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Review Article

Recent progress in the application of energy technologies in Large-Scale building Blocks: A State-of-the-Art review

Habtamu Bayera Madessa, Mohammad Shakerin [*], Espen Helberg Reinskau, Mehrdad Rabani

Department of Built Environment, Oslo Metropolitan University, Norway

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ABSTRACT

The transition to clean and sustainable energy systems in the building sector is vital to reduce global greenhouse gas emissions. In this regard, shifting the focus from single buildings to clusters of buildings, such as at the district level, can provide more effective sustainable solutions. In this study, the term Multi Building Energy Systems (MBES) was introduced to represent various scales, from local communities to districts and larger urban areas. This approach reflects a more inclusive understanding of sustainability potentials for large-scale building blocks that goes beyond traditional boundaries. Such systems encompass the aggregated energy impacts of multiple buildings whether physically proximate or connected via smart grid technologies that enable two-way energy and information flows. This paper comprehensively reviewed case studies on MBES that have achieved zero-energy, nearly-zero-energy, and positive-energy performance. The literature review, facilitated by a combination of database searches and snowball search techniques, has yielded 67 relevant case studies. The findings revealed diverse pathways towards achieving optimal renewable energy production depending on the location and the climate. Integration of renewable energy sources and energy storage systems is pivotal in achieving economies of scale, reducing operational costs, and enhancing resilience and reliability of energy supply at the neighbourhood scale. Total energy use and emissions reduction could be achieved by considering the architectural features of the building stocks. The study highlighted the need for adaptive strategies in MBES implementation to address challenges such as power grid overloads and the complexities of spatial arrangement, to meet current demands, while ensuring long-term energy resilience and sustainability in evolving urban landscapes. The limited adoption of MBES simulation software suggests a need for accessible tailored software. Future research should focus on developing advanced personalised energy management and control strategies, while continuously assessing emerging technologies for improving MBES performance.

1. Introduction

In Europe, buildings are responsible for approximately 40 % of total energy consumption and 36 % of CO_2 emissions [1]. Transitioning to a clean and sustainable energy system in this sector has become a crucial goal to meet the United Nations' Sustainable Development Goals, specifically related to affordable and clean energy, sustainable cities, and climate action [2]. In response, the European Union (EU) passed a directive in 2010 mandating all new and renovated buildings to meet passive house standards by 2015, nearly zero energy buildings (nZEB) by 2020 and net zero energy buildings (NZEB) by 2030 [1,3].

An NZEB is defined as a building that achieves an annual net energy consumption of zero by balancing its energy usage with on-site renewable energy production [4,5]. In contrast, an nZEB exhibits high energy performance, with the majority of its minimal energy needs met by renewable sources, either on-site or nearby [3,5]. This is accomplished

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Abbreviations: **Acronym**, **Description**; CO2, Carbon Dioxide; nZEB, Near zero emission building; NZEB, Net zero emission building; EU, European Union; NZEN, ZEN, Zero emission neighbourhood; PED, Positive energy district; PEN, Positive energy neighbourhood; PEB, Positive energy building; MBES, Multi-building energy system; HVAC, Heating, ventilation, and air conditioning; PV, Photovoltaic; ZEC, Zero emission community; BIPV, Building integrated photovoltaic; DHC, District heating and cooling; DH, District heating; HP, Heat pump; RES, Renewable energy source; CHP, Combined heat and power; STC, Solar thermal collector; GSHP, Ground source heat pump; TES, Thermal energy storage; EES, Electrical energy storage; PHES, Pumped hydro energy storage; DHW, Domestic hot water; SST, Seasonal thermal storage tank; BTES, Borehole thermal energy storage; BHE, Borehole heat exchanger; UHI, Urban heat island; GWHP, Groundwater heat pump; ICE, Internal combustion engine; MILP, Mixed integer linear programming; GIS, Geographical information system.

[*] Corresponding author at: OsloMet – Oslo Metropolitan University, P.O. Box 4 St. Olavs plass, N-0130 Oslo, Norway.
E-mail address: Mohammad.shakerin91@gmail.com (M. Shakerin).

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through optimally combining energy-related technologies, and minimizing primary energy imports [5]. The key difference between NZEB and nZEB lies in NZEB's focus on balancing energy import and export, while nZEB emphasizes employing the best technology combinations to reduce primary energy imports [4,5].

The long-term goal of the EU is to reduce greenhouse gas emissions from the built environments by 85–90 % by 2050 [1,3,6]. The urgency of this concept and its goal of reducing buildings' energy and environmental footprints have garnered significant attention from the research community [7–10]. To address these concerns from a wider perspective, the concept of zero energy has been extended to encompass multiple buildings. This facilitates adapting the principles of nZEB and NZEB at a neighbourhood, district, and community scale [11–14]. For instance, the Net Zero Energy Neighbourhood (NZEN) and nearly Zero Energy Neighbourhood (nZEN) concepts address several limitations of nZEB and NZEB by taking into account the mutual influence between buildings and their surroundings. An nZEN is defined as a cluster of buildings where the overall energy demand is low and is partly met by renewable energy self-produced within the neighbourhood [15]. This contributes to enhancing the potential for managing and sharing energy and resources at the district level [16–19]. Another potential benefit of nZEN/NZEN is the mitigation of energy poverty, which refers to the limited accessibility and high costs associated with renewable energy among low-income communities [2].

Additionally, the concept of Positive Energy Districts (PEDs), alternatively referred to as Positive Energy Neighbourhoods (PEN) or Positive Energy Blocks (PEB), represents a promising approach for facilitating the transition to sustainable energy systems [20]. PEDs focus on urban and regional energy systems primarily powered by renewable energy sources (RES) to provide stability and flexibility in energy supply [2]. This concept has evolved from similar concepts such as NZEB which emphasizes meeting energy requirements through locally accessible and environmentally sustainable renewable sources [20,21]. This becomes particularly relevant when considering the context of PEDs, which are embedded in urban and regional energy systems dominantly driven by renewable energy. The overarching objective is to provide security and flexibility of energy supply, thereby synergizing with the need for aggregated energy flexibility from multiple buildings to optimize overall energy system efficiency [22]. The EU has introduced the Strategic Energy Technology Plan with a target to establish 100 PEDs by 2025 to contribute to carbon neutrality through energy efficiency and net zero energy balance [21].

The idea of transitioning from single buildings to building clusters demands a thorough understanding, assessment, and regulation of the potential for local renewable energy production, integration, and grid connectivity among buildings at an aggregated level. There are significant opportunities for the integration of different energy systems like district heating and cooling (DHC) systems, solar thermal/electric systems, ground source heat pumps (GSHP), and biomass-based combined heat and power (CHP) at the district scale [23–27]. When the energy production systems combine with energy storage systems, it helps to optimize the utilization of RES within the building clusters, thereby enhancing energy security and resilience against disruptions in energy supply within the building blocks [28–31]. For instance, Zhang et al. [31] provided a comprehensive framework for understanding urban energy systems at the building cluster level that emphasizes the potential of the building cluster approach to maximize solar energy harvesting, building performance, and distributed energy management. This approach focused particularly on the incorporation of building integrated RES solutions [31]. A cluster of buildings implies that several buildings can be located physically next to each other and digitally connected to control and manage their energy usage, local energy generation, and grid connectivity [32,33]. The aggregation of energy flexibility from several buildings, especially with heterogeneous energy demands and provisions for energy storage mechanisms, is necessary to ensure a significant impact on the energy systems and grids, in contrast to the limited energy management of a single building [34–36].

Various terms such as community [37,38], neighbourhood [39–41], district [13,42,43], and cluster [44] have been frequently used in the literature to describe an area containing multiple buildings [14]. While many studies on the neighbourhood scale focus on the optimisation of RES, energy storage, spatial conditions, and energy grid, there is still a lack of clear definition of boundaries for clusters of buildings such as neighbourhood and district level and their energy performance indicators [13].

Given the diverse interpretations and lack of consensus on the boundaries for defining neighbourhoods, districts, and communities, the present study adopted the term "multi-building energy system (MBES)" to establish a consistent framework for a unified understanding of the concept. This term disregards specific boundaries for building blocks and instead encompasses all energy systems that involve more than one building, considering the interactions between buildings, the energy grid, energy storage, and the aggregated effects of these connections. By employing the term MBES, a more inclusive and versatile approach can be employed when addressing various types of built environments and their energy systems. It is worth noting that while electric vehicles and their integration into MBES are indeed significant, especially in the context of nearly or net-zero-energy building stock [45], this review primarily focused on building energy technologies and their infrastructure-related aspects of MBES. The role of electric vehicles and energy flexibility, particularly in the implementation of large-scale photovoltaic (PV) systems, is a vast domain in itself and merits a separate detailed exploration.

In addition, terms reflecting the energy ambitions in the context of this paper refer to MBES that strive to be nearly zero, zero-energy, or energy-positive. The energy performance of MBES is not only affected by the building and climate-related factors such as local weather and construction characteristics but also energy usage patterns stemming from the socio-economical and functionality of the buildings connected to the integrated MBES [36,46–48]. Thus, it is important to note that individual buildings in the MBES can be less energy efficient than zero energy, especially when MBES is considered to be energy positive. Achieving nearly zero energy or better levels for existing buildings requires minimizing the energy loss from the building body, optimization of HVAC systems, minimizing energy consumption and producing energy renewable on-site. In nZEB renovation projects, the production of energy, whether electric or thermal, is frequently imperative. This necessity arises from the elevated energy consumption observed in existing buildings, persisting even after enhancements and optimizations of technical and physical parameters have been implemented [49].

Assessing energy and environmental performance at a multi-building scale can be beneficial compared to a single-building scale. As an intermediary between a single building and a city, energy performance, the integration of RES, and energy distribution can be better assessed by accounting for the community characteristics and inter-building interactions [13]. Analysing morphology, density and geometrical layout can contribute to reducing transport, emissions and energy use for heating and cooling, better utilization of solar energy and increase the accuracy of energy simulation [30,50,51]. MBES analysis can help reduce the negative effects on urban microclimate, which in turn leads to energy savings [52,53].

The power grid within the boundary of MBES plays a crucial role in determining its energy flexibility. It not only ensures stability but also allows for efficient management and optimization of energy and costs. Two-way grids, also known as smart grids, enable bidirectional flows of energy and information, allowing for better communication and coordination between energy producers and consumers [54]. This virtual connectivity allows for more efficient management and optimization of energy consumption and production, enabling buildings and communities to reach a balance between energy consumption and production while also contributing to overall grid stability and sustainability [14,54–56]. The integration of RES into these smart grid systems further underscores the need for adaptive and advanced energy management strategies to maintain grid stability and optimize energy use while ensuring occupant comfort [36,57–59].

Though it is not the main focus of this review paper, it is worth mentioning that the design and operational strategies of energy storage systems, such as batteries and underground heat storage, require critical consideration of the distinct energy usage profiles (both electric and thermal energy) of the various buildings within the MBES [57,60]. This means that, for example, the energy load profiles of the various buildings, such as residential buildings, office buildings, school buildings, and nursery buildings within MBES, should be monitored for the optimal operation of both the building clusters, the energy system and energy storage of the MBES. Such considerations contribute to a more stable energy supply, facilitating a reduction in energy usage, and greenhouse gas emissions, and the establishment of a more sustainable energy system [34,46,61,62].

The global shift towards sustainable energy has intensified research on energy-efficient buildings and communities. Previous review articles have illustrated the diverse boundaries and aspects of MBES such as the technical, social, economic, and environmental impact of urban development efforts [13,14,45,63–75]. Aghamolaei et al. highlighted the significance of incorporating sustainable strategies at the early design stages for district-scale energy-efficient design. They emphasised the need for various strategies and solutions to achieve this goal [65]. Furthermore, Charani et al. provided an in-depth overview of energy master planning for achieving net-zero emission city districts, emphasizing the role of renewable energy systems, energy storage, and efficient technologies [75]. The potential and requirements for using responsive building envelopes to manage complex interactions between building clusters and utility grids have also been reviewed [76]. A framework for implementing responsive building envelopes in zero-energy neighbourhoods is proposed. The product of the framework was a presentation of optimal responsive building envelopes for demand-side management, energy performance and user comfort. Focus on key performance indicators was suggested, as the measurement of responsiveness and control strategies is currently lacking [76]. Integration of PV through facades, pavements and shading devices and the role of information and computer technology and smart grids for efficient renewable energy management MBES was described in a review [77]. The review studied smart cooling systems for the urban environment and the role of renewable energy and zero-carbon technologies in covering future cooling demand [77]. Heiskanen and Matschoss emphasized the adoption of renewable energy technologies in European residential buildings, focusing on the varying market maturity across nations [67]. The study revealed that socio-economic, cultural, and policy differences significantly impact renewable technology adoption rates [67]. Soares et al. underlined ten pivotal research areas for the sustainable built environment, promoting the integration of energy supply and demand [68]. Amaral et al. extended this discussion to the influence of urban factors on nearly zero-energy districts [13]. Koutra et al. introduced the urban zero-energy district (U-ZED) tool, aiming to merge building and district evaluations, offering a comprehensive sustainability assessment method [69]. At the same time, Saheb et al. highlighted the endeavours of European municipalities in achieving zero-energy communities [70]. With technological advancements, Sola et al. emphasized urban-scale energy modelling tools, facilitating the assessment of city-wide energy efficiency [71]. Moreover, Zahedi et al. employed machine learning to predict energy management in cold-climate regions with an accuracy of 88.6 % [45]. By a comprehensive review of 33 global open datasets on building energy use, along with their applications and challenges, Jin et al. underscored the scarcity and importance of city-level building energy data in shaping energy policies [73]. Koutra et al. critically evaluated the challenges in designing PEDs in urban contexts [74]. Meanwhile, Mousavi et al. reviewed the positive energy building models, urging the integration of data-driven tools to achieve net positive energy performance [66].

The large-scale integration of energy systems poses challenges as well. Often, it requires substantial infrastructure upgrades and investments [78,79]. Additionally, regulatory frameworks and policies at national and regional levels may lack consistent support for large-scale energy integration, hindering the development and deployment of an integrated energy system. The public's acceptance of large-scale energy system integration is also a potential concern, predominantly attributed to shared spaces and concerns regarding privacy in data sharing [67,80]. Addressing these challenges is essential for realizing the maximum potential of integrated energy systems within MBES and fostering a more sustainable and resilient energy landscape.

Despite the significant research efforts that have been made in this area, there is a lack of a focused comprehensive and consistent evaluation of the different technologies and solutions that have been proposed for energy-efficient and sustainable MBES. This has led to a need for a more in-depth comparative analysis of the existing literature on energy-efficient and sustainable MBES, aiming to identify patterns in the use of innovative solutions and to compare the energy and economic promises of different studies. While several studies have explored the fields related to MBES, the current body of literature often presents a fragmented understanding, with individual works predominantly focusing on isolated aspects of the energy system such as energy performance in specific building types [67], advancements in integration of specific renewable energy technologies [68,75], or the adoption of energy systems at a district scale without a comprehensive integration of building and urban scale considerations [69]. Acknowledging this fragmented approach, the present paper offers a unique contribution by comprehensively reviewing a wide range of literature, including case studies on MBES developments that have achieved zero-energy, nearly-zero-energy, or positive-energy performance. Instead of a mere compilation, this review effectively integrates various facets of MBES such as renewable energy conversion systems, energy storage systems, and energy performance optimization in a multitude of geographical contexts and large-scale built environments. A salient feature of this review is its emphasis on both technological and architectural perspectives, providing a holistic understanding that is often missing in extant literature. The research outputs not only address the suitability of energy technologies proposed for case studies in terms of energy performance and associated costs but also place them in the larger context of urban and architectural design. This is particularly crucial given the intrinsic relationship between building design, urban form, and energy performance. Furthermore, the review considers factors such as inter-building interactions and interactions between micro- and main energy grids.

The rest of this paper is structured as follows: Section 2 describes the review method including the data collection and evaluation processes. Afterwards, the outcomes of the bibliographic and content analyses are presented in Section 3, which is followed by a discussion of the reviewed items in Section 4. Finally, the main findings together with recommendations for future research are presented in Section 5.

2. Methods

The present review utilized a structured combination of string-detecting searches in databases of Web of Science and Scopus as well as secondary snowball search techniques backwards and forward, to ensure comprehensive coverage of the topic. This systematic and comprehensive approach was chosen to bridge the discrete understanding often evident in existing literature. By combining string-detecting searches with snowball techniques, we aimed to provide a holistic exploration of MBES, capturing interconnections that might be overlooked in more traditional, linear search methods. The flow chart in Fig. 1 shows the search process conducted in this study.

