planning. Given the large share of fossil fuels still used for household heat in many countries, the work highlights the value of detailed building-stock data and the role of hydrogen infrastructures for balancing and supplying energy in urban quarters. The approach contributes to the methodological toolkit for sector-coupled planning where electricity, heat, and gas networks co-evolve toward climate neutrality.

5 Decentralised Micro-Hydropower for Remote Communities

Ramalho et al. [16] explore the development of micro hydropower systems in Amazonia using multiple axial-flow turbines installed in very low-head settings beneath small concrete bridges. The paper demonstrates how locally appropriate infrastructure integration can support rural electrification while avoiding the environmental footprint of larger hydropower developments. This contribution highlights the importance of decentralised renewable options tailored to geographical and socio-economic constraints.

6 Deep Reservoir Dynamics: Seepage with Creep Effects

Liu et al. [17] investigate seepage characteristics of deep tight reservoirs while accounting for creep, a time-dependent deformation process that can substantially influence permeability and flow behaviour. The work develops a mathematical model integrating creep impacts into coupled seepage analysis and validates it through numerical experiments. Such advances can inform safer and more efficient management of deep subsurface systems relevant to resource extraction, geothermal development, and long-term subsurface utilisation.

7 Industrial Retrofits and Load Balancing in Drilling-Rig Mud Pump Drives

Pavković et al. [18] address efficiency losses in legacy deep drilling rigs where paired DC motors for mud pumps are supplied by a single power converter, resulting in electrical power imbalance. The paper proposes an innovative closed-loop control system for electrical load balancing and analyses its potential

to improve efficiency and operational robustness. Beyond its drilling application, the study exemplifies how targeted retrofits and control upgrades can extend asset lifetimes while improving energy performance—an important strategy for industrial decarbonisation.

8 Cross-Cutting Insights and Conclusions from the Special Issue

Several cross-cutting insights emerge from these contributions. First, the Special Issue illustrates the importance of combining component-level innovation (e.g., advanced modelling of batteries or reservoirs) with system-level evaluation (e.g., techno-economic comparisons and planning frameworks). Second, flexibility and resilience appear as recurring requirements—whether through hybrid heating, hydrogen storage, or storage technology selection for island systems. Third, infrastructure revitalisation and retrofit strategies (repurposed wells, drilling-system upgrades, hybrid retrofits) underscore pragmatic pathways that complement greenfield deployment. Finally, multiple papers demonstrate the value of context-sensitive solutions for regions with specific constraints, including islands and remote communities. The papers featured in this Special Issue demonstrate the breadth of sustainable fields' research and the continued expansion of integrated energy–water–environment systems engineering. By addressing building-sector decarbonisation, geothermal revitalisation, storage design, decentralised renewables, subsurface modelling, and data-driven planning, the contributions collectively support the development of flexible, resilient, and low-carbon systems.

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