International Journal of Sustainable Energy Planning and Management Vol. 43 2025 123–139

International Journal of
Sustainable Energy Planning and Management

Analysis of City Energy Systems Modeling Case Studies: A Systematic Review

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ABSTRACT

Cities are adopting energy planning strategies and emission reduction targets in line with national decarbonization targets. Modeling and scenario assessments are used to support energy planning. City energy systems are complex systems including interactions and interdependencies, as well as the specifics of the local city context. To investigate the representation of city-specific system complexities in existing case studies, a systematic literature review methodology is applied, and model applications are analyzed using a comparative analysis framework. Additionally, research objective themes used to define the specific aims are explored. Key modeling characteristics include scale aspects, method description, system definition, scenario formulation, and case-specific model inputs. The findings of this study suggest that city case studies have a diverse representation of modeling approaches. However, the analysis of model characteristics shows a limited representation of modeling features, such as stakeholder participation and local air pollution impacts that are unique to the urban context. In terms of research objective themes behind the model application, four research themes are identified. Studies aimed at identifying pathways to future low-carbon energy systems and evaluating policy impacts on the city energy systems are the most stated research objective themes for modeling city energy systems.

Keywords

Energy systems modeling;
Energy Planning;
City energy systems;
Case-studies.

http://doi.org/10.54337/ijsepm.9335

1. Introduction

Under the UNFCCC, the Paris Agreement was adopted with targets to limit global temperature rise to 1.5°C by the end of the century compared to pre-industrial levels due to rapid increase in greenhouse gas (GHG) emissions [1]. Increasing GHG emissions has been identified as a global problem with its roots in intensive energy use [2]. Understanding the fact that energy-related emissions are the most significant contributors to total anthropogenic emissions, it is inevitable that a rapid transition in the energy system is required to realize the targets set under the Paris Agreement [3].

Energy systems are transitioning across the world, driven by increased renewable energy penetration, changing regulatory frameworks, increasing electrification, the emergence of new market players, and increased consumer engagement [1]. For the transition toward a decentralized system, an energy supply based on renewable energy sources and increased energy efficiency measures are identified as the main drivers. Energy systems based on renewable energy sources are tailor-made at the local level, accounting for the local context [4]. Also, local actors play a significant role in improving building efficiency through building renovation, efficient end-use appliances, and district heating networks [5]. From a policy perspective, the role of local governance has been seen as critical to the development of effective policy measures [6]. Considering the role of local actors in the transition of the energy system, strategic planning at the municipal level is deemed essential to achieve desired climate goals. Local energy planning makes it possible to understand the local context, support the utilization of physical characteristics, and provide a platform for stakeholder interaction [7].

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Abbreviations

CAF	Comparative analysis framework
ESM	Energy systems modelling
GHG	Greenhouse gases
SEP	Strategic energy planning
SLR	Systematic literature review
UESM	Urban energy system models

Over the past few years, cities have become proactive in climate mitigation through a diverse set of projects and actions. Perspective on local-level changes and adaptation of sustainable pathways at the regional levels gained importance after Agenda 21, the global action plan for sustainable development [8]. With the introduction of several initiatives, including C40 Cities, Covenant of Mayors, and Viable Cities, among others, cities have been identified as central parts of climate change mitigation strategies through local energy planning. In the context of the EU, local energy planning was first introduced in the Scandinavian region in the last few decades. In Sweden, the municipalities are required to have a municipal energy plan according to the Act on Municipal Energy Planning from 1977 [9]. In 2010, Strategic Energy Planning (SEP) was introduced among the Danish Municipalities for local energy planning. The Danish Energy Agency introduced the definition of SEP: *"A planning tool that allows municipalities to plan local energy conditions for a more flexible and energy-efficient energy system, in preparation for the potential transition to a more renewable energy-based supply, and where energy savings are exploited in a way that is socially most energy effective"* [7].

Diverse definitions exist for cities. The term city is interchangeably used for urban areas, urban agglomerations, and metropolitan areas, among other things. In this analysis, the city represents cities, urban areas, and municipal boundaries in the urban context.

Energy planning at the city level has also been defined in several scientific articles over the last decades and has been gaining importance. It is mainly defined as a process of determining an optimal mix of energy supply and demand-side measures to contribute toward the national strategies for energy system decarbonization. Over the years, cities have adopted local energy planning strategies and set ambitious mid-century GHG emission reduction targets, with increasing shares of renewables and improved energy efficiency [10]. However, planning the development of such a complex system is challenging. Local energy systems are identified as socio-technical systems interacting with different system aspects. From a techno-economic perspective, local energy systems are affected by multi-scale aspects, i.e., temporal and spatial, multiple sectors, and technological, economic, and structural aspects involving multiple investment and operational decisions. Social, environmental, conceptual, and institutional issues are also essential to account for [10,11]. This makes the city system a complex system, including different interactions and interdependencies.

To overcome the complexities of city energy systems and to support the decision-making by the local authorities in coherence with the national strategies, the development of models and scenarios is identified as the first step of local energy planning [2]. Models are a formal representation of a natural system, and local energy system models can be defined as a combined system utilizing available energy to fulfill the service demands of a designated area. Scenarios are a representation of a future development strategy that significantly influences decision-making [12,13].

Energy models are being extensively used to support evidence-based policy decisions globally, having been in use since the 1960s. Energy models have developed over time with continuous developments based on the needs and the questions the models are expected to answer. Energy models have been used as tools to provide solutions to energy and environmental issues. With the introduction of city-level energy strategy development, researchers and practitioners have extensively used computational models to represent complexities of the local environments, system interdependencies, and cross-sectoral interactions. Techno-economic studies based on optimization and simulation techniques are identified as key to the representation of complex systems and decision support for strategic energy planning to obtain a reliable, efficient, and resilient energy infrastructure in the future [5,10,11]. Over the last decade, several modeling approaches have been developed and used for city energy planning.

