Renewable and Sustainable Energy Reviews 198 (2024) 114402

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Systematic review: Upscaling energy retrofitting to the multi-building level

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ARTICLE INFO

Keywords:
Energy-efficiency
Retrofitting
Non-residential
Office
Educational
Well-being
Neighbourhood
Zero emissions
Zero energy
Literature review
Bibliometric analysis

ABSTRACT

Retrofitting the building stock is pivotal to achieving climate neutrality by 2050. Most of the existing research on energy efficiency focuses on new residential buildings. The focus must shift to multi-building retrofits, thereby more frequently including non-residential buildings. As multi-building and non-residential projects are given a lighthouse role in achieving current global climate goals, more research should focus on this potential. This study covers single- and multi-building retrofitting projects. It also explores the role of non-residential projects, typical project settings, energy reduction achievements and the added complexity of the multi-building scale. The chosen methodology combines a systematic literature search with a subsequent critical metadata and full-text review of more than 80 peer-reviewed scientific papers. The results show that the number of studies in the research field has increased substantially in the last few years, while the research mostly originates from Europe and focuses on the residential building typology. This research is partly transferable to similar climate zones elsewhere, while a large proportion of climate zones remains unexplored. The current body of definitions and requirements regarding energy retrofitting is an impediment to the comparability of projects, and particularly the multi-building scale is in need of international guidance. Future research should focus on making retrofit measures more applicable internationally, while unifying project boundaries. The stronger inclusion of non-residential retrofitting projects as lighthouse projects including social aspects is needed. Retrofitting that covers energy production and sharing has great potential and should be seen as an opportunity.

1. Introduction

1.1. Climate goals and energy retrofitting on a European scale

Renovating the building stock to fulfil ambitious climate neutrality goals is one of the greatest and most time-sensitive challenges the building and construction sector has faced. National and international climate goals such as the United Nations Sustainable Development Goals [1], with Sustainable Development Goal 11 Sustainable Cities and Communities [2], or the climate reports from the Intergovernmental Panel on Climate Change [3] aim for goals to be achieved in just a few years. In Europe, the building and construction sector, including new and existing buildings, needs to be transformed into a climate-neutral sector within the next 26 years to fulfil the climate goal of carbon neutrality in 2050 [4]. 2030 milestones include a minimum of 40% reduction of greenhouse gas emissions compared to the 1990 level (a new 2020 proposal requires for at least 55%), at least 32% renewable energy share, and at least a 32.5% improvement in energy efficiency compared to projection calculations [5]. For the building and construction sector, there must be a focus on energy-efficient retrofitting to achieve climate neutrality within the existing built environment. The projection that almost all of today's buildings will still exist in 2050 emphasises the need to act now. With its Renovation Wave [6], the European Commission "aims to at least double renovation rates in the next ten years and make sure renovations lead to higher energy and resource efficiency. This will enhance the quality of life for people living in and using the buildings, reduce Europe's greenhouse gas emissions, foster digitalisation, and improve the reuse and recycling of materials. By 2030, 35 million buildings could be renovated and up to 160,000 additional green jobs created in the construction sector […] But only 1% of buildings undergo energy efficient renovation every year, so effective action is crucial to making Europe climate-neutral by 2050" [7]. Recent data from the International Energy Agency (IEA) concerning the building sector reveals that more than 20% of total global energy use can be attributed to residential buildings, almost 10% to non-residential buildings, and less than 5% to building construction. The same is true for 17%, 11%, and 9% of CO_2 emissions, respectively [8]. In Tracking Buildings 2022 the IEA concludes that the building industry is far from being on track concerning climate goals [9].

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https://doi.org/10.1016/j.rser.2024.114402
Received 20 September 2023; Received in revised form 3 January 2024; Accepted 25 March 2024

Abbreviations

EPBD	Energy Performance of Buildings Directive
EU	European Union
HVAC	Heating, ventilation and air conditioning
IEA	International Energy Agency
NZEB	Nearly zero-energy building (alt. "net" and "emission")
PED	Positive energy districts
PRISMA	Preferred reporting items for systematic review and meta-analyses

1.2. Building typology and project scale

To increase renovation rates, the European Renovation Wave specifically targets three focus areas for building renovation, namely (1) energy poverty and worst-performing buildings, often associated with social and multi-apartment housing, (2) public buildings and social infrastructure, and (3) the decarbonisation of heating and cooling [6]. The three areas are described as "a priority for policy and financing because they offer a huge potential for increasing renovation rates while delivering large energy savings and healthier and more comfortable buildings for citizens" [[6], p. 20]. The focus on public buildings and social infrastructures thereby includes building typologies such as office and school buildings, which are expected to be "serving as a role model and reference point" [[6], p. 23]. Despite the strategy having been in place for several years now, there still seems to be a lack of research specifically targeting non-residential buildings. A literature review by Ohene et al. on net-zero-emissions buildings (NZEB) addressed several building typologies on both the single- and multi-building scale and revealed that the keyword "residential buildings" was far more prominent than "office buildings" and "educational buildings". The same study analysed "policy targets", 11 of which included commercial buildings, either directly or indirectly, while only two specifically targeted residential buildings and dwellings [10]. This represented a mismatch between strategies that included non-residential buildings, and the existing research, which mostly concerned residential buildings. The authors therefore stressed the need to reduce energy use and emissions in commercial buildings, and the need for more research. Scaling up from single- to multi-building retrofit projects has also been a frequent research topic in recent years. A scoping review by Fahlstedt et al. on carbon abatement strategies in building refurbishment included the most represented building typologies and the move towards the neighbourhood scale [11]. In this study of building typologies, the authors conclude that most of the available research focuses on residential buildings and raise the concern that the current renovation strategy is determined by the homeowners' capital, while retrofitting public buildings might present less financial uncertainty. Moreover, the authors concluded that "[n]o standardized method exists for assessing several buildings on a larger scale with a broader scope" [[11], p. 13]. Focusing on energy performance at the district level, Amaral et al. concluded in their review that an expansion of the nearly zero-energy principles to urban scales is needed and "should be understood as an opportunity" [[12], p. 32] in future research.

The aim of this study is to contribute to the existing knowledge and to closing the identified gaps by comprehensively targeting the move towards energy retrofitting on a multi-building scale. The topics of increased upgrading and the multi-building project scale have until now mostly been separated. Combining them is expected to have unexplored sustainability potential that can contribute to achieving set climate goals, especially when utilising non-residential buildings as lighthouse projects, implemented on a global scale. The synthesis leads to new aspects such as energy sharing and social sustainability within an existing neighbourhood, but also increased project complexity. Recommendations for stakeholders are given on the basis of the analysis of current approaches, including their contributions and shortcomings.

The remaining parts of this study contain a description of methods and materials in section 2, and a description of results divided into a metadata analysis and full-text analysis in section 3, followed by a discussion of the results and limitations in section 4, and finally, conclusions and suggestions for further developments in section 5.

2. Methods and materials

2.1. Systematic search and review

Methods and materials used in this study are two-fold and combine (1) a systematic search and screening of scientific literature with (2) a critical review of the identified literature. The review approach is chosen as it allows for insights into rapidly changing and substantial fields of research, accounting for existing knowledge, as well as past developments. A systematic search and review is considered suitable as it "[c]combines [the] strengths of [a] critical review with a comprehensive search process" [[13], p. 95]. Included studies can be summarised in tabular form and the outcome allows for a documentation of current knowledge, recommendations for practice, and limitations. The approach is considered more suitable than the commonly used scoping review, of which the perceived weaknesses include the limitation that the outcome is not suitable for policy or practice recommendations [13]. A comprehensive process is needed to systematically and reproducibly search and screen all scientific publications associated with the topics of research. The approach is based on the commonly applied PRISMA 2020 method [14]. The subsequent critical review "goes beyond mere description of identified articles and includes a degree of analysis and conceptual innovation" [[13], p. 93]. It is composed of a metadata review in RStudio using the Bibliometrix package [15] and a detailed full-text analysis and review following the scope of the established research objective. The perceived weakness of a critical review is that there is no requirement for systematicity of the presentation [13]. This weakness is addressed by initially extracting research topics and targeting them consistently throughout the remaining sections of the study. The topics are presented at the end of this section.

Both databases of scientific literature, Scopus and Web of Science, were considered suitable, as they are frequently used in related research. Scopus has previously been used for research of net-zero-energy buildings (NZEBs) [16], net-zero-emission buildings [10], carbon abatement strategies in building refurbishment [11], and zero-emission neighbourhoods and positive-energy districts [17]. Web of Science has previously been used for research on positive-energy buildings and community systems [18], net-zero-energy buildings [19], carbon abatement strategies in building refurbishment [11], and zero-emission neighbourhoods and positive-energy districts [17]. Combining both databases gives more complete search results of available scientific literature.

The search was aimed at energy retrofitting of buildings and building components within multi-building settings, with an emphasis on non-residential, i.e. office and educational buildings. The search terms included (1) multiple abatement goals, (2) energy as an indicator, (3) diverse project scales and typologies, (4) upgrading types and (5) terms for the multi-building scale, as summarised in Table 1. The selection of terms related to the abatement goals and the multi-building scale was based on the state-of-the-art review by Brozovsky et al. [17] on zero-emission neighbourhoods and positive energy districts, to ensure the use of established terminology. The expression "multi-building" is used throughout this work to represent the diverse terminology used in the literature to represent projects exceeding the scale of individual buildings.

