Advancing urban energy system planning and modeling approaches: Gaps and solutions in perspective

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ABSTRACT

The role of cities in reducing global greenhouse gas emissions is rapidly evolving, as evidenced by significant growth in transnational municipal networks and local climate strategy adoption over the past decade. A large number of energy system modeling and planning tools are available to urban energy planners, but the majority of review studies focus on summarizing the capabilities of these tools. Comparatively few reviews examine the array of gaps in the field alongside potential solutions, particularly from both expert and practitioner viewpoints. This study aims to fill this gap. It provides a pragmatic, comprehensive overview of technical, methodological, and institutional gaps and solutions amongst urban energy system modeling tools and methods. It also compares solutions in order to identify relatively high-impact and easy-to-implement recommendations for tool developers, researchers, urban energy planners, policymakers, and other decision-makers. Key methodological solutions include developing: 1) more integrated modeling approaches; and 2) more comprehensive energy modeling scenarios to represent social factors and system imperfections. Technical solutions to improve data gaps include implementing: 1) increased privacy controls; 2) robust, secure communication architectures; and 3) improved data sharing platforms. Institutional solutions, which have some of the highest expected impacts in the field, include establishing: 1) centralized energy data regulation and collection authorities; 2) centralized frameworks to support the development of municipal energy planning departments; 3) training programs to build local capacity; 4) increased open data licensing in the public sector; and 5) improved scientific standards for transparency, reproducibility, and uncertainty analyses in energy modeling.

1. Introduction

Urban areas currently accommodate over half of the world’s population and over 70% of global energy-related CO₂ emissions, with these statistics expected to be even higher by 2050 [1]. As such, cities play a vital role in the global transition towards a low-carbon emission and sustainable energy future. The importance of integrating local-scale energy system planning into long-term, large-scale energy strategies has gained traction over the past 15 years. This growing trend has largely been driven by the advent of transnational municipal networks, such as the Global Covenant of Mayors and C40 Cities, which advocate for climate change adaptation through local climate strategies [2,3].

As cities become more engaged in global initiatives to mitigate climate change, they require adequate tools and methods to plan local, sustainable energy strategies. Urban energy system modeling and planning tools (UESMs) can broadly be defined as frameworks that provide quantitative, system-level analyses to support local energy strategy development and decision-making. Energy models first emerged as linear programming-based tools to support national energy strategy decision-making in the wake of the oil crisis during the 1970s [4]. These models evolved to represent higher temporal scales for a wider range of applications during the 1990s, as decision-makers increasingly recognized their value for long-term planning [5]. However, today’s energy landscape presents increasingly complex energy system issues and interactions, due to decentralized generation, decentralized energy markets, flexible demand-side management using smart grids and storage, intermittent renewable energy-based generation, and scenario analysis under uncertain climate change conditions, amongst others. Increasingly decentralized energy systems also mean that cities, and UESMs, will play a key role in supporting national energy strategies in the long-term. Energy modeling approaches, particularly at the local scale, require further development in order to meet modern energy system modeling and design challenges (e.g., relating to data gaps, standardization, intuitional support, and the representation of energy system issues and technologies).

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List of abbreviations

DMU Decision-making under uncertainty
DR Demand response
DSM Demand-side management
HPC High performance computing
ICT Information and communications technology
IPCC Intergovernmental Panel on Climate Change
IRENA International Renewable Energy Agency
LUT Land use and transportation
RCA Robust and secure communication architectures
RETS Renewable energy technologies
UESMs Urban energy system modeling and planning tools
UHI Urban heat island

An array of UESMs exist with widely ranging, often overlapping, capabilities and objectives. Urban energy planners must navigate the breadth of available UESMs in order to identify a suite of suitable tools for themselves. Review studies attempt to facilitate this task by providing overviews of modeling tools and capabilities across the field. For example, two widely-cited review studies of software tools for the integration of renewable energy technologies into energy systems are authored by Connolly et al. [6], and Sinha and Chandel [7]. More recently, Ringkjø et al. also provided a comprehensive and detailed overview of 75 prevalent energy modeling tools and their capabilities [8].

However, relatively few researcher papers have attempted to identify key challenges and opportunities in this field in comparison. Two notable exceptions include Keirstead et al. who review approaches and challenges in energy system modeling in Ref. [5], and Pfenninger et al. who provide a broader view of imminent energy modeling challenges in Ref. [4]. Even fewer studies focus on implementable solutions to identified gaps. There is a need for a comprehensive review study in this field which not only consolidates information on both theoretical and practical gaps and challenges, but also offers solutions to identified problems, and recommendations for further development of urban energy system modeling tools and methods in order to meet today’s energy planning challenges. Thus, this study aims to:

1) provide a uniquely consolidated, comprehensive, and pragmatic overview of the gaps and challenges in the UESM field through literature review and by conducting interviews, surveys, and workshops with UESM experts and practitioners;
2) present a range of technical, methodological, and institutional solutions to tackle the identified gaps and challenges; and
3) develop a juxtaposed, interlinked analysis of these problems and solutions. This analysis considers both the relative impacts of solutions in the field, and their relative ease of implementation in order to identify high-impact, realizable solutions for developers, researchers, urban energy planners, policymakers, and other decision-makers with limited resources to advance this highly topical field.

2. Review methods

A range of methods are employed in order to gather data on UESMs, identify gaps, and develop solutions. The authors identified over 30 review studies focused on assessing energy system modeling/planning tools, their methods, and related issues [4–34], and over 90 local-scale case studies using UESMs. These investigations were reviewed in order to identify energy modeling gaps and challenges, as well as potential solutions across technical, methodological, and institutional categories.

The aforementioned literature review was supplemented with findings based on approximately 40 surveys and interviews which were conducted with energy modeling experts and practitioners in the field. Participants included energy system modelers and researchers, tool developers, municipal energy planners, electricity network planners and operators, and local policy and decision-makers. Additionally, a focus group discussion was conducted with urban energy modeling experts to review findings, receive feedback, and gain additional insights. The authors also collaborated with the International Renewable Energy Agency (IRENA); IRENA provided feedback on this study through more than five formal review stages, in addition to bilateral discussions.

The aforementioned research avenues are harnessed to consolidate findings regarding gaps/challenges (section 4) and potential solutions (section 5) across the UESM field. These solutions are then assessed and compared with respect to their ease-of-implementation and relative impact based on connectedness to, and effects on, other challenges and solutions (section 6). This ultimately enables the identification of the most effectual pathways towards advancing this field for target audiences ranging from researchers to municipal-level decision-makers.

3. Background

3.1. Urban energy system modeling tools

As mentioned, UESMs provide quantitative, system-level analyses to support energy strategy development and decision-making. They can be subdivided into several, sometimes overlapping categories. UESMs can be defined in terms of providing the following main functions [8]:

1) operational decision support to optimize the operation and dispatch of energy technologies (typically on short-term, high temporal resolutions);
2) investment decision support to optimize capacity planning of energy technologies embedded in a system (typically on long-term, low temporal resolutions);
3) scenario planning to investigate a range of possible long-term scenarios, including varying policies, technologies, and other exogenous and endogenous conditions (e.g., regarding prices, technical learning curves, and energy demands); and
4) power systems analysis to assess power flows, faults, and system dynamics (typically at a high spatial and temporal resolution)

These UESMs can be further categorized methodologically as bottom-up or top-down models, and as simulation, optimization, accounting-based, and/or equilibrium models [8]. This study focuses on UESMs that can be applied at the local scale for holistic energy system planning; thus, it primarily focuses on tools that provide operational and investment decision support, as well as scenario assessment.

