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Supporting climate-neutral cities with urban energy modeling: a review of building retrofit scenarios, focused on decision-making, energy and environmental performance, and cost

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ABSTRACT

Climate deadlines are fast approaching, and city action plans must address slashing carbon emissions using scarce financial resources. Urban energy modeling (UEM) supports building sector transformation by quantifying energy use and emissions in baseline and retrofit scenarios. Additionally, many UEM studies evaluate retrofit costs and financial returns. This review of 26 UEM studies critically analyzes how studies decide to model retrofit measures or impose scenario constraints, and how energy, emissions, and costs are quantified. The results show divergent quantification approaches among the reviewed literature, hindering the usefulness and comparability of the studies for policymakers. The findings also indicate challenges with renewable energy production and heating via heat pumps, including increased peak electrical loads and seasonal mismatches in generation and consumption, which are mitigated by measures reducing building energy demand and energy use, demand-response measures to curtail peaks, and district sources of endogenous energy. The value of the decision-making analysis is to signal pathways toward innovation and stakeholder collaboration for city plans, highlighting approaches using context analysis to generate and share energy in districts, economic criteria to mirror real-world conditions, and stakeholder engagement to meet local priorities. Finally, perspectives for future UEM studies support policymakers guiding the transformation to climate neutrality.

1. Introduction

Climate deadlines are fast approaching: most G20 countries have pledged net-zero greenhouse gas (GHG) emissions by 2050 (United Nations Environment Programme (UNEP) 2021), and the European Union (EU) mission “100 climate-neutral cities by 2030” aims for 100 cities, or districts thereof, to reach net zero by end of the decade. Acting as innovation hubs, the 100 cities are expected to lead a systematic transformation in the EU before the 2050 cutoff (European Commission (EC) 2020a). For mission success, cities must focus on buildings, as the sector accounts for 36% of energy-related GHG emissions and 40% of energy use in the EU (European Commission (EC) 2020b). The EU’s proposed recast of the Energy Performance of Buildings Directive (EPBD), calls for zero-emissions buildings following the “efficiency-first principle” with high energy performance and minimal energy demand, to be covered by on-site renewable energy systems (RES), renewable energy communities, or district energy systems (DES) (European Commission (EC) 2021).

The field of urban energy modeling (UEM) supports a transformation of the built environment, helping cities quantify current energy use, and compare energy and emissions reduction strategies, including retrofits to the building stock (Hong et al., 2020). Many UEM studies also quantify retrofit costs, which supports policymakers leading the transformation with scarce financial resources. For the EU “100 cities” mission, costs are estimated at €96 billion by 2030 across all sectors, or €10,000 per citizen (European Commission (EC) 2020a). Thus, UEM can play a valuable role in identifying impactful and cost-effective measures, providing insight for policymakers to create incentives and stimulate action in the building sector (Ang, Berzolla, and Reinhart, 2020).

1.1. Previous reviews and research gap

Previous reviews help define the term UEM in this work, including reviews on UBEM (Reinhart and Davila, 2016), USEM (Sola, Corchero, Salom, and Sanmarti, 2020), and urban energy system modeling

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Nomenclature

Abbreviations

COP	coefficient of performance
DES	district energy system
DHW	domestic hot water
ECM	energy conservation measures
EPBD	energy performance of buildings directive
EPS	expanded polystyrene
EV	electric vehicle
GHG	greenhouse gas
HFA	heated floor area
HP	heat pump
HRV	heat recovery ventilation
IRR	internal rate of return
KPI	key performance indicator
LCC	life cycle costing
MCDA	multi-criteria decision analysis
NPV	net present value
NZE	net zero energy
PM	particulate matter
PV	photovoltaic
RES	renewable energy system
SPP	simple payback period
UEM	urban energy model
UBEM	urban building energy model
USEM	urban-scale energy model
WTP	willingness to pay

(Moghadam, Delmastro, Corgnati, and Lombardi, 2017). Reinhart & Davila (Reinhart and Davila, 2016) identified urban building energy modeling (UBEM) as automated workflows for physics-based models of heat and mass flows to determine operational energy use for groups of buildings. Sola et al. (Sola, Corchero, Salom, and Sanmarti, 2020) describe urban-scale energy modeling (USEM) to include not only building operational energy, but also energy supply, transportation energy, and other energy sub-models. Torabi Moghadam et al. (Moghadam, Delmastro, Corgnati, and Lombardi, 2017) reviewed urban energy system models, which use mathematical and hybrid approaches.

Previous reviews also highlight the overlap between UEM research and policymaking. One argued that the field must increase engagement between researchers and planners, policymakers, and utility representatives (Reinhart and Davila, 2016). Another reviewed four UBEM use cases including building stock-level carbon reduction strategies, asserting that output in ranges of plausibility best serves policymakers, rather than fixed values that are likely to be inaccurate. The authors cite examples of how studies can help cities in cost-benefit analysis to determine measures with the greatest energy or cost savings, thus prioritizing these using policy levers and incentives (Ang, Berzolla, and Reinhart, 2020).

The foregoing reviews discuss the basic workings of the urban models, and other reviews have detailed modeling workflows and tools in UBEM (Ferrari, Zagarella, Caputo, and Bonomolo, 2019, Ferrando, Causone, Hong, and Chen, 2020, Johari et al., 2020, Abbasabadi and Ashayeri, 2019), and thus these technical details are not further covered here. Many preceding reviews note the capability of UEM to demonstrate retrofits and cite examples of measures implemented and energy savings.

What is missing is a state-of-the-art on retrofit scenario analysis in the UEM literature, identifying how studies quantify energy performance, CO_2 emissions, and retrofit costs. Additionally, previous reviews have not thoroughly analyzed which retrofit measures or scenario constraints are selected for modeling and why. Another gap, literature reviews to date have not sufficiently analyzed how the UEM literature engages with policymakers or other stakeholders, nor whether studies are meeting the needs of these actors, as advocated in previous reviews (Ang, Berzolla, and Reinhart, 2020, Reinhart and Davila, 2016).

1.2. Research motivation and relevance

In a review outside UEM focusing on drivers and barriers for the climate-neutral transition, Huovila et al. (Huovila et al., 2022) conclude that cities need support to develop and evaluate action plans, advance innovative solutions, and increase stakeholder collaboration. The present work analyzes decision-making, energy and environmental performance, and cost within retrofit-focused UEM studies to highlight how the field of UEM can provide cities such support.

This work summarizes and categorizes retrofits selected in the reviewed UEM studies, and analyzes how studies decide to model measures and scenarios or impose scenario constraints. Commonalities and differences are identified, emphasizing approaches that are novel or lead to significant reductions in energy or emissions. Approaches quantifying energy, CO_2, and retrofit costs are reported and compared in this work, highlighting strengths and weaknesses. Studies using UBEM, USEM, and mathematical/hybrid approaches are considered under the umbrella term of UEM if they quantify operational energy for clusters of buildings, and those modeling retrofits are included for review. The objective of the analysis is to provide the state-of-the-art of retrofit-focused UEM studies, helping standardize how future works present results to be coherent and comparable for policymakers.

This work compares post-retrofit energy and CO_2 reductions in the reviewed studies, though the present authors caution that those outcomes are limited to the context from which they arise, due to varying climate, construction standards, and other factors. Another limitation is due to the geography of studies reviewed, as posited by Janda et al. (Janda et al., 2019), who assert that a concentration of 90% of UBEM case studies from the Global North will exacerbate development challenges for informal settlements in the Global South, as assumptions from northern models become embedded in southern ones. In the current review, the literature selection method resulted in the same narrow geographic scope forewarned by Janda et al., and thus findings from this study must be limited to their specific locations, and must not be generalized to the Global South.

Motivating this review despite geographic limitations is the imbalance in CO_2 emissions described by Hickel (Hickel, 2020). Therein, the Global North (defined as USA, Canada, Europe, Israel, Australia, New Zealand, and Japan) was found responsible for 92% of historical CO_2 emissions exceeding a 350 ppm threshold, whereas the Global South (i.e. the rest of the world) accounts for only 8% of emissions, using per-capita, consumption-based attribution. Thus, one can argue for the Global North's duty to rapidly slash emissions, particularly in the building sector in Europe where 75% of buildings have poor energy performance (European Commission (EC) 2021), an aim this review seeks to support.

1.3. Research questions and structure

To bridge the research gap and meet the foregoing objectives, this work seeks to answer the following research questions:

1 **Decision-making.** How do UEM studies decide which retrofit measures to model and which constraints to impose as scenario inputs?
2 **Performance analysis.** Which indicators are used in UEM studies, and how do pre- and post-retrofit performance levels compare?

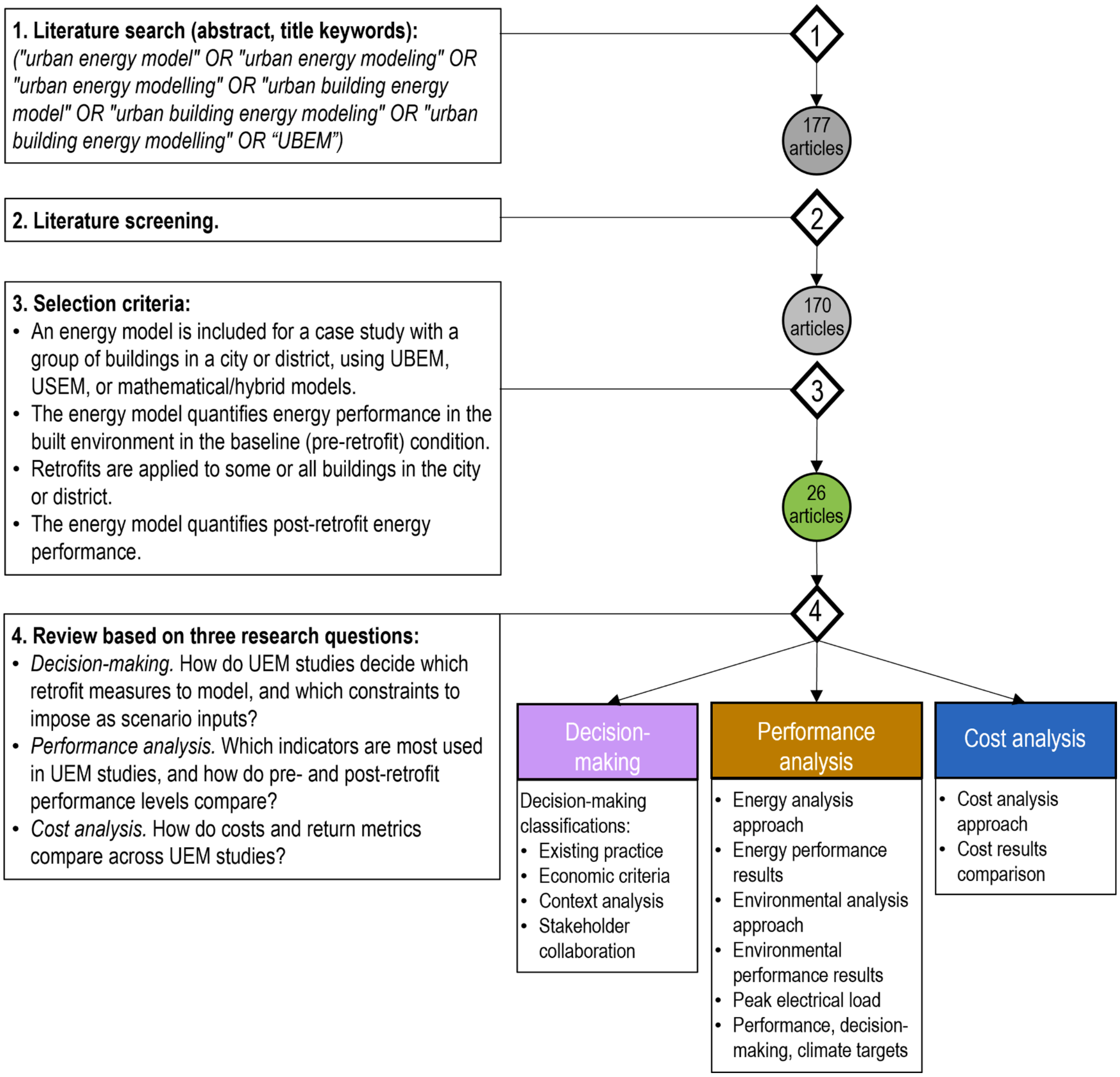

Fig. 1. Overview of the review methodology.

