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Ten questions concerning the design of urban energy systems

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ABSTRACT

Urban energy systems (UES) design must adapt to the multifaceted challenges of an evolving global energy landscape. This study examines ten critical questions that define current challenges, methodologies, and future priorities in UES design, providing a comprehensive understanding of techno-economic and socio-institutional aspects. It first examines the lateral and vertical interactions across spatial scales, sectors, and time, as well as the evolving needs in heating, cooling, transportation, and renewable integration. Consequently, the study critically assesses the capabilities and limitations of current energy system modeling practices, highlighting challenges related to data requirements, system complexity, scalability, and uncertainty analysis. It then discusses building energy demand and building stock modeling to provide high-resolution analyses of decarbonization pathways and to support effective demand-side management and storage solutions. As these approaches require data, the role of data availability and governance in UES design through the integration of advanced technologies such as artificial intelligence is reviewed. Moreover, it is important to consider dimensions beyond digital tools. The study discusses the inclusion of broader environmental dimensions beyond greenhouse gas emissions into UES planning to ensure sustainable pathways. It also emphasizes the role of governance, policy, business models, and social engagement in successful deployment of UES. Finally, this study analyzes how UES design can enable emerging urban visions and address the unique challenges faced by low- and middle-income countries in the Global South. By answering the ten most relevant questions on UES design, this paper aims to examine the future priorities of UES design and to offer actionable solutions for creating more resilient, fair, and sustainable urban energy futures.

1. Introduction

1.1. Background and definition

The transformation of cities is essential to tackle climate change and to advance the global energy transition [1,2]. Although cities occupy only 3% of the earth's land surface, they host 60 % of the human population and contribute over 70% of global carbon emissions [1]. They also generate over 80% of global GDP [3] and serve as hubs of innovation, infrastructure, and cross-sectoral collaboration, making them key enablers of systemic change. The urban energy landscape is evolving due to techno-institutional changes, such as advancements in distributed energy resources, evolving policies and regulations [4,5], digitalization, the depletion of fossil fuels, and the increasing challenges of climate change [6–10]. Recent policies and governance frameworks, such as the EU Clean Energy Package (RED II, 2018; EMD II, 2019) and the European Green Deal, set ambitious targets for renewable energy deployment, energy efficiency, and energy security [11–13]. These policies emphasize the importance of citizen and community engagement in designing more sustainable and citizen-centric urban energy systems (UES) [14–21]. In response, many cities are adopting ambitious decarbonization strategies, including increasing renewable energy integration, sector coupling, and electrifying traditionally carbon-intensive sectors like transportation and heating [22–25]. Achieving climate and energy policy goals requires UES design to consider rapid decarbonization and defossilization while balancing the energy policy trilemma [26]: ensuring energy security, sustainability, and affordability. Meeting energy and climate policy objectives also demands fundamental shifts toward digitalized, decentralized, and democratized UES [5,7,27–29]. Although increasing integration of distributed energy sources addresses

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climate change issues in UES, new challenges regarding system integration and governance are emerging, which need to be addressed through system-thinking and design approaches.

Various definitions of UES exist in the literature. Keirstead, Jennings, and Sivakumar (2012) describe UES as the combined processes of acquiring and using energy to meet urban energy service demands while capturing the influence of urban form, economic function, and energy supply attributes [30]. Pastor, Fraga, and López-Cózar (2023) define UES as systems that use energy to meet urban heating, cooling, and transport needs [31]. Building on the JPI Urban Europe definition, Koirala et al. (2024) describe UES as efficient and flexible decentralized systems composed of interconnected consumers and producers that actively manage renewable energy production and consumption while minimizing greenhouse gas emissions [32,33]. Based on these definitions, in this 10Q paper, we analyze UES as inherently complex socio-technical systems that integrate diverse actors, decision-making entities, and technological components within multi-level institutional frameworks [34,35]. These systems are also assumed to span multiple spatial scales, from buildings and neighborhoods to districts and entire cities, integrating various energy carriers, technologies, and infrastructures while interacting with users, transmission and distribution grids, mobility, and information and communication technologies (ICT) to ensure a secure and sustainable energy supply. We define UES as integrated systems that manage and optimize the generation, distribution, conversion, storage, and consumption of multiple energy vectors across urban areas, involving diverse stakeholders and spatial scales. UESs are multi-dimensional, integrating physical infrastructures, urban forms, governance processes, and socio-economic and environmental contexts. Unlike district energy systems with centralized generation or micro-grids focused solely on localized electricity management, UES are overarching systems encompassing various emerging techno-economic and socio-institutional options for integrating energy in the urban built environment. They play a critical role in energy and climate policy agendas, serving as innovation hubs for energy efficiency and climate neutrality strategies. With increasing prominence in research and policy landscape, UES are vital to advancing sustainable and just urban transitions.

1.2. State-of-the-art and research gaps

The emergence of distributed energy resources has accelerated the adoption of renewable energy and storage technologies, enabling innovative bottom-up approaches driven by citizen initiatives and supported by local authorities and energy system stakeholders [7,36–39]. Various energy system integration approaches and urban visions are reshaping UES design, such as community micro-grids [40], integrated community energy systems [7,41–43], energy communities [16,28,29,38,44,45], positive energy districts (PEDs) [32,46–48], zero-energy communities [49], and zero-emission neighborhoods [50]. These configurations are critical pathways for scaling decarbonization efforts while fostering sustainable solutions with strong stakeholder engagement in UES design.

The previous ten question papers have also addressed various aspects of UES design. Sareen et al. (2022) examine the challenges and opportunities of implementing PEDs in Europe, emphasizing the importance of context-specific solutions, rapid implementation, and collaborative governance for successful urban energy transitions [47]. Hong et al. (2020) focus on the necessity of computational tools and urban datasets to optimize energy performance in buildings at the urban scale, highlighting key challenges in energy efficiency, sustainability, and resilience [51]. Good et al. (2017) explore the concept of "smart districts" by addressing ten critical questions across physical, commercial, planning, and operational dimensions, proposing a flexibility-based approach to energy efficiency and critiquing traditional energy models [52]. Finally, Mavromatidis et al. (2019) discuss the latest advancements in modeling Distributed Multi-Energy Systems (D-MES), covering key topics like optimization versus simulation, technical constraints, integration with urban energy models, uncertainty, scalability, and holistic modeling [53]. While these existing 10Q papers have significantly advanced the discourse on UES design, each approach the topic from a specific thematic angle, including PEDs, building energy modelling, smart districts, and modelling of D-MES, respectively. This 10Q paper is distinct in its integration of techno-economic, socio-institutional, and environmental dimensions. By reflecting on the systemic complexity of UES design, it underscores the need for holistic planning and governance frameworks. The review provides a guiding structure for both researchers and practitioners, while also highlighting emerging challenges and the current lack of actionable insights.

Beyond the above-mentioned 10Q papers, previous research on UES design is fragmented on techno-economic and social-institutional dimensions. Many studies have focused primarily on techno-economic modeling approaches to planning UES [7,42,43,47,54–58]. For example, Volpe et al. (2022) studied the role of prosumers and electricity exchange between buildings [59]. Burg et al. (2023) performed a spatiotemporal analysis of Switzerland's waste heat potential, considering different temperature levels and seasonal fluctuations [60]. Neumann et al. (2021) explored different urban typologies by combining energy efficiency and renewable energy measures [61]. These studies offer valuable insights into the technical feasibility of UES but risk proposing solutions incompatible with actual societal needs and institutional conditions. Moreover, these studies employ sophisticated mathematical models, which are also often beyond the reach of urban planners and practitioners. In UES design, local energy planners, researchers, and decision-makers must often manage incompatible modeling tools and data sets. The existing techno-economic energy system planning models often provide a constrained, static, and isolated view of UESs in this multi-actor context. Research on the social and institutional aspects of UES is also evolving. Koutra et al. (2023) unveiled multiple gaps in human-centric solutions and regulatory frameworks [62]. Casamassima et al. (2022) reviewed the economic, social, and environmental aspects [63]. Nguyen and Batel (2021) propose a framework to create a more just and inclusive UES [64]. Guarino et al. (2022) reviewed sustainability assessment approaches and found that environmental, social, and economic perspectives were less included [65]. Zhang et al. (2021) emphasized the importance of technology, building types, boundaries, and business models. They highlighted the lack of non-technological aspects [66]. UES design is more about the process than the method itself, and the focus should be on the communication and involvement of stakeholders in creating shared urban visions [67]. Ideally, techno-economic and institutional design must converge in complex socio-technical systems such as UESs. This means careful planning and strong alignment between energy sectors, actors, institutions, and business models are needed in UES design.

This 10Q paper responds to a critical gap in the current literature: the absence of integrative frameworks that connect the techno-economic, socio-institutional, environmental, and spatial dimensions of UES design. Despite growing interest in urban decarbonization, existing studies often treat these aspects in silos, lacking systemic perspectives that account for techno-economic constraints, spatial interdependencies, governance complexities, and equity concerns. Holistic planning approaches and integrated governance frameworks remain largely underdeveloped. By synthesizing these dimensions, this paper offers a guiding structure for researchers and practitioners, identifies emerging challenges, and outlines actionable research directions to support more coherent and impactful UES development.

1.3. Scope and contributions

This 10Q paper contributes to a structured and integrative framing of UES through the "Ten Questions" format, offering a holistic perspective that bridges technical, spatial, and institutional dimensions. While prior "10Q" papers have addressed closely related themes such as energy modeling, energy systems, and climate policy, none have focused explicitly on the complexity and specificity of urban energy systems design, which are shaped not only by physical infrastructure, economics and modeling choices but also by spatial planning, social equity, and governance dynamics. The contribution of this paper is twofold: (i) we synthesize fragmented insights across disciplines into a synthesis that reflects the systemic, multi-scalar nature of UES challenges; and (ii) we offer a guiding framework for researchers, planners, and policymakers to navigate this complexity and identify research gaps, methodological trade-offs, and integration opportunities. By situating UESs as both technical systems and socio-institutional constructs, this paper advances the state of the art and sets the stage for more holistic and practice-oriented research in the field.

Fig. 1 presents an overview of this paper, highlighting the current state, emerging trends, key challenges, advanced techniques, and future goals in UES design. It builds on the UES definition above and extends the discussion to include contextual aspects, modeling techniques, data availability, and environmental and societal considerations, offering insights into the prospects of UES design. While many of the questions are forward-looking, they are grounded in emerging practices and are intended to bridge current initiatives with future development trajectories in UES design. This review not only covers existing literature but also highlights where the UES design has yet to go, directly leading to some of the 10Q below.