Over 100 energy system modeling tools are available to modeling experts and practitioners for energy system planning on local and larger scales [6–8]. Table 1 summarizes a set of more than 60 available UESMs that can be applied for local-scale planning. The geographical scope of these tools ranges from the international to the local scale. Tools designed specifically for local-scale applications (i.e., from project to citywide scales) are italicized in Table 1.

3.2. Data requirements

UESMs require significant amounts of input data to models. In general, the following types of data sets are required by UESMs; these sets can vary in terms of temporal, spatial, sectoral, or other resolutions depending on the scope of the energy system modeling problem. Further details are provided in Ref. [35]:

- Demand-side data includes consumption profiles at annual or higher temporal resolutions, at citywide or higher spatial resolutions, by zoning sector, and by energy carrier. Long-term models often require projected demand data in future years as well. Demand elasticity and
Table 1

| Range of available UESMs (italicized UESMs designed for local-scale applications only) [6–8].
| AURORAxmp | Balmorel | Calliope | CASPOC | City Energy Analyst (all-inclusive) |
| CityGML | CityInfSight | CitySim | ClearPath | COMPOSE |
| CUBB EnergyPLAN | CYME | EnergyPlus | energyPro | ENPEP-BALANCE |
| ETM | eTransport | Fisuc | FlexGIS | GEMS |
| HEAT+ | HOMER | HYPERSIM | HGOGA | IEARUS |
| INSEL | INVERT/Ellab | IPSA 2 | KomMod | LEAP |
| MAED | MESSAGE | MODEST | NEMS | Network Planner |
| OpenDSS | OSeMOSYS | PLEXOS | PRIMES | ProdRisk |
| PyPSA | RAPSim | RETScreen | SAM | SIMPOW |
| SimStadt | SIENA | STAR | STREAM | SWITCH |
| Syncity | TIMES/MARKAL | TRANCE | TRNSYS | UMI |
| Urbs | WASP | | | |

flexibility data is required for models focused on demand-side management as well.

- **Supply-side data** includes generation and fuel supply profiles at annual or higher temporal resolutions, at citywide or higher spatial resolutions, by zoning sector, and by energy carrier. Supply technology data is also often required, including installed and planned capacities, technical specifications, and operational performance.

- **Technical performance data** includes performance factors and costs by system size and application. Long-term models must often make assumptions regarding the evolution of these parameters in future years as well.

- **Technology installation potentials** include renewable and non-renewable energy technology installation potentials at the spatial scale required by the model (e.g., at a building, district or citywide level). Installation potentials consider zoning restrictions, network capacities to accommodate integration, and other factors.

- **Energy resource potentials** include renewable and non-renewable energy resource estimates at appropriate spatial and temporal scales. They consider natural resources, import capacities and availabilities, and infrastructure limits.

- **Infrastructure data** describes capacities, layouts, performance parameters, and other details regarding networks, buildings, and others. The level of spatial resolution is dictated by the modeling scope.

- **Emission data** may include direct and indirect (e.g., lifecycle) emission data for energy carriers, technologies, and infrastructure.

- **Microclimate and weather data** includes information on local weather patterns and climate, including local phenomena such as urban heat island effects. This data is useful for renewable energy resource and demand estimations, as well as smart energy management in cities.

4. Gaps and challenges

This section identifies overarching challenges in the field of urban and general energy systems modeling. The aim is to identify not only technical and methodological challenges in existing tools and methods, but also pragmatic barriers to higher UESM adoption rates in local energy planning decision-making processes. In addition to discussing the gap itself, each section discusses the factors that have contributed to the formation of the gap and key barriers which inhibit its resolution.

The gaps identified in this section are based on the range of review methods described in section 2. These include literature review and expert and practitioner insights obtained through surveys, interviews, and workshops. Gaps are broadly categorized as technical and methodological challenges (section 4.1), or institutional challenges (section 4.2). Technical and methodological challenges refer to the technical limitations that existing UESMs face, including systemic and theoretical gaps in modeling approaches. Institutional challenges describe organizational, educational, and structural gaps which inhibit the increased adoption and effective use of UESMs for urban energy planning. The presented gaps and challenges, along with section headers, are summarized in Fig. 1 for ease of reference.

4.1. Technical and methodological challenges

4.1.1. Data gaps

Data challenges in modeling are multifaceted in nature. The various aspects for consideration are discussed in the following sections, including factors that have contributed to this gap and barriers that inhibit its resolution.

4.1.1.1. Availability and accessibility. Limited data availability and accessibility is due to several reasons. Data collection and distribution is notoriously inhibited by privacy issues [36]. Ownership across multiple sources can also inhibit accessibility. Licenses from data issuing institutions tend to be closed, disallowing further data sharing and publication [36]. This results in inefficient data collection by researchers who often duplicate collection efforts.

Available data faces other accessibility and efficiency issues as well. A lack of centralized regulatory standards and metrics results in inadequate sharing platforms. There is also the issue of limited information and communications technology (ICT) infrastructure to collect data. The resources required to improve ICT and data collection can be costly and time intensive.

4.1.1.2. Quality and consistency. As mentioned, there are few centralized standards on the wide-scale collection and distribution of energy-related data. Therefore, data sets vary greatly across sources and sectors, and data lacks consistency in content, structure and quality. Cajot et al. also note that differences in “physical and administrative scales and actors induce scarce, dispersed and low quality physical data, which reduces the quality of models” [37]. Poor standards mean that collected data can be erroneous as well, with few quality controls in place.

4.1.1.3. Granularity. Many models employ coarser resolutions than desired when appropriate spatial or temporal data is unavailable. Pfenninger et al. identified this trend by surveying 219 studies, amongst which 44% used district or coarser spatial scales and 58% used annual or greater temporal scales [5].

Haydt et al. and Poncelet also et al. stress the importance of temporal resolution when considering significant shares of renewables, finding that models with insufficiently detailed temporal resolutions can lead to sub-optimal renewable energy technology (RET) investments, an over-estimation of the demand that can be met by RETs, and an underestimation of operating costs [36,39].

The availability of model input data at the required temporal or spatial resolution remains a challenge. Data is frequently collected at lower temporal and spatial resolutions than modeling requires. For example, energy supply data statistics are usually available at an annual level for key sectors, but not at higher temporal (e.g., hourly) or spatial (e.g., sectoral) resolutions [40–42].

4.1.1.4. Data management. As energy systems become increasingly decentralized, renewable energy-based, and intelligent, the amount of data transacted between systems and subsystems grows immensely [43–46]. A number of big data sources are transforming energy management and utilities as well [44].

1 Bold text in section 4 highlights contributing factors to gap formation and/ or barriers to resolution.
Data comes from different sources, sensors, locations, and owners; therefore, it is highly heterogeneous in nature and is generated in large volumes. In order to manage this data, it must be produced in compatible and consistent formats, especially for systems retrofit at later dates. Data management must also ensure secure and private data transmission to address privacy concerns. Data maintenance and ensuring that data libraries are up-to-date is also a resource-intensive task. Diverse districts are also likely to present a wide range of systems which may use different communication protocols, have different ages, and face dissimilar privacy issues [47].

4.1.2. Transparency and reproducibility in energy modeling

Transparency refers to the degree to which the inner workings of a modeling framework (and the models generated using it) are explained in terms of equations and assumptions through documentation, source code, and input/output files. A lack of transparency in modeling inhibits the understanding, credibility, trust in, and ultimately usefulness of UESMs. Reproducibility comes hand-in-hand with transparency, referring to the degree to which models and results can be reproduced or verified by others. Energy system models are often critiqued because they are found to be nontransparent and non-reproducible [4]. Pfenninger et al. also point out that “energy policy research ostensibly lags behind other fields in promoting more open and reproducible science” [48]. The transparency of energy models impacts how well sustainable energy planning suggestions based on modeling results are received and, ultimately, implemented in communities [49,50].

