Energy Conversion and Management: X 30 (2026) 101670

Contents lists available at ScienceDirect

Energy Conversion and Management: X

journal homepage: www.sciencedirect.com/journal/energy-conversion-and-management-x

Systemic pathways for the decarbonization of energy systems☆,☆☆

A B S T R A C T

A shift in the global decarbonization discourse is evident—from optimizing isolated components to designing interoperability across energy flows, materials, and governance frameworks. This Editorial introduces selected papers published in the special issue of Energy Conversion and Management: X, collectively representing a mature phase of sustainability research: renewable integration, digitization of thermal processes, waste heat valorization, and the development of fair net-zero governance models. It is shown that system-level decarbonization requires coordinated design across spatial, temporal, and institutional dimensions. The special issue is structured around four integrative themes: (1) heat as a recoverable resource; (2) storage as temporal infrastructure; (3) digitalisation as operational decarbonisation; and (4) governance for credible net-zero trajectories.

1. Introduction: from efficiency to integration

The **SDEWES** research community has, over the 2022–2024 period, provided a platform for presenting key contributions to the integration and decarbonisation of energy systems [1]. While collaboration with *Energy Conversion and Management* spans more than a decade, the more recent sequence of Special Issues published in *Energy Conversion and Management: X* has rapidly matured into a stable and thematically coherent publication framework. Two consecutive editorials published in 2022 and 2023 articulated a shared methodological trajectory, signalling a shift from isolated technological efficiency towards coordinated, cross-sectoral system integration. The 2022 editorial [2] emphasised industrial decarbonisation, waste-heat valorisation, micro-scale ORC systems and renewable-integration strategies, while the 2023 editorial [3] expanded the scope to include renewable-energy communities, AI-driven optimisation, urban nature-based solutions and infrastructure planning under climate-change constraints.

Earlier ECM and ECMX editorials further codified this methodological grammar, in which system credibility is engineered through synchronisation across energy vectors, spatial scales and institutional layers rather than through isolated efficiency gains [4,5]. The present Special Issue continues along this trajectory by consolidating recent advances into a coherent narrative of integrated, system-level decarbonisation.

Over the past years, this collaboration has matured into a stable research pipeline in which a well-established international research community functions as a generator of high-quality, thematically coherent manuscripts, while *Energy Conversion and Management* (ECM) and *Energy Conversion and Management: X* (ECMX) provide the publication architecture that consolidates these contributions into recognisable scientific trajectories. Earlier Special Issues emphasised that this community operates as a long-standing global research network, continuously expanding methodological and thematic frontiers in energy, water, and environmental systems—an aspect repeatedly highlighted in previous editorials that noted the sustained growth of a worldwide research team emerging from recurring international collaborations. Likewise, the ECMX Special Issues of 2022 and 2023 served not merely as publication outlets but as structured venues that organised selected contributions into coherent thematic narratives, reinforcing the emerging role of integrative, multi-vector thinking in system decarbonisation. Through this continuous cycle—community consolidation, thematic synthesis, and Special Issue publication—the ECMX-led framework has evolved into one of the most dynamic and conceptually productive conference–journal ecosystems in the energy-systems field.

Within this framework, ECMX has become the natural home for contributions that span technologies, temporal scales, and governance layers. Its Special Issues typically organise 15–25 manuscripts into structured narrative constructs—rather than unstructured collections—so that thermal systems, hydrogen integration, storage, digitalisation, spatial planning, and governance can be read as interacting infrastructure layers. The authors of the present editorial draw on long-standing engagement with this research ecosystem and with ECM/ECMX—as contributors, reviewers, guest editors, and organisers across multiple Special Issues—and collectively represent several decades of research in thermodynamics, heat transfer, hydrogen systems, storage modelling, and urban-energy policy. Their role here is not merely to summarise manuscripts but to situate them within a maturing decarbonisation narrative in which research communities and Special Issues

☆ This article is part of a special issue entitled: 'SDEWES 2024_ECMX' published in Energy Conversion and Management: X.

☆☆ This editorial summarises the most significant contributions from the SDEWES 2024 Special Issue in *Energy Conversion and Management: X*, reflecting the evolution of energy systems research from technological efficiency towards systemic integration.

https://doi.org/10.1016/j.ecmx.2026.101670

Available online 13 February 2026
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co-produce both knowledge and continuity.

Conceptually, this research community has shifted over the past decade from analysing isolated efficiency improvements toward exploring integrated, multi-vector and dynamically coordinated decarbonisation pathways. Classical engineering approaches, which typically optimised technologies in isolation, are progressively being replaced by models that recognise that system-wide performance emerges from the interactions among thermal, electrical, material and digital infrastructures. This shift—from optimisation to orchestration—defines the analytical backdrop for the 2024 Special Issue. Deep decarbonisation outcomes are now understood to depend on the coordinated use of energy-system and power-grid models under unified planning horizons and harmonised temporal resolutions, as illustrated by Lotze et al. [5]. Beyond technology co-optimisation, their results confirm that transitions of hardware (heat pumps, battery energy storage systems, sCO_2 and ORC cycles) must be synchronised with control, market and infrastructure constraints at compatible temporal granularities. More recently, Kılkış et al. [6] have characterised the sustainable development of energy, water and environment systems itself as a key opportunity for decarbonisation, reinforcing the view of this research ecosystem as a testbed for systemic, multi-vector transitions.

Recent literature exemplifies this systemic turn across spatial scales. At the community scale, Calise et al. [7] show that the thermo-economic feasibility and renewable self-sufficiency of an existing residential district in Italy depend on coherent configuration, thermal flexibility and high-fidelity dynamic scheduling rather than on technology sizing alone. Extending this logic to mixed-use urban fabrics, Marrasso et al. [8] assess alternative energy-system configurations for Positive Energy Districts and introduce composite performance indicators that jointly capture energy autonomy, emissions, and operational interactions between uses. At the building level, Olympios et al. [9] propose a holistic optimisation framework for the co-design and operation of electricity, heating, cooling and hydrogen technologies, explicitly treating buildings as multi-vector hubs rather than single-service loads. Jahanbin et al. complement these insights by demonstrating that hybrid battery–hydrogen storage integration becomes cost-optimal only when PV share, storage inertia, conversion dynamics and stochastic demand flexibility are jointly optimised within a unified planning horizon [10]. Bartolucci et al. further demonstrate that the performance of combined heat and power systems depends not only on component efficiencies but on design–operation coupling driven by real load data, storage behaviour and biogenic-fuel integration [11]. Kim et al. show that lignin depolymerisation dynamics depend on synchronised reaction conditions, solvent polarity and catalyst–medium interactions, confirming that catalytic upgrading is fundamentally a multi-parameter synergy problem [12].

Thermal energy storage (TES) is increasingly framed as temporal infrastructure rather than as a passive buffer within fixed system boundaries. At the materials scale, Ryšavý et al. and Čespiva et al. show that metastable phase-change materials deliver reliable performance only when crystallisation pathways, cycling stability, and long-term degradation are jointly optimised, effectively treating time as an explicit design variable [13,14]. At the plant scale, Mersch et al. develop a unified thermo-economic framework for adiabatic compressed-air energy storage that compares packed-bed and liquid TES concepts across power levels from 10 to 100 MW and discharge durations of up to 9 h [15]. Their results—round-trip efficiencies reaching approximately 76% and energy capital costs close to 140 USD/kWh for dual packed-bed configurations—demonstrate that techno-economic feasibility is governed by coordinated multi-medium energy pathways rather than by any single storage technology in isolation.

At the district scale, Vivian et al. extend this temporal perspective into the spatial domain by analysing PV self-consumption in fifth-generation district heating and cooling networks under renewable-energy-community schemes [16]. Their results show that electrical and thermal domains must be co-designed at district level if PV sharing, heat pumps, and low-temperature networks are to achieve meaningful gains in both self-consumption and CO_2 reduction [16]. Taken together, these studies position TES as a multi-medium, multi-scale temporal infrastructure, fully aligned with contemporary system-level approaches to integrated, multi-timescale optimisation in energy systems research.

District heating and cooling (DHC) research further consolidates this coupled temporal–spatial logic. Furubayashi and Kudo map low-temperature DHC deployment in Akita City, illustrating how waste-heat sources, snow storage and distributed heat pumps can be orchestrated as a single, seasonally adaptive infrastructure [17]. In parallel, Moradpoor et al. analyse the integration of industrial hydrogen production with district heating networks in cold climates under different building-renovation levels, showing that waste-heat availability, renovation depth and network temperature regimes jointly determine the cost-effective coupling margin between electrolysers and DHC systems [18]. Guarino et al. analyse road-integrated seasonal thermal storage and show that pavements can operate as embedded solar-thermal collectors, delivering substantial CO_2 reductions while re-using urban surfaces as energy assets [19]. At the subsurface scale, Pavković et al. show that deep geothermal wells—accessed via retrofitted deep-drilling rigs and intended for high-temperature applications—can underpin baseload heat supply and provide high-temperature reservoirs suitable for hybridisation with ORC or Kalina cycles [20]. In parallel, Girgibo et al. use long-term monitoring and ARIMA-based forecasting in the Suvilahti district (Vaasa, Finland) to show that sediment temperatures track rising water temperatures with a lag, implying an increasing technical potential for sediment-heat utilisation under climate-change scenarios [21]. Together, these studies recast cities, roads, sediments and deep wells as spatially distributed, dynamically evolving thermal resources that must be integrated into systemic, cross-vector planning rather than treated as static, stand-alone assets.