The objective of this article was to review recent developments in MBES by summarizing and mapping various energy system design approaches. The primary focus was on analysing the potential of available technologies and resources to achieve zero or positive energy status,

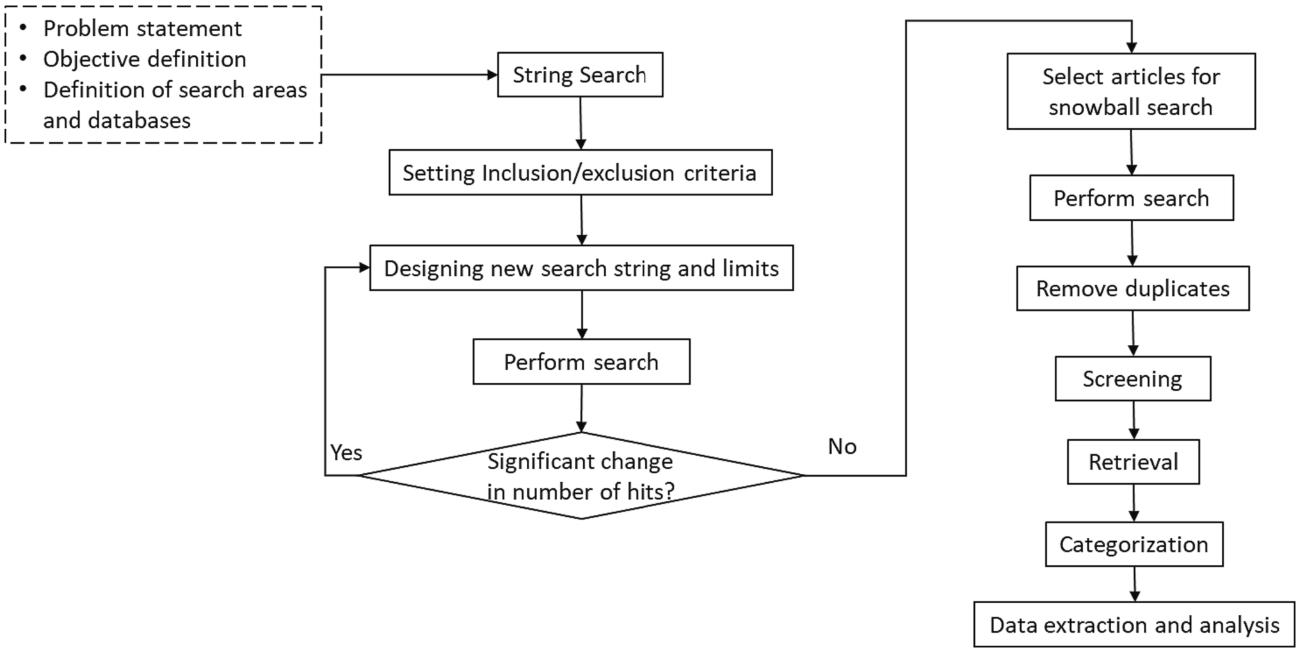

Fig. 1. Flow chart of the string search and secondary survey process for the present study.

based on case studies conducted in real-world locations. This served as the basis for the search process to identify key trends and patterns in MBES advancements.

The search terms and inclusion/exclusion criteria used in the study were set a priori, along with the data extraction process. Documents of interest were peer-reviewed articles published in the English language between 2016 and 2023. To effectively capture the relevant cases to address the question of this research, four search blocks were defined, describing the boundaries and focus of the search. The key terms associated with the blocks were used in various combinations in both databases. The search fields in both databases were Title, Abstract, and Keywords. Table 1 shows the matrix of key terms used to navigate the search in each database.

Urban energy planning is a relatively recent discipline. Thus, there is no standard terminology for distinguishing the spatial and energy boundary of a portion of the city. Previous studies have identified several notations. As a result, this can lead to ambiguity in the definition and planning of ZEN, PED, and ZEC, or similar concepts [13,14]. Therefore, the first block was focused on capturing articles related to the "neighbourhood" scale. These terms were used to identify studies on a group of buildings or an area within a city but larger than a single building. Additionally, incorporating synonyms is aimed at capturing articles that may not explicitly use the term "neighbourhood" but discuss energy systems at this scale.

The second block focused on identifying articles that discuss specific energy performance targets or ambition levels for building mass. These terms have been chosen to capture literature that specifically addresses the energy performance goals of communities or neighbourhoods, rather than focusing on other aspects of MBES studies. These terms were used in the literature to describe different levels of energy performance with "zero energy" or "net zero energy" referring to a state where the total energy consumption of a district or community is equal to the renewable energy generated on-site, while "positive energy" or "energy self-sufficient" refers to a state where the district or community produces more energy than it consumes [13,14].

The third block was used to determine the applied or practical proposals for energy-ambitious MBES. This included terms to identify articles that provide an in-depth analysis of implemented solutions and their energy and economic performance. These terms will help to exclude conceptual or theoretical studies that do not provide an evaluation of the actual implementation of energy technologies at the MBES. In the fourth block, the search was refined to articles that specifically addressed certain design and/or performance-related aspects of their study. The search process in Scopus and Web of Science led to 368 initial hits. Fig. 2 shows the number of items processed at each stage.

From a total of 194 unique hits from both databases, 81 articles were discarded as they had irrelevant focuses to this study (e.g. ZEB, transportation, business model etc.). Thus, 113 articles were sought for retrieval. These articles were screened through the full text based on certain inclusion criteria. The studies included must have used measured or validated data specific to the site of the study. In addition, they must have proposed or investigated an energy system as the main objective of the study and have analysed the system in detail. Moreover, to obtain information about the suitability of studies in different typologies only studies that mentioned the size and composition of the studied energy boundary were included. This could be any form of representation of the studied subject in terms of geometrical and architectural data at the building or MBES level, as well as the community composition, density, and structure of the MBES. Therefore, 38 articles that fit the mentioned criteria were included. Furthermore, while the matrix of key terms provided a structured approach to the search, the search strategy was

Table 1
Matrix of key search terms, highlighting the studies of interest in the search process.

Blocks	Typology definition	Energy ambition level	Study type and approach	Design and performance
Search terms	Neighbourhood	Zero energy	Case study	performance evaluation
	District	Nearly zero energy	Simulation	energy efficiency
	Community	Positive energy	Experiment	energy consumption
	Urban	Net zero energy	Field test	cost reduction
	Microgrid		monitoring	techno-economic
	Cluster		Design	Energy storage
	Block		Implementation	

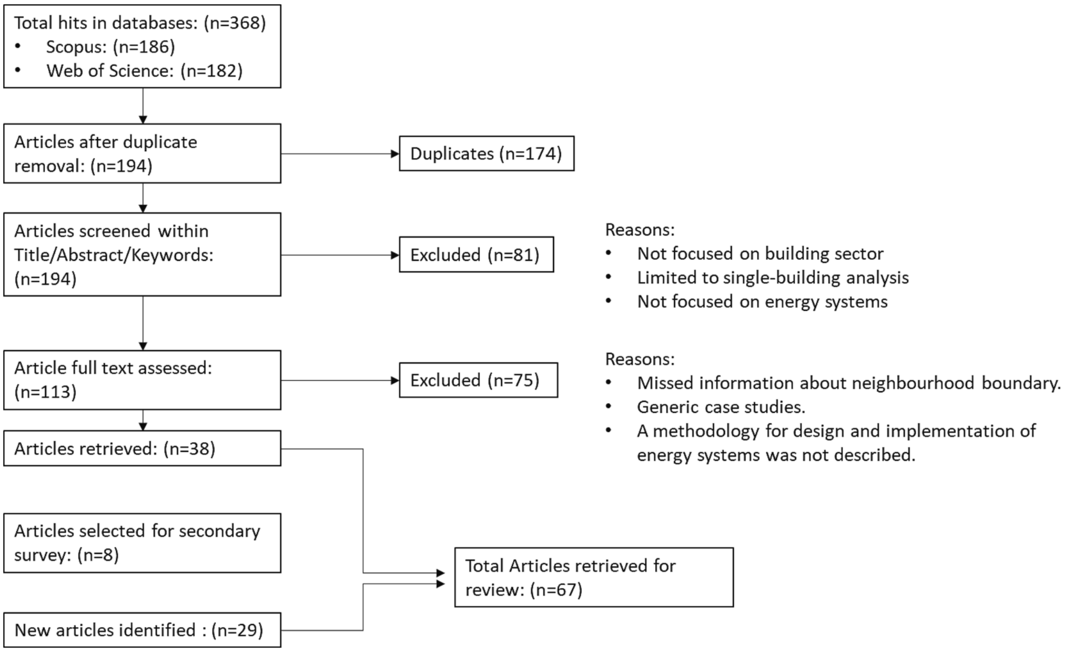

Fig. 2. Result of the search process in Scopus and Web of Science as well as snowball search.

not limited to these terms alone. To ensure comprehensiveness, articles' references identified in the initial search were also examined for relevance, leading to the inclusion of significant works that might have been missed in the primary search. To broaden the scope of the search a snowballing was carried out by examining the reference lists of the articles initially identified through the database search. Articles that were frequently cited and deemed central to the field such as [52,81–83] were further examined. This process was repeated iteratively until no new relevant articles were identified. This process followed the same inclusion criteria as the database search and yielded 29 more articles.

Finally, the literature survey resulted in a total of 67 articles that were used for this review. To effectively organize and analyse the relevant information about each included study, the extracted data was classified according to 1) the main RES exploited and the energy conversion mechanism, 2) the Location and typology of the MBES, and 3) the main methods and tools.

3. Results

The literature survey process resulted in a total of 67 relevant case studies on MBES with a specific focus on the demonstration of energy efficiency and conversion mechanisms to enable ZEN, PED, NZEN, ZED, and the application of similar concepts. The information presented in each article was analysed according to the categorization described in the previous section.

3.1. Contextual factors influencing MBES analysis

Zero energy and positive energy MBES are becoming increasingly popular worldwide. This is mainly due to the proven techno-economic potentials of ZEB concepts and the modernization of energy infrastructure through digitalization and electrification across all sectors [14,63]. In addition, recent policies and directives with specific attention to the sustainable development of districts toward carbon-free and self-sufficient communities have driven stakeholders in the energy sector to harness locally available RES in various forms and utilities [6,19,84].

In this section, we examine the influence of various contextual factors on the analysis and implementation of multi-building energy systems (MBES). Recognizing the importance and interplay of these factors in shaping the performance and feasibility of energy systems offers valuable insights into the adaptability and effectiveness of MBES in diverse settings.

3.1.1. Geographical distribution

Table 2 presents the countries in which the examined MBES projects are either already operational or are being planned for development, as a response to relevant national and/or international energy policies. The studies were distributed over 23 countries and 10 diverse climate zones. Köppen climate classification, which represents various climate zones based on temperature and precipitation patterns, as well as the country of the study was used to map the geographical distribution of the reviewed cases [85]. The identified climates included Cfb (Oceanic), Csa (Mediterranean, hot summer), Cfa (Humid subtropical), Dfb (Humid continental, warm summer), BSh (Semi-arid, hot steppe), BSk (Semi-arid, cold steppe), BWh (Arid climate, hot desert), Dwa (Cold continental, dry winter, hot summer), Dfc (Subarctic, cool summer), Cwa (Humid subtropical, dry winter). Approximately one-third of the case studies were situated in disparate regions of Canada [30,85–92], Italy [24,52,62,83,93–96], and the USA [38,97–100]. The climate zone most extensively studied was Cfb, corresponding to a significant portion of the Western European countries, namely Belgium [101], Denmark [23,61,102,103], France [28], Germany [104–106], Italy [94,101], Netherlands [19,60,107], and Switzerland [26,108–110]. This could be expected due to the rigorous policy and funding support in the EU [21]. This diverse set of examples and the geographical characteristics of each case show the vast solution space for achieving energy sustainability targets and the ZEN or PED concept. However, this also points to the various constraints and resources which could make the optimal solutions different case by case.

3.1.2. Building types

The reviewed MBESs were residential, public, commercial, or mixed in terms of functionality. Half of the collected case studies were conducted within the residential sector, and nearly half were a mix of residential, public and commercial buildings within the studied boundary, as shown in Fig. 3. Commercial and public built sectors were the focus of 4 case studies.

The predominance of residential-focused and mixed-use case studies

Table 2
Geographical distribution of case studies.

	Cfb	Csa	Dfb	Cfa	Cwa	BSh	Dfc	BSk	BWh	Dwa	Total
Canada			8								8
Italy	1	4		2		1					8
USA			1	1				3			5
Denmark	4										4
Switzerland	4										4
Finland			1				3				4
China				2						2	4
Germany	3										3
Netherlands	3										3
Hong Kong					3						3
Pakistan					1				2		3
Canary Island						3					3
Israel		2									2
Spain		2									2
South Korea					1					1	2
Sweden			1				1				2
Austria	1										1
Belgium	1										1
France	1										1
Greece		1									1
Portugal		1									1
Turkey		1									1
Egypt									1		1
Total	18	11	11	5	5	4	4	3	3	3	67

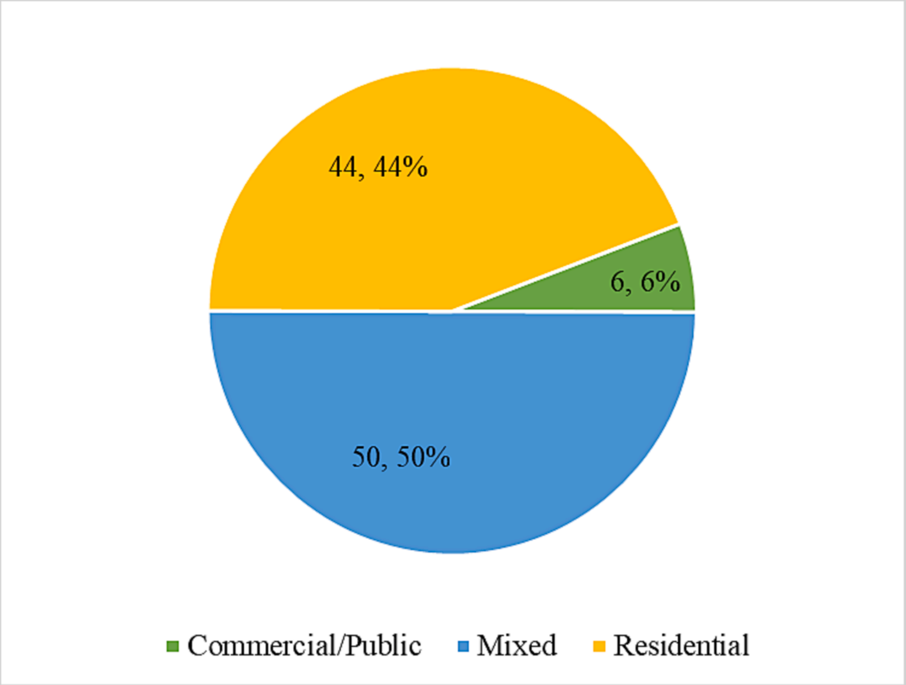

Fig. 3. Type of studied MBES based on the building function.

in the collected data can be attributed to several factors. Residential case studies often represent a significant portion of the overall building stock in urban areas and tend to have a substantial impact on energy consumption patterns [42,106,111,112]. As a result, there is considerable interest in understanding and optimizing the energy performance of residential buildings within MBES.

Commercial and public buildings, although important, were less prevalent in the overall building landscape. The energy consumption patterns in commercial and public buildings can be more diverse and complex due to varied operational schedules, equipment use, and occupant behaviour. This complexity may make it more challenging to develop generalized models and strategies for MBES in these sectors, leading to fewer case studies such as one focusing exclusively on commercial and public buildings [38,82,113,114]. The high number of mixed-use case studies demonstrated the relevance of MBES across different building types and the potential benefits of integrating various sectors to achieve synergies in energy management and sustainability [115].

3.1.3. *Criteria defining MBES*

The studied MBES were analysed based on the territorial boundaries as well as urban architectural features and population density, as shown in Fig. 4. Several spatial units were used in the case studies to define the magnitude of the studied MBES and its boundary.