There are several reasons for a lack of transparency and reproducibility in energy systems modeling. One key challenge is that energy systems models, by their nature, are not verifiable against observable physical phenomena [4,51]. This motivates criticism against the use of energy system models in policy decision-making in Europe and beyond [4]. Beyond this, transparency can be hindered by author and stakeholder concerns, including safeguarding intellectual property rights and “trade secrets” to maintain a competitive edge in markets and research. Modelers are often unable to detail data sources due to non-disclosure agreements as well. Politically, governments can also keep sensitive model information and data closed to avoid unwanted societal and economic impacts or backlash [48].

High transparency can lead to unwanted exposure for authors as well. Significant time and effort are required to properly document models and to respond to feedback, feature requests, and bug reports in the case of open-source code. There is little academic glory in these tasks and, ostensibly, a limited push by academic communities to raise transparency and reproducibility standards [48]. It can also be difficult for modelers to disseminate models and receive user feedback, the latter of which also requires significant time and effort. Low usage or feedback rates can generate a sense of futility that discourages modelers from sustained future efforts in this direction.

4.1.3. Balancing model resolution, complexity, and computational tractability

Two general modeling approaches are employed in urban energy systems modeling which aim to balance model resolution and computational tractability. Models with long time horizons and/or broad spatial scopes tend to compromise temporal and spatial granularity in order to maintain computational tractability (e.g., as in Ref. [52–54]). On the other hand, models with short time horizons and/or narrow spatial scopes are able to use finer temporal and spatial resolutions (e.g., as in Refs. [55,56]). A balance between model size and resolution is needed in order to manage the computational demand of models as we approach computational limits, and it comes with its own set of challenges.

RETs with variable energy renewable energy resources require careful balancing of model resolution and computational tractability. Després et al. find that even relatively detailed long-term energy models lack the temporal resolution needed to include inter-temporal constraints to fully consider the variability of renewable energy resources [57]. Using sample time periods (e.g., typical seasonal days as in the aforementioned examples) also limits the analysis of storage technologies where chronological detailing is important [58]. However, Poncelet et al. find that significant gains in accuracy can be made through the appropriate selection/representation of time slices to capture renewable variability in long-term models (compared to simply increasing temporal resolution and computational demand) [59]. Pfenninger also
4.1.4. Emerging technologies and UESMs

The emergence of smart grid and demand-side management technologies and techniques can play a pivotal role in the design and operation of sustainable urban energy systems. Their representation in UESMs enables better-informed, holistic energy system design. For instance, the representation of these technologies is needed to accurately forecast demand and identify sector-coupling opportunities (e.g., between decentralized electricity generation and storage in the transportation sector using battery-electric vehicles in virtual power plant applications). The consideration of these technologies is essential for optimal system design and component sizing as well, including long-term infrastructure and energy conversion technology investment planning to minimize system-level costs and/or emissions. The following sections discuss smart grid and demand-side management challenges in UESMs in more detail.

4.1.4.1. Smart grid integration. UESMs are often used to consider smart grid operation implicitly in energy models without explicitly modeling novel smart grid technologies and controls. This is frequently observed when an energy system’s operation is optimized using a perfect foresight, deterministic model. Unless explicitly evaluated, such models assume that the necessary control strategies, associated technologies, and stakeholder cooperation are in place to optimally operate energy systems. The costs of smart systems can be reflected in models, but this is rarely observed. As smart grid technologies and strategies develop, so too will the need for UESMs to explicitly model these systems, especially for utilities or other project planners seeking to test and invest in them (e.g., through smart grid pilot projects).

The lack of development of smart grid considerations in UESMs is directly linked to the nascent nature of this field [61]. Smart and microgrids currently struggle with underdeveloped markets, non-standardized and sparsely distributed ICT, and underdeveloped regulations. To illustrate, Eurelectric identifies a number of regulatory gaps which impede smart grid investments in the EU [62]. These include sub-optimal rates of return; a lack of clarity regarding the roles and responsibilities of individual market players; regulatory instability; and cost efficiency evaluation schemes that penalize R&D expenditure on smart grid pilot projects [62].

The nascent of this field translates to a lack of unified smart grid control and management strategies as well. A range of modeling approaches are currently being evaluated in literature to identify best practices in this regard. Approaches include game theory, multi-agent systems, model predictive control, and peer-to-peer networking using blockchain technologies, amongst others described in Refs. [47]. Overall, an iterative learning process will be required between theory and application before best practices emerge in this field, and with these developments, so too will UESMs evolve.

4.1.4.2. Demand-side management. Demand response (DR) or demand-side management (DSM) are closely related to smart and microgrids. DR refers to changes in consumer energy demand that are facilitated by incentives, technologies, or consumer awareness. It has strong applications to renewable energy integration, particularly within smart grid applications [63,64]. For example, DR can be used as an ancillary service to balance excess RET generation with loads within smart networks. Dynamic pricing schemes and virtual power plants can also be used to balance variable RET energy supply and demand. Many models built using UESMs consider energy demand to be predictable and uncontrollable in current and future energy systems (e.g., in perfect foresight optimization models). This usually simplifies modeling. However, as energy systems become more decentralized and intelligent, consumer and producer definitions become blurred and representing DR in urban energy models becomes increasingly relevant. UESMs that allow for modeling real-time pricing schemes, local energy trading, and demand elasticity provide more flexibility to consider DR in urban energy models. Several UESMs offer these considerations, but like smart grid technologies, DR system details and costs need to be explicitly modeled in future energy systems.

Demand-side management faces similar barriers and challenges as mentioned for smart grid integration in the preceding section; i.e., it is a nascent field where methods, technologies, regulations, and standards are not yet mature, and iterative exploration is required through pilot projects and theoretical studies supported by UESMs.

4.1.5. Integrated models

There are limited attempts to integrate energy systems models and UESMs across multiple disciplines [5]. This translates to shortsighted modeling results and decision-making. However, researchers have shown how combining modeling strategies, such as spatial analysis and energy system modeling, can mutually benefit both urban spatial and energy planning [37,65].

Cajot et al. emphasize the need for modeling sustainability measures on multiple levels (e.g., energy efficiency measures at the low-level building scale up to low-carbon transport systems on a citywide scale) [37]. Després et al. also discuss a gap between energy modeling and power system modeling tools [57]. Until now, the objectives and strengths of these two types of tools have not been effectively combined, although soft-linking some tools (e.g., TIMES and PLEXOS) is possible and efforts are increasingly being made to couple these approaches [57].

Another area for improved model integration is between urban land use and transportation (LUT) models and energy system models [5]. Combining these approaches involves the integration of both descriptive models of human behavior and normative models of urban supply systems [5]. LUT models are large, generally econometric models which describe key dynamics in urban environments, such as land use change and transportation usage.

There are several contributing factors and barriers to resolving this modeling challenge. First, and perhaps foremost, there is a lack of interdisciplinary dialogue and collaboration to learn from and combine the advantages of different modeling approaches across fields. This includes dialogue between urban and urban energy planners, national and local scale energy planners, and modeling experts and practitioners, amongst others [66]. Poor interdisciplinary and cross-sectoral communication means missed sector-coupling opportunities, oversights, and suboptimal decision-making. Conflicting interests between groups can make this challenging, resulting in a lack of political motivation to
harmonize communication between institutions. Many research funding opportunities also have a narrow focus, leaving little incentive for researchers to collaborate outside of their fields when it is not required.

4.1.6. Uncertainty in modeling

Energy system models deal with a high degree of uncertainty, from data inputs to model outputs. Long-term energy scenarios are especially afflicted by uncertain future assumptions; for example, regarding economic development, population and demand growth, urban development, technology development, future costs, long-term resource availability, future policies, and climate change impacts. Scenarios are defined based on current knowledge, historical trends, and other assumptions, which can be highly uncertain.