3 **Cost analysis**. How do costs and return metrics compare across UEM studies?

The first research question regards inputs to a UEM study, while the second two are about how studies analyze outputs of the energy model or cost model.

After outlining the review methodology in Section 2, the work turns to answering the research questions in Section 3. Therein, decision-making in retrofit-focused UEM studies, measurement of energy and environmental performance, and retrofit cost analysis are reviewed in three corresponding sub-sections. Section 4 provides a discussion of these results, highlighting strengths and weaknesses. Section 5 provides a conclusion and perspectives for future studies.

2. Methodology

The review was conducted in four steps: literature search, screening, selection, and review as per Fig 1. First, the Scopus scientific database was used to search abstracts, titles, and keywords for the terms depicted. Results were filtered to include only articles in English in peer-reviewed journals. The search was run on 30 May 2022, yielding an initial 177 results. Second, articles were screened based on journal subject area and article title to exclude unrelated topics, which were mainly articles in other fields sharing the acronym "UBEM". This excluded seven articles, leaving 170. Third, studies were selected for review if they met all criteria noted in the figure, equal to 26 articles. Fourth, the literature review was conducted according to the three research questions posed in Section 1.3. Here, papers were read and analyzed according to decision-making classifications, energy and environmental analysis approaches and performance, and cost analysis and comparison. Categories to organize and summarize results are further depicted in the figure. Finally, all results are discussed together and conclusions are presented.

Applying the selection criteria, UEM articles were excluded if they created baseline models of energy performance at the district or city scale, but did not apply retrofits. Studies with modified occupancy or HVAC assumptions only (but no retrofits) were also excluded.

The 170 articles returned in the search and screened date back to 2005, while the 26 articles selected for review are more recent, with over 80% published in the past 5 years, as indicated by Fig 2. This highlights the relevance of retrofits in current UEM research.

3. Results

Table 1 summarizes the 26 reviewed articles, with over 60% of case studies in Europe, 35% in North America, and 4% in Asia. Case study size varied from 5 to 83,541 buildings, ranging from smaller studies at the block or campus scale to city-scale projects, such as the case of all buildings in Boston (Cerezo Davila, Reinhart, and Bemis, 2016), 87% of

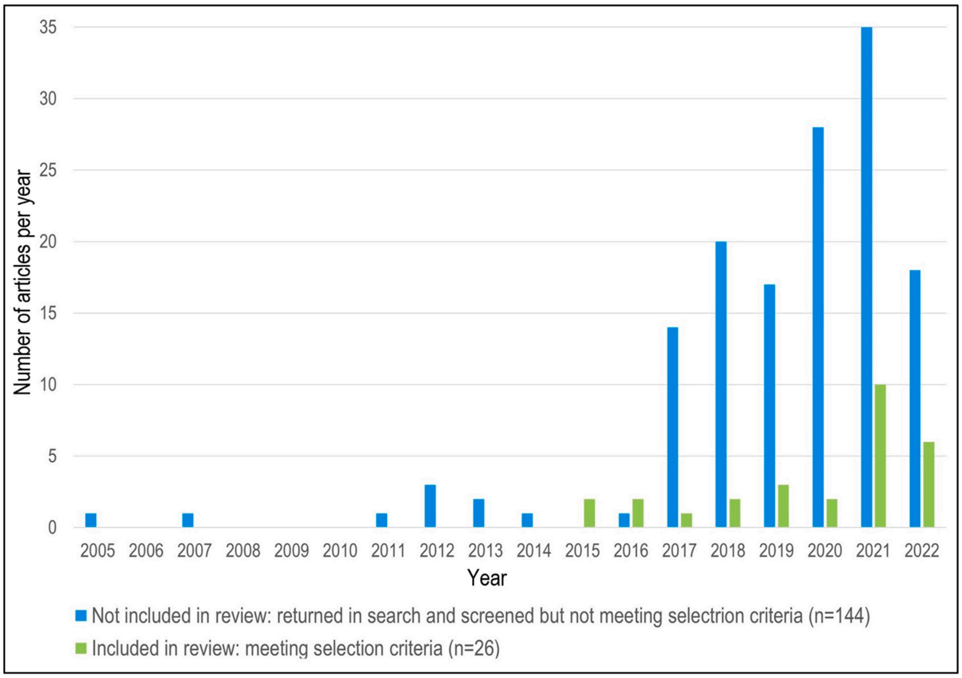

Fig. 2. Number of UEM articles, by year, highlighting articles including retrofits.

all buildings in Changsha (Deng, Chen, Yang, and Chen, 2022), or all multi-family residences in Gothenburg (Mata, Wanemark, Österbring, and Shadram, 2020). Most cases are intermediate sizes, considered as neighborhood or district scale, located in mixed or cool climates, with 15% of cases each in warm or cold climates.

3.1. Retrofit decision-making

This section analyzes retrofit decision-making in UEM studies, meaning which measures are selected, and how studies decide on measures to model or scenario constraints to impose. Here, energy conservation measures (ECMs) are singular actions, whereas a scenario is a combination of one or more ECMs. Around two-thirds of reviewed studies modeled multiple scenarios. Scenario inputs also include constraints, such as investment and workforce limitations affecting the implementation of ECMs within scenarios, as described in the following sub-sections.

To summarize measures selected in the studies, this work groups ECMs into four categories: (i) building envelope, (ii) mechanical systems, (iii) electrical & controls systems, and (iv) renewable & district energy systems. Fig 3 depicts the frequency of ECMs observed. Labels indicate each measure's rank of frequency within each category, such that #1 is most common among reviewed studies, #2 is second-most common, etc. Beyond the frequency of ECMs, Appendix Table A1-A4 further detail ECMs as specified in the studies.

Building-level ECMs were demand-side measures, reducing building energy need or energy use. ECMs included upgrading existing elements (e.g. heating systems) or adding those not present in baseline condition (e.g. heat recovery ventilation; HRV). It appears that supply-side ECMs were not present at the building level, with photovoltaic (PV) energy shared among the district, even if individual panels were installed on building rooftops. District-level measures were all supply-side in the RES/DES category, either adding new elements (e.g. onsite PV) or connecting to existing infrastructure (e.g. expanding DES systems). District ECMs to reduce demand (e.g. mitigating heat islands to lower cooling loads) were not observed in the 26 studies.

In terms of objectives in modeling retrofits, around one-third of the reviewed studies aimed to support local sustainability plans (Mohammadiziazi, Copeland, and Bilec, 2021, Zivkovic et al., 2016), city-wide fossil-fuel-free targets (Pasichnyi et al., 2019, Pasichnyi, Wallin, and Kordas, 2019), regional net-zero energy (NZE) targets (Hosseini Haghighi, de Uribarri, Padsala, and Eicker, 2022, Wang, El Kontar, Jin, and King, 2022), or European Green Deal targets (Buckley, Mills, Letellier-Duchesne, and Benis, 2021, Buckley, Mills, Reinhart, and Berzolla, 2021). Other studies aimed primarily at other aspects of UEM research, such as workflow or tool development, while secondarily including retrofits to demonstrate model functionality (Szcześniak, Ang, Letellier-Duchesne, and Reinhart, 2022, Charan et al., 2021, Mohammadiziazi, Copeland, and Bilec, 2021, Nagpal and Reinhart, 2018, Deng, Chen, Yang, and Chen, 2022, Nutkiewicz, Choi, and Jain, 2021).

How studies selected retrofit measures and scenario constraints is investigated based on four decision-making classifications developed in this work: (i) existing practice, (ii) economic criteria, (iii) context analysis, or (iv) stakeholder collaboration. Studies may exhibit elements of more than one category, though the predominant classification for decision-making according to this review is indicated in Fig 3, below the listed references on the x-axis.

While a clear relationship does not emerge between decision-making classification and retrofits selected, as the following sub-sections detail, analyzing decision-making here may signal pathways to innovation, meet local priorities, and increase stakeholder collaboration.

3.1.1. Existing practice

Retrofit decision-making was often based on existing practice. This includes studies selecting measures described as "off-the-shelf" or "common" for the local area (Nagpal and Reinhart, 2018, Simoes et al., 2019, Nutkiewicz, Choi, and Jain, 2021, Chen, Hong, and Piette, 2017), or those not stating why specific ECMs were selected (Hosseini Haghighi, de Uribarri, Padsala, and Eicker, 2022, Buckley, Mills, Reinhart, and Berzolla, 2021, de Rubeis, Giacchetti, Paoletti, and Ambrosini, 2021). Two selected measures deemed suitable to the archetype buildings or novel algorithm studied (Pasichnyi, Wallin, and Kordas, 2019; Szcześniak et al. 2022).

Also included in this decision-making category is retrofit selection based on literature, including research studies, technical reports, or standards. For example, one study used results from the authors'

Table 1
Case studies in reviewed articles, listed in descending order of heating degree days (HDD). HDD source: (Italian Organization for Standardization (UNI) 2016) for Italian urban areas and (BizEE Software 2022) for all others. Building types: E = Educational; H = Hospitality; R = Residential with sub-types MF = Multi-family and SF = Single-family; C = Commercial with sub-types O = Office and Ret = Retail. Climate zones based on (American Society for Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) 2020): 3A = warm humid; 3B = warm dry; 4A = mixed humid; 4C = mixed marine; 5A = cool humid; 5B = cool dry; 6A = cold humid; 6B = cold dry. * = climate zone estimated from the nearest weather station in (American Society for Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) 2020).

Reference	Heated floor area (m^2)	No. buildings	Building type	Country	Urban Area	Degree days Heating (base 15.5°C)	Cooling (base 22°C)	ASHRAE climate zone
Hosseini Haghighi, de Uribarri, Padsala, and Eicker, 2022	-	2,950	R-SF	Canada	Kelowna	3150	194	5A
Mata, Wanemark, Österbring, and Shadram, 2020	16,693,700	5,901	R-MF	Sweden	Gothenburg	3045	24	6A
Pasichnyi et al., 2019	14,180,000	5,400	R-MF	Sweden	Stockholm	3004	48	6A
Pasichnyi, Wallin, and Kordas, 2019	23,440,000	5,532	R-MF (58%); C-O (42%)	Sweden	Stockholm	3004	48	6A
Wang, El Kontar, Jin, and King, 2022	-	148	Mixed-use	USA	Denver	2697	317	6B/5B
Szcześniak, Ang, Letellier-Duchesne, and Reinhart, 2022	-	2,014	Mixed-use	USA	Chicago	2556	342	5A
Charan et al., 2021	761,805	-	Mixed-use	USA	Chicago	2556	342	5A
Fonseca and Schlueter, 2015	-	1,392	Mixed-use	Switzerland	Zug	2305	108	5A*
Mohammadiziazi, Copeland, and Bilec, 2021	-	209	E (31%); H (24%); C-O (14%); Other C (31%)	USA	Pittsburgh	2299	226	4A
Cerezo Davila, Reinhart, and Bemis, 2016	-	83,541	Mixed-use	USA	Boston	2281	241	5A
Nagpal and Reinhart, 2018	1,113,123	100	E	USA	Boston	2281	241	5A
Issermann, Chang, and Kow, 2021	-	5,736	R	Germany	Wuppertal	2222	89	5A*
Buckley, Mills, Letellier-Duchesne, and Benis, 2021	155,314	418	R-MF (69%); R-SF (31%)	Ireland	Dublin	2146	4	5A
Buckley, Mills, Reinhart, and Berzolla, 2021	82,300	1,247	R-SF	Ireland	Dublin	2146	4	5A
Zivkovic et al., 2016	7,420,950	-	R (96%); Public (4%)	Serbia	Niš	1958	315	4A
Nouvel et al., 2015	300,000	1,000	R	Netherlands	Rotterdam	1889	54	4A
Mutani and Todeschi, 2021	-	41,848	R	Italy	Turin	1847	283	4A
de Rubeis, Giacchetti, Paoletti, and Ambrosini, 2021	119,226	769	R-SF	Italy	Aquila	1756	291	4A*
Zarrella et al., 2020	100,143	13	E (94%); R-MF (6%)	Italy	Padua	1656	262	4A*
Teso et al., 2022	-	57	R	Italy	Venice	1582	276	4A
Simoes et al., 2019	-	-	R	Italy	Cesena	1515	208	4A*
Deng, Chen, Yang, and Chen, 2022	236,600,000	59,322	Mixed-use	China	Changsha	1052	750	3A
Nutkiewicz, Choi, and Jain, 2021	-	29	C-O	USA	Sacramento	1003	506	3B
Blazquez, Suarez, Ferrari, and Sendra, 2021	-	1,699	R-MF	Spain	Cordoba	892	795	3A
Chen, Hong, and Piette, 2017	7,015,201	940	C-O (97%); C-Ret (3%)	USA	San Francisco	750	49	4C
Caro-Martínez and Sendra, 2018	1,997	5	R-MF (90%); R-SF (10%)	Spain	Seville	546	743	3A

previous research, applying similar measures to a new case study (Blazquez, Suarez, Ferrari, and Sendra, 2021). Two studies analyzed electrical supply system reports, for gaps in providing electricity through renewable sources in Germany (Issermann, Chang, and Kow, 2021), and for economically detrimental effects of large RES on supply infrastructure, providing mitigating measures when adding PV across Boston (Cerezo Davila, Reinhart, and Bemis, 2016). Two others selected ECMs per recommendations of specialized research institutions including the German Institute for Housing & Environment (Nouvel et al., 2015) and the U.S. National Renewable Energy Laboratory (Wang, El Kontar, Jin, and King, 2022). Studies in Sweden and Italy used current building efficiency standards from their respective national legislation to guide the selection of envelope measures (Mata, Wanemark, Österbring, and Shadram, 2020, Zarrella et al., 2020).