These ten questions highlight the need to integrate UES design with techno-economic, social, institutional, and spatial dimensions that are central to a UES framework. Throughout the questions, we demonstrate how stakeholder priorities, planning constraints, and climate change risks should inform UES design. The questions Q1-Q2 provide contextual information on the UESs covering physical infrastructures and urban forms, as well as techno-spatial and demand-related aspects of UES. Q1 is important for understanding how UES interact across different spatial scales (including coordination between transmission and distribution grid operators) and sectors, helping to identify synergies and optimize resource use. Q2 explores how evolving demands in sectors like heating, cooling, transportation, renewable integration, climate change, and extreme weather events influence the UES design. Q3-Q5 address modelling and data availability issues, focusing on the technological and operational aspects of UES. Q3 sheds light on the strengths and weaknesses of existing energy system modeling approaches and identifies gaps in data requirements, scalability, and uncertainty analysis, and the need for scenario-based modelling. Q4 provides insight into the building energy demand, stock characteristics, and retrofitting strategies, supporting the design of energy-efficient, low-carbon urban environments. Q5 discusses the critical role of data and artificial intelligence (AI) in the design and governance of UES, emphasizing the need for dynamic, high-resolution, and well-structured data to support decision-making at various scales. Q6-Q7 focuses on further relevant dimensions of UES such as environment, policy, governance, and business models. Q6 covers other environmental aspects such as air quality, water usage, land use, and the impact on local ecosystems. Q7 highlights the importance of technological, societal, governance, policy, and business model aspects, influencing equity, stakeholder engagement, regulatory frameworks, and long-term sustainability. Q8-Q10 provide an outlook into the future, considering urban vision, application to the global south, and research agenda. Q8 examines how UES can be designed to align with diverse urban visions and associated challenges. Q9 highlights the unique challenges faced by low- and middle-income countries anchoring on current practices and real-world examples from the global south. Finally, Q10 identifies key future research areas to guide further development of UES design.

2. Ten questions

Q1. What lateral and vertical interactions are relevant to UES design?

Background: UES design intersects with urban planning processes, stakeholder engagement, urban context, and climate considerations. UES are becoming increasingly complex due to decentralization, electrification, and the growing integration of renewable energy sources. Existing energy grid infrastructures, both at the transmission and distribution levels, are being reinforced or retrofitted to meet growing demands for flexibility across multiple energy vectors, electrification of different sectors, and increasing share of renewables, leading to higher energy networks and balancing costs. Increasing decentralization of the energy system and emerging local energy initiatives also contribute to the energy system integration and governance challenges of the UES. These transformations demand greater flexibility from infrastructure and governance systems. The design of equitable and sustainable UES requires the consideration of vertical interactions, including spatial relations (e.g., buildings, districts, national as well as grid levels) and governance, and lateral interactions between energy sectors (e.g., sector coupling) or energy carriers (e.g., energy conversion). In addition, temporal relations (e.g., seasonal aspects), climate conditions, and system interdependencies are also considered, leading to diverse energy system integration concepts. Moreover, the urban context, including population density, land use patterns, infrastructure layout, and existing building stock, strongly shapes both the opportunities and constraints for UES design and integration.

Vertical interactions occur between grid-level (transmission and

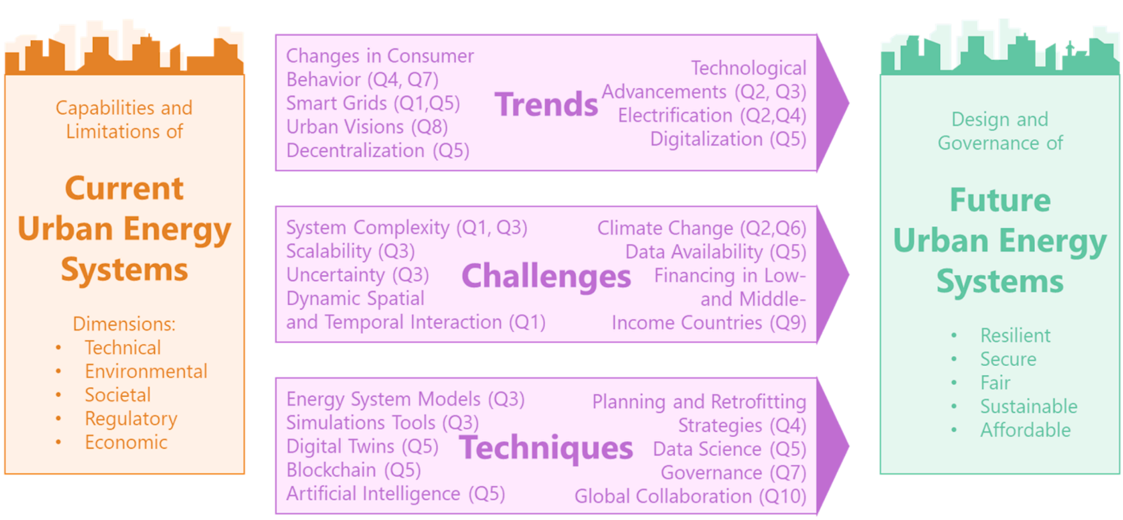

Fig. 1. Trends, challenges, and techniques of UES design.

distribution system operators) and levels of governance or planning (e.g., municipal, regional, national), focusing on issues like coordination across energy flows, regulatory frameworks, and multi-level policy alignment. The design of UES generally requires vertical interactions, including spatial (interaction between distribution and transmission network levels, local and national scales, and spatial disparities) and temporal relations. Distribution and transmission grid operators are key stakeholders in UES design, with legitimate concerns and decision-making power. Assessing the impact of the development of decentralized generation and storage technologies and urban energy demands requires investigating the resulting future network capacity planning of the overall energy system [68]. At the same time, the lateral interactions occur within the same governance level and spatial scale. UES combine different energy vectors (such as electricity, gas, oil, biomass, and heat) to provide various energy services (heating, cooling, transport, and appliances for buildings and industry). UES should be able to coordinate different energy carriers and actors to provide a specific energy service that can increase the demand-side flexibility of the energy system without any service interruption [75]. Such systems can also facilitate the integration of non-dispatchable renewable energies into the power grid and avoid greenhouse gas emissions from traditional power plants [76].

In a nutshell, the design and planning of UES intersect with spatial, institutional, and socio-political dynamics across multiple scales. Understanding and managing these cross-cutting dimensions is essential for developing resilient, equitable, and low-carbon urban energy transitions.

Concepts and current practices: Current UES models and planning tools often focus on technical optimization and economic or environmental performance. Sector coupling, multi-vector coordination (e.g., electricity, heat, fuels), and grid-responsive strategies such as dynamic pricing are increasingly being explored to enhance demand-side flexibility and system efficiency. With the electrification of demand sectors and an increasing share of renewables, dynamic tariffs for energy and grid usage are becoming more relevant. Several countries have already begun implementing them to manage demand peaks and to enable grid flexibility and balancing [69]. Digitalization, data availability (smart grid and metering infrastructures), and regulatory innovation are pre-conditions for the implementation of a dynamic tariff system. Dynamic tariffs strengthen the link between UES design and operationalization of flexibility, enabling it to be responsive to evolving market signals. Efforts are also emerging to model vertical interactions between local and national planning levels, and between distribution and transmission networks. However, these approaches are not yet fully integrated, especially when it comes to linking spatial, temporal, and institutional aspects of UES.

Moreover, national policies need to support local participation to catalyze the national energy transition. At the same time, national policies also clearly impact local-level planning [70]. Thellufsen and Lund (2016) developed a methodology to analyze how well the local plans integrate with Denmark's surrounding national energy system [71]. Similarly, Yazdanie et al. (2017) studied the role of local energy systems in the national energy transition under different policy scenarios. They demonstrated an enormous potential for urban, rural, and suburban communities to ramp up the utilization of local energy resources to meet local demand and support national energy transition goals [72].

In addition, different energy sectors (electricity, heating, fuels, transport) are increasingly being interconnected through sector coupling [25]. For example, Biéron et al. (2025) demonstrated that systems coordinating heat pumps with natural gas boilers providing residential space heating and domestic hot water can decrease the emissions of European electricity generation [77] by using a control strategy based on GHG emissions [78]. In addition to sector-coupled UES, islanded micro-grids [79] and autarkic energy systems [39,42] play a crucial role in enhancing resilience by ensuring localized energy self-sufficiency and reducing dependency on centralized infrastructures, particularly in the face of grid disruptions or extreme events such as heatwaves and dunkelflautes (extended period without solar and wind energy generation). Back-up generators and sector-coupling are examples of future-proofing strategies as they capture multi-vector synergies to enhance the resilience of UES.

Economic, environmental, and social impact assessments are important to design sustainable UES (see Q6 and Q7). Several studies demonstrated that cost-efficient solutions can also have environmental benefits, unlocking the potential of their co-benefits through lateral analysis. For instance, Yazdanie et al. (2017) showed that Basel's GHG emission reduction target by 2050 can be reached in a cost-optimal solution [70]. However, applying this cost-optimizing solution is highly related to social acceptance of the envisioned actions. Horak et al. (2022) reviewed 20 modeling frameworks for UES at district and city scales [74]. Their study demonstrated that most tools evaluate the systems' economic and environmental impacts. However, the environmental impact is generally restrained to GHG emissions, and the social implications are rarely included. These observations motivated Q6 regarding the environmental considerations beyond the GHG emissions and Q7 concerning the societal, governance, policy, and business models aspects.

Concepts such as district heating and cooling [80], local energy communities [7], virtual power plants [81], or positive energy districts [46] (discussed further in Q8) focus on local complementarity between the different energy carriers, local energy resources, and energy producers and consumers.

Challenges: Many studies consider the integration of high shares of renewable energy in UES, which can be constrained by the grid and its stability requirements [73]. Large-scale electrification of demand (e.g., heat pumps and electric vehicles) as well as high penetration of renewables can quickly turn into a nightmare scenario for distribution and transmission grid operators, as seen, for example, in the Netherlands. Consequently, it is necessary to consider the interdependencies within the energy value chain. Vertical interdependencies—such as coordination between grid operators and governance institutions—are insufficiently captured in tools modelling UES design, even though they significantly affect infrastructure investment, regulatory alignment, and planning [74]. Lateral interactions between energy sectors and carriers are similarly underrepresented, limiting the ability to assess system-wide synergies and resilience strategies. Most tools also lack the ability to simulate temporal dynamics like seasonal variability or extreme events. Furthermore, social dimensions such as public acceptance, equity, and institutional coordination are rarely integrated into modeling approaches, undermining the practical relevance and inclusivity of UES planning.

