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Abstract

Purpose: Show how governance, finance, digital twin (DT)/AI analytics, circular water–energy, nature-based solutions (NbS), and equity can jointly drive low-carbon, resilient, just urban energy transitions in emerging regions**.**

Methodology: PRISMA review (2014–Q1 2024) screened 500, retained 80 studies/policy records. Dual coding (kappa >0.78). Meta-ranges kept metrics with ≥3 consistent studies. Thematic triangulation mapped enablers, barriers, and gaps across Nigeria, Sub-Saharan Africa, and Southeast Asia to generate contextual performance and sequencing insights.

Findings: Efficiency, combined with distributed renewables and demand response, cuts emissions by 18–42%. DT/predictive analytics reduce district energy intensity by 5–12% and O&M by 10–25%. Circular measures lower utility energy intensity 8–22% and offset 20–40% potable demand. NbS cut peak runoff 20–55%, inundation depth 10–25%, heat island 0.5–2.5°C. Equity actions reduced the energy burden by 5–18% and prioritized flood exposure by 20–40%. Enablers: polycentric coordination, interoperable data, blended finance, standardized metrics, ethical AI, just transition framing**.**

Unique Contribution to Theory, Practice and Policy: Meta-range synthesis clarifies performance bands linking technical gains with resilience and equity outcomes. Regional DT/AI maturity and circular leverage points inform sequencing in Nigeria, Sub-Saharan Africa, Southeast Asia, underscoring the need for synchronized data governance and integration**.** Adopt interoperable data and AI charters; expand blended, performance-linked finance tied to resilience and equity KPIs; incentivize leak analytics, modular digestion, reclaimed cooling; mandate equity and anti-displacement audits; build DT validation capacity; apply equity-adjusted valuation.

Keywords: *Urban Energy Planning, Circular Water–Energy Nexus, Digital Twin, Nature-Based Solutions, Governance, Equity, Just Transition*

JEL Codes: *Q48, Q25, O33, Q57, Q58, D63, R58*

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INTRODUCTION

Urban areas generate the most global energy-related greenhouse gas emissions while being hotspots of climate risk, including heat waves, pluvial and coastal flooding, drought stress, and critical infrastructure interdependency failures (Acuto et al., 2018; Rogelj et al., 2018; Seto et al., 2021; Steffen et al., 2015). Rapid growth in sub-Saharan Africa and Southeast Asia amplifies the urgency of planning frameworks that internalize cross-sector couplings among electricity, thermal energy, mobility, water services, and land use. Siloed paradigms struggle to address nonlinear hazards, socio-spatial vulnerability gradients, and evolving demand patterns (Markolf et al., 2018; Olazabal et al., 2019). Capital scarcity, data gaps, and infrastructural informality constrain low-carbon deployment in many African and Nigerian urban contexts (Pelling et al., 2024; Ogunmodede et al., 2023; Adelekan, 2021). Southeast Asian megacities face compounded subsidence, tidal and pluvial flood interactions, and energy–water dependencies (Chan et al., 2022). Nigeria's rapidly expanding cities exemplify the challenges in risk-informed energy siting and service reliability under data governance deficits (Adelekan & Asiyanbi, 2016).

Five converging domains underpin transformative potential: (1) polycentric, adaptive governance integrating municipal, metropolitan, national, and network scales (Andonova, 2022; Hsu et al., 2020); (2) diversified, performance-oriented finance (OECD, 2023); (3) digital twin (DT) and AI ecosystems for forecast, optimization, and scenario exploration (Mohammadi & Taylor, 2021; Fuller et al., 2020); (4) circular water–energy nexus strategies leveraging reuse, resource recovery, and flexible demand (Garcia & You, 2018); and (5) equity and transition integration across distributional, procedural, and recognitional dimensions (Sovacool et al., 2020; Bouzarovski et al., 2023).

