Journal of Sustainable Development of Energy, Water and Environment Systems

http://www.sdewes.org/jsdewes

Year 2026, Volume 14, Issue 4, 1140775

Review Article

Journal of Sustainable Development of Energy, Water and Environment Systems - Volume XIV

***Doris Beljan*[*1], *Neven Duić*[1,2]**

[1]Faculty of Mechanical Engineering and Naval Architecture, Zagreb, Croatia
e-mail: doris.beljan@fsb.unizg.hr

[2]Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile
e-mail: neven.duic@fsb.unizg.hr

Cite as: Beljan, D., Duić, N., Journal of Sustainable Development of Energy, Water and Environment Systems – Volume XIV, J. sustain. dev. energy water environ. syst.,, 14(4), 1140775, 2026, DOI: https://doi.org/10.13044/2026.14.edt

ABSTRACT

The Journal of Sustainable Development of Energy, Water and Environment Systems (JSDEWES) is an international journal dedicated to the improvement and dissemination of knowledge on methods, policies and technologies for increasing the sustainability of development by decoupling growth from natural resources and replacing them with knowledge-based economy, taking into account its economic, environmental and social pillars, as well as methods for assessing and measuring sustainability of development, regarding energy, transport, water, environment and food production systems and their many combinations. In total, 80 manuscripts were published in Volume XIV, all of them reviewed by at least two reviewers. The Journal of Sustainable Development of Energy, Water and Environment Systems would like to thank reviewers for their contribution to the quality of the published manuscripts.

KEYWORDS

Editorial

INTRODUCTION

This editorial discusses the contributions of the papers belonging to Volume XIV of the Journal of Sustainable Development of Energy, Water and Environment Systems (JSDEWES), an international journal dedicated to the improvement and dissemination of knowledge on methods, policies and technologies for increasing the sustainability of development by decoupling growth from natural resources and replacing them with knowledge-based economy, taking into account its economic, environmental and social pillars, as well as methods for assessing and measuring sustainability of development, regarding energy, transport, water, environment and food production systems and their many combinations.

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* Corresponding author

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RENEWABLE ENERGY TECHNOLOGIES AND POWER SYSTEMS

The continued expansion of renewable energy technologies is increasingly determined by how individual technologies interact with investment conditions, electricity demand and network infrastructure rather than by conversion efficiency alone. Real-options methods can explicitly represent the value of investment timing and managerial flexibility under uncertainty [1], while techno-economic assessment methods can complement this and evaluate photovoltaic performance under specific local conditions [2]. Hernández Palma et al. applied these concepts to photovoltaic supply of critical loads in a healthcare facility in Barranquilla, Colombia, comparing conventional net-present-value analysis with a real-options framework, thus demonstrating the importance of accounting for managerial flexibility when evaluating renewable-energy investments under uncertainty. Distributed photovoltaic deployment also depends strongly on the system into which new capacity is introduced. Optimisation of distributed photovoltaic generation can improve its allocation and integration within local electricity systems [3], while climatic conditions and technology configuration can significantly alter the economic and environmental performance of solar-energy systems [4]. For that reason, Saeed examined three decades of distributed photovoltaic development in China and considered how this experience could inform deployment in Yemen, emphasising phased implementation, pilot projects and adaptation of policy mechanisms to local conditions as means of reducing investment risk and supporting photovoltaic development. Hence, technology availability alone does not guarantee adoption. Economic, institutional, technical and social factors can all constrain decentralised renewable-energy deployment [5] and the relative importance of these barriers can differ substantially among national contexts [6]. Warburg et al. brought these dimensions together through a systematic review, SWOT analysis and analytical hierarchy process assessment of solar-energy penetration in Sub-Saharan Africa. The study provides a structured assessment of the technical, economic, institutional and socio-economic factors affecting solar deployment in the region. Furthermore, as decentralised systems become more complex, reliability and maintenance become increasingly important. Reliability-oriented maintenance can prioritise components according to their contribution to system risk [7] and multi-criteria approaches can combine reliability with economic and

operational indicators [8]. Nyambura et al. addressed these issues through edge analytics and predictive-maintenance models for off-grid renewable-energy systems, demonstrating how decentralised data processing and machine learning can support fault prediction and improve the operation of systems in areas with limited grid access.

At larger spatial scales, renewable integration is increasingly constrained by electricity networks. Renewable expansion can create mismatches between national generation strategies and regional transmission capacity [9]. Nevertheless, distributed flexibility can contribute to system balancing when coordinated with grid operation [10]. Arfaoui et al. investigated the hosting capacity of the Moroccan transmission system for additional wind and photovoltaic generation and showed that hosting capacity depends on plant location, network connectivity and operating conditions as well as installed capacity. Moreover, converter-dominated systems introduce an additional challenge because declining synchronous inertia changes system dynamics [11], so grid-oriented performance indicators can help evaluate how individual technologies contribute to wider system behaviour [12]. For that reason, Yahyaoui et al. studied grid integration at converter level through experimental validation of a zero-crossing-detection sinusoidal pulse-width-modulation method for grid-synchronised inverters, demonstrating the applicability of a low-cost microcontroller for practical renewable-energy converters.