3.1.2. Economic criteria

Economic criteria could be used as a basis to select ECMs, or to impose scenario constraints using discounted cost approaches of net present value (NPV) or life cycle costing (LCC). The discounted approaches develop investor perspectives of profitability, thus creating rules within the model to decide whether ECMs are implemented.

Examples of selecting ECMs include one case targeting low- to medium-cost ECMs suited to commercial buildings (Mohammadiziazi, Copeland, and Bilec, 2021), and another adding HRV, noting that professional building owners consider these energy-saving and profitable (Pasichnyi et al., 2019). In the latter, window replacement was described as energy-saving but often not justified based on investment cost versus energy saved, a hypothesis tested.

Applying the discounted cost approaches to create scenario constraints were two multi-family residential studies in Sweden (Pasichnyi et al., 2019, Mata, Wanemark, Österbring, and Shadram, 2020). One sought positive NPV under multiple discount rates to determine how many buildings in the model could profitably implement one or both of the ECMs tested (Pasichnyi et al., 2019). Similarly, the second case used LCC to calculate cost-effectiveness, one of three constraints to evaluate which ECMs would be realized by 2050. Other constraints were placed on workforce and investment capacity, simulating limitations among firms to complete renovations based on a percentage of HFA in the building stock, and limited capital for renovation based on a maximum annual investment. Performance was significantly lower in constrained scenarios, suggesting that growth in construction sector capacity including job creation is imperative to achieve retrofit levels of local

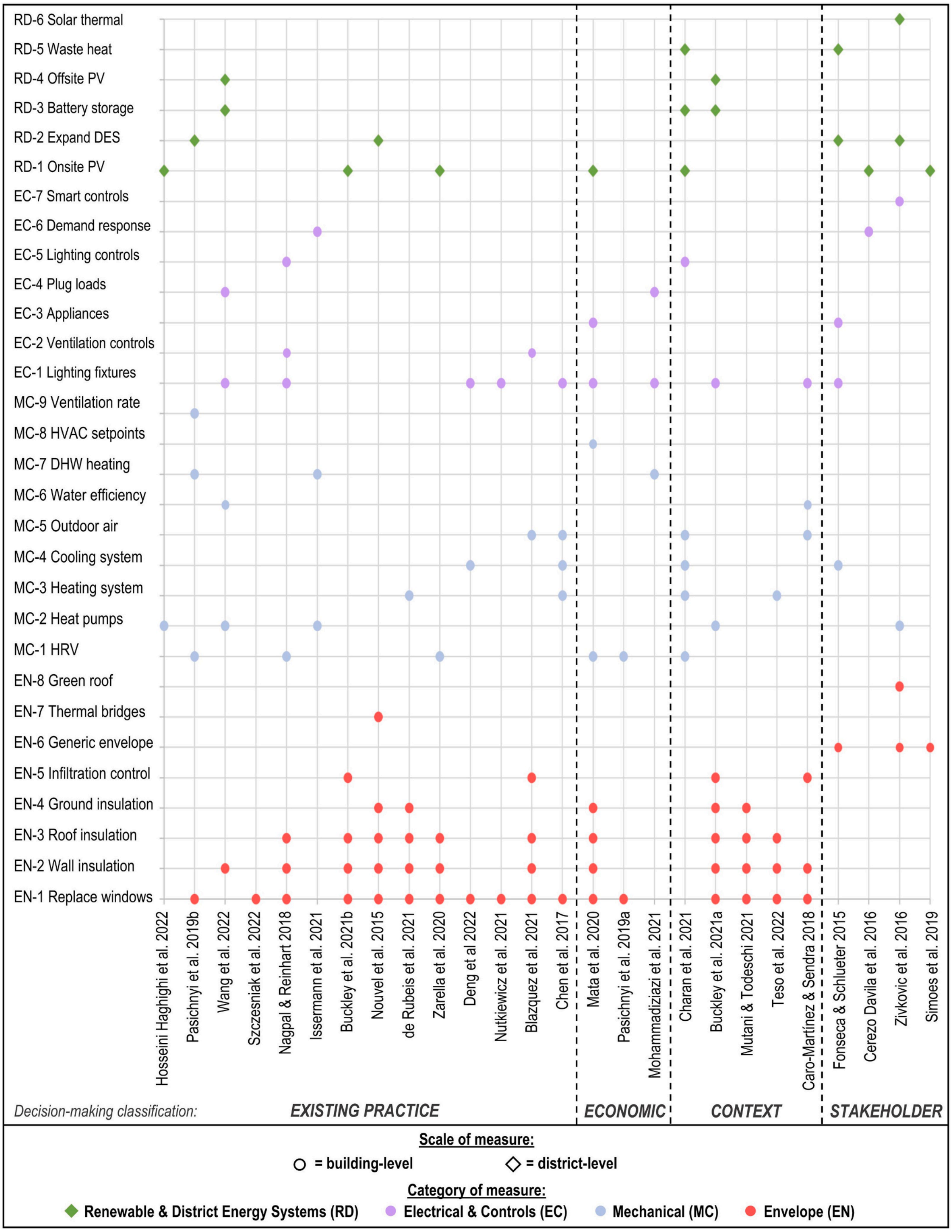

Fig. 3. ECMs in the reviewed studies, based on four retrofit categories, and ranked by frequency based on label number. Predominant decision-making classification is also indicated.

climate goals (Mata, Wanemark, Österbring, and Shadram, 2020).

3.1.3. Context analysis

Analyzing local context was used to select building-level ECMs, or used site resource assessment for district-level measures. For example, one study analyzed energy performance certificates for 42,000 buildings in Turin, Italy, extrapolating the most common retrofits in the existing building stock, then modeling these in the unrenovated stock. The approach accounts for constraints of the existing building stock, the context, and imputed homeowner preferences (Mutani and Todeschi, 2021).

Local context analysis also meant prioritizing measures conforming to historic conservation rules, including window substitution and measures to building interiors (Teso et al., 2022, Caro-Martínez and Sendra, 2018). In Seville, Spain, one study applied exterior insulation only to interior courtyard walls rather than street-facing historic façades (Caro-Martínez and Sendra, 2018). In a historic district in Venice, Italy, installation of roof insulation was planned via unheated attics to avoid altering historic building fabric. Boilers could be easily replaced, but since inaccessible piping would remain, the authors decreased system

Table 2

Energy assessment method, energy services, and energy/emissions quantified in reviewed studies. Time resolution: A = annual; M = monthly; H = hourly; SH = sub-hourly. Energy services: Htg = heating; Clg = cooling; DHW = domestic hot water; Ltg = lighting; Eqp = equipment. + = gas cooking equipment only.

Ref. No.	ENERGY ASSESSMENT METHOD: Measured	Calculated: Data-driven	Calculated: Forward: A/M steady-state	Forward: H simplified dynamic	Forward: H/SH full dynamic	ENERGY SERVICES: Htg	Clg	DHW	Ltg	Eqp	Overall	ENERGY QUANTIFICATION: Energy need	Energy use	Energy generated	Primary energy	Peak electrical load	EMISSIONS: Heating-related CO_2	Overall CO_2
(Hosseini Haghighi, de Uribarri, Padsala, and Eicker, 2022)			√			√							√	√			√	
(Mata, Wanemark, Österbring, and Shadram, 2020)				√		√		√			√		√	√				
(Pasichnyi et al., 2019)	√	√			√	√							√					
(Pasichnyi, Wallin, and Kordas, 2019)	√	√			√	√							√			√		
(Wang, El Kontar, Jin, and King, 2022)					√						√		√	√		√		√
(Szcześniak, Ang, Letellier-Duchesne, and Reinhart, 2022)					√						√		√					
(Charan et al., 2021)					√	√	√	√	√	√	√		√	√		√		
(Fonseca and Schlueter, 2015)	√			√		√	√	√	√	√	√		√		√			√
(Mohammadiziazi, Copeland, and Bilec, 2021)					√	√	√		√		√		√					
(Cerezo Davila, Reinhart, and Bemis, 2016)					√						√					√		
(Nagpal and Reinhart, 2018)					√						√		√					
(Issermann, Chang, and Kow, 2021)					√						√					√		
(Buckley, Mills, Letellier-Duchesne, and Benis, 2021)					√						√		√	√				√
(Buckley, Mills, Reinhart, and Berzolla, 2021)					√						√		√					√
(Zivkovic et al., 2016)		√	√			√							√				√	
(Nouvel et al., 2015)	√	√		√		√		√		√+			√				√	
(Mutani and Todeschi, 2021)		√		√		√		√					√					
(de Rubeis, Giacchetti, Paoletti, and Ambrosini, 2021)			√			√						√	√		√			
(Zarrella et al., 2020)				√		√	√					√		√				
(Teso et al., 2022)					√	√						√	√				√	
(Simoes et al., 2019)		√	√								√		√	√				√
(Deng, Chen, Yang, and Chen, 2022)					√						√		√					
(Nutkiewicz, Choi, and Jain, 2021)	√	√			√						√		√					
(Blazquez, Suarez, Ferrari, and Sendra, 2021)					√	√	√						√		√		√	
(Chen, Hong, and Piette, 2017)					√						√		√					
(Caro-Martínez and Sendra, 2018)					√	√	√				√		√		√			

efficiency. Considering criteria in economic and social domains for insulation selection, advanced technologies (such as aerogel or vacuum insulation panels) could provide thin wall insulation on the interior side, but at a prohibitive cost for the social housing district. Thus, two pathways were modeled using common EPS insulation: exterior EPS, which could be applied to other (non-historic) studies, and interior EPS to historic buildings – a measure that costs less than advanced technologies but consumes more living space (Teso et al., 2022).

Site resource assessments were used to investigate generating or sharing energy at district level. Two cases studied waste heat from commercial or industrial buildings using cooling in winter, to be shared with residences for space heating or domestic hot water (DHW) (Charan et al., 2021, Fonseca and Schlueter, 2015). This could provide up to 26% of the total annual heating load for a district in Chicago (Charan et al., 2021). The site assessments also studied ambient sources of local energy for district heating or cooling, using the local lake in Zug, Switzerland, (Fonseca and Schlueter, 2015) or a canal in Dublin (Buckley, Mills, Letellier-Duchesne, and Benis, 2021). In Zug, combining the local lake as a source and a sink of thermal energy plus waste heat from industrial and commercial buildings could lead to reductions of 70% and 60% in GHGs and primary energy use, respectively (Fonseca and Schlueter, 2015). In Dublin, in addition to ambient energy, unused rooftop space in the adjacent community was studied atop public buildings, a new development, and a train station. With annual offsite PV generation roughly equal to energy use in the retrofitted district, the authors evaluated options of self-consumption, export to the national grid, offsetting seasonal loads in the mixed-use development, and ultimately recommended offsetting energy of the local light rail system, based on its monthly demand best matched to PV energy generated (Buckley, Mills, Letellier-Duchesne, and Benis, 2021).