Barriers include fragmented data stewardship (Richardson et al., 2023), limited creditworthiness and preparation pipelines (OECD, 2023), underdeveloped resilience and equity metrics (Sharifi, 2021; Olazabal et al., 2019), and insufficient longitudinal evaluation of AI/DT performance (Eker et al., 2019). This study contributes by synthesizing cross-cutting evidence into an energy planning-centric framework, establishing meta-range performance bands for governance, finance, technology, nexus, equity interventions, and proposing context-sensitive policy pathways relevant to Sub-Saharan Africa, Southeast Asia, and Nigeria (Garcia & You, 2018; Ramaswami et al., 2016). Research questions focus on government–finance configurations, intervention performance ranges, the implications of DT/AI equity, the efficacy of equity interventions, and strategic policy acceleration levers (Sovacool et al., 2020).

Problem Statement

Urban energy planning still lacks integrated treatment of resilience, equity, and technological innovation; scholarship is dominated by high-capacity global pilots, while African (especially Nigerian) contexts remain underrepresented (Pelling et al., 2024; Adelekan, 2021). This study addresses the absence of cross-domain synthesis spanning governance, finance, digital twin/AI, the circular water–energy nexus, and equity, alongside the shortage of empirical evidence and validation pathways for low-capacity, data-fragmented cities, and the limited analysis of transition distributional and co-benefit impacts. The findings aim to inform policymakers, municipal planners, regional financiers, and vulnerable communities across Nigeria, Sub-Saharan Africa, and Southeast Asia.

METHODOLOGY

Protocol

A PRISMA-aligned systematic review (2014–Q1 2024) encompassed academic databases (Scopus, Web of Science, ScienceDirect, IEEE Xplore) and policy repositories (IPCC, IEA, OECD) (IPCC, 2022a; IPCC, 2022b; OECD, 2023).

Search Strategy, Screening, and Data Extraction

Keyword clusters encompass governance/polycentricity, digital twin/AI, circular water–energy, Nature-Based Solutions (NBS), green infrastructure, transition/energy justice, and financing instruments (Garcia & You, 2018; Kabisch et al., 2017). Regional terms (such as those used in Africa, Southeast Asia, and Nigeria) ensure contextual relevance (Adelekan, 2021; Chan et al., 2022). From 500 initial records, 350 full texts were evaluated; 80 met the inclusion criteria, emphasizing urban energy-resilience relevance, methodological transparency, and empirical or modelling rigor (Sharifi, 2021). Structured coding captures the governance typology, financial instruments, intervention classes, outcome metrics (including energy intensity, emissions, and flood/heat mitigation), equity dimensions, and enabling/barrier factors (Olazabal et al., 2019; Sovacool et al., 2020). Dual coding (15%) yielded $\kappa > 0.78$.

Synthesis, Bais & Limitations

Due to heterogeneity, a meta-range synthesis was aggregated from performance intervals that required at least three independent studies with comparable metrics (Sharifi, 2021). Ranges reported Min–Max and IQR when the density was allowed. Publication bias favors high-capacity city pilots (Berrang-Ford et al., 2021); and underrepresentation of African informality elevates uncertainty (Pelling et al., 2024). DT/AI claims often lack multi-year validation (Fuller et al., 2020).

Ethical/Data Governance and PRISMA Flow

The extraction recorded AI bias mitigation disclosures (with low prevalence) (Heikkilä et al., 2022). No personal data was processed. Reasons for exclusion include scope mismatch, insufficient methodology, duplicates, and non-urban focus (Sharifi, 2021).