Photovoltaic generation is also increasingly integrated with electric mobility. Solar-powered electric-vehicle charging can reduce dependence on grid electricity when local photovoltaic generation is combined with storage [13], and coordinated charging can further adapt vehicle demand to power-system conditions [14]. Similarly, Mohd Mawardi et al. developed a photovoltaic-powered electric-vehicle charging system integrating battery storage, a bidirectional buck-boost converter, maximum-power-point tracking and proportional-integral control. Their simulations showed how storage can reduce grid dependence while maintaining the operation of the charging system. Additionally, charging infrastructure must also be considered at system level. Fast-charging deployment introduces important technical and economic requirements [15], while optimised charging can increase utilisation of existing distribution-grid capacity and reduce network stress [16]. To investigate the relation of renewable power and charging stations, Slimani et al. developed a Pinch Power methodology for sizing hybrid renewable systems and electric-vehicle charging stations. Applied to photovoltaic, wind and battery configurations, the approach demonstrated both the economic attractiveness of photovoltaic-battery solutions in the studied case and the temporal complementarity provided by wind generation. It is evident that distribution-network impacts become more pronounced as vehicle penetration rises. Electric-vehicle charging can materially alter feeder loading and voltage conditions [17] and grid-aware charging strategies can reduce reinforcement needs and improve utilisation of local network capacity [18]. Thus, Karmoun et al. examined the effect of electric-vehicle charging on the medium-voltage network of Oujda, Morocco. Their network modelling identified increasing line-loading constraints with growing electric-vehicle penetration, highlighting the need to coordinate transport electrification with distribution-grid planning.

At component level, photovoltaic performance is increasingly treated as a combined thermal, optical and control problem. Thermal management can improve module efficiency by reducing operating temperature [19], while heat-pipe concepts provide an alternative route for increasing heat removal from energy-conversion devices [20]. Indartono et al. experimentally investigated photovoltaic thermal management using a pulsating heat pipe with different working fluids and filling ratios. Their experiments with methanol- and ethanol-based configurations examined how operating conditions influence heat removal and photovoltaic performance. Additionally, optical conditions are equally important because radiation and thermal behaviour interact in determining solar-system performance [21], as local surface properties and albedo can materially influence photovoltaic yield [22]. Chiteka and Enweremadu examined the effects of dust accumulation on photovoltaic performance through a coupled thermal and optical framework. The model considers both optical attenuation and

the thermophysical behaviour of deposited particles, providing a more detailed representation of soiling-related photovoltaic losses. Equally important is advanced optimisation that can support operation under rapidly changing conditions. Meta-optimised particle-swarm approaches have been shown to improve maximum-power-point tracking in photovoltaic systems under varying operating conditions [23] and comparative metaheuristic applications demonstrate the usefulness of these methods for parameter estimation in energy-system models [24]. For that reason, Anssari et al. addressed maximum-power extraction under rapidly changing irradiance using an adaptive particle-swarm-optimisation maximum-power-point-tracking approach. The proposed method was evaluated under fluctuating environmental conditions, where identification of the appropriate photovoltaic operating point becomes particularly challenging. Digital monitoring adds another layer of operational intelligence. Combining image-based measurements with machine-learning analysis can support detailed diagnosis of photovoltaic-module behaviour under changing operating conditions [25], while smart monitoring can reduce dependence on continuous manual inspection and improve fault detection [26]. Thus, Carbono dela Rosa et al. developed a smart photovoltaic-cell monitoring system combining electroluminescence imaging, current-voltage characteristics, adaptive neuro-fuzzy inference and cloud-based monitoring. The approach links image-derived condition indicators with electrical performance to support automated identification of photovoltaic degradation. Short-term photovoltaic forecasting can improve electricity-system scheduling and operation [27], while recurrent neural-network approaches can capture temporal dependencies in renewable-resource data [28]. Baba and Palanga combined a nonlinear physical photovoltaic model with a long short-term memory network for photovoltaic power modelling and forecasting. Their hybrid approach improved forecasting performance compared with the physical or individual data-driven models considered separately.

The increasing share of variable renewable electricity strengthens the role of hybrid storage and multi-technology systems. Hybrid off-grid systems can combine photovoltaics, wind, batteries and fuel cells to maintain autonomous supply [29], while battery and hydrogen storage fulfil different temporal balancing functions and can therefore complement one another [30]. Wahdan et al. applied this concept to a photovoltaic-battery-hydrogen configuration for a self-sufficient lunar microgrid. Photovoltaic arrays, electrolysis, hydrogen storage, fuel cells and alternative battery technologies were modelled to investigate system sizing and reliability under the unusual generation and demand conditions of a lunar application. However, storage performance must also be assessed over the system lifetime. Accurate electro-thermal battery models and parameter-estimation procedures are important when storage behaviour is represented within long-term energy-system operation [31], but predictive control can coordinate renewable generation and storage while considering operating constraints [32]. Kafando and Yamegueu explicitly incorporated battery ageing into optimisation of a stand-alone photovoltaic system. Their iterative procedure showed that battery degradation and replacement can affect optimal storage sizing and system economics and should therefore be represented in long-term off-grid system design. Similar considerations apply to rural electrification. Optimised hybrid renewable systems can provide economically feasible supply for isolated communities [33], as local demand profiles strongly influence the preferred configuration and installed capacities [34]. Nghuumbwa et al. developed an adaptive hybrid renewable-energy-system model for rural electrification and applied it to three locations in Namibia. Multi-objective optimisation considered life-cycle cost, levelised electricity cost, reliability, unused renewable electricity and carbon dioxide emissions. Furthermore, hybrid-system design is also relevant for environmentally sensitive tourism regions, where detailed representation of individual components improves the modelling of hybrid renewable microgrids [35] while the importance of decarbonising energy supply associated with tourism infrastructure can be seen in associated carbon-footprint assessments [36]. For that reason, Rayhan et al. optimised hybrid renewable-energy systems for sustainable tourism in mangrove

regions of Bangladesh, Vietnam and Brazil. HOMER Pro optimisation followed by DIgSILENT PowerFactory analysis demonstrated the potential for high renewable penetration and reductions in costs and greenhouse-gas emissions compared with diesel-based supply.