The established search terms were combined into a single search query for each database, using their specific search syntaxes that also allow for Boolean and proximity operators. Document titles, abstracts

Table 1
Search terms applied in Scopus and Web of Science.

Abatement goal	Unit	Scale and typology	Upgrading type	Multi-building scale
Low	Energy	Dwelling	Retrofitting	Neighbourhood
Nearly zero		Building stock	Refurbishment	Block
Net zero		Envelope	Modernization	District
Zero		House	Renovation	Precinct
Nnet positive		Building	Optimization	Settlement
Positive		Non-residential	Revitalization	Community
Plus		Office		
Passive		University		
		Campus		

and keywords were searched in Scopus, while titles, abstracts, author keywords and "keywords plus" were searched in Web of Science. Both databases account for British and American spelling variations.

The search was performed on July 20, 2023 and revealed 502 documents from Scopus and 575 from Web of Science. A total of 807 documents remained after 270 documents had been removed using RStudio and the Bibliometrix package, as they were either duplicates or non-accessible [15]. Fig. 1 and Table 2 display the workflow from the search to the screening for suitable research literature. Ultimately, 83 papers remained for detailed full-text review.

Each screening phase, as displayed in Fig. 1, had associated exclusion criteria, ensuring that only suitable and peer-reviewed literature related to the research objective was left for analysis. A description of the individual criteria is displayed in Table 2.

The 83 documents that remained after the screening process were analysed and reviewed in two steps. The first step was an analysis of their metadata using Biblioshiny, resulting in a selection of bibliometric graphs representing annual scientific production, thematic evolution, most represented countries and most represented keywords [15]. This analysis used bibliometric metadata fields such as titles, keywords, countries of authors and publication, years of publication etc., that are contained in the search results. The purpose of the bibliometric study is to give an overview of the research field. The second step of the literature review was a manual analysis of the publications' full texts. The following topics were extracted for this review.

1. Represented study **locations and climate zones.**
2. Covered energy- and emissions-related **definitions and regulations.**
3. Applied **retrofitting measures and achieved energy consumption reduction.**
4. Covered **case study building typologies.**
5. Aspects of **scaling up from single-to multi-building retrofits.**
6. Representation of **comfort, well-being and other social aspects in multi-building retrofitting.**

The numbering of the listed topics corresponds to their coverage in the sections 3.2 and 4.2.

3. Results

The following section contains the results of the metadata and full-text analysis of the 83 documents that remained after screening. The metadata section is divided into aspects of scientific production over time, the topical development over time, the countries of origin of performed research, and the most frequent keywords. The full-text analysis goes into more depth concerning covered locations and climate zone settings (3.2.1), followed by energy- and emission-related definitions and regulations (3.2.2), applied retrofitting measures, and achieved reductions of energy consumption (3.2.3). Furthermore, the analysis includes typically covered case-study building typologies (3.2.4), the implications of scaling up from single-to multi-building retrofits (3.2.5), and how comfort, well-being and other social aspects can be addressed in multi-building retrofitting (3.2.6).

3.1. Metadata analysis

The analysed literature spans 24 years from 1999 to 2023. Scientific production has been particularly high since 2020, which makes for 60% of all 83 documents. The first year of consistent production is 2013, as can be seen in Fig. 2. Scientific motivation and production are often connected to advances and changes in policies and standards. The increase in publications after 2012 may therefore possibly be connected to the implementation of the Energy Performance of Buildings Directive 2010/31/EU (EPBD) and the Energy Efficiency Directive 2012/27/EU as legal acts in 2010 and 2012, respectively. Both directives have since been updated multiple times and are referred to in several of the analysed documents [12,20–26]. Since 2018, the EPBD has mentioned "integrated district or neighbourhood approaches" [[27], p. 22] as a solution, which is possibly one of the triggers of the increase in annual scientific production shortly afterwards, with an expected greater focus on multi-building scale approaches.

The assumed relation between the studied literature, legal acts and policies enforced by the European Commission is explored further by looking at the most represented countries of the corresponding authors and the most represented countries of scientific production, as displayed in Fig. 3. The analysis of countries of scientific production not only accounts for the main authors' countries, but also includes all of the publications' co-authors [29]. It can be observed that of the top 14 of the corresponding authors' countries ($n \geq 2$), all but four countries are EU member states. Of these four, Norway is associated with the EU through European Economic Area agreements, while the UK was part of the EU until 2020. The same goes for the countries of scientific production, where only three of the top 13 ($n \geq 6$) are not currently part of the EU.

The thematic evolution of document titles displayed in Fig. 4 is used to further explore the change in research motivation over the years, and as expected, reveals a shift in focus. The strong focus on "energy" and "buildings" up to 2020 has shifted to include "community" since 2021, and "renovation" since 2022.

The suspected move towards larger, multi-building retrofits is explored further by looking at the most frequent keywords found in the analysed literature. While the search query specifically included the search terms "neighbourhood", "block", "district", "precinct",

Scopus

TITLE-ABS-KEY(((low OR "nearly zero" OR "net zero" OR zero OR "net positive" OR positive OR plus OR passive) PRE/2 (energy)) AND (dwelling OR "building stock" OR envelope OR house OR building OR "non residential" OR office OR university OR campus) AND (retrofitting OR refurbishment OR modernization OR renovation OR optimization OR revitalization) AND (neighbourhoods OR block OR district OR precinct OR settlement OR community))

Web of Science

TS=(((low OR "nearly zero" OR "net zero" OR zero OR "net positive" OR positive OR plus OR passive) NEAR/2 (energy)) AND (dwelling OR "building stock" OR envelope OR house OR building OR "non residential" OR office OR university OR campus) AND (retrofitting OR refurbishment OR modernization OR renovation OR optimization OR revitalization) AND (neighbourhood OR block OR district OR precinct OR settlement OR community))

"settlement" and "community", and the analysis of titles reflects a shift to the community scale, only a few of the most frequent keywords specifically relate to that larger multi-building scale. Looking at the most frequent author's keywords, only the three keywords "district heating", "district" and "positive energy district" among the top 15 keywords ($n \geq 3$) are specifically associated with the larger scale, and none of the top 16 keywords plus (generated from titles, available for Web of Science search results [30], $n \geq 6$), as displayed in Fig. 5. Examining the coverage of non-residential building typologies, no non-residential typology is among the top results of either the author's keywords or keywords plus, which on the contrary include "residential buildings" in shared seventh position.

3.2. *Full-text analysis*

3.2.1. *Locations and climate zones*

Exploring the position of European research in this domain, the full-text analysis of case study locations revealed a similar result to the metadata analysis. 55 of the 83 studies mention a total of 80 case studies. Of the case study locations, 87.5% are in Europe, while the remaining 12.5% are in Asia, as listed in Table 3. 65 of the 70 European cases are within the EU (excluding Norway and England) which again points towards a strong effect of European definitions and regulations. See more on the topic in section 3.2.2 on definitions and regulations.

The differing level of detail when it comes to the description of locations does not allow for an association with specific climate zones in all cases (as the country level often does not refer to a unique climate zone), which was only possible in 72 cases. The Köppen-Geiger representation is the climate zone system used here [80,81], Fig. 6 displays the distribution of all 72 instances (the darker the colour, the higher the number of case studies). Concentrations can be seen in warm temperate (Cxx) and "snowy" continental climate zones (Dxx). Only one instance is in a tropical climate (Aw) and three are in an arid climate (Bxx). The two most represented climate zones are Dfb (cold, warm summer) and Cfb (temperate, no dry season, warm summer), which can be associated with western and eastern Europe, respectively, and similar climates on other continents.

3.2.2. *Definitions and regulations*

Analysing the literature found revealed multiple definitions and a diversity of terminology related to energy- and emission-efficient retrofitting in the building and construction sector. Research of the field is therefore difficult to unify or compare, even though many studies that cover the topic have been undertaken. The issue of non-uniform