RESULTS AND THEMATIC SYNTHESIS

Governance and Financing

Polycentric governance enhances coordination, knowledge diffusion, and policy transfer, supporting coherent multisector energy plans (Gupta et al., 2015; Andonova, 2022; Hsu et al., 2020). Open-data regimes reduce information asymmetry and investor risk premiums (Attard et al., 2022; Richardson et al., 2023). City networks accelerate the diffusion of benchmarking and resilience frameworks (Broto & Bulkeley, 2014). Financing innovation encompasses green/sustainability-linked municipal bonds (Flammer, 2021), blended finance leveraging DFI concessional tranches, resilience bonds that connect hydrological performance to coupon adjustments (OECD, 2023), land value capture for transit-energy integration (Gouldson et al., 2016), and climate budget tagging. Enablers: Codified action plans with KPIs (Hsu et al., 2020), asset registries (Ramaswami et al., 2016), risk stress testing (Markolf et al., 2018), and embedded equity safeguards that reduce procedural delays (Sovacool et al., 2020; Heffron & McCauley, 2018). Constraints: Municipal creditworthiness gaps, project preparation deficits, and standardized MRV scarcity in many African contexts (Allan et al., 2022; Pelling et al., 2024; Ogunmodede et al., 2023). Case illustrations: Rotterdam's sponge + energy efficiency synergy (van den Berg et al., 2021); Singapore's centralized adaptive governance enabling water reuse energy optimization (Tortajada & Zhang, 2021); and Kigali's low-emission mobility with PPP and concessional finance (Uwizeyimana et al., 2023). Causal inference limitations persist due to selection bias; higher-capacity cities concurrently adopt robust MRV and advanced finance.

Resilience and Nature-Based Solutions

Hybrid gray–green systems, instrumented with telemetry and IoT sensing, enable dynamic, model-predictive adaptation, translating real-time hydrometeorological data into anticipatory storage, diversion, and cooling actions (Kabisch et al., 2017; Raymond et al., 2017; Frantzeskaki, 2019). Meta-analyses show combined green roofs, bioswales, and permeable pavements can cut peak runoff 20–55% , while incremental urban canopy expansion lowers localized peak air temperatures by 0.5–2.5°C, dampening heat-driven electricity peaks (Vieira et al., 2018) and contributing to modest building cooling demand reductions that, when aggregated, free grid capacity for electrification. Mangrove–levee hybrids attenuate inundation depths by 10–25%, reducing overtopping probabilities for coastal substations and transport corridors (Chan et al., 2022), while sponge landscape retrofits limit cascading outage risk by shielding transformers and switchgear from short-duration pluvial surges (Markolf et al., 2018).

Constructed wetlands and detention systems simultaneously remove pollutant loads and yield energy savings through reduced high-lift pumping and aeration requirements, improving lifecycle cost–benefit ratios (Garcia & You, 2018). Integrated circular water–energy design further supports decentralized anaerobic digestion and reclaimed water loops, enhancing resilience value stacking even where formal creditworthiness is weak. However, without safeguards, amplified amenity and microclimate gains can trigger green gentrification, necessitating anti-displacement provisions, affordability covenants, and community land instruments. Meanwhile, participatory co-design and inclusive stewardship norms can elevate maintenance reliability and socio-political legitimacy (Satterthwaite et al., 2020). Practice cases illustrate contextual pathways: Cape Town's "Day Zero" crisis response braided aggressive demand reduction, aquifer recharge, decentralized green infrastructure, and behavioral feedback loops to defer system failure (Ziervogel, 2019); Lagos is advancing wetland and mangrove buffer integration into multi-hazard flood strategies despite implementation frictions tied to informality and tenure ambiguity (Adelekan, 2021); and Ibadan's community-driven, low-cost green–blue interventions show how locally governed micro-infrastructure can scale cumulatively to reduce hazard exposure while building social capital (Ajibade, 2019). Collectively, these insights underscore the need for equity-anchored, telemetry-enabled hybrid infrastructure portfolios that internalize socio-spatial vulnerability, monetize avoided outages and health externalities, and align just transition objectives with measurable hydrologic, thermal, and energy system performance gains.

Circular Water–Energy Nexus

Circular interventions deliver co-benefits in terms of energy intensity, emissions, and water security (Garcia & You, 2018). Leak analytics: 5–15% non-revenue water reduction with 2–8% energy savings. Anaerobic digestion + CHP offsets 30–70% of plant electricity (Corbitt et al., 2022; Howells et al., 2016). Variable frequency drive optimization reduces the pumping energy by 8–18% (Garcia & You, 2018). Reclaimed water for district cooling offsets 20–40%

of potable demand (IEA, 2022). Heat recovery (wastewater/data centers) curbs the primary demand for district energy by 5–12% (Garcia & You, 2018; Lund et al., 2017). Sector coupling: Integrating water reuse and thermal storage reshapes the net load, facilitating renewable integration (Lund et al., 2015; Mathiesen et al., 2015; Ramaswami et al., 2016). The flexible scheduling of pumping aligns with periods of low marginal emissions (Howells et al., 2016; Garcia & You, 2018). Barriers include capital intensity, tariff misalignment, limited feed-in incentives for biogas, and O&M skill gaps (OECD, 2023). Enablers: Stable reuse standards, concessional finance, and digital asset management (Fuller et al., 2020; Attard et al., 2022).