Industrial decarbonisation exhibits the same degree of systemic interdependence observed across integrated energy systems. Farooq et al. demonstrate that catalytic pyrolysis of furniture-industry residues depends on the coordinated interaction of catalyst microstructure, vapour–solid contact dynamics and secondary cracking pathways [22]. Kim et al. show that lignin upgrading requires simultaneously optimised solvent polarity, hydrogen-donor availability and catalyst acidity, with product yields emerging from the coupling of homogeneous and heterogeneous reaction environments [12]. Valizadeh et al. conclude that pyrolytic conversion over spinel-type oxides is governed by pore architecture, oxygen-vacancy mobility and redox cycling, which together regulate deoxygenation and aromatisation pathways [23]. Khani et al. reveal that hydrogen production from furniture waste via catalytic gasification hinges on synchronised gasification temperature, spinel crystallinity and metal–support interactions that modulate reforming and water–gas-shift reactions [24]. Sharma et al. similarly highlight the need to integrate material and energy flows by showing that bioethanol production from wastepaper delivers meaningful circularity benefits only when thermally and operationally embedded within broader process-energy systems [25].

Advanced thermodynamic pathways reinforce this systemic perspective. Li et al. [26] introduce a performance-recovery coefficient to characterise recuperator behaviour in supercritical CO_2 Brayton cycles, demonstrating that cycle performance depends on tightly coupled thermal and hydraulic parameters. In parallel, Wang et al. show that convective enhancement in compact heat exchangers based on triply periodic minimal-surface geometries emerges only when geometric curvature, flow redistribution and turbulent transport are jointly optimised [27]. Collectively, these studies underscore that industrial decarbonisation performance—whether in catalytic conversion, hydrogen production, or advanced power cycles—is governed by coupled geometric, material and thermodynamic interactions, a principle that also underpins recent research on hydrogen–CO_2 hybrid storage concepts and reversible electro-thermal cycles [28].

Digitalisation forms the third cornerstone of the integration paradigm. Benić et al. demonstrate that predictive hydraulic control substantially outperforms manual or rule-based operation in drilling and off-road machinery [29]. Coraci et al. show that deep reinforcement learning significantly improves thermal-energy management in buildings [30], while Maturo et al. introduce multi-level predictive control strategies that optimise the coordination of phase-change materials with building-integrated renewables [31]. Collectively, these studies confirm that predictive optimisation, digital twins and AI-enabled control architectures are becoming fundamental operational enablers of decarbonisation. At the system-planning scale, Parrado-Hernando et al. extend digital integration to long-term modelling by developing a method that transfers hourly-resolution energy-system dynamics into annual integrated-assessment frameworks—enabling embodied-carbon accounting, flexibility representation and multi-vector coordination to be consistently embedded into strategic decarbonisation models [32]. Most recently, Parrado-Hernando et al. [33] apply this methodology to the EU27 region and demonstrate that preserving temporal fidelity of generation-conversion-storage interactions is critical for integrated-assessment models to yield credible net-zero infrastructure pathways, confirming that hardware-level transitions must evolve coherently with multi-resolution, control-aware planning horizons.

Building-envelope research reinforces the same integrative logic. Spanodimitriou et al. show that passive retrofits achieve energy savings exceeding 40% only when climatic conditions, orientation and urban morphology are jointly considered—highlighting that envelope performance is a coupled climatic–spatial problem rather than a material-property issue [34]. They provide complementary evidence for hot-climate retrofits, demonstrating that passive strategies in the Iranian context deliver robust savings only when materials, occupancy patterns and microclimate effects are simultaneously modelled. Vassiliades et al. demonstrate that active solar façades influence both indoor comfort and local microclimate, explicitly linking building operation with urban-scale boundary conditions [35]. Herrando et al. further reveal that effective renovation strategies must integrate institutional constraints and regional planning frameworks alongside technical measures [36].

Taken together, these studies position the building envelope not as a static architectural boundary but as an interoperable energy–climate–urban interface, governed by cross-domain interactions and coordinated design across scales—an approach consistent with contemporary system-level perspectives on decarbonisation that emphasise synchronisation across physical, operational and institutional domains rather than isolated component optimisation.

Finally, biomass-to-energy and hybrid thermochemical pathways show that circular resource flows depend on integrated reaction chemistry, heat transfer and supply-chain optimisation. Insyani et al. show that hydrodeoxygenation performance depends on catalyst structure and solvent interactions [37], while Ling et al. analyse biomass oxygen-fuel circulating fluidised-bed systems with integrated sCO_2 cycles [38]. Plata et al. further demonstrate that biodiesel produced from palm-based waste cooking oils exhibits strong dependency on prior cooking conditions, confirming that upstream thermal use influences downstream fuel quality and conversion efficiency [39]. Erić et al. highlight the importance of coupled devolatilisation kinetics and reactor design [40]. Stančin et al. complement this by showing that the co-pyrolysis of polyurethane foam and sawdust exhibits strong synergistic effects, with plastic content significantly influencing bio-oil yield and composition—emphasising the role of feedstock formulation in waste-to-energy systems [41]. Zhang et al. further show that chars produced under elevated pressure exhibit complex fragmentation and mineral transformation behaviour during combustion, highlighting how pressure history shapes ash behaviour and reactivity in solid-fuel systems [42]. These insights align with SDEWES 2024 contributions on electrolysis-enhanced renewable hydrogen and CO_2–hydrogen hybrid systems [43].

Across all domains—thermal systems, hydrogen integration, TES, DHC, industrial processes, bioenergy, spatial planning, digitalisation and governance—a single conclusion emerges: systemic decarbonisation requires synchronisation, not selection. The 2024 SDEWES–ECMX Special Issue embodies this paradigm through nineteen manuscripts spanning renewable electrolysis, heat decarbonisation, transport optimisation, system integration, digitalisation, energy communities, governance structures and circular planning. Together, they reflect a mature conceptual framework in which technologies, networks and institutions operate as coordinated infrastructures across space, time and decision layers. The decarbonisation challenge is no longer identifying optimal components—it is engineering coherent systems.

2. Heat as a recoverable resource

The second thematic cluster focuses on the transformation of heat from a passive by-product into a fully recoverable and redistributable energy vector. Modern decarbonisation increasingly relies on harnessing local, low-grade, and seasonally variable thermal resources—including wastewater, industrial effluents, geothermal gradients, sediment heat, and latent heat storage materials.

Furubayashi and Kudo illustrate this shift through their district heating and cooling model for Akita, Japan, where municipal waste heat and stored snow act as complementary thermal assets [17]. Even under moderate linear heat density, the integrated network outperforms both kerosene boilers and stand-alone heat pumps, demonstrating how climatic adversity becomes a leverage point for system-wide optimization.

Spatially similar principles guide the work of Guarino et al., who couple road-integrated thermal collectors with borehole thermal energy storage (BTES) for school heating in Southern Italy [19]. Their TRNSYS simulations reveal substantial CO_2 savings and highlight the latent potential of urban surfaces to operate as diffuse solar-thermal collectors embedded within existing city infrastructure.

Complementary low-carbon technologies exhibit similar integration requirements: Ciappi et al. demonstrate that the performance stability of oscillating-water-column systems depends on the coherent co-design of chambers, turbines, and power-conditioners—mirroring the systemic coupling challenges seen in solar-thermal and geothermal infrastructures [44].

New evidence further reinforces the role of low-temperature network architectures. Vivian et al. analysed fifth-generation district heating and cooling (5GDHC) networks and demonstrated that such networks effectively exploit waste or renewable low-temperature heat when integrated with distributed heat pumps, although seasonal mismatch between PV output and heating demand limits electrical self-consumption [16]. Their results confirm that electricity-sharing models can complement thermal-recovery strategies, especially in urban areas where low-cost renewable or waste heat is abundant.

D'Agostino et al. extend this solar-integration perspective by showing that fixed and tracking PV configurations yield markedly different NZEB performance depending on heating-demand profiles and balancing strategies, highlighting the need to co-optimise solar geometry with building thermal characteristics [45].

Bilardo, Ferrara and Fabrizio likewise demonstrate that solar-driven cooling in nearly-zero-energy buildings performs optimally only when climatic variability, storage sizing, and façade interactions are co-designed—reinforcing that thermal management is inherently a systems problem [46].

Additional synergies emerge at the solar-conversion interface: Altegoer, Hussong and Lindken demonstrate that back-mounted chimney-type evaporative cooling can improve PV efficiency, illustrating how thermal-management strategies enhance electrical generation within integrated heat–power systems [47]. Extending the control-driven temporal lens into distributed thermal infrastructure, Wei et al. show that model predictive control orchestrates district thermochemical reservoirs with storage and cost performance emerging from forecast-aligned control horizons [48]. Scaling the same systemic substitution logic to national grids, Sousa et al. demonstrate that resource substitution and flexibility valuation reshape renewable-system investment priorities, reconfirming that system credibility is governed by coordinated temporal–spatial orchestration rather than capacity choice alone [49].

Material-oriented approaches strengthen the thermodynamic foundation of heat recovery. Recent research by Čespiva, Ryšavý, Charvát and co-authors shows that sodium acetate trihydrate (SAT) latent-heat systems exhibit pronounced path dependence: crystallisation stability is governed not only by material composition but also by environmental temperature, thermal cycling history and heat-exchanger geometry [13,14]. These studies demonstrate that SAT-based latent-heat storage operates reliably only when phase behaviour, module design and charging–discharging regimes are jointly optimised. This evidence reinforces the broader system-level view that thermal storage reliability emerges from coordinated thermophysical, geometric and operational design, rather than from materials selection in isolation.

Egea et al. confirm this thermo-material interdependence for domestic hot-water applications, showing that scraped-surface heat exchangers enhance latent-heat extraction only when geometric, rheological and thermal-cycling parameters are co-engineered [50].

A further thermo-biochemical perspective is provided by Wang et al., who develop a 3D multiphysics model of biomass-pile self-heating that couples microbial metabolism, low-temperature oxidation, moisture migration and porous-media convection [51]. Their simulations reproduce the two-stage thermal evolution observed in large outdoor piles—an initial microbiological warming phase up to ~ 320 K followed by oxidation-driven escalation or stabilisation depending on ventilation and moisture pathways. By identifying the parametric thresholds that separate benign heating from runaway ignition, the study demonstrates that biomass heat behaviour is not an intrinsic material property but a coupled thermo-biochemical system whose stability must be engineered through integrated modelling of reaction kinetics, transport processes and storage geometry. This adds a crucial thermal-risk dimension to the SDEWES perspective that recoverable and residual heat must be governed through systemic, rather than component-level, controls.