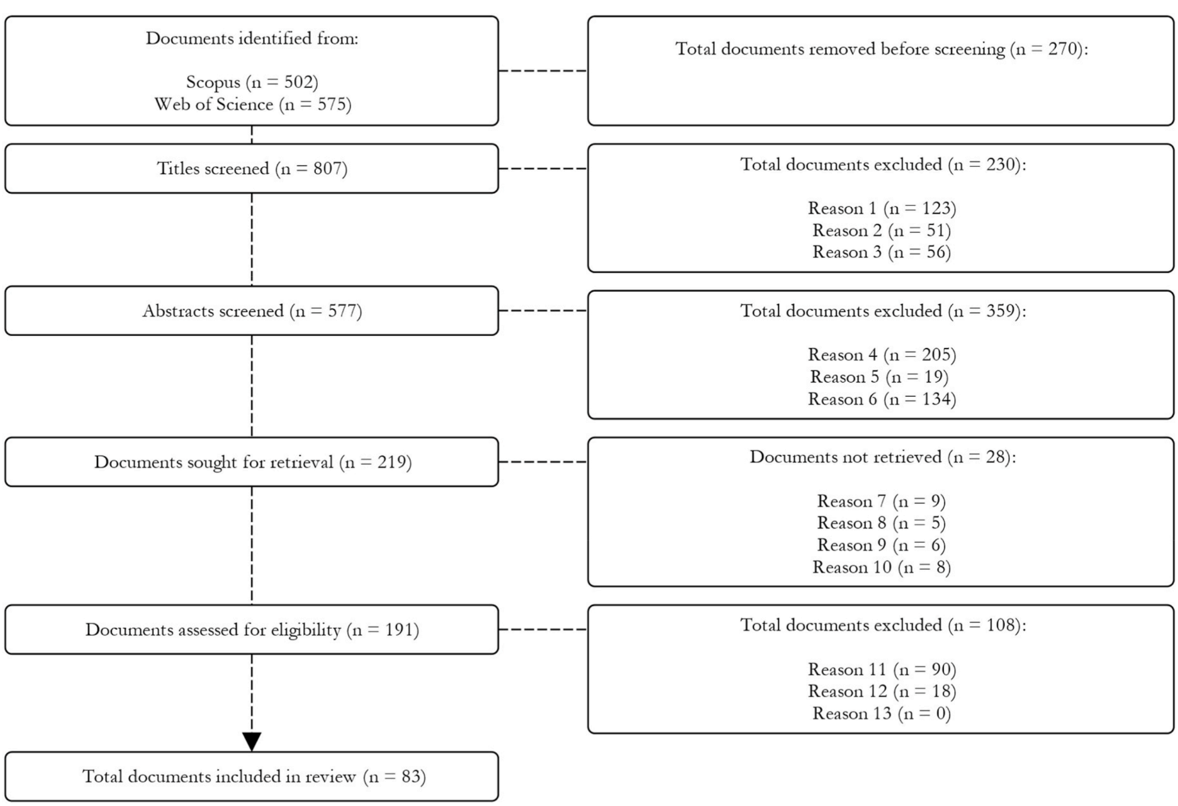

Fig. 1. PRISMA flow diagram, (Page et al. [14], adapted).

Table 2
Exclusion criteria applied throughout the screening process.

Reason	Description	Excluded	Remaining
	Title screening	**230(total)**	**577**
Reason 1	Unrelated areas of research such as chemistry or computer science etc.	123	
Reason 2	Research unrelated to energy-efficient building retrofitting such as material sciences etc.	51	
Reason 3	Document types: books, book chapters, conference proceedings, notes, reports	56	
	Abstract screening	**359 (total)**	**219**
Reason 4	Unrelated areas of research/unrelated research topics (reasons 1 and 2)	205	
Reason 5	Non-applicable document types (reason 3), non-English, duplicates	19	
Reason 6	Non-applicable building scale or type such as new buildings or individual rooms	134	
	Full-text retrieval	**28 (total)**	**191**
Reason 7	Non-retrievable full text	9	
Reason 8	Non-English literature	5	
Reason 9	Duplicate document	6	
Reason 10	Excluded due to quality issues	8	
	Full-text analysis	**108 (total)**	**83**
Reason 11	No energy retrofitting on single- or multi-building scale	90	
Reason 12	Non-applicable building type or scale	18	
Reason 13	No relation to the multi-building scale	–	

definitions for energy and emission strategies is taken up in several studies in the field, on both the single- and multi-building scale [17,82]. Among others things, this resulted in the unified definitions of high energy performance buildings [82] for the single-building scale, and climate friendly neighbourhood [17] for the multi-building scale, for energy and emission related standards. Table 4 presents the concepts named in the two publications mentioned, extended with additional concepts revealed during the literature analysis of this study. Especially the multi-building scale seems to be non-uniform. One reason might be the added uncertainty of the definition of scale. Commonly found terms include "neighbourhood", "district", "community", "campus" and "city", without any clear distinction or number of buildings that clearly results in one of the scales.

To circumvent the need to define yet another concept, the authors use "single-building" and "multi-building" as terms throughout this work to differentiate between measures on the single-building and the combined multi-building scale. The larger scale thereby includes aspects such as sharing mechanisms, transportation and the outdoor environment. The actual dimensions must be defined project-specifically and can even exceed the city scale.

The single-building concept of nearly zero energy buildings (NZEB) is defined in the Energy Performance of Buildings Directive (EPBD) [27] and is referenced by multiple analysed documents. More relevant for this study's topic, however, are mentions of the multi-building scale. Although not addressed directly, the EPBD hints at the extension of the NZEB concept in multiple instances:

- RES (renewable energy sources) can be "on-site or nearby" [[27], p. 3]
- strategies must include "initiatives to promote smart technologies and well-connected buildings and communities" [[27], p. 6]
- "the Commission shall examine […] integrated district or neighbourhood approaches […] for example by means of overall renovation schemes applying to a number of buildings in a spatial context instead of a single building" [[27], p. 22]
- "district or block heating and cooling systems" [[27], p. 28] positively influence the energy performance calculation

The hints align with mentions in the Renovation Wave that classify Positive Energy Districts (PEDs) as part of the strategy to "deliver […] faster and deeper renovations for better buildings" [[6], p. 4] and state that neighbourhood-based approaches are to be placed at its heart [6]. Several publications have picked up the topic of PEDs, with six studies, equivalent to 60%, published since 2022 [21,41,42,47,52,54,60,88,94,95].

3.2.3. *Retrofitting measures and achieved reductions in energy consumption*

In this section, groups of retrofitting measures, as applied throughout the analysed literature, and the associated reductions of energy consumption, are established, based on the case studies of Table 3. Only case studies for which energy consumption as an indicator is extractable are considered. Reviews are not covered, due to the large number of different buildings covered in single publications. The chosen indicator for energy is kWh/(m^2•a), since this incorporates all project scales (i.e. considering both individual buildings and multi-building projects) and percentage reductions to account for different reporting styles (i.e. primary energy and delivered energy). Retrofitting measures are categorised into general groups, to account for most of the analysed studies' designs and reporting styles, as displayed in Table 5. Almost all recorded instances consider envelope retrofitting upgrades, followed by measures related to HVAC upgrades and the installation of renewable energy.

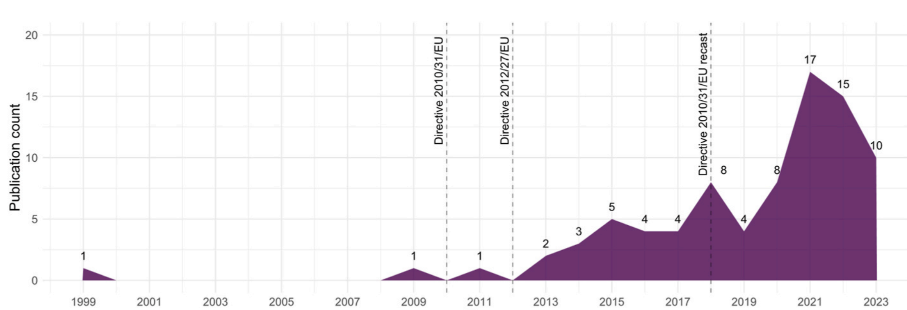

Fig. 2. Annual scientific production (Biblioshiny [28], graphically adapted).

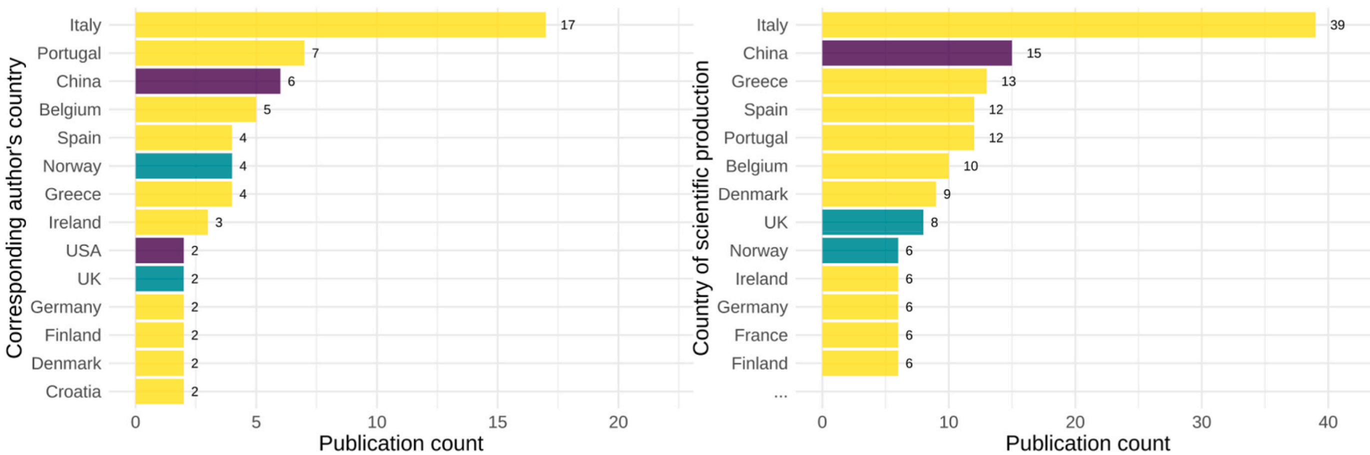

Fig. 3. Top 14 (n ≥ 2) corresponding authors' countries (left) and top 13 (n ≥ 6) countries of scientific production (right), with EU member states in "yellow", EU-related under the European Economic Area or former EU member states in "green", and non-EU countries in "purple" (Biblioshiny [28], graphically adapted).