There is both expected and unexpected uncertainty in modeling. Unexpected uncertainty includes external system shocks, instabilities, and black swan events. These include changing political actors and agendas, unstable international and national policy frameworks, geopolitical conflicts and consequences, unanticipated climate change impacts, and technology breakthroughs, to name a few. These can also give rise to rapid changes in societal values. Unexpected uncertainty is rarely accounted for in energy planning scenarios.

Expected uncertainty is somewhat more straightforward to tackle, however. Data uncertainty, for example, can be introduced by measurement error, proxy data sources, simulated data, and adjusted approximations (e.g., downscaling national level data to an urban scale). Where uncertainty ranges are known, these can be explicitly described and considered in models; however, Pennington et al. found that the majority of the papers they investigated did not explicitly describe methods of dealing with parameter uncertainty. They also found that deterministic optimization models were particularly weak in describing uncertainty ranges and methods, presumably due to the sheer scale of model parameters and unknown uncertainties. There is a need for researchers to better describe input data uncertainties and how these impact their modeling methodology.

Quantifying uncertainty in energy system modeling faces various hurdles. Where long-term energy system modeling scenarios are involved in governmental decision-making, disagreements and concerns about societal impacts can slow down, block or otherwise limit analyses; for example, regarding the long-term impacts and costs of climate change, both locally and nationally. Quantifying uncertainty ranges for data inputs can also be inherently challenging, particularly when data is limited or unknown. This is often the case for large energy models (e.g., citywide models) with many data inputs. Limited transparency in research regarding uncertainty handling in modeling approaches is also a barrier to effective uncertainty analysis.

4.1.7. Modeling human behavior and challenges in developing countries

The majority of energy system models focus on technological and economic factors, with relatively little analysis of human behavioral factors, indirect costs, and socio-political or non-financial barriers to deploying technologies. Yet, these factors are some of the key barriers to advancing urban energy systems, particularly in developing country contexts; their underrepresentation results in high model uncertainty. Factors prevalent in developing country contexts which tend to be neglected in energy system models are discussed in the following sections.

Underdeveloped modeling approaches to tackle these issues in UESMs partly due to a lack of interdisciplinary collaboration and research funding to address them. Integrating modeling approaches across disciplines in the context of energy system modeling is inherently challenging. The data inputs needed to develop fundamental modeling techniques are also not readily available in many cases, and there may be limited political willpower to bridge data gaps (e.g., due to conflicts of interest or resource limitations).

4.1.7.1. Modeling poor power sector performance

Several developing countries grapple with poor power sector management and performance issues. Faulty planning, poor financing, and insufficient operation and maintenance contribute to suboptimal power system design, which results in unsatisfied local electricity demand even where excess capacity is available. These systems sometimes exhibit tariffs that are below average operating costs or long-term marginal production. Financing problems are further exacerbated by inadequate revenue collection; significant losses occur when utility bills remain unpaid by government-protected actors that can avoid legal consequences.

Many UESMs assume perfect model conditions, markets, and foresight, thereby neglecting the aforementioned imperfections. However, energy system models must represent power sector issues either explicitly (e.g., technically through performance parameters) or implicitly (e.g., through scenario design and uncertainty analysis). The representation of corruption in the power sector also relates to the challenge of modeling suboptimal decision-making.

4.1.7.2. Informal and transitioning economy representation

The informal economy refers to off-the-record economic transactions that are unrepresented in official indicators such as GDP. Its size is often significant in developing countries, an estimated 35–40% of GDP in Sub-Saharan African countries.

Energy models rarely explicitly consider or represent the informal economy. However, given its potential size, its consideration is vital for accurately estimating demand, representing energy economies, understanding system dynamics, and generating more meaningful modeling results overall.

4.2. Institutional challenges

The challenges described in this section relate to institutional factors which inhibit increased UESM utilization and their effectiveness for sustainable energy planning in cities. They encompass organizational, structural, and educational gaps in the institutions in which UESMs are embedded.

4.2.1. Municipal recognition as energy planners

The Intergovernmental Panel on Climate Change (IPCC) identifies urban planning as a key emissions mitigation measure in the fight against global warming. Yet, municipal recognition as an integral part of the energy planning process by centralized, national authorities is lacking in many countries. Municipalities require support and financing by these authorities in order to build stronger independent urban energy planning departments and integrate/harmonize them with centralized energy planning and policy groups. The harmonization of energy planning departments across scales will also enable municipalities to provide inputs to strategic central energy plans (and vice versa).

This would result in increased UESM utilization and more informed model development.

The recognition of municipalities as key GHG emission mitigation actors is relatively recent and, thus, centralized institutional frameworks are not yet mature enough to support them in most regions. However, a central administrator for urban energy planning can facilitate the implementation of local energy policies. Administrative complexity, fragmented government institutions, and political instability are immediate barriers to closing this gap. The implementation of solutions is also restricted by financial and budget constraints.
4.2.2. Capacity building within municipal governments

One of the most commonly identified barriers to increased UESM utilization is a lack of capacity building according to both experts and practitioners in the field. The authors found this both through outreach and in literature. Caputo and Pasetti found that “municipal offices often lack knowledge and authority regarding energy planning, even in the technical offices in charge of the built environment” [37]. Nuorvik and Ahonen also identified this as a key barrier in Ref. [66].

Several barriers inhibit the improvement of technical capacity within municipal energy planning departments. Developing training programs and urban energy planning departments requires significant financial resources which may not be available [66]. The lack of recognition of municipalities as key energy planning actors is a key contributor to poor capacity development and financing in this area. Fragmented government institutions, across multiple levels and sectors, along with administrative complexity slow change as well.

4.2.3. Interdisciplinary cooperation

A lack of interdisciplinary collaboration and dialogue has been identified as a key barrier to overcoming several existing challenges. This pervades across multiple levels, both within and outside of the field (e.g., between energy modeling experts and practitioners, national and local scale energy planners, urban planners and urban energy planners, and modeling experts across disciplines).

Nuorvik and Ahonen observed a lack of cooperation between urban and energy planners in all partner countries in their program [66]. This is due, in part, to poor structural organization. The authors observed that planners work in independent organizations with their interactions being limited to occasional meetings, requests, and insubstantial back-and-forth commentaries on plans [66]. They call for training and closer collaboration between groups, presumably supported by a central, integrative energy planning authority.

A lack of interdisciplinary cooperation also exists at a research level. Project funding opportunities with a strong emphasis on multi- and interdisciplinary collaboration are lacking to tackle this challenge and build more comprehensive modeling methodologies.

4.2.4. Disseminating UESM knowledge

As part of an outreach survey, almost 40 participants were asked to identify the energy system modeling tools that they had heard of. Although over 100 energy system modeling tools exist, practitioner and expert participants were, on average, familiar with approximately 4 and 8 of these tools, respectively. The tools which experts were more familiar with (e.g., TIMES/MARKAL and OSeMOSYS) were not as familiar to practitioners as user-friendly tools like RETScreen (and vice versa). This difference points to gaps both in knowledge and communication within the field. Several UESMs are also methodologically similar to one another, which indicates a degree of duplicated efforts due, in part, to a lack of awareness of other UESMs in the field.

Bridging knowledge gaps in energy system modeling requires overcoming limited interdisciplinary dialogue, as discussed. It also requires educational programs, particularly for practitioners (e.g., urban energy planners), in order to help them gain an awareness of and skillset in using UESMs. However, implementing such programs is inhibited by financial barriers, underdeveloped municipal energy planning departments, and a lack of central support.

4.2.5. Communicating model results

The effective communication of energy system modeling results to a broader audience is another challenge identified by experts and practitioners in the field. Model results need to be presented in more digestible formats which are tailored to different stakeholders (e.g., potential investors, urban planners, and the public). Models and their underlying assumptions must also be made transparent. This is important in order to build stakeholder trust and increase engagement in the urban energy planning process [49,50,68].