Wind and hydropower broaden the renewable portfolio and introduce additional design and integration questions. Rotor aerodynamics and wake behaviour directly influence turbine and wind-farm performance [37], while alternative turbine geometries demonstrate the value of adapting designs to specific resource conditions [38]. Lazarevikj et al. investigated the site-specific design of a horizontal-axis wind-turbine blade. Using blade-element-momentum analysis and selected airfoil families, the study demonstrates how local wind conditions can be incorporated directly into aerodynamic turbine design. At portfolio level, wind and solar systems can be designed to improve temporal matching between generation and demand [39], while the value of demand-side management changes as variable renewable shares increase [40]. Accordingly, Halili et al. proposed a technology-agnostic framework for wind-solar hybrid systems that extends the assessment from resource complementarity towards temporal integration with demand. Their results demonstrate that the preferred renewable mix depends on whether the objective is generation smoothing, transition behaviour or minimisation of demand mismatch. Additionally, small hydropower provides an additional decentralised option as micro-hydropower systems can use multiple small axial-flow turbines where conventional large turbines are unsuitable [41] and pumps operated as turbines can provide a lower-cost alternative, although efficiency and stability depend strongly on geometry and operating conditions [42]. Ruttanawijit et al. reviewed hydrokinetic turbines for shallow-water applications, comparing design parameters, reported performance and technological maturity. Their analysis distinguishes technologies supported by field validation from configurations that have demonstrated high efficiencies mainly under laboratory conditions. Low-head rural hydropower can also be developed through alternative hydraulic structures. Techno-economic tools for small hydropower can support site-specific feasibility assessment and technology selection [43]. Hydraulic-turbine design can be strengthened through coupled numerical tools that link component geometry with predicted flow performance [44]. For that reason, Koua-Mbani et al. developed an analytical model of a submersible threshold hydraulic micro-dam for non-diverted low-head rivers. The approach is intended to assess rural hydroelectric production without relying on conventional river-diversion schemes.

HYDROGEN, ALTERNATIVE FUELS AND INDUSTRIAL DECARBONISATION

Alternative fuels remain relevant where direct electrification is technically difficult or where fuel-based infrastructure is likely to persist during the transition. Biogas and biomethane can replace fossil fuels while simultaneously providing a route for organic-waste utilisation [45] so locally available bioenergy resources can support decentralised energy supply where conventional infrastructure is limited [46]. Tiruneh et al. reviewed current practices and the potential for sustainable implementation of biogas technology in Eswatini. Drawing on experience with pilot installations, the authors identified technical, institutional, economic, climatic and socio-cultural factors affecting system performance and long-term use. The climate benefit of household biogas also depends strongly on the actual operation. Household digesters can show considerable variation in performance according to feedstock and operating practice [47], while methane that is produced but not effectively captured and used reduces the environmental benefit of the system [48]. For that reason, Ntaganda et al. measured biogas venting from household digesters in Rwanda. Their analysis showed that methane venting can partly offset the climate benefits of domestic biogas when gas production is poorly matched to household cooking demand. Liquid biofuels provide another route for using waste-derived resources. Waste-cooking-oil quality affects the characteristics of the resulting biodiesel [49], while combustion behaviour and pollutant emissions can vary substantially with blend composition and operating conditions [50]. Therefore, Hirabe et al. investigated biodiesel

produced from blends of Croton oil and waste cooking oil with carbon-based nanoparticles. The work evaluates production and physicochemical characteristics and illustrates the potential of combining non-food and waste-derived feedstocks with fuel-performance enhancement techniques.

Hydrogen extends renewable-fuel options towards mobility and sectors with stricter energy-density requirements; however, hydrogen and fuel-cell vehicles continue to face technical, infrastructure and market barriers [51]. Advanced energy-management strategies can coordinate fuel-cell and battery operation while accounting for energy use and degradation [52]. Consequently, Slouma et al. reviewed machine-learning applications in fuel-cell-based hybrid electric vehicles, with particular emphasis on energy-management strategies. The study compares approaches for coordinating fuel cells, batteries and other power sources while considering operating cost and component degradation. Moreover, aviation presents an even more demanding application, and hydrogen infrastructure is essential for linking production, storage and future end users [53], while the preferred hydrogen delivery configuration depends strongly on the scale and spatial concentration of demand [54]. Building on that, Schrötter et al. reviewed hydrogen uses in aviation across storage, infrastructure, propulsion and fuel-demand considerations. The study discusses alternatives including liquid hydrogen, cryo-compressed storage and hydrides together with their implications for future hydrogen-powered aircraft. These end-use applications depend strongly on low-carbon production. Regional renewable-resource quality strongly influences green-hydrogen potential [55], as production costs depend on the combined sizing and operation of renewable generation, electrolysers and supporting infrastructure [56]. At regional energy-system level, deep decarbonisation requires hydrogen deployment to be coordinated with renewable expansion, electrification and additional system flexibility [57]. Therefore, Samuel et al. optimised renewable-energy resources for green-hydrogen production in Lüderitz, Namibia. They used a genetic algorithm to determine combinations of wind, photovoltaic and battery capacity capable of supporting the targeted hydrogen-production system.