Studies have used several modeling approaches and replicated local contexts, aiming at identifying transition pathways that support energy system transformations at city levels. Considering the increasing utilization of energy models to support city energy planning processes, it is deemed essential to understand how the models are applied in local contexts. In previous studies, different modeling approaches have been analyzed in the form of extensive literature reviews. The feasibility of modeling platforms as local-level modeling tools for the analysis of the built environment has been evaluated [14]. The study analyzed the characteristics of available models and reviewed modeling approaches to integrate social factors into the techno-economic models. Review of energy system optimization models aiming at identifying modeling approaches and future challenges relative to municipal-level energy systems was presented [15]. Spatiotemporal energy modeling tools for integrated demand-supply analyses of urban energy systems have been conducted based on ten modeling dimensions [16]. The review of existing UESMs (Urban Energy System Models) focused on multi-domain UESMs was provided through the interaction of different sub-models [17]. A comprehensive overview of gaps and challenges associated with the UESM tools has been provided based on a literature review combined with surveys, interviews, and workshops with the relevant stakeholders [18].

However, a comprehensive review of scientific literature on the application of energy systems models to city-based case studies is lacking. Thus, this study contributes to the existing knowledge base of UESM reviews by analyzing the implementation of different modeling approaches to specific city cases. The unique traits possessed by different city contexts, which are often complex and diverse, make it essential to examine case-specific implementations of energy models. Every city or urban setting has specific objectives and approaches to applying modeling tools to analyze the development of their energy system. In this context, this review places a strong emphasis on evaluating the representation of city-specific system complexities in the modeling and identifying key research objectives these case studies aim to fulfill. The review of modeling applications to city-specific case studies has been conducted to answer the following two research questions:

How are city-specific energy system complexities represented in city energy system modeling case studies?

What are the key research objective themes used to define the specific aims for modeling the city energy systems?

The rest of the paper is structured as follows: Section 2 presents the methodological framework for selecting relevant literature and developing an analysis framework with objective categorization. Section 3 presents the comparative analysis of the identified cases. Section 4 offers a discussion on the different case studies based on the identified characteristics. A brief conclusion of the study follows it.

2. Methodology

A systematic literature review (SLR) procedure is adopted to conduct this study. The SLR uses a pre-defined systematic methodological approach. Study [19] prescribes a stepwise method to conduct a systematic review, which is followed in this study.

- The first step of the SLR methodology is to define the research questions and the research plan, which has been presented in Section 1.
- The second step is the selection of relevant literature. Section 2.1 briefly explains this step.
- The third step of SLR is to analyze the selected literature to answer the identified research questions.

2.1 Selection of literature

Scientific articles on city case studies were selected to investigate the application of energy systems modeling to cities. A structured approach was adopted to select the relevant case studies. The approach pursued includes

Local OR Urban OR City (Title)
AND
Energy (Title)
AND
Transition OR Planning (Title-Abstract-Keyword)
AND
Modelling OR Model (Title-Abstract-Keyword)
AND
Case Study (All)

Figure 1: Boolean expression for the selection of case studies.

adopting a search strategy with pre-defined boolean expressions. The boolean expressions used to search the literature are presented in Figure 1. The online database SCOPUS was used to search for relevant articles.

The application of boolean expression in all places in the text resulted in an unfeasible number of articles. To ensure that the amount of literature is feasible while ensuring that the relevant articles are noticed, the authors carefully specified the positioning of different search strings. The selected literature was further filtered based on the timeline (2010-2022), language (English), and document type (Articles).

The search query returned 492 research publications. The articles were further refined in a four-step process. The refinement of articles in the four steps was based on the research objectives of this SLR study. The selection was based on the relevance of the articles and the authors' understanding. The refining process was used to finalize a list of 31 articles to be analyzed in this SLR. The step-wise refinement of articles is presented in Figure 2. Furthermore, one further study outside the search query deemed relevant was included in the review.

2.2 Literature Analysis

A comparative analysis framework (CAF) has been designed to assess the selected articles. The design process included identifying and structuring the key modeling characteristics. The identified features in the framework are chosen based on the literature available on energy system model development and complemented by the authors' knowledge base. Section 2.2.1 presents the design of the analysis framework used for comparing case studies.

The second step of the literature analysis included analyzing the primary research objectives of the case studies to identify the research objective themes behind the application of selected case studies.

2.2.1 Comparative Analysis Framework

This section explains the design of the analytical framework. In this study, the framework is used to investigate how city energy system complexities are represented in the energy system modeling case studies. Key modeling characteristics are identified based on an initial review of the selected case studies.

The identified modeling characteristics of city-level energy system models are divided into the following categories: scale aspects, modeling approach, system definition, scenario formulation, and case-specific modeling inputs. The design of the analysis framework is based on the framework used in [20], to review local energy transition processes. The designed analysis framework and the key modeling characteristics used in the analysis framework are presented in Figure 3.

Scale Aspects:

Temporal scale: With growing energy demand in cities, smart energy systems play a critical role in the transition of the energy system. In smart energy systems, the temporal distribution of the energy demand plays a crucial role in managing base and peak loads. Additionally, increasing shares of decentralized power generation with high intermittency is identified as a significant transition measure in cities and improved temporal resolution is essential to the representation of highly intermittent technologies [18]. The temporal resolution of the city energy systems model is thus critical to the replication of changing energy systems in cities. City energy systems models can have varying temporal resolutions ranging from hourly, daily, seasonal, to annual time slices. The second dimension of the temporal scale is the time horizon of the model. The time horizon defines the critical aspects of city energy systems planning and can be short-term, ranging between 1 to 10 years; mid-term, ranging from 10 to 20 years; or long-term, more than 20 years.