5. Bridging gaps

Poor model transparency inhibits the understanding of model results and poor stakeholder communication prevents modelers from gaining insights into how their results and approach are interpreted. These insights are not only needed to improve the effectiveness of communication, but can also improve the modeling methodology itself.

5.1. Technical solutions

This section identifies a range of potential solutions to bridge the identified gaps. These solutions seek to improve urban energy modeling approaches and the frameworks they are embedded in order to improve their usefulness and widespread uptake.

Solutions are presented in two main sections: section 5.1 presents technical solutions to address the primarily technical and methodological gaps identified in section 4.1, while section 5.2 presents institutional recommendations to address technical, methodological, and institutional gaps. Each section discusses the solution, gaps addressed, and resources requirements for implementation.

5.1.1. Tackling data issues

5.1.1.1. Data sharing platforms. Open data sharing platforms have the potential to significantly improve data availability, data accessibility, transparency, and reproducibility3 for urban and renewable energy system models. A number of open energy system databases are documented in Ref. [69], encompassing a range of scales and scopes. However, most open energy system databases focus on the national rather than the municipal scale. These databases should be expanded to include local-scale datasets, or parallel data sharing platforms should be developed with a local-scale energy database focus for cities worldwide.

Current data sharing platform initiatives would benefit from consolidation across their different scopes and scales to provide modelers with a centralized data resource. This would also ease the streamlining and standardization of data formats, content, licensing, structure, and quality.

Cities would benefit not only from databases that provide model input data, but also from documented UESM experiences by other cities. Transnational municipal networks provide an ideal platform to organize such experiential case study databases.

5.1.1.2. Mathematical methods to fill data gaps. Mathematical methods provide a practical approach to filling data gaps where physical data collection is infeasible (e.g., due to the physical scale, available resources, and/or limited infrastructure). Mathematical approaches to simulate data are especially important in the case of cities in developing countries, where there may be few alternatives.

A range of mathematical approaches are used to fill data gaps in urban energy system modeling. Top-down and bottom-up methods are used to disaggregate and aggregate data, respectively. A bottom-up approach benefits from having a high level of detail, and a top-down approach benefits from having implicitly captured real-world influences.

Statistical methods, simulation models, and data mining techniques are also used to fill data gaps in energy system models. Table 2 describes exemplary studies which employ these methods to fill data gaps.

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3 Bold text in section 5 highlights gaps addressed by the given solution.
5.1.1.3. Privacy and security controls. Privacy and security controls in data collection are required to bridge data gaps in modeling. Ensuring the protection of personal identifiers is essential to encouraging participation in data sharing programs (e.g., through smart grid meters) and to increase the effectiveness of data sharing incentive structures (discussed in section 5.2.1.2). Privacy and security measures also facilitate information and communication technology rollout programs through public acceptance.

The Federal Trade Commission recommends several best practice approaches in privacy control [89]. These include the collection of only essential data for a specific purpose, as well as data anonymization, encryption, and aggregation. Data over-collection is identified as "one of the most serious potential security hazards in a smart city" in Ref. [90]. The authors present a mobile cloud framework to prevent data over-collection and to improve user data security [90]. However, cloud solutions present other security challenges, such as tracing network attacks.

In order to implement privacy and security controls, supporting regulations (section 5.2.1.1.), robust communication architectures, and supporting ICT (section 5.1.1.4) are needed as well. These measures take time to realize and roll out; however, best practices can be enacted by electric utilities and device manufacturers in a bottom-up approach until regulations and technologies mature at a wider scale.

5.1.1.4. ICT and robust communication architectures. The communication capabilities of existing power systems are limited to basic functionalities for system monitoring and control [91]. These systems do not yet meet the communication requirements of automated, intelligent power systems [91]. Therefore, advancements in communication architectures and ICT are needed for district-level energy management in current networks [47].

Robust and secure communication architectures (RCA) are needed to implement privacy and security solutions in data collection and transmission. RCA also strengthens ICT and its deployment (e.g., the rollout of smart meters and other IoT devices). Together, they enable more efficient data collection and provide high temporal and spatial resolution data. They yield big data sources that can be processed to close data gaps in urban energy models. RCA and ICT also facilitate the implementation of incentivized data sharing programs or mandates.

RCA solutions must manage large quantities of heterogeneous data in smart networks, from multiple sources and sensors in different locations and with potentially different owners. They must also handle the communication of different smart grid information packets, including demand response drivers, electricity prices, distributed energy generation, storage flows, and electric mobility transactions [46].

There is a wide array of literature on the development of RCA and ICT in smart grids [91–94]. In order to implement RCA, ICT infrastructure is needed, including new measurement devices, faster multi-level communication systems, and fast controllers to manage wide-area control systems. RCA solutions also require methods to handle big data analytics, efficient data network management, and high performance computing techniques (e.g., cloud computing) [46]. Significant investments are needed for large-scale RCA and ICT rollout; however, experts estimate that the opportunity cost of not undertaking these endeavors is higher than the investments needed to transform existing grids [94]. Pilot projects are an essential part of this transition.

5.1.2. Improving UESM approaches

The following sections describe recommendations to improve the methods that modelers use to design and execute models using existing UESMs.

5.1.2.1. Comprehensive scenario design. Scenarios prescribe the investigative framework behind a model run. They describe assumed conditions and data inputs in a model which, together, form an internally consistent and coherent storyline. Urban energy models require more comprehensive scenario design in the following areas.

Socio-technical factors and system deficiencies

Scenario development presents opportunities for modelers to represent socio-technical and techno-economic factors in energy models. Human behavior, social risks/opportunities, and factors prevalent in developing countries can be represented, at least partly, through scenarios (e.g., see Ref. [4,95,96]).

| Primary category | Example methodology | Data gap(s) filled | Ref. |
|------------------|---------------------|--------------------|------|
| Statistical methods | Multiple linear regression and student t-test to estimate appliance ownership; probability functions reflecting human behavioral patterns used to determine time-of-use of appliances and generate load curves | Electricity demand in rural households of developing countries | [70,71] |
| | Markov chain used to generate occupancy patterns | Domestic lighting demand | [72] |
| | Field measurements of power demand and mail surveys used to form probability distributions to generate residential load profiles; Monte Carlo methods applied to simulate randomness in household behavior | Residential electricity load profile | [73,74] |
| | Regression model applied to generate heat demand profiles in non-residential building stocks (schools) in Norway | Non-residential heat demand profiles | [75] |
| | Building thermal performance modeling using EnergyPlus and TRNSYS | Building heating and cooling demand profiles | [76–80] |
| | Thermal dynamic model developed using thermal resistance networks | Energy load profiles for appliances, domestic hot water, and space heating demands | [81] |
| | UHI effect modeling using computational fluid dynamics (CFD), applied to urban models (e.g., meso and micro scale) | UHI effect quantification | [82] |
| | MATSim agent-based transportation model created to estimate future transportation sector demand in Croatia | Transportation demand | [83] |
| | Probabilistic agent-based model used to determine EV charging demand in an urban area and its impacts on the local distribution network | Transportation demand, distribution network impacts | [84] |
| | Renewables.ninja; uses weather data to simulate solar PV and wind energy power plant outputs worldwide | PV and wind power plant generation | [85] |
| Data mining | Data mining of smart meter datasets used to analyze appliance usage in a household throughout a year, and to forecast consumer behavior | Electricity load profiles | [86] |
| | Data mining framework used to analyze and forecast electricity consumption | Electricity load profiles | [87] |
| | OpenGridMap; crowdsourcing used to collect electricity network component data; statistical methods and graph theory applied to build network models | Network/infrastructure models | [88] |
Scenario modeling provides the possibility to test socio-technical failures even when the methods to model these behaviors are limited. For example, scenario designers can consider different suppressed energy demand impacts as a part of a demand input sensitivity analysis. Scenarios can also be used to model poor power sector performance (e.g., through increased operation and maintenance costs, technical failures, load shedding, and financial losses). Scenarios can consider the impacts of different social acceptance levels as well (e.g., through constraints on implementable energy efficiency metrics, such as building renovation rates over time).