Industrial decarbonisation broadens the problem from fuel substitution to process design, technology retirement and resource integration. Numerical modelling of co-combustion in industrial kilns can resolve fuel-conversion and process effects relevant to cleaner high-temperature operation [58], while computational analysis of alternative-fuel co-firing in rotary kilns further demonstrates the role of detailed flow and combustion modelling in industrial decarbonisation [59]. Ghimire et al. examined the energy-transition potential of zigzag brick kilns using experimental analysis and computational-fluid-dynamics modelling. Thermal behaviour, airflow and emissions were assessed under different operating and fuel conditions to support cleaner operation of this energy-intensive industry. Existing combustion equipment also needs to be retired in an appropriate sequence. For example, boiler technologies can differ substantially in atmospheric emissions [60], so multi-criteria decision methods combine economic, technical and environmental considerations to prioritise interventions [61]. Ivezic et al. developed a fuzzy decision model for prioritising the decommissioning of environmentally harmful boilers in Serbia. The framework integrates financial, climate and air-pollution criteria, demonstrating how environmental considerations can be incorporated into retirement decisions. At process level, integrated ecodesign can combine technical, economic and environmental assessment [62]. Coupling optimisation with Life Cycle Assessment can reveal trade-offs that are not visible when only direct energy savings are considered [63]. Aquino et al. integrated Pinch Analysis with Life Cycle Assessment for the optimisation of industrial processes producing ammonia, bioethanol and biomass-based hydrogen. Their results demonstrated substantial opportunities for energy and cost reduction while also identifying environmental impacts associated with the additional process-integration equipment. Industrial residues can also themselves become part of new low-carbon pathways. For example, aluminium-containing waste can serve as a potential feedstock for hydrogen production [64], but thermochemical characterisation is necessary before industrial slags can be safely and effectively valorised [65].

In that respect, Al Najada et al. investigated hydrogen and aluminium hydroxide production from aluminium slag in Saudi Arabia. Seawater hydrolysis was combined with artificial-intelligence-based forecasting of future aluminium and slag availability to explore recovery of valuable products from an industrial waste stream.

BUILDINGS, ENERGY EFFICIENCY AND CLIMATE-RESPONSIVE DESIGN

Building decarbonisation increasingly combines passive design, renewable-energy production and adaptation to changing climatic conditions. Facade shading can reduce unwanted solar gains and cooling demand [66], while building-integrated photovoltaic technologies demonstrate that envelope components can simultaneously provide conventional building functions and generate electricity [67]. Due to this, Martínez-Rodríguez et al. optimised photovoltaic cantilevers on a Mediterranean university-building façade. The selected configuration combines shading with renewable electricity generation, reducing cooling requirements while producing electricity and modifying winter heating requirements. Moreover, solar energy can also supply industrial heat. The economics of low-carbon steam supply depend strongly on temperature level and infrastructure requirements [68] and hybrid renewable-heat systems can combine solar energy with more dispatchable sources to improve reliability [69]. Moikoyo et al. modelled and optimised a linear Fresnel reflector system for direct steam generation in Kenyan tea factories, where optical optimisation and thermal analysis were used to assess the ability of concentrated solar heat to substitute conventional process-energy sources. In residential applications, renewable supply should ideally follow demand reduction, as net-zero performance depends both on renewable capacity and on the temporal definition of the building energy balance [70]. For that, HVAC zoning and operation are important for reducing energy use while maintaining thermal comfort [71]. Allam et al. developed a two-stage optimisation procedure combining building-envelope efficiency improvements with photovoltaic and battery sizing for a Moroccan residential building, where the framework treats demand reduction and renewable-energy supply as interconnected stages of building design.

Climate change alters the conditions under which buildings will operate, as future warmer climates generally reduce heating requirements but increase cooling demand [72]. It is essential that building-energy modelling incorporate future weather scenarios during the design process [73]. Hence, Siakas et al. simulated the impact of future climate change on the energy demand of Finland’s building stock. The results indicate declining heating demand but increasing cooling requirements and overheating risks, demonstrating that climate change modifies rather than simply reduces building-energy challenges. Operational decarbonisation also needs to be evaluated from a lifecycle perspective as, for example, the environmental impacts of photovoltaic systems depend on technology configuration and balance-of-system components [74]. Environmental assessment of photovoltaic applications shows that PV deployment should be evaluated beyond electricity generation alone and should include wider system-level environmental effects [75]. Therefore, Ormuž and Žmak compared the life-cycle environmental impacts of residential rooftop photovoltaic electricity with the Croatian grid mix for a case study in Zagreb. Under the assumptions considered, rooftop photovoltaics showed substantially lower climate-change and fossil-resource impacts.