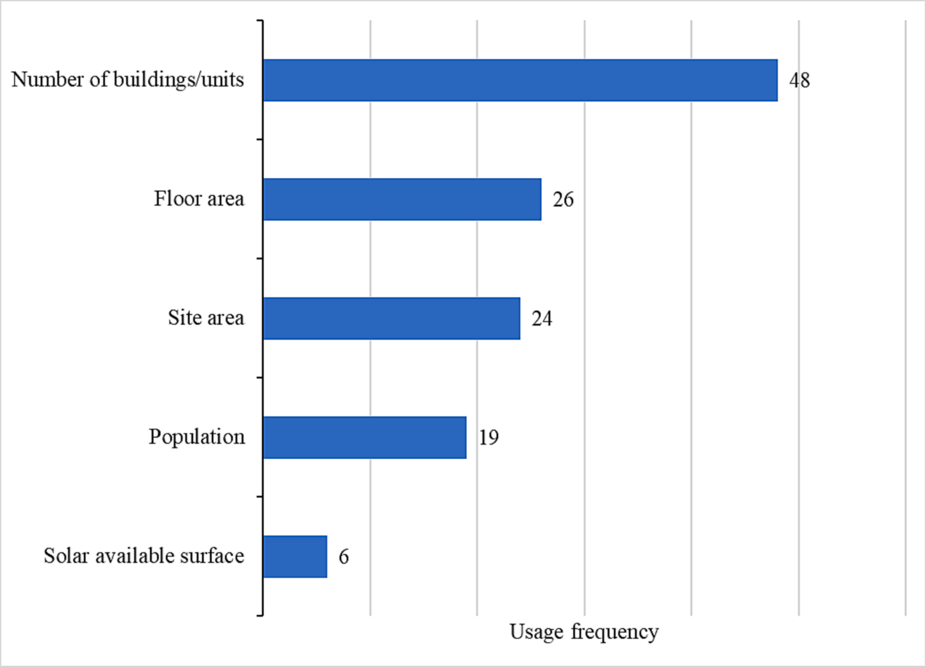

Fig. 4. Criteria used for the definition of MBES.

The number of buildings or units was the most reported geometrical information about the size of the MBES (-48 out of 67 cases), followed by floor area. A "unit" generally refers to an individual residential or commercial space within a larger building or complex. A unit is a self-contained living or working space with separate facilities, such as a kitchen, bathroom, and other amenities.

Out of the 48 cases that reported the number of buildings, most cases were between 10 and 100 buildings or units, as shown in Fig. 5. Meanwhile, 9 % of the analysed MBES were considered more than 1000 buildings in the scope of the study, some of which focused on the energy resource availability within a larger boundary such as the energy demand for a village, densely built districts, or an island city. Less than 10 buildings were presented in one-fifth of the reviewed cases. Several units were mentioned in only 10 articles, of which 5 were accompanied by the number and type of buildings.

The second most reported boundary was building or unit floor area (26 out of 67 cases), as numerous tools and methodologies for modelling and simulation of building energy performance consider gross or heated floor area as the unit of assessment. The reported building sizes range from 55 m^2 of single-family houses [28] to almost 300 m^2 of apartments for residential buildings [88] and 450 to 10,000 m^2 for commercial and public buildings such as schools, hotels, and hospitals [37]. By using the number of buildings as a criterion for delineating the MBES, the upscaling of test cases became more convenient. A common approach to define the boundaries of MBES was by considering a reference design for each type of building (e.g. single-family house, apartment, townhouse, school, hotel, hospital, mall, etc.) and upscaling the building models to MBES by clustering the total number of buildings with unique design

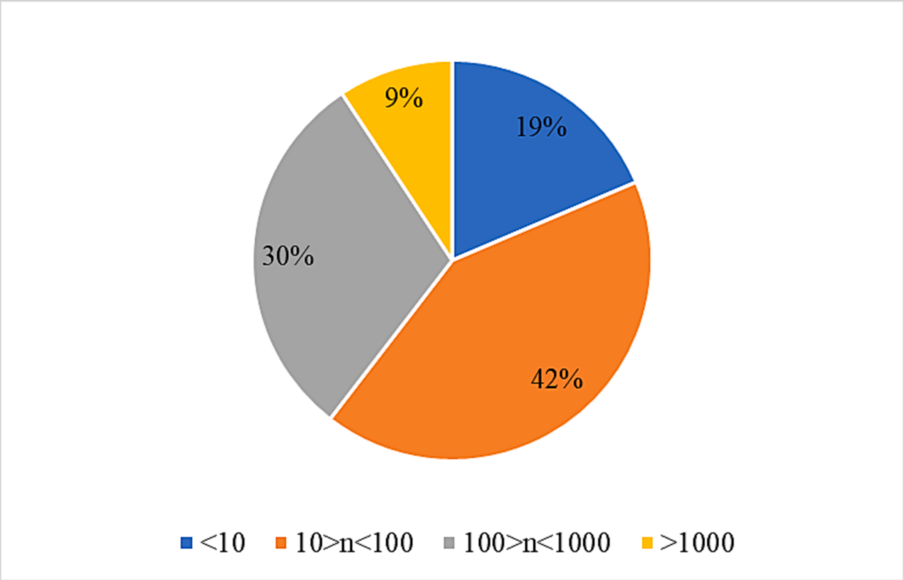

Fig. 5. Number of buildings reported in the case studies. "n" is the number of buildings.

within the territories of the studied area [47].

Some studies presented the information about site or land area, which often included descriptions of the ratio of each built sector [30,90,115]. This form of boundary definition was mostly used in studies where an MBES did not exist a priori, hence the suitable approach was to assess the urban morphology and a coarser spatial resolution. Few case studies were on island communities where the scale of the project was reported by the total land area [27,34,102,116].

Out of 67 reviewed studies, 19 provided details on the occupancy profiles or population within the defined MBES boundary. This indicates a research gap in the nuanced understanding of how different occupancy behaviours impact the energy dynamics of MBES. A commonly given information was occupancy per unit or building type, which was particularly prevalent in detailed energy simulation and analyses of heating, ventilation and air conditioning (HVAC). Some studies disclosed the total number of inhabitants within the community or each building. This was often together with the information about the total area of the studied region. However, the absence of information regarding occupancy profiles and population density about the proposed MBES may impede a fair comparison between different MBES analyses. This limitation arises because variations in energy demand intensity and supply can significantly influence the design and optimal control of MBES across different settlement forms.

Few studies only mentioned the surface area available for the integration of solar systems into MBES, as the focus of these investigations was to assess the solar power generation potential. This included the rooftop area, building horizontal area, car parking shading surface area [97], and space between buildings [117].

3.2. Energy technologies

Upscaling the energy systems from a single building to an MBES requires considering all the available energy sources in the area. Hence, MBES must have a proper energy conversion design and control approach that enables the integration of multiple energy sources. Recent studies often perform design decision-making analyses on the area based on climatic features and urban typology [118]. Achieving a zero or positive energy status and cost optimality often requires the adoption of multiple technologies, while considering the grid interaction of supply and demand.

The most used energy system was PV, showing a strong focus on solar energy for power generation among the studies, as shown in Fig. 6. The popularity of PV systems observed in 75 % of the studies with different climate conditions (50 out 67 cases) to a great degree could be attributed to its environmental benefits, reduced deployment, and operational costs. In addition, the modular nature of PV equipment allows for easy scalability and grid integration. Some studies investigated the potential of PV systems for improving central power generation capacity, while a more prevalent practice was on-site electricity generation via building integrated PV (BIPV) modules installed on rooftops, façades, or other available surfaces [82,97]. For example, a net-zero energy community was established in Jincheon, South Korea, using BIPV, car parking shadings, and other public areas [82].

DHCs deliver thermal energy (heating and cooling) to multiple buildings within a district or region, through a network of underground pipes. These systems are energy-efficient and can help to reduce emissions by utilizing waste heat, renewables, or other low-carbon energy sources. Therefore, most of the countries with already established DHC networks have investigated the design and performance improvement of DHC systems by integrating other RES such as PV, Solar thermal collector (STC) systems, as well as heat pumps (HP) and CHP sourced by biomass [19,61,82,83,103].

Half of the studies included one or several types of HP systems, among which GSHP was among the most studied. Three case studies utilized HP in MBES, however, the authors did not specify details about the type of HPs used [23,42,61]. An absorption HP was used in one study

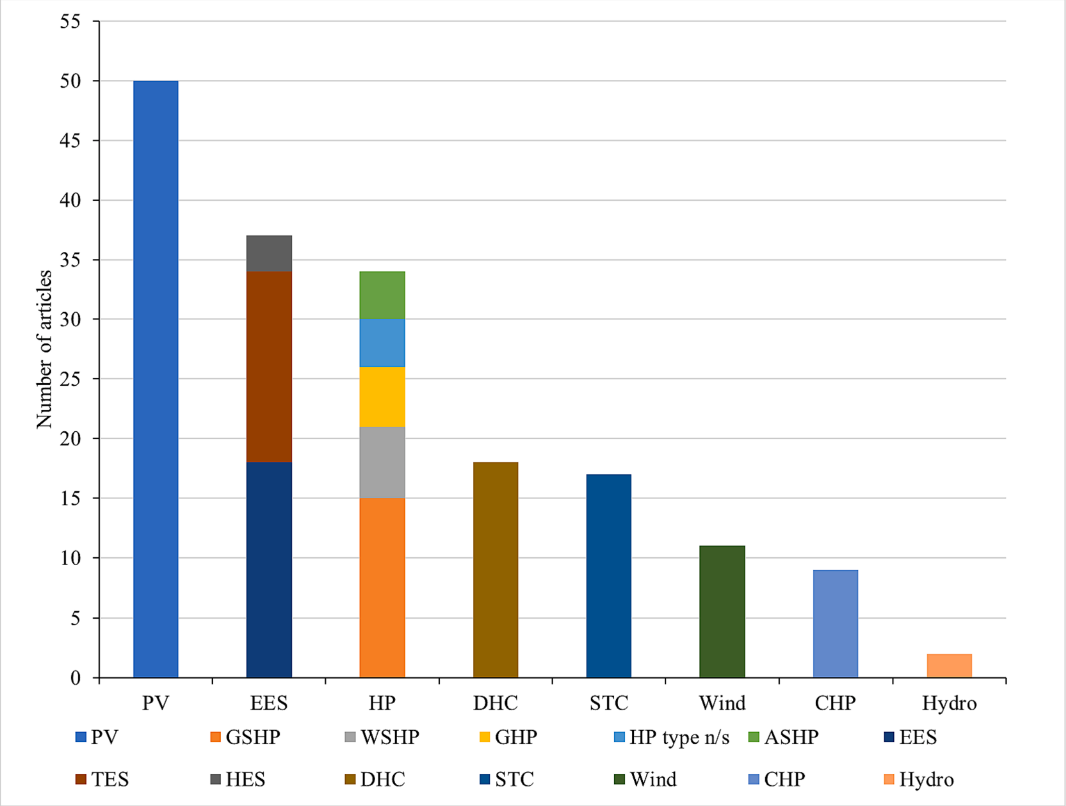

Fig. 6. Occurrence of energy system technologies utilized in case studies.

as one of the elements in a hybrid MBES [87].

Another point of interest in the identified case studies was the use of energy storage mechanisms. The prevalence of energy storage systems, particularly thermal energy storage (TES) and electrical energy storage (EES), highlights the importance of balancing energy supply and demand in MBES projects. These energy management solutions were proposed in 25 % of studies with various configurations. Thermal energy storage systems are often purposed for short-term use via hot water tanks or long-term underground storage. Electricity generation through PV and wind was optimized by using battery energy management systems, supercapacitors, and pumped hydro energy storage (PHES).

The following subsections describe the case studies based on the main energy system for the studied boundary, followed by case studies that considered the effect of site typology and resource availability on the energy design and performance.

3.2.1. *Heat pumps and district heating systems*

District heating (DH) systems and HPs are clean energy conversion technologies that have proven to be sustainable and able to foster multiple RES, therefore facilitating the challenge of grid flexibility and stability. Hence, a great portion of the studies (9 cases) proposed novel HP or DH-centred energy systems or studied the integration of RES into existing configurations. For example, the rate of heat loss in DH systems was reduced by lowering the network's operating temperature levels. Low-temperature DH was defined as a system that only requires heat exchangers in the substations to supply temperatures higher than 50 °C for end use. Ultra-low temperature DH was defined as systems with a supply temperature below 35 °C, used for floor heating systems and preheating of DHW, while coupled with an auxiliary heating mechanism such as an HP for DHW preparation [119,120]. Low and ultra-low temperature levels were found beneficial for fostering more locally available low-grade heat, while neighbourhood-scale HPs located in Denmark were analysed [61,103].

Heat distribution via DH was improved in a net-zero energy community in Jincheon, South Korea by using a hybrid renewable energy solution, as shown in Fig. 7. The MBES utilized a central HP coupled with a geothermal heat exchanger and sewage waste heat as sources. Furthermore, the authors considered a central seasonal thermal storage tank charged by thermal energy from STC Simulation results showed that increasing the size of seasonal thermal storage tanks can reduce HP energy consumption, resulting in promising energy savings with relatively short payback time [82].

Abokersh et al presented a sustainability analysis of a solar-assisted DH system for residential communities in Emmen, Netherlands. Buildings were equipped with roof-mounted STCs, and PV panels for on-site energy production. Heating demand was covered by STCs feeding a central water-to-water HP that was used for charging a seasonal thermal storage tank (SST) and a hot water tank. Through a multi-objective optimization using artificial neural networks and genetic algorithms, the authors found that with the proposed configuration positive energy can only be achieved for larger community sizes, while near-zero energy status can be achieved at any community size [19]. A case study in urban residential and commercial areas in Sicily, Italy proposed a model for the design of a prosumer-based energy grid using MATLAB and the Carbon Trust Biomass Decision Support Tool. The study identified biomass DH and PV panels as reliable energy sources in the region. The energy system design highlighted electricity sharing among buildings while achieving significant reductions in grid electricity import and improved energy distribution in thermal networks [24]. In cold climates with high heating demand, the waste heat from industrial processes could be used as a heat source in buildings. For example, the utilization of excess heat from waste incineration in DH was investigated for a new Finnish residential neighbourhood via a borehole thermal energy storage (BTES) to store the waste heat during the summer. The authors found waste heat storage as a cost-effective solution for decreasing DH consumption and emissions. BTES achieved annual energy storage efficiencies of 48–69 %, enabling waste heat to meet 37–89 % of the annual heat demand. Despite the district not producing its energy and the risk of suboptimal system performance in individual district designs due to high return temperatures, a city-wide expansion of the net-zero energy district charging loop concept could enhance incineration heat utilization by rerouting return flows between BTES systems [121].

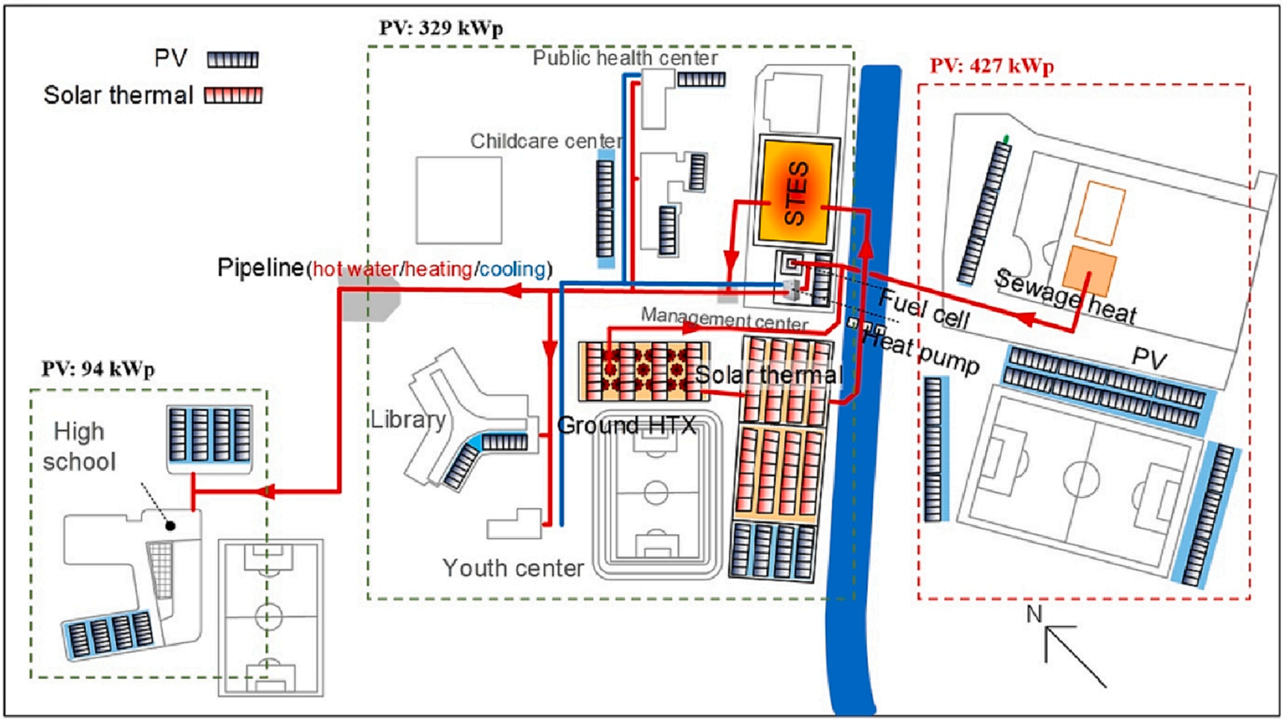

Fig. 7. Layout of the hybrid renewable energy system in Jincheon, South Korea. . Reproduced from [82]

The viability of utilizing household HPs to provide power in the market for frequency restoration reserve was analysed by evaluating the electrical load offered by a plus-energy neighbourhood [104]. Another study in Sweden was analysed to investigate the impact of reliance on distributed HPs on power grid overloads. The study compared the performance of the HP solution with the existing DH system [122]. A neighbourhood in Aalborg, Denmark, was studied in detail to determine the building-level energy efficiency requirements to achieve a clean DH system. The calculations indicate that a shift to individual HPs can reduce annual emissions by up to 20 %, with an additional cost of 40 % [23].