3.1.4. Stakeholder collaboration

To aid retrofit decision-making, studies could engage diverse stakeholders including planners, city government officials, design consultants, public and private companies, citizens, and other local stakeholders (Fonseca and Schlueter, 2015, Zivkovic et al., 2016, Simoes et al., 2019). Two studies used multi-criteria decision analysis (MCDA), wherein stakeholders discuss and rank criteria to be used in scenario analysis (Zivkovic et al., 2016, Simoes et al., 2019). Both used similar criteria related to energy performance, carbon dioxide and particulate emissions, and renewable energy self-production, though one added qualitative criteria such as aesthetics and ease of implementation to the MCDA in Cesena, Italy (Simoes et al., 2019).

Beyond criteria ranking, studies directly involved stakeholders in the creation of scenarios (Fonseca and Schlueter, 2015, Zivkovic et al., 2016). In one, the stakeholders designed future redevelopment schemes, which the researchers later evaluated for reductions in power capacity for electricity and district heating/cooling, finding possible reductions of up to 24%, 48%, and 26%, respectively, compared to current levels (Fonseca and Schlueter, 2015). In Niš, Serbia, a second study involved stakeholders to a greater degree, soliciting input and feedback throughout multiple stages of the research, from defining system boundaries to analyzing baseline and proposed scenarios, and co-creating scenarios with stakeholders. The co-created scenario increased energy efficiency by 34% and reduced CO_2 emissions by 80% compared to baseline; while these values are slightly lower than researcher-created scenarios, the authors conclude that the co-created scenario better accounted for local priorities of affordability, indoor comfort, economic development, and political will (Zivkovic et al., 2016).

In a single-stakeholder approach, another study worked with the City of Boston to create and validate the first urban building energy model at such scale, aiming at reducing building-related CO_2, identifying economic opportunities, and enhancing energy resiliency (Cerezo Davila, Reinhart, and Bemis, 2016).

3.2. Energy and environmental performance

This section describes how the reviewed studies analyze energy and environmental performance, presents key performance indicators (KPIs), and compares results among studies.

3.2.1. Energy analysis approach

A summary of energy assessment methods, energy services, and energy quantified is provided in Table 2, and further detailed as follows. Nearly all studies quantified baseline energy performance using KPIs of energy use (or need) for the district in megawatt-hours (MWh) and/or using values normalized by HFA in kilowatt-hours per square meter (kWh/m^2). Post-retrofit energy performance was reported variously: in fixed quantities of energy use (MWh), normalized energy use (kWh/m^2), and percentage reduction from baseline. Mean savings values with plausible plus/minus ranges, as suggested by a previous review (Ang, Berzolla, and Reinhart, 2020), were not observed in the 26 studies. All studies reported site energy, except four reporting source (primary) energy. Nearly all studies reported energy performance on an average annual basis, except two studies reporting peak electrical power on design days for heating (Issermann, Chang, and Kow, 2021) or cooling (Cerezo Davila, Reinhart, and Bemis, 2016).

Half of the studies modeled heating energy only, and overall energy in the other half. Overall energy use means all energy services including heating, cooling, DHW, lighting, and equipment. For context, across all EU building sectors, 27% of energy use is for space heating, 16% for process heat, 5% for hot water and other heating, and 2% for cooling, plus 50% for non-heating/cooling (Fleiter et al., 2017). For households, which consume over one-quarter of the EU's final energy, heating is more significant: space heating consumes 63% of energy plus 15% for DHW, whereas electrical lighting and appliances use 15%, space cooling 0.4%, and all other uses total 7% (Eurostat 2022).

This work classifies energy based on ISO 52000 (International Organization for Standardization (ISO) 2017) for overall energy use and heating energy need (or use). In some cases, it was not clear whether studies measured heating energy need or use, interchanging terms "demand" and "consumption". Heating energy need and use differ by the efficiency of combustion-based heating systems, ranging from 90% to 95% for heat generation in the retrofit condition of studies, as per Appendix Table A2. For electrified heat pump (HP) systems, energy need and use differ by the coefficient of performance (COP), which ranged from 2.5 to 5.0 post-retrofit. Emission or other losses were not specified for the systems.

Changes in energy performance from baseline to retrofit condition were based on simulations or calculations, not on real scenarios with monitored data, even if monitored data were used to create some baseline models (indicated in Table 2). Energy performance was often reported with and without RES or DES, which highlights reductions in demand for grid energy due to envelope, mechanical, and electrical ECMs, before adding RES or switching to DES as low-carbon, alternative energy sources. Emphasizing such reductions is in line with the "efficiency-first principle" of the proposed EPBD recast (European Commission (EC) 2021), though the studies did not refer to this principle.

3.2.2. Energy performance results

Energy results are depicted in Fig 4 with normalized energy performance in baseline and retrofit conditions on the left y-axis, and percentage reduction from baseline on the right y-axis. For studies modeling multiple scenarios, the scenario with maximum absolute reduction is shown in bars, and the relative reduction for this scenario is shown in points, with the ECMs in scenarios labeled using codes established in this work (see Fig 3). Points include tails ranging down to minimum savings values in other scenarios of the same study. One exception reported savings ranges depending on building type, so the maximum and minimum shown here are different building types in the same scenario (Wang, El Kontar, Jin, and King, 2022). Four colors

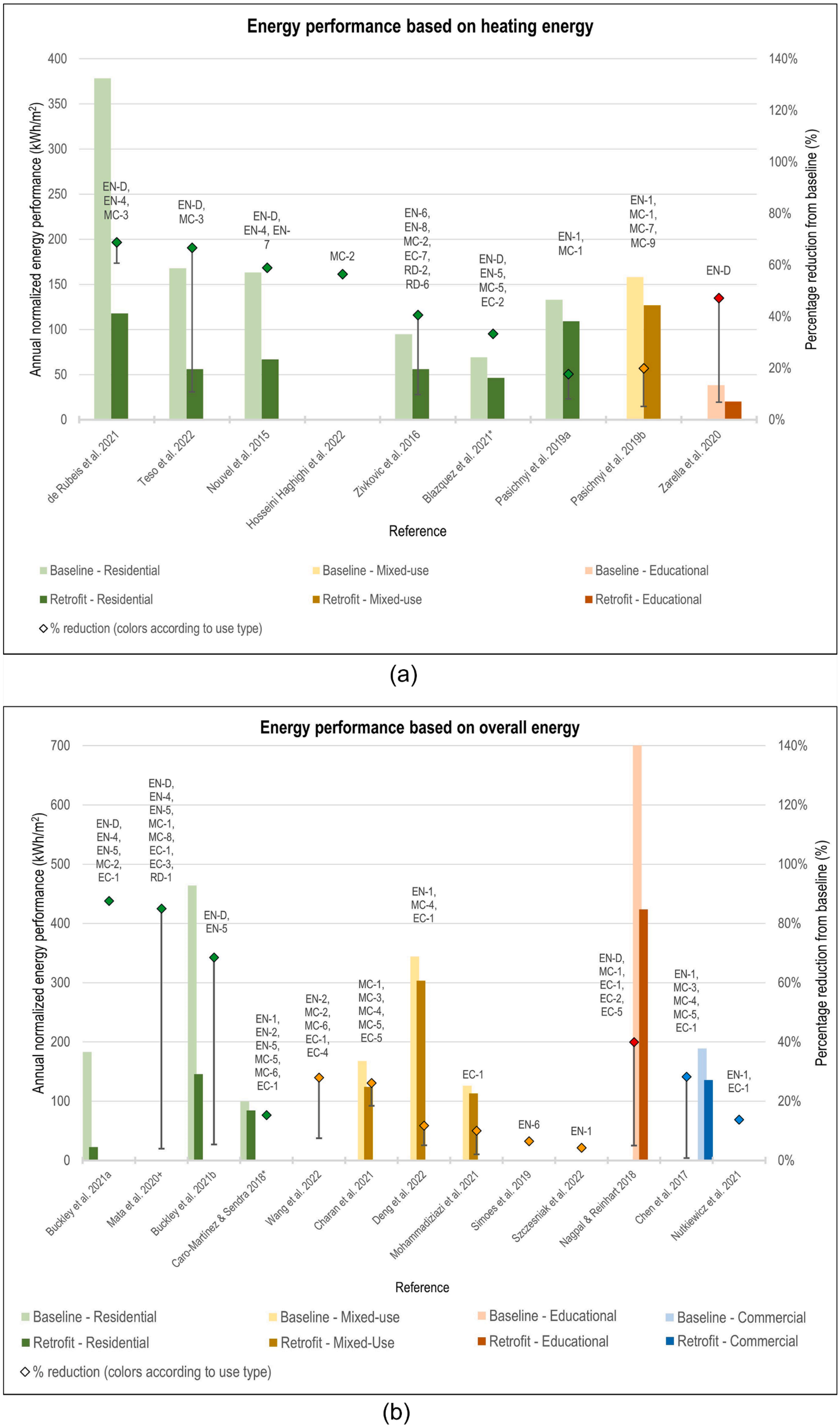

Fig. 4. Annual normalized energy performance in pre- and post-retrofit conditions, plus post-retrofit energy reduction percentage, for heating (Fig. 4a) and overall energy (Fig. 4b). + values include PV generation; otherwise values exclude PV generation; * energy performance reported using primary energy; otherwise, all values are site energy. ECM codes are as per those developed in this work – see Fig 3 for codes.

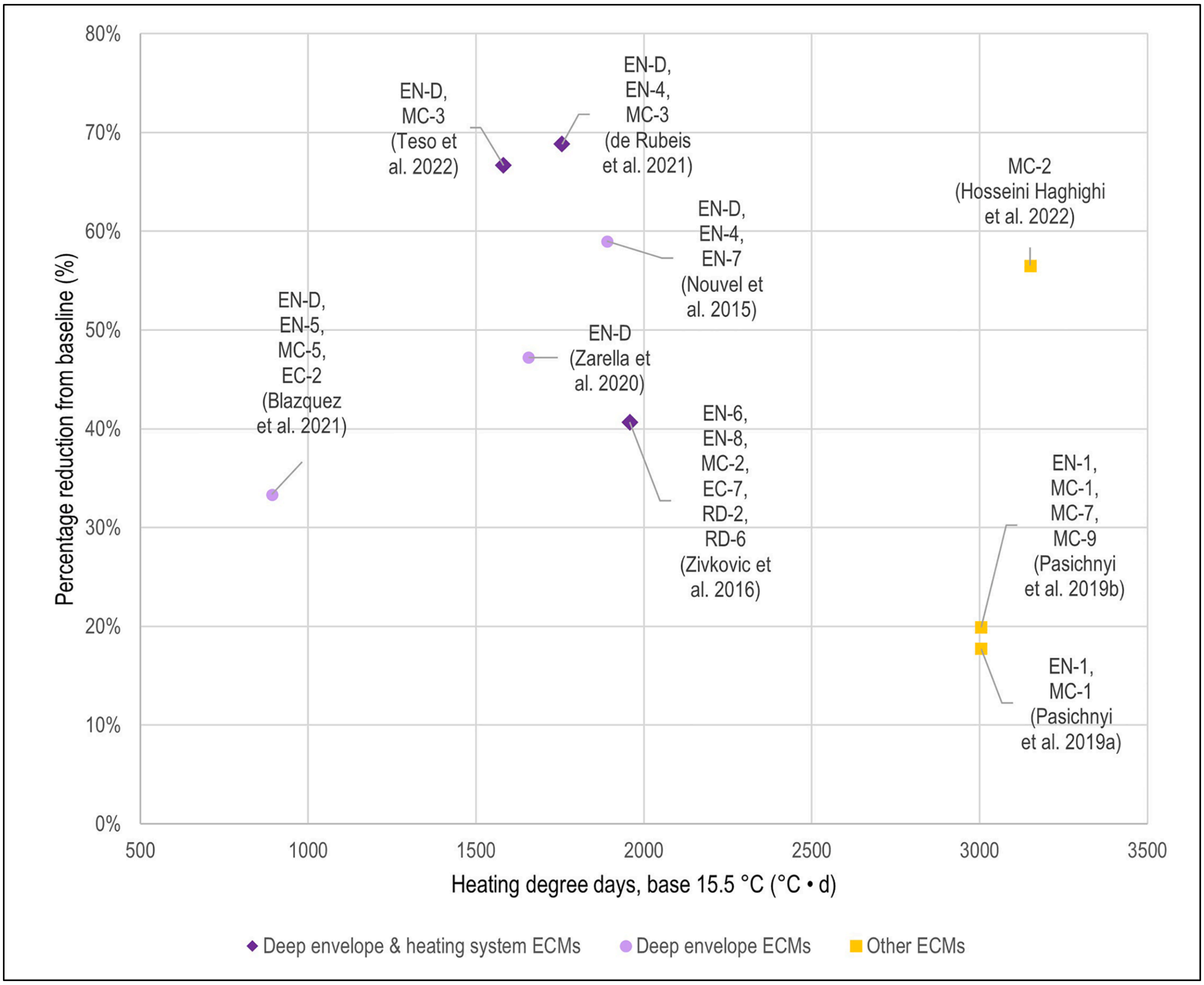

Fig. 5. Heating degree days against percentage reduction from baseline heating energy. See Fig 3 for ECM codes. All studies are predominantly residential cases.

indicate the predominant building type, and separate figures indicate studies quantifying heating and overall energy.