Future directions: Future research must consider the spatial, temporal, sectoral, and institutional complexity of UES design. This includes embedding governance mechanisms, digitalization, and regulatory innovations such as dynamic tariffs into both design and operational models. A key priority is to bridge urban-scale UES with national or macro-energy systems [82] by explicitly modeling vertical and lateral interactions, including transmission-distribution network co-ordination. Advancing these capabilities will support more robust, participatory, and scalable UES solutions that contribute meaningfully to broader energy transition and climate goals.

Q2. How do trends in urban sub-sectors such as electricity, heating/cooling, and transport influence the design of UES?

Background: As illustrated in Fig. 2, UES are increasingly influenced by trends in electricity, heating/cooling, and transportation sectors. These sub-sectoral shifts—driven by electrification, climate change, decentralization, and local renewable integration—reshape how energy is produced, distributed, and consumed in cities. The urban energy landscape must adapt to divergent dynamics, such as innovative tariff structures, growing centralization in thermal grids, and decentralization in the power systems, alongside the rise of electric vehicles and demand-side flexibility needs. These evolving conditions demand a rethinking of

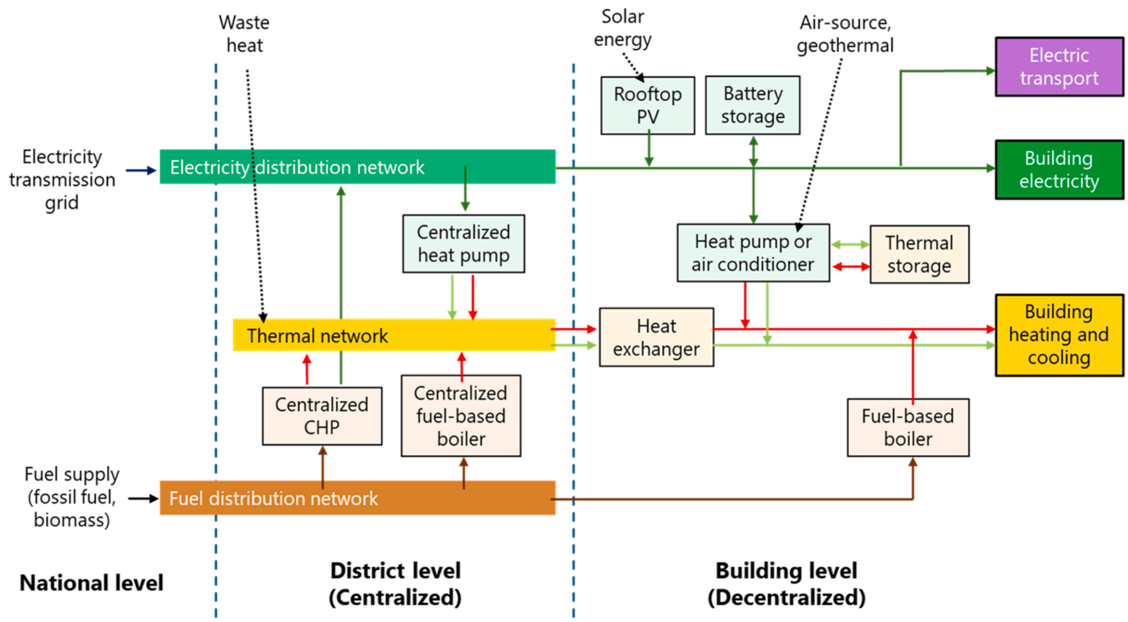

Fig. 2. Interconnection between electricity, heating, and transport demand sectors in UES.

UES design that is adaptive, resilient, and capable of managing cross-sectoral interdependencies. UES design should also be informed by local governance structures, land-use policies, and climate adaptation and mitigation strategies.

Concepts/Approaches: Designing UES requires integrated approaches that consider multi-sectoral demand patterns and local resource availability. A comprehensive understanding of the heating and cooling demand trends is crucial for designing UES. Emerging developments in the heating and cooling sectors, such as electrification, fifth-generation district and cooling networks [80], prosumers feeding energy in district heating networks, and small local thermal micro-grids (e.g., nanoverbund [83]), influence the design of UES. Gjoka et al. (2025) found that the heating and cooling in buildings with fifth-generation district heating and cooling systems is more effective regarding GHG emissions, self-sufficiency, and system cost compared to the electrification of buildings' heating and cooling with air-sourced heat pumps coupled with PV panels and batteries [80]. Aggregating buildingś data across the city provides a comprehensive analysis of urban heat demand, which supports planning for district heating and energy infrastructure, allowing for better forecasting of peak demands and assessing the impact of efficiency measures like retrofitting [84,85].

As cities adopt electric transportation methods, energy systems must handle the resulting increase in electricity demand [86]. This is particularly challenging for cities with limited electricity import capacity, where balancing demand and supply requires additional generation and grid upgrades [87]. EV charging introduces variability in demand patterns, and uncontrolled charging during peak hours can strain the grid. Consequently, UES must incorporate flexible charging infrastructure and demand management to maintain grid stability [88]. Vehicle-to-Grid and Vehicle-to-Home concepts are emerging which could contribute to energy balancing through storage on wheels.

Climate-responsive UES design leverages high-resolution data to incorporate urban morphology, heat stress, and microclimatic conditions, enabling better anticipation of peak loads and resilience to extreme weather events. Climate change is expected to significantly impact urban energy supply and demand, particularly during extreme weather events such as heatwaves, dunkelflautes, and urban flooding, making climate-resilient UES essential. By integrating high-resolution climate data, UES can better predict peak loads and respond efficiently to rising cooling needs and demand-supply mismatch [89]. Climate change also intensifies urban micro-climate effects, exposing densely built areas to greater heat stress and poor air quality. Urban morphology, the layout and structure of cities, further influences energy use and resilience. However, appropriate design can help mitigate micro-urban climate effects by regulating heat exposure, enhancing airflow, and incorporating cooling elements such as vegetation and water, contributing to more livable and climate-adapted urban environments. Classifying urban forms in UES models can improve resilience and optimize energy consumption under changing climate conditions [90,91]. The objective to minimize emissions leads to, in most cases, increased electrification. With the increased share of intermittent renewables and cooling loads and the corresponding temporal and spatial mismatch between supply and demand, greater flexibility in the energy system is required to make it more resilient.

Local renewable resources like solar energy, geothermal, and biomass can enhance urban resilience and sustainability by reducing dependence on distant power plants and decreasing transmission losses. For example, cities with rooftop space may adopt solar PV and battery storage to meet increased electricity demand. Innovative tariff structures, such as dynamic tariffs, can be implemented to improve local self-consumption and grid balancing.

As discussed in Q1, the interaction between electricity, heating, transportation, and industry is crucial for UES efficiency and sustainability. Linking heat and electricity networks enables greater flexibility, though careful management is needed to ensure grid stability. For example, integrating electricity and heating allows renewable sources like solar PV to work alongside heating technologies, enhancing overall energy efficiency. Heat pumps, for instance, convert excess electricity into heat, which is particularly beneficial in regions where biomass is expensive [93]. Additionally, waste heat from data centers and industrial activities can be harnessed for urban heating, reducing overall energy consumption while promoting sustainability. Coordination across residential, commercial, and industrial sectors can also reduce greenhouse gas emissions, making energy use more efficient across diverse settings [94].

Challenges: The ongoing trends in demand sub-sectors introduce several challenges in UES design. Decentralized demand patterns often misalign with centralized infrastructure design, complicating grid planning and sector integration. Limited electricity import capacity in some urban areas makes transport and heating/cooling electrification a grid management burden without adequate flexibility measures. The shift towards electric vehicles (EVs) significantly impacts the UES by introducing new demand peaks and volatility. Extreme weather events, like heatwaves and dunkelflautes, stress urban infrastructures, highlight the need for climate-responsive UES design. At the same time, urban design, space constraints, and layout optimization remain challenges for maximizing rooftop PV potential [92]. Data and modeling gaps hinder the classification of urban forms and their energy behavior, weakening predictive capabilities. Moreover, the complexity of UES—shaped by political, economic, and stakeholder factors—can complicate integration and renewable transitions [95]. Such Institutional and stakeholder complexity further complicates cross-sector coordination and regulatory alignment, particularly in relation to integrating dynamic tariffs and distributed generation.

Future directions: The evolving demands of heating, transportation, and cooling due to electrification, climate change including extreme weather events, and local renewables necessitate adaptive and resilient UES designs. To meet evolving urban energy demands, UES design must integrate cross-sectoral interactions explicitly within modeling tools, linking electricity, heat, transport, and industry through common infrastructures and operational logics. The higher temporal and spatial granularity, including seasonality, and urban form topologies should be embedded, to better anticipate demand shifts and ensure system resilience. Participatory governance and planning coordination across municipal, regional, and national levels need to be enhanced to improve policy alignment and institutional readiness. Socio-technical modeling frameworks that reflect behavioral patterns, public acceptance, and distributional effects alongside technical and economic criteria need to be developed. By incorporating precise demand models, well-designed tariffs, flexible infrastructure, local renewables, and sectoral interplay, cities can optimize their energy systems to meet current and future needs, contributing to sustainable urban development.

Q3. What are the capabilities & limitations of energy system modeling approaches in UES design?

Background: The complexity of planning and operating UES is increasing due to multi-vector (sector coupling) and multi-actor contexts [96,97], the integration of intermittent renewable energy sources, multi-actor governance, changes in consumer behavior, and the shift from unidirectional energy flows to bidirectional interactions involving prosumers (see vertical integration in Q1 and sub-sector trends in Q2). Integrated energy system models provide a well-established framework to address these growing challenges [98–100]. In particular, models based on mathematical optimization methods like linear programming (LP) and mixed integer linear programming (MILP) have become foundational tools in the energy system modeling community for UES design ranging from the building to city scale and beyond [51,53,74,97,101]. While this question focuses on optimization and modeling techniques, these approaches must align with broader UES principles by explicitly incorporating spatial system dynamics, distributional impacts, and governance contexts into model design and interpretation

Methods/Approaches: The optimization models based on LP/MILP (collectively referred to as LP for readability from now on) facilitate the assessment and optimization of UES towards multiple objectives, such as minimizing system costs, minimizing CO_2 emissions, or maximizing the self-sufficiency of a system [102,103]. Via a multi-objective optimization of the underlying system, the solution space within the energy trilemma can be mapped, and the solution can be selected based on additional system and actor's requirements. According to the World Energy Council, the energy trilemma defines the tradeoff between energy security, energy equity, and environmental sustainability [26]. This trade-off is a Trilemma, since reaching all targets simultaneously is utopian. LP offers a method for objective assessment of these trade-offs in multi-actor contexts via the determination of Pareto-optimal solutions.