Digital Twins and AI

DT evolution spans static geospatial models to real-time cyber-physical platforms that integrate sensors, SCADA, and IoT streams (Batty, 2018; Mohammadi & Taylor, 2021; Fuller et al., 2020). Semantic interoperability and modular simulation engines improve the scenario reliability (Ketzler et al., 2020). Performance ranges: Predictive flood modeling extends the lead time by 15–40% (Deng et al., 2021; Batty, 2018); district energy DT optimization reduces the intensity by 5–12% (Mohammadi & Taylor, 2021; Fuller et al., 2020); leak detection ML yields 10–25% O&M savings and 5–15% energy savings; building energy twins achieve 8–20% reductions; and mobility optimization curbs the EV peak load by 6–15% (Reardon & Marsden, 2019; McKenna & Parag, 2019). Equity: Risk of algorithmic invisibility in under-instrumented informal settlements (Satterthwaite et al., 2020; Richardson et al., 2023). Data trusts and bias audits enhance accountability (Heikkilä et al., 2022). Bottlenecks: proprietary legacy systems, sensor drift, limited municipal data science capacity, and procurement not embedding ethics KPIs (Attard et al., 2022).

Equity, Energy Justice, and Just Transition

Only transition principles—distributional, procedural, recognitional, and digital justice—guide equitable benefit allocation and participatory inclusion (Heffron & McCauley, 2018; Sovacool et al., 2020; Jenkins et al., 2021). Lifeline tariffs and efficiency retrofits reduce the low-income expenditure share by 5–18% (Bouzarovski et al., 2023; Jenkins et al., 2021). A gender-responsive transit design improves perceived safety by 15–30% (Ng & Acker, 2023; Ratanavilasut & Tan, 2022). Informal settlement upgrading lowers flood exposure by 20–40% (Satterthwaite et al., 2020; Adelekan, 2021). Community energy cooperatives enhance localized resilience and acceptance (Walker et al., 2014; McKenna & Parag, 2019). Digital literacy hubs support participation in demand response and distributed solar enrollment (McKenna & Parag, 2019; Sovacool & Griffiths, 2020). Intersectional burdens, such as cooling poverty and unpaid adaptation labor, require disaggregated data collection (Bouzarovski et al., 2023).

Discussion

Synergies

Governance and data integration amplify financial readiness and DT predictive accuracy, enhance performance MRV, and reduce risk premiums. Circular water-energy assets provide flexible demand-shaping renewable integration (Garcia & You, 2018; Howells et al., 2016). NbS co-delivers hydrological and microclimate benefits that safeguard the energy infrastructure and moderate cooling loads (Kabisch et al., 2017; Demuzere et al., 2019).

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Trade-offs and Uncertainty Governance

Digitization without equity frameworks risks a spatial investment bias (Heikkilä et al., 2022; Richardson et al., 2023). NbS-driven amenity uplift may induce displacement-absent anti-gentrification safeguards. Proprietary DT ecosystems create lock-ins (Fuller et al., 2020). Adaptive management via robust decision-making and dynamic pathways benefits federated DTs that link urban scales (Ramaswami et al., 2016; Markolf et al., 2018).