A complementary perspective on heat-system performance comes from the analysis of residential combustion processes. Szramowiat-Sala et al. develop neural-network and LSTM-based predictive models that link fuel type, combustion technology and operational output with real-time flue-gas composition, including CO_2 and organic gaseous compounds (OGC) [52]. Their results demonstrate that emission profiles in small-scale heat generators are highly system-dependent and can only be accurately captured when combustion dynamics, airflow patterns and fuel characteristics are jointly modelled. This aligns with the SDEWES view of heat as a system-embedded resource: environmental performance in residential heating cannot be optimised through fuel choice alone, but requires integrated predictive control of combustion conditions. Complementing these findings, Farooq et al. highlight analogous dynamic behaviour in stratified molten-salt thermoclines used for seasonal storage, where internal mixing, stratification stability and flow management control usable exergy [22]. Together, these contributions position latent-heat storage as an integrated thermo-material subsystem whose performance emerges from coupled material, geometric, and operational interactions rather than from intrinsic material properties alone. Geothermal and sub-surface resources provide another stable foundation for recoverable heat.

Karasalihović Sedlar et al. extend this geothermal perspective by demonstrating that mature oil fields can be retrofitted for stable geothermal-brine production, provided that appropriate institutional and regulatory mechanisms are in place to support dual-resource exploitation [53].

A complementary mining-based perspective is provided by Barzantny et al., who analyse the integration of waste heat from active and abandoned coal mines into the district heating system of Gliwice [54]. By recovering low-temperature heat from mine water and ventilation air through high-temperature heat pumps, their case study identifies around 3 MW of recoverable capacity and roughly 96 TJ of annual heat per source—equivalent to about 10% of the city's current heat demand. The CO_2 balance reveals that net emission reductions are only achieved under a decarbonised power mix, underscoring that mine-related heat recovery must be embedded within coordinated electricity and heat-system transitions rather than pursued as an isolated infrastructure add-on.

At the industrial level, ORC-based systems continue to expand the frontier of waste-heat utilisation across a wide range of scales. While recent research has increasingly addressed large-scale geothermal and solar-thermal hybrid configurations, Fatigati et al. provide experimental verification of scroll-expander technology tailored for small ORC units recovering exhaust heat from internal-combustion engines. Their results demonstrate a mechanical power increase of approximately 25% through the use of a dual-intake geometry [55]. This finding is particularly relevant for distributed industrial heat sources, where both temperature levels and mass-flow rates exhibit strong temporal variability.

At smaller scales, Ancona et al. show that solar-driven micro-ORC systems can meaningfully support residential heat recovery, indicating that ORC-based valorisation can extend beyond industrial waste heat into the domain of decentralised household energy systems [56].

Additional insights arise from electrothermal studies. Al Kindi et al. show that thermal-energy storage coupled with flexible nuclear generation substantially increases system-level balancing capacity without penalising reactor efficiency, transforming high-temperature heat into a dispatchable resource [57].

District systems demonstrate strong potential for wastewater-based heat recovery, with Ivezić et al. quantifying the efficiency gains and peak-load flexibility introduced by wastewater heat pumps in Serbian district heating and cooling (DHC) systems [58]. Beyond system-level performance, low-grade heat emerges as a spatially embedded resource whose effective utilisation depends on urban form and infrastructure readiness. GIS-based urban energy models such as PrioriTEE (2022) confirm that the exploitation of diffuse thermal potentials is strongly conditioned by urban density, climatic drivers, and the technical feasibility of retrofitting substations for low-temperature operation [59].

Across these diverse contributions—from sediment heat to distributed ORC systems—the evidence converges on a consistent conclusion: low-grade heat is no longer a loss term but a recoverable, distributable, and optimisable pillar of future decarbonised systems.

This systems perspective on transport decarbonisation is further strengthened by Degiuli et al.'s contribution, which quantifies how seemingly minor operational factors can produce substantial CO_2 penalties [60]. Using RANS-based CFD modelling, the authors show that thin biofilm layers on ship hulls and propellers can increase brake power demand by more than 30% under typical operating conditions, leading to CO_2 emission increases of 3–13% per hour depending on fouling severity and ship type. Their simulations across major global routes demonstrate that maintenance scheduling and hull-cleanliness strategies can yield absolute CO_2 savings on the order of tens to hundreds of tonnes per voyage—a scale comparable to technological retrofits. These findings underline that maritime decarbonisation hinges not only on fuels and propulsion technologies, but also on data-informed operational optimisation.

A parallel perspective emerges in urban public transport, where Noussan et al. perform a well-to-wheels comparison of battery-electric and biomethane buses [61]. Their analysis demonstrates that both alternatives achieve substantial emission reductions relative to diesel benchmarks—74% for electric buses and up to 79% for biomethane under the current EU feedstock mix—while highlighting the sensitivity of results to feedstock pathways, grid carbon intensity, and passenger load factors. The study shows that biomethane derived from residues such as manure can deliver net-negative upstream emissions, whereas electric-bus performance is increasingly shaped by the temporal alignment between charging patterns and renewable-electricity availability. These findings confirm that urban-bus decarbonisation is not solely a technology choice but a system-integration problem linking fuel pathways, grid behaviour, and urban mobility patterns—resonating with broader scenario-based assessments of passenger mobility policies and their climate impacts, such as those presented by Siebenhofer et al. [62].

3. Storage as temporal infrastructure

Energy storage today represents far more than an auxiliary buffer for intermittent renewables—it functions as the temporal infrastructure of decarbonised systems, shaping how variability is absorbed, redistributed, and synchronised across sectors. For example, at the microgrid scale, a techno-economic study by Ndiaye et al. demonstrates that integrating advanced storage components (lithium batteries and supercapacitors) significantly improves local energy management strategies, underscoring the role of storage as critical temporal infrastructure even in decentralised systems [63]. This principle is strongly reflected in the three storage-focused SDEWES 2024 papers—each operating at a different scale of system integration [28,43,64].

A complementary optimisation perspective within hybrid multi-source systems is provided by the contribution, which applies a Mantis Search Algorithm to a PV–wind–fuel-cell architecture [65]. Their results show that metaheuristic scheduling can substantially enhance temporal balancing, reliability margins and operational robustness in decentralised renewable systems, reinforcing the broader conclusion that storage and generation must be co-optimised under temporal constraints rather than treated as independent design variables.

In [43] Vizza et al. show that PV–electrolyser coupling reaches optimal techno-economic performance at PV-to-electrolyser ratios of 1.3–1.6, with hydrogen production costs approaching 4.2 €/kg, effectively using hydrogen as a *temporal coordination medium* linking diurnal photovoltaic profiles with the inertia of industrial demand. The study treats hydrogen not merely as a chemical product but as a temporal coordination medium, aligning diurnal solar cycles with the inertia of industrial consumption. These insights closely align with recent global analyses of green hydrogen supply chains, where system-level design—rather than electrolyser efficiency—dominates overall performance [66].

It also aligns with broader system-level decarbonisation modelling, including Herc, Pfeifer and Duić, who demonstrate that progressively higher renewable penetration requires co-optimised expansion of storage, demand response and hydrogen pathways to manage curtailment, cost and carbon constraints in transitional power systems [67].

More complex temporal architectures appear in paper of Guisado Falante et al. where they develop a reversible electro-thermal–geological storage concept based on transcritical CO_2 cycles [28]. Their turbomachinery and recuperator analyses reveal that compressor inlet pressure, turbine expansion ratio and heat-exchanger effectiveness jointly determine charge–discharge stability under off-design operation—a multivariable coupling that mirrors similar thermo-reactive sensitivities reported for structured hydrogen-production reactors in composite packed beds [68]. By integrating heat-pump charging and Brayton-cycle discharging into a single loop, the study demonstrates how conversion and storage can be engineered as a unified continuum, rather than as discrete unit operations.

At the materials scale, paper by Kang et al. examines LLZO solid electrolytes and shows that precursor chemistry, dopant distribution and microstructural homogeneity tightly govern ionic conductivity and cycling stability [64]. As solid-state batteries increasingly serve as short-duration buffers in hybrid PV–battery–hydrogen architectures, such materials-level constraints define the physical limits of system-level flexibility.

Complementary evidence from Furubayashi and Kudo and Guarino et al. reinforces this multiscale perspective, showing how geothermal and borehole-based thermal-storage architectures can smooth diurnal and seasonal mismatches in district-energy and solar-thermal systems [17,19]. Mahon et al. further generalise these insights in their review of aquifer, borehole, pit and tank seasonal thermal energy storage, identifying operating-temperature windows, recovery efficiencies and geological constraints that effectively position seasonal TES as a temporal backbone for future low-temperature district-heating networks [69]. Vivian et al. reach a similar conclusion for fifth-generation district-energy systems, demonstrating that stable electricity–heat exchange requires coordinated optimisation of distributed heat pumps, PV and thermal buffers [16].

Taken together, the three SDEWES contributions illustrate that time—not capacity alone—has become the fundamental organising principle of decarbonised energy systems. Hydrogen conversion chains, CO_2-based cycles, seasonal TES and solid-state batteries emerge not as isolated technologies, but as interoperable temporal assets whose primary value lies in shaping when and how energy becomes available, dispatchable and convertible across sectors.

In this sense, recent storage-oriented research reflects a broader conceptual evolution in decarbonisation thinking: the organising principle has shifted from individual devices to the temporal structuring of energy systems. Storage technologies increasingly function as the mechanisms through which renewable intermittency is transformed into reliable and predictable system behaviour. Their value therefore extends beyond nominal energy capacity, residing instead in their ability to shape when, how, and under which conditions energy becomes available, dispatchable, and convertible across sectors.

4. Digitalisation as operational decarbonisation

Digitalisation has become a structural enabler of decarbonisation, transforming flexibility from a static system attribute into a continuously optimised operational capability. The contributions in this cluster demonstrate that cyber-physical integration, data-driven control, and model-based optimisation are redefining how energy systems absorb renewable variability, manage grid constraints, and synchronise multi-vector operation.