Furthermore, multi-stage transition paths can be investigated via LP models and aid in designing long-term scenarios and strategies to reach the targets of the examined system [104]. Recent advancements in LP frameworks include integrating demand-side management (DSM) capabilities [105,106]. Overall, these developments have established LP as a preferred method to navigate the complexity of sector-coupled UES, supporting holistic multi-actor decision-making from a local to regional scale and beyond [74,101,107].

UES models enable the exploration and quantification of the potential impact and role that technology development could have within future energy systems. By conducting sensitivity analyses on selected critical techno-economic parameters, such models provide insights into the feasibility, competitiveness, and potential market penetration of new technologies under various future scenarios. This approach supports informed decision-making and strategic investment by highlighting the techno-economic thresholds that novel technologies must achieve to be viable within envisioned energy system configurations.

Challenges: However, despite the advancements in recent decades, optimization models for UES design still face several shortfalls. For example, UES design optimization models often assume perfect competition among the actors of energy markets and perfect foresight [99] and lack robust mechanisms to incorporate uncertainty, consider multi-actor interactions, and to explore alternative solutions, such as near-optimal solutions, and are focused on techno-economic investigations only [101,108–110]. However, the inclusion of uncertainty analysis and near-optimal solution analysis gains importance in recently published studies [111–113]. One fundamental challenge regarding uncertainty analysis is to determine the variables in a system introducing uncertainty. So far, the choice of variables to perform uncertainty analysis is often heuristic, based on experience and best guesses of the modeler, leading to potential biases. We therefore suggest a more systematic approach towards uncertainty analysis.

Furthermore, the comparability and reproducibility of energy system models are often low since uniform guidelines on how to parameterize and document technology parameters, time-series, and boundary conditions are largely unavailable or not standardized. Such standard guidelines would significantly accelerate model development, scalability, and reproducibility. Developing common data and documentation practices and releasing them open source are challenges the UES modeling community faces. Yazdanie and Orehounig (2021) highlight data availability and other methodological and technical challenges of UES modeling [101] [115–117] summarize the current state-of-the-art open-source models. By addressing these challenges, UES models can advance and overcome their limitations.

For mature and widely implemented technologies, detailed techno-economic parameters—including capital expenditure (CAPEX), operational expenditure (OPEX), conversion efficiencies, and economic and technical lifetimes -are readily accessible from specialized reports and authoritative sources like the IEA Clean Energy Technology Guide [118]. However, for emerging or developing technologies, these parameters are typically less certain and must be approximated or projected. Moreover, scenario-based UES design is important to assess their capacity to cope with extreme weather events, as well as to account for different technology adoption pathways (including adoption of low TRL technologies such as vehicle-to-Grid and Vehicle-to-Home by first movers, sandboxes), cost, and efficiency trajectories.

Future directions: To enhance the robustness, adaptability, and applicability of UES design models, future research is needed in several directions. Addressing challenges related to the uncertainty of input parameters can lead to a more resilient design of UES. Determining robust transition paths of energy systems under uncertainty is increasingly becoming a requirement for UES planning models. Due to the high dimensionality of UES planning models, which often involve thousands of parameters, comprehensive uncertainty analysis becomes computationally infeasible. Modelers often use Monte Carlo simulations or Bayesian methods to assess variability, but this selective parameter approach can introduce bias in UES design. Addressing this limitation requires advancements in uncertainty methods to identify the objectively most relevant parameters to consider for uncertainty analysis [119]. A more targeted uncertainty analysis can be conducted based on the selected parameters. Surrogate models can further reduce the complexity of investigating a large set of parameters [120].

Furthermore, determining alternative solutions near the mathematical optimum leads to additional insights on system interdependences and near-optimal solutions, which should be considered in determining the most robust path [113,121–123]. Robust paths must also consider multi-actor institutional context, human behavior, such as changing work schedules, incentives to participate in the energy system as prosumers, and incentives, as well as willingness to invest in energy transition– factors often neglected by current models.

While LP UES models determine optimal UES configurations, they often lack the capability to consider (non-linear) physical behaviors required for system operation. Coupling LP models with models at higher and lower levels of abstraction can further advance system integration and de-risk decision-making [124]. Validation of proposed modeling techniques is essential and relies on operational data, whose availability and importance are discussed in Q5.

Navigating data complexity can be facilitated via knowledge graphs, data semantics, and ontologies [114]. However, further advancements in the community on how to document and publish energy system modeling data are required.

In summary, current energy system modeling approaches, particularly LP and MILP, provide essential tools for UES design, offering scalability, sector coupling, and multi-objective optimization across various urban scales. These models enable planners to address key challenges, including integrating renewable energy, enhancing DSM, and optimizing costs and emissions. However, limitations persist, particularly in handling non-linear dynamics, data accessibility, and uncertainty analysis, which constrain the adaptability of these models in complex, future scenarios and multi-actor contexts. Future advancements, such as coupling models and scales through platform-based design [124], rapid-solving mathematical methods [99], open-source data [125], and integration with AI and digital twins [33] (further discussed in Q5), are anticipated to address these challenges and elevate the robustness and real-time applicability of UES models, supporting a more flexible and resilient urban energy landscape. Modeling approaches should go beyond techno-economic optimization by incorporating stakeholder-defined criteria and allowing for scenario co-creation with planners, utilities, and communities. By addressing these research priorities, UES modeling can evolve from static techno-economic planning tools to dynamic, multi-actor, and resilient planning frameworks that support real-time decision-making in the context of deep urban decarbonization and energy transition to mitigate climate change risks.

Q4. How can building energy demand and building stock modeling support UES design?

Accurately estimating current and future building energy demand is essential for UES design, as buildings account for a large share of urban energy use and are increasingly affected by climate change . Spatial and temporal demand variations inform decisions on centralized vs. decentralized solutions, low-carbon heating options, and renewable electricity integration, while considering resource availability and infrastructure constraints defined by the UES model. The potential for demand reduction through retrofits (including corresponding investment costs and embodied emissions), as well as demand shifting (while maintaining thermal comfort), serves as input to the UES model. High spatial and temporal resolution of building energy demand also makes it suitable for coupling with grid planning models to estimate where reinforcement in distribution and transmission infrastructure may be needed.

Urban Building Energy Modeling (UBEM) has emerged as a valuable tool for estimating energy demands across large-scale urban environments with high spatial and temporal resolution [126,127]. UBEM can integrate physics-based simulation engines to capture the impacts of environmental conditions, retrofit interventions, and occupant behavior [100]. Bottom-up models, where energy demand is estimated based on detailed building characteristics [128], are increasingly being used. These models consider factors like building type, construction period, insulation levels, heating efficiency, and external influences such as climate conditions, shading, and surrounding structures [129]. Additionally, machine learning can improve demand estimation at both building and urban scales [130]. Creating a reliable building energy model requires collecting input data, simulating the energy demands using a thermal model, and predicting future energy demands in response to the changing building stock. This process also needs to be semi-automated to enable non-experts to simulate energy demands using a limited set of parameters from publicly available sources. UBEM and building stock dynamics models enable detailed analysis of potential decarbonization pathways through building envelope retrofits, heating system replacements, and renewable energy integration.

Input Data: Effective UBEM simulations start with comprehensive descriptions of the building stock, including building geometry, construction standards, occupant presence and activity schedules, and climate data. This input data is critical to ensure that models reflect the energy performance characteristics of urban buildings under varying conditions. While building geometry and climate data are often readily available, uncertainties in building construction and occupant behavior are more challenging to address [126]. Insulation standards (segmented by building construction period) and typical building usage patterns (segmented by the primary use of the building) may be employed as in CESAR-P [129] or DIMOSIM [131]. It may be challenging to obtain qualitative data on the existing building stock, especially regarding the thermal envelopes of the buildings. Consequently, some studies attempted to calibrate models at the district scale to assess the space heating demand [132] or the urban heat island effect [133]. This calibration is particularly relevant for model-based retrofit analyses [134].

Energy demand simulations: Physics-based UBEM tools enable the evaluation of heating and cooling energy demand based on dynamic heat and mass flow models. Common thermal simulation engines used within UBEM workflows include EnergyPlus [135], TRNSYS [136], and IDA-ICE [137]. Predefined activity and occupancy schedules are used to account for thermal gains. However, UBEM should move beyond stand-alone building simulations to consider inter-building interactions, such as shadowing and longwave reflection between neighboring buildings, as well as the urban climate (spatial variations of the ambient temperature and wind speed due to the building density in the area) [138]. The effects of urban vegetation, such as shading and evaporative cooling, are challenging to represent in standard building energy simulations, which typically only account for basic geometric shading or integrated vegetation like green roofs. More advanced approaches couple urban microclimate and UBEM models, enabling a detailed assessment of how building morphology and vegetation influence local temperature, humidity, and wind speed, with significant implications for thermal comfort and building energy demand [139,140]. For large urban areas, only a few representative building archetypes (identified using grouping/supervised [141], clustering/unsupervised [142], or semi-supervised methods [143]) are generally employed [144]. The heating and cooling demands are then upscaled, significantly reducing the simulation time. Such a method can also be directly applied to identify representative district archetypes [145].

Stock Dynamics: A comprehensive understanding of stock dynamics is essential to predict how urban building stocks will evolve. Simple rate models are commonly used to estimate the impact of new construction, demolition, and renovation activities, where rates are exogenously defined based on past trends and/or projected scenarios. In contrast, agent-based building stock models (ABBSM) [146] offer a more nuanced approach, simulating decision-making processes at the building level and incorporating factors such as policy changes, energy prices, and retrofit costs. Material Flow Analysis (MFA) further enhances our understanding of building stock dynamics by modeling the flows of construction, demolition, and renovation activities. Using historical and projected population data alongside assumptions about dwelling lifetimes and renovation cycles, MFA provides a basis for forecasting future construction and renovation needs [147].