The urban scale further links building energy with vegetation, spatial planning and biomass supply. Vegetated roofs can interact with photovoltaic systems by changing local thermal conditions [76]. However, their environmental and economic feasibility depends strongly on climate and design assumptions [77]. Accordingly, Pirouz et al. investigated a Mediterranean bio-solar green roof combining vegetation and photovoltaic modules. Measurements demonstrated interactions between the green roof, photovoltaic generation and roof temperature and showed the potential of the combined approach for reducing surface temperatures in warm climates. Likewise, Urban Building Energy Models can estimate energy

demand across large building stocks [78] and Energy Performance Certificate data can support spatial identification of renovation priorities [79]. Schriefers et al. compared state-provided urban building-energy-model data with actual consumption data for Krefeld, Germany. Their analysis examined how spatial aggregation affects the usefulness of building-energy information for municipal energy assessment and planning. Biomass heating similarly requires a wider system boundary, as harvesting and transport can contribute substantially to the environmental burden of woody-biomass supply chains [80] and the sustainability of perennial biomass crops depends on climatic and cultivation conditions [81]. Due to this, Cvetinović et al. carried out a life-cycle assessment of beech wood chips and Miscanthus briquettes in Serbia. By accounting for harvesting, transport, processing and electricity supply, the study demonstrates why the sustainability of biomass heating depends on the complete supply chain rather than combustion alone.

WATER SYSTEMS, TREATMENT AND THE WATER-ENERGY NEXUS

Water sustainability spans efficient use, treatment, contaminant removal, energy consumption and resource recovery. Smart-irrigation models can support more efficient scheduling and redistribution of irrigation water [82], while detailed droplet models can represent transport processes and provide a basis for analysing droplet trajectories under controlled operating conditions [83]. Similarly, Arifjanov et al. analysed sprinkler-droplet trajectories using optical observation and mathematical modelling. High-speed tracking and image processing were combined with trajectory models to improve understanding of droplet motion and support more efficient irrigation-system design. Additionally, artificial intelligence is increasingly used in water-quality assessment. Machine-learning methods can estimate treatment indicators from operational data [84], while drinking-water quality is also influenced by treatment processes and operating conditions [85]. Therefore, Al-Ataby et al. applied machine learning to water-quality and potability prediction. The study demonstrates how class balancing, feature engineering and selection of appropriate machine-learning models can substantially improve water-quality classification. Wastewater is also increasingly viewed as a resource stream rather than only a waste. Bioelectrochemical systems can recover energy and nutrients from wastewater [86] and modified biochar produced from waste materials can adsorb phosphorus and other nutrients [87]. Wijaya et al. investigated simultaneous recovery of ammonium and phosphate from wastewater using magnesium-activated biochar produced from temple waste. Kinetic and equilibrium analyses, including experiments with real wastewater, connect waste valorisation with nutrient recovery.

Desalination provides one of the clearest connections between water and energy. Data-driven methods can significantly improve forecasting and coordination across complex supply chains [88]. Similarly, sustainability assessment highlights the importance of linking production, logistics and final demand [89]. Mohsen and Mohsen reviewed the integration of machine learning into desalination supply chains. Their analysis extends beyond optimisation of the desalination process itself to applications in forecasting, operation, logistics and other stages of water-production systems. Renewable-powered desalination also requires coordination of water demand with variable generation. Solar-powered reverse-osmosis systems need to be evaluated from energy, economic and environmental perspectives [90], while hybrid renewable generation and storage can improve water-production reliability [91]. Ben Rhouma et al. compared fuzzy-logic and mixed-integer-linear-programming energy-management strategies for a hybrid photovoltaic-wind reverse-osmosis desalination system. The study examines alternative approaches for coordinating variable renewable generation with desalination demand. Saline-water management can also focus on preventing intrusion before downstream treatment becomes necessary, since seawater intrusion can increase the need for energy-intensive desalination [92]. Predictive simulation has been used to assess control measures for seawater intrusion in coastal aquifers [93]. Al-Madhlom et al. instead

considered intervention at the hydrodynamic level, investigating seawater intrusion in estuary rivers using hydrodynamic modelling and proposing river-channel contraction as a potential means of modifying hydraulic conditions and limiting saline intrusion.

Adsorption provides a complementary route for contaminant removal, where dolomite can act as a low-cost sorbent for dissolved pollutants [94] and magnetic modification can improve adsorption performance and simplify separation after treatment [95]. Lopez et al. investigated magnetic nanoparticles supported on dolomite for nickel removal from water. The modified material showed improved adsorption performance compared with untreated dolomite, demonstrating the potential of enhancing abundant mineral substrates for wastewater treatment. Likewise, agricultural residues can serve as effective sorbents for dissolved contaminants [96] and construction and mineral residues can also be repurposed for removal of metal ions [97]. For that reason, Rocca et al. examined Moringa oleifera residues as sustainable adsorbents for nickel removal. Untreated and chemically modified materials were compared, illustrating both the potential of the residue as a low-cost adsorbent and the trade-off between modification performance and processing complexity. Water quality should also be monitored after storage and dispensing as water quality can change while passing through collection, treatment and distribution systems [98]. Changes in water quality can also occur within distribution and dispensing systems, particularly through interactions with system materials [99]. Tarnini et al. assessed microparticle contamination and water-quality parameters in hot and cold dispenser water. Water from dispensers was compared with the original sources to determine whether dispenser systems and post-treatment processes modify water quality. On the other hand, rural water-pumping technologies can generate direct socioeconomic benefits when they are adapted to local resource and community conditions [100], but technology selection must reflect local hydrogeological conditions and available maintenance capacity [101]. Therefore, Santillan Gomez et al. experimentally evaluated rope pumps and manual volumetric pumps for groundwater extraction in Peru. Both systems were found applicable within particular groundwater-depth ranges, with their relative performance changing according to well conditions.