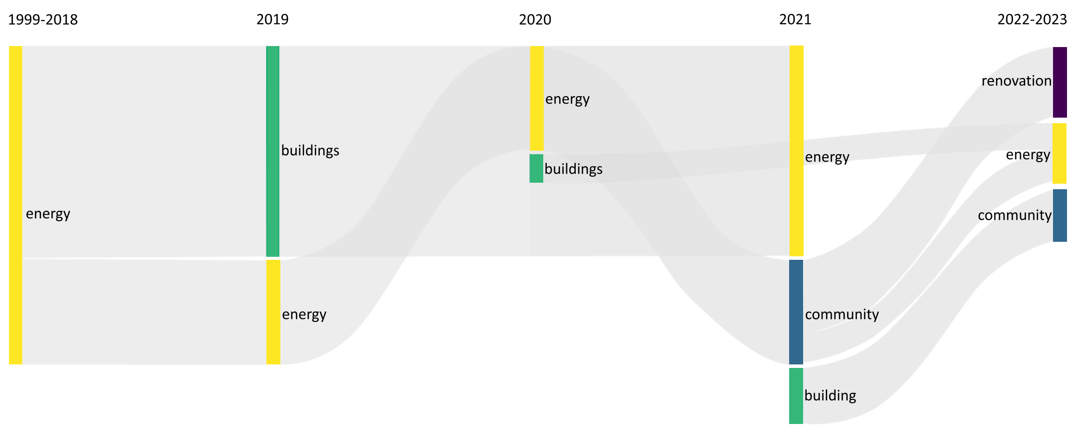

Fig. 4. Thematic evolution map of titles (unigrams), sliced (Biblioshiny [28], graphically adapted).

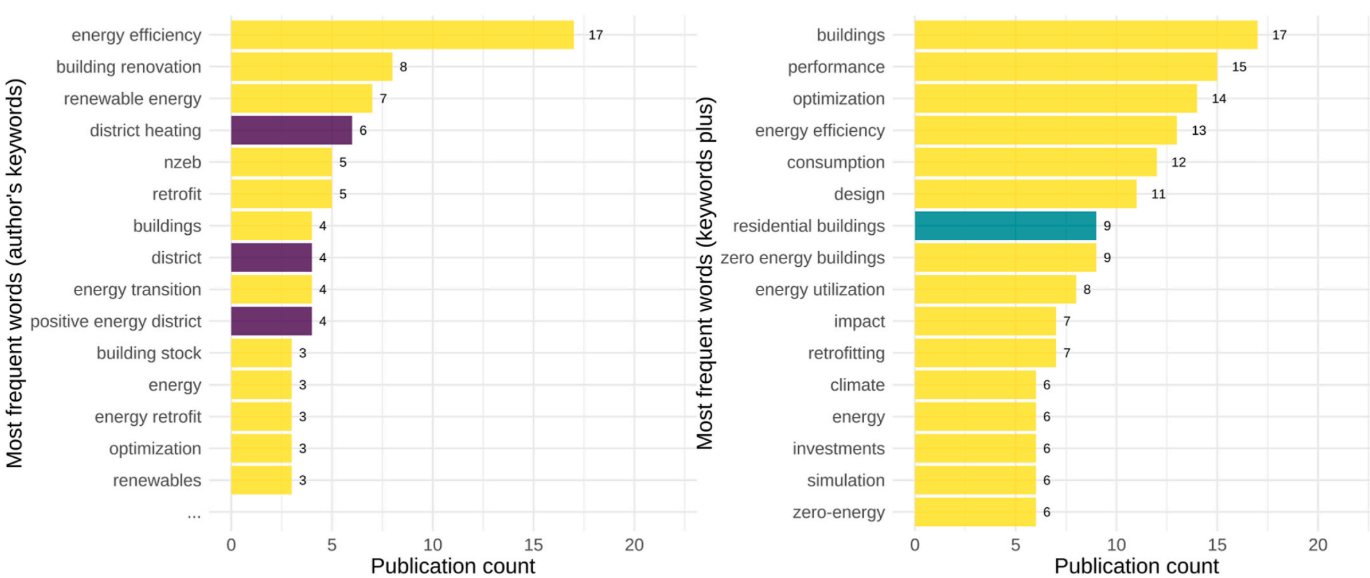

Fig. 5. Top 15 (n ≥ 3) author's keywords (left) and top 16 (n ≥ 6) keywords plus (from Web of Science), with keywords specifically targeting the multi-building scale and specific building typologies in "purple", keywords related to the residential typology in "green", and the remaining keywords in "yellow" (Biblioshiny [28] graphically adapted).

Table 3
Case study locations covered in analysed literature.

Continent	Country	No. of case studies	References
Europe	Italy	14	[21,23,26,31–41]
	Spain	9	[22,42–48]
	Germany	8	[34,42,43,49–52]
	Austria	5	[37,44,49,50,52]
	Denmark	5	[34,44,49,53,54]
	Sweden	5	[20,42–44,55]
	Norway	4	[20,34,56,57]
	Portugal	4	[44,58–60]
	Greece	4	[61–64]
	Finland	3	[24,65]
	Belgium	2	[66,67]
	France	2	[52,68]
	Ireland	2	[69,70]
	Czech Republic	1	[44]
	England	1	[71]
	Netherlands	1	[72]
Asia	India	5	[73,74]
	China	4	[75–78]
	Thailand	1	[79]
SUM		80	

In Fig. 7, the energy consumption reductions achieved throughout all case studies analysed are presented, both in kWh/(m^2•a), since that equalises project scales (i.e. considering both individual buildings and multi-building projects), and per cent [%], to account for different report styles (i.e. primary energy and delivered energy). All but one instance report savings, i.e. energy reductions, while the application of retrofitting in one instance leads to higher subsequent energy consumption.

For the analysis of achieved reductions of energy consumption in the cases analysed, the percentage reduction is chosen as an indicator for further analysis. Most projects achieved a reduction of energy consumption close to 50% as can be seen in Fig. 8. The mean analysed reduction of energy consumption through retrofitting was 51.2%, ranging from 39.4% to 63.1% within a 95% confidence interval. The maximum reduction was 155% (eventually producing excess energy), while one study reported a negative effect of retrofitting measures, resulting in an additional 96% of energy consumption after the retrofitting measures were implemented.

Looking at the implemented measures displayed in Fig. 9, it becomes clear that most studies focus on envelope retrofitting (85%), new HVAC systems (63%), and the installation of renewable energy sources (56%). Only a few studies incorporate measures for controls and schedules (11%), infiltration specifically (15%), lighting (26%) and spatial changes (4%), such as the extension of the floor area as a measure. The figure shows both the number of studies in which the individual measures were applied, and the corresponding share of all studies.

3.2.4. *Case studies and building typologies*

Results presented in this subsection contain the wide range of building typologies and varying project sizes covered in research, from single-building retrofits to multi-building projects. This section looks at both the building typology and project scales. An overview of results is displayed in Table 6. In research focusing on both individual and multiple buildings, it was observed that residential buildings were the most prominent building typology. Research of multi-building projects outnumbered research on a smaller scale. The next most frequently covered building typologies after residential buildings were educational buildings, followed by multiple building typologies combined in entire neighbourhoods.

The multi-building scale dominates the scientific literature analysed, due to the definition of search terms which specifically included "neighbourhood", "block", "district", "precinct", "settlement" and "community". Only 13 studies specifically targeted educational and office buildings, despite being represented in the search with the terms: "office", "university" and "campus".

3.2.5. *Scaling up from the single- to the multi-building scale*

Energy standards and goals have for many years been discussed on a single-building scale, with less focus on the multi-building scale of neighbourhoods, districts, cities etc. This limitation is still recognised within recent literature (i.e. [26,48,73,87,88]). The individual building is seen as a starting point for overall energy reduction, but cannot be considered in isolation, as its performance is highly dependent on its surroundings, which set boundary conditions. Such conditions can be determined by the local climate, including the air quality, noise levels, temperatures, the provision of indoor and outdoor spaces, and the access to infrastructure and other services [31]. Additional dependencies include, but are not limited to, urban airflows, heat island effects, building geometries and occupants' behaviour [25,101]. Table 7 displays advantages of larger-scale projects identified in the analysed literature.

