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Analysis of life cycle assessment and energy efficiency strategies in social housing: a systematic review

Análise das estratégias de avaliação do ciclo de vida e eficiência energética em habitação social: uma revisão sistemática

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ABSTRACT This article presents a systematic review of the literature on life cycle assessment (LCA) and energy efficiency in social housing, focusing on the interaction of these aspects with the electrical grid. The study evaluates different LCA methodologies applied to housing projects, considering variations in construction parameters, energy performance, climate context, and methodological choices. The review revealed important gaps in existing approaches, especially regarding the absence of a standardized methodology for assessing environmental impacts beyond carbon emissions and energy consumption. The main issues addressed in the article were: (i) mitigation strategies for energy efficiency in social housing (RQ1), which highlight operational energy use as the main contributor to environmental impact during the life cycle of social housing; (ii) design alternatives for social housing with a focus on energy efficiency (RQ2), which highlight the importance of the climatic context, building typology, and insulation system for energy efficiency; and (iii) material intervention strategies (RQ3), which discuss the embodied impacts of insulation materials, emphasizing the importance of considering these effects when evaluating alternative materials and construction techniques. The review concludes that, although design alternatives and construction materials have a significant impact on energy efficiency, the lack of a comprehensive assessment that considers all aspects of the life cycle limits the ability to draw definitive conclusions about best practices. The article emphasizes the need to adopt an integrated and comprehensive environmental assessment methodology that considers not only carbon emissions and energy consumption but also other relevant environmental impacts. The implementation of a more systemic approach is essential to advance the construction of more sustainable social housing, meeting the principles of the circular economy and promoting the transition to low-carbon electricity systems.

Keywords: Life Cycle Assessment (LCA); energy efficiency; social housing; building materials; environmental impacts

RESUMO

Este artigo apresenta uma análise sistemática da literatura sobre a avaliação do ciclo de vida (ACV) e eficiência energética em habitação social, com foco na interação desses aspectos com a rede elétrica. O estudo avalia diferentes metodologias de ACV aplicadas a projetos habitacionais, considerando as variações nos parâmetros construtivos, no desempenho energético, no contexto climático e nas escolhas metodológicas. A revisão revelou lacunas importantes nas abordagens existentes, especialmente no que tange à ausência de uma metodologia padronizada para a avaliação dos impactos ambientais além das emissões de carbono e do consumo de energia. As principais questões abordadas no artigo foram: (i) estratégias de mitigação para a eficiência energética em habitação social (RQ1), que destacam o uso operacional de energia como o principal responsável pelo impacto ambiental durante o ciclo de vida das habitações sociais; (ii) alternativas de design para habitação social com foco em eficiência energética (RQ2), que evidenciam a importância do contexto climático, da tipologia do edifício e do sistema de isolamento para a eficiência energética; e (iii) estratégias de intervenção material (RQ3), que discutem os impactos incorporados de materiais de isolamento, ressaltando a importância de considerar esses efeitos na avaliação de alternativas de materiais e técnicas construtivas. A revisão conclui que, embora as alternativas de design e os materiais de construção tenham um impacto significativo na eficiência energética, a falta de uma avaliação abrangente que considere todos os aspectos do ciclo de vida limita a capacidade de tirar conclusões definitivas sobre as melhores práticas. O artigo enfatiza a necessidade de adotar uma metodologia integrada e abrangente de avaliação ambiental que contemple não apenas as emissões de carbono e o consumo de energia, mas também outros impactos ambientais relevantes. A implementação de uma abordagem mais sistêmica é essencial para avançar na construção de habitação social mais sustentável, atendendo aos princípios de economia circular e promovendo a transição para sistemas de eletricidade de baixo carbono.

Palavras-chave: Avaliação do Ciclo de Vida (ACV); eficiência energética; habitação social; materiais de construção; impactos ambientais

1. Introduction

Global population growth has driven an increasing demand for energy, whose environmental impacts are becoming increasingly evident (Ascione *et al*., 2024a). In response, the United Nations Sustainable Development Goals (SDGs), specifically Goal 7, set the target of increasing the global rate of improvement in energy efficiency from 1.3% per year to 2.7% per year between 2015 and 2030 (Dahiya & Laishram, 2024). Complementarily, in Europe, the International Energy Agency (IEA) has outlined an ambitious goal of reducing global emissions by 80% by 2050, encouraging European countries to prioritize actions aimed at energy efficiency (Passer *et al.*, 2016). In this context, the construction sector emerges as a strategic element in achieving these goals, accounting for about 40% of global energy consumption and 30% of annual greenhouse gas emissions (UNEP, 2009). The design characteristics of buildings, such as type, size, and shape, play a decisive role in their environmental impact, influencing the embodied energy, operational consumption, and useful life of buildings (Bertoli *et al.*, 2024). Given its relevance, the sector has great potential to mitigate contemporary environmental and energy issues (Pannier *et al.*, 2021).