Energy reductions from baseline to retrofit conditions are reported without PV-generated energy, to highlight demand reductions due to ECMs; one exception is where results excluding PV energy were not provided (Mata, Wanemark, Österbring, and Shadram, 2020). Studies that did not report normalized energy performance are represented only with a percent reduction.

Among scenarios showing greater post-retrofit energy reductions in the reviewed studies, common ECMs are observed in residential cases in mixed to cold climates. Savings of at least 40% of heating or overall energy were shown in six studies modeling deep envelope retrofits (EN-D) (Teso et al., 2022, Zarrella et al., 2020, de Rubeis, Giacchetti, Paoletti, and Ambrosini, 2021, Nouvel et al., 2015, Buckley, Mills, Letellier-Duchesne, and Benis, 2021, Buckley, Mills, Reinhart, and Berzolla, 2021). In this context, deep envelope retrofits mean replacing windows and adding wall and roof insulation (EN-1, -2, and -3, respectively). The pattern is similar for the study in Niš (Zivkovic et al., 2016) which applied generic envelope retrofits (EN-6) defined not by building element but by energy class within the context. Energy savings of over 40% were also associated with heat pumps (MC-2) in three studies (Hosseini Haghighi, de Uribarri, Padsala, and Eicker, 2022, Zivkovic et al., 2016, Buckley, Mills, Letellier-Duchesne, and Benis, 2021) or combustion-heating system upgrades (MC-3) in three others (Teso et al., 2022, Zarrella et al., 2020, de Rubeis, Giacchetti, Paoletti, and Ambrosini, 2021).

Further indicating a link between retrofit outcomes and selected ECMs are wide ranges of savings over multiple scenarios within studies, as indicated in the figure by long tails below points. While savings exceeded 60% in cumulative scenarios in two studies (Buckley, Mills, Reinhart, and Berzolla, 2021, Teso et al., 2022), less than 11% of energy was saved when only increasing roof insulation or adding draft excluders (Buckley, Mills, Reinhart, and Berzolla, 2021), and only substituting windows or refurbishing boilers (Teso et al., 2022). In one study, a scenario without constraints saved 85% in overall energy, whereas requirements for cost-effectiveness and other investment and workforce limitations reduced ECM implementation, resulting in savings of only 4% (Mata, Wanemark, Österbring, and Shadram, 2020).

Retrofit savings also depended on building type. Three cases included only non-residential buildings, and these do not follow trends of residential buildings with deep envelope retrofits and/or heating system upgrades. On a university campus in Boston, a scenario applying only envelope upgrades to laboratories, offices, and dormitories resulted in 5% overall energy savings, whereas savings of 40% resulted from a cumulative scenario improving lighting and controls (EC-1, -2, and -5) and adding HRV (MC-1) (Nagpal and Reinhart, 2018). A study of commercial buildings in San Francisco showed little overall energy savings from window substitution or heating system upgrades—around 1% each—whereas combining economizers (MC-5) and upgraded lighting fixtures (EC-1) saved approximately 25% from baseline (Chen, Hong, and Piette, 2017).

Energy performance in baseline condition also influenced retrofit outcomes, especially in residential cases measuring heating energy. Here, higher absolute values of baseline energy represent inefficient

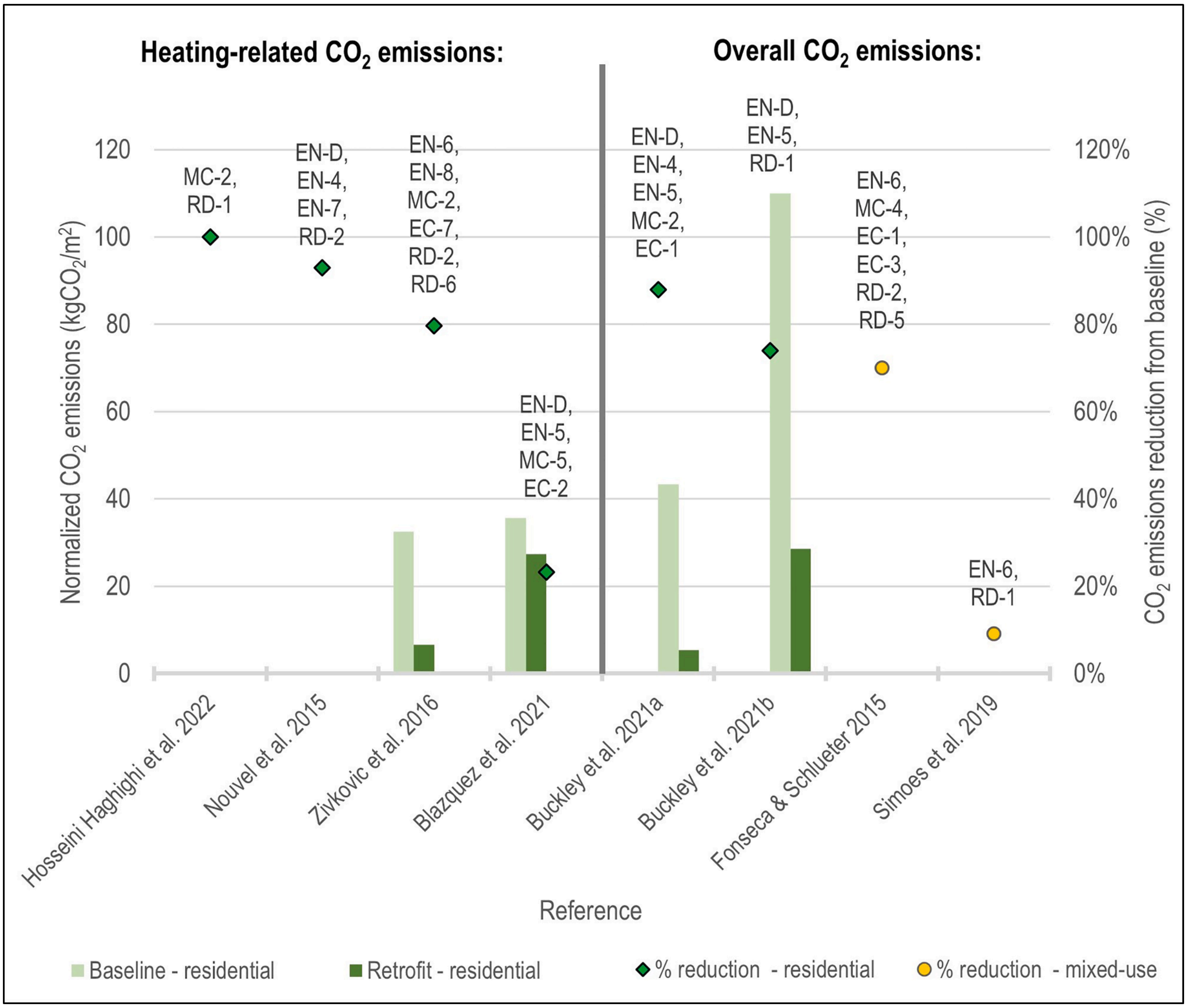

Fig. 6. Annual post-retrofit reductions in overall or heating-related CO_2. Zero values for the left y-axis indicate that normalized emissions were not provided. See Fig 3 for ECM codes.

buildings, which deep envelope retrofits can mitigate. Among residential cases with deep envelope retrofits, three studies (de Rubeis, Giacchetti, Paoletti, and Ambrosini, 2021, Teso et al., 2022, Nouvel et al., 2015) had baseline heating energy values at least 1.5 times greater than two others (Zivkovic et al., 2016, Blazquez, Suarez, Ferrari, and Sendra, 2021), with a significant difference in results; the former three showed reductions ranging from 59% to 67%, compared to 33% to 41% savings in the latter two.

The results did not show a clear relationship between climate and post-retrofit energy reductions. Fig 5 shows heating degree days against heating energy only, to avoid confusing the effect of lighting or appliance ECMs, which decrease overall energy but have negligible relation to heating degree days. Many residential studies in mixed climates with deep envelope retrofits had higher post-retrofit heating energy reductions (Zivkovic et al., 2016, Nouvel et al., 2015, de Rubeis, Giacchetti, Paoletti, and Ambrosini, 2021, Zarrella et al., 2020, Teso et al., 2022). Two cases in cold climates showed lesser reductions, both including only window substitution among envelope ECMs (Pasichnyi et al., 2019, Pasichnyi, Wallin, and Kordas, 2019). On one hand, excluding the latter two, the figure could indicate an increase in heating energy savings as heating degree days increase. On the other hand, the comparison is confounded by divergent baseline energy performance, as noted in the previous paragraph, and a lack of data to establish a clear trend, with only one heating energy study in warm climates (Blazquez, Suarez, Ferrari, and Sendra, 2021).

3.2.3. Environmental analysis approach

After energy performance, environmental performance was the next most common area of analysis, as observed in 10 of 26 studies. Nearly all used the KPI of CO_2 in pre- and post-retrofit conditions, though one study referred to CO_2 equivalent (CO_{2eq}) (Hosseini Haghighi, de Uribarri, Padsala, and Eicker, 2022) and another reported greenhouse gas (GHG) emissions (Fonseca and Schlueter, 2015). Reporting reductions from baseline to retrofit conditions, total tonnes of CO_2 (t_{CO2}), kilograms of CO_2 per square meter (kg_{CO2}/m^2), and percentage savings were common. Studies quantifying only heating energy reported heating-related CO_2 reductions, and those quantifying overall energy reported overall CO_2 reductions, as per Table 2.

Few studies measured environmental KPIs other than CO_2. One of two exceptions reported particulate matter (PM) emissions in baseline and retrofit scenarios, not further specifying $PM_{2.5}$ or PM_{10} (Simoes et al., 2019). Another reported carbon monoxide, methane, volatile organic compounds, sulfur dioxide, and nitrogen oxides, in addition to CO_2, for each scenario modeled (Zivkovic et al., 2016).

3.2.4. Environmental performance results

Post-retrofit CO_2 reductions in the reviewed studies are summarized in Fig 6. For studies with multiple scenarios, only the scenario with the maximum-reported CO_2 reduction is shown, including the ECMs indicated.

Considering heating-related and overall CO_2 emissions, six studies

Table 3
Cost-related information in the reviewed studies. Cost sources: G = governmental report; P = private company report; U = utility company costs; S = a previous study; D = default values from modeling software.

Reference	COSTS REPORTED Investment cost		Operational cost/ savings		COST SOURCES Investment cost	Operational cost	FINANCIAL RETURN MEASUREMENT NPV/ LCC	SPP	Current energy costs & savings
	Total cost	Unit cost	Total cost	Unit cost					
(Mata, Wanemark, Österbring, and Shadram, 2020)		√		√	G; S	P; S	√		
(Pasichnyi et al., 2019)					P	P	√		
(Wang, El Kontar, Jin, and King, 2022)				√	-	U			√
(Charan et al., 2021)	√		√		G	U	√		
(Buckley, Mills, Letellier-Duchesne, and Benis, 2021)		√		√	G	G		√	
(Buckley, Mills, Reinhart, and Berzolla, 2021)		√		√	G	G		√	
(Mutani and Todeschi, 2021)		√		√	G	-			√
(Zarrella et al., 2020)	√				G	-			√
(Teso et al., 2022)	√			√	G	G			√
(Simoes et al., 2019)	√				D	D			
(Chen, Hong, and Piette, 2017)		√			D	D		√	

reduced 69% or more CO_2 after retrofits, and these all used the ECM of deep (EN-D) or generic envelope (EN-6) retrofit, except for one (Hosseini Haghighi, de Uribarri, Padsala, and Eicker, 2022). Three of these studies included HPs as part of the retrofit strategy (Hosseini Haghighi, de Uribarri, Padsala, and Eicker, 2022, Buckley, Mills, Letellier-Duchesne, and Benis, 2021, Zivkovic et al., 2016). Notably, all of the foregoing are residential studies in mixed to cold climates.