Thermal desalination provides an alternative pathway where low-grade heat is available. Low-temperature or rejected heat can be used as an energy source for freshwater production [102], but heat-and-mass exchanger performance can change significantly with process parameters and fouling conditions [103]. Therefore, Sereda et al. experimentally investigated optimal operating conditions for a film humidifier in a small-scale thermal desalination system. A thermodynamic model was validated against measurements and used to assess the parameters influencing humidification performance. Related heat-and-mass-transfer processes also determine cooling-tower performance. Heat- and mass-transfer performance is strongly influenced by operating temperatures and process conditions [104], while surface geometry and operating parameters can materially alter transfer coefficients [105]. For that reason, Obregon-Quinones et al. investigated the effect of operating conditions on the volumetric mass-transfer coefficient in a laboratory cooling tower with perforated inclined plates. The experiments identified inlet water temperature and liquid flow among the principal variables influencing mass-transfer performance. Wastewater-treatment models are meanwhile being extended towards emerging contaminants. Process optimisation can reduce the energy requirements of wastewater treatment [106], but conventional biological treatment may require additional mechanisms when newer micropollutants are considered [107]. Vilela et al. modelled silver-nanoparticle removal in wastewater-treatment plants. Conventional activated sludge, anaerobic-oxic and Bardenpho configurations were compared with respect to nanoparticle removal and nitrogen-treatment behaviour under different operating conditions. At the broadest scale, Water-Energy-Nexus studies reveal links between resource use and Sustainable Development Goals [108]. Effective Water-Energy-Food governance also depends on institutional coordination as well as physical resource flows [109]. On those grounds, Gual et al. examined temporal interactions within the Water-Energy-Food-Ecosystem nexus across

the 27 European Union Member States. Their analysis used data from 2001-2023 and investigated relationships among Sustainable Development Goals related to food, water, energy and ecosystems.

ENVIRONMENTAL PROTECTION AND CLIMATE ADAPTATION

Environmental monitoring increasingly combines conventional measurements, artificial intelligence and spatial analysis to understand how pollutants move through connected systems. Water-management measures are important for reducing pollutant loads originating from agricultural activities [110]. Environmental assessment of intensively cultivated areas shows that agricultural activity can produce measurable pressures on surrounding soil and ecosystem quality [111]. Therefore, Diankha et al. investigated chemical pollution from agricultural drainage in the Djoudj National Bird Park in Senegal. Their measurements identified contamination by heavy metals and pesticide residues and highlighted the role of agricultural drainage pathways in transporting pollutants. On the other hand, plastic pollution requires different monitoring approaches. Deep-learning systems can detect small objects in complex visual environments [112] and modern object-detection architectures can retain useful performance under variable lighting and partial occlusion [113]. Khriss et al. developed an improved deep-learning method for detecting marine plastic litter. The modified object-detection architecture addresses challenges including reflections, small objects and partial occlusion in marine environments. Aerial observation extends these methods to larger spatial scales. Plastic-derived particles can persist and move between environmental compartments [114], so automated classification can improve characterisation of heterogeneous waste and litter streams [115]. Grari et al. assessed YOLO models for plastic-litter quantification using drone imagery of coastal beaches. The comparison demonstrated high counting performance and the potential of automated aerial-image analysis for monitoring marine litter.

Microplastics and heavy metals illustrate the persistence of contaminants once they enter aquatic systems. Microplastics can accumulate in urban rivers under the influence of multiple source categories [116] and wastewater and surface-water pathways can transport plastic particles between environmental compartments [117]. Darsini et al. identified and characterised microplastics in urban rivers of Surakarta, Indonesia. Microscopy and ATR-FTIR measurements were used to analyse microplastics in water and sediments across sites affected by different urban and agricultural activities. Contaminants can remain associated with natural environmental matrices through adsorption and desorption processes [118], while interactions between heavy metals and aquatic biomass illustrate the potential for uptake and accumulation within biological systems [119]. For that reason, Shehu et al. monitored mercury concentrations in selected marine biota from Vlora Bay, Albania. While overall concentrations were relatively low, spatial differences associated with historically industrialised areas underline the importance of continued environmental monitoring.

Environmental protection increasingly overlaps with climate adaptation and water governance. Water-footprint analysis can reveal how consumption in one region creates resource pressure elsewhere [120] and water-resilience assessment highlights vulnerabilities where critical activities depend strongly on freshwater availability [121]. Ore Areche et al. examined hydrosocial connectivity from Andean headwaters to coastal landscapes through water-footprint, governance and ecosystem perspectives. The study links pressures such as inefficient irrigation, cryosphere loss and fragmented governance with potential nature-based and traditional water-management responses. Moreover, local adaptation requires decision-support systems that balance several sustainability dimensions. Municipal sustainability assessment benefits from multiple indicators rather than a single performance measure [122], while local climate commitments require practical frameworks that translate strategic objectives into specific interventions [123]. Based on this, Hetesi et al. developed a sustainability-based monitoring and decision-support framework for local climate adaptation

through water-retention measures. Their method combines site-selection criteria and monitoring while preventing strong performance in one sustainability dimension from completely compensating for poor performance in another.