Boolean Expression
492 Articles
Article Title and Source Title Review
290 Articles
Abstract Review
114 Articles
Model Methodology Review
51 Articles
Full Article Review
31 Articles (Final List)

Figure 2: Step-wise filtering process for the finalization of articles.

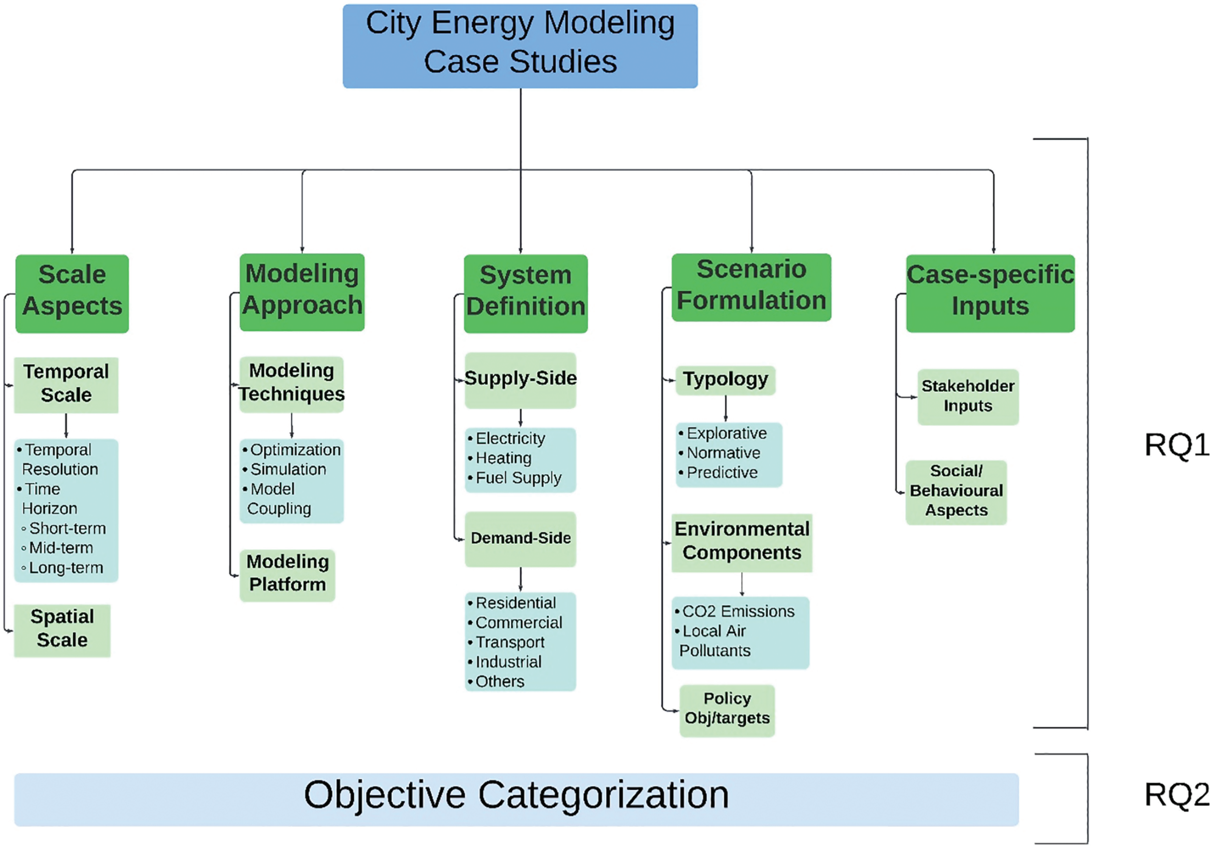

Figure 3: CAF for the analysis of city energy modeling case studies.

Spatial scale: In the transition towards a sustainable energy system with increased energy efficiency and the use of renewable energy, the spatial dimension of the system is very important [21]. To achieve the desired climate goals, energy system design is moving towards decentralized energy generation with high penetration of renewable energy combined with demand-side measures. The deployment of measures to improve energy end-use and increased penetration of renewable energy sources shows high dependency on weather and spatial characteristics. Considering the importance of efficient energy end-use and increasing penetration of decentralized energy sources in the transition of city energy systems, the representation of the spatial scale of city energy system models is crucial.

Modeling approach

Several modeling tools are available based on the needs of the model developer. In this analysis, the modeling approach for the analyzed case studies is characterized by modeling techniques and platforms/tools for their development. The most common modeling techniques used in local energy system models are based on optimization or simulation with different approaches/mathematical models. The optimization and simulation techniques have been applied using various locally designed and commercially available platforms. Some of the most used platforms are TIMES, BALMORAL, LEAP, and OSEMOSYS.

System definition

When dealing with local systems, it is vital to understand how energy systems are categorized within the model. The definition of an energy system is primarily based on the supply-side and demand-side sectors. In the case of energy supply systems, studies focus on the development plans of individual sectors, e.g., heating or electricity; more integrated models include the different sectors associated with the energy system. From the demand-side perspective, different sectors were analyzed, including residential, commercial, industrial, transportation, and other sectors. In this study, when examining the modeling cases, the supply and demand-side sectors and technological resolution of the model cases have been used to define the energy system.

Scenario formulations

Scenario typology: In energy systems models, scenarios are used to describe both possible future developments and different expected futures. In [22], the authors have described scenario typologies based on prospective studies exploring possible, probable, and preferable scenarios. In this analysis framework, the authors aim to categorize the scenarios based on three categories: predictive, explorative, and normative, as identified in [22]. The chosen scenario depends on the type of questions the modelers aim to answer, and it is crucial to understand the scenario typology selected for the different objective categories.