Climate impacts
Urban microclimates, urban heat island effects, and long-term global climate change impact local energy demand, economic growth, resource availability, and demographic development [97–99]. These impacts can be formulated as boundary conditions and input data in energy scenarios. For example, economic impacts can be reflected through changes in sector growth rates, discount rates, inflation rates, and local trade assumptions in scenarios, while resource impacts can be reflected through increased costs and constrained availabilities. Local climate change impacts can generally be represented in scenarios by altering techno-economic, demand, and supply input data and constraints in models.

Future urban landscape changes and energy impacts
Urban densification introduces demographic and land use changes that impact energy demand input data in models. Densification also impacts RET installation potentials on buildings (e.g., for solar energy-based technologies) and building thermal performance [100]. These impacts can be modeled as changes in installation potentials and heating/cooling demand input profiles in modeling scenarios, for example. Other long-term changes in the built environment which affect energy demand profiles also include increased building efficiency and changes in urban transportation modes.

5.1.2.2. Integrating modeling approaches. The scope of prevailing UESMs should be broadened by integrating modeling approaches with different urban, social, and energy system foci. Such integrative methods consider multidimensional system aspects and can be used to model commonly neglected factors, such as behavioral impacts and system imperfections. Various model integration opportunities and attempts are described below.

Research funding/calls are needed to advance the integration of urban planning, behavioral, and other multidisciplinary modeling approaches with UESMs. Bridging data gaps to improve the availability of spatial information in the urban environment is essential in order to effectively integrate spatial planning tools as well. Interdisciplinary collaboration between urban and energy planners, from municipal planning departments to academic energy researchers, is needed for a comprehensive development approach to integrated UESMs.

Power system models
Most UESMs lack detailed power system models. Desprets et al. discuss this disconnect between energy and power system models at length in Refs. [57]. They propose two approaches to integrate power system considerations into long-term energy models; the first involves building a simulation function of a power system using a detailed power system model. The second incorporates an explicit power system modeling tool into a long-term energy model at a high computational cost [57]. Soft-linking tools has also been attempted between these two types of models; for example, TIMES and PLEXOS are soft-linked in Ref. [101]. Neglecting power systems analysis in energy models can result in undervaluing flexible resources, underestimating wind curtailment, and overestimating the use of baseload power plants [101].

Land-use transport and behavioral models
Few attempts have been made to integrate land-use transport (LUT) models with energy models. For example, a spatially explicit LUT model is integrated with long-term energy modeling scenarios for Tokyo in Ref. [102]. LUT models are also integrated as part of an interdisciplinary modeling approach in Refs. [103]. Both of these studies stress the importance of considering urban heat island (UHI) effects in urban energy models as well; LUT models can help with UHI effect mitigation by considering land use planning options (e.g., revegetating vacant suburb areas) [102,103]. Behavioral models can also be used to integrate social factors in energy models. For example, Virote and Neves-Silva use stochastic models to predict building energy consumption based on occupant behavior in Ref. [104]. Integrating occupant behavior in building energy simulation models is also done in Ref. [105].

Spatially detailed models
Many UESMs lack detailed relative spatial information (e.g., using GIS data) and instead allow modelers to implicitly design spatially disaggregated models. This is suitable for certain applications (e.g., city-wide models where high disaggregation can be computationally expensive). However, detailed spatial information is useful for low-level applications and detailed system design (e.g., at a district scale).

Scenarios can also be used to model poor power sector performance (e.g., through constraints on implementable energy efficiency metrics, such as building renovation rates over time). Behavioral models can also be used to integrate social factors in energy models. For example, Virote and Neves-Silva use stochastic models to predict building energy consumption based on occupant behavior in Ref. [104]. Integrating occupant behavior in building energy simulation models is also done in Ref. [105].

5.1.2.3. High performance computing and model design. Advanced computational methods can improve the computational tractability of large and high resolution urban energy models. Advanced computational methods, such as high performance computing, are also needed to support the management and processing of high data loads generated by smart grids and decentralized RETs (i.e., using RCA).

High performance computing (HPC) refers to the practice of aggregating computing power to perform complex calculations at high speeds. A wide range of HPC services are available [108].

HPC provides a brute force approach to balancing computational tractability and model size; however, computational gains can also be achieved through astute model design. Methods to effectively define representative time steps in energy planning models and their computational gains, particularly in the context of intermittent renewable generation, are presented in several studies [59,60,109–111]. The optimal degree of aggregation in a model varies by scope and application, but temporal and spatial downscaling have been shown to be effective methods to balance model complexity with computational demand in several cases [59,60,112–114].

5.1.2.4. Parallelizable modeling techniques. Parallelizable modeling techniques can facilitate modeling interactions across different scales and actors in energy systems [4,47]. This is increasingly relevant as energy systems become more decentralized, renewable, and multi-layered. Parallelizable modeling techniques can help balance model resolution and computation tractability in multi-scale urban energy system models [4]. They are also particularly suitable for representing smart grid architectures given their inherently decentralized structures and scalability [47].

Parallelizable modeling techniques fall within the domain of complexity science [115]; they seek to represent individual components (or agents) in a simple formulation, and then specify the rules each component follows to interact with its environment [4]. This allows for decoupling processes at different scales more easily than in the more common UESM approach of defining interactions between many components and simulating the integrated system as a whole (which can be computationally demanding) [4]. One example of a modeling framework based on parallelizable modeling techniques is EMCAS, an agent-based electricity market model [116].
5.1.2.5. **Smart/microgrid and demand response modeling.** Smart grid, microgrid, and demand side management technologies require better representation in UESMs. This would also make UESMs more useful in the design of pilot projects to test smart grids and DSM technologies.

Depending on the model scope, the representation of smart and micro grids can vary from capturing investment, operation, and maintenance costs in optimization models to implementing control and operation strategies in simulation models (e.g., using agent-based models, model predictive control, game theory, or peer-to-peer networking using blockchain technologies [47]).

Some UESMs offer DSM considerations through demand elasticities, real-time electricity pricing, and local energy trading capabilities (e.g., TIMES and EnergyPLAN). However, developing comprehensive smart/microgrid and DSM capabilities in UESMs requires further tool development. Parallelizable modeling techniques (section 5.1.2.4) may prove particularly useful for addressing scaling issues in this context. Pilot projects to test and establish best practices in these fields will also guide UESM development.

5.1.3. **Support studies**

5.1.3.1. **Pilot projects.** Pilot projects are needed to test and advance nascent technologies, including the integration of smart grids, DSM, and ICT with decentralized RETs. Such pilot projects can help identify scalable ICT solutions and best practices in control and management strategies [117–119]. They can also be used to test and develop local energy markets and to shape regulations [120–122]. These advances benefit UESM development (e.g., to represent system components and their configurations, determine costs, and to implement control and operation algorithms in models). UESM development, in turn, helps to develop further pilot projects in an iterative learning process.

Implementing pilot projects requires both public and private funding by research institutes, transmission and distribution system operators, other public utilities, and private enterprises.

5.1.3.2. **Benefit studies.** Quantifying the benefits of implementing solutions to bridge data gaps and improve institutional instruments is needed in order to motivate systemic change. These studies must weigh the economic benefits of implementing solutions against costs, and engage stakeholders on all levels in order to have meaningful system impacts. Benefit studies also help decision-makers allocate limited resources to those solutions with the greatest gains.