There are several difficulties associated with extending projects beyond the single-building scale. Generally, when the scale increases, more stakeholders are affected, and new boundary definitions are

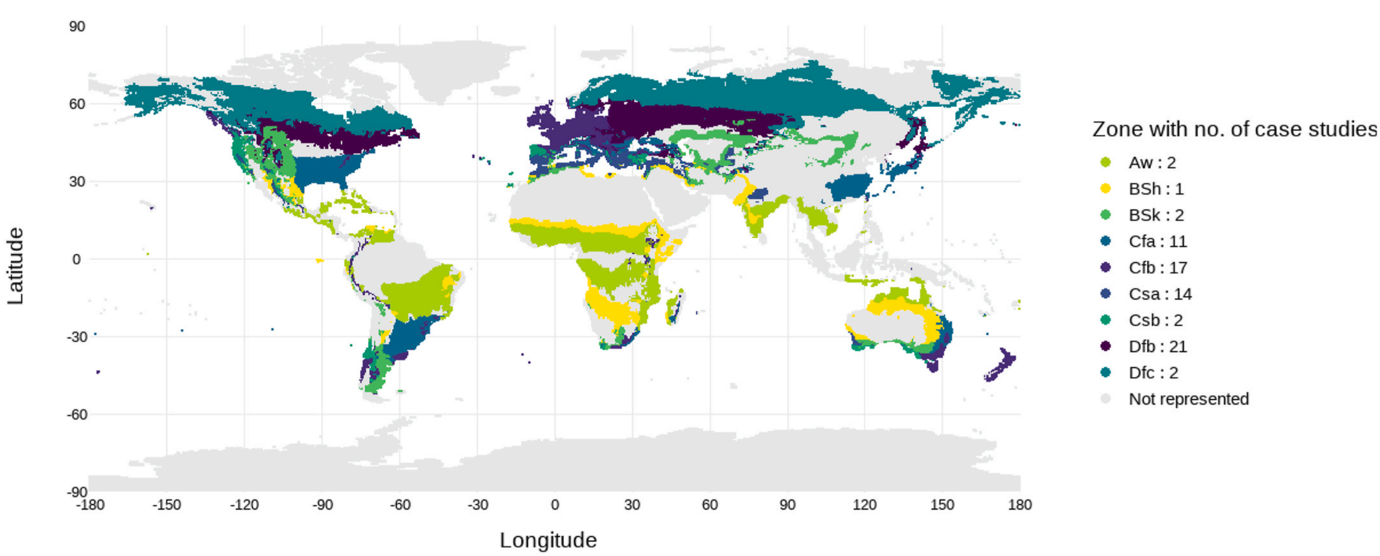

Fig. 6. Case study climate zones according to the Köppen-Geiger climate classifications.

Table 4
Selection of energy and emission goals at single-building and multi-building levels, according to Verhaeghe et al. [82] and Brozovsky et al. [17], extended.

High energy performance buildings [82]		Climate friendly neighbourhoods [17]	
(Nearly) zero energy buildings	[20,32,36,46,69,70,76,83,84]	Nearly zero energy neighbourhoods	[51,85]
Net zero energy buildings	[19,63,79,86,87]	Zero emission neighbourhood	[57]
(Net) positive energy buildings	[18,87]	Positive energy district	[31,42,45,47,60,88]
		Nearly zero energy district	[12]
		Net zero energy neighbourhood	[66,72]
		Net zero energy district	[21,89]
		Net zero energy communities	[73,90]
		Zero energy districts	[41]
Additional definitions on a single-building scale		**Additional definitions on a multi-building scale**	
Low-carbon buildings	[71,75]	Near(ly) zero & positive energy communities	[26,61]
High-performance buildings	[91]	Positive energy communities	[18]
Low-energy buildings	[92]	Nearly zero energy community	[67]
Net-zero-emission buildings	[10]	Net zero energy campuses	[93]
		(Smart) Low energy districts	[43,52]
		Post carbon cities	[40]
		High-performance buildings	[91]
		Net zero energy neighbourhoods	[74]

needed [12,38]. Additional technical infrastructure is likely to be required in retrofitting projects, to enable energy sharing within defined boundaries. The increase in the number of people affected by measures requires considerations that tackle possible rent increases and provide a temporary relocation strategy during retrofitting work [98]. The increase in numbers of stakeholders also imposes difficulties related to energy trading contracts, the ownership and maintenance of renewable energy systems such as photovoltaics (PV) installations [74], and the general need for mutual agreements as a social barrier [48,74]. New boundaries are not only energy-related, but also concern the urban climate, urban morphology, public spaces and inter-building transport [12]. Physical, temporal and other boundaries must be combined with administrative boundaries following "historical, cultural, urban or other criteria" [[89], p. 786].

There is no unified approach to tackling multi-building retrofitting projects in planning. This is not only due to the relative novelty of the field, but also because projects are often unique. Energy modelling must include both detailed single-building and multi-building aspects, to adequately represent the entire system while optimising its entities [32,33]. Aspects of the single-building scale include the modelling of individual energy demand and energy production, and suggestions for retrofitting measures. In contrast, the multi-building scale includes energy sharing, multi-building peak shaving and trade-offs, and a more general formulation of energy and sustainability goals and policies. This leads to bottom-up approaches to energy calculations at a building level, combined with top-down approaches determining the multi-building energy calculations and other inter-building aspects [61,97]. To achieve this combination, it is essential to make deliberate choices when it comes to simulation tools. Since it is still not considered feasible to consider highly detailed building energy models in a multi-building project simultaneously, multi-building simulations "must compromise on the precision of simulation for an individual building, but they can evaluate

Table 5
Retrofitting measures applied throughout the case studies analysed. Measures of the group "control" include measures such as the change of schedules and other control mechanisms, while spatial measures include measures such as the extension of floorspace during retrofitting.

Authors	Ref.	Retrofitting measures						
		HVAC	Control	Envelope	Infiltration	Lighting	Ren. Energy	Spatial
Husiev et al. (2023)	[48]	YES		YES			YES	
Rose et al. (2022)	[54]			YES				
Javier García-Ballano et al. (2022)	[46]			YES				
Hainoun et al. (2022)	[52]	YES	YES	YES			YES	
Bruck et al. (2022)	[42]			YES				
Bertoncini et al. (2022)	[40]	YES		YES			YES	
Aruta et al. (2022)	[41]	YES		YES			YES	
Qu (2021)	[77]	YES	YES	YES		YES	YES	
Hong et al. (2021)	[78]	YES	YES	YES		YES		
Gouveia et al. (2021)	[60]			YES				
Erba and Pagliano (2021)	[31]	YES		YES		YES	YES	
Ascione et al. (2021)	[33]	YES		YES			YES	
Roser et al. (2020)	[51]	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Bisello (2020)	[37]						YES	
Ascione et al. "nZEB" (2020)	[32]	YES		YES			YES	
Ascione et al. "cost-optimal" (2020)	[32]	YES					YES	
Paiho et al. (2019)	[65]			YES				
Mora et al. (2018)	[23]	YES		YES		YES		
De Santoli et al. (2018)	[36]			YES	YES			
Becchio et al. (2018)	[21]	YES		YES			YES	
García Kerdan et al. (2017)	[71]	YES		YES	YES	YES	YES	
Camporeale et al. (2017)	[22]			YES				
Lohse et al. (2016)	[50]	YES		YES	YES			
Almeida et al. (2016)	[58]	YES		YES			YES	YES
Zhivov et al. (2015	[49]	YES		YES	YES	YES	YES	
Rose et al. (2015)	[53]	YES		YES		YES	YES	
Åberg and Henning (2011)	[55]	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.