The first of these contributions, paper [70], presents Bovesecchi et al.'s dynamically controlled photovoltaic–battery system for the Rome Technopole. Their simulations show that system self-sufficiency ranges from 65% to nearly 100% depending on inverter dispatch strategy, SOC forecasting, and temporal resolution of the control algorithm. This aligns with digital-control sensitivity reported by Vivian et al., who demonstrate that PV–heat-pump coordination in 5GDHC networks is highly dependent on forecasting accuracy and control logic [16]. Aunedi et al. similarly confirm that multi-model optimisation of UK heat-decarbonisation pathways hinges on model-based scheduling rather than hardware alone—reinforcing the conclusion that control-layer intelligence is now a primary determinant of system performance [71].

A complementary control-layer perspective emerges from health-aware and degradation-informed optimisation approaches increasingly applied to hybrid energy systems. Across recent studies on fuel-cell–battery and other multi-vector configurations, energy-management frameworks that explicitly internalise component ageing, efficiency decay, and cyclic stress demonstrate fundamentally different optimal dispatch behaviour compared to purely performance-driven control. By embedding degradation dynamics directly into dynamic or predictive optimisation schemes, these approaches co-optimise short-term efficiency and resource use with long-term system availability and cost. The consistent finding is that neglecting degradation mechanisms leads to systematically biased temporal power allocation and distorted lifecycle cost trajectories, reinforcing the conclusion that digital control is no longer merely an operational add-on but a structural determinant of multi-vector system performance across time and scales.

A comparable digital-systems perspective shapes, where Rajaković et al. extend Serbia's EnergyPLAN framework by embedding hourly AC power-flow calculations [72]. Their hybrid model captures voltage margins, congestion clusters, and cross-border interactions, producing physically verifiable pathways for large-scale renewable integration.

This is fully consistent with the decarbonisation-pathway optimisation of Herc, Pfeifer and Duić, who show that realistic national-system transitions require validation through operationally constrained modelling rather than unconstrained long-term planning [67].

Methodological continuity appears in Parrado-Hernando et al. [32], whose statistical annual-indicator framework embeds hourly-resolution dynamics into long-term planning without losing operational realism. Their co-simulation approach mirrors the structural logic of research of Rajaković et al.: digitalisation turns planning from a static projection into a continuous, multi-resolution optimisation process capable of reconciling techno-economic and electrical feasibility [72].

Uncertainty, too, is reshaped by digital modelling. In paper of Cuenca et al. apply probabilistic hydro-inflow scenarios to evaluate expansion strategies in Ecuador's hydro-dominated system, demonstrating that hydrological variability can reverse investment priorities [73]. Mazzeo et al. provide parallel evidence, showing that renewable-system performance in hybrid PV–wind configurations is strongly conditioned by environmental uncertainty and flexibility of hydrogen integration [74]. Together, these studies confirm that resilience is computationally engineered, not an afterthought of physical redundancy.

Digitalisation further deepens the integration of material and energy flows. Schützenhofer et al. demonstrate that material-resource optimisation and circularity must be embedded into digital planning frameworks if decarbonisation and resource efficiency are to progress together [75].

A further industrial digitalisation perspective is offered by Herrando et al., which develops a real-time Digital Twin of a continuous co-extrusion process in the rubber industry [76]. By integrating CFD, FEM and reduced-order models within a physics-based framework, the study enables multi-objective optimisation of line velocity, curing and foaming parameters. The results demonstrate that industrial manufacturing lines can provide meaningful electrical flexibility with minimal impact on thermal demand. Operating at higher line velocities is shown to reduce total CO_2 emissions and energy costs, illustrating how Digital Twins can synchronise operational schedules with external grid conditions. This contribution highlights that industrial decarbonisation increasingly relies not only on hardware efficiency, but on real-time, model-based process intelligence capable of coupling production dynamics with energy-system constraints.

At the industrial scale, digital co-simulation drives measurable reductions in CO_2 intensity. The Digital Twin Rubber Industry study shows that higher line speeds—traditionally assumed to increase energy use—can reduce specific emissions because shorter batch durations enhance electrical flexibility and minimise idle losses. Comparable digital-optimisation effects appear in Wang et al., where coordinated geometric–thermal optimisation of TPMS-based heat exchangers produces greater efficiency gains than hardware retrofits alone, underscoring the primacy of digital engineering over traditional equipment upgrades [27].

Industrial-sector decarbonisation exhibits similar patterns: Asadzadeh and Andersen show that optimal operation of bio-oil-fuelled cogeneration plants is achievable only through dynamic system modelling and predictive control, positioning digital-twin methodologies as essential tools for process-industry optimization [77].

At the urban scale, a complementary digital-modelling contribution is provided by Álvarez-Sanz et al., which integrates Heating Degree Day (HDD) concepts with XGBoost-based machine-learning models to estimate building heating demand across large residential districts [78]. By generating more than 50,000 representative building scenarios, the authors show that variable-base-temperature HDD modelling can achieve MAPE values as low as 15%, substantially outperforming traditional HDD approaches while retaining low data requirements compatible with open cadastral datasets. The ability to operate with limited inputs makes the model particularly suitable for rapid district-level energy diagnosis, renovation-strategy assessment and urban-transition planning. More broadly, this work illustrates how scalable, data-efficient digital tools are becoming central to building-stock decarbonisation and urban energy-system planning.

The built environment demonstrates the same transition. Gaucher-Loksts et al. show that coordinated optimisation of building-integrated PV and heat pumps meaningfully increases self-consumption and demand-side flexibility [79].

Barone et al. reach similar conclusions for concentrating PV/T façade systems, showing that performance gains arise only when optical, thermal and control parameters are jointly coordinated—further emphasising the systemic nature of building-integrated renewables [80].

Vassiliades et al. further demonstrate that active-solar façades alter both indoor comfort and microclimate dynamics—evidence that buildings are becoming digitally orchestrated energy assets rather than passive thermal loads [35].

Complementing these findings, Alhindawi and Jimenez-Bescos show that thermal-comfort prediction in passive buildings depends critically on high-resolution climatic and airflow modelling, reinforcing the role of digital analytics as a prerequisite for climate-responsive building operation [81].

Demand response (DR) naturally emerges as part of this broader evolution. While the contributions in this Special Issue do not introduce explicit DR control algorithms, related studies illustrate how digital monitoring and regulation already shape system flexibility. Batista da Silva et al. show how digital monitoring influences PV adoption dynamics and user behaviour [82], while Wołosz demonstrates that digitally regulated transient airflow systems can function as controllable flexibility resources [83]. Together, these examples support the contemporary interpretation of demand response as a form of virtual storage, in which digital coordination and control partially substitute for physical storage capacity by reshaping demand profiles in time.

These findings converge on a three-layer structure through which digitalisation operates:

(1) **System-scale digital integration:**Coupled national models (e.g., Rajakovic et al.) integrate market behaviour, grid constraints and interconnector dynamics, resembling advanced European co-simulation platforms where market clearing, unit commitment and nodal balancing share a unified optimisation kernel [72].
(2) **Local and district-level digital control:** Flexible PV–BESS systems and low-temperature district networks employ MPC-style optimisation and forecasting to align distributed resources with real-time system needs [70].
(3) **Industrial and process-level digital twins:** Real-time co-simulation in industrial systems synchronises thermal and electrical behaviour with grid carbon intensity, effectively turning production lines into dispatchable hybrid resources.

Across all layers, a single conclusion emerges: Digitalisation is becoming the operational backbone of decarbonisation. Energy systems no longer rely solely on physical assets—batteries, hydrogen, thermal storage—but increasingly on algorithmic flexibility: predictive models, control strategies and cyber-physical platforms that continuously match renewable supply with multi-vector demand.

Digital intelligence has effectively become a new form of infrastructure—governing when storage systems charge, when heat pumps operate, how PV curtailment is avoided, how industrial loads are sequenced, and how national grids absorb gigawatt-scale variable renewables. This evolution marks a logical next phase in decarbonised energy-system design: a shift from system integration towards system orchestration, in which digital and physical components co-evolve to deliver reliable, adaptive and ultimately net-zero operation.

5. Governance and equity in the net-zero transition

The human and institutional dimensions of the energy transition emerge as a distinct analytical layer that shapes decarbonisation outcomes no less than technological innovation. The contributions in this cluster demonstrate that governance structures, equity frameworks, and community-level participation constitute the conditions under which system-level decarbonisation either succeeds or stalls. In contrast to earlier decades—when institutional design was treated as an external constraint—recent research positions it as an integral component of energy-system optimisation.

This institutional dimension extends to urban mobility as well: Abid et al. show that energy-efficient urban planning can deliver system-level transport-sector savings comparable to technological retrofits, underscoring that infrastructure design and governance jointly shape decarbonisation outcomes [84].

At the urban scale, Ayala Chauvin et al. show that the effectiveness of distributed-energy and demand-response programmes depends as much on institutional coordination and tariff design as on the underlying technological infrastructure, highlighting governance as a primary enabler of urban energy autonomy [85].

A central conceptual contribution comes from Ebersold et al., who introduce the category of avoidable greenhouse gas emissions. Their framework distinguishes between emissions that are technically avoidable (given current available technologies) and those that are economically avoidable (given investment constraints and market prices). This distinction allows for a more transparent definition of corporate carbon-neutrality strategies, reducing the ambiguity surrounding mitigation potential and residual emissions [86].

While Ebersold et al. articulate the accounting foundations of institutional decarbonization, Peñalvo-López et al. (Energy Community Cost Model) focus on community-scale equity [86,87]. Their simulation of energy communities in Spain and Colombia evaluates electricity-sharing arrangements under varying ownership structures, tariff designs, and load profiles. By operationalising a community-level cost-of-electricity indicator (COE_1), the authors quantify the distributional consequences of decentralised generation and identify conditions under which vulnerable households become net beneficiaries rather than net payers. These findings align with recent integrated assessment modelling by Parrado-Hernando et al. which demonstrates that equitable decarbonisation scenarios in the EU27 require not only technological deployment, but also governance architectures capable of coordinating variability, curtailment, and flexibility across socio-technical layers [33].