3.2.2. *Energy storage technologies*

Energy storage systems play a crucial role in MBES by enabling the efficient and effective management of RES. As the demand for clean energy continues to grow, energy storage technologies provide a means to store excess energy generated from solar, wind, or other renewable sources during peak production periods, while enhancing the resilience and flexibility in energy logistics. As such, energy storage systems are critical components and are expected to play an increasingly important role in future energy systems. A total of nine examples were found, emphasizing the energy storage solutions in MBES. Out of these, four were related to borehole thermal storage and the rest were focused on electrical energy storage systems.

3.2.2.1. Thermal energy storage. The spatial restrictions in urban neighbourhoods can affect the design of ground thermal energy storages. Borehole heat exchanger (BHE) length influences heat extraction capabilities. To satisfy thermal energy requirements, several BHEs can be installed, however maintaining proper separation distances is essential to minimize interaction, which restricts the number of BHEs. Moreover, space limitations and drilling constraints related to aquifers and infrastructure protection are challenges in densely populated urban areas [26]. The cooling effect and the feasibility of shallow BTES concerning thermal comfort and long-term geothermal energy storage potential for urban neighbourhoods have been investigated [26,105]. Neighbourhoods in Calgary, Canada and Vartiosaari, Finland used thermal solar collector systems combined with BTES. Simulation of the performance of the thermal solar collector and energy storage systems in the neighbourhood aligned with similar existing neighbourhoods [27,92]. Such a design was shown to be able to cover 70 % of the total energy usage of the neighbourhood [92]. However, low self-sufficiency for heating demand was found when optimizing the use of thermal storage and the size of STCs [27].

3.2.2.2. Electric energy storage. A multi-objective optimization approach was implemented to assess the potential of long-term hydrogen storage and short-term batteries and thermal storage systems in the context of Switzerland. Optimal configuration and sizing were investigated for several energy carriers such as central PV, hydro, and wind power generation as well as conversion technologies including HPs, fuel cells, electrolysers, and gas turbines and boilers. Findings indicated that rural neighbourhoods due to higher renewable energy potential could benefit from long-term storage systems, while urban neighbourhoods with low surpluses could consider short-term battery and thermal storage systems. The study concluded that increased renewable technology use and building retrofit rates are necessary to meet future energy targets [109].

The use of pumped hydro storage in some studies showed improvement potential for energy supply and grid integration performance while reducing electricity bills and CO_2 emissions [114,116]. A case study investigated three renewable energy system cases in Hong Kong including rooftop solar PV, offshore wind turbine, hybrid pumped hydro, and hydrogen vehicle storage. The study found that pumped hydro storage with a high utilization efficiency of 80.54 % improves supply and grid integration performance while also slightly increasing carbon emissions [114]. A similar case study was carried out on the island community of El Hierro in the Canary Islands. In this MBES, wind turbines, solar thermal collectors, PV, and electric storage, with a centralized wind-coupled pump hydro storage connected to the main grid were utilized. The study, conducted using TRNSYS software, aimed at optimizing system design. Results demonstrated that the centralized pumped hydro storage could cover 85 % of energy demand while incorporating PV fields increased renewable energy penetration to 70 %. To further improve energy independence, the study recommends exploring additional technologies [116].

A newly developed district containing residential houses and offices in Switzerland was used as a case study. The focus was on the optimization of the size of energy supply mechanisms such as CHP, PV, natural gas, boilers, the energy distribution network layout, and operation strategies based on thermal energy storage (hot water tank) and electrical energy storage (battery bank). Simulations based on a MILP optimization model showed that a conventional district with only boilers connected has the highest cost and CO_2 emissions annually [110].

3.2.3. *Combined heat and power*

Systems based on CHP and micro-CHP have emerged as promising technologies for MBES due to their ability to generate both electricity and heat. Such systems can provide a more reliable and resilient source of energy by reducing dependence on centralized power plants and the grid. As MBES continue to gain popularity, the role of CHP and micro-CHP systems will likely become increasingly important in meeting local energy demands [28,83,91]. 6 case studies centred on the CHP system for the MBES were identified.

The performance of an eco-neighbourhood in North-West France with an integrated micro-CHP system was studied by mathematical model and showed potential for reduction of primary energy consumption.[28]. However, in the case study of Project ECO-life in Belgium, the neighbourhood was not carbon neutral. This was due to the performance disparity between the DH distribution network and mini-CHP plants, as well as reliance on natural gas coverage by 43 % during the studied period. The proposed ECO-life community MBES consisted of a biomass-driven DH network, mini-CHP plants, as well as grid-connected BIPVs. Further, the authors investigated a scenario with the operation of biomass-based mini-CHP systems at full capacity of 83 % efficiency. Results showed a near-zero emission performance with the additional share of renewable energy generation by mini-CHP being 8 % [101]. CHP performance is influenced by building type and neighbourhood composition. The influence of residential and commercial buildings on the performance of waste-to-energy (WtE) CHP in neighbourhoods has been researched. Two CHP plants, single and double-stage incinerator-based CHP, were studied and choosing single or double-stage CHP depended on commercial building type, commercial land fraction and commercial land to total land ratio [91].

An article examined the performance of various energy schemes in agricultural and zootechnical communities in Turin, Italy, for sustainable development. The scenarios involved the use of innovative technologies such as anaerobic digestion, CHP, and biogas upgrading, in connection with DHC networks [94]. Novel examples of sustainable MBES based on alternative energy sources were algae-powered neighbourhoods investigated in [99,123]. A case study focused on the design of an algae-powered CHP energy system for four different neighbourhood types in Atalanta, USA. The discussed system for urban waste conversion into energy had three main parts: pre-cultivation processing to turn waste into nutrients, algae cultivation, and post-cultivation processing to convert algae into energy [99].

3.2.4. *Solar-driven MBES*

Solar energy, a renewable and abundant source of power, can be harnessed in two primary ways. The first method involves the use of PV cells, which convert sunlight directly into electricity through the PV effect. The second method is through absorbing solar radiation as thermal energy, which can be achieved through solar thermal collectors. These collectors, such as flat-plate collectors capture and convert sunlight into heat, which can then be used for various thermal applications, including heating water or powering a steam turbine to generate electricity [92,94]. These technologies are the most technically mature with well-established designs and could fit in a wide range of energy schemes. In this study, it was found that a great portion of articles (18 out of 68) were dedicated to the investigation of solar energy systems in the building sector, especially by employing BIPV panels. These could be rooftops, wall and façade installations as well as window upgrades [89,93,111,124,125]. Thermal energy can be generated by PV-enabled HVAC and HP systems or through direct thermal energy generation via STCs. Both systems are often accompanied by energy storage systems to accumulate solar energy harvested during the day to be used later in peak hours [62].

The increasing integration of solar-driven energy sources has intensified the need for energy flexibility. Hence, buildings need to adapt dynamically, ensuring both network demands and comfort standards are met. Multiple strategies integrated with such energy systems may provide the required energy flexibility, from harnessing building thermal mass for energy storage to implementing active storage systems and multi-network connections [1,3]. Despite the absence of a standardized "energy flexible district" definition, the consensus is clear: manage energy generation, storage, and consumption to maximize renewable use and minimize carbon emissions [93]. Building envelopes and structural elements play a pivotal role, acting as "passive" thermal storage. Research indicates that a building's insulation level dictates its energy flexibility [38,93,109,111].

Design and optimal performance of solar-based energy systems can be challenging due to local weather and irradiance limits, as well as neighbourhood typology. A case study in Toronto, Canada analysed 50 vintage single-detached homes to investigate community-scale energy retrofits. A saturation of available roof area with PV achieved a net-zero balance [88].

Sub-hourly data from a neighbourhood in Utrecht, Netherlands with 40 full electric net-zero energy buildings equipped with air source HPs and rooftop solar PV panels were collected and analysed, see Fig. 8 [60]. Although renovations could achieve NZEN status, there would remain challenges with occupant behaviour and temporal mismatch between energy demand and generation. High electricity injections in the summer, coupled with a negative correlation between energy demand and generation left the grid vulnerable to over-voltage issues. Winter posed challenges with under-voltage issues due to 100 % electric heating and hot water production. Additionally, the low self-consumption rate of 15–25 % indicated high grid reliance, though demand response programs utilizing local energy flexibility could potentially increase this rate. A multi-building-level approach could reduce the need for over-dimensioning local generation, while reversible mode HPs were necessary to stabilise the grid and improve thermal comfort during the summer [60].

Rooftop extensions can help reach nearly zero energy levels in MBES. A methodology has been developed for designing a roof extension and installing PV panels and STC implemented in the Chantrea neighbourhood in Pamplona, Spain. The findings showed that the primary energy consumption of the existing buildings was reduced by 74 % [125].

Stand-alone PV technology for a typical residential community in Pakistan was mathematically modelled. An algorithm was proposed for the optimization of sizing and life cycle cost analysis of the off-grid system, considering climatic parameters such as solar radiation and site temperature [126]. The same author conducted another case study of a grid-connected PV-based for a rural community in Pakistan. The life cycle costs of the proposed system, including capital costs, operating and maintenance costs, the replacement cost of components, and energy usage were evaluated. The cost benefits of the PV-powered rural communities and off-grid energy supply were addressed compared to existing grid rates. [127].

The usable PV area and placement of the PV arrays in solar-based MBES configurations were found to an important design parameter in several studies. The energy performance of a mixed-use neighbourhood in Calgary, Canada, equipped with BIPV was studied by simulating energy consumption and generation potential. Some buildings with large roofs (single-family houses, schools) could achieve energy positivity by BIPV, while multi-story buildings generate only a fraction of their energy use [90].

Another study on PV capacity estimation in urban areas of Islamabad, Pakistan was conducted in [117]. The study involved the detection of rooftop areas and the optimization of the placement distance of PV panels for better energy yield while taking into account the shading benefits to the building helping to reduce the cooling load [117]. A multivariate sampling-based approach was used to identify the solar power integration potential of representative building typologies in the residential building historic district in Lisbon, Portugal. The investigation covered building characterization, solar irradiation assessment, available areas and orientation, and the calculation of electricity

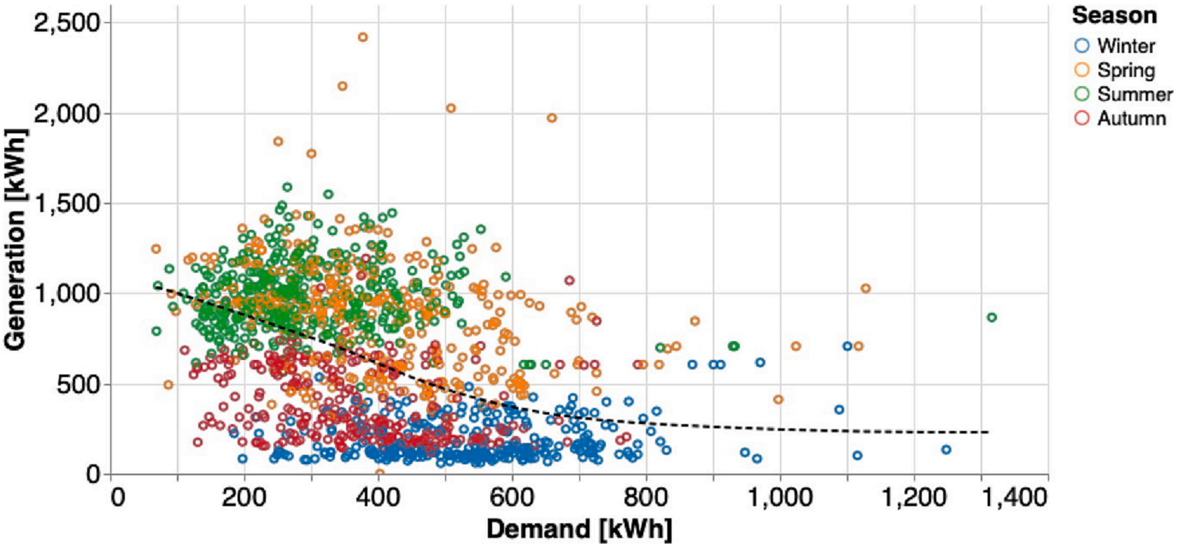

Fig. 8. Monthly energy demand and energy generation of 40 full electric net-zero energy buildings during the year [60].

production and costs for PV technologies. The paper highlighted the potential of implementing PED to mitigate energy poverty in the district, with retrofitting measures reducing energy needs for heating and cooling by 84 % and 19 %, respectively [111]. A case study in Naples, Italy performed a multi-stage optimization approach for deploying and maximizing the energy potential of the community [62]. Solar energy was considered as the main energy source coupled with batteries, while different heating/cooling systems and retrofit measures were compared. The optimization algorithm used was a brute-force search followed by multi-objective optimization with the sustainability of the proposed solutions as the objective function [62].

Optimal energy saving for buildings in a neighbourhood with BIPV and STC as main RES technologies was researched in Eskisehir, Turkey, in a neighbourhood of 42 buildings where 34 buildings were residential, 7 were officers, and one was a light industrial building. Global costs and market barriers caused by high investment costs and long payback periods were considered according to the methodology described in EN 15459:2007, and the neighbourhood was modelled by zero energy level description from the European Union and national energy efficiency policies [128]. According to the results, single-building energy efficiency measures could yield a 35 %-40 % improvement at the cost-optimal solution and 50 %-70 % at the near-zero energy level. A further 10 % enhancement was obtained through a district-level energy systems approach, with solar thermal and PV panels playing a vital role in reaching the EU targets for energy efficiency and carbon emissions. This was due to the space constraints and significant investment burden that would be imposed on single buildings [128].

Microclimate mitigation affects building thermal-energy performance in near-zero residential settlements [52]. A design-stage method for multiscale microclimate improvement correlated to thermal-energy analysis in a residential neighbourhood of four houses in central Italy has been developed. A microclimate simulation was performed for three scenarios to access a realistic weather profile for a dynamic thermal-energy simulation. The three scenarios were (1) increasing vegetation percentage, (2) increasing solar reflectance on building surfaces and (3) a combination of the two [52].

In designing MBES, understanding the impact of urban heat islands (UHI) is important as it can affect the performance and efficiency of energy technologies [95,129]. For example, solar panels can be less efficient in UHI areas due to the higher temperatures, which can cause the panels to overheat and lose efficiency [52]. Similarly, district cooling systems may need to be designed differently to accommodate higher cooling loads in UHI areas. Moreover, incorporating strategies to mitigate UHI in MBES can improve their performance and efficiency. Examples of such strategies include increasing green space and vegetation, designing buildings and streets to promote natural ventilation, and using cool materials and green roofs. These strategies can help to reduce the urban heat island effect, thereby reducing energy demand for cooling and improving the overall sustainability of MBES. Research on the optimization of BIPV installations in a district of Rome, Italy presented. The study adopted a methodology that could take into account the urban environment and UHI effects on energy demand and supply predictions. For mitigation of UHI penalties, a refurbishment scenario including upgrading the glazing ratios and reflectivity of the surfaces such as asphalt and shadings was considered [95].

A novel community-scale solar energy system in La Palma used floating PV installations on water storage. A tailor-made mathematical open-source model was generated in Python. The model featured both static and dynamic primary energy balance constraints for two rural and urban districts [130]. While the static approach utilized a consistent primary energy factor (PEF) based on the local grid mix, the dynamic method adjusted the PEF hourly, reflecting the grid's changing energy composition. By doing so, it could account for imported electricity by multiplying it with the specific PEF, ensuring a more accurate representation of energy generation. This dynamic primary energy balancing mechanism offers significant potential for optimizing PEDs or other communal energy systems, particularly when integrated with energy storage for enhanced flexibility. Such a model is especially relevant for closed island systems like the Canary Islands, where electricity tariffs don't align with local generation realities. In rural and urban cases, the net present value was raised by up to 31 % and 27 %, respectively, contingent on the space allocated for PV systems. Nevertheless, when grid impact was reduced, the economic merits dropped due to the high expense associated with battery installations [130].