Environmental components: Since the adoption of the Paris Agreement, the key objective of energy systems models has been to identify the best combination of supply and demand-side measures leading to the desired decarbonization targets. While some studies focus on GHG emissions, other studies also include local air pollutants as an essential aspect of local energy planning. So, this model characteristic is analyzed to identify the environmental impacts being monitored in the case studies.

Policy objectives/targets: Countries have committed to decarbonizing energy systems and adopted targets for renewable energy shares, energy efficiency, and emission reduction. With increasing collaboration between local authorities such as the Covenant of Mayors and Viable Cities, the adoption of climate mitigation strategies at city levels is gaining importance [23,24]. At local levels, energy strategies are often designed to synchronize with national and global targets. Scenario formulations for city energy models are designed based on the desired policy objectives/targets and identify suitable pathways to achieve them. Policy objectives considered in the scenario formulation process are a crucial part of model-based case studies.

Case-specific model inputs

Stakeholders inputs: Successful implementation of energy planning processes depends on the integration of various actors and stakeholders, e.g., local administrators, building owners, urban planners, etc, into the process. Local stakeholders can play different roles as facilitators, regulators, and consumers in supporting energy planning at the city-level [25]. In the modeling case studies, the participatory involvement of local stakeholders makes it easier to cover the various aspects of local energy planning, such as local future visions, needs, and interests of the involved citizens. Thus, including key stakeholders in the model-based decision-making process makes the process more feasible to implement by considering the local societal, cultural, and environmental aspects.

Social/behavioural aspects: The importance of the social context in energy system models has been widely recognized by energy modelers. In recent years, improvement has been seen in the ability of the models to account for customer behavior to make more realistic projections [6]. Most of the low-carbon developments, such as energy efficiency measures, electric vehicle deployment, and decentralized energy production, directly involve consumers. It makes it necessary to include behavioral aspects in the energy models to obtain more realistic outcomes and, at the same time, indicate the barriers to the deployment of low-carbon developments. Hence, it is crucial to analyze if the case studies include the social aspect of the CAF.

2.2.2 Objective categorization

Research objectives are used to define the specific aims of the studies. From an energy modeling perspective, the studies aim to answer specific questions regarding the future of energy systems under different developments. To answer the research question on the key research objective themes being applied to the city energy systems modeling, a two-step analysis is conducted. In the first step, the key research objective themes are identified. At the local level, models have been adopted to overcome the challenges associated with the security, affordability, and resilience of the energy system, as well as dealing with environmental concerns. With increasing interest in UESMs, case studies are also conducted to enhance the capacity-building of the model development process.

After the characterization of research objective themes, the stated objectives of the selected literature are analyzed. The research objectives of modeling studies are manifold, and there could be an overlap between the different identified categories. Hence, objective categorization is based on the main objective statements and research questions presented in the literature.

3. Results and Analysis

This section presents the findings of the literature review. Section 3.1 presents the outcome of the comparative analysis, which aimed to answer the research question on the representation of energy systems planning

Table 1: Selected literature along with their general characteristics.

Serial No.	Title	Journal	Year	Geographical Focus	Source
1	Pathways for sustainable municipal energy systems transition: A case study of Tangshan, a resource-based city in China	Journal of Cleaner Production	2022	China	[6]
2	Transport decarbonization in big cities: An integrated environmental co-benefit analysis of vehicles purchases quota-limit and new energy vehicles promotion policy in Beijing.	Sustainable Cities and Society	2021	China	[5]
3	Balancing the Energy Trilemma in energy system planning of coastal cities	Applied Energy	2021	China	[26]
4	Methodology for integrated modeling and impact assessment of city energy system scenarios	Energy Strategy	2020	Spain	[10]
5	Local energy system design support using a renewable energy mix multi-objective optimization model and a co-creative optimization process.	Renewable Energy	2020	Japan	[4]
6	City energy modelling - Optimising local low-carbon transitions with household budget constraints	Energy Strategy Reviews	2019	Portugal	[11]
7	Spatially resolved urban energy systems model to study decarbonization pathways for energy services in cities	Applied Energy	2020	Brazil	[27]
8	Development of a GIS-based platform for the allocation and optimization of distributed storage in urban energy systems	Applied Energy	2019	Germany	[28]
9	Transforming cities towards sustainable low-carbon energy systems using emergy synthesis for support in decision-making	Energy Policy	2016	Croatia	[12]
10	Cost optimal Urban Energy Systems Planning in the context of national energy policies: A case study for the city of Basel	Energy Policy	2017	Switzerland	[13]
11	The use of energy system models for analysing the transition to low-carbon cities – The case of Oslo	Energy Strategy Reviews	2017	Norway	[2]
12	A Comprehensive Planning Method for Low-Carbon Energy Transition in Rapidly Growing Cities	Sustainability	2022	China	[29]
13	Capturing the long-term interdependencies between building thermal energy supply and demand in urban planning strategies.	Applied Energy	2020	Italy	[30]
14	Modeling for diversifying electricity supply by maximizing renewable energy use in Ebino city southern Japan	Sustainable Cities and Society	2017	Japan	[31]
15	A model of optimization for local energy infrastructure development	Energy	2016	Poland	[32]
16	Scenarios and policies for sustainable urban energy development based on LEAP model – A case study of a postindustrial city: Shenzhen China	Applied Energy	2019	China	[33]
17	Long-term implications of electric vehicle penetration in urban decarbonization scenarios: An integrated land use–transport–energy model	Sustainable Cities and Society	2021	China	[34]
18	Linking dynamic building simulation with long-term energy system planning to improve buildings' urban energy planning strategies	Smart Cities	2020	Italy	[35]