River management presents a related multi-objective challenge. Basin sustainability requires environmental conditions to be reconciled with socioeconomic water use [124], as changes in flow can greatly affect dissolved oxygen and other indicators of river-water quality [125]. Soekarno et al. extended environmental-flow assessment in regulated rivers by integrating hydraulic modelling, habitat suitability and water quality. Applied to the Citarum River, the study demonstrates that ecological habitat and water-quality objectives can imply substantially different flow requirements. Similarly, green infrastructure and Nature-Based Solutions extend adaptation from individual measures to urban and basin scales. Green-roof design influences rainfall interception and hydrological performance [126] and ecosystem services can significantly change the cost-benefit balance of sustainable drainage systems [127]. Therefore, Busch et al. investigated the hydrological functioning of a bromeliad green roof, focusing on rainfall interception and evapotranspiration. Their prototype experiments provide information relevant to the use of green roofs as compensatory urban-drainage measures. Blue-green infrastructure can also reduce flood impacts while generating additional urban sustainability benefits [128]. Urban vegetation can influence building and neighbourhood environmental performance [129]. For that, Jurić et al. developed guidelines for implementing Nature-Based Solutions in the Danube River Basin. The framework considers green, blue and hybrid infrastructure together with the environmental and societal challenges that restoration measures are intended to address.

CIRCULAR ECONOMY, WASTE AND RESOURCE RECOVERY

The circular economy shifts attention from waste treatment after generation towards management of materials across their complete lifecycles. Difficult-to-recycle plastics can be transformed into useful chemical or energy products [130], but organisational and institutional barriers can prevent technically feasible circular measures from being adopted [131]. Sumarmi et al. investigated relationships between green products, green packaging, purchasing decisions and green-economy outcomes among micro, small and medium-sized enterprises in East Java's tourism sector. Their structural-equation analysis highlights the role of purchasing behaviour in connecting circular product strategies with economic outcomes. Stakeholders can also perceive barriers to circularity differently. Ecodesign can translate circular-economy principles into practical measures for more efficient resource use [132]. However, building-sector studies show persistent differences between circular-economy theory and implementation [133]. Mihajlović et al. analysed circular-economy opportunities and barriers in Serbia using the analytical hierarchy process. Companies and experts assigned different priorities to social, financial and institutional barriers, demonstrating that stakeholder groups can perceive the obstacles to circular transition differently.

Material valorisation is also expanding into new applications. Additive-manufacturing technologies can increasingly process non-conventional feedstocks [134], where biological and industrial residues can provide useful secondary materials after appropriate preparation [135]. Gebregewergs et al. investigated the feasibility and mechanical performance of residues from Prosopis juliflora as feedstock for additive manufacturing. Different plant fractions and manufacturing processes were assessed, demonstrating that material suitability depends strongly on both residue type and processing route. Still, the construction sector represents a much larger material-stock problem. Circularity indicators are increasingly used to quantify material and product loops [136], while construction and demolition waste recovery is strongly influenced by market conditions and practical implementation challenges [137]. Mosgaard et al. studied circular practices in eight Danish construction companies. Their cases show that circularity can emerge in response to operational challenges rather than only through

predetermined strategies and emphasise the contribution of employees and end users to extending product and material lifetimes.

Thermal-treatment and industrial residues illustrate the transition from disposal towards recovery at the end of material lifecycles. Heavy-metal behaviour must be controlled before incineration ash can be safely reused [138], so modern waste-to-energy systems increasingly seek both energy and secondary-material recovery [139]. Kouame et al. compared dry and quenched incinerator bottom ash from the perspective of environmental protection and resource valorisation. Differences in particle-size distribution and trace-metal behaviour provide information relevant to the safe reuse of these residues. Municipal waste policy can alter material flows before treatment occurs, so the attractiveness of resource-recovery pathways depends on economic and market conditions [140]. Detailed information on waste generation and transfers can improve municipal system optimisation [141]. Pereira and Cunha evaluated implementation of a Pay-as-You-Throw system for urban waste management in Guimarães, Portugal. The results associate the system with reduced landfill disposal and improved recycling as well as economic and behavioural effects relevant to municipal circular-economy strategies. Some industrial residues can additionally contribute to carbon management. Carbon-capture technologies create their own lifecycle material and energy burdens [142], so capture, utilisation and storage pathways therefore need to be coordinated with wider industrial-transition strategies [143]. Watjanatepin et al. proposed a dynamic Life Cycle Assessment framework for mineral carbonation of steel slags used as a carbon-capture, utilisation and storage technology in agriculture. The framework accounts for emissions from the treatment process and subsequent carbon uptake, allowing environmental performance to be considered over time.