Demand-side flexibility: With the increase of non-dispatchable electricity generation in the power system, the balance of the grid needs to be shifted from electricity generation to demand. Consequently, UBEMs are also used to evaluate the space heating demand flexibility in residential buildings [148] through passive thermal storage based on the building's thermal mass [149] or active thermal storage based on a hot water tank [150]. In the case of passive thermal storage, the internal walls and furniture inside the buildings impact its thermal inertia and should, therefore, be carefully modeled [149]. Moreover, models of the occupants' behavior can be used to represent the occupants' interactions with the thermostat settings [151]. Assessing the flexibility of the other residential electricity demands requires knowledge of activity and occupancy schedules to estimate the flexibility potential of electric appliances and domestic hot water storage. Residential flexibility must be explicitly assessed at a district level to account for the differences in building construction and occupancy patterns [152].

Within the context of increased electrification of heating demand and mobility, as well as higher shares of non-dispatchable generation (as discussed in Q2), UBEM models are becoming increasingly relevant in shaping UES design due to their spatiotemporal resolution. These trends are expected to lead to local grid congestion and hosting capacity issues, necessitating increased demand reduction, curtailment, enhanced demand-side management, and, ultimately, reinforcements of the distribution and transmission grid infrastructure. If these aspects are left out of the UES modeling framework, the economic and environmental impacts of the proposed UES design may be overestimated, and a different design would have been more optimal [153]. With increased data availability, improved methods for data acquisition and the incorporation of real-time urban environmental conditions would enhance the accuracy and spatial coverage of these predictions, as addressed in Q5. However, limited data availability for the regions in the Global South remains a challenge. Moreover, moving beyond the impacts of energy use during operation, these models should also strive to incorporate the life cycle and circularity aspects of building retrofits and new construction, as addressed in Q6. A detailed examination of the policy and economic factors driving renovation and construction activities will further enhance the accuracy of these models in projecting energy demand patterns over time.

Q5. What role does the increasing availability of data and AI techniques play in UES design?

Background: Data availability is critical for UES's effective design, adaptation, and governance [154,155]. UES design is not only the static layout and sizing of system components but also an iterative, data-informed process that spans planning, operation, control, and continuous adaptation over time. Compared to building- or small-scale energy systems, UES are characterized by dynamic environmental and systemic interactions [124,156] (see Q1) and multi-actor decision-making [157]. Dynamic data includes for example,data on energy demand, supply patterns, infrastructure (including buildings, urban transportation systems, and energy distribution networks), microclimate and weather, and emissions [101]. The availability of such dynamic data benefits decision-making at different scales. At the macro level, longitudinal datasets support predictive analyses aiding long-term planning for energy transitions [101] and evidence-based policymaking [159], e.g., for climate resilience[160] or renewable energy integration [101]. At the micro level, drawing from dynamic data, consumers can reduce emissions or costs by identifying consumption patterns and adjusting behaviors or using specific technologies.Additionally, access to data enables smart and fair operation of energy systems from both the site owner's and the distribution system operator's (DSO) perspectives. Conversely, a lack of this data can lead to poorly calibrated models, which can, in turn, lead to wrong decisions. Therefore, significant efforts exist to improve further data collection in the context of UES systems by developing new technologies. New sensing technologies and the Internet of Things (IoT)-enabled systems, e.g., smart meters, increasingly collect these data [155].

But even if the data is collected, the sheer volume and variety of this data complicates the process and analysis using traditional methods [148]. Hence, effective UES governance through data requires innovative automated and human-led approaches to navigate and leverage this data [161]. Key tools include artificial intelligence (AI) and digital twins (DTs).

Methods and Approaches: AI can systematically learn from large, structured, and unstructured datasets, providing real-time insights for decision-making. In doing so, AI methods such as machine learning can support load forecasting and the prediction of distributed energy resources and future demand, reducing human error and improving system reliability [162]. Additionally, AI can streamline operations and enhance control systems to increase system resilience and performance [163], e.g., for the use of renewable energy [161,164]. For example, the Nostradamus AI tool forecasts renewables generation, accessible load, and market pricing [165], while GridFM [166], a foundational model proposed by IBM, is pre-trained on power flow models and uses multimodal data for tasks such as outage prediction, load, and renewable forecasting [167]. AI can also support the development of autonomous systems for data-driven real-time decisions, e.g., on energy distribution or automatic bidding on energy markets [168]. Moreover, data-driven applications can support grid-aware planning and operation of UES, including congestion management, predictive maintenance, and flexibility optimization. For example, GridAware, part of Google's Tapestry Grid Planning toolset, uses computer vision to detect potential problems in physical networks, identifying maintenance needs before they cause an outage [167,169].

To interact with the data, the AI-supported analysis, and the subsequent control of UES systems based on the data, the concept of a digital twin is increasingly pursued. Digital twins are virtual representations of a complex physical asset in the digital space, enabled by continuous data synchronization and information exchange between the digital and the physical counterpart [33], providing real-time control feedback. DTs allow proactive system management, e.g., predicting system and component failures and providing feedback to maintenance and operations. Furthermore, by integrating interdisciplinary data (e.g., urban infrastructure and energy-related data), DTs enhance cross-sectoral and transparent stakeholder coordination and multi-actor governance. For example, urban planners and policymakers can use DTs for scenario simulation and get data-driven decision support. At the same time, non-experts can interact with complex energy systems more easily to generate tangible solutions to their specific needs [171]. Commercial DT solutions include the Energy Digital Twins by Siemens [170].

Challenges and future directions: The increasing data availability also comes with an increased need for effective data governance. Governance is needed to enable and incentivize the collection, structure, accessibility, and shareability of *the right data* and its compliance with data governance standards, such as FAIR (Findability, Accessibility, Interoperability, and Reusability) [172].

First, a systematic collection is important considering the appropriate spatial and temporal resolutions for the intended purpose [155]: high-resolution data is necessary for real-time system control, while lower-resolution data suffices for long-term planning of urban energy infrastructures [101,173]. Data is, however, often non-homogenously collected [174], with some urban regions having more abundant data due to individual programs or initiatives, such as Energy Cities [175], Digicities [176], EERA [177], and HESTIA [178].

After its collection, the data must be structured and interpretable to ensure correct use and enable semantic searches, allowing users to find and compare data easily based on common terms and structures. Domain-specific ontologies can simplify data management and clarify the meaning of data across diverse thematic domains to enhance interpretability and interoperability [174].

Data accessibility needs to be technically enabled by using open-access repositories, but open-access datasets on energy consumption patterns at the building [159] and district scale [158] remain sparse. Concurrently, data privacy concerns remain key. Anonymization and aggregation techniques can protect sensitive data while enabling broader use [116]. For instance, the General Data Protection Regulation (GDPR) [179] sets clear guidelines on personal data protection, which must be considered in energy data governance. To overcome the lack of available open-access data, stakeholders should be incentivized to share their data.

Q6. What environmental aspects should be considered in UES design beyond operational GHG emissions?

To achieve net-zero emissions by mid-century and meet peak temperature targets [181], decarbonization efforts are central to the design of UES [182]. However, efforts to reduce greenhouse gas (GHG) emissions in the built environment and UES have tended to focus primarily on operational emissions [183]. As grid decarbonization progresses and operational emissions decline, the importance of embodied emissions from material extraction and production will increase [184]. However, GHG-driven climate change is only one part of our triple planetary crisis, as holistic environmental design should also include biodiversity loss and pollution [185] in the context of the critical planetary boundaries within which humans are safe to operate [186]. In addition, net-zero emission goals to mitigate climate change risks must also be aligned with broader sustainable development goals (SDGs) [187], which include an equitable net-zero transition, socio-ecological sustainability, and the pursuit of broad economic opportunity [181].

Metrics beyond GHG emissions are essential for broadening sustainable UES design, incorporating a wider range of environmental factors. While sustainability efforts in UES have been made, there is still a need to refine metrics and tools that address a broader scope of environmental and socio-economic impacts beyond operational GHG emissions. Exemplary metrics include circular economy indicators tied to material extraction and production [188], as proposed to quantify the circularity of electricity generation systems [189,190]. Beyond GHG emissions, the impact of UES on environmental sustainability dimensions, such as land use [191] or aspects of biodiversity like noise or light pollution, habitat loss, and water consumption [192], are equally important. Also, human-centric environmental design metrics are essential and include indicators such as thermal comfort [193], daylighting [194], or overall well-being [195]. Safety and climate resilience [160] are further proposed dimensions important to ensure future-proof UES.

Key trade-offs between different metrics must be addressed, alongside the necessary focus on individual sustainability issues, particularly when balancing environmental priorities with economic, social, and technological considerations. For example, cost can often compete with environmental goals. Similarly, there is a trade-off between occupant-centered features, such as thermal comfort or lighting quality, and minimizing environmental impact [199]. The choice of technological tradeoffs also adds complexity, especially as UES increasingly link different sectors [200]. Achieving sustainable urban change depends on targeted interventions and broader shifts in systems thinking, often causing rebound effects due to unforeseen system responses [201]. A good understanding of behavior change, system restructuring, and strategic leverage points would provide pathways for system transformation [202].

In the meantime, tools to assess a holistic environmental impact and manage UES transformation and implementation are urgently needed, as frameworks and metrics alone will not drive practices toward a more sustainable built environment [205]. In addition to modeling (see Q3), life-cycle assessment (LCA) remains the most widely used method to quantify the environmental impacts of human activities across all stages, from resource extraction and production to usage, disposal, and transportation [185]. LCA is gaining traction in energy system analyses for assessing the full scope of environmental impacts associated with energy generation, distribution, and consumption [197]. In practice, various governance tools intend to foster sustainable UES. An example is green building certification [198], even though less than 20% of the attributes included address the specific goals of the 2030 SDG Agenda [196].

Overall, much work remains to be done on overarching sustainability considerations for UES, most importantly focusing on metrics beyond GHG emissions, their tradeoffs, and tools both for the design and adoption of sustainable UES. Proposed regenerative frameworks focusing on degrowth and actively enhancing the health and resilience of the global social-ecological system might point to the future of sustainable UES design [203,204]. Beyond technical metrics, environmental assessments must also be contextualized within governance structures and spatial planning practices that influence how environmental burdens and benefits are distributed across urban populations. The link between environmental metrics and planning practices needs to be further strengthened, emphasizing that sustainability indicators (e.g., circularity, air quality, water use) must be embedded in urban development strategies and co-created with local communities.

Q7. What societal, governance, policy, and business model aspects are relevant for UES design?