(Table 1 continue)

(Table 1 continue)

19	The dawn of urban energy planning – Synergies between energy and urban planning for São Paulo (Brazil) megacity	Journal of Cleaner Production	2019	Brazil	[36]
20	Planning a sustainable urban electric power system with considering effects of new energy resources and clean production levels under uncertainty: A case study of Tianjin, China	Journal of Cleaner Production	2018	China	[37]
21	Modelling the future low-carbon energy systems - case study of Greater Copenhagen, Denmark	International Journal of Sustainable Energy Planning and Management	2019	Denmark	[38]
22	The design of 100 % renewable smart urban energy system: The case of Bozen-Bolzano	Energy	2020	Italy	[39]
23	Planning regional energy system with consideration of energy transition and cleaner production under multiple uncertainties: A case study of Hebei province, China	Journal of Cleaner Production	2020	China	[40]
24	Addressing rising energy needs of megacities – Case study of Greater Cairo	Energy and Buildings	2021	Egypt	[41]
25	Cities and Greenhouse Gas reduction: Policy makers or policy takers?	Energy Policy	2019	Canada	[42]
26	Energy supply modelling of a low-CO2 emitting energy system: Case study of a Danish municipality	Applied Energy	2017	Denmark	[43]
27	Scenarios for sustainable heat supply and heat savings in municipalities – The case of Helsingor, Denmark	Energy	2017	Denmark	[44]
28	Ambition meets reality – Modelling renovations of the stock of apartments in Gothenburg by 2050	Energy and Buildings	2020	Sweden	[45]
29	Sectoral energy-carbon nexus and low-carbon policy alternatives: A case study of Ningbo, China	Journal of Cleaner Production	2017	China	[46]
30	An integrated supply-demand model for the optimization of energy flow in the urban system	Journal of Cleaner Production	2016	India	[47]
31	Interconnection of the electricity and heating sectors to support the energy transition in cities	International Journal of Sustainable Energy Planning and Management	2019	Sweden	[48]
32	The Impact of Local Climate Policy on District Heating Development in a Nordic city – a Dynamic Approach	International Journal of Sustainable Energy Planning and Management	2021	Sweden	[49]

complexities in city energy models. Section 3.2 presents the results of the objective categorization.

Table 1 lists 31 articles, with their title, publication year, journal series, and geographical focus.

3.1 Literature review based on the analysis framework

The key modeling characteristics of the selected case studies are analyzed using CAF. The findings from the CAF are presented below, along with a summary of the findings attached as supplementary material.

3.1.1 Scale aspects:

Temporal scale: Among the analyzed cases, 18 out of the 32 studies have modeled for a long-term horizon with different temporal resolutions. Long-term studies often have annual time resolution, with some case studies implementing higher resolution aggregating into representative Day/Night/Peak or specific hours during the days. Three cases have included hourly resolution in their long-term energy models. Eight studies have modeled for the mid-term horizon with similar representation for temporal resolution as long-term case studies. Short-term studies include two studies with periods shorter than ten years and four studies focused on modeling specific future years. This group of studies mainly includes hourly temporal resolutions with two cases modeling at annual resolution.

Spatial Scale: Spatial model aspects are specified in 11 out of the 32 articles. Studies have modeled/represented spatial aspects in their models in different ways based on their specific applications. Four studies have disaggregated cities into multiple zones or regions to account for different features associated with the regions. Five studies have used spatial mapping to represent the service demand of the building stock. Lastly, two studies have coupled the energy model with the GIS/Urban land use model to account for the spatial aspects of energy system development [28,42].

3.1.2 Modeling approach

Modeling techniques: Most studies have applied mathematical models based on optimization techniques to develop their energy models. 19 studies use different optimization models, and 12 studies use simulation techniques. The case study focused on modeling building renovations [45] and used a combination of simulation and optimization. Within the optimization and simulation techniques, different mathematical formulations are implemented. In addition, five studies have used model-couping to apply multiple approaches in their case studies. Table 2 shows the different modeling approaches used within optimization, simulation, and model-coupling.

Modeling platforms: Different modeling tools or platforms are being used to develop case study models. These tools include several commercially available platforms and several independent modeling platforms developed by research institutions. Figure 4 shows the representation of modeling platforms among the analyzed case studies.

3.1.3 System definition

The definition of a system varies significantly among the studies analyzed based on their specific research questions. Focused on the energy supply infrastructure, studies with an overall energy supply infrastructure aimed at fulfilling aggregated energy demands for city systems have a significant representation. Studies

Table 2: Summary of the modeling techniques being applied.

Optimization	Simulation	Model Coupling
Linear Optimization [2,5,11,13,41,47,48,50]	Scenario analysis [6,33]	GIS + Dynamic Simulation [10]
Multi-Objective Optimziation [4,26]	Dynamic Simulation [10,51]	GIS + Simulation + Optimization [28]
Mixed-Integer linear optimization [27,43,49]	Simulation [12,31,36,46]	Simulation + Multi-level perspective [29]
Dynamic, Non-Linear Optimization [32]	Partial Equilibrium [34]	Robust Optimization + Two-stage stochastic Programming [37]
Partial Equilibrium Optimization [38]		Simulation + Multi-Criteria Analysis [39]
Interval-fuzzy full-infinite programming [40]		Simulation + Urban land-use model [42]
		Operational Optimization + Iterative Modeling [44]
		Simulation + Optimization [45]

Figure 4: Modeling tools with usage frequency represented by the font size.

focusing on the demand-side measures have mainly focused on the building sector, with heating and electricity supply infrastructure. Transportation sector representation is mainly included in the overall energy system representation, with the exception of two studies focusing specifically on the transportation sector.