A complementary perspective on distributive fairness and cost allocation in community-based energy systems is provided by Peñalvo-Lopez et al., which evaluates the annual cost of electricity for different community members under varying ownership models, tariff structures and consumption profiles [87]. The analysis shows that equity outcomes in Energy Communities depend less on aggregate renewable penetration than on intra-community allocation rules and governance arrangements. These results underline that, in community-scale decarbonisation, institutional design and allocation mechanisms often exert a stronger influence on socio-economic performance than technological optimisation alone.

Huang demonstrates that electricity consumption is deeply shaped by socio-economic factors such as income, household size, and appliance ownership, revealing that wealthier households tend to consume disproportionately more electricity per capita [88]. These findings underscore that social inequality directly affects energy use patterns and should be considered when designing low-carbon policies—reinforcing that socio-institutional context is inseparable from technical feasibility.

Doukas and Trachanas further highlight that issues of inequality, autonomy and social acceptance often determine whether low-carbon technologies are adopted, reinforcing that socio-institutional context is inseparable from technical feasibility [89].

Corral Fernández et al. further emphasise the need for integrated planning by showing that linear optimisation of energy–water–food systems in rural Sub-Saharan contexts substantially mitigates local resource inequalities and strengthens infrastructural resilience [90].

Recent advances also underscore the material dimension of sustainability in building-scale electrification. Carrasco and May use automated text analysis across 241 open-access papers to map how circular economy concepts are treated in literature on low-energy housing components—particularly photovoltaic systems, lithium-ion batteries, inverters, and heat pumps [91]. Their findings confirm a dominant focus on emissions and energy while identifying a critical data gap regarding end-of-life, recycling, and reliability indicators. As electrical components proliferate in net-zero energy buildings, such analyses are essential to ensure that material sustainability complements decarbonisation and cost-efficiency.

Institutionally relevant environmental planning is further exemplified in the contribution by Němcová, who develops an optimisation model for the siting of waste-to-energy (WtE) facilities under regional constraints [92]. The model integrates spatial feedstock distributions, logistics costs, environmental-risk indicators, and social-acceptance parameters. This approach reinforces the emerging consensus that WtE systems must be assessed not only through thermodynamic and economic metrics but also through social-licence dimensions—public perception, zoning constraints, and participatory planning processes. Recent analyses similarly highlight that spatial planning, governance structures, and institutional conditions frequently outweigh technical indicators in determining whether energy-infrastructure projects advance toward implementation [93,94].

A direct methodological contribution to this emerging domain is provided by [95], which delivers one of the first empirical validations of longwave Mean Radiant Temperature (MRT) using aerial thermography. The study compares UAV-based thermal imagery with Ladybug Tools (LBT) simulations across 20 monitored points in an urban square, demonstrating RMSE values of approximately 3°C and MAPE around 10%—well within accepted accuracy thresholds for outdoor microclimate modelling. Beyond validating LBT for outdoor thermal-comfort assessment, the analysis reveals critical sensitivities related to model setup, vegetation representation and the availability of high-resolution climatic data. These findings reinforce the view that digital climate analytics are becoming foundational instruments for evidence-based, climate-resilient public-space design and urban governance.

These contributions align with a broader wave of post-2022 scholarship that reframes decarbonisation as a negotiated institutional and socio-technical process. Governance structures increasingly mediate issues such as land-use conflicts, emission-allocation disputes, distribution of transition costs, and the regulation of hazardous inputs. In the industrial sphere, Prasad et al. show how health and environmental concerns around petroleum-based extraction solvents, and the associated regulatory responses, are catalysing a shift toward greener, bio-based alternatives—illustrating that process change is often driven as much by safety and policy frameworks as by extraction efficiency [96]. In the buildings sector, Piselli et al. develop user–building interaction models for low-carbon heating solutions based on large-scale social surveys across several European countries, demonstrating that cultural context, occupant practices and perceptions of innovative systems can alter simulated heating-energy needs by up to 43% [97]. Taken together, these studies reinforce the view that institutional, regulatory and behavioural dimensions critically shape the feasibility and realised performance of decarbonisation pathways across sectors.

Digitalisation increasingly overlaps with governance. Sustainability-oriented building digital twins, such as the eLUX lab prototype Tagliabue et al., illustrate how IoT-enabled BIM models can move rating systems from static checklists to dynamic, real-time decision-support dashboards [98]. Scaled to the community level, such digital twins would allow municipalities to stress-test tariff reforms, resilience strategies, and equity outcomes across decarbonisation scenarios. By resolving energy and climate exposures at neighbourhood scale, these tools reveal where vulnerabilities to thermal stress, outages, or energy poverty are most acute. Integrating them with validated MRT-based microclimate diagnostics (López-Cabeza et al.) supports a shift from reactive planning to predictive, evidence-driven urban governance [95].

Another emerging institutional theme concerns material and waste governance, increasingly shaped by system-modelling requirements. Tracking embodied carbon along circular-economy pathways is not only a regulatory challenge but also a modelling one, as it requires harmonised data structures, boundary definitions, and accounting rules that can be operationalised within integrated energy-material optimisation frameworks. Likewise, growing regulatory pressure on critical materials—documented in recent EU circularity reports (European Commission, 2023)—reinforces the need for policy frameworks that are compatible with techno-economic models capable of jointly optimising material reuse, recycling flows, and energy-system operation, rather than treating governance and system design as separate domains.

Across these diverse cases, one coherent insight emerges: decarbonisation is neither solely a technical nor solely an economic challenge; it is fundamentally an institutional process conditioned by governance capacity, social structures, and local legitimacy. The contributions analysed here show that energy communities reshape distributional outcomes; microclimate metrics shape public-space equity; WtE siting reflects negotiated regional priorities; and corporate decarbonisation depends on credible emission accounting. In each case, the technological pathway is inseparable from the institutional context that enables or obstructs its implementation.

The SDEWES 2024 contributions therefore reaffirm that achieving net-zero targets requires not only advances in energy storage, digitalisation, and sector coupling but also robust governance ecosystems capable of orchestrating participation, equity, transparency, and social acceptance. The institutional dimension, long treated as an externality, has become a first-order design parameter of the energy transition.

6. Outlook: towards coherent decarbonisation architectures

Recent contributions reveal a clear methodological convergence across disciplines: thermodynamic rigour, systemic modelling, digital optimisation and institutional governance increasingly form a unified analytical space rather than separate research domains. The papers selected for this Special Issue demonstrate that decarbonisation succeeds only when technologies, infrastructures and institutions operate as interoperable systems rather than as isolated components.

Across renewable–hydrogen coupling [28,43], heat valorisation and thermal-network optimisation [17,19], cyber-physical flexibility and governance-driven emissions accounting [70,72,86], a unifying insight emerges: sustainability is shifting from component-level efficiency towards system-level synchronisation across physical, digital and institutional domains.

Looking forward, research in this field should advance this convergence through four strategic directions:

Advanced thermal–electrical coupling at community scale. The integration of heat pumps, phase-change materials, geothermal buffering, and hydrogen electrolysis requires co-optimised thermal and electrical dispatch. Recent analyses of seasonal storage and hybrid district heating show that the value of flexibility increases dramatically when thermal and electrical vectors are jointly scheduled [99]. Future efforts should extend these findings toward neighbourhood-level multi-vector hubs.

Multi-vector modelling of CO_2 utilisation, hydrogen, and TES cycles. The electro-thermal–geological concepts explored in [28], together with PV–electrolyser optimisation in paper by Vizza and recent system-level assessments of CO_2 utilisation and storage [43,100] and seasonal thermal energy storage [69], indicate that hydrogen, CO_2-based cycles, and thermal storage evolve most effectively when modelled as interdependent temporal infrastructures. Developing unified simulation frameworks that capture reversible cycles, chemical vectors, long-duration storage and power-flow constraints is a critical next step.

Circular resource accounting embedded in system optimisation. The integration of material flows into energy models aligns with global trends in critical-material governance (European Commission, 2023) and recent SDEWES contributions that increasingly treat materials, energy, and emissions as co-optimised system variables rather than external constraints. Sharma and Chani show how embodied energy, water, and carbon matrices can be operationalised for building-scale sustainability assessment, providing quantitative inputs suitable for system-level optimisation [25]. Nedić et al. extend this perspective to regional bioeconomy transitions, identifying material-flow constraints and circular-carbon opportunities that directly interact with energy planning and infrastructure deployment [101]. At the digitalisation layer, Schützenhofer et al. demonstrate that digital-twin frameworks can integrate circular-building intelligence with energy-performance modelling, enabling feedback between material stocks, operational energy demand, and retrofit strategies [102]. Embedding resource depletion, recycling pathways, and embodied carbon directly into energy-system planning thus enables full life-cycle decarbonisation rather than operational decarbonisation alone.

The relevance of material efficiency in long-term decarbonisation is further supported by Neumann and Hirschnitz-Garbers, who demonstrate that 100% renewable-energy scenarios remain feasible only when circular-material strategies are combined with absolute reductions in final energy demand [103].

Social and institutional co-design of infrastructure. The distributional impacts revealed by Peñalvo-Lopez et al., the integration of energy-poor households into renewable energy communities [87], neighbourhood-scale solar-planning tools [104,105], and public risk perceptions of DACCS [106] highlight that equity, participation, and governance are measurable parameters, not externalities. Together, these studies show that who participates, under which rules, and with what information fundamentally reshapes both the cost allocation and the perceived legitimacy of low-carbon investments. Co-designed infrastructures—where residents, municipalities and system operators iteratively negotiate tariff structures, ownership models and risk-sharing mechanisms—tend to deliver not only higher social acceptance, but also more robust flexibility and resilience outcomes over time. In this sense, institutional design becomes a core optimisation variable of net-zero pathways, rather than a boundary condition to be handled ex post.