Benefit studies can motivate the establishment of a centralized data collection authority, regulatory measures for open data licensing and data sharing, increased research funding to tackle data issues, and institutional frameworks to support municipal energy planning department development.

Research funding is required to commission benefit studies. These studies are relatively “low hanging fruits” in the spectrum of suggested recommendations, especially given their potentially significant consequences.

5.1.3.3. **Stakeholder feedback studies.** Targeted stakeholder feedback studies enable modelers to learn about issues with model comprehensibility and transparency. Modelers can use this information to improve how effectively they convey model results, which is essential for facilitating public acceptance of renewable energy projects in communities and impacting energy planning decisions [49,50,68].

Focus study groups should consist of different target audiences, including the general population; expert multidisciplinary stakeholders (e.g., local policy-makers, decision-makers, investors, and utilities); and expert model developers and researchers. Tailored studies should include user testing and focus group discussions with follow-up feedback. Such studies improve stakeholder dialogue and engagement.

Implementing focus group studies is a relatively straightforward solution as these can be conducted by modelers at a distributed level, even under budget constraints.

5.2. **Institutional solutions**

5.2.1. **Regulatory measures, institutional frameworks, and standards**

5.2.1.1. **Centralized energy data collection and regulation authority.** Establishing a centralized energy data collection and regulation authority on a regional, national, or international level is arguably one of the highest impact, top-down approaches to resolving data gaps. Such an authority can improve data availability, accessibility, quality, management, transparency, and privacy issues by establishing regulations, standards, and orchestrating technical solutions. It can administer local branches to collect and manage data, and enhance transparency by supporting open data licensing and data sharing platforms. They can also facilitate ICT rollout programs.

Data collection standards and best practices by a central authority help ensure consistent data structuring and content. They also prescribe communication protocols and data management standards.

Establishing a centralized data collection authority requires top-down organization and funding from governmental or international energy organizations.

5.2.1.2. **Incentivize and mandate data sharing.** Regulatory measures can mandate and incentivize data sharing by relevant actors. These measures not only fill data gaps directly, but also facilitate ICT rollout through data sharing programs. Cajot et al. recommend the implementation of an energy law that requires key actors (e.g., public utilities and TSOs) to supply municipal authorities with supply and demand data [37]. They also recommend mandating external studies and data collection, as in the Geneva Cantonal “GEothermie 2020” project [37, 123].

Incentive programs can be implemented to encourage data sharing by private actors, such as businesses and individual consumers. Incentives can take the form of financial rewards, acknowledgement schemes, and other participatory benefits (e.g., rebates on energy bills).

Implementing data sharing regulatory measures and incentives requires that adequate ICT and supporting resources/infrastructure are in place to collect data. Privacy and security controls must also be sufficiently developed to protect participants. A central data regulation authority would facilitate the implementation of these measures.

5.2.1.3. **Open data licenses by public institutions and services.** Public institutions and services that supply data (such as statistical offices, government agencies, and transmission and distribution system operators) should issue open data licenses where possible.

Open licensing increases efficiency in data collection by improving data accessibility and availability, reduces duplicate data collection efforts, and improves transparency in energy modeling. Open data licenses also support open source approaches in energy modeling.

The push for open data licenses can be facilitated by a centralized energy data collection and regulation authority (section 5.2.1.1). Open data must take privacy considerations into account by removing personal identifiers and aggregating data where possible.

5.2.1.4. **Scientific standards and norms.** Scientific standards and norms have the potential to improve the ways in which modelers develop and present UESM studies. Two focal areas for improvement are discussed below.

**Open and transparent energy models**

Increasing openness and transparency in energy modeling facilitates reproducibility, improves credibility and trust in models, increases research quality, reduces duplicated research efforts, provides
transparency for political and social discourse, and makes UESMs and data more accessible to researchers and municipalities around the world, regardless of funding access [36,48]. Individual researchers can also gain personal benefits, such as increased visibility, citations, and future contracts.

Scientific research funding agencies, publishers, and modeling communities can transform the culture surrounding openness and transparency in energy system modeling through increased open data and open source requirements in research calls and contracts; through increased transparency and reproducibility standards; and by educating modelers about the benefits of open approaches.

Higher documentation standards should be established to increase transparency as well; this should include documentation targeted at different levels of stakeholders where appropriate (e.g., documentation aimed at experts, investors, and the general public). This facilitates stakeholder and public engagement.

**Increased uncertainty analysis in energy models**

Although several quantitative methods exist for analyzing uncertainty in energy models, a significant share of case studies have failed to comprehensively address this [5]. However, uncertainty analysis in energy models is vital for robust, informed RET decision-making in cities. It also strengthens energy models by improving transparency with respect to uncertain assumptions and parameters.

Uncertainty analysis is especially important for decision-making under uncertainty (DMU). DMU in long-term energy models includes assumptions of urban climate change impacts, energy system shocks, economic growth, and energy demand growth, amongst others.

More stringent academic standards are needed to encourage explicit uncertainty handling in energy models. This can be achieved in a top-down approach by publishers and scientific reviewers, as well as from a bottom-up perspective by energy modelers and energy modeling communities.

5.2.1.5. Central institutional frameworks to support municipal energy planning

Central governments must recognize the importance of municipal energy planning within national energy strategies by establishing frameworks to support municipal energy planning department development statewide, harmonize communication and cooperation between different governmental planning departments, and incorporate municipal governments into national and regional energy planning processes. These frameworks lead to local capacity building and provide support for UESM training programs (discussed in section 5.2.2). These frameworks can also benefit data collection by mandating and organizing data collection.

Sperling et al. and Cajot et al. identify the need to establish these institutional frameworks in Refs. [37,124]. They call on the state to provide municipalities with planning instruments, and propose a novel strategic energy planning model to promote stronger integration between administrative scales, departments and actors [37,124].

Developing, implementing, and maintaining new institutional frameworks requires central state resources. Studies are also needed to quantify the national and local scale benefits of these frameworks in order to motivate and justify their establishment.

5.2.2. Training programs

UESM training programs can help build technical capacity in municipal energy departments. They can be used to generate awareness about the suite of available UESMs; teach energy planners how to select the right tools for their applications; and provide software training. Educational programs should also target both urban energy planners and urban planners in order to identify synergies between these groups, encouraging them to work together on interdisciplinary urban energy planning issues supported by UESMs [66].

Centralized frameworks aimed at municipal capacity building can motivate the development of these training programs and provide financing support. Mandating the use of UESMs in urban energy planning decision-making by municipal authorities would also facilitate training enrollment and further capacity building.

5.2.3. Financing and research calls

Public and private sector investment and research calls are needed to implement solutions to improve UESMs and their use for urban RET planning. Research calls should focus on developing methodological advancements in UESMs, such as integrating modeling methods (section 5.1.2.2) and performing benefit studies (section 5.1.3.2). Public and private sector investors in emerging technologies (e.g., smart grids), as well as commercial UESM developers also have an incentive to invest in developing UESM capabilities to maintain a competitive edge (e.g., by representing smart grid and demand response technologies in UESMs).

Centralized institutional frameworks and regulatory bodies (sections 5.2.1.1 and 5.2.1.5) would be assets in advocating for the allocation of public funds towards research, municipal capacity building, and other technical and institutional solutions to improve UESMs and increase their use.

6. Solutions in perspective and pathways forward

Gaps and solutions in this field are highly interconnected in nature. One solution can address multiple gaps or facilitate solutions that, in turn, resolve other gaps. A bridged gap can also serve as a solution to resolve other issues. The interconnected relationships between gaps and solutions are graphically summarized in Figure 2. This infographic enables comparison of possible pathways relative to one another in order to identify a set of focal solutions which consider both impact and achievability in the field; this analysis aids decision-makers to make informed decisions about how best to allocate limited resources to advance urban energy planning methods and applications.