SUSTAINABLE PLANNING, GOVERNANCE, SOCIETY, DIGITALISATION AND EDUCATION

The technological transitions described in the preceding chapters depend equally on institutions, information, behaviour and planning. Digitalisation can support sustainability assessment and operational management, although digital systems themselves consume resources. Digital technologies can contribute to sustainability only when their material and energy requirements are also considered [144]. Public-sector digitalisation can reduce administrative burdens while creating new requirements for information infrastructure [145]. Eisinger Balassa and Buics investigated sustainable digital transformation through the example of a university enrolment process. Process mapping identified reductions in administrative effort and material use while also demonstrating that digitalisation does not automatically produce sustainability benefits when information flows and information-technology practices are poorly designed. Data-driven methods also allow new sustainability indicators to be derived from existing datasets. Socio-economic and financial indicators can reveal systematic differences in sustainability performance [146] and corporate-level emissions benchmarking illustrates how firm-level datasets can be structured to compare sustainability performance across companies [147]. Alsayyad and Fadel applied machine-learning regression to the prediction of Environmental, Social and Governance scores using firms' financial indicators. Their analysis demonstrates the potential of financial data and machine-learning methods to support ESG-performance assessment in the oil and gas sector.

Technology adoption nevertheless remains dependent on public attitudes. Perceptions of low-carbon fuels and technologies vary with knowledge, demographic characteristics and environmental awareness [148] and attitudes towards energy transitions are also shaped by wider social and economic concerns [149]. Pambudi et al. modelled public acceptance of biofuel in Indonesia using structural-equation and mediation analysis. The study shows how knowledge, attitudes and perceptions interact in shaping acceptance and highlights the importance of behavioural factors in alternative-fuel adoption. Climate policy similarly

interacts with broader development objectives. Climate measures can create both synergies and trade-offs with Sustainable Development Goals [150], so sectoral climate strategies therefore need to be assessed beyond their direct mitigation effect [151]. Zdraveva et al. analysed how agriculture and forestry climate policies contribute to sustainable development in North Macedonia. Using a participatory approach, the study identifies synergies and trade-offs between sectoral climate measures and broader Sustainable Development Goals.

Integrated planning becomes essential as mobility, electricity and urban systems converge. Sustainable urban-mobility planning needs to consider transport demand, land use and institutional capacity together [152], so spatial planning of transport infrastructure should coordinate accessibility with wider urban development [153]. Matus Acuña et al. developed a multi-model platform for assessing sustainable electromobility futures in Chile. The platform connects vehicle adoption, urban planning, transport, electricity-distribution networks and generation expansion, enabling interactions between sectors that are often modelled independently to be assessed together. Long-term energy planning faces the same need to reconcile competing objectives. Energy-system investment pathways are strongly influenced by the drivers used to represent the transition, with policy measures potentially having a larger effect on decarbonisation than changes in technology or fuel costs [154]. Multi-objective optimisation can represent trade-offs among alternative transition pathways [155] and participatory approaches can incorporate stakeholder priorities and local knowledge into energy planning [156]. As energy-system models become more detailed, transparent model selection is also increasingly important; capability-based multi-criteria assessment can help identify modelling tools that best correspond to the requirements of a specific planning problem [157]. Therefore, Cabrera et al. developed a fuzzy multi-objective energy-planning tool for sustainable energy mixes in Colombia. The approach combines economic and carbon-dioxide objectives with evaluation of economic, technical, environmental and social criteria to support energy-planning decisions involving competing objectives.

Education forms the final component because integrated sustainability planning requires professionals able to work across disciplinary boundaries. Practical sustainability education can strengthen learning by connecting classroom instruction with real-world interventions [158] and living-lab approaches provide a framework for combining education, experimentation and local sustainability projects [159]. Schmitt et al. examined Living Lab approaches to sustainability education in Rwanda and Côte d'Ivoire. Their work connects education, community involvement and practical renewable-energy and water-treatment applications within a common capacity-building framework. Sustainability competencies also depend on how students acquire and apply knowledge. Learning preferences can influence how effectively scientific and sustainability concepts are communicated [160]. Future STEM professionals increasingly require combinations of technical, interpersonal and systems-thinking capabilities [161]. Thus, Abina et al. examined scientific empathy and learning preferences in European higher education. Surveys conducted across five institutions showed preferences for visual and hands-on learning and differences between preferred approaches for sustainability and entrepreneurship topics. Active learning provides another route for developing interdisciplinary capabilities. Team-based and problem-based learning can strengthen engagement with sustainability-oriented engineering problems [162], while interdisciplinary teaching can improve the ability of students to connect technical design with environmental and societal consequences [163]. Building on that, Noronha Rodrigues et al. evaluated team-based learning in Green Infrastructure education. Team assessments outperformed individual assessments, while student responses highlighted high engagement and the importance of instructor facilitation in interdisciplinary sustainability education.

CONCLUSION

Volume XIV of the Journal of Sustainable Development of Energy, Water and Environment Systems provides insights into the latest research regarding topics of Renewable Energy Technologies and Power Systems, Hydrogen, Alternative Fuels and Industrial Decarbonisation, Buildings, Energy Efficiency and Climate-Responsive Design, Water Systems, Treatment and the Water-Energy Nexus, Environmental Protection and Climate Adaptation, Circular Economy, Waste and Resource Recovery and Sustainable Planning, Governance, Society, Digitalisation and Education. Taken together, the contributions highlight recent progress and the continuing need for an integrated transition towards a more sustainable, innovative, and holistic energy, water, and environment paradigm. In this work, novel methods, concepts, and solutions are presented, not only from JSDEWES Volume XIV but also from special issues from the recent scientific literature and novel research from recent SDEWES Conferences.

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This is editorial coauthored by Editor-in-Chief **Neven Duić**.