Finance Additionality, Capacity, Equity Integration Gaps and Interdependencies

Attribution complexities arise from the interaction of policy and financial instruments; standardized counterfactual modeling and transparent open-ledger MRV can mitigate greenwashing (OECD, 2023). Hybrid skill sets (systems modeling, equity evaluation, and data governance) are scarce (Sovacool et al., 2020; Jenkins et al., 2021). Open-source modeling libraries and South–South exchanges can shorten the learning curve (Ramaswami et al., 2016). Distributional metrics are improving, but procedural and recognitional indicators are less institutionalized (Heffron & McCauley, 2018; Sovacool et al., 2020). Early equity co-design reduces legal and social contestations. Cascading failures (water pumps, grid substations, and mobility) underscore integrated resilience planning to avoid misallocation of adaptation capital (Markolf et al., 2018; Sharifi & Yamagata, 2016).

Policy Recommendations

Governance and Standards: Create polycentric coordination bodies with mandatory data-sharing ontologies (Gupta et al., 2015; Andonova, 2022; Hsu et al., 2020). Interoperable semantic models (Ketzler et al., 2020). Financing: Expand performance-linked NbS/resilience bonds with multi-benefit KPIs (OECD, 2023). Build project preparation facilities for circular water–energy infrastructure (Garcia & You, 2018; Howells et al., 2016). Regulation: Mandate energy–water co-optimization assessments for significant capital projects (Ramaswami et al., 2016; Lund et al., 2017). Provide tiered incentives for reclaimed water integration (IEA, 2022). Data and Ethical AI: Institutionalize AI ethics charters covering bias audits, explainability, and community consultation (Heikkilä et al., 2022). Implement data trusts on steward-sensitive socio-spatial datasets (Sovacool et al., 2020). Equity: Requires equity impact assessments at planning gates; enforces anti-displacement mechanisms for large NbS and transit-energy districts (Heffron & McCauley, 2018). Capacity: Fund interdisciplinary training in systems modelling, hydrological risk, financing, and algorithmic accountability (Jenkins et al., 2021). Monitoring and Evaluation: Standardize MRV dashboards integrating energy, resilience, and equity metrics (Sharifi, 2021; Olazabal et al., 2019). Encourage anonymized benchmark consortia (Hsu et al., 2020).

Collaboration: Facilitate South–South exchanges on blended finance and low-cost circular pilots (Pelling et al., 2024; Ogunmodede et al., 2023).

Future Research and Limitations

Equity-adjusted cost–benefit frameworks that integrate avoided outage costs and health co-benefits require standardization (Jenkins et al., 2021; Sovacool et al., 2020). Federated DT validation protocols and interoperable uncertainty quantification methods remain nascent (Ketzler et al., 2020; Fuller et al., 2020). Additionality methodologies for blended finance require robust counterfactual baselines. Algorithmic fairness metrics specific to urban energy services must address the representation gaps (Heikkilä et al., 2022). Integrating circular nexus modeling with socio-spatial vulnerability mapping will optimize intervention prioritization

(Garcia & You, 2018). Limitations: Heterogeneous metrics obviate formal meta-analyses, publication bias toward successful pilots (Berrang-Ford et al., 2021); and variable equity indicator definitions. Temporal maturity bias affects DT's impact on sustainability (Mohammadi & Taylor, 2021). Gray literature stability is uncertain (IBM & Dublin City Council, 2016).

Data Gaps: Informal settlements and secondary cities are underrepresented; remote sensing plus targeted ground truthing could expedite inclusion (Adelekan, 2021).

CONCLUSION AND RECOMMENDATIONS

Conclusion

Integrating decarbonization, resilience, and justice requires governance, finance, and digital convergence, coupled with circular water–energy strategies and ethically governed digital and AI platforms (Ramaswami et al., 2016; Garcia & You, 2018; Sovacool et al., 2020). NbS and hybrid infrastructure contribute to protective hydrological and thermal services that indirectly reinforce energy reliability and lower demand (Kabisch et al., 2017; Demuzere et al., 2019). Equity-centered interventions bolster legitimacy and accelerate implementation, while mitigating distributional and procedural risks. Persistent barriers—data fragmentation, capacity imbalances, limited additionality metrics, and algorithmic bias- necessitate standardized resilience/equity indicators, federated DT validation, and equity-adjusted valuation frameworks (Ketzler et al., 2020; Jenkins et al., 2021). A transition reframes success beyond aggregate emissions toward fair and inclusive outcomes (Bouzarovski et al., 2023; Sovacool et al., 2020). Adaptive learning loops, open data stewardship, and inclusive financing architectures provide actionable pathways for diverse urban contexts, fostering coherent and sustainable energy planning.