Fig. 2 conveys three pieces of information through an element’s shape, outline thickness, and color. An oval refers to a proposed solution (section 5), while a shaded rectangle refers to a presented solution (section 4). Outline thickness indicates the relative impact that a solution/gap has; the thicker the outline, the higher the perceived impact or benefit. Elements with more connections and greater contributions towards resolving the connected solutions/gaps demonstrate thicker outlines. Line thickness values are subjectively assigned based on expert opinion and by applying cumulative weighted functions. Gap (i.e., rectangular) outlines are treated specially; in addition to the number of connected elements, rectangle outline thickness is determined based on the perceived relative contribution of filling the gap towards the overall goal of improving UESMs/methods to better enable sustainable energy planning for cities. Thicker gap outlines indicate higher impact pathways towards this goals.

Outline color corresponds to the ease of implementing a solution or filling a gap, based on expert opinion of the availability and accessibility of required resources for implementation. A 5-color gradient heat map is used for this purpose, from blue (easiest) to red (most difficult). The color scale assignment legend is defined in Table 3.

Several key solution pathways emerge in Fig. 2. Corresponding recommendations are presented in three main categories: advancing UESMs/methods (section 6.1); institutional solutions to advance the prevalence/applications of UESMs (section 6.2); and filling data gaps to ease UESM utilization (section 6.3). Relatively easy-to-implement solutions are also highlighted to improve and support UESM approaches/utilization (section 6.4).

6.1. Developing UESMs/methods

Two of the highest impact solutions to improve UESMs and their consideration of RETs are integrating modeling approaches (section 5.1.2.2) and comprehensive scenario design (section 5.1.2.1). Both of these solutions provide a more comprehensive approach to urban energy
models and the consideration of RETs in them.

UESMs are technically adept at representing a wide range of RETs in models (i.e., in terms of technical performance parameters, costs, appropriate temporal representation, etc.). However, they require a more holistic approach to consider the multifaceted issues surrounding renewable and distributed energy system integration in urban environments. Integrating land-use-transport, high resolution spatial planning, behavioral, and power grid system models with UESMs, for example, addresses this problem. In-depth energy scenario design also allows modelers to consider a range of issues that impact RET integration planning, such as urban densification, local climate change impacts, and representing socio-technical factors (e.g., the impacts of corruption on power sector operation in developing cities).

These solutions are needed to bridge gaps in representing human behavior and underrepresented issues in energy systems of developing countries. They enable models to better consider and evaluate trade-off options by considering the entire urban system and its dynamics. In doing so, integrated UESMs provide higher quality analyses to make better informed planning decisions.

Implementing these solutions requires interdisciplinary collaboration to develop integrated methods and models. This is achievable by coordinating a small number of participants across different disciplines; however, advanced models/methods will take some time and effort to establish in the field.

6.2. Institutional solutions to support/improve UESM use

Some of the highest impact solutions in Fig. 2 are institutionally-related. Apart from the need for financing and research calls, the establishment of a centralized energy data regulation and collection authority (section 5.2.1.1) and centralized frameworks to support urban energy planning departments (section 5.2.1.5) are essential in order to enable local-scale renewable energy planning using UESMs. These centralized governing bodies have far-reaching impacts on the effective utilization of UESMs, from implementing regulatory/technical measures in order to bridge data gaps, to coordinating interdisciplinary, cross-sectoral collaborations within the energy sector and strengthening municipal energy planning departments. However, this recommendation is also amongst the most difficult to implement given the large number of participants involved across scopes and scales, as well as the need for central government support and funding.

Centralized frameworks to support municipal energy planning
departments are also needed to build local technical capacity, especially through UESM training programs (section 5.2.2). Educational programs support the widespread use of UESMs to develop sustainable, renewable energy plans in cities. Although they benefit from central support, these programs can be developed by a relatively small number of specialists and are, therefore, comparatively easy to implement.

Another potentially highly effective, yet simple solution is establishing higher standards by scientific publishers and research funding agencies for more transparent, open, and reproducible energy models, as well as improved uncertainty analysis in studies (sections 5.2.1.4). The explicit acknowledgement of these issues by scientific authorities can catalyze a cultural shift in the field to improve UESM approaches.

Increased open data licensing in the public sector (section 5.2.1.3) is another important institutional measure to fill data gaps by allowing energy modelers to readily share data sources with each other. Open licenses also support higher transparency, reproducibility, and open source UESMs. However, open licensing will be difficult to fully achieve given data privacy issues.

6.3. Technical measures to fill data gaps

Given the pervasiveness of data obstacles in energy modeling, further technical solutions are suggested to resolve data gaps (in addition to the institutional measures recommended in the preceding section). Privacy controls and robust, secure communication architectures (sections 5.1.1.3 and 5.1.1.4) are high impact solutions because they have clear direct and indirect effects. Directly, they protect the identities of participants and enable the transmission and management of large volumes of data. Indirectly, they support other data gap solutions; for instance, ensuring the secure, private, and scalable transmission of energy data facilitates ICT rollout programs and increases confidence in participatory data sharing programs/incentives. Privacy controls and RCA also address privacy, security, and management concerns with respect to data sharing platforms.

Improving data sharing platforms (section 5.1.1.1) is a highly effective direct solution to filling data gaps as well. They are also considerably easier to implement than privacy controls and RCA, as fewer actors, technical factors, and policy considerations are involved.

6.4. Other easily implementable solutions

There are a handful of recommendations which demonstrate both high potential impacts and are relatively straightforward to implement. One of these recommendations, setting higher standards by scientific authorities, has already been mentioned above. Another recommendation is performing benefit studies (section 5.1.3.2). These studies can be performed by a handful of specialists in a relatively short timeframe, and they can catalyze the implementation of most of the institutional solutions discussed (e.g., establishing centralized authorities/frameworks, issuing open data licenses, and incentivizing data sharing).

Another relatively easy solution to implement is diversified documentation standards for urban energy models (section 5.2.1.4). The availability of different levels of documentation for different types of users/stakeholders both increases the transparency of models and facilitates the communication of model results. This fundamental solution can be implemented at the individual level, making it one of the “lowest hanging fruits” of the proposed recommendations.

7. Conclusion

Cities are key players in reducing global greenhouse gas emissions and mitigating long-term climate change impacts. A range of UESMs exist which support sustainable urban energy planning initiatives today, but gaps in the field prevent the effective rollout, uptake, and usage of these approaches.

This study harnesses a wide range of review methods in order to identify UESM challenges and solutions, from a literature review to survey data and focus group discussions. Outreach includes both experts and practitioners in the field in order to gain a broader spectrum of insights into theoretical and practical UESM challenges and barriers.

Although a range of technical and methodological UESM challenges have been identified in this work, the current range of UESMs provides energy planners with powerful technical capabilities as a basis from which to develop long-term energy strategies. Institutional challenges, however, are some of the largest barriers to the effective uptake and applications of UESMs in cities. Therefore, although key technical recommendations have been made to improve the implementation and effectiveness of UESMs, some of the highest impact recommendations demand systemic institutional change. Institutional changes resulting in increased UESM utilization can also catalyze technical improvements through improved resource support.

The comprehensive and comparative assessment of UESM gaps and solutions in this work provides developers, researchers, urban energy planners, policymakers, and other decision-makers with guidance on where and how to focus limited resources in order to advance UESMs and their applications; the need for which is more pressing now than ever before.

CRediT authorship contribution statement

M. Yazdanie: Methodology, Conceptualization, Investigation, Formal analysis, Visualization, Writing - original draft, Writing - review & editing, Project administration. K. Orehounig: Supervision, Funding acquisition, Project administration, Conceptualization.

Declaration of competing interest

The authors 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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