3.1.4 Scenario formulation

Scenario typology: Based on the scenario typology definition, the authors categorized the scenarios under the predictive, explorative, and normative types. While the defined scenarios for most of the case studies have been categorized into one of the three identified types, some studies used more than one scenario type in their scenario development. Figure 5 presents the distribution of scenario types among the identified categories.

Most studies seem to use explorative scenario types with predefined system measures to evaluate their impacts on the energy systems. Some studies define the measures based on policies, while others implement specific measures to see what can happen if we act in a certain way. The next most used typology is normative, with main targets on emissions but also some with other future targets like targets on renewable energy share. The mixed type corresponds to the scenario development, including a mix of the identified scenario types. This includes a combination of explorative and normative scenarios. For two studies [4,32] the authors couldn't categorize the scenarios.

Environmental components: Environmental components are either used as an indicator to assess the performance of alternative scenarios or used as targets in the scenario development process. Due to the identified importance of climate change mitigation efforts, most studies have included CO2 or CO2 equivalent emissions in their assessment. Out of the 32 cases, 26 have included emissions in their analysis, with five studies also including local air pollution. Due to the identified nature of scenario types, with most explorative scenarios (Figure 5), emissions are used to assess alternative scenarios. Normative scenarios with emission targets have used CO2 emissions in the description of scenarios. In the case of a case study of Gothenburg, net-zero CO2 emission constraints are applied in all the scenarios [48].

Policy aspects: Eleven studies have included policy aspects in their scenario development process. In the cases of [2,11,27], emission reduction targets are translated into normative scenarios. In the other studies, policy statements are translated into measures in the explorative scenario development. Apart from the 11 cases, three studies have stated policies to compare the scenario performance with stated policy objectives.

3.1.5 Case-specific model inputs

Stakeholder inputs: Stakeholder engagement in the modeling case studies is not yet seen as a common practice at the urban levels. Out of the selected cases, only five studies include stakeholders in their model development process. In the case of Takashima, the authors interact with the community promotion council for participatory backcasting and the selection of optimal solutions [4]. Municipality stakeholders were included as part of the project [11]. In the case of Oslo's energy model, city representatives were included in the process of identifying individual measures for the energy system development [2]. In the case of Kiertz, local administration and technical staff were included in the model development process [32].

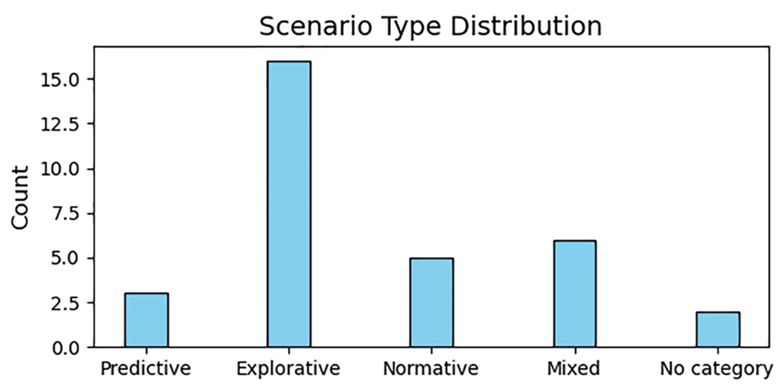

Figure 5: Case-study distribution based on the scenario type.

Societal perspective: Societal perspectives have limited representation in the analyzed case studies, with only five studies stating the inclusion of social perspectives. Social perspectives included, as specified in the studies, are the health impacts of road transportation [5], income as household constraints [11], and the societal cost of energy [32]. In the case of Tianjin, fulfilling energy demand has been identified as the social aspect of the study [37]. For the Vancouver case study, behavioral parameters are estimated from market research and choice surveys [42].

3.2 Analysis of objective categorization

The outcomes of the analyses are presented in two steps to identify the key research objectives behind the application of modeling approaches to city energy systems. Firstly, study objective themes are identified.

The research objectives contributing to the model case applications are categorized into five groups as presented below:

- **Pathways to low-carbon energy futures**: Studies with the primary objective of identifying pathways to achieve an energy system transition in the future.
- **Policy insights**: Studies stating their primary objective being providing policy recommendations to decision-making bodies to achieve a desired energy system transformation.
- **Policy impacts**: Studies that aim to analyze the impact of existing policies and plans on the energy system are identified under this category.
- **Energy security**: Studies were conducted to provide insights into developing local energy systems modeling, keeping energy security issues in mind
- **Capacity building of model development:** Research objectives aimed at improving the model development process of UESMs are identified.

Secondly, the research objectives of the selected literature are analyzed and categorized into the themes identified in the first step.

3.2.1 Pathways to low-carbon energy futures

The most common objective category for local energy systems modeling case studies is identified as pathways to future low-carbon energy systems, with 10 cases stating their research objective along this theme.

Within this category, the primary approach followed was based on the identification of cost-optimal pathways to move towards decarbonized local energy systems with the application of different optimization techniques. In [11], the authors state, "... *aims to investigate the optimal solutions for the transition to a municipality low-carbon energy system.*" A Linear Optimization bottom-up technology explicit model was developed to investigate the optimal solutions. Similarly, the authors state the objective "... *to investigate how Sønderborg can become a low-CO2 emitting municipality by 2029 in an energy-efficient and cost-effective way, while also keeping its biomass consumption close to the limits of the locally available residual biomass resources*" in [43].

Another approach commonly applied within the theme included investigating the feasibility of selected development pathways based on simulation techniques. In the case study of Bozen-Bolzano, "… *the objective of the work lies in demonstrating how it is feasible to implement a 100% renewable system in an Alpine city*".