A modelling framework was proposed to design net-zero energy districts in Denver, USA. The framework combined building and power system modelling to select efficient measures and generation technologies. The study considered PV on building roofs, car canopies, and ground-mounted PVs, as well as an electrical energy storage system. A district control scheme was proposed to achieve net-zero emissions while mitigating grid impact [97]. Similarly, in Florida, USA, a case study was conducted on a small community on Anna Maria Island. The community achieved net-zero energy by installing PV panels on building roofs, two solar carports, and a nearby warehouse building. Additionally, energy efficiency measures were employed, including extra insulation and waste heat recovery from water-source HPs [38].

A case study in Milan, Italy analysed an existing district for transforming into PED through a mix of retrofitting and installation of HPs and PV panels. The building energy performance was analysed using an EnergyPlus model based on laser scanning surveys and on-site inspections, with occupancy and occupant-related load profiles created using data-driven procedures. The analysis highlighted the pivotal role of energy flexibility in optimizing renewable energy utilization, balancing the supply–demand dynamics, and managing intermittent energy sources. The potential of buildings to act as "energy banks," adapting their energy consumption and storage based on grid needs, was also emphasized. The study found that reducing energy needs through efficiency measures can drastically reduce the area required for PV installation, while also providing greater flexibility [93].

A study investigated a smart city in South Korea, aiming to assess the effectiveness of solar generation through PV, PV thermal (PV/T), and STC systems. The lower power generation rate of PV/T than the PV system was due to low temperatures in winter. However, the STC system could reduce operating energy compared to the PV and PVT systems. The study suggested that GSHP could be used as an energy storage system, and the grid interaction rates and self-sufficiency could be improved by increasing the capacity and size of the TES by controlling the number of HPs [33].

A neighbourhood in the Canary Islands with "several" households and a public school equipped with a smart energy grid, PV systems, Li-ion battery storage and a pool for energy balancing was studied for operation optimization of distributed energy resources. A non-linear mathematical programming model that considers battery degeneration and operation of domestic hot water was solved using Gurobi optimizer software. An energy pool for balancing energy supply and demand was important for the operation of the smart grid. The neighbourhood, located in the Canary Islands, has great solar potential which allows for zero energy neighbourhood and energy-positive neighbourhood levels [34].

3.2.5. *Hybrid energy systems*

Three studies took advantage of multiple energy sources to increase the availability and storage capacity of MBES. A hybrid MBES could be identified as a system driven by several factors whose size and functionality were decided based on multiple technologies and possibly with more than one RES [29,131].

An example of such MBES was found in a mixed community in Beijing, China with residential and public buildings. A distributed energy system that combined hybrid energy storage including a hot water tank, battery and a supercapacitor was proposed, as shown in Fig. 9. The system was optimized with two operation strategies for energy storage, which could yield 55 % primary energy saving and 63.5 % emission

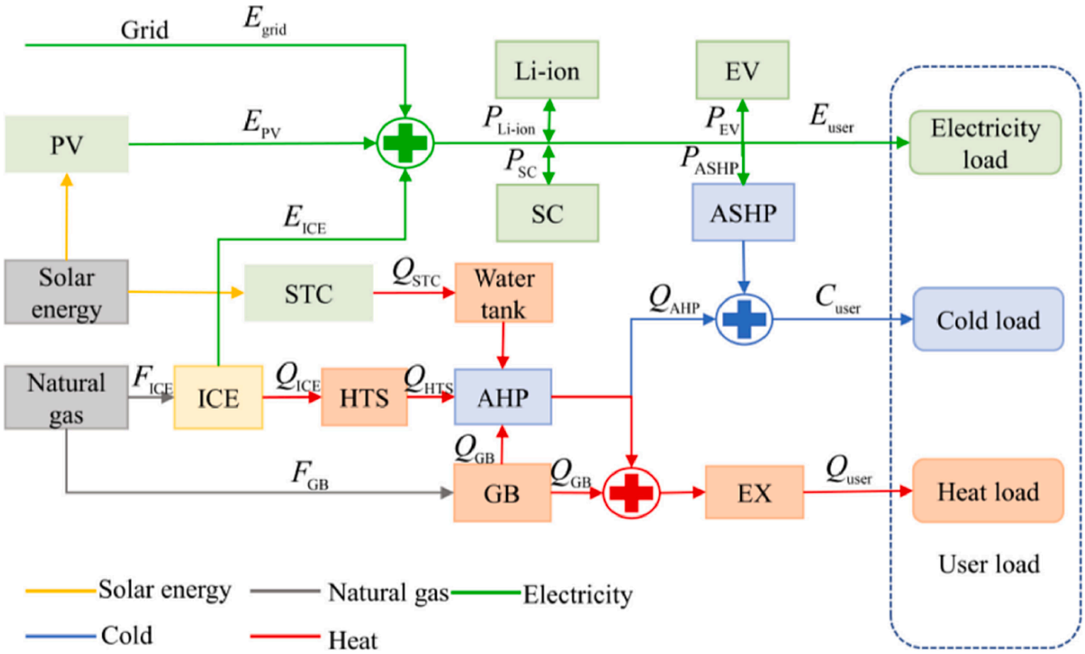

Fig. 9. Layout of the MBES proposed in [132].

reduction [132].

An energy grid with a CHP system integrated with Ground Water Heat Pump (GWHP) and BIPV systems, was designed for use in the neighbourhood in a building cluster in Milan, Italy. The CHP system was powered by biomass boilers to supply heat and hot water to buildings during the winter season [83]. A study conducted in Beijing, China focused on multi-objective optimization algorithms to determine the best combination of energy sources and technologies while considering energy efficiency and economic factors for a hybrid energy storage system with a distributed energy system for office, school, and residential buildings. The central MBES configuration shown in Fig. 10 was structured and consisted of PV panels, an internal combustion engine (ICE), a power-to-gas (P2G in Fig. 10) plant, and Li-ion batteries. The P2G technology was used to convert excess electricity into hydrogen through water electrolysis and then generate methane and water by reacting hydrogen and CO_2 under catalyst action [115]. The electricity was supplied to the users by PV and ICE, while the excess heat from ICE was stored in high-temperature thermal storage (HTS Fig. 10). Thermal energy was covered via air-sourced and absorption HPs sourced by gas boilers and high-temperature storage.

3.3. Modelling approaches and analytical tools

An overview of the utilized tools to design and analyse the performance of MBES is shown in Fig. 11. The diagram illustrates the frequency of usage for each tool across the research projects. Various other specialized tools such as ResStock, BEopt, URBANopt, MAPED, ASCOT, GenOpt, Carbon Trust Biomass Decision Support Tool, ESP-r,

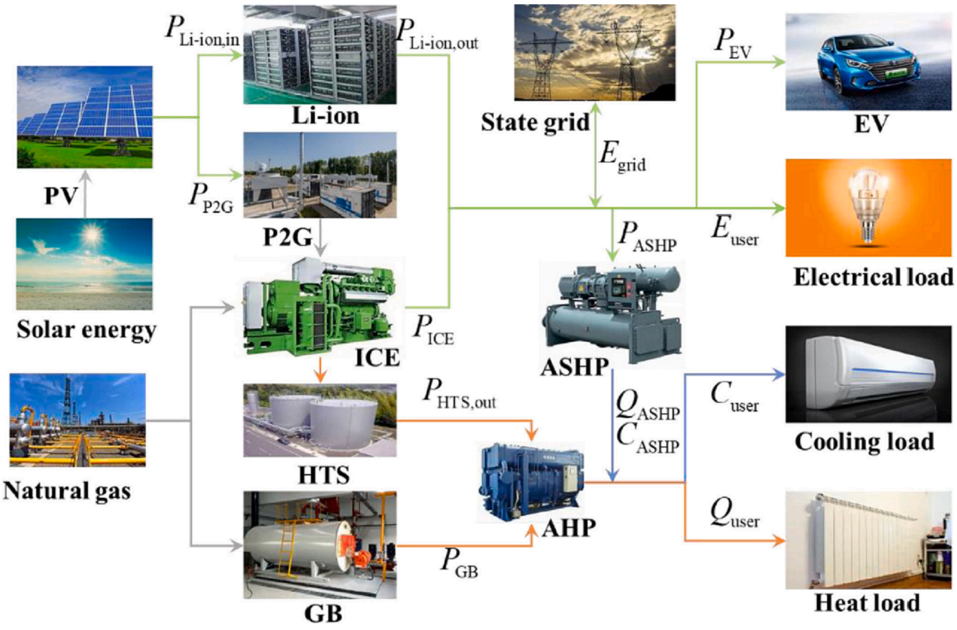

Fig. 10. The proposed hybrid MBES in [115].

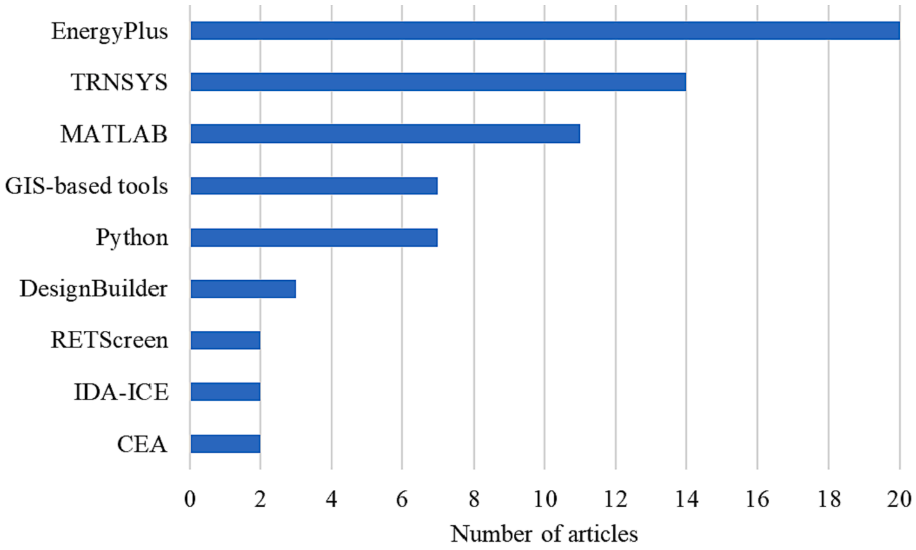

Fig. 11. Distribution of software tools and methods used in MBES studies, showing tools with a frequency of usage of at least two times.

Pandapower, System Advisory Model (SAM), OpenGeoSys, CESAR, EnFloMatch, were employed in individual studies.

The case studies investigated in this study frequently used TRNSYS [133] or EnergyPlus [33,37,124] as the main simulation software for buildings including passive and active systems. The general principle of these simulation software for capturing the interaction of the energy flows is usually based on the nodal analysis of the network-wide energy and flow rate balances [82]. Active systems such as PV panels, battery storages, and BTES may be sized statically using technical datasheets and incorporation of efficiency factors into the dynamic performance models [82,86,95]. The generated models were then extended to the neighbourhood scale by replicating and combining each unique architectural design [100,109]. Such modelling approaches often treat the individual energy demand of the buildings via the implementation of statistical analysis of measured data or empirical relations, compensating the weather uncertainties. Building 3D models were developed in DesignBuilder software in several cases, and multi-tool chain methodologies connecting several simulation tools and optimization algorithms were proposed [37]. The integration of system designs and performance optimization strategies is often required, as the iterative nature of these model structures allows for fine-tuning the sizing parameters and investigation of various operation and control scenarios [19]. Among the optimization tools, Mixed Integer Linear Programming (MILP) and genetic algorithm procedures were highly used and coded in MATLAB or Python [24 130,133,134]. Few cases presented tailor-made calculation tools which indicate the shortage of standard methods for the design and performance analysis of MBES [122,130].

There are two approaches to urban energy simulation tools: building energy simulation (bottom-up) and building stock generalization by statistical data (top-down) [135]. The use of a bottom-up approach in urban planning requires the existence of a community with specific needs and expectations, who are willing to participate in the planning process. However, in cases where there is no “bottom level”, such as in the planning of a new settlement or a large city expansion, a top-down approach may be the only option available to planners. The field of energy simulation is advancing, and different techniques are being developed to evaluate energy efficiency and greenhouse gas emission reduction measurements [135].

Surveying the location and exploring the availability of resources as well as spatial modelling of the neighbourhood including interactions among supply demand sides were often established by Geographical Information Systems (GIS) [50,123,133,136]. Willmann et al. compared the results of energy demand simulation using TRNSYS (bottom-up approach) and the City Energy Analyst (CEA) toolbox (top-down approach) for five non-residential case study buildings in Weimar, Germany. Results were validated with measured energy consumption data. It was found that the top-down energy simulation platform could accurately replicate the actual energy consumption data of a city quarter, surpassing the bottom-up simulation software which required a large amount of input data. Nonetheless, when using the provided coarse data set, none of the simulation software could robustly match the consumption data for individual building simulations. [135].

A modelling method for algae-based power systems in an MBES was developed through the integration of a graphical interface system (GIS) and BIM for multi-scale problems, from algae cultivation to the fabrication of construction components, from buildings to neighbourhood systems. The GIS-based algae model considered parameters such as population, waste stream flows and solar access in a neighbourhood to determine per capita energy use intensity and the ratio of energy production from algae systems. The BIM system for algae-powered buildings accounted for solar capture potential for building facades, orientation and spacing of photobioreactors [123].

A new framework for designing energy systems for zero-carbon districts in Montreal, Canada was developed. The framework integrated an urban building energy model with an urban energy system model to predict heating and cooling demand and automatically size different energy system configurations. The study compared two renewable energy systems comprising PV panels and GSHP. The case study demonstrated that the integrated framework can successfully predict heating and cooling demands in multiple spatiotemporal resolutions. [87].

A new GIS platform has been developed in Spain to assess energy savings from refurbishment measures in scattered residential buildings located in an orographically complex area. Solar thermal collectors and geothermal technologies were considered using dynamic simulation tools such as TRNSYS, GenOpt, and MATLAB. The study utilized updated solar irradiation and geological maps and official databases to evaluate representative buildings for annual energy demand and savings. [133].

A case study conducted in an urban district in Shanghai, China proposed an extended design method for district-scale urban design that integrates renewable energy production, energy consumption, and stormwater management systems, while also considering human experiences in cities. The method used GIS, parametric modelling techniques, and multidisciplinary design optimization tools to enable collaborative design decision-making. [136].

A top-down control method was used to optimize the performance of a cluster of four different types of nZEBs (hotel, office, shopping centre, and restaurant) in Hong Kong. The study aimed to improve load matching, reduce grid interaction, and lower energy bills for a system that includes PV panels, wind turbines, and batteries for electricity storage. The top-down control method used a genetic algorithm to optimize the energy system operation of the nZEB cluster for the next 24 h and coordinated the operation of each nZEB on an hourly level using non-linear programming. [113].

EnergyPlus, Radiance, and ENVI-met simulation software linked through Grasshopper were utilized to MBES in neighbourhoods in Tel Aviv, Israel. The study examined two building typologies, focusing on on-site BIPV generation implemented on both rooftops and facades for high-rise and courtyard structures in various scenarios. Using Grasshopper, a visual programming tool integrated into Rhinoceros 3D CAD software, the researchers were able to investigate the intricate connections between morphology, density, energy balance, and environmental quality. This analysis was performed by considering energy load match, spatial daylight autonomy, and the universal thermal climate index as performance indicators. Summer outdoor comfort and energy load match were optimized with linear typology, daylight availability was optimized with high-rise typology, and energy and environmental quality were optimized with courtyard typology. The limitations of the workflow were uneven and long computational time, separate simulations for energy, daylight and outdoor climate and up-scaling to larger areas would be time-consuming and hardware-demanding [124].

In Vienna, Austria, a case study was conducted to examine the conversion potential of four urban typologies towards PED. A home-built bottom-up modelling tool MAPED (Model for Energy Analysis of Positive Energy District) was developed by the Austrian Institute of Technology (AIT). The overall workflow of the MAPED tool is presented in Fig. 12. The tool was employed to evaluate the energy demand supply of urban districts and to test different scenarios and implementation measures [42]. The MAPED approach assessed final and useful energy demands by considering demographic, social, and technological data of the district and factors influencing energy demand, such as population growth, household size, appliance usage, and new technology adoption. Future trends for these factors were introduced as scenarios, enabling the evaluation of measures required to transform the district into a PED [42].