"Getting the engineering right is not always enough" in UES [206]. Successful approaches must embed technical solutions within societal frameworks, governance structures, policy mechanisms, and business model dimensions to meet diverse needs, promote equity, and encourage widespread adoption, as illustrated in Fig. 3. Societal aspects address public acceptance, citizen engagement, equity, and behavior; policies provide regulatory support and incentives; business models ensure financial sustainability; and governance shapes decision-making and stakeholder involvement. While these pillars are interconnected (e.g., governance shapes policy, and business models often rely on policy support), they will be addressed individually to clarify their distinct roles in UES design. The figure also emphasizes the interactions of these dimensions with the technical domain, which is essential for the success of UES, and is addressed extensively in Q1-Q5.

For UES design, *societal considerations* like public acceptance, equity, and behavioral change are critical. Cultivating public acceptance and citizen engagement begins with designing technologies and systems that align with societal needs and provide clear local benefits, making adoption more likely. Participatory processes that involve diverse stakeholders, such as residents, planners, utilities, and policymakers, ensure that local knowledge and values are incorporated into UES design. Early community involvement in decision-making and planning also helps overcome resistance and build support [207]. Additionally, UES design must promote equity and energy justice, ensuring that the benefits of sustainable energy reach all socioeconomic groups, particularly vulnerable populations, preventing widening inequalities, and ensuring fair access to clean, affordable energy [208–210]. Finally, encouraging behavioral change through education and incentives to shift and reduce energy usage is key to supporting sustainability goals [211,212].

Policy support is vital for the transformation of UES, as it addresses technical, economic, business, and governance challenges while fostering innovation and ensuring widespread adoption. A policy mix is necessary to tackle this complexity, as single policy instruments are often insufficient [213]. Financial incentives, regulatory frameworks, and market-based mechanisms—such as subsidies, tax breaks, and carbon pricing—drive innovation and adoption [214,215]. Policies must also be coordinated across local, regional, and national levels to avoid inefficiencies or conflicting goals [216,217]. Moreover, policies must be adaptable, allowing UES to integrate emerging technologies and new business models without significant regulatory revisions [218]. Lastly, long-term stability is critical, as consistent and predictable policies create confidence for investors and stakeholders, ensuring sustained support for sustainable UES design [219,220].

Innovative business models are key to the financial viability of UES [221,222]. Models like energy-as-a-service [223] (where consumers pay for energy (and other) services on a subscription basis instead of a

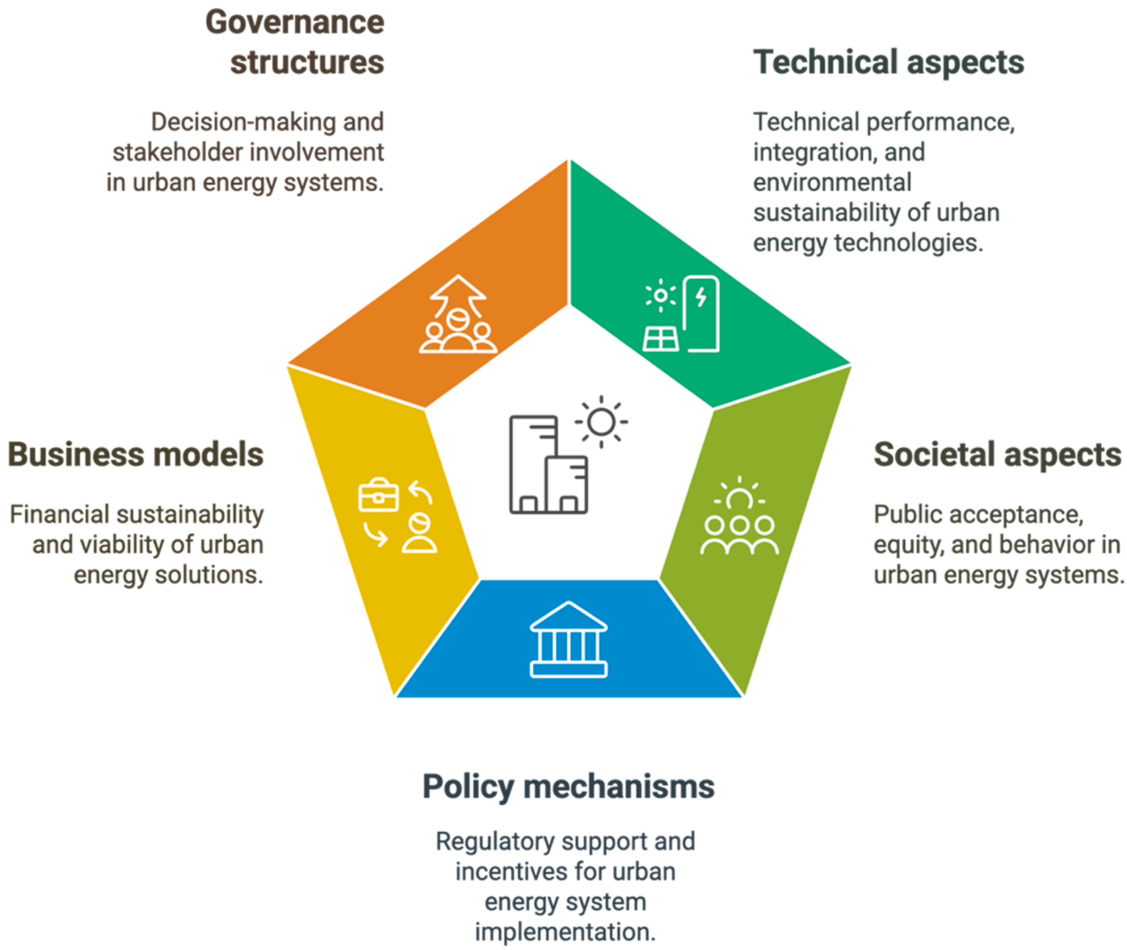

Fig. 3. Technical, societal, policy, business models, and governance dimensions of UES design.

volumetric energy charge) and community energy projects [224,225] (where local residents co-own renewable energy systems and self-consume local generation) distribute risks and benefits and promote sustainable development. Public-private partnerships further support sustainable UES projects by aligning public-sector goals with private-sector investment and innovation, enabling the feasibility of large-scale projects through shared costs and risks [226–229]. To enable these models, investment mechanisms, such as third-party financing, green bonds, and energy performance contracting play a crucial role, reduce the financial burden on governments or communities, attract private capital, and ensure projects can scale effectively [230].

Finally, *governance* provides the overarching framework to coordinate stakeholders — governments, businesses, and communities — and ensure that each has a defined role in the planning, implementation, and management of UESs. Multi-level governance ensures alignment between local, regional, and national authorities, allowing local initiatives, such as renewable energy communities, to integrate with national energy transition goals [231–233]. In practice, however, misalignments frequently occur, e.g., when national incentive schemes are not aligned with local planning goals and instruments, or when responsibilities across governing departments (e.g., energy, housing, mobility, etc.) are unclear. As a result, cross-sector governance is equally important to ensure that sectors like buildings, mobility, and energy supply are coordinated to support shared sustainability objectives [234]. For example, linking building efficiency initiatives with transport electrification helps create synergies that optimize energy use and reduce emissions. Finally, governance frameworks must also be adaptable, allowing them to respond to evolving technologies and societal needs. This flexibility ensures that UES governance supports long-term sustainability while remaining responsive to future challenges.

Overall, designing UES requires an integrated approach that blends technical aspects with societal, governance, policy, and business model dimensions. By addressing these together, UES can achieve sustainability and widespread adoption, driving the transition toward a cleaner, more resilient future. However, UES modeling often falls short in addressing these complex interactions, limiting the integration of these key dimensions.

Q8. How can UES design support different urban visions?

Urban visions refer to forward-looking frameworks or concepts that outline a desired future state for cities and urban areas [235]. They serve as guiding principles and a framework of tools and solutions for the broader urban societal objectives, often emphasizing sustainability, sufficiency, efficiency, and engagement. UES design supports urban vision's specific goals and strategies on sustainability, sufficiency, efficiency, and engagement. As further elaborated in Table 1, UES design can prioritize 15-minute cities focusing on key metrics such as spatial proximity, accessibility, and efficiency, while the focus on reducing energy consumption and promoting renewable energy would be key towards a 2000-watt society and positive energy districts, whereas collaborative energy planning could enable energy communities. Nature-based solutions and nature-positive cities are also important in an urban vision that harmonizes UES goals with urban ecology, environment, resilience, and well-being [236,237]. Innovative UES design can support and be supported by different urban visions by aligning its design objectives and strategies with the specific priorities of each vision.

While visions and qualitative attributes are crucial for conceptualizing UES, the lack of widely accepted quantitative metrics to assess

Table 1
Interplay between urban visions and urban energy system design.

Urban visions	Definition / Interplay with UES	Tools /interventions	Ref.
15-minute cities	The '15-minute City' is a new urban planning concept developed by Carlos Moreno in 2016, envisioning human-centric urban environments. This concept redefines existing urban policies, especially around mobility. It is expected to contribute positively to net-zero UES.	Efficiency, urban forms and structures	[239]
2000-Watt Society	The '2000-Watt Society' is a vision of a sustainable future with a high standard of living and frugal energy consumption and carbon emissions. It envisions fair and equitable sharing of global energy and material resources. The concept is being adopted by and demonstrated in several cities in Switzerland, such as Zürich and Basel. The '2000-Watt Society' concept leads to lower energy consumption and higher efficiency in UES and contributes to urban visions through sufficiency. Yet, this could conflict with increasing electrification of heating and transport sectors through heat pumps and electric vehicles, respectively. Nevertheless, through a smart and integrated approach, UESs can enable a low-carbon and high efficiency future by coordinating such assets across spatial and temporal scales.	Efficiency, and sufficiency	[240]
Net-zero carbon cities and Positive energy districts	Net-zero carbon cities go beyond the vision of low-carbon cities by defossilization, carbon sequestering landscapes, circular economy strategies, and sufficiency measures. Positive energy districts (PEDs), defined as energy-efficient and energy-flexible urban areas with net-zero emissions and annual surplus renewable energy, are an emerging concept with immense potential to provide scalable pathways for the decarbonization of the built environment. Yet, the high penetration of renewables in net-zero cities and PEDs without affordable local energy storage could lead to grid integration challenges. This can be resolved through different flexibility measures such as community energy storage, coordinated electric vehicle charging, and demand-side management.	Transformation of energy supply, efficiency, and sufficiency	[46, 47, 241]
Energy communities	Energy communities are *"modern development to re-organize local energy systems to integrate distributed energy resources and engage local communities."* They contribute to urban visions through higher engagement of local communities.	Citizen engagement, transformation of energy supply, efficiency, and sufficiency	[7]

what constitutes a "good" or "better" UES remains a critical gap in the literature. Existing approaches tend to assess UES performance based on sectoral indicators—such as energy efficiency, renewable energy share, local self-consumption or greenhouse gas emissions reduction—rather than system-wide integration or socio-technical performance. In energy-specific contexts, Key Performance Indicators (KPIs) are often project- or technology-specific (e.g., levelized cost of energy, reliability indices, or flexibility metrics), which limit their comparability across UES typologies or scales.