3.2.2 Policy impact

The second most common objective category behind the case studies is the role of local/national policies on energy system development. Eight case studies have stated their key objective within the theme of policy impact. These models evaluate the impact of certain policies and measures.

In the case study on transport decarbonization in Beijing, the authors aim to answer "… *what is the energy and environmental impact of quota-limit policies in big cities like Beijing?*" [5]. Similarly, studies aim to investigate the role of national/local policies as the author states their research objective as "... *testing the combined effect on city energy use and GHG emissions of policies enacted at the municipal level and policies enacted simultaneously by senior levels of government*"[42]. Another study, aiming to investigate the impact of policy on the future district heating system state their research objective as "*to investigate impacts of climate policies on the cost efficient future development of an urban heating system*" [49]. Due to the identified theme of the objective category, most studies have applied explorative scenarios in their analysis except [2], also using normative scenarios to apply GHG mitigation targets set within the policy framework.

3.2.3 Policy insights

From the selected literature, only 4 out of the 32 studies state their research objective around the theme of providing insights to support decision-making processes. One example of the objective around this theme is stated as "... *The aim is to allow the city's stakeholders to make decisions based on the results issued from the proposed futures*" in [10]. Another study focused on highlighting the role of municipal decision-makers stated their objective as "... *to highlight the important role that municipal policy-makers can play in guiding future energy planning investments towards sustainable energy infrastructure*" [26].

3.2.4 Energy security

Research objectives focused on energy security are identified as the least common theme, with only three studies out of the selected 32 cases. The focus of this set of studies lies in identifying pathways to deal with future energy demands. Examples of objectives within this theme include "*minimizing the social cost of supplying a local community with final energy*" in [32] and "*to assess different pathways to cope with rising energy needs (supply and demand) deriving from informal settlements' inhabitants' relocation to outskirts dwellings with improved access to energy and a higher transport demand*" in [41]. Since this category of studies focuses on fulfilling future energy needs, two out of three studies have applied optimization techniques to identify least-cost solutions to satisfy increasing end-use service demands.

3.2.5 Capacity building of model development

City energy systems have been identified as complex systems with multi-scale aspects and quantitative and qualitative complexities. Energy Systems Modeling (ESM) at the city level has been gaining interest from the scientific community. At this stage, it is evident that the modeling of city energy systems needs further development. Most studies have also stated their objectives aimed at contributing to the development of city energy systems modeling methods. Thus, in this section, the objectives from the perspective of the contribution of the case studies toward the capacity-building of ESM are analyzed. 27 articles have stated research objectives aimed at contributing to the continuous development process of city energy system models.

The most common methodological development identified in the reviewed cases is regarding different forms of model integration. Different forms of integrations are applied in the methodological development presented in the case studies. Integration types include intra/inter-sectoral integration [10,11,44,47,48,51]. The authors stated their objective as "... *focus on interconnections between the electricity and heating sectors*" [48] highlighting inter-sectoral integration. Examples of intra-sectoral integration include research focused on "*linking the results of the urban stock analysis with an energy planning tool to analyze both demand and supply decarbonization measures and their economic impact*" [51].

Integration of energy systems with related concepts was highlighted in three case studies [4,12,26]. The authors stated their objective as "... *at a local scale with the integrated approach including engineering tools, socio-economical evaluations, and participatory processes,*" highlighting the integration of stakeholder inputs and socioeconomic aspects into the energy systems model [4]. Another important integration included city energy systems combined with behavioral/social constraints [11]. The research objective was to "*analyze how the city energy system readjusts to comply with CO2 emissions targets when household income levels constrain the adoption of more efficient and clean technologies.*"

The second significant contribution of the modeling case studies is regarding multi-scale aspects, including spatial and temporal aspects. Key contributions include high temporal and spatial resolution to evaluate the service demands and model coupling using GIS/Land-Use with energy modeling. Case studies focused on better representation of service demands using hourly temporal resolutions in their long-term models [26,45,50,51]. For improved spatial aspects, city boundaries were divided into zones [27,34], using GIS mapping for generating input data on service demands [28,45,50], and model coupling [28,42].

Apart from method improvement, new modeling tools are also utilized to fill the identified research gaps. These include the risk aversion optimization model (Robust Optimization, two-stage stochastic programming) to analyze the trade-off between system cost and safety [37] and the application of IFFIP (Interval-Fuzzy full-infinite programming) for Renewable Energy Supply Planning using the IFFIP-RES tool [40].

Apart from the above-stated methodological contributions, case studies have highlighted their contribution to methodology development for specific urban contexts. Different urban settings included heavy industrial cities [6], fast-growing cities in emerging economies [29], post-industrial cities [33], and case-specific local energy planning [38,46]. Apart from the common trends, other model development methods include model coupling using simulation with multi-criteria analysis [39]. Method improvement focused on specific sectors, including the improvement in the methodology for city transport [5] and building-specific stock modeling [45].

4. Discussion

The comparative analysis framework presents a group of case studies applying different modeling approaches and features to fulfill their identified research objectives. While the analysis presents an understanding of designing modeling case studies to answer the defined research questions, it also highlights a lack of representation of several essential aspects from the context of urban/local energy systems planning.

Scale aspects of the modeling case studies are well covered in the analyzed case studies based on their desired research objectives—a good mix of studies with temporal resolution ranging from hourly resolution to annual resolution. Depending on the requirement of temporal granularity, studies have often used representative days/hours to deal with computational challenges when modeling for a long-term horizon. For short-term horizons, studies have managed to use high resolutions to represent hourly variations. Higher spatial resolution is somewhat limited in the analyzed case studies. The main aspects of spatial mapping include different zones within cities, along with building stock representation. Our findings also show that a diversified mix of modeling methodologies is being applied to model the city energy systems.