Recommendations

Urban policymakers and financing partners should first institutionalize interoperable data and ethical AI charters to reduce information irregularities, investor risk premiums, and algorithmic exclusion, while simultaneously scaling blended and performance-linked finance instruments tied to transparent, standardized resilience and equity KPIs. Parallel incentives for circular water–energy integration, such as leak analytics, modular anaerobic digestion, and reclaimed water for district or process cooling, should be structured to shape flexible demand and facilitate the penetration of renewable energy. Equity impact and anti-displacement assessments must become gating requirements for major NbS and integrated energy–water investments, ensuring that hydrological and microclimate gains do not catalyze exclusion. Building local systems modelling and federated DT validation capacity, particularly in under-instrumented settlements, will narrow uncertainty ranges and improve adaptive planning. Finally, developing equity-adjusted valuation methods and robust finance additionality frameworks is essential to prevent greenwashing, sharpen capital allocation, and align decarbonization, resilience, and justice outcomes across rapidly urbanizing regions.

Ethical statement: The study conforms to standard ethical values.

Conflict of Interest declaration: The author declares that they have no affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

REFERENCES

1. Acuto, M., Parnell, S., & Seto, K. C. (2018). Building a global urban science. Nature Sustainability, 1(1), 2–4.
2. Adelekan, I. (2021). Flood risk and climate resilience in Lagos, Nigeria. Climate and Development, 13 (10), 879–891.
3. Adelekan, I., & Asiyanbi, A. (2016). Flood risk perception in flood-affected communities in Lagos. Natural Hazards, 80 (1), 445–469.
4. Ahlborg, H., & Nightingale, A. J. (2018). Theorizing power in energy transitions. Energy Research & Social Science, 38,1. Acuto, M., Parnell, S., & Seto, K. C. (2018). Building a global urban science. Nature Sustainability, 1 (1), 2–4.
5. Ajibade, I. (2019). Planned retreat in Lagos: Environmental justice and uneven adaptation futures. Global Environmental Change, 57, 101939.
6. Amenta, L., & van Timmeren, A. (2018). Beyond waste: Circular city planning. Sustainability, 10 (12), 4394
7. Andonova, L. (2022). The governance of city climate networks. Global Environmental Politics, 22 (1), 60–82.
8. Aronson, M. F. J., et al. (2022). Urban biodiversity and nature-based solutions in African cities. Sustainability, 14 (5), 2891.
9. Attard, M., et al. (2022). Open data for sustainable urban mobility governance. Sustainable Cities and Society, 80,103795.
10. Bai, X., et al. (2018). Six research priorities for cities and climate change. Nature Climate Change, 8, 129–132.
11. Berrang-Ford, L., et al. (2021). A systematic global stocktake of evidence on human adaptation. *Nature Climate Change, 11, 999–1006.
12. Bouzarovski, S., Thomson, H., & Cornelis, M. (2023). Energy poverty and justice in the urban transition. Energy Research & Social Science, 96 102949.
13. Broto, V. C., & Bulkeley, H. (2014). Urban experiments as climate governance. Global Environmental Change, 26, 136–144.
14. Carmin, J., et al. (2015). Urban climate adaptation and governance. Climatic Change, 129,1–2.
15. Castán Broto, V. (2020). Urban energy landscapes. Cambridge University Press.
16. Chatzivasileiadi, A., et al. (2015). Renewable energy and smart energy systems in smart cities. Sustainable Cities and Society, 14, 104–115.
17. Chan, F., et al. (2022). Coastal adaptation pathways in Southeast Asia. Climate Risk Management, 36, 100443.
18. Corbitt, R., et al. (2022). Energy recovery in wastewater treatment. Journal of Cleaner Production, 339,130512.
19. Creutzig, F., et al. (2019). Demand-side solutions to climate change mitigation. Nature Climate Change, 9, 796–802.
20. De Coninck, H., & Benson, S. M. (2014). Carbon dioxide capture and storage: Update. Annual Review of Environment and Resources, 39, 243–270.
21. De Coninck, H., et al. (2018). Strengthening and implementing the global response to the threat of climate change. Energy Research & Social Science, 46, 316–329.
22. Demuzere, M., et al. (2019). Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green infrastructure. Landscape and Urban Planning, 182,12–27.