The figure highlights the value of expanding existing DES (RD-2), as three such studies show significant CO_2 savings from baseline (Fonseca and Schlueter, 2015, Zivkovic et al., 2016, Nouvel et al., 2015). While building-level retrofits led to energy performance improvements of a maximum of 41% and 59%, adding low-carbon district heating meant corresponding CO_2 reductions of 80% and 93% (Zivkovic et al., 2016, Nouvel et al., 2015).

Savings in CO_2 due to onsite PV (RD-1) were less significant. One case reduced 69% and 74% of CO_2, using deep envelope retrofits and a cumulative scenario adding PV, respectively (Buckley, Mills, Reinhart, and Berzolla, 2021). Another reduced emissions by 99% after adding HPs only, and 100% with HPs and onsite PV (Hosseini Haghighi, de Uribarri, Padsala, and Eicker, 2022). The minor difference here is due to fuel switching from natural gas to electricity in baseline to retrofit conditions. With a largely decarbonized electrical grid in Kelowna, Canada, the emissions factor for grid electricity was smaller by a factor of 74 compared to natural gas, at 179 g_{CO2}/kWh for gas and 2.43 g_{CO2}/kWh for electricity. For context, grid electricity emission factors in other reviewed studies were significantly higher, including 237 g_{CO2}/kWh in Ireland (Buckley, Mills, Letellier-Duchesne, and Benis, 2021), 308 g_{CO2}/kWh in Italy (Zarrella et al., 2020), and 393 g_{CO2}/kWh in Serbia (Zivkovic et al., 2016).

3.2.5. Peak electrical load

A less common area of analysis was peak electrical load, using peak power as a KPI (measured in kW or MW). Five studies demonstrate retrofits to reduce peak electrical loads, including two simulating demand response measures by modifying HVAC setpoints (Issermann, Chang, and Kow, 2021, Cerezo Davila, Reinhart, and Bemis, 2016). One reduced electrical load by approximately 9% over three evening hours, lowering setpoints by 3 °C for electrified heating systems (via HPs) in German residential buildings (Issermann, Chang, and Kow, 2021), and a second reduced peak loads by 28% during the hottest hour of the year using 2 to 4 °C setpoint increases in commercial buildings in Boston, in addition to installing PV on 50% of rooftops (Cerezo Davila, Reinhart, and Bemis, 2016). In Chicago, HVAC upgrades, natural ventilation, and daylight controls reduced peak electrical power by 4% (Charan et al., 2021). A mixed-us case in Colorado added electric vehicle (EV) charging to buildings, initially increasing peak power by 3% to 43%, while adding EVs and battery storage subsequently reduced peak power by 11% to 29% from baseline, due to load shifting effects (Wang, El Kontar, Jin, and King, 2022). In Stockholm, buildings using electrical radiators were quantified at 4.5% of the city's total grid power, to be potentially reduced by switching to district heating, or to heat pumps in locations where DES was unavailable (Pasichnyi, Wallin, and Kordas, 2019).

3.2.6. Performance, climate targets, and net zero energy

The results did not show a clear relationship between post-retrofit energy savings and decision-making classifications developed in this work (i.e. existing practice, economic criteria, context analysis, or stakeholder collaboration). Rather, studies with greater post-retrofit energy or CO_2 reductions among the reviewed literature tended to have climate-related goals. These included: a case supporting the local sustainability plan, showing a post-retrofit CO_2 reduction of 80% (Zivkovic et al., 2016); two aiming to reach European Green Deal targets, reporting energy and CO_2 reductions ranging from 74% to 88% (Buckley, Mills, Letellier-Duchesne, and Benis, 2021, Buckley, Mills, Reinhart, and Berzolla, 2021); and two works seeking to aid regional NZE planning, both reporting NZE outcomes (Hosseini Haghighi, de Uribarri, Padsala, and Eicker, 2022, Wang, El Kontar, Jin, and King, 2022). In other studies, it was not clear how retrofit performance was related to local sustainability or energy plan outcomes (Mohammadiziazi, Copeland, and Bilec, 2021, Pasichnyi et al., 2019, Pasichnyi, Wallin, and Kordas, 2019).

Of the two NZE studies, one can be considered net positive for heating energy only, showing that PV energy generated meets annual HP heating energy use in the district, with an excess to be self-consumed or exported equivalent to 35% of post-retrofit heating energy use (Hosseini Haghighi, de Uribarri, Padsala, and Eicker, 2022). The second case increased efficiency through building-level ECMs, and reduced overall annual grid energy use to zero by adding energy through offsite, ground-level PV panels (Wang, El Kontar, Jin, and King, 2022).

An annual average basis for NZE was standard in the studies, though a finer time resolution reveals a seasonal mismatch between PV generation and HP energy use. Monthly analyses show minimum PV generation in December, amounting to 2%-5% and 7% of annual heating energy use, for two representative buildings in the Kelowna study (Hosseini Haghighi, de Uribarri, Padsala, and Eicker, 2022) and the Dublin district (Buckley, Mills, Letellier-Duchesne, and Benis, 2021), respectively. At this time, heating consumption is highest – around 23%-24% and 19% of the annual heating energy use. Conversely in July, both cases show zero heating and maximum PV generation, amounting to 20%-60% and 27% of annual heating energy use in the studies in

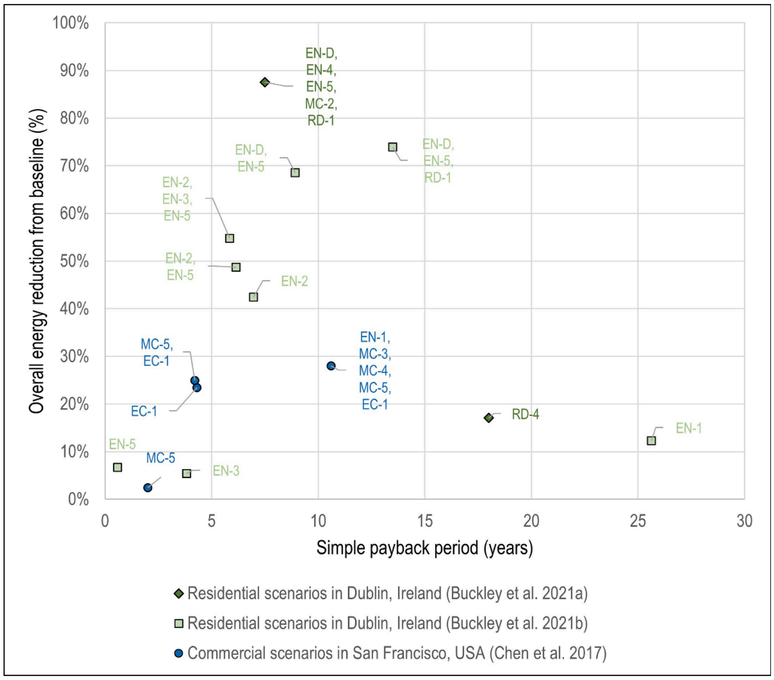

Fig. 7. SPP and percent energy reduction from baseline. Each point represents a separate scenario, labeled with ECM codes established in this work – see Fig 3 for codes.

Kelowna (Hosseini Haghighi, de Uribarri, Padsala, and Eicker, 2022) and Dublin (Buckley, Mills, Letellier-Duchesne, and Benis, 2021), respectively. Since the Kelowna study (Hosseini Haghighi, de Uribarri, Padsala, and Eicker, 2022) analyzed heating energy only, excess energy is assumed to be exported, and not quantified for other uses in the district. In Dublin (Buckley, Mills, Letellier-Duchesne, and Benis, 2021), the authors proposed numerous other uses for the generated energy, minimizing the mismatch in energy production and use, as discussed in Section 3.1.3.

3.3. Retrofit costs

3.3.1. Cost analysis approach

Over 40% of the studies provided cost analysis, as per Table 3. Most of these reported retrofit investment costs including: total scenario cost (Zarrella et al., 2020, Simoes et al., 2019), or unit costs on a per-building, per-area, or other basis (Mata, Wanemark, Österbring, and Shadram, 2020, Buckley, Mills, Letellier-Duchesne, and Benis, 2021, Buckley, Mills, Reinhart, and Berzolla, 2021, Teso et al., 2022, Chen, Hong, and Piette, 2017). Two studies provided ranges, for costs per zone in the study (Mutani and Todeschi, 2021) or energy savings per building type (Wang, El Kontar, Jin, and King, 2022). One study costed the PV system only (Charan et al., 2021).

The majority of studies used government sources for investment costs, such as price lists, energy department reports, and other government agency research. Private company reports were also used. Notably, no reviewed study review determined costs with input tailored to the specific case, whether from contractors or consultants specializing in the retrofits modeled. Thus, the costs originate on a per-unit basis in published literature, and the reviewed studies either analyzed costs and returns per unit, or upscaled to the district level based on total floor area. None of the reviewed studies applied percentage discounts to district projects to reflect economies of scale, though one noted that the concept should induce considerable savings on total costs, but without further details (Buckley, Mills, Letellier-Duchesne, and Benis, 2021).

About half of the studies analyzed costs on a one-time basis only, without discounting future cash flows, using investment costs and energy savings, or using the KPI simple payback period (SPP). The other half used discounted approaches which consider the time-value of money, including NPV and LCC.

The non-discounted approaches considered only the current period, using one-time investment cost and annualized savings, either as a quantity of energy or monetary value. Three studies from Italy compared investment costs to: reduced heating energy use (in MWh) in a 13-building district (Zarrella et al., 2020); ranges of energy savings (in MWh) per zone in a district of over 40,000 buildings (Mutani and Todeschi, 2021); and percentage reduction in normalized energy cost (in euros per kWh/m^2) from baseline to retrofit (Teso et al., 2022). A case in Colorado, USA, did not quantify investment costs but rather annual energy charges, demand charges, and credits for renewable energy production, finding energy cost reductions of up to 40% when adding off-site PV panels and battery storage (Wang, El Kontar, Jin, and King, 2022).

Anther non-discounted cost approach was SPP, which divides initial investment costs by annualized monetary savings, for a result in years. Thus, SPP considers time in its calculation, but without discounting or considering changes in energy costs over time. Two residential studies in Ireland reported SPP of 7.5 and 18 years (Buckley, Mills, Letellier-Duchesne, and Benis, 2021) and 8.9 years (Buckley, Mills, Reinhart, and Berzolla, 2021) for comprehensive retrofit packages, compared to 0.6 years for a single-ECM scenario with the quickest payback (Buckley, Mills, Reinhart, and Berzolla, 2021). The lower SPP means that the initial investment cost is paid back more quickly by annual energy savings. Similarly, for multiple scenarios in a commercial case study in San Francisco, SPPs were 2.0 and 10.6 years for economizers and a cumulative scenario, respectively (Chen, Hong, and Piette, 2017).

Discounted methods including NPV and LCC are other approaches to analyzing costs, based on the concept that future income or savings have less value than those in the present, calculated using a discount rate. With a lifetime of 25 years and discount rates of 4%, 8%, and 20%, a case in Stockholm determined which of three scenarios would have positive NPV for groups of multi-family buildings clustered at district heating metering points (Pasichnyi et al., 2019). The results showed that adding HRV was economically viable (i.e. positive NPV) at 21% of metering points across the city, whereas window substitution and a cumulative scenario were generally not economically viable.

The related approach of LCC was used for PV systems in Chicago (Charan et al., 2021) and a city-wide retrofit program for nearly 6,000 buildings in Gothenburg (Mata, Wanemark, Österbring, and Shadram, 2020). Both cases included initial investment and energy costs in the LCC calculation and used investment periods of 5 to 40 years depending on the ECMs modeled. While not specified in the former study, maintenance and operational costs and a discount rate of 4% factored into the LCC calculation in the Gothenburg study (Mata, Wanemark, Österbring, and Shadram, 2020). The Chicago case showed that profitably adding PV is possible, with a lower cost than business-as-usual over 25 years (Charan et al., 2021). Results on which ECMs were cost-effective were not clear in the Gothenburg case, which applied retrofits in 11 scenarios with multiple constraints through year 2050. Instead, the study makes clear that unrestricted scenarios could save 85% of baseline energy by 2050, while cost-effectiveness constraints would dwindle savings to 15%. Investment and workforce constraints would further decrease ECM uptake, leading to only 4% savings (Mata, Wanemark, Österbring, and Shadram, 2020).