Urban compact areas, especially cities, are the most impacted by local air pollution problems. Mitigation of GHG emissions is essential at the national level to reach the stated long-term emission reduction targets. From an urban perspective, it is also necessary to evaluate the impact of transition measures on local air pollution mitigation. Our findings observed that most local case studies conduct their analysis around CO_2 emissions when including environmental components. The limited representation of local air pollution in the analysis highlights a lack of urban context in the case studies. It is essential to incorporate the same in energy systems analysis to investigate the transformation of the city energy systems.

Aimed at supporting local decision-making, local models should provide information needed by the stakeholders. Stakeholder involvement in the scenario development process could significantly improve the usability of model outcomes for city-level decision-makers. Previous literature has often highlighted the importance of including stakeholders in city energy systems planning, mainly due to its focus on policy implementation. However, there is still a lack of stakeholder participation in the scientific literature on city-level energy modeling cases. Improved stakeholder representation, especially in the scenario design process, could provide additional benefits and confidence to the decision-makers to base their policy decision on energy models.

The inclusion of social/behavioral aspects is still relatively limited in the selected case studies. Case studies have attempted to incorporate behavioral aspects through assumptions on economic representations. The inclusion of income perspectives to account for the deployment of end-use technologies [11] and the representation of private-economic perspectives to reflect on individual decisions [32,44] are some of the approaches applied. City energy systems models require detailed techno-economic systems placed in their social context. City modeling case studies aimed at evaluating policy impact often model individual decisions, which makes it critical to include private economic context in the models. While there have been some attempts at integrating social aspects, there is still a lack of representation of societal perspectives in the urban energy modeling case studies. Socially relevant issues like income constraints, unjust transformation measures, willingness to accept changes, and health aspects should be better integrated into the development of local energy system models.

The objectives of local energy models differ from national/regional models. Planning at the city level is mainly used for policy implementation as opposed to national energy planning, which has a strong focus on policy development. Among the themes analyzed for conducting city energy modeling studies, policy impact analysis is a common theme in these cases. However, most cases often follow the theme driving national models with normative decarbonization targets being used to design scenarios.

With continuous development in city energy systems modeling, most studies have highlighted their contribution to the capacity building of UESMs. With the transition from centralized fossil-based solutions to a more decentralized system based on renewable energy sources, there is an increased need to apply integrated approaches to energy systems planning [4]. Few energy systems models have highlighted their contribution to developing integrated ESMs. Key contributions among the selected studies include sectoral integrations and coupling ESMs with behavioral/societal aspects. Sectoral integrations are aimed at the representation of energy use and emissions in the analyzed cases. However, with increasing reliance on electrification and deployment of bio-resources in sectoral transformations, it is increasingly important to account for resource competition among sectors in integrated assessments of city energy system models. Lastly, due to the unique characteristics of local energy systems, capacity building of modeling cases based on specific urban contexts could play a crucial role in guiding model development focused on specific local contexts.

This systematic review aims to add value to the existing literature by analyzing the representation of essential modeling features in city case studies. The analysis sheds light on the strengths of the existing model setups. It identifies features with limited representation that can be further improved to improve the usability of modeling case studies to support energy planning processes. This kind of review can be identified as a more forward-looking future prospect and acts as a basis for going further into critical areas of development of urban energy systems modeling.

5. Conclusion

Based on a systematic literature review of peer-reviewed city energy systems modeling case studies, the representation of city energy systems planning complexities is investigated. The findings regarding scale aspects show that a diverse mix of temporal and spatial scales is being implemented. The most applied temporal scale in the analyzed case studies is the long-term horizon with annual time resolution; however, certain studies have also applied higher temporal resolution to long-term planning horizons. Studies focusing on improving spatial resolution at the city level have disaggregated cities into zones based on different characteristics. In addition, a few studies have coupled energy models with GIS mapping to improve spatial resolution. In terms of method definition, the studies have applied a diverse mix of approaches based on optimization and simulation techniques using different tools. TIMES and LEAP are identified as the most utilized platforms for optimization and simulation, respectively.

Findings on scenario typology suggest that explorative scenarios aimed at identifying the role of specific measures in the energy system account for most case-specific model characteristics. Policy statements being translated into applied measures are used to design explorative scenarios. Normative scenario designs are most often based on long-term CO_2 emission reduction targets. In terms of environmental components, most studies analyze CO_2 emissions, with very limited representation of local air pollution. In terms of case-specific model inputs, very limited representation of stakeholder engagement and societal perspectives is observed in the analyzed studies.

In addition to the analysis framework, the themes of the research objectives are categorized. Based on the review of research objectives for the selected case studies, four themes are identified. The most common theme identified is the pathways to future low-carbon energy systems. Additionally, research objectives aimed at evaluating policy impacts on the city's energy systems are observed. In terms of objective characterization from the perspective of capacity building, model integration has been identified as the most common contribution to city-level modeling applications. Due to the unique characteristics of cities, methodological developments aimed at modeling specific urban contexts have also been observed in the analyzed case studies.

In conclusion, city-level case studies are increasingly represented in the field of energy systems modeling, demonstrating significant developments with a wide range of modeling approaches. However, model aspects that are deemed important in urban contexts are rather limitedly represented in city-level case studies.

Acknowledgments

This work received funding support from the Swedish Energy Agency research program E2B2 – energy-efficient built environment (project nr. P2022-00922) and the project FlexSUS: Flexibility for Smart Urban Energy Systems, Sweden (Swedish Energy Agency project nr. 47809-1) in the framework of the joint programming initiative 'ERA-Net Smart Energy Systems' with support from the European Union's Horizon 2020 research and innovation programme (grant number 775970).

Supplementary material

Supplementary material can be found at https://doi.org/10.54337/ijsepm.9335

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