The interplay between urban visions and UES design is important in shaping sustainable cities. Urban visions include long-term societal goals such as carbon neutrality, sufficiency, accessibility, resiliency, and equity, which directly influence the solution space of UES design. Urban visions offer a set of tools to achieve these goals, as illustrated in Table 1. For example, 15-minute cities focus on transforming urban forms and structures, enhancing urban efficiency through spatial proximity to key services. Similarly, a 2000-watt society is achieved through means of both efficiency and sufficiency, with the focus on lower energy demand per capita. For positive energy districts, primary energy demand, energy autonomy, renewable energy shares, GHG emissions, and storage capacity would be performance metrics. Further environmental performance metrics beyond GHG emissions are discussed in Q6. UES design responds to these urban visions at an appropriate planning scale, ranging from building and district levels (e.g., positive energy districts) to the urban and regional scale. The design process involves iterative, participatory, and data-driven methods that connect long-term urban visions with short-term trade-offs.

In addition, UES will contribute to several existing urban visions at the continental level, such as the EU Green Deal for climate neutrality by 2050 [221], and at the national level, such as the Swiss Energy Strategy 2050 [238]. UES also contribute to several UN sustainable development goals (SDGs) [187]. At the same time, technological advancements are redefining the boundaries of urban visions by enabling more digital, smart, adaptive, and resource-efficient districts and cities. UES design supports these visions in different ways, as summarized in Table 1. Such synergies are increasingly vital as cities aim to meet global climate goals while addressing local socio-economic priorities.

These urban visions face challenges due to the complexity of UES [156,157,242] at the intersection of urban planning, energy systems, social dynamics, citizen engagement, and environmental sustainability. Predicting technological advancements, policy shifts, and socio-economic changes required for long-term objectives of urban visions introduces significant uncertainties in UES planning [123,231]. Addressing these challenges requires collaborative efforts among actors across disciplines, innovative technologies, and adaptive governance approaches to align urban vision with achievable and measurable outcomes [7,33]. UES design must be integrated with urban visions through an inter- and transdisciplinary approach to address these challenges and to harmonize UES with the spatial design of the city [243].

UES also significantly impacts building-scale energy standards, including zero-energy buildings (ZEBs) [244] and other energy-efficient design principles. UES can enable ZEB approaches by providing reliable, low-carbon energy sources at the district level, such as district heating, cooling, and local renewables integration. UES also impacts other building-scale energy standards, such as net-zero energy buildings (NZEBs) [245], positive energy buildings (PEBs) [246], and energy-plus buildings [247]. These design concepts allow for optimizing energy production, consumption, and storage at the building level, contributing to overall urban visions. Energy-efficient buildings can interface with UES, creating a synergy between building-scale energy standards and UES. This integration ensures that energy flows are optimized, contributing to both the efficiency and resiliency of the entire UES.

Q9. What factors must be taken into consideration for UES solutions in the Global South?

Low- and middle-income countries (LMICs) in the Global South are among the world's fastest-growing regions, with rapidly expanding environmental footprints [248]. Over 60% of annual global emissions are attributed to the Global South, with ten countries (including India and China at the top) accounting for nearly 80% of these emissions [249]. LMIC populations, which are increasingly moving to urban areas, are the world's most vulnerable to the impacts of climate change, facing heightened risks of disruption, displacement, and mortality due to extreme heat, flooding, drought, sea-level rise, and ecosystem collapse [250–252]. Addressing these challenges in the Global South is not only a moral imperative, but also a vital opportunity for the development of sustainable, resilient cities and UES, as well as meaningful global emissions reductions [253].

A range of factors must be considered for UES development in the Global South, including demand dynamics, societal, economic, technical, and governance factors. In addition to the trends mentioned in Q2, future energy demand in the Global South will be affected by socio-economic development, increasing cooling demand, and migration. Almost 1.2 billion people are energy-poor and in the dark, including 733 million people with no electricity connection [254]. Space cooling is expected to rise dramatically in LMICs, with associated CO_2 emissions projected to increase by up to 85% globally by 2050 [255]. Another estimate places median demand growth for cooling at 14% higher than current global residential electricity consumption [256]. Heat waves will also create peak demands that stress distribution networks and demonstrate significant equitability issues (e.g., up to an 800% increase in space cooling demand in India by 2050 will be driven by only 15% of the population) [257,258]. Climate change-induced migration, driven partly by heat stress and extreme weather events, will affect cross-border and domestic (e.g., rural-urban) migration. Approximately 143 million people in the Global South will be displaced due to climate change impacts [251]. Urban population changes due to climate change-induced migration will dramatically affect local energy demand and resilient UES planning [259]. Climate migration will also exacerbate local informal sector growth. The informal sector represents approximately 30-40% of economic production in LMICs today [260], and over 60% of workers worldwide are employed informally [261], many of whom reside in dense informal urban settlements, exacerbating UES planning challenges. Numerous studies stress the importance of factoring informal sector dynamics into long-term planning models, as informality impacts energy consumption, growth, and energy system planning [262–267].

These challenges underscore the need for just and equitable transitions in UES design. In addition to the discussion in Q7, the consideration and inclusion of informal workers, financing measures, and anti-discriminatory programs and policies for vulnerable urban populations are particularly important in the Global South context [250,268,269]. Apergi et al. (2024) have developed a quantitative approach to assess energy justice, which supports just UES transitions [270]. Sustainable, resilient, and equitable UES deployment in the Global South must also consider economic barriers such as affordability and fair financing mechanisms [269,271]. Local currency instability (including inflation and depreciation effects that impact the exchange rate) impacts long-term sustainable UES development, the risks of which should be evaluated using planning models, as demonstrated for Accra, Ghana [272].

UES solutions also face technical and operational hurdles in different LMICs. Poor operation and maintenance of energy infrastructure, insufficient installed power generation capacity, high technical and non-technical losses, reliance on imports, poor revenue collection, electricity theft, and poor financing of power companies are some issues hindering UES development in the Global South [263].

However, significant heterogeneity exists across LMICs, making it clear that no single UES solution fits all. This diversity also presents valuable opportunities for innovation and flexibility. In many cases, LMICs have not only addressed longstanding energy challenges but have also demonstrated a level of agility often absent in Global North contexts. For example, driven by limited grid access, a high penetration of off-grid and mini-grid solutions has emerged in Sub-Saharan Africa, South Asia, and Southeast Asia [273]. Papua New Guinea [274], Nigeria [275], and India [276] have become global leaders in deploying off-grid solar home systems and community mini-grids. In climates with high heating demand, particularly in post-Soviet states and China, district heating networks are also more extensive and better integrated than in many Western European and North American nations [277]. The absence of legacy infrastructure in many LMICs has also allowed for faster adoption of clean technologies, avoiding the sunk costs and inertia associated with outdated systems. This has enabled leapfrogging in several sectors [278]; in addition to off-grid solar PV in Sub-Saharan Africa, Brazil has leapfrogged to become a global leader in biofuel production [279], and China is advancing electromobility at an unprecedented scale [280]. As such, LMICs characterized by unique climatic, infrastructural, institutional conditions do not only face distinct energy challenges but also offer new possibilities for adaptive and forward-thinking UES development.

Even when favorable technical and economic conditions exist, UES often fail where multi-level governance challenges persist [281]. Poor coordination between jurisdictional levels, uneven distribution of power resources and capacities, central-local conflicts, corruption patterns, and veto power at different jurisdictional levels affect low-carbon development in LMICs, as observed in the Philippines and Indonesia [281]. Communities require empowerment to catalyze the energy transition, particularly in areas where decentralized energy governance is weak and superseded by state monopolies, such as in Kenya [282]. Checks and balances in multi-level governance are needed to mitigate energy access inequities [282]. Such governance approaches are also required in the Global North, as discussed in Q7.

The heterogeneity of governance structures across LMICs is also notable. Centralized, state-led governance structures, characterized by national control over UES planning and limited local autonomy, such as in Ethiopia, can overlook local needs or resilience [283]. In contrast, decentralized local-led governance provides a framework for local autonomy and innovation, and can fill governance gaps, as demonstrated in Sao Paulo (Brazil) [284], Shariatpur (Bangladesh) [285], Migori (Kenya) [286], and Gujarat (India) [287]. Hybrid, multi-level governance, where responsibilities are shared across national, regional, and local actors, have also taken shape in South Africa [288]. However, if not implemented with care, local governance structures can suffer from a lack of coordination, financing, and technical capacity at the local level in LMICs [289,290].

The social, economic, technical, governmental, and climatic landscapes of LMICs differ significantly; thus, it is vital to tune UES solutions to local conditions [249]. Models support sustainable and resilient UES planning; however, they must go beyond techno-economic analyses to consider local multidisciplinary challenges. Quantitative technical modeling approaches to UES planning dominate research, while the aforementioned factors remain relatively under-investigated yet vital for successful urban energy transitions worldwide [291].

Q10. What future priorities should be addressed to ensure UES are sustainable, resilient, and capable of meeting global challenges?

Ensuring sustainable and resilient UES requires prioritizing integrated design methods, environmental and societal considerations, and international collaboration. These priorities form the foundation for addressing global challenges and achieving a just and sustainable energy transition.

Integrated design method: Given the complex nature of UES design, significant efforts should be devoted to developing more effective design methods that capture multiple relevant dimensions. Integrated solutions are essential as UES are part of larger energy systems, where higher-level transitions significantly influence local systems. Designing UES requires moving beyond optimizing resources within urban boundaries to addressing spatial and temporal dynamics across multiple scales [74,292] (see also Q1-Q3). UES design methods must also consider long-term changes and system uncertainties. Integrating uncertainty considerations into planning processes is also essential for building resilient, adaptable systems capable of addressing future challenges. Techniques such as scenario analysis, sensitivity assessments, and probabilistic modeling enable planners to accommodate diverse possible futures [123,293–296].