23. Deng, Y., et al. (2021). Machine learning for urban flood prediction. Water Resources Research, 57 (4), e2020WR029176.
24. Flammer, C. (2021). Corporate green bonds and environmental performance. Journal of Financial Economics, 142 (2), 499–516.
25. Frantzeskaki, N. (2019). Urban sustainability transitions with nature-based solutions. Current Opinion in Environmental Sustainability, 39, 1–8.
26. Fuller, A., et al. (2020). Digital twin: Enabling technologies. IEEE Access, 8, 108952–108971.
27. Fuso Nerini, F., et al. (2018). Mapping synergies between energy and the Sustainable Development Goals. Nature Energy, 3, 10–15.
28. Garcia, D. J., & You, F. (2018). The water-energy-food nexus in urban sustainability. Applied Energy, 228, 975–989.
29. Giezen, M., et al. (2018). Adapting the adaptive planning approach. Environmental Science & Policy, 83,125–131.
30. Gouldson, A., et al. (2016). The economics of low carbon cities. Energy Policy, 91, 447–457.
31. Heikkilä, M., et al. (2022). Ethical governance of AI in smart cities. AI & Society, 3 1461–1475.
32. Hsu, A., et al. (2020). Performance determinants of subnational climate action. Nature Communications, 11, 5405.
33. Hurlbert, M., & Rayner, S. (2018). Adaptive governance of energy systems transitions. Energy Research & Social Science, 37,254–259.
34. IBM & Dublin City Council. (2016). Flood alert digital twin pilot report.
35. Intergovernmental Panel on Climate Change. (2022a). AR6 WGII: Impacts, adaptation, and vulnerability.
36. Intergovernmental Panel on Climate Change. (2022b). AR6 WGIII: Mitigation of climate change.
37. International Energy Agency. (2022). Water-energy nexus in urban infrastructure.
38. Jenkins, K., McCauley, D., Heffron, R., Stephan, H., & Rehner, R. (2021). Energy justice: A policy review. Energy Policy, 156, 112410.
39. Kabisch, N., et al. (2017). Nature-based solutions for urban climate resilience. Urban Forestry & Urban Greening, 21, 1–19.
40. Ketzler, B., et al. (2020). Digital twins in urban water management. Water, 12 (11), 3183.
41. Lim, C., et al. (2022). Virtual Singapore: A federated digital twin. Computers, Environment and Urban Systems, 95, 101836.
42. Lund, H., et al. (2015). Smart energy systems for coherent 100% renewable energy and transport solutions. Applied Energy, 145 139–154.
43. Lund, H., et al. (2017). Smart energy Europe: The technical and economic impact. Energy, 132, 845–859.
44. Markolf, S. A., et al. (2018). Interdependent infrastructure vulnerabilities. Earth's Future, 6 (8), 1359–1379.
45. Mathiesen, B. V., et al. (2015). Smart energy systems for coherent 100% renewable solutions. Applied Energy, 145, 139–154.
46. McCollum, D. L., et al. (2018). Interaction of SDGs and energy systems. Nature Energy, 3,10–15.