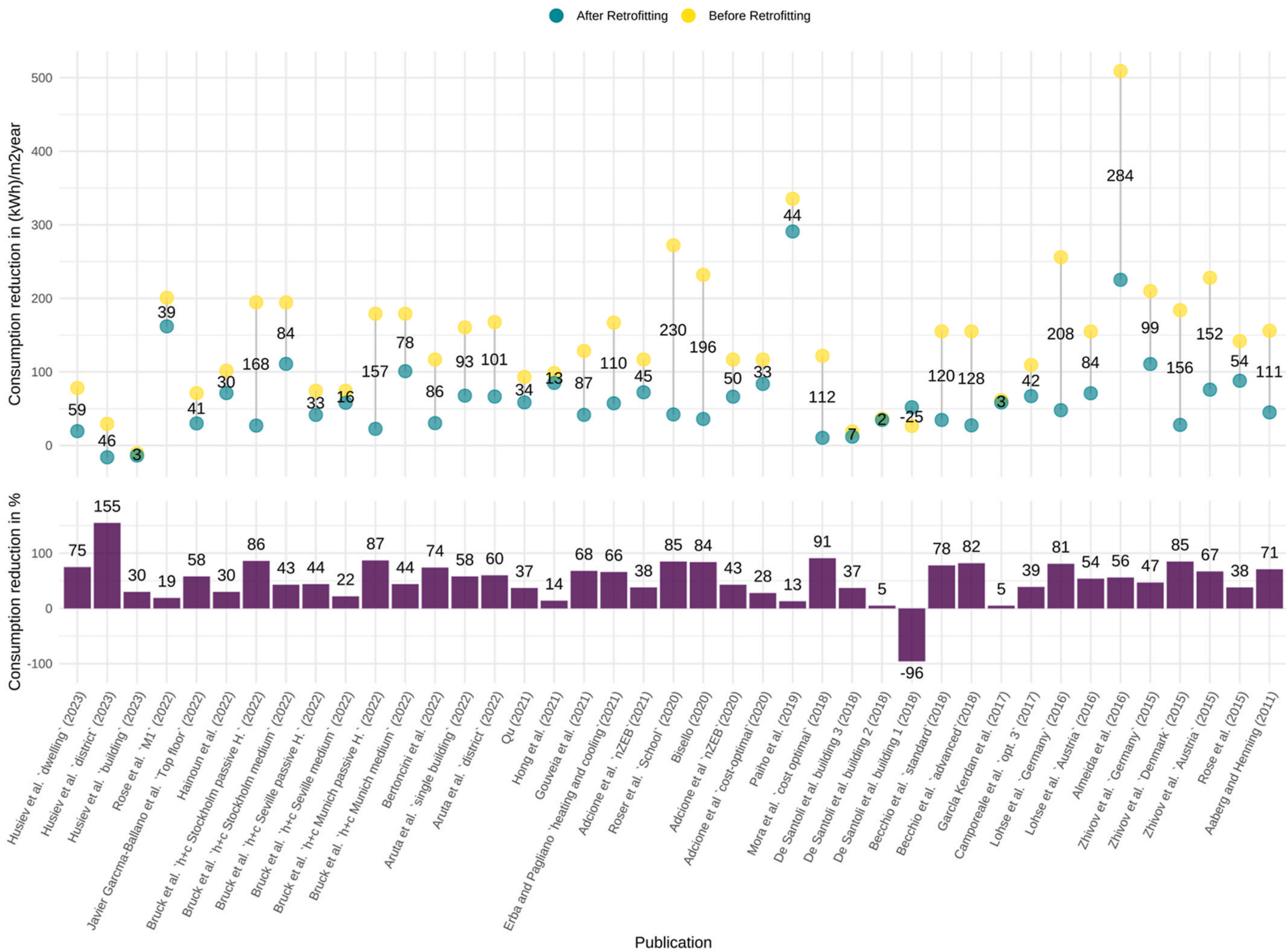

Fig. 7. Reductions of energy consumption after retrofitting as reported in the literature. Abbreviations used represent the specific case chosen from the publication, with "M1" meaning alternative M1, "opt 3" meaning option 3 and "h + c" meaning option heating and cooling.

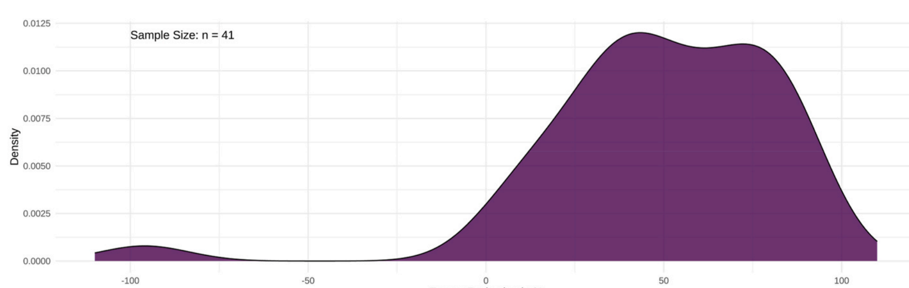

Fig. 8. Analysis of energy consumption reductions found in the analysed literature.

the impacts of energy saving measures (ESMs) with a reasonable level of accuracy" [[97], p. 2]. Modelling approaches include a Pareto multi-objective approach [32,33] or energy evaluations at building level, which are then used for macro-scale analyses [61]. Buildings can be grouped according to their energy profiles, to enable inter-building sharing. The analysed literature included grouping or clustering strategies [76] and a building classification according to a generally recognised building typology or archetypes [21,97,103]. Research showed that it can be beneficial to group buildings of diverse energy characteristics to achieve the maximum sharing potential, lower energy imports, reduced energy peaks, and better performance [76]. Previous multi-building case studies, such as those referenced here, can offer valuable insights and support decision-making strategies when choosing modelling approaches [32,33,45,61,65,96,104–106]. The larger scale brings with it additional aspects such as the inclusion of social and non-technical aspects of stakeholder involvement.

3.2.6. Comfort, well-being and other social aspects in multi-building retrofitting

Well-being and other social aspects are frequently covered in the literature and are part of the move to the multi-building scale. Aspects of comfort and indoor environmental quality are the two aspects mentioned most frequently [25,31,34,51,70,71,78]. Retrofitting can in some cases lead to lower indoor environmental quality, which can be

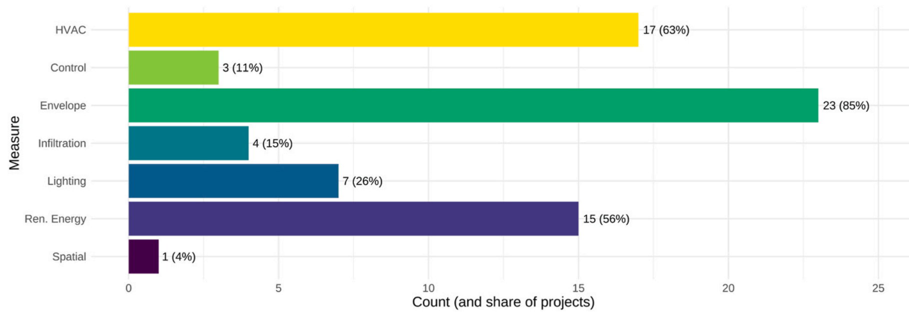

Fig. 9. Number of studies in which individual groups of retrofitting measures were applied, as well as the corresponding share of all studies.

Table 6
Represented building typologies and project sizes.

Typology	Single-building scale	Multi-building scale
Residential	[20,44,48–50, 58,82,84]	[21,22,26,37,40–42,46–48,51,52, 54,55,60–62,67,68,70,72–74,90]
Non-residential		
Educational	[23,34,44,49]	[39,49,51,53,93,96]
Office	[50,77,79]	[78]
Community clinic	[35]	
Community centre	[71]	
Sports centre	[63,64]	
Mixed typologies		
Mixed non-residential		[75]
Residential and office		[52,97]
Residential and industrial		[52]
Residential and public		[52]
Residential and educational		[38,56]
Neighbourhoods		[32,33,59,65,76,98,99]
Cities		[57]
Countries		[24,69,100]

Table 7
Advantages of moving from the single- to the multi-building scale identified in the literature.

Advantages of the multi-building scale	Sources
Better management of energy generation and consumption mismatch than for single buildings	[12,25,41,65,72, 73,88,93]
Lower investment costs, better feasibility (e.g. per user or m^2)	[40,41,73,86]
Better energy distribution through smart grids leads to overall reduced energy use	[41,54,98,102]
A necessity to fulfil international agreements and goals	[40,41,48,73]
More options for large-scale technologies, better availability, and simpler operation and maintenance	[41,86]
More flexibility in energy generation, including off-site production of renewable energy	[41,86]
More options for incentives and stakeholder encouragement for retrofitting projects	[65]
Minimising worst-case planning by accounting for occupant influences and seasonal effects	[72]
Neighbourhood investments benefit residential, tertiary and educational buildings economically	[47]
Availability of neighbourhood-scale measures, i.e. transportation, ground-water and streetlights etc.	[74]

observed in pre- and post-retrofit surveys. A study of a school campus in Germany showed that teachers rated eight out of 13 indoor environmental quality aspects as better before the refurbishment, while nine of the 13 aspects were the same or improved for students after refurbishment [51]. One study mentions that both buildings and their occupants can influence each other. While occupants' behaviour can lead to a performance gap between planned and actual behaviour, building energy reduction might lead to decreased ventilation and consequently reduced indoor environmental quality, which might in turn trigger new user behaviour [70]. Improved indoor environmental quality, better energy performance, and greater sustainability are considered especially advantageous in educational projects where the students can act as communicators [34] and the buildings as contributors to local sustainability [93].

Retrofitting is generally seen as a good opportunity for the implementation of social aspects and well-being related measures, which is addressed by multiple sources [23,31,34,49,91,100,107]. Co-benefits of energy and economically motivated retrofitting measures include aspects of comfort and health in general. The greatest benefits are expected from targeting the most energy-inefficient buildings, socially vulnerable populations, users willing to adopt new measures, and high-diversity user groups [100]. Retrofits that increase both energy efficiency and indoor environmental quality also increase the overall economic value of projects [107]. Energy-related rebound effects are commonly observed as a characteristic of post-retrofitting user behaviour [20,21,100]. They can lead to higher energy consumption or an energy imbalance, emphasising the need for quality assurance and quality control/verification [31,49]. Rebound effects covered in the scientific literature analysed can occur due to (1) oversaturation in the energy market due to lower energy demand, (2) higher goods and services consumption following lower energy bills, and (3) economic growth made possible by improved energy efficiency, which in turn leads to additional energy needs [21].

The topics of comfort and (social) well-being in larger projects specifically were also covered in the literature found [12,21,38,40,45,68, 91,98,108]. The general aim is to advocate human-centred retrofitting projects [45] that not only include energy performance, CO_2-equivalent emissions reduction and economic advantages, but also improved indoor comfort conditions [98]. Human-centred approaches may also include "human activities within the district, as well as management and maintenance methods" [[38], p. 3]. Human activities include the transportation of goods and people within defined system boundaries. Transportation as a topic includes technical aspects, such as energy from transportation [12], and social aspects, such as spatial quality, which are more difficult to define. Spatial quality, as an example, can contain the four determinants of "views, internal spatiality and spatial arrangements, the transition between public and private spaces and perceived, built and human densities" [[68], p. 269] [109], which are both individual and subjective. Other aspects include the human need for local energy security and the right to have a say when it comes to decisions related to energy solutions [40], the needs of an ageing society, and cultural heritage [108]. While some measures on a multi-building scale might conflict with others, co-benefits can be categorised and exploited project-specifically [37,47].