Integrated decarbonisation as a systems-engineering blueprint

Taken together, these contributions signal a shift toward a coherent decarbonisation architecture:

- heat is recovered and recirculated, not wasted;
- storage is temporal and multiscale, not merely volumetric;
- digitalisation serves as operational intelligence, not an add-on;
- governance provides verifiability, equity, and legitimacy, not constraints.

As the SDEWES network expands, its cross-disciplinary framework—linking thermodynamics, digital systems, materials science, and governance—positions it as both a laboratory for integrative methods and a blueprint for how real-world energy transitions must be orchestrated.

References

[1] Duic N. Journal of sustainable development of energy, water and environment systems - volume X. J Sustain Dev Energy Water Environ Syst 2022;10(4):1–3. https://doi.org/10.13044/j.sdewes.2022.10.edt.

[2] Astiaso Garcia D, Dionysis G, Raskovic P, Duić N, Ahmad Al-Nimr M. Advanced technological options for sustainable development of energy, water and

environment systems upgrade towards climate neutrality. Energy Conv Manag: X 2024;22:100528. https://doi.org/10.1016/j.ecmx.2024.100528.

[3] Astiaso Garcia D, Raskovic P, Duić N, Al-Nimr MA. Technologies and strategies fostering the sustainable development of energy, water and environment systems. Energy Conv Manag: X 2024;24:100736. https://doi.org/10.1016/j.ecmx.2024.100736.

[4] Chu W, et al. Recent advances in technologies, methods, and economic analysis for sustainable development of energy, water, and environment systems. Energies Sep. 2022;15(19):7129. https://doi.org/10.3390/en15197129.

[5] Lotze J, Moser M, Savvidis G, Keles D, Hagenmeyer V. The complementary role of energy system and power grid models: an analysis of the European energy transformation from a holistic perspective. Energ Conver Manage 2024;315:118761. https://doi.org/10.1016/j.enconman.2024.118761.

[6] Kılkış Ş, Krajačić G, Duić N, Rosen MA, Ahmad Al-Nimr M. Sustainable development of energy, water and environment systems as a key opportunity for decarbonisation. Energy Conv Manag 2024;320:118953. https://doi.org/10.1016/j.enconman.2024.118953.

[7] Calise F, Cappiello FL, Cimmino L, Dentice d'Accadia M, Vicidomini M. Thermo-economic analysis and dynamic simulation of a novel layout of a renewable energy community for an existing residential district in Italy. Energy Conv Manag 2024;313:118582. https://doi.org/10.1016/j.enconman.2024.118582.

[8] Marrasso E, Martone C, Pallotta G, Roselli C, Sasso M. Assessment of energy systems configurations in mixed-use positive energy districts through novel indicators for energy and environmental analysis. Appl Energy 2024;368:123374. https://doi.org/10.1016/j.apenergy.2024.123374.

[9] Olympios AV, et al. A holistic framework for the optimal design and operation of electricity, heating, cooling and hydrogen technologies in buildings. Appl Energy 2024;370:123612. https://doi.org/10.1016/j.apenergy.2024.123612.

[10] Jahanbin A, Abdolmaleki L, Berardi U. Techno-economic feasibility of integrating hybrid battery-hydrogen energy storage system into an academic building. Energ Conver Manage 2024;309:118445. https://doi.org/10.1016/j.enconman.2024.118445.

[11] Bartolucci L, Cordiner S, De Maina E, Mulone V. Data-driven optimal design of a CHP plant for a hospital building: highlights on the role of biogas and energy storages on the performance. Energies 2022;15(3):858. https://doi.org/10.3390/en15030858.

[12] Kim HU, et al. Direct conversion of lignin to high-quality biofuels by carbon dioxide-assisted hydrolysis combined with transfer hydrogenolysis over supported ruthenium catalysts. Energ Conver Manage 2022;261:115607. https://doi.org/10.1016/j.enconman.2022.115607.

[13] Ryšavý J, et al. Optimisation of metastable supercooled liquid phase change material for long-term heat energy accumulation. Energy Conv Manag: X Jul. 2025;27:101061. https://doi.org/10.1016/j.ecmx.2025.101061.

[14] Čespiva J, et al. Critical crystallisation issue in sodium acetate-based latent heat accumulation substance. Energy Conv Manag: X Jul. 2025;27:101168. https://doi.org/10.1016/j.ecmx.2025.101168.

[15] Mersch M, Sapin P, Olympios AV, Ding Y, Mac Dowell N, Markides CN. A unified framework for the thermo-economic optimisation of compressed-air energy storage systems with solid and liquid thermal stores. Energy Conv Manag 2023;287:117061. https://doi.org/10.1016/j.enconman.2023.117061.

[16] Vivian J, Chinello M, Zarrella A, De Carli M. Investigation on individual and collective PV self-consumption for a fifth generation district heating network. Energies 2022;15(3):1022. https://doi.org/10.3390/en15031022.

[17] Furubayashi T, Kudo Y. Design and analysis of a district heating and cooling system that uses waste heat and dumped snow in Akita City, Japan. Energy Conv Manag: X Jul. 2025;27:101203. https://doi.org/10.1016/j.ecmx.2025.101203.

[18] Moradpoor I, Koivunen T, Syri S, Hirvonen J. The benefits of integrating industrial hydrogen production with district heating in Cold Climates with different building renovation levels. Energy 2024;303:131953. https://doi.org/10.1016/j.energy.2024.131953.

[19] Guarino S, Buscemi A, Bonomolo M, Beccali M, Lo Brano V. Low-carbon heating solutions using road thermal collectors and seasonal energy storage in mediterranean climates. Energy Conv Manag: X Jul. 2025;27:101167. https://doi.org/10.1016/j.ecmx.2025.101167.

[20] Pavković D, Cipek M, Krznar M, Benić J. A retrofitting control system design suitable for deep borehole drilling using legacy draw-works mechanical brake hardware. Energ Conver Manage 2022;260:115589. https://doi.org/10.1016/j.enconman.2022.115589.

[21] Girgibo N, Mäkiranta A, Lü X, Hiltunen E. Statistical investigation of climate change effects on the utilization of the sediment heat energy. Energies 2022;15(2):435. https://doi.org/10.3390/en15020435.

[22] Farooq A, et al. Valorization of furniture industry-processed residue via catalytic pyrolysis with methane. Energ Conver Manage 2022;261:115652. https://doi.org/10.1016/j.enconman.2022.115652.

[23] Valizadeh S, Valizadeh B, Kang BS, Shim H, Park Y-K. Enhanced generation of aromatic-enriched bio-oil from sewage sludge pyrolysis using zeolite-based catalysts under H2-rich conditions. Energ Conver Manage 2024;311:118530. https://doi.org/10.1016/j.enconman.2024.118530.

[24] Khani Y, et al. Thermal conversion of organic furniture waste to hydrogen fuel via catalytic air gasification over monolithic spinel-type oxide-supported nickel catalysts. Energ Conver Manage 2023;288:117132. https://doi.org/10.1016/j.enconman.2023.117132.

[25] Sharma V, Abbas R, Sodré JR, Ayad SMME, Belchior C. Model for energy consumption and costs of bioethanol production from wastepaper. J Sustain Dev Energy Water Environ Syst 2022;10(4):1–11. https://doi.org/10.13044/j.sdewes.d10.0431.

[26] Li XL, Tang GH, Fan YH, Yang DL. A performance recovery coefficient for thermal-hydraulic evaluation of recuperator in supercritical carbon dioxide Brayton cycle. Energ Conver Manage 2022;256:115393. https://doi.org/10.1016/j.enconman.2022.115393.

[27] Wang J, Chen K, Zeng M, Ma T, Wang Q, Cheng Z. Investigation on flow and heat transfer in various channels based on triply periodic minimal surfaces (TPMS). Energ Conver Manage 2023;283:116955. https://doi.org/10.1016/j.enconman.2023.116955.

[28] Falante J. et al., "Preliminary Study of Turbomachinery operation in a novel electrothermal and geological energy storage based on transcritical CO2 cycles". In: Proceedings of the 19th Conference on Sustainable Development of Energy, Water and Environment Systems, Rome, Italy: SDEWES Centre.

[29] Benić J, Karlušić J, Šitum Ž, Cipek M, Pavković D. Direct driven hydraulic system for skidders. Energies 2022;15(7):2321. https://doi.org/10.3390/en15072321.

[30] Coraci D, Brandi S, Capozzoli A. Effective pre-training of a deep reinforcement learning agent by means of long short-term memory models for thermal energy management in buildings. Energ Conver Manage 2023;291:117303. https://doi.org/10.1016/j.enconman.2023.117303.

[31] Maturo A, Vallianos C, Buonomano A, Athienitis A. A novel multi-level predictive management strategy to optimize phase-change energy storage and building-integrated renewable technologies operation under dynamic tariffs. Energ Conver Manage 2023;291:117220. https://doi.org/10.1016/j.enconman.2023.117220.

[32] Parrado-Hernando G, et al. Capturing features of hourly-resolution energy models through statistical annual indicators. Renew Energy 2022;197:1192–223. https://doi.org/10.1016/j.renene.2022.07.040.

[33] Parrado-Hernando G, Herc L, Feijoo F, Capellán-Pérez I. Capturing features of hourly-resolution energy models in an integrated assessment model: an application to the EU27 region. Energy 2024;304:131903. https://doi.org/10.1016/j.energy.2024.131903.

[34] Spanodimitriou Y, et al. Passive strategies for building retrofitting: performances analysis and incentive policies for the Iranian Scenario. Energies 2022;15(5):1628. https://doi.org/10.3390/en15051628.

[35] Vassiliades C, Savvides A, Buonomano A. Building integration of active solar energy systems for façades renovation in the urban fabric: Effects on the thermal comfort in outdoor public spaces in Naples and Thessaloniki. Renew Energy 2022;190:30–47. https://doi.org/10.1016/j.renene.2022.03.094.