Advanced modeling methods and techniques: Developing and implementing novel approaches based on advanced modeling methods are pivotal in driving efficiency and resilience in UES. The adoption of cutting-edge technologies and methods, particularly AI, can significantly improve the efficiency and quality of UES design [297]. Emerging tools leverage advancements in sensing, data science, and machine learning to analyze real-time data, offering greater precision and insights for planning processes [180,298–300].

Environmental and societal priorities: Addressing environmental and societal priorities is key to achieving a fair and sustainable urban energy transition, ensuring that ecological goals align with social equity (see Q6 and Q7). Holistic urban energy planning integrates environmental, social, and economic considerations, addressing trade-offs and identifying synergies for more sustainable and equitable urban systems [301,302]. UES design will benefit from resilience metrics and adaptive planning approaches that allow for iterative adjustments as risks and technologies evolve in the future. Diverse stakeholder engagement is critical to collaborative UES design. Involving local communities and key actors in planning and implementation ensures the incorporation of varied perspectives and local knowledge. Early and continuous stakeholder involvement, transparency, trust-building, and effective communication are foundational to creating just and sustainable UES [294,303,304].

International collaboration: Strengthening international collaboration is vital to overcoming the shared UES challenges and fostering global progress toward sustainability. International collaboration focusing on specific areas of UES design, such as IEA EBC programme (Annex 93, 95 and 96), helps create a clear vision and accelerate transitions. This approach facilitates knowledge sharing and collaboration among cities tackling similar challenges, enabling the dissemination of best practices and lessons learned [46]. Success depends on selecting appropriate topics tailored to the unique characteristics of each urban area, alongside customized design solutions and urban visions (see Q8). Supporting the Global South through technology transfer, skills development, and financial resources is essential to advancing global climate goals (Q9). Collaborative efforts also foster innovative solutions that benefit all regions, promoting a shared path toward sustainability [1,2,305,306].

In summary, advancing UES design requires integrated multi-scale solutions, advanced planning methods, prioritizing social and environmental equity, and international collaboration to address global challenges and drive a just and sustainable energy transition.

3. Discussion and conclusions

Urban Energy Systems (UES) are inherently complex socio-technical systems, and UES design should carefully consider spatial planning, technical innovation, and socio-institutional contexts. UES represent more than a configuration of energy technologies in urban contexts—they are means to the broader transition toward integrated, adaptive, and socially grounded urban infrastructures. The layered complexity of UES demands not only multi-disciplinary expertise but also a diverse perspective that bridges silos and engages with the trade-offs and tensions that characterize real-world decision-making.

A central finding of this paper is that the design of UES is closely tied to the urban context in which they are embedded. The sectoral and spatial integration (Q1–Q2) necessary for energy transitions, such as through sector coupling, distributed generation, and multi-energy systems, requires planners to navigate between immediate efficiency gains and long-term system resilience. Yet this balancing act is not without tension: efforts to maximize infrastructure performance can lead to path dependencies and lock-in effects that constrain future flexibility for UES evolution. For example, the deployment of large-scale district heating systems can be environmentally beneficial over time but may entail significant upfront carbon emissions and risk social issues if not inclusively designed.

Optimization and digitalization-based modeling tools (Q3–Q5) offer a powerful lens to address complexity, explore future scenarios, and support decision-making under multiple objectives. However, these tools are often bound by assumptions of perfect foresight, limited treatment of uncertainty, and underdeveloped socio-institutional dimensions. A key gap is the integration of uncertainty analysis and near-optimal solution spaces in a way that is computationally feasible and supports decision-making. There is also a persistent lack of standardized data practices and open repositories, which hinders model transparency, comparability, and scalability. These limitations signal a need for advanced modeling approaches that prioritize robustness, openness, and integration with behavioral and institutional factors.

Beyond the technical domain, Q6–Q7 broaden the design paradigm by emphasizing life-cycle environmental metrics, circular economy principles, social equity, and governance mechanisms. These dimensions are not peripheral but central to the legitimacy, durability, and acceptability of UES. Yet trade-offs between environmental sustainability and affordability, or between innovation and social acceptance, remain unresolved. For instance, inclusive business models that distribute costs and benefits equitably across communities are essential yet are often not embedded in traditional techno-economic assessments. Bridging this gap requires participatory planning frameworks and multi-actor governance that are aligned with power asymmetries, institutional fragmentation, and contextual differences across cities and geographies.

The Q8–Q10 shifts the lens to future-oriented, globally relevant design principles. It emphasizes that successful UES cannot rely on external blueprints or isolated innovations. Instead, they must respond to local priorities and challenges, especially in the Global South, where issues like energy access, informal economy, and climate vulnerability define the UES design space. At the same time, long-term visions must incorporate systemic resilience, not just to technical failures, but to disruptive weather events such as heatwaves, dunkelflautes, and flooding. This calls for a reframing of UES design around adaptive, modular, and inclusive principles, where infrastructure is co-developed with communities and resilient to a range of plausible futures.

This paper adopted a deliberately broad perspective to reflect the complex, multi-layered nature of urban energy systems. Rather than focusing on a single technology, model, or context, it addressed the interplay between technical, environmental, social, economic, and institutional dimensions, shaped by varying urban conditions and world regions. While each of these areas has a large body of literature dedicated to it, they are often approached in isolation. Our goal was to bring them into dialogue, highlighting the need for integrative thinking to design effective and context-appropriate UES. The paper also emphasized that successful UES design requires balancing technical solutions with participatory processes, ensuring that environmental, social, and economic objectives are met coherently. By adopting an inter- and transdisciplinary perspective, we aimed to support more robust, inclusive strategies that respond to the complex realities of sustainable urban development.

To summarize, this paper provides the following recommendations for future research for advancing UES design:

- Move beyond single-objective optimization toward identifying robust and near-optimal multi-objective solutions that account for uncertainty, stakeholder diversity, and institutional inertia.
- Integrate modeling tools within broader decision-support frameworks that couple technical outputs with governance, behavioral, and equity considerations.
- Design UES that are context-aware, reflecting urban morphology, social practices, and governance capacities, particularly in geographies in the global South.
- Establish shared, open, and standardized data infrastructures—including ontologies and knowledge graphs—to improve model transparency, comparability, and reproducibility.
- Foster interdisciplinary and transdisciplinary collaboration by embedding stakeholders—energy communities, municipalities, grid operators, civil society, and academia—throughout the design process.
- Evaluate trade-offs not just in terms of metrics such as cost and emissions, but in terms of life-cycle impacts, resilience, equity, and adaptive capacity.

Ultimately, UES design is a strategic arena for shaping sustainable urban futures. It requires more than technical excellence and demands integrative design thinking and institutional innovation. By embracing inter- and transdisciplinary approaches and fostering global collaboration, the UES community can move from fragmentation toward convergence. This transition will be essential for realizing cities that are not only energy-efficient and low-carbon but also livable, inclusive, and resilient across generations.

Description of authors' expertise on the topic

The **Urban Energy Systems Laboratory at Empa** focuses on developing methods, strategies, and solutions to transform buildings, neighborhoods, and cities into energy-efficient, net-zero systems. The co-authors bring diverse expertise in urban energy systems. **Dr. Binod Koirala** explores the techno-economic, environmental, and socio-institutional aspects of energy transformation from local to transnational levels. **Ms. Ana Bendiek-Laranjo** develops data-driven solutions for digital building stock characterization and circular construction strategies. **Dr. Marianne Biéron** investigates the interactions between buildings and the power grid, focusing on GHG-based controllers and energy flexibility. **Dr. Yi-Chung Barton Chen** models multi-sector energy systems using geospatial data. **Dr. Gabriele Humbert** optimizes energy systems, storage technologies, and sector coupling. **Dr. Jens Hunhevicz** focuses on data-driven governance for circularity and sustainability in the built environment. **Dr. Robin Mutschler** develops methods to optimize regional and national energy system configurations, including carbon cycles (CCUS). **Dr. Michel Obrist** specializes in industrial decarbonization pathways and future energy technologies' roles in urban systems. **Dr. Elliot Romano** studies the potential flexibility of demand in large-scale energy systems and the carbon assessment of grid electricity. **Dr. Natasa Vulic** assesses decarbonization strategies for the built environment, considering techno-economic, social, and policy aspects. **Dr. Mashael Yazdanie** focuses on long-term, systems-level modeling for sustainable and resilient local energy planning, with experience across several continents. **Dr. Georgios Mavromatidis** develops computational methods at the technology-policy interface to support sustainable urban energy transitions.

CRediT authorship contribution statement

B. Koirala: Validation, Resources, Investigation, Conceptualization, Writing – original draft, Software, Methodology, Formal analysis, Writing – review & editing, Supervision, Project administration, Funding acquisition. **A. Bendiek-Laranjo:** Writing – review & editing, Formal analysis, Investigation, Writing – original draft. **M. Biéron:** Writing – original draft, Writing – review & editing, Formal analysis, Investigation. **Y.C. Chen:** Writing – review & editing, Investigation, Visualization, Writing – original draft, Formal analysis. **G. Humbert:** Writing – original draft, Writing – review & editing, Formal analysis, Investigation. **J. Hunhevicz:** Investigation, Writing – original draft, Writing – review & editing, Formal analysis. **R. Mutschler:** Funding acquisition, Writing – original draft, Writing – review & editing. **M. Obrist:** Visualization, Writing – original draft, Writing – review & editing. **E. Romano:** Writing – review & editing, Formal analysis, Investigation, Writing – original draft. **N. Vulic:** Supervision, Writing – original draft, Formal analysis, Writing – review & editing, Investigation. **M. Yazdanie:** Writing – review & editing, Formal analysis, Investigation, Writing – original draft. **G. Mavromatidis:** Writing – original draft, Resources, Investigation, Writing – review & editing, Supervision, Methodology, Conceptualization, Validation, Project administration, Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Binod Koirala reports financial support was provided by Swiss Federal Office of Energy. Marianne Bieron reports financial support was provided by ETH Board. Robin Mutschler reports financial support was provided by Swiss Federal Office of Energy. Natasa Vulic reports financial support was provided by Swiss federal office of Energy. Gabriele Humbert reports financial support was provided by Swiss Federal Office of Energy. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration

During the preparation of this work, the authors used language editing tools such as Grammarly, DeepL, and ChatGPT to improve language and readability. After using these tools, the author reviewed and edited the content as needed and take full responsibility for the content of the publication.

Data availability

No data was used for the research described in the article.

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