A case study has been analysed to demonstrate the results of a design decision-making methodology applied to a mixed neighbourhood in the Netherlands equipped with BIPV and a central GSHP. A probabilistic sensitivity analysis was conducted through Monte Carlo simulations to evaluate the options. [107].

A procedure for analysing energy efficiency is proposed for the energy-efficient refurbishment of buildings on a neighbourhood scale. The procedure combines energy simulation, 3D modelling, and visualization, with the primary goals of facilitating information dissemination, enhancing dynamic calculation capabilities, and providing decision-making support. The procedure was tested in a neighbourhood in Suonenjoki, Finland where operational cost, energy usage and CO_2 emissions of six refurbishment scenarios were analysed. Simulation data were compared to actual measured data. The procedure gives simulated vs measured heat consumption and DH power. The six scenarios were baseline (existing building and systems), GSHP, exhaust air HP, solar DH, grid-connected PV, solar heat collectors and envelope renovation. A comparison of the proposed procedure vs other known procedures for energy-efficient refurbishment of buildings on a district scale was presented [137].

To provide information about energy efficiency impact on a large scale while minimizing the efforts in modelling single buildings, a co-simulation environment has been proposed. Challenges related to modelling thermal behaviour, calculating energy demand, shading and room temperature settings in a neighbourhood were addressed. Scaling thermal building simulation from a single building to MBES is feasible if model creation is automated. The method can automate model creation to thermal zone control, which gives a realistic heat load profile. Real-time control is limited by the number of buildings, and the complexity of the simulation, and its applicability is valid for single optimization runs only. [106].

3.4. Typology

The urban form and typology of buildings play a crucial role in the realistic assessment of MBES. This section explores various studies that have investigated the impact of building typology on the optimal design and operation of MBES. Urban form and typology effect on energy performance and carbon emissions of MBES were studied, in the City of Macau, China. Results show that simulation is up to 20 % more accurate when including typology and form factor. [50].

Optimization of urban form, energy balance and environmental quality has been researched in Mediterranean districts. Performance effects for building (typology, wall-to-window ratio and glazing properties) and urban design parameters (distance between buildings, floor

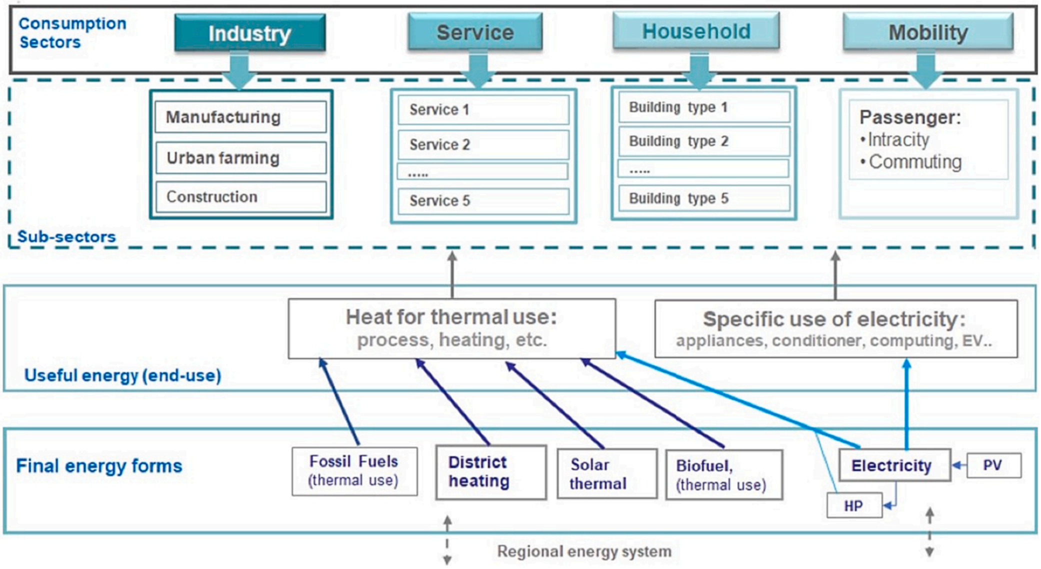

Fig. 12. Workflow of MAPED tool as described by AIT [42].

area ratio and orientation) were evaluated for residential and commercial buildings in Tel Aviv, Israel. A courtyard typology outperformed the other typologies in energy load matching and spatial daylight autonomy, especially for lower-density districts [81]. Research on building energy consumption and solar energy trade-offs in a PV-based residential neighbourhood was investigated in China. The effects of increased solar panel installation were analysed using the Monte Carlo procedure and actual energy use was obtained through survey and electricity bills of the analysed neighbourhood. High-density configurations had the biggest potential for solar retrofitting [112].

Mixed-use neighbourhood layout patterns have an impact on solar access and resilience. This was studied by authors in [30] for a district consisting of around 1300 residential units and 200 commercial units on a total land area of 161 874 m^2 located in Calgary, Canada. A rectangular, circular, and hexagonal layout was analysed. The construction design of all neighbourhoods was identical. Results revealed that when the optimal orientation of buildings (main façade facing south ± 30°) was maintained, the solar access was affected by less than 3 % by changing neighbourhood layout [30].

The case study of PEDs in Austria showed that only the detached housing neighbourhoods have the potential to become PEDs due to the sufficient available surfaces for the production of local renewable energy. The study revealed that PEDs require a very high level of energy efficiency and sufficient open spaces for local renewable energy generation [42].

A case study was conducted in Montreal, Canada and evaluated a “double density” scenario where each existing detached house in a community is replaced with two equal-sized new houses on the same land lot, equipped with various energy efficiency measures and a BIPV roof. [86]. The study concluded that the two new houses utilized 30 % less energy than the existing house, each requiring 65 % less electricity, and producing nearly three times more electricity than they consumed. The combination of energy efficiency and on-site renewable energy production could facilitate a transition from energy consumption to production, enabling retrofitting of existing communities into resilient PEDs [52].

The impact of design parameters of a solar neighbourhood in terms of energy efficiency and carbon footprint has been analysed on neighbourhoods in Calgary, Canada. Parameters include energy performance, the density of buildings, mixed-use vs. residential neighbourhood, and the location of the commercial centre. Energy performance is measured as energy demand for all building operations minus potential energy production through rooftop PVs. Simulations showed that energy consumption and greenhouse gas emissions could be reduced by up to 75 % depending on the density and usage patterns within the neighbourhood [89].

3.5. Feasibility studies

Energy planning for MBES requires considering various objectives in the decision-making process, including emission reduction, investment costs, indoor comfort, and operation reliability. The applicability of multi-criteria decision analysis in the context of net-zero energy districts was explored in [96]. for evaluating alternative requalification strategies for a net-zero energy district has been studied using the PROMETHEE method. The method is used for comparing four strategies for constructing a net-zero energy district and selecting the optimal solution for economic and environmental purposes. A neighbourhood in Turin, Italy with 635 dwellings and 1950 inhabitants has been used as a case study to investigate four strategies developed by combining two criteria: 1) standard and advanced building envelope retrofit measures, representing the currently used building materials in the local market and the most technologically advanced options. 2) Energy efficiency measures for the DH and CHP-driven MBES with two energy carriers, natural gas (the existing option) and biomass (the advanced option). PV panels were utilized as roof-mounted modules in all retrofit choices. The use of multicriteria decision analysis in the context of net-zero energy districts. The results indicated that for the studied location despite higher investment costs, the strategy using biomass-fuelled MBES and advanced building retrofit could remarkably reduce the environmental footprints aligned with EU targets.[96].

Spatial optimization on a neighbourhood scale with consideration to renewables and water harvesting integration was studied in Gothenburg, Sweden. The optimal configuration of the built environment area, PV area, wind turbine number and occupation area, and battery and water harvester storage capacity for electricity and water prices in a neighbourhood was analysed. The model was multi-objective and used generic algorithms to minimize life cycle costs while maximizing renewable and water harvesting reliability[138].

The energy hub approaches describe the relation between energy input and output to include decentralized and local energy technologies in MBES, and input from a building to evaluate energy demand. The approach can evaluate and size urban energy systems according to their energy-autonomy, economic and ecological approach [139]. The energy of an island city in Denmark is supplied by 6 wind turbines, PV installations in residential areas, and 3 DH networks covering 65 % of the heat demand of the community. The energy system including all the energy grids was modelled according to the latest Danish building regulations to become the first Danish self-sufficient and carbon–neutral island by 2030. Several enhancement solutions were compared including individual HPs, biomass DH, PV, and PV/T. The models were developed via a deterministic approach using CEA software. [102]. In another study, a framework using CEA software was developed to analyse an industrial neighbourhood in Zug, Switzerland. The framework was used to calculate solar energy potential, optimise energy and heating systems, a multi-criteria analysis and a life cycle analysis and benchmarking [108].

A highly dense urban district in Helsinki, Finland was studied to find the optimal techno-economic solutions for achieving self-sufficiency. The analysed MBESs involved PV systems, wind power, GSHP, battery, and thermal energy storage. A rule-based control method for maximizing energy coverage was implemented and validated by the EnergyPLAN energy systems model. Further, a linear programming optimization in MATLAB was used to minimize the life cycle costs based on the renewable energy capacities and operation. The results indicate that it was more feasible to aim for a PED or NZED than full energy self-sufficiency for individual buildings, as the latter is extremely expensive. Based on the results, investment in wind power is the most profitable, and battery storage becomes less valuable when self-sufficiency is reduced. Due to high population density and limited renewables, the physical boundary of a district may not fit the required renewable energy installations if high self-sufficiency is targeted [134].

A case study was conducted on a positive energy neighbourhood in Greece to identify the optimal combination of technologies, via a parametric analysis using suitable technical and financial criteria. Several combinations of geothermal HPs, PV panels, retrofit measures, DHC and batteries were analysed. The research found that higher levels of insulation and geothermal HPs were the best way to achieve self-supply targets from both energetic and economic perspectives. Insulation measures reduced the size of the HP, however with higher investment costs. The study indicated the need for a combination of energy efficiency and renewable energy supply strategies [118].

The development of a zero-energy community in cold regions can be expensive due to higher building energy demand and less solar incidence availability. However, geothermal energy can support a zero-energy community through integrated techno-economic packages. Several tools were combined to design and simulate a geothermal-based zero-energy community in Idaho, USA. The electricity and thermal energy supply was analysed, considering several components and combinations. For instance, in the case of a full-electric load, the integration of a geothermal well-field and an electrical power generation plant was deemed necessary. However, for the direct utilization of thermal energy, supplementary components such as a geothermal-heated hot water production facility, thermal energy storage system, and district heat network were considered for optimal performance. The study found that geothermal electricity generation can compete with residential rooftop PV for communities of around 1200 homes or more and can achieve cost parity with community-scale PV if excellent geothermal resources are available [100].

A case study was conducted in Cairo, Egypt to evaluate the feasibility of a sustainable Zero Energy Community consisting of 52 buildings, residential buildings, hospitals, universities, schools, hotels, office buildings and a mall. The system employed wind turbines and PV panels. The authors used DesignBuilder for modelling the community buildings and EnergyPlus software for energy simulations. Results showed a 57.6 % reduction in average annual energy consumption. Building payback periods range from 1 to 10 years, demonstrating the feasibility of ZEC concepts in hot climates [37].

In Denver, an analysis was conducted on a campus undergoing significant redevelopment to measure and optimize both the economic cost and grid independence measures towards a net-zero energy district. Solar PV, ground source and water source HPs, and biomass CHP were used as on-site RES. Multiple energy scenarios were analysed to achieve net-zero energy with and without on-site energy storage. Results show that combinations of PV and CHP can be cost-advantageous in terms of the levelized cost of energy. The HP option offered a sustainability advantage in lowering the total energy load by 10 % [98].

Coastal communities such as the one studied in Hong Kong investigated the possible solutions for achieving zero energy at the community level through the integration of a novel hybrid offshore wind, tidal energy generation system, and solar thermal energy district cooling and heating system. The study assessed the design and operation sustainability of several configurations using load matching, carbon emissions, payback time, and net present value for two scenarios: one without a battery and the other with a battery. The optimal combination of renewable energy cases with offshore wind turbines and tidal streams has the best annual load matching, with community-scale electricity storage increasing technical performance. However, the comparison between scenarios indicates that the community-scale battery reduces operation-cycle profits but reduces equivalent CO_2 emissions [25].

4. Discussion

Through the analysis of various studies, promising energy technologies have been identified for MBES. The exploration and assessment of MBES have been instrumental in unveiling the vast potential of integrated approaches to energy management at large scales within the built sector. A noticeable feature that emerges from the reviewed literature is the diversity in research methodologies. Predominantly, the studies have leveraged simulation-based models to decode the multifaceted dynamics inherent in MBES. Notably, a plethora of tools, such as TRNSYS, DesignBuilder®, EnergyPlus, and Polysun, have been at the forefront of these endeavours, highlighting the importance of robust and precise modelling in comprehending the complexity of the MBES landscape [37,83,95,121].

4.1. Challenges and promises of large-scale MBES

The complexity of the integration of RES into MBES presents both notable advantages and substantial challenges. The presence of solar, wind, biomass, and other renewable technologies improves the design and operational efficiency of MBES. However, Understanding the interplay between these renewable sources is essential for realizing the full potential of MBES.

Among the advantages are the economies of scale that can be achieved, leading to potentially lower costs per unit of energy produced or saved, and a broader impact on environmental sustainability. Overall, the studies suggest that neighbourhood-scale HPs and DH solutions have the potential for significant energy savings and emission reduction. Management of HPs at cluster level with rule-based demand response participation strategies, as showcased by a Southern German neighbourhood with 25 buildings, demonstrated financial viability provided energy market prices change accordingly [104]. This underlines the necessity for adaptive strategies in the real-world implementation of MBES [122].

Large-scale RES integrations also offer enhanced opportunities for innovative energy storage solutions and smart grid applications that can significantly improve the resilience and reliability of the energy supply [27,116]. Challenges such as power grid overloads were noted, with potential solutions offered such as the use of thermal mass as thermal energy storage [122]. Moreover, the use of thermal storage units and triple pipes can help increase the utilization factor and cost-effectiveness [103]. Considering seasonal thermal storage tanks integrated with a central HP system was proven cost and energy-saving [82]. This mirrors the wider industry sentiment that, while technological advancements in the MBES sector hold great promise, they are not without their challenges, especially when scaled up [122]. Efficiency improvement measures for building envelopes, HVAC systems, and renewable energy production can achieve emission reduction over a short period, but investment in energy efficiency measures remains relevant in the long term given the expected rise in energy prices [23,140]. The electrical distribution system can also be optimized by considering biomass-fuelled DH systems and prosumer interactions in MBES design [24].

MBES with energy storage exhibits much lower CO_2 emissions compared to the conventional district and is more cost-effective than a system without storage [110]. BHEs were shown to be significantly influenced by neighbouring boreholes. This interference can interrupt HP operations, pointing to the intricacies of the spatial arrangement in MBES. Thermal regeneration was proposed as a solution to the resulting interruption in HP operation [26,105,121]. Energy efficiency measures and integration of RES, such as PV and thermal solar collectors with BTES, were found to be effective in achieving nearly zero energy balance when connected to BTES. Some studies indicated that a neighbourhood could supply a significant portion of energy demands by using BTES connected with STC [30]. This suggests that the right synthesis of energy sources and storage can lead to neighbourhoods significantly addressing their energy needs. Hence, it’s important to note that the interplay of energy sources and storage in MBES provides a unique advantage over single-building designs. The aggregation of energy demands and supplies across multiple buildings allows for more significant energy balancing and resilience via an increased possibility of peak-shaving and peak-shifting, a feature that is limited in individual building energy systems [113,114,127]. This collective approach can lead to enhanced efficiency and reliability in addressing neighbourhood-wide energy requirements. However, these benefits come with their own set of difficulties. One of the primary challenges is the increased complexity of coordinating a larger number of diverse energy systems and user profiles, which can complicate maintenance and management.

The findings from the energy system relying on CHP showed the potential benefits of neighbourhood-scale CHP systems for reducing primary energy consumption and achieving high self-consumption ratios of on-site produced energy. These results are particularly relevant given the increasing demand for energy efficiency and the need to reduce carbon emissions in the built environment [28 94]. One important consideration was the choice of the CHP system and its components. The choice of single or double-stage CHP depends on the type of building and land fraction. It was found that for buildings with a low commercial land fraction, a single-stage waste-to-energy (WtE) CHP system is preferred, while for those with a higher commercial land fraction, a double-stage system is more suitable. [24,91]. This highlights the importance of considering the specific context of the neighbourhood when designing CHP systems to ensure their effectiveness and efficiency. Moreover, the most profitable scenarios involved the use of anaerobic digesters coupled with co-generation systems and the upgrading of urban solid waste. These findings suggest that neighbourhood-scale CHP systems have the potential to not only improve energy efficiency but also provide economic benefits to the community [94]. However, this specificity in design suggests that neighbourhoods may not employ a one-size-fits-all approach. Instead, they need to analyse their unique requirements and constraints to derive maximum benefits from CHP systems. These findings can help inform the optimal design and implementation of MBES systems at the neighbourhood scale and ultimately contribute to a more sustainable and energy-efficient built environment. Meanwhile, the integration of sophisticated energy management systems in MBES is essential for achieving significant improvements in both energy cost and indoor comfort. Such systems can lead to efficient and intelligent management of energy supply and demand, especially when the use of intermittent RES is centred on optimizing on end-user's preferences and operational costs [36,46,106,113,134].