4. Discussion

The discussion section is structured according to the previously presented results, i.e. divided into corresponding subsections. The metadata analysis is discussed briefly (4.1), followed by a more in-depth discussion of the full-text results (4.2). That includes a discussion of covered locations and climate zones (4.2.1), definitions and regulations (4.2.2), retrofitting measures and achieved reductions in energy consumption (4.2.3), case studies and building typologies (4.2.4), scaling up from the single- to the multi-building scale (4.2.5), and comfort, well-being and other social aspects in multi-building retrofitting (4.2.6).

4.1. Metadata analysis

The metadata analysis shows that research of the topic of large-scale retrofitting has gained popularity in recent years, especially since 2021. Both the annual scientific production depicted in Fig. 2 and the thematic evolution map of titles displayed in Fig. 4 confirm the trend. This increased research motivation, likely triggered by previous EU policies, seems to apply mostly to European countries, as can be observed from a review of the corresponding authors' countries and the countries of scientific production. The only other countries in the top positions are China, the USA, the UK, and Norway, despite the need for global application of climate goals. Active research participation might be another reason for the cluster. The IEA currently (at the end of 2023) has 16 ongoing projects, of which multiple projects relate to energy efficiency at multi-building level [110]. Taking IEA Annex 83 on Positive Energy Districts as an example, 16 out of the 20 participating countries overlap with the case study locations identified in the search conducted for this work, which is equivalent to 80%. Similar observations can be made for other IEA Annexes and Tasks. Concerning global mitigation efforts, this limited group of countries represents a gap. Keywords related to the multi-building scale and non-residential projects are not contained as frequently as expected, despite recent advances. Only the three keywords "district heating", "district" and "positive energy district" specifically refer to the larger multi-building scale, when looking at the most frequent authors' keywords and keywords plus. This was an unexpected finding, as the search terminology specifically included both aspects.

4.2. Full-text analysis

4.2.1. Locations and climate zones

The cluster of research performed in European counties, that was also observed while analysing full texts, has little informative value concerning how representative the performed research is, which is why the specific climate zones covered were studied. The analysis shows that research was mostly performed on projects in temperate climates with either no dry seasons (Cfa, Cfb) or dry summers (Csa), in line with the Köppen-Geiger classification described in section 3.2.1. The only other frequently covered climate zone is a continental climate with warm summers (Dfb). These climate zones cover most of the European continent, as displayed in Fig. 6. Since the climate zones are not limited to Europe and also exist elsewhere, the same research applies to a certain degree to large parts of North and South America, southern Africa, and coastal areas in Asia and Australia, at least concerning climate conditions. Only a few climate zones are frequently covered. Tropical climates (class A), arid climates (class B), some of the temperate climates (class C), most of the continental climates (class D), and polar and alpine climates (class E) are underrepresented so far. The climate zones can furthermore no longer be considered static, due to the rapidly changing climate conditions. The consequences of climate change are already clearly apparent, as shown by the heatwaves in 2022 and the resulting droughts throughout Europe. Such events are not yet reflected in the analysed literature, but are expected to be a prominent driver of future research and topics such as the climate resilience of buildings. Current Köppen-Geiger classifications include future climate-zone projections based on the Representative Concentration Pathway 8.5 also used in reports of the Intergovernmental Panel on Climate Change [111–113]. The Representative Concentration Pathway 8.5, scenario represents the version with the highest projected emissions, making it an extreme prediction [112]. Yet retrofitting projects should include some form of future climate predictions, in order to contribute positively to the future built form. Furthermore, despite research applying to other locations with similar climate characteristics, many aspects are not transferable, including applicable local definitions and regulations.

As observed, there are significant contrasts in scientific production, seen across the globe, while common climate goals are in place. This does not necessarily mean less interest but, for example, a lack of resources for research. To address this issue, regulations, definitions, concepts and solutions should increasingly be harmonised internationally. Global organisations, such as the United Nations (UN), have great potential for the future development and management of aggregated knowledge.

4.2.2. Definitions and regulations

The definitions and regulations found in the analysed literature align with previous studies on the topic and extend the list of definitions used even further. Most definitions found for the single-building scale align with previous efforts [82]. New definitions include low-carbon buildings, high (energy) performance buildings, low-energy buildings, and net-zero-emission buildings, equally targeting reduced energy and reduced emissions. A similar observation can be made for the multi-building scale, where previously established definitions [17] were most frequently represented, but were extended by eight additional definitions. On this larger scale, new concepts mostly target energy, which is as expected, since the search terms used only included the energy reduction aspect, and not the one of emissions reduction. The two most prominent definitions represented throughout the analysed literature are the NZEB definition for nearly zero energy on the single-building scale, as per EPBD [27], and the PED definition for positive energy districts on the multi-building scale. Despite mentions of PEDs by the European Commission and an established working group [114], there is no manifestation in directives comparable to NZEB to the authors' knowledge yet, as the IEA Annex 83 Subtask A is still working on that definition [115].

Multiple new and similar definitions and concepts indicate a clear interest in this topic, but also slow down global impact. For application in a larger context, clear common directives and regulations must be set up.

4.2.3. Retrofitting measures and achieved reductions in energy consumption

Looking at the body of literature currently available, it becomes clear that, for the most part, retrofitting efforts consist of a combination of measures of different groups, combining passive and active measures. The discussion of passive vs. active measures was taken up in multiple studies, as the feasibility is dependent on aspects such as project location and local climate. Sola et al. [43] discuss and conclude that passive building envelope measures alone can lead to long payback times, especially in mild climates compared to cold climates. Bruck et al. [42] address the same topic and conclude that while positive effects on emission reductions can be achieved independently of the climate, the economic value of passive retrofitting is higher in cold climates. Bougiatioti et al. [62] conclude that ventilation and shading might be more efficient measures compared to thermal insulation alone when moving to study locations in more southern parts of Greece compared to other parts of the country. Furthermore, even though energy efficiency might be the main objective in many retrofitting projects, economic aspects must always be considered. Cost efficiency can be utilised to evaluate the feasibility of measures or to decide between multiple alternative solutions, which is mentioned in both the EPBD and the Renovation Wave [48]. The application of cost-optimal solutions throughout the analysed literature was apparent. Finally, despite the goal often being zero energy for both small and large projects, the analysis shows that levels equal to or below zero for energy consumption were only achieved in one instance where the energy consumption was previously positive [36].

Achieving the goal of zero energy is within reach. However, the potential of retrofitting on a larger scale offers additional advantages such as energy sharing, and must be further explored.

4.2.4. Case studies and building typologies

The search terminology used in this study favours non-residential over residential buildings, as well as multi-building projects over single-building projects. Despite the use of terms such as "non-residential", "office", "university" and "campus" associated with non-residential buildings of office and educational typology, residential projects outnumbered non-residential projects, on both the single- and multi-building scales. This is an unexpected finding and only 14 publications covered the typologies emphasised, with seven for office and educational usage on a multi-building scale, and seven additional publications looking at mixed typology projects on a neighbourhood scale. This shows yet another gap in the development of retrofitting measures towards climate goals, especially as public buildings, such as universities, are expected to be retrofitted first, since they serve as a "role model and reference point" in the European Renovation Wave [[6], p. 23]. Mixed typologies, however, represent a large share of the literature, which includes both residential and non-residential buildings on various scales. The high proportion of mixed-typology projects indicates a focus on the difficulties and opportunities that come with the move away from single-typology projects. Mixed-typology projects are a good representation of the outcome of retrofitting efforts, as separation into single typologies becomes artificial considering that the majority of the building stock is in need to be retrofitted.

Combining typologies can bring advantages in terms of different energy characteristics that can cancel each other out if combined systematically [76]. These effects were only covered sparsely, and buildings were typically generalised into archetypes [21,97].

4.2.5. Scaling up from the single- to the multi-building scale

The topic of scaling up renovation projects within zero-energy and zero-emission settings was included in the research analysed. The focus of the mentions was on the advantages and disadvantages that accompany the larger scale. The difficulty of defining multi-scale retrofit projects is highlighted by the varying definitions used, as well as the lack of clear international guidance. The analysis of identified scientific literature reveals that projects typically focus on either the single- or the multi-building scale, rather than an incrementally changing built form that includes both scales. This either-or approach is advantageous in terms of project definitions and allows for comparison between before and after characteristics of one or more buildings. However, when considering the need to retrofit large portions of existing buildings, this either-or approach may not be sufficient. As energy balances and network capacity demands are altered with each retrofitted building, a more future-oriented scenario may involve renovating individual buildings incrementally, to ultimately result in entire neighbourhoods, districts, cities, etc. The implications of such stepwise retrofitting for energy supply and demand, as well as the power grid, have yet to be addressed in detail within the literature. A possible reason is that new and adapted forms of energy management are strongly dependent on national and regional supply, technical regulations, and legal roles of ownership including both public and private actors [116]. It must be kept in mind that reduced heat demand due to energy efficiency measures on a larger scale can negatively affect district energy systems in terms of aspects such as co-production [55]. New and emerging solutions for energy trading on a larger scale, including both electricity and heat, may utilize blockchain technologies and smart contracts between the individual system actors [102].

There is interest in scaling up from the single- to the multi-building scale and strategies are emerging as the benefits are apparent. However, there is a need for common guidelines, definitions and general regulations at the international level to facilitate cooperation and the sharing of new knowledge and experience in order to accelerate the implementation of results on a larger scale.