Finally, financial approaches can be integrated with MCDA to evaluate scenarios. In Cesena, Italy, it was not clear whether discounted methods were used, though investment and maintenance costs until 2030 were quantified. Stakeholders used financial results combined with environmental criteria such as CO_2 and particulate emissions, plus qualitative criteria in the social domain such as aesthetics, ease of implementation, and local development potential, to rank alternatives and assist city action planning (Simoes et al., 2019).

3.3.2. Cost results comparison

One basis of retrofit cost comparison uses initial investment divided by the quantity of energy saved annually. Three studies reported this metric, including 0.27-8.18 €/kWh for five scenarios on a university campus in Italy (Zarrella et al., 2020), and 0.07-4.11 €/kWh for scenarios in two residential districts in Ireland (Buckley, Mills, Letellier-Duchesne, and Benis, 2021, Buckley, Mills, Reinhart, and Berzolla, 2021). Such savings can be compared to the local cost of energy, reported as 0.25-0.26 €/kWh for grid electricity in the two Irish studies (Buckley, Mills, Reinhart, and Berzolla, 2021, Buckley, Mills, Letellier-Duchesne, and Benis, 2021), though the Italian campus study (Zarrella et al., 2020) did not state district heating energy costs, and none of these reported gas costs.

In addition to comparing investment and energy costs, another comparison approach uses building owners' willingness to pay (WTP), a field of research within behavioral economics. Citing previous research (Sustainable Energy Authority of Ireland (SEAI) 2018), Irish homeowners' WTP for energy savings was noted as 0.127 €/kWh, and thus only one scenario adding draft excluders (EN-5) fell within this threshold (Buckley, Mills, Reinhart, and Berzolla, 2021). Other reviewed studies did not mention WTP for retrofits.

Another comparison approach uses SPP, which was reported in two studies (Buckley, Mills, Letellier-Duchesne, and Benis, 2021), (Chen, Hong, and Piette, 2017) and calculated in this work for a third (Buckley, Mills, Reinhart, and Berzolla, 2021) based on reported values of energy savings. Fig 7 shows SPP plotted against post-retrofit energy savings for scenarios in residential and commercial cases, indicating that investments with short payback times (e.g. less than 5 or 10 years) are associated with both small and large energy savings. This highlights that shorter payback times can result from either ECMs with low initial investment costs (and often relatively low energy savings), or ECMs with greater savings that compensate for their higher initial costs.

In the figure, the residential studies (Buckley, Mills, Letellier-Duchesne, and Benis, 2021, Buckley, Mills, Reinhart, and Berzolla, 2021) show that comprehensive scenarios including deep envelope retrofits (EN-D), alone or combined with HPs (MC-2), have a high ratio of energy savings to SPP, in two cases reducing baseline energy by 69% and 88% compared to 42% to 55% energy savings in three less-comprehensive scenarios, while adding only 0.5 to 3.1 years in payback time. Single-ECM scenarios at both far left and right of the figure show baseline energy savings all less than 20%, with a significant range in SPP, such as draft excluders (EN-5) with SPP of 1 year to window substitution (EN-1) with SPP of 26 years.

The commercial study (Chen, Hong, and Piette, 2017) shows very different outcomes than the residential studies, as comprehensive scenarios do not increase the ratio of energy savings to SPP. Instead, adding outdoor air with economizers (MC-5) plus efficient lighting fixtures (EC-1) reduce 25% of baseline energy, with an SPP of around 4 years. A cumulative package adding window substitution (EN-1) plus heating and cooling system upgrades (MC-3 and -4) only marginally increases energy savings, but more than doubles payback time.

4. Discussion

As noted, scenarios with deep envelope retrofits, alone or combined with HPs or upgrades to combustion-heating systems, had higher levels of post-retrofit energy and CO_2 performance among the reviewed studies. This was observed in residential and mixed-use buildings in mixed to cold climates, and thus one must limit the finding based on building type and location.

Among residential studies with greater post-retrofit energy and environmental performance, only two (Buckley, Mills, Letellier-Duchesne, and Benis, 2021, Buckley, Mills, Reinhart, and Berzolla, 2021) specified infiltration measures, along with two other reviewed studies (Blazquez, Suarez, Ferrari, and Sendra, 2021, Caro-Martínez and Sendra, 2018). In UBEM calibration studies outside this review, infiltration was a significant factor affecting building-stock energy demand (Sokol, Davila, and Reinhart, 2017, Wang et al., 2020), which was not thoroughly addressed in the reviewed studies.

Other shortcomings in energy and CO_2 quantification are related to divergent approaches in the reviewed literature. Studies variously reported baseline and post-retrofit energy use or CO_2 emissions in normalized values (kWh/m^2 or kg_{CO2}/m^2), using absolute quantities (MWh or t_{CO2}), or reporting percent reductions from baseline. Extensive calculations in the present work were required to comprehend and compare energy and emissions results, though this was not always possible as 12 cases did not provide total district HFA (as per Table 1). To communicate with policymakers, who may be non-energy experts, reporting should be standardized and normalized.

Another inconsistency in studies calculating overall energy, two used primary energy to sum the combination of energy services (heat, DHW, cooling, lighting, and equipment) (Fonseca and Schlueter, 2015, Caro-Martínez and Sendra, 2018), while all others used site energy. A strength, converting to primary energy accounts for different energy carriers (e.g. gas for heating, electricity for lighting, etc.). Using a single standard, such as 52000-1 (International Organization for Standardization (ISO) 2017), would maintain comparability between studies despite divergent national primary energy factors. Alternatively, different primary energy factors can be used to capture country specificity, but these factors should be declared in the analysis.

The reviewed studies indicate challenges related to increases in hourly peak electrical loads with large-scale PV and electrified heating via HPs, as well as monthly mismatches with maximum PV production in July and maximum heating energy consumption in December. Quantifying hourly peak power could uncover further mismatches to be resolved. At the building level, mitigating these effects include applying the "efficiency-first" principle with ECMs to continuously reduce thermal energy need and building energy use, as well as demand-response measures to curtail peaks. At the district level, site resource assessments used to quantify potential generation or sharing of energy could help offset gaps in electrical supply during winter heating. Such examples should be repeated and expanded upon in the future.

Cost outcomes from the studies cannot be generalized, due to limited data and divergent methods reporting costs and savings. More valuable than a comparison of reported costs is this review's analysis of cost approaches. A strength of non-discounted approaches is their ease of comprehension for non-financial experts. With a result in years, SPP provides a simple cost comparison for multiple scenarios within the same building typologies and locations.

Another non-discounted measure, investment cost per energy savings can benchmark against local energy costs, which policymakers can use to communicate with homeowners. Comparing the metric to WTP for retrofits may be useful as policymakers consider subsidies or other policies. Only one study compared scenario costs against Irish homeowners' WTP (Buckley, Mills, Reinhart, and Berzolla, 2021), yet this effort suggests value for UEM studies to connect work on energy and monetary savings to other fields such as behavioral economics. Cost per kWh saved appears to be a common language among the two fields; in addition to the study WTP referenced (Sustainable Energy Authority of Ireland (SEAI), 2018), other research has shown homeowners' WTP for retrofits averaging 1.97 €/kWh in Germany based on 2005 data (Grosche and Vance, 2009), or ranging 0.013 to 1.076 €/kWh in Croatia depending on the retrofit type and based on 2015-16 surveys (Matosović and Tomšić, 2018). The wide-ranging values reinforce the importance of context, as costs and WTP are dependent on location, building type, and time.

Shortcomings of non-discounted cost metrics include using only one-time costs and annualized energy savings, thus lacking a perspective of costs and value over time, and not allowing for changing financial assumptions. Discounted approaches, conversely, can capture complexity over time for district- and city-wide retrofit scenarios, which would certainly be multi-year projects. Methods such as NPV and LCC can account for inflation, interest, and other rate changes, include debt to finance retrofits, and discount cash flows to reflect a professional investor's time-value concept of money. Discounted approaches imposing investment and workforce constraints can mirror real-world conditions.

Another strength, NPV and LCC are not limited to investment cost and energy savings, as highlighted by studies that analyzed operational and maintenance costs. Such costs are not equal between ECMs over their lifetimes and may change financial balances over 25 years. Discounted approaches can also monetize asset value increases at the end of the investment period, a co-benefit from retrofitting largely missing from the financial analysis of the reviewed studies.

Another cost concept absent from the approaches reviewed was economies of scale, which requires costing retrofits on a district basis, not summing costs for individual buildings—a drawback of using unit costs in published literature. A UEM study outside this review used costs quoted by a contractor (Rezaei et al., 2021), an approach not used in the reviewed studies. Therein, the authors suggest a cost reduction of 35% for a cumulative district scenario, due to economies of scale and/or government subsidies, though it was not clear if this percentage was confirmed by the contractor. Thus, economies of scale could be further explored by UEM studies, potentially by collaborating with contractors and cost consultants through the MCDA process.

Evaluating scenarios with stakeholder collaboration and MCDA can address factors motivating building owners to retrofit besides financial cost and savings. A strength, using diverse stakeholders broadens analysis beyond investor perspectives. In particular, two studies involved diverse stakeholders in scenario evaluation, ranking criteria in economic, environmental, and social domains. Criteria included not only CO_2 but other harmful emissions, investment and maintenance costs, as well as criteria absent in other studies such as aesthetics, ease of implementation, and local production of energy sources (Simoes et al., 2019, Zivkovic et al., 2016). Another strength here is the co-creation of scenarios with stakeholders to ensure local priorities would be met (Zivkovic et al., 2016).

In addition to decision-making using stakeholder collaboration, there are strengths in the economic criteria and local context approaches. Studies focusing on economic criteria may help policymakers understand the limits of economic feasibility, and where policy levers or subsidies may be necessary. Studies using context analysis highlighted that historic buildings need well-planned solutions, and that site resource assessments can uncover endogenous sources of energy in districts. Analogous to the argument for economies of scale, site resource assessment treats the district not as a collection of buildings, but as an integrated whole.

5. Conclusion and future perspectives

This review provides the state-of-the-art of UEM studies modeling building retrofits at the district- and city-scale, focusing on decision-making, energy and environmental performance, and cost.

Regarding the first research question on how UEM studies select measures and scenario constraints to model, this work uses four categories to code retrofit measures for scenario comparison, including envelope, mechanical systems, electrical & controls systems, and renewable & district energy systems. The work also classifies decision-making in the reviewed studies according to four categories: existing practice, economic criteria, context analysis, or stakeholder collaboration.

For the second research question investigating pre- and post-retrofit performance, the review describes how UEM studies quantify energy in baseline and retrofit conditions, providing a comparison of energy performance in the studies. The results do not show a correlation between post-retrofit performance outcomes and decision-making approach; rather, performance was linked to whether studies had climate-related objectives. Performance was also linked to specific ECMs, including greater energy and emissions reductions for deep envelope retrofits in residential buildings in mixed to cold climates.

Regarding the third research question on cost and return metrics in UEM studies, the review details cost approaches in the reviewed studies, highlighting how costs can be compared between projects under the limitation that they are for similar locations, building types, and times.

Other limitations include a small dataset for energy performance, especially in warm climates and non-residential building types. Cost data were even more limited. Thus, findings cannot be generalized for performance in warm climates or non-residential buildings, nor for costs in any context. Another limitation arises from the narrow geography of cases reviewed, almost all from the Global North, and thus implications of this study must not be applied to the Global South.

Future literature reviews could update this work as new retrofit-focused studies are published in the burgeoning field of UEM, and could include new visualizations to unlock patterns in the data. Perspectives for future UEM research arise from the strengths and weaknesses discussed for decision-making, energy and emissions quantification, and cost analysis in this work. In summary, future studies in the field can support policymakers by:

- standardizing and normalizing results to be comparable and understandable for non-energy experts, providing total and normalized energy use and CO_2 emissions in baseline and post-retrofit conditions, percentage reductions, and total district HFA;
- stating primary energy and CO_2 emission factors, quantifying consumption of electricity, gas, and other energy carriers in baseline and post-retrofit conditions, and identifying local costs for these utilities;
- providing ranges of plausible energy savings by modulating uncertain simulation parameters such as infiltration (Ang, Berzolla, and Reinhart, 2020);
- analyzing hourly peak electrical loads to mitigate negative effects on electrical supply infrastructure, and reducing seasonal mismatches in generation and consumption;
- providing financial metrics which policymakers can use to communicate with homeowners and professional investors, including SPP and investment cost per annual energy saved, as well as discounted approaches such as NPV and LCC;
- incorporating contractors and cost consultants into the MCDA process to capture economies of scale;

- connecting to other research fields focused on retrofits, including consumer behavior for WTP for retrofits, and MCDA to broaden criteria in scenario evaluation;
- considering how decision-making can increase innovation and stakeholder collaboration, reflecting real-world economic conditions, creating and analyzing scenarios with diverse stakeholders, and assessing site resources to uncover endogenous energy in districts.