[36] Herrando M, Gómez A, Fueyo N. Supporting local authorities to plan energy efficiency in public buildings: from local needs to regional planning. Energies 2022;15(3):907. https://doi.org/10.3390/en15030907.

[37] Insyani R, et al. Improved hydrodeoxygenation of lignin-derived oxygenates and biomass pyrolysis oil into hydrocarbon fuels using titania-supported nickel phosphide catalysts. Energ Conver Manage 2022;266:115822. https://doi.org/10.1016/j.enconman.2022.115822.

[38] Ling JLJ, et al. Analysis of operational characteristics of biomass oxygen fuel circulating fluidized bed combustor with indirect supercritical carbon dioxide cycle. Energ Conver Manage 2022;259:115569. https://doi.org/10.1016/j.enconman.2022.115569.

[39] Plata V, Ferreira-Beltrán D, Gauthier-Maradei P. Effect of cooking conditions on selected properties of biodiesel produced from palm-based waste cooking oils. Energies 2022;15(3):908. https://doi.org/10.3390/en15030908.

[40] Erić A, Cvetinović D, Milutinović N, Škobalj P, Bakić V. Combined parametric modelling of biomass devolatilisation process. Renew Energy 2022;193:13–22. https://doi.org/10.1016/j.renene.2022.04.129.

[41] Stančin H, et al. Influence of plastic content on synergistic effect and bio-oil quality from the co-pyrolysis of waste rigid polyurethane foam and sawdust mixture. Renew Energy 2022;196:1218–28. https://doi.org/10.1016/j.renene.2022.07.047.

[42] Zhang J, Shi Z, Zheng Y, Tan H, Wang X. Fragmentation and mineral transformation behavior during combustion of char produced at elevated pressure. Energ Conver Manage 2022;258:115538. https://doi.org/10.1016/j.enconman.2022.115538.

[43] Vizza D, Caponi R, Bocci E, Del Zotto L, Bassano C. Cost effective hydrogen production of coupled photovoltaic and electrolyzer systems considering plant lifetime and geographical location. Energy Conv Manag: X Jul. 2025;27:101136. https://doi.org/10.1016/j.ecmx.2025.101136.

[44] Ciappi L, Simonetti I, Bianchini A, Cappietti L, Manfrida G. Application of integrated wave-to-wire modelling for the preliminary design of oscillating water column systems for installations in moderate wave climates. Renew Energy 2022;194:232–48. https://doi.org/10.1016/j.renene.2022.05.015.

[45] D'Agostino D, Minelli F, D'Urso M, Minichiello F. Fixed and tracking PV systems for net zero energy buildings: comparison between yearly and monthly energy balance. Renew Energy 2022;195:809–24. https://doi.org/10.1016/j.renene.2022.06.046.

[46] Bilardo M, Ferrara M, Fabrizio E. The role of solar cooling for nearly zero energy multifamily buildings: performance analysis across different climates. Renew Energy 2022;194:1343–53. https://doi.org/10.1016/j.renene.2022.05.146.

[47] Altegoer D, Hussong J, Lindken R. Efficiency increase of photovoltaic systems by means of evaporative cooling in a back-mounted chimney-like channel. Renew Energy 2022;191:557–70. https://doi.org/10.1016/j.renene.2022.03.156.

[48] Wei Z, Tien PW, Calautit J, Darkwa J, Worall M, Boukhanouf R. Investigation of a model predictive control (MPC) strategy for seasonal thermochemical energy storage systems in district heating networks. Appl Energy 2024;376:124164. https://doi.org/10.1016/j.apenergy.2024.124164.

[49] Sousa J, Lagarto J, Fonseca M. The role of storage and flexibility in the energy transition: substitution effect of resources with application to the Portuguese

electricity system. Renew Energy 2024;228:120694. https://doi.org/10.1016/j.renene.2024.120694.
[50] Egea A, García A, Herrero-Martín R, Pérez-García J. Experimental performance of a novel scraped surface heat exchanger for latent energy storage for domestic hot water generation. Renew Energy Jun. 2022;193:870–8. https://doi.org/10.1016/j.renene.2022.05.057.
[51] Wang Y, Yin C, Mandø M. "Modelling and Validation of Self-heating in a 3D Biomass Pile". In: Proceedings of the 19th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES 2024), Rome, Italy: SDEWES Centre.
[52] Szramowiat-Sala K, Krpec K, Penkala R, Ryšavý J. Data-driven prediction of pollutants emission from small-scale heating units using temporal deep learning. Energy Conv Manag: X Oct. 2025;28:101322. https://doi.org/10.1016/j.ecmx.2025.101322.
[53] Karasalihović Sedlar D, Kurevija T, Macenić M, Smajla I. Regulatory and economic challenges in the production of geothermal brine from a mature oil field. Energy Sour, Part B: Econ, Plan, Policy 2022;17(1):2097336. https://doi.org/10.1080/15567249.2022.2097336.
[54] Barzantny M, Kostowski W, Nol D, Żymełka S, Kalina J, Stanek W. The Silesian paradox: Using coal mines for district heating decarbonization – a case study on waste heat recovery from groundwater and ventilation air. Energy Conv Manag: X Jul. 2025;27:101166. https://doi.org/10.1016/j.ecmx.2025.101166.
[55] Fatigati F, Di Giovine G, Cipollone R. Feasibility assessment of a dual intake-port scroll expander operating in an ORC-based power unit. Energies 2022;15(3):770. https://doi.org/10.3390/en15030770.
[56] Ancona MA, et al. Solar driven micro-ORC system assessment for residential application. Renew Energy 2022;195:167–81. https://doi.org/10.1016/j.renene.2022.06.007.
[57] Al Kindi AA, Aunedi M, Pantaleo AM, Strbac G, Markides CN. Thermo-economic assessment of flexible nuclear power plants in future low-carbon electricity systems: role of thermal energy storage. Energy Conv Manag 2022;258:115484. https://doi.org/10.1016/j.enconman.2022.115484.
[58] Ivezic D, Zivkovic M, Manic D, Madzarevic A, Pavlovic B, Danilovic D. Evaluation of the effects of wastewater heat pump integration into district heating systems by simulation. Therm sci 2023;27(3 Part B):2443–54. https://doi.org/10.2298/TSCI220813168I.
[59] "Decision Support Tool for Energy Efficiency Measures in Public Buildings," Interreg MED Programme, 2019. [Online]. Available: https://prioritee.interreg-med.eu/.
[60] Degiuli N, Martić I, Grlj CG, Zhang M. The detrimental impact of biofilm on ship fuel consumption and CO2 emissions. Energy Conv Manag: X Oct. 2025;28:101296. https://doi.org/10.1016/j.ecmx.2025.101296.
[61] Noussan M, Laveneziana L, Prussi M, Chiaramonti D. Well-to-wheel greenhouse gas emissions comparison of electricity and biomethane urban buses. Energy Conv Manag: X Oct. 2025;28:101232. https://doi.org/10.1016/j.ecmx.2025.101232.
[62] Siebenhofer M, Ajanovic A, Haas R. On the future of passenger mobility and its greenhouse gas emissions in cities: scenarios for different types of policies. J Sustain Dev Energy Water Environ Syst 2022;10(4):1–19. https://doi.org/10.13044/j.sdewes.d10.0424.
[63] Ndiaye A, Locment F, De Bernardinis A, Sechilariu M, Redondo-Iglesias E. A techno-economic analysis of energy storage components of microgrids for improving energy management strategies. Energies 2022;15(4):1556. https://doi.org/10.3390/en15041556.
[64] Kang HE, Kim MW, Lee JH, Kwon J, Yoon YS. Influence of different lithium precursors on the crystal structure and ionic conductivity of Li7La3Zr2O12 solid electrolyte. Energy Conv Manag: X Jul. 2025;27:101147. https://doi.org/10.1016/j.ecmx.2025.101147.
[65] Aldawsari S, Anayi F. "Optimizing a hybrid photovoltaic/wind/fuel cell hybrid off grid energy system using mantis search algorithm". In: Proceedings of the 19th Conference on Sustainable Development of Energy, Water and Environment Systems, Rome, Italy: SDEWES Centre.
[66] Bhandari R. Green hydrogen production potential in West Africa – Case of Niger. Renew Energy 2022;196:800–11. https://doi.org/10.1016/j.renene.2022.07.052.
[67] Herc L, Pfeifer A, Duić N. Optimization of the possible pathways for gradual energy system decarbonization. Renew Energy 2022;193:617–33. https://doi.org/10.1016/j.renene.2022.05.005.
[68] Wu Z, Guo Z, Yang J, Wang Q. Effect of diameter distribution of particles on methane steam reforming in multi-channel grille-sphere composite packed bed. Energ Conver Manage 2022;265:115764. https://doi.org/10.1016/j.enconman.2022.115764.
[69] Mahon H, O'Connor D, Friedrich D, Hughes B. A review of thermal energy storage technologies for seasonal loops. Energy 2022;239:122207. https://doi.org/10.1016/j.energy.2021.122207.
[70] Bovesecchi G, Andreozzi F, Petitta M, Pierro M, Perez R, Cornaro C. Flexible photovoltaic generation strategy for Rome Technopole. Energy Conv Manag: X Jul. 2025;27:101204. https://doi.org/10.1016/j.ecmx.2025.101204.
[71] Aunedi M, Yliruka M, Dehghan S, Pantaleo AM, Shah N, Strbac G. Multi-model assessment of heat decarbonisation options in the UK using electricity and hydrogen. Renew Energy Jul. 2022;194:1261–76. https://doi.org/10.1016/j.renene.2022.05.145.
[72] Rajakovic N, Ivanović B, Bjelic IB, Rajić T. Coupling of the planning and power system analysis software for high-level penetration of renewable energy sources. Energy Conv Manag: X Oct. 2025;28:101298. https://doi.org/10.1016/j.ecmx.2025.101298.
[73] Cuenca W, Benalcazar P. "Capacity expansion planning model of hydroelectricity-based systems: an Ecuadorian energy mix case study". In: Proceedings of the 19th Conference on Sustainable Development of Energy, Water and Environment Systems, Rome, Italy: SDEWES Centre.
[74] Mazzeo D, Herdem MS, Matera N, Wen JZ. Green hydrogen production: analysis for different single or combined large-scale photovoltaic and wind renewable systems. Renew Energy 2022;200:360–78. https://doi.org/10.1016/j.renene.2022.09.057.
[75] Schützenhofer S, Kovacic I, Rechberger H. Assessment of sustainable use of material resources in the architecture, engineering and construction industry - a conceptual framework proposal for Austria. J Sustain Dev Energy Water Environ Syst 2022;10(4):1–21. https://doi.org/10.13044/j.sdewes.d10.0417.
[76] Herrando M, Viejo I, Calvo S, Izquierdo S. "Development of digital twins to increase energy flexibility and energy efficiency of manufacturing processes in the rubber industry". In: Proceedings of the 19th Conference on Sustainable Development of Energy, Water and Environment Systems, Rome, Italy: SDEWES Centre.
[77] Asadzadeh SM, Andersen NA. A predictive dynamic model of a smart cogeneration plant fuelled with fast pyrolysis bio-oil. J Sustain Dev Energy Water Environ Syst 2022;10(4):1–36. https://doi.org/10.13044/j.sdewes.d10.0430.
[78] Álvarez-Sanz M, Villanueva-Díaz C, Campos-Celador Á, Terés-Zubiaga J, Larrinaga P. Combining heating degree days method and machine learning techniques: implementation of a new model for mapping buildings heating demand at urban scale. Energy Conv Manag: X Jan. 2026;29:101503. https://doi.org/10.1016/j.ecmx.2025.101503.
[79] Gaucher-Loksts E, Athienitis A, Ouf M. Design and energy flexibility analysis for building integrated photovoltaics-heat pump combinations in a house. Renew Energy 2022;195:872–84. https://doi.org/10.1016/j.renene.2022.06.028.
[80] Barone G, et al. Modelling and simulation of building integrated Concentrating Photovoltaic/Thermal Glazing (CoPVTG) systems: Comprehensive energy and economic analysis. Renew Energy Jun. 2022;193:1121–31. https://doi.org/10.1016/j.renene.2022.04.119.
[81] Alhindawi I, Jimenez-Bescos C. Computational approach to predict thermal comfort levels at summer peak conditions in passive house based on natural ventilation. J Sustain Dev Energy Water Environ Syst 2022;10(4):1–21. https://doi.org/10.13044/j.sdewes.d10.0419.
[82] Batista Da Silva H, Thakur J, Uturbey W, Martin V. Analysis of residential rooftop photovoltaic diffusion in India through a Bass model approach. J Sustain Dev Energy Water Environ Syst 2022;10(4):1–10. https://doi.org/10.13044/j.sdewes.d10.0423.
[83] Wołosz KJ. Energy analysis of an industrial nozzle with variable outlet conditions during compressible and transient airflow. Energies Jan. 2022;15(3):841. https://doi.org/10.3390/en15030841.
[84] Abid H, Strunge Kany M, Mathiesen BV, Næss P, Elle M, William Maya Drysdale D. Quantification of savings for the European transport sector through energy efficient Urban planning. J Sustain Dev Energy Water Environ Syst 2022;10(4):1–14. https://doi.org/10.13044/j.sdewes.d10.0426.
[85] Ayala-Chauvin M, Riba Sanmartí G, Riba C, Lara P. Evaluation of the energy autonomy of urban areas as an instrument to promote the energy transition. Energy Sources, Part B: Economics, Planning, Policy 2022;17(1):2053897. https://doi.org/10.1080/15567249.2022.2053897.
[86] Ebersold F, Hechelmann R-H, Völker M, Oetzel J, Buchenau N. Avoidable greenhouse gas emissions in the context of corporate carbon neutrality strategies. Energy Conv Manag: X Oct. 2025;28:101321. https://doi.org/10.1016/j.ecmx.2025.101321.
[87] Peñalvo-López E, Valencia-Salazar I, León-Martínez V, Buriticá-Arboleda CI. Methodology for assessing cost of electricity for energy community members. Energy Conv Manag: X Oct. 2025;28:101258. https://doi.org/10.1016/j.ecmx.2025.101258.
[88] Huang W-H. Sources of inequality in household electricity consumption: evidence from Taiwan. Energy Sources Part B 2022;17(1):1966133. https://doi.org/10.1080/15567249.2021.1966133.
[89] Doukas H, Trachanas GP. Social acceptance, sources of inequality, and autonomy issues toward sustainable energy transition. Energy Sources Part B 2022;17(1):2121383. https://doi.org/10.1080/15567249.2022.2121383.
[90] Corral Fernandez C, Winklmaier J, Narany TS. Linear modelling of water potential and supply for decentralized energy-water-food systems - case study St. Rupert Mayer, Zimbabwe. J Sustain Dev Energy Water Environ Syst 2022;10(4):1–17. https://doi.org/10.13044/j.sdewes.d10.0422.
[91] Carrasco FA, May JF. Material sustainability of low-energy housing electric components: a systematic literature review and outlook. Sustainability 2025;17(3):852. https://doi.org/10.3390/su17030852.
[92] Němcová L, Pluskal J, Šomplák R. The integration of a new waste-to-energy plant: Waste flows modelling and pricing strategies for financial sustainability. Energy Conv Manag: X Apr. 2025;26:101054. https://doi.org/10.1016/j.ecmx.2025.101054.
[93] Nastasi B, Markovska N, Puksec T, Duić N, Foley A. Ready solutions for today and tomorrow - renewable and sustainable energy systems. Renew Sustain Energy Rev 2024;196:114341. https://doi.org/10.1016/j.rser.2024.114341.
[94] Østergaard PA, Duic N. Sustainable energy planning and management with energy scenario modelling, GIS tools and demand projection. IJSEPM 2024;42:1–4. https://doi.org/10.54337/ijsepm.9184.
[95] Lopez-Cabeza VP, Videras-Rodriguez M, Gomez-Melgar S, Andujar-Marquez JM. Methodology for the use of aerial thermography as a validation method for outdoor thermal comfort simulations. Energy Conv Manag: X Oct. 2025;28:101257. https://doi.org/10.1016/j.ecmx.2025.101257.