4.2.6. Comfort, well-being and other social aspects in multi-building retrofitting

The concept of well-being in building retrofitting is relatively new and was vague in the literature researched, since so far social aspects are not well-defined in the context of building and construction. This can be partly associated with the interdisciplinary nature of well-being, since, from a human perspective, it is rooted in many fields of social sciences such as philosophy, ergonomics, medicine and psychology [117]. The terminology used ranges from traditional indoor comfort metrics, to co-benefits of energy retrofitting, and new planning aspects such as spatial quality, human-centred planning, and inclusion of user behaviour such as rebound effects. A conceptual approach to well-being in buildings was established in 2019 by scoping which aspects were applied in building research [118]. The nine themes discovered are (1) environmental satisfaction and/or comfort, (2) mental health, (3) physical health, (4) hedonic or subjective well-being, (5) eudaimonic well-being, (6) social well-being, (7) productivity and cognitive performance, (8) other and (9) unspecified. For the establishment of the nine themes and the diverse nature of single- and multi-building scales, only research which "primarily addressed aspects of the physical environment (as opposed to the social environment)" [[118], p. 20] was included. Still, research of single- and multi-building scales was represented equally. In research specifically focusing on the multi-building scale and well-being, the five aspects of (1) community connectedness, (2) safety and security, (3) physical health, (4) mental health and (5) diversity were established [117]. Each of the five indices has associated attributes that can be assessed using a calculation method provided. The method uses equal weighting for all the variables and results, leading to an evaluation of cities using a well-being index. The evaluation method was originally applied to entire cities, but the authors state that this is one of the limitations and that evaluations on a district level "would contribute greatly to fine-grain analysis and understanding of well-being in a local sense" [[117], p. 18]. As for other aspects covered in this review, well-being on single- and multi-building scales is not defined uniformly, which is seen as a gap in the development of future mass retrofits. A recent literature review on the indirect effects of high-performance buildings at different scales proposes a more general approach to well-being and social aspects using the term "co-impacts", which can account for both positive and negative impacts. The authors advocate not including well-being as a mere sub-category of social considerations, but as a category in itself, to indicate the importance of the topic [91].

Retrofitting measures have the potential to increase the quality of life by including a wider spectrum of interdisciplinary social aspects in the design. This can result in increased well-being and reduced social challenges and inequalities among users.

4.3. Limitations

There are limitations to this work's methodology, despite the efforts to make it as unbiased and objective as possible. The search of the Scopus and Web of Science databases builds the basis for the entire study. The search was undertaken in English, which may exclude relevant research in other languages. The search terms themselves were chosen according to the authors' best knowledge and were aimed at keeping the search as broad as possible, in an effort to extract a comprehensive literature subset for the subsequent analysis. At the same time, the systematic search solely of scientific databases leads to an exclusion of literature not published through scientifically peer-reviewed channels, possibly excluding relevant grey literature such as project reports, white papers etc. The material covered is thus unlikely to be exhaustive, which is an inherent limitation of any review, as Booth et al. note [119]. Achieving a state of complete exhaustiveness in literature reviews is unnecessary for their intended purposes, and practical constraints, such as keyword combinations and the selection of scientific databases, impose limitations. The search, using only English-language search terms, may have a limiting effect on the search results, or even create a bias when it comes to study countries and locations. Non-English-language research in other databases cannot be detected even though it might exist and offer insights into other local or national developments.

Analysing a relatively small subset of quality-assessed studies from the identified literature body is one of the characteristics of a systematic search. However, quality assessment is a manual and subjective process when conducting a literature review. Consequently, other experts might include a slightly different subset of literature in the analysis, which again represents a common limitation of literature reviews. Resulting effects can be a differing number of references and statements covered in the individual sections.

Another limitation concerns the analysis and comparison of the studies found, since various analysis and reporting styles had to be taken into account. As a result, the resolution of the analysis of the case study locations had to be reduced to the country level, even though multiple studies contained more detailed and specific location information (see section 3.2.1). Moreover, the retrofitting measures applied had to be grouped into general groups, e.g. “envelope”, as not all studies contained more detailed descriptions of the chosen measures (see section 3.2.3). The comparison of energy consumption reductions achieved through retrofitting was made using kWh/(m^2•a) and per cent as indicators, accounting for projects of diverse scales and for projects using multiple energy definitions, i.e. primary energy and delivered energy (see section 3.2.3). This limitation does not allow for more in-depth analysis and comparison of the case studies found, which, as an example, makes any statement about the savings effect of individual retrofitting measures impossible.

5. Conclusions and further developments

The search of the two databases Scopus and Web of Science was performed on July 20, 2023 and includes 83 publications ranging from 1999 to 2023. The identified scientific literature clearly shows a rise in publications since 2021 and a corresponding trend towards more research at the multi-building level. The countries of origin of the research suggest a strong link to regulations by the European Commission and research efforts such as the multiple energy-related research projects by the IEA. The analysis also shows that the cluster of research performed in European countries can partly represent climate conditions relevant for countries on other continents, while this does not account for local definitions and regulations or predicted future climate scenarios. Many climate zones are not represented at all. The analysed keywords indicate that the multi-building scale and non-residential typologies are less prominently represented than expected. The amount of different terminology found to represent both the single- and multi-building scales and associated objectives represents an impediment to the comparability of projects. Observed effects of research efforts to unify terminology were relatively small, with NZEB and PED as those most represented. Both are referred to by the European Union, while the latter is still under development. The analysed research recognised multiple advantages of the larger scale that include better handling of energy, lower investment costs, greater flexibility and better opportunities for stakeholder involvement. Despite the obvious advantages of larger-scale projects, new issues arise. These include modelling and planning approaches that must be changed to fit both building-specific and overall aspects such as sensible energy-clustering of buildings, more complex social- and travel-related user behaviour, spatial quality and hard-to-define project boundaries. Concerning expected reductions of energy consumption by retrofitting, the mean effect reported was −51.2% of energy consumption. Of cases that displayed a lower reduction, 50% did not include renewable energy sources as a measure. This indicates a limit to how much energy reduction can be achieved without compensation through energy production. Most projects predominantly implemented passive measures of envelope retrofitting, which is reported to be economically feasible, mostly in cold climates. Measures for HVAC systems and updated energy supply, as well as the installation of consumption-compensating renewable energy sources, were applied in most cases.

Several gaps in retrofitting on a multi-building scale with focus on energy efficiency identified in this study should be addressed in future research:

(1) To achieve the climate goals set, the number of energy retrofitting projects spanning multiple climate zones and buildings, and applying uniform boundary conditions, must be increased. That would increase comparability and international applicability, but is currently difficult to achieve due to a lack of both documented solutions, pilot projects, international guidelines, and uniform definitions. Future efforts are suggested to either target the national level (i.e. Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN) in Norway) or the international level (i.e. PED in Europe), instead of individual case studies.
(2) Non-residential projects are currently underrepresented, despite being defined as a starting point in international efforts to increase renovation rates. Educational retrofitting projects can specifically profit from their diverse user groups as communicators. University campus projects are regarded as favourable pilot cases, as they are often publicly owned and funded, while being situated in an active research environment. The potential of multi-building energy retrofitting projects is so far underestimated, as these cases are poorly represented in research, while they should be seen as an important measure to increase the quality of life by reducing social challenges and inequalities at the neighbourhood level, alongside environmental and financial gains.
(3) Additional efforts are needed during and after retrofitting, as more than half of the cases covered do not fulfil the international deep renovation requirements. Conventional, and often partial energy retrofitting projects should be replaced by more in-depth and comprehensive projects. More frequent integration of on- or off-site renewable energy sources and smart sharing are required. Additional establishment of local energy networks for a group of buildings with a single owner is a recommended starting point, as this simplifies sharing and trading, as well as reducing the renewables-induced strain on national grids.

This study offers new insights that enhance the understanding of energy retrofitting on the multi-building scale. In particular, the evolution of the topic, tracking of academic production, identification of research gaps, and suggestions for future research and policy actions, are a contribution to the field. The presented results have the potential to inform developers and owners of large building portfolios, as well as policy makers. The findings call for stronger international efforts on alignment of definitions, and more systematic reporting of results from energy retrofitting measures and their effectiveness. Solely analysing scientific literature in the English language extracted from two scientific databases represents the main limitation of the study. Future research on the topic should aim at overcoming this limitation by also including multi-language grey literature and additional sources of specialised literature worldwide in the analysis. Suitable platforms for such an undertaking are, for instance, IEA annexes and tasks. Finally, the findings highlight the need for more research on multi-building energy retrofitting as an important contributor to achieving global climate change targets, addressing energy shortages and gaining a more sustainable built environment in line with the United Nations Sustainable Development Goals.

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.

Acknowledgement

- We gratefully acknowledge the input and feedback given by Lars Gullbrekken from SINTEF Community while preparing the methodological approach, David Collins from the NTNU Department of Architecture and Technology for help during the proofreading phase, and Tanja Scheffler from the NTNU Department of Architecture and Technology during the screening and visualisation phase.

- This analysis has been written within the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN). The authors gratefully acknowledge the support from the ZEN partners and the Research Council of Norway (project no. 257660)

- Open Access Funding by the Norwegian University of Science and Technology, NTNU.

All data used in this analysis can be made available upon request.

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