Such approaches can help policymakers develop and evaluate action plans, signal paths to innovation, and gain stakeholder acceptance. Cities creating action plans themselves can look to precedents in this work, especially regarding retrofit decision-making, to guide the rapid transformation of the built environment toward climate-neutral cities.

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

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

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Appendix A

Table A1, Table A2, Table A3, Table A4

Table A1
Envelope retrofit details in reviewed studies. IGU = insulated glass unit; SHGC = solar heat gain coefficient; EPS = expanded polystyrene; PUR = polyurethane; ACH = air changes per hour. $^{+}$ = pressure conditions not stated for infiltration rate (e.g. natural pressure, blower-door test, etc.)

Reference	Wall insulation *U*-value in W/(m^{2}K). *(measure noted)*	Roof insulation *U*-value in W/(m^{2}K) *(measure noted)*	Floor insulation *U*-value in W/(m^{2}K) *(measure noted)*	Infiltration measures	Window Replacement *U*-value in W/(m^{2}K) *(measure noted)*	SHGC
(Mata, Wanemark, Österbring, and Shadram, 2020)	0.30	0.25	0.30	-	2.0	-
(Pasichnyi et al., 2019)	-	-	-	-	0.8	-
(Pasichnyi, Wallin, and Kordas, 2019)	-	-	-	-	0.78	-
(Szcześniak, Ang, Letellier-Duchesne, and Reinhart, 2022)	-	-	-	-	1.69	0.311
(Nagpal and Reinhart, 2018)	0.20	0.15	-	-	1.96	0.40
(Buckley, Mills, Letellier-Duchesne, and Benis, 2021)	0.41 to 0.15	0.15 to 0.13	1.58 to 0.61	Depending on building type, reduce infiltration from 0.4 to 0.2 or 0.1 ACH, or from 0.2 to 0.1 or 0.05 ACH^{+}	2.0 to 1.3	-
(Buckley, Mills, Reinhart, and Berzolla, 2021)	0.26 *("Dryline" insulation to interior walls)*	0.13 *(250 mm fiberglass insulation)*	n/a	Use draft excluders to reduce infiltration from 0.4 to 0.2 ACH^{+}	1.2 *(Replace single glass with double IGU)*	-
(Mutani and Todeschi, 2021)	Overall opaque envelope *U*-values approx. 1.18 to 0.65 for pre-1990 buildings Overall opaque envelope *U*-values approx. 0.91 to 0.34 for post-1991 buildings			-	Approx. *U* 3.62 to 2.55 & 3.06 to 1.75 for pre-1990 & post-1991 buildings, respectively	-
(de Rubeis, Giacchetti, Paoletti, and Ambrosini, 2021)	0.53 to 0.29 *(50 to 100 mm EPS)*	0.53 to 0.29 *(50 to 100 mm EPS)*	0.52 to 0.30 *(50 to 100 mm EPS)*	-	1.9 to 1.8 *(Replace single glass with double IGU)*	-
(Zarrella et al., 2020)	0.27	0.24	-	-	1.4	0.35
(Teso et al., 2022)	0.30 *(EPS to interior or exterior surfaces)*	0.23	-	0.5 ACH in baseline condition; retrofit infiltration rate not noted^{+}	2.2	-
(Deng, Chen, Yang, and Chen, 2022)	-	-	-		1.66	0.17
(Nutkiewicz, Choi, and Jain, 2021)	-	-	-	-	1.82	0.25
(Blazquez, Suarez, Ferrari, and Sendra, 2021)	0.54 *(50 mm PUR injection to air chamber in walls)*	0.39 *(60 mm to flat roof; 80 mm to sloped roof; "filter slab" insulation)*	-	Reduce air leakage at windows to 3 m^3/(h m^2) under 100 Pa	1.5 to 1.4 *(Replace single glass with double IGU)*	-
(Chen, Hong, and Piette, 2017)	-	-	-		1.43	0.18
(Caro-Martínez and Sendra, 2018)	*(50 to 80 mm mineral wall to exterior of courtyard walls)*	-	-	Reduce air leakage at windows from 100 to $\leq$50 m^3/(h m^2) $^{+}$	2.65 to 2.56 (glass) & 3.0 to 2.93 (overall) *(Replace single glass with double IGU)*	-

Table A2
Mechanical retrofit details in reviewed studies. WSHP = water-source heat pump; COP = coefficient of performance; DHW = domestic hot water; HRV = heat recovery ventilation. [+] HP type not specified; [++] HP type and COP not specified, [+++] no further system specifications provided.

Reference	Heating & Cooling Systems	DHW Heating	Ventilation Measures
(Hosseini Haghighi, de Uribarri, Padsala, and Eicker, 2022)	Replace with WSHPs, COP 2.5	-	-
(Mata, Wanemark, Österbring, and Shadram, 2020)	-	Replace DHW systems to reduce power density to 2 W/m^2	Add HRV, efficiency coefficient of 0.75
(Pasichnyi et al., 2019)	-	-	Add HRV, efficiency coefficient of 0.50
(Pasichnyi, Wallin, and Kordas, 2019)	Modify setpoints for heating to 21°C	-	Add HRV in archetypes 1 and 3 Adapt ventilation flow rate to 0.35 l/s•m^2 in archetype 2
(Charan et al., 2021)	Replace with 4-pipe fan coils[+++]	-	Add HRV Add natural ventilation
(Mohammadiziazi, Copeland, and Bilec, 2021)	Modify setpoints for heating from 21 to 20°C and cooling from 24 to 25.5°C	-	-
(Nagpal and Reinhart, 2018)	-	-	Add sensible HRV in laboratory exhaust, and enthalpy HRV in all other buildings
(Buckley, Mills, Letellier-Duchesne, and Benis, 2021)	Replace with HPs[+], COP 5	-	-
(Issermann, Chang, and Kow, 2021)	Replace with HPs[++]	Existing DHW systems replaced with HPs[++]	-
(Zivkovic et al., 2016)	2030 heat supply partly based on HPs[++]	-	-
(de Rubeis, Giacchetti, Paoletti, and Ambrosini, 2021)	Replace existing with condensing gas boilers, 0.92 or 0.95 efficiency	-	-
(Zarrella et al., 2020)	-	-	Add HRV to all non-residential buildings, efficiency coefficient of 0.60
(Teso et al., 2022)	Replace existing with condensing gas boilers, 0.9 efficiency	-	-
(Deng, Chen, Yang, and Chen, 2022)	Replace existing mini-split HPs with high-efficiency units, COP 4.5 Replace existing chillers with high-efficiency units, COP 6.3	-	-
(Blazquez, Suarez, Ferrari, and Sendra, 2021)	-	-	Shift to natural ventilation during summer nights
(Chen, Hong, and Piette, 2017)	Gas-fired heating systems, 0.95 efficiency Rooftop cooling upgrades, single- and multi-zone, seasonal COP 5.15 Chiller upgrades seasonal COP 6.27	-	Add air economizers to existing HVAC systems
(Caro-Martínez and Sendra, 2018)	-	Reduce water consumption from 28 to 21L per person/day so DHW demand falls from 12.30 to 9.23 kWh/m^2	Increase natural night-time ventilation period in summer from 7 to 10 hours

Table A3
Electrical & controls retrofit details in reviewed studies. LPD = lighting power density; LED = light emitting diode.

Reference	Lighting Fixtures	Controls	Appliances
(Mata, Wanemark, Österbring, and Shadram, 2020)	Installation of efficient lighting equipment, reducing electricity consumption by 25%, reducing LPD to 0.51 W/m^2	-	Installation of efficient appliances, reducing electricity consumption by 25%, power density of 2.1 W/m^2
(Charan et al., 2021)	-	Add daylighting controls	-
(Mohammadiziazi, Copeland, and Bilec, 2021)	Replace lighting fixtures with LED lamps, LPD reduced by 50% to 75% for different buildings	-	Add appliances with ENERGY STAR label, assumed to be 15% lower plug and process loads
(Cerezo Davila, Reinhart, and Bemis, 2016)	-	Demand response: raise cooling demand temperature by 2-4°C in peak evening hours (2 hours per evening from 5-7 pm)	-
(Nagpal and Reinhart, 2018)	Upgrade all lighting fixtures to LPD of 8 W/m^2	Add vacancy sensors for ambient lighting in non-regularly occupied spaces Add sensor-based automated dimming in all perimeter spaces Add zone CO_2 sensors to control ventilation based on demand Add active air quality sensing in laboratories to setback unoccupied airflow rates	-
(Issermann, Chang, and Kow, 2021)	-	Demand response: lower heating demand temperature by 3°C in peak evening hours (approx. 2.5 hours per evening)	-
(Buckley, Mills, Letellier-Duchesne, and Benis, 2021)	Upgrade lighting fixtures, reducing LPD from 5 to 1.8 W/m^2	-	-
(Zivkovic et al., 2016)	-	Sensors, metering devices, thermostats, and controllers for energy savings ranging from 5-12%	-

(continued on next page)

Table A3 (*continued*)

Reference	Lighting Fixtures	Controls	Appliances
(Nutkiewicz, Choi, and Jain, 2021)	Upgrade all lighting fixtures to LEDs, LPD decrease of 27% from baseline	-	-
(Blazquez, Suarez, Ferrari, and Sendra, 2021)	-	Occupancy sensors to control ventilation based on demand	-
(Chen, Hong, and Piette, 2017)	Upgrade all lighting fixtures to LEDs, LPD of 6.46 W/m^2	-	-
(Caro-Martínez and Sendra, 2018)	Upgrade lighting fixtures, reducing LPD from 5 to 3.3 W/m^2	-	-

Table A4
Renewable and district energy systems in reviewed studies.

Reference	RES components added	Annual electrical energy generated by RES			System and/or installation details
		Added annual RES energy generation (MWh)	Added annual RES energy generation, normalized (MWh/ building)	Added annual RES energy generation, normalized (kWh/m^2 of HFA)	
(Hosseini Haghighi, de Uribarri, Padsala, and Eicker, 2022)	Onsite PV to building rooftops	36,444	44.47	-	Min. 40 m^2 installed/house with min. total annual insolation of 1,100 kWh/m^2 East-west gable roofs have PV panels on both slopes; north-south orientations have PV only on south slope PV panel efficiency of 15%
(Mata, Wanemark, Österbring, and Shadram, 2020)	Onsite PV to building rooftops	309,000	52.4	18.5	10%, 30%, and 50% of roof area (in different scenarios)
(Wang, El Kontar, Jin, and King, 2022)	Offsite, ground-level PV	-	-	-	Added PV panels offsite on ground level since 75% of rooftops have PV in baseline condition Sized to achieve NZE for case study Added PV not quantified in %, m^2, or MWh, though energy performance in studies was reported net of PV energy generated
(Charan et al., 2021)	Onsite PV to building rooftops	-	-	-	100% of roof area Total power capacity of 3503 kW
(Cerezo Davila, Reinhart, and Bemis, 2016)	Onsite PV to building rooftops	-	-	-	50% of roof area PV panel efficiency of 15% Instead of annual PV production, the study reported hourly maximum: 48 MWh produced during peak electrical consumption on design cooling day
(Buckley, Mills, Letellier-Duchesne, and Benis, 2021)	Offsite PV panels, adjacent to case study	4,865	-	-	Total installed area of 30,613 m^2 To be installed on local railway station canopy, on flat roofs of public buildings, and on roofs of a mixed-use redevelopment
(Buckley, Mills, Reinhart, and Berzolla, 2021)	Onsite PV to building rooftops	700	0.56	8.5	Total installed area of 27,738 m^2 area Avg. 20 m^2/building All terraced houses with southerly aspects
(Zarrella et al., 2020)	Onsite PV to building rooftops	1,302	100.2	13.0	40% of roof area Total installed area of 8,651 m^2 Avg. 665.5 m^2/building PV modules oriented south oriented, tilt of 30° PV panel efficiency of 15%
(Simoes et al., 2019)	Onsite PV plus mix of other RES not specified	87,500	-	-	-

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