In this sense, social housing emerges as an essential mechanism for promoting energy efficiency, especially through standardized compact housing projects aimed at low-income populations (Bertoli *et al*., 2024). In England, for example, the social housing stock totals 4.4 million units, of which 2.8 million belong to registered private providers and 1.6 million are owned by local governments (Grainne Cuffe, 2022). At the same time, in developing countries, housing deficits and low levels of industrialization stand out as pressing challenges. In Ecuador, in 2015, the housing deficit reached 587,110 units, representing 13.4% of the total stock (Macias *et al.*, 2017). In Brazil, in 2019, the housing deficit totaled 5.8 million units, with low-income families being the most affected (MDR, 2018). In both cases, social housing programs have been implemented to mitigate the housing shortage (Macias *et al.*, 2017). In the United Kingdom, the *Decent Homes Standard* assesses the adequacy of public housing. During the 2020–2021 fiscal year, 8% of properties managed by local councils were classified as inadequate, while this rate was only 0.4% among registered private providers, falling to 0.3% in the following year (Grainne Cuffe, 2022). However, evidence indicates that many social housing units still do not meet minimum energy efficiency standards, posing a significant challenge for low-income families (Bertoli *et al.*, 2024; Dalbem *et al.*, 2019; Flamant *et al.*, 2022; Macias *et al.*, 2017). Thus, building design and energy use are critical factors in ensuring energy security and mitigating the effects of climate change (Song *et al.*, 2018).

Given this scenario, the construction sector has intensified efforts to implement strategies that promote energy conservation in buildings, aligning itself with sustainable development goals (Kalangos, 2017). These initiatives aim to address environmental issues while minimizing the consumption of materials and energy throughout the life cycle of buildings (Rosa *et al.*, 2014). Life cycle assessment (LCA) stands out as a robust tool for quantifying the environmental impacts associated with construction, allowing for a comprehensive analysis from material production to demolition and disposal (Ingrao *et al.*, 2018).

2. Previous life cycle assessment of energy efficiency measures in residential buildings

Recent research has emphasized the importance of energy efficiency strategies in buildings, addressing aspects related to the life cycle of materials and energy operations. Tettey, Dodoo, and Gustavsson (2019) explored the effects of primary energy throughout the life cycle of a residential building, highlighting that integrating the selection of structural materials with the design of low-energy buildings and efficient operating systems is crucial to reducing and significantly improving energy consumption. Complementing this analysis, Monteiro, Freire, and Soares (2021) investigated the environmental and energy impact of three design alternatives for homes in southern Europe, noting that larger proportions of windows relative to walls increase embodied energy, especially due to the use of aluminum-framed windows and double glazing. Cusenza *et al.* (2022) used the *BEM/TRNSYS* tool to model the energy performance of two thermal insulation scenarios, with and without battery storage systems, assessing operational carbon emissions. Similarly, Hasik *et al.* (2019) used Python to simulate the energy consumption of various office designs, highlighting that the type of energy source can outweigh traditional energy efficiency considerations in terms of environmental impact. Sharif and Hammad (2019b), in turn, applied artificial neural networks (ANNs) to optimize energy retrofit scenarios considering costs, energy consumption, and environmental impacts. In the field of eco-efficiency, Tadeu *et al.* (2022) proposed a strategy integrating life cycle assessment (LCA) with cost-effectiveness analyses to prioritize energy conservation measures (ECMs) in building *retrofits*. Studies such as those by Kneifel *et al.* (2018), based on the Low Energy Consumption Residential Database (BIRD), indicate that advances in energy efficiency reduce operational consumption but often increase embodied energy due to greater use of materials. Zhan *et al.* (2018) corroborated these findings using a hybrid LCA approach to measure energy and CO_2 emissions in urban residential buildings in China. For Europe, Gulotta *et al.* (2021) introduced the *BOHEEME (Bottom-up Harmonized Energy-Environmental Models for Europe)* method, which combines *bottom-up* modeling, dynamic energy simulation, and LCA to evaluate residential stock renovation strategies. Results show that improvements in the vertical envelope can reduce carbon emissions associated with heating and cooling demand by up to 20%. Ajayi, Oyedele, and Ilori (2019) addressed the growing relevance of embodied carbon, noting that while the operational phase significantly influences emissions from fossil fuel-based buildings, embodied impacts can reach up to 60% of the total in high energy efficiency projects. In addition, Dixit and Singh (2018) identified critical factors affecting energy efficiency in buildings, including system boundaries, analysis methods, and geographic location. For island contexts, Kylili, Ilic, and Fokaides (2017) demonstrated that the use of insulating materials in walls contributes positively to energy efficiency without a significant increase in total embodied energy. In Mediterranean climates, Stephan and Stephan (2020) proposed solutions to achieve net-zero emissions in apartment buildings, including reducing electricity consumption and using photovoltaic systems with batteries, despite the initial impact of emissions associated with installation. In methodological terms, Mahlan *et al.* (2024) developed the *Integrated Life Cycle and Energy Simulation (ILES)* approach to investigate wall systems in homes in India and Australia. Najjar *et al.* (2019) used mathematical optimization combined with *Building Information Modeling* (BIM) and LCA to assess the impact of building envelopes on energy consumption, highlighting the influence of exterior walls and windows in homes in Rio de Janeiro. These approaches reveal a comprehensive overview of the interactions between energy efficiency, embodied energy, and environmental impacts, reinforcing the need to consider the complete life cycle of buildings in design, retrofit, and sustainable construction strategies.