4.2. Pivotal role of solar energy in MBES design

Solar energy has increasingly become important as a RES for MBES. Studies have shown that integrating solar energy in the form of PVs and deep envelope retrofits can reduce community energy demand by up to 69 % and achieve net-zero balance, respectively [88]. The assessments on the life cycle cost benefits of PV-powered rural communities and off-grid energy supply highlighted the potential for neighbourhood-scale PV systems to not only be environmentally and economically beneficial but also financially sustainable over the long term [127]. However, there are challenges associated with solar energy integration, such as energy demand mismatch and electrical infrastructure impact, making it technically infeasible to provide electricity to the community in the absence of local seasonal energy storage to bridge the gap [88]. Moreover, PV placement distance was optimized using deep learning algorithms to analyze the self-shading effect, energy yield, and cooling load reduction, which resulted in the optimal placing distance between PV panels with reasonable economic viability [117]. Moreover, microclimate mitigation strategies have also been shown to decrease outdoor temperature up to 2 °C, saving up to 70 % energy when integrated on an MBES scale compared to a single-building scale [52]. However, a progressive increase of PV surfaces at the district level can cause a decrease in module productivity of 11 %, if they are installed on 60 % of the district's facade area [95]. In terms of building types, single-family houses and schools with large roofs can achieve energy positivity with BIPVs, while multi-story buildings generate only a fraction of their energy use. Greenhouse gas emissions were found to be significantly lower for single-story houses and school buildings than for multi-story buildings [90]. Battery installations also play a crucial role in solar energy integration. A dynamic primary energy balance constraint that depends on the allocation of correct primary energy factors is crucial, and reducing coincident peak demand is recommended to achieve energy resilience due to the inherent imbalance between energy demand and supply [130]. In addition, increasing the capacity and size of thermal energy storage and controlling the number of HPs can improve grid interaction rates and self-sufficiency [33].

In addition, the optimal reliance on solar energy has been identified as a crucial factor impacting hybrid MBES performance, while reducing the grid energy import during the winter has been identified as a critical factor for reducing overall costs [115]. The combination of PV systems and CHP could reduce energy costs, while superior energy performance was more feasible with reliance on HPs for energy distribution in hybrid MBES [98].

4.3. Importance of aligned urban forms in MBES

Urban form and building shape can have a significant impact on the performance of community energy systems, particularly those based on solar energy. By considering these factors in the design of energy systems, it is possible to optimize energy efficiency, minimize energy losses due to shading, and promote the adoption of renewable energy technologies. This can lead to more sustainable and resilient communities. Meanwhile, simulation accuracy could be increased when typology and form factors are incorporated, as demonstrated in [50]. Maintaining optimal building orientation by positioning the main facade towards the south within a range of ± 30 resulted in a minimum reduction of solar access due to the neighbourhood layout [30]. High-density configurations are most amenable to solar retrofitting [112]. The potential to establish PEDs is confined to detached housing neighbourhoods owing to the availability of adequate surfaces for generating local renewable energy. Studies indicated that PEDs necessitate high energy efficiency and sufficient open spaces for local renewable energy generation [42]. Dynamic simulation of solar thermal collectors and geothermal technologies, revealed significant energy savings potential in single or isolated buildings [133].

4.4. Identification of an optimal MBES design

The feasibility studies covered a variety of MBES technologies and strategies. While the reviewed case studies provide a foundational understanding of energy technologies' performance at the community and district levels, the variability in occupancy patterns was less addressed in the overall energy management systems. The most effective solutions depend on a combination of factors such as investment cost, socio-economic and environmental impacts, local renewable resources, and building characteristics. Several studies have analysed and simulated different energy sources and technologies to determine the optimal combinations of energy supply systems. Results have shown that the proposed systems relying on biomass CHP, offshore wind turbines, and tidal streams have the potential to be promising solutions for achieving self-sufficiency and reducing CO2 emissions [83 25]. Additionally, the use of community-scale electricity storage was found to increase technical performance, although it may reduce operation-cycle profits [25]. Moreover, the larger the scale of RES integration, the more pronounced the impact of local climate and location-specific factors on energy system performance. This necessitates a highly tailored approach to energy system design that accounts for these local variations. For example, the energy yield of PV systems can vary significantly with latitude, while DH systems may face different efficiency challenges based on urban density and building types present. A combination of HPs and PV/T was able to produce heat 20 % more than the demand of an island city with a 6200 population while significantly reducing electricity usage [102]. A strategy including DH and biomass with advanced retrofit was identified as the best solution from energy performance and environmental impact perspectives, however with the highest investment cost [96]. PV systems were considered one of the most feasible options in most cases due to their cost-effectiveness. However, some authors suggested that from a technical standpoint, wind turbines may also be a suitable alternative [138]. Investment in wind power was shown to be profitable, but the physical boundary of a district may not fit the required renewable energy installations if high self-sufficiency is targeted [134]. Higher levels of insulation and geothermal HPs were found to be the best way to achieve self-supply targets from both energetic and economic perspectives but with higher investment costs [118]. Geothermal energy was found to be a viable alternative compared to residential rooftop PV if sufficient geothermal resources were available. To further improve the appeal of geothermal energy, the integration of thermal energy storage and a geothermal-heated hot water production plant would be advantageous [100,133]. Thermal storage and properly sized battery storage were also identified as ways to improve energy efficiency and reduce HP size in MBES [87]. This implies that thermal storage can leverage the differential heat production and demand across buildings, reducing the overall dependency on HPs and their energy consumption. Similarly, appropriately scaled battery storage can optimize the use of PV systems within the collective framework, enhancing the self-consumption ratios of renewable energy across the neighbourhood.

Especially, in a district-level MBES, the optimal integration of RES and storage systems is critical for addressing large-scale energy needs effectively. These systems must not only fulfil current demands but also be designed with expandability and adaptability in mind, allowing for future expansions and technological advancements. Such foresight ensures that neighbourhoods remain energy resilient and sustainable over time, capable of adapting to evolving energy landscapes and increasing demands.

5. Conclusion

This study presented an overview of current research on MBES across various scales and geographical contexts. Different case studies have been investigated to reveal the advancements in energy technologies and ambitious levels of MBES within diverse architectural contexts. This review offered a foundation for researchers, policymakers, and practitioners to further advance the development and optimization of MBES, assisting the ongoing transition towards sustainable and resilient urban energy systems. Unique to this study was a holistic approach that combined diverse geographical contexts, varying MBES scales, and a wide array of energy ambitions. This comprehensive perspective provided a more nuanced understanding, offering a roadmap that considers both the macro and micro intricacies of MBES advancements by drawing the following insights from the reviewed articles:

- *Energy performance improvement potential*: Energy ambitions at MBES scales consistently outperform standalone building systems. Adopting such an approach during the planning and design phase facilitates optimal utilization of RES. Evidence from different countries and climates reveals that ambitious levels like nZEN/NZEN have shown promising potential in reducing greenhouse gas emissions from buildings.
- *Geometrical parameters*: The significance of geometrical parameters, including typology, density, morphology, orientation, and centrality, is evident. Accounting for these factors in optimization processes throughout the design phase of MBES and urban development plans significantly reduces energy use, especially for space heating and cooling. while the current review has identified key factors influencing the efficiency of renewable energy systems, the significant role of thermal comfort must be acknowledged. Achieving higher levels of thermal comfort often necessitates increased energy usage, presenting a potential conflict with cost and energy-saving optimization goals.
- *Tools and software*: Although the emergence of MBES-specific simulation software offers great promise, their widespread adoption in the planning phase is limited. Potential solutions include clustering based on building attributes and scaling up from smaller neighbourhood designs.
- *Vast solution space for optimality*: The optimal renewable energy production largely depends on location and climate conditions. Furthermore, efficient energy storage contributes to cost-effectiveness and emission reduction. Long-term energy storage is more practical for rural areas, whereas short-term storage is essential in urban areas to achieve zero-energy status effectively. Given the vast solution space for optimal MBES design, it's essential to integrate a diverse mix of renewable sources tailored to local climate and human-related constraints. This flexibility allows for more resilient and adaptive energy systems that can respond to varying demands and environmental conditions.

The transition towards widespread adoption of MBES faces several challenges. One of the primary obstacles is the absence of standardized regulations and policies specifically tailored for MBES, which can hinder broader acceptance and implementation. Additionally, the high initial investments required for MBES can act as a deterrent for many potential stakeholders, making it challenging to secure the necessary funding for these projects. Furthermore, as with the introduction of any innovative technology, the public's perception and trust play a pivotal role. Ensuring that communities have a clear understanding and acceptance of MBES is paramount for its successful integration and operation in urban settings.

The limited uptake of MBES-specific simulation software in planning underscores a critical gap. To bridge this, future work should concentrate on developing accessible and versatile tools that act as part of an energy management system, enabling finer control and optimization tailored to the specific dynamics of MBES. Such tools would greatly benefit stakeholders and entrepreneurs by providing detailed and actionable insights for energy system planning and management at various scales. In addition, Given the intricacies of balancing energy efficiency with the geometrical parameters and thermal comfort demands in MBES, further research should investigate practical implementations that enhance occupant comfort without compromising the efficiency gains, especially considering the diverse climatic contexts that influence MBES designs. Furthermore, it is important to explore advanced control strategies, such as data-driven model predictive control. Such strategies can optimally respond to the dynamics and uncertainties within the MBES, ensuring their reliability and effectiveness. In this regard, there remains a significant opportunity for future research to delve into the impact of occupancy patterns, for example, personalised thermal comfort on these systems. Such studies would contribute valuable insights into the design of smarter, more adaptive energy management systems based on the dynamic and varied nature of occupancy behaviours, further refining the operational efficiency of MBES. In parallel, it's crucial to keep examining emerging technologies such as hydrogen energy storage systems and smart energy hub technologies, assessing their potential to improve MBES performance and resilience.

CRediT authorship contribution statement

Habtamu Bayera Madessa: . **Mohammad Shakerin:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Espen Helberg Reinskau:** . **Mehrdad Rabani:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, 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.

Data availability

Data will be made available on request.

References

[1] Commission, E., *Energy performance of buildings directive.* 2019.
[2] Derkenbaeva E, et al. Positive energy districts: Mainstreaming energy transition in urban areas. Renewable and Sustainable Energy Reviews 2022;153:111782.
[3] Recast E. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Official Journal of the European Union 2010;18(06):2010.
[4] Jaysawal RK, et al. Concept of net zero energy buildings (NZEB) - a literature review. Cleaner Engineering and Technology 2022;11:100582.
[5] Hasan, A., A. Mohamed, and H. Mohamed. Net-and nearly-zero energy buildings: A review of the definitions and case studies. in Proceedings of the Sixth International Conference on Heating, Cooling and Air Conditioning, Tehran, Iran. 2015.
[6] Lindholm O, Rehman HU, Reda F. Positioning positive energy districts in european cities. Buildings 2021;11.
[7] Marszal AJ, et al. Zero Energy Building–a review of definitions and calculation methodologies. Energy and Buildings 2011;43(4):971–9.

[8] Marique A-F, Reiter S. A simplified framework to assess the feasibility of zero-energy at the neighbourhood/community scale. Energy and buildings 2014;82:114–22.

[9] Ala-Juusela M, et al. Positive energy building definition with the framework, elements and challenges of the concept. Energies 2021;14(19):6260.

[10] Becchio C, et al. Decision making for sustainable urban energy planning: An integrated evaluation framework of alternative solutions for a NZED (Net Zero-Energy District) in Turin. Land Use Policy 2018;78:803–17.

[11] Ohene E, Chan AP, Darko A. Review of global research advances towards net-zero emissions buildings. Energy and buildings 2022:112142.

[12] Albert-Seifried V, et al. Definitions of positive energy districts: a review of the status quo and challenges. Sustainability in Energy and Buildings 2021;2022:493–506.

[13] Amaral AR, et al. Review on performance aspects of nearly zero-energy districts. Sustainable Cities and Society 2018;43:406–20.

[14] Brozovsky J, Gustavsen A, Gaitani N. Zero emission neighbourhoods and positive energy districts – a state-of-the-art review. Sustainable Cities and Society 2021;72:103013.

[15] Kari Sørnes (SINTEF), I.S.S., Eyvind Fredriksen (SINTEF), Fredrik Martinsson (IVL Swedish Environmental Research Institute), Ander Romero (Tecnalia), Francisco Rodriguez (Tecnalia), Patrice Schneuwly (CEA), *Final report on common definition for nZEB renovation.* IVL Swedish Environmental Research Institute, 2014.

[16] Lobaccaro G, et al. A methodological analysis approach to assess solar energy potential at the neighborhood scale. Energies 2019;12(18).

[17] Anastasovski A. What is needed for transformation of industrial parks into potential positive energy industrial parks? A review. Energy Policy 2023.

[18] Gholami H, Røstvik HN, Steemers K. The contribution of building-integrated photovoltaics (Bipv) to the concept of nearly zero-energy cities in europe: Potential and challenges ahead. Energies 2021.

[19] Abokersh MH, et al. Sustainability insights on emerging solar district heating technologies to boost the nearly zero energy building concept. Renewable Energies 2021.

[20] Clemente C., Civiero P., Cellurale M. Positive energy districts [peds]. marilisa cellurale for inclusive and sustainable urban development; Sustainable Mediterranean Construction, 2020.

[21] Bossi S, Gollner C, Theierling S. Towards 100 positive energy districts in europe: Preliminary data analysis of 61 European cases. Energies; 2020.

[22] Heendeniya CB, Sumper A, Eicker U. The multi-energy system co-planning of nearly zero-energy districts – Status-quo and future research potential. Applied Energy 2020;267:114953.

[23] Rose J, Thomsen KE, Balslev-Olesen O. *The Balance between Energy Efficiency and Renewable Energy for District Renovations in Denmark*. Sustainability (Switzerland) 2022.

[24] Volpe R, et al. Optimal design and operation of distributed electrical generation for Italian positive energy districts with biomass district heating. Energy Conversion and Management, 2022.

[25] Li M, et al. Techno-economic analysis of the transition towards the large-scale hybrid wind-tidal supported coastal zero-energy communities. Applied Energy 2022.

[26] Miglani S, Orehounig K, Carmeliet J. A methodology to calculate long-term shallow geothermal energy potential for an urban neighbourhood. Energy and Buildings 2018;159:462–73.

[27] Paiho S, Hoang H, Hukkalainen M. Energy and emission analyses of solar assisted local energy solutions with seasonal heat storage in a Finnish case district. Renewable Energy 2017;107:147–55.

[28] Romdhane J, Louahlia H, Marion M. Dynamic modeling of an eco-neighborhood integrated micro-CHP based on PEMFC: Performance and economic analyses. Energy and Buildings 2018;166:93–108.

[29] Arent DJ, et al. Multi-input, Multi-output Hybrid Energy Systems. Joule 2021;5(1):47–58.

[30] Hachem-Vermette C. and K. Singh, Mixed-use neighborhoods layout patterns: Impact on solar access and resilience. Sustainable Cities and Society; 2019. p. 51.

[31] Zhang X, et al. A review of urban energy systems at building cluster level incorporating renewable-energy-source (RES) envelope solutions. Applied Energy 2018.

[32] Häring T, et al. Microgrid Oriented modeling of space heating system based on neural networks. Journal of Building Engineering 2021.

[33] Kim MH, et al. Self-sufficiency and energy savings of renewable thermal energy systems for an energy-sharing community. Energies 2021.

[34] Cortés P, et al. Near-optimal operation of the distributed energy resources in a smart microgrid district. Journal of Cleaner Production 2020;252.

[35] Wang J, et al. Occupant preference-aware load scheduling for resilient communities. Energy and Buildings 2021.

[36] Korkas CD, et al. Intelligent energy and thermal comfort management in grid-connected microgrids with heterogeneous occupancy schedule. Applied Energy 2015;149:194–203.

[37] Fouad MM, Iskander J, Shihata LA. Energy, carbon and cost analysis for an innovative zero energy community design. Solar Energy 2020.