[96] Prasad W, Wani AD, Khamrui K, Hussain SA, Khetra Y. Green solvents, potential alternatives for petroleum based products in food processing industries. Cleaner Chem Eng 2022;3:100052. https://doi.org/10.1016/j.clce.2022.100052.

[97] Piselli C, Pisello AL, Sovacool BK. From social science surveys to building energy modeling: investigating user-building interaction for low-carbon heating solutions in Europe. Energy Rep 2022;8:7188–99. https://doi.org/10.1016/j.egyr.2022.05.119.

[98] Tagliabue LC, Cecconi FR, Maltese S, Rinaldi S, Ciribini ALC, Flammini A. Leveraging digital twin for sustainability assessment of an educational building. Sustainability 2021;13(2):480. https://doi.org/10.3390/su13020480.

[99] Sadeghi H, Jalali R, Singh RM. A review of borehole thermal energy storage and its integration into district heating systems. Renew Sustain Energy Rev 2024;192:114236. https://doi.org/10.1016/j.rser.2023.114236.

[100] Shu DY, Deutz S, Winter BA, Baumgärtner N, Leenders L, Bardow A. The role of carbon capture and storage to achieve net-zero energy systems: Trade-offs between economics and the environment. Renew Sustain Energy Rev 2023;178:113246. https://doi.org/10.1016/j.rser.2023.113246.

[101] Nedić Z, Ambroš I, Janić I, Bošković A, Cestarić D, Kulišić B. From the wood-based community to the circular, carbon-neutral and sustainable bioeconomy: recommendations for the transition. J Sustain Dev Energy Water Environ Syst 2024;12(2):1–11. https://doi.org/10.13044/j.sdewes.d12.0495.

[102] Schützenhofer S, et al. Digital ecosystem to enable circular buildings – the circular twin framework proposal. J Sustain Dev Energy Water Environ Syst 2024;12(2):1–20. https://doi.org/10.13044/j.sdewes.d12.0500.

[103] Neumann K, Hirschnitz-Garbers M. Material efficiency and global pathways towards 100% renewable energy systems – system dynamics findings on potentials and constraints. J Sustain Dev Energy Water Environ Syst 2022;10(4):1–20. https://doi.org/10.13044/j.sdewes.d10.0427.

[104] Grewal KS, Hachem-Vermette C, Yadav S. Decision-making method to prioritize and implement solar strategies on neighborhood level. Energy Rep 2024;12:2062–76. https://doi.org/10.1016/j.egyr.2024.08.009.

[105] Vecchi F, Stasi R, Berardi U. Modelling tools for the assessment of renewable energy communities. Energy Rep 2024;11:3941–62. https://doi.org/10.1016/j.egyr.2024.03.048.

[106] Arning K, Linzenich A, Ziefle M, Meuleneers L, Rezo D, Aßen NVD. Eliciting laypeople's mental models and risk perceptions of direct air carbon capture and storage: implications for effective risk communication. Energy Rep 2024;12:1068–79. https://doi.org/10.1016/j.egyr.2024.06.070.

Mladen Tomić[a,*], Predrag Rašković[b], David Astiasio Garcia[c], Neven Duić[d]

[a] *University of Novi Sad, Faculty of Technical Sciences, Department of Energy and Process Engineering, Novi Sad, Serbia*

[b] *Faculty of Technology, University of Niš, Leskovac, Serbia*

[c] *Department of Planning, Design and Architecture Technology, Sapienza University of Rome, Italy*

[d] *Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, Croatia*

[*] Corresponding author.

E-mail addresses: mladen.tomic@uns.ac.rs (M. Tomić), raskovic@tf.ni.ac.rs (P. Rašković), davide.astiasogarcia@uniroma1.it (D.A. Garcia), Neven.duic@fsb.hr (N. Duić).