47. McKenna, R., & Parag, Y. (2019). Distributed energy prosumers. Renewable and Sustainable Energy Reviews, 113,109257.
48. Meijer, A., & Bolívar, M. P. R. (2016). Governing the smart city. Government Information Quarterly, 33 (2), 372–382.
49. Mohammadi, N., & Taylor, J. (2021). Smart city digital twins. Journal of Management in Engineering, 37 (2), 04020102.
50. Mueller, N., et al. (2020). Urban green space and mobility in superblocks. Environment International, 135,105337.
51. Ng, M., & Acker, A. (2023). Gender-responsive transit planning. Transport Policy, 128, 34–45.
52. Ogunmodede, A., et al. (2023). Data governance and smart city development in Nigeria. Cities, 139,104321.
53. Olazabal, M., et al. (2019). A cross-scale worldwide analysis of coastal adaptation planning. Cities, 95,102438.
54. Organisation for Economic Co-operation and Development. (2023). Scaling up finance for nature-based solutions.
55. Pasimeni, M. R., et al. (2019). Indicators for urban green infrastructure planning. Ecological Indicators, 96, 146–157.
56. Pelling, M., et al. (2024). Urban adaptation governance in African cities. Climate and Development, 16 (1), 12–24.
57. Ramaswami, A., et al. (2016). Urban systems integration for environmental sustainability. Environmental Science & Technology, 50 (14), 7725–7736.
58. Ratanavilasut, R., & Tan, H. (2022). Disability-inclusive urban transport in Southeast Asia.Sustainable Cities and Society, 84,104011.
59. Raymond, C. M., et al. (2017). A framework for assessing and implementing nature-based solutions. Ecosystem Services, 29, 229–247.
60. Reardon, L., & Marsden, G. (2019). Smart mobility: Contemporary policy approaches. Transportation Research Part A, 131,290–302.
61. Ribeiro, P., & de Sousa, L. (2021). Integrated urban climate planning. Journal of Environmental Planning and Management, 64 (14), 2505–2526.
62. Ribeiro, P. J. G., & Pena Jardim Gonçalves, L. A. (2019). Urban resilience: A conceptual framework. Sustainable Cities and Society, 47, 101528.
63. Rogelj, J., et al. (2018). Mitigation pathways compatible with 1.5°C. Nature Climate Change, 8, 325–332.
64. Samuelson, R., et al. (2021). Comparative analysis of urban heat mitigation strategies. Sustainable Cities and Society, 74, 103188.
65. Seto, K. C., et al. (2021). Urban land teleconnections and emissions. Nature Reviews Earth & Environment, 2, 699–715.
66. Sharifi, A. (2021). Urban resilience assessment: A systematic review update. Sustainable Cities and Society, 64,102516.
67. Sharifi, A. (2022). Resilience-oriented urban form: A critical review. *Sustainable Cities and Society, 76,103442.
68. Sharifi, A., & Yamagata, Y. (2016). Principles and criteria for assessing urban resilience. Sustainable Cities and Society, 27, 222–232.
69. Sovacool, B. K., & Griffiths, S. (2020). The cultural dynamics of energy. Energy Policy, 141,111468.

70. Sovacool, B. K., Hook, A., Martiskainen, M., & Baker, L. (2019). Decarbonization and its discontents: Energy justice implications. Nature Energy, 4, 1008–1016.
71. Sovacool, B. K., et al. (2017). Vulnerability in the energy system. Energy Policy, 109,10–26.
72. Sovacool, B. K., et al. (2020). Energy justice in transitions. Applied Energy, 282, 116273.
73. Steffen, W., et al. (2015). Planetary boundaries: Guiding human development. Science, 347 (6223), 1259855.
74. Turnheim, B., et al. (2015). Evaluating sustainability transitions policy mixes. Research Policy, 44 (3), 522–540.
75. Uwizeyimana, D., et al. (2023). Low-emission mobility in Kigali. Sustainable Cities and Society, 90, 104247.
76. Ürge-Vorsatz, D., et al. (2018). Lock-in and opportunities for decarbonizing buildings. Energy Research & Social Science, 40, 89–101.
77. van den Berg, H., et al. (2021). Sponge infrastructure performance in Rotterdam. Water Science & Technology, 84 (7), 1680–1693.
78. Vieira, J., et al. (2018). Green infrastructure and urban planning: A review. Science of the Total Environment, 651, 1083–1093.
79. Wainstein, M. E., & Bumpus, A. (2016). Finance innovation and sociotechnical transitions. Environmental Innovation and Societal Transitions, 21, 26–40.
80. Walker, G., et al. (2014). Community energy systems and social sustainability. People, Place and Policy, 8 (3), 36–50.