[38] Huang S, et al. An open-source virtual testbed for a real net-zero energy community. Sustainable Cities and Society 2021.

[39] Janzadeh A, Zandieh M. Design feasibility of a net-zero energy neighborhood in Qazvin. Energy Efficiency 2021.

[40] Guarino F, et al. Energy planning methodology of net-zero energy solar neighborhoods in the Mediterranean basin. Science and Technology for the Built Environment 2016.

[41] Nematchoua MK. From existing neighbourhoods to net-zero energy and nearly zero carbon neighbourhoods in the tropical regions. Solar Energy 2020.

[42] Neumann HM, et al. Analysis and evaluation of the feasibility of positive energy districts in selected urban typologies in Vienna using a bottom-up district energy modelling approach. *Energies* 2021.

[43] Sesil Koutra, V.B., Christos S. Ioakimidis, A Simplified Methodological Approach Towards the Net Zero Energy District. *Smart Cities, Green Technologies, and Intelligent Transport Systems* 2016.

[44] Shen L, Sun Y. Performance comparisons of two system sizing approaches for net zero energy building clusters under uncertainties. Energy and Buildings 2016.

[45] Zahedi R, et al. Modelling community-scale renewable energy and electric vehicle management for cold-climate regions using machine learning. Energy Strategy Reviews 2022.

[46] Korkas CD, Baldi S, Kosmatopoulos EB. Grid-connected microgrids: Demand management via distributed control and human-in-the-loop optimization. In: Advances in renewable energies and power technologies. Elsevier; 2018. p. 315–44.

[47] Li X, Wen Net-Zero J. Energy Building Clusters Emulator for Energy Planning and Operation Evaluation. Computers, Environment and Urban Systems. 2017.

[48] Piselli C, et al. Assessing users' willingness-to-engagement towards Net Zero Energy communities in Italy. Renewable and Sustainable Energy Reviews 2021.

[49] Ricardo Mateus SMSaMA. The importance of the solar systems to achieve the nZEB level in the energy renovation of southern Europe's buildings. International Conference on Building Integrated Renewable Energy Systems 2017.

[50] Li ZW, Quan SJ, Yang PPJ. Energy performance simulation for planning a low carbon neighborhood urban district: a case study in the city of Macau. Habitat International 2016;53:206–14.

[51] Hachem C, Athienitis A, Fazio P. Evaluation of energy supply and demand in solar neighborhood. Energy and Buildings 2012;49:335–47.

[52] Castaldo VL, et al. How outdoor microclimate mitigation affects building thermal-energy performance: a new design-stage method for energy saving in residential near-zero energy settlements in Italy. Renewable Energy 2018;127:920–35.

[53] Li X, et al. Urban heat island impacts on building energy consumption: a review of approaches and findings. Energy 2019;174:407–19.

[54] Zafar R, et al. Prosumer based energy management and sharing in smart grid. Renewable and Sustainable Energy Reviews 2018;82:1675–84.

[55] Nematchoua MK, Marie-Reine Nishimwe A, Reiter S. Towards nearly zero-energy residential neighbourhoods in the European Union: a case study. Renewable and Sustainble Energy Reviews 2021.

[56] Tumminia G, et al. Grid interaction and environmental impact of a net zero energy building. Energy Conversion and Management 2020;203:112228.

[57] Korkas CD, et al. Occupancy-based demand response and thermal comfort optimization in microgrids with renewable energy sources and energy storage. Applied Energy 2016;163:93–104.

[58] Odonkor P, et al. Adaptive energy optimization toward net-zero energy building clusters. Journal of Mechanical Design 2016.

[59] Fan G, et al. Energy management strategies and multi-objective optimization of a near-zero energy community energy supply system combined with hybrid energy storage. Sustainable Cities and Society 2022.

[60] Kazmi H, et al. Energy balances, thermal performance, and heat stress: disentangling occupant behaviour and weather influences in a Dutch net-zero energy neighbourhood. Energy and Buildings 2022.

[61] Arabkoohsar A. Non-uniform temperature district heating system with decentralized heat pumps and standalone storage tanks. Energy 2019;170:931–41.

[62] Aruta G, et al. Optimizing the energy transition of social housing to renewable nearly zero-energy community: The goal of sustainability. Energy and Buildings 2023.

[63] Marotta I, et al. Environmental sustainability approaches and positive energy districts: a literature review. Sustainability 2021;13(23).

[64] Salom J, et al. An evaluation framework for sustainable plus energy neighbourhoods: moving beyond the traditional building energy assessment. Energies 2021.

[65] Aghamolaei R, et al. Review of district-scale energy performance analysis: Outlooks towards holistic urban frameworks. Sustainable Cities and Society 2018.

[66] Mousavi S, et al. Data-driven prediction and optimization toward net-zero and positive-energy buildings: a systematic review. Building and Environment 2023;242:110578.

[67] Heiskanen E, Matschoss K. Understanding the uneven diffusion of building-scale renewable energy systems: a review of household, local and country level factors in diverse European countries. Renewable and Sustainable Energy Reviews 2017.

[68] Soares N, et al. A review on current advances in the energy and environmental performance of buildings towards a more sustainable built environment. Renewable and Sustainable Energy Reviews 2017;77:845–60.

[69] Koutra S, et al. Towards the development of a net-zero energy district evaluation approach: A review of sustainable approaches and assessment tools. Sustainable Cities and Society 2018;39:784–800.

[70] Saheb Y, Shnapp S, Johnson C. The Zero Energy concept: making the whole greater than the sum of the parts to meet the Paris Climate Agreement's objectives. Current Opinion in Environmental Sustainability 2018;30:138–50.

[71] Sola A, et al. Multi-domain urban-scale energy modelling tools: a review. Sustainable Cities and Society 2020.

[72] Sola A, et al. Simulation tools to build urban-scale energy models: a review. Energies 2018.

[73] Jin X, et al. A review and reflection on open datasets of city-level building energy use and their applications. Energy and Buildings 2023.

[74] Koutra S, et al. 'Decarbonizing Europe' A critical review on positive energy districts approaches. Sustainable Cities and Society 2023;89.

[75] Charani Shandiz S, Rismanchi B, Foliente G. Energy master planning for net-zero emission communities: state of the art and research challenges. Renewable and Sustainable Energy Reviews 2021;137:110600.

[76] Taveres-Cachat E, et al. Responsive building envelope concepts in zero emission neighborhoods and smart cities - a roadmap to implementation. Building and Environment 2019;149:446–57.

[77] Kolokotsa D. Smart cooling systems for the urban environment. Using renewable technologies to face the urban climate change. Solar Energy 2017;154:101–11.

[78] Wubah D, et al. Funding community sustainable development using zero energy buildings. International Journal of Sustainability in Higher Education 2021;22 (1):29–43.

[79] Jędrzejuk H, Chwieduk D. Possibilities of upgrading warsaw existing residential area to status of positive energy districts. Energies 2021.

[80] Uspenskaia D, et al. Challenges and barriers for net-zero/positive energy buildings and districts—empirical evidence from the smart city project sparcs. Buildings 2021.

[81] Natanian J, Aleksandrowicz O, Auer T. A parametric approach to optimizing urban form, energy balance and environmental quality: The case of Mediterranean districts. Applied Energy 2019.

[82] Kim MH, et al. Techno-economic analysis of hybrid renewable energy system with solar district heating for net zero energy community. Energy 2019.

[83] Aste N, et al. A renewable energy scenario for a new low carbon settlement in northern Italy: Biomass district heating coupled with heat pump and solar photovoltaic system. Energy 2020.

[84] Ferrante T, Villani T. Positive energy districts and energy efficiency in buildings: An innovative technical communication sheet to facilitate policy officers' understanding to enable technologies and procedure. Energies 2021.

[85] Beck HE, et al. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Scientific Data 2018;5(1):180214.

[86] Bambara J, Athienitis AK, Eicker U. Residential Densification for Positive Energy Districts.: Frontiers in Sustainable Cities; 2021.

[87] Samadzadegan B, et al. Novel Energy System Design Workflow for Zero-Carbon Energy District Development. Frontiers in Sustainable Cities 2021.

[88] Wills AD, Beausoleil-Morrison I, Ugursal VI. A modelling approach and a case study to answer the question: What does it take to retrofit a community to net-zero energy? Journal of Building Engineering 2021.

[89] Hachem C. Impact of neighborhood design on energy performance and GHG emissions. Applied Energy 2016;177:422–34.

[90] Hachem-Vermette C, Cubi E, Bergerson J. Energy performance of a solar mixed-use community. Sustainable Cities and Society 2016;27:145–51.

[91] Singh K, Hachem-Vermette C. Influence of mixed-use neighborhood developments on the performance of waste-to-energy CHP plant. Energy 2019; 189.

[92] Hachem-Vermette C, et al. Towards achieving net-zero energy communities: Investigation of design strategies and seasonal solar collection and storage net-zero. Solar Energy 2019.

[93] Erba S, Pagliano L. Combining sufficiency, efficiency and flexibility to achieve positive energy districts targets. Energies 2021.

[94] Maturo A, et al. Design and environmental sustainability assessment of energy-independent communities: The case study of a livestock farm in the North of Italy. Energy Reports 2021.

[95] Boccalatte A, Fossa M, Ménézo C. Best arrangement of BIPV surfaces for future NZEB districts while considering urban heat island effects and the reduction of reflected radiation from solar façades. Renewable Energy 2020.

[96] Becchio C, et al. A MCDA-based approach for evaluating alternative requalification strategies for a net-zero energy district (NZED). Multiple Criteria Decision Making 2017:189–211.

[97] Doubleday K, et al. Toward a subhourly net zero energy district design through integrated building and distribution system modeling. Journal of Renewable and Sustainable Energy 2019.

[98] Saarloos BA, Quinn JC. Net-zero energy districts and the grid: An energy-economic feasibility case-study of the national western center in Denver, CO, USA.. Buildings; 2021.

[99] Quan SJ, et al. Decentralized algal energy system design at various urban densities and scales. Energy Procedia 2017;143:767–73.

[100] Becker W, et al. Technoeconomic Design of a Geothermal-Enabled Cold Climate Zero Energy Community. Journal of Energy Resources Technology, Transactions of the ASME 2021.

[101] Janssens A, et al. Transforming social housing neighbourhoods into sustainable carbon neutral districts. Energy Procedia 2017;132:549–54.

[102] Jepsen BKH, Haut TW, Jradi M. Design, Modelling and Performance Evaluation of a Positive Energy District in a Danish Island. Future Cities and Environment 2022.

[103] Arabkoohsar A, Alsagri AS. A new generation of district heating system with neighborhood-scale heat pumps and advanced pipes, a solution for future renewable-based energy systems. Energy 2020;193:735–46.

[104] Romero Rodríguez L, et al. Heuristic optimization of clusters of heat pumps: a simulation and case study of residential frequency reserve. Applied Energy 2019; 233–234:943–58.

[105] Meng BY, et al. Evaluating the thermal impacts and sustainability of intensive shallow geothermal utilization on a neighborhood scale: lessons learned from a case study. Energy Conversion and Management 2019;199.

[106] Zucker G, et al. A new method for optimizing operation of large neighborhoods of buildings using thermal simulation. Energy and Buildings 2016;125:153–60.

[107] Walker S, et al. An assessment methodology of sustainable energy transition scenarios for realizing energy neutral neighborhoods. Applied Energy 2018;228: 2346–60.

[108] Fonseca JA, et al. City Energy Analyst (CEA): integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts. Energy and Buildings 2016;113:202–26.

[109] Murray P, et al. A comparison of storage systems in neighbourhood decentralized energy system applications from 2015 to 2050. Applied Energy 2018;231: 1285–306.

[110] Sameti M, Haghighat F. Integration of distributed energy storage into net-zero energy district systems: optimum design and operation. Energy 2018;153:575–91.

[111] Gouveia JP, et al. Positive Energy District: A Model for Historic Districts to Address Energy Poverty. Frontiers in Sustainable Cities 2021.

[112] Yang TR, Zhang XL. Benchmarking the building energy consumption and solar energy trade-offs of residential neighborhoods on Chongming Eco-Island, China. Applied Energy 2016;180:792–9.

[113] Huang P, et al. A top-down control method of nZEBs for performance optimization at nZEB-cluster-level. Energy 2018.

[114] Liu J, et al. Net-zero energy management and optimization of commercial building sectors with hybrid renewable energy systems integrated with energy storage of pumped hydro and hydrogen taxis. Applied Energy 2022.

[115] Liu Z, et al. Multi-scenario analysis and collaborative optimization of a novel distributed energy system coupled with hybrid energy storage for a nearly zero-energy community. Journal of Energy Storage 2021.

[116] Barone G, et al. Increasing renewable energy penetration and energy independence of island communities: a novel dynamic simulation approach for energy, economic, and environmental analysis, and optimization. Journal of Cleaner Production 2021.

[117] Zubair M, et al. Assessment of photovoltaic capabilities in urban environments: a case study of islamabad, Pakistan. Journal of Solar Energy Engineering, Transactions of the ASME 2020.

[118] Sougkakis V, et al. An investigation on the feasibility of near-zero and positive energy communities in the greek context. Smart Cities 2020.

[119] Wirtz M, et al. Temperature control in 5th generation district heating and cooling networks: an MILP-based operation optimization. Applied Energy 2021;288: 116608.

[120] Lund H, et al. The status of 4th generation district heating: Research and results. Energy 2018;164:147–59.

[121] Hirvonen J, Kosonen R. Waste incineration heat and seasonal thermal energy storage for promoting economically optimal net-zero energy districts in finland. Buildings 2020.

[122] Arnaudo M, Topel M, Laumert B. Techno-economic analysis of demand side flexibility to enable the integration of distributed heat pumps within a Swedish neighborhood. Energy 2020;195.

[123] Dutt F, et al. Modeling algae powered neighborhood through GIS and BIM integration. Energy Procedia 2017;105:3830–6.

[124] Natanian J, Auer T. Beyond nearly zero energy urban design: a holistic microclimatic energy and environmental quality evaluation workflow. Sustainable Cities and Society 2020.

[125] Aparicio-Gonzalez E, Domingo-Irigoyen S, Sanchez-Ostiz A. Rooftop extension as a solution to reach nZEB in building renovation. application through typology classification at a neighborhood level. Sustainable Cities and Society 2020:57.

[126] Rafique MM, Bahaidarah HMS, Anwar MK. Enabling private sector investment in off-grid electrification for cleaner production: optimum designing and achievable rate of unit electricity. Journal of Cleaner Production 2019.

[127] Rafique MM, Rehman S, Alhems LM. Developing zero energy and sustainable villages – a case study for communities of the future. Renewable Energy 2018.

[128] Kalaycıoğlu E, Yılmaz AZ. A new approach for the application of nearly zero energy concept at district level to reach EPBD recast requirements through a case study in Turkey. Energy and Buildings 2017;152:680–700.

[129] Cardinali M, et al. Microclimate mitigation for enhancing energy and environmental performance of Near Zero Energy Settlements in Italy. Sustainable Cites and Society 2020.

[130] Bruck A, Díaz Ruano AS, Auer H. A critical perspective on positive energy districts in climatically favoured regions: an open-source modelling approach disclosing implications and possibilities. Energies 2021.

[131] Ammari C, et al. Sizing, optimization, control and energy management of hybrid renewable energy system—a review. Energy and Built Environment 2022;3(4): 399–411.

[132] Guo J, et al. A new collaborative optimization method for a distributed energy system combining hybrid energy storage. Sustainable Cites and Society 2021.

[133] Soutullo S, et al. Methodology for quantifying the energy saving potentials combining building retrofitting, solar thermal energy and geothermal resources. Energies 2020.

[134] Laitinen A, et al. A techno-economic analysis of an optimal self-sufficient district. Energy Conversion and Management 2021.

[135] Willmann A, et al. A comparison of bottom-up and top-down modelling approaches in urban energy simulation. The International Building Performance Simulation Association 2019.

[136] Yang PPJ, et al. A geodesign method of human-energy-water interactive systems for urban infrastructure design: 10KM2 near-zero district project in shanghai. Engineering 2018.

[137] Paiho S, et al. A new procedure for assessing the energy-efficient refurbishment of buildings on district scale. Sustainable Cities and Society 2019;46.

[138] Campana PE, et al. Spatial optimization of residential urban district - energy and water perspectives. Energy Procedia 2016;88:38–43.

[139] Orehounig K, Evins R, Dorer V. Integration of decentralized energy systems in neighbourhoods using the energy hub approach. Applied Energy 2015;154:277–89.

[140] UNI, E., *Energy performance of buildings—calculation of energy use for space heating and cooling.* Standard UNI EN ISO, 2008. **13790**: p. 2008.