2.1. Past life cycle assessment of energy efficiency in social housing

Previous studies indicate that life cycle assessment (LCA) applied to social housing is still limited, especially in the context of energy efficiency. For example, Macias *et al*. (2017) analyzed three construction methods in Ecuador: isolated confirmation, load-bearing walls, and confined masonry. The results showed that energy consumption during the operational phase varies from 81.1% to 97.0%, while embodied energy contributes 3.0% to 18.9%. This discrepancy reflects inadequate thermal insulation standards in low-income housing. Bertoli *et al.* (2024), using LCA and life cycle cost analysis, evaluated the thermal performance of single-family homes in Brazil, demonstrating that improvements in the building envelope can reduce annual energy consumption by 20%, with decreases of 12% in global warming emissions and 17% in cumulative energy demand. In Chile, Flamant *et al.* (2022) analyzed energy modernizations under different climatic conditions, finding that embodied energy accounts for up to 60% of carbon emissions during renovations, while energy operation contributes about two-thirds of the total impact.

These findings are reinforced by Pombo, Rivela, and Neila (2019), who highlight the relevance of Life Cycle Thinking for formulating sustainability policies and developing effective retrofit solutions. Sartori and Calmon (2019) investigated the pre-operational and operational phases of retrofit measures in two typical neighborhoods, observing energy consumption between 19.8 GJ/m² and 21.0 GJ/m², and greenhouse gas emissions between 917.7 $kgCO_2/m^2$ and 938.4 $kgCO_2/m^2$. Shrestha (2021) conducted a comparative analysis of construction systems in mountainous regions of Nepal, demonstrating that materials such as interlocking blocks and compressed stabilized earth have lower energy consumption (15,150 MJ-eq/m² and 923 $kgCO_2$-eq/m², respectively) compared to fired bricks (24,877 MJ-eq/m² and 1,560 $kgCO_2$-eq/m²). These data illustrate the impact of material choices on energy efficiency and emissions throughout the life cycle of buildings. Although the literature addresses specific aspects of energy efficiency in social housing, the systematic integration of these analyses into housing policies and construction guidelines is still scarce. The goal of achieving the UN Sustainable Development Goals (SDGs) by 2030 requires a greater focus on applying LCA to identify strategies that reduce the energy footprint of social housing (Dahiya & Laishram, 2024).

A systematic review of the literature provides a comprehensive and structured overview of a specific topic, enabling the identification of relevant trends and gaps in knowledge (Sartor *et al*., 2014). While recent studies, such as that conducted by Dahiya and Laishram (2024), have investigated the energy life cycle of buildings to develop strategies for reducing the energy footprint in the construction sector, there is still no systematic review focused on the contribution of social housing to minimizing the energy footprint. This absence in the literature represents a significant gap that justifies this investigation. This systematic review aims to document and analyze strategies that use LCA to minimize the energy footprint of social housing over the last 10 years. The research focuses on the following research questions:

1. What are the key strategies for an energy-efficient social housing project?

2. What is the most appropriate design alternative for social housing, considering energy efficiency, environmental impacts, and integration with the electrical grid?

3. How can the best material interventions be incorporated to build social housing with lower

carbon emissions and greater energy efficiency, considering possible changes in the electricity matrix?

3. Methodology

The methodology of this analysis followed three main phases. In the first phase, academic publications were collected through extensive searches in the *Scopus* and *Web of Science* databases, which are widely recognized for their relevance in the field of building energy analysis (Dahiya & Laishram, 2024). A comprehensive Boolean search phrase was used, combining terms such as “LCA” OR “Life Cycle Assessment” AND “Social housing” OR “Social dwellings” OR “Social buildings” OR “Public housing” OR “Low-income housing” AND “Energy efficiency” AND “Electricity grid mix.” This approach allowed for the identification of a wide range of relevant, peer-reviewed articles published between 2015 and 2024.

In the second phase, the collected literature was examined using strict inclusion and exclusion criteria. Articles were included if they addressed the research questions quantitatively or qualitatively or presented well-founded discussions on the subject (Mirabella *et al.*, 2018). A bibliometric analysis guided the filtering process. Excluded materials included publications that were not in English, gray literature, draft articles, and comments, due to concerns about the rigor of peer review and the feasibility of translation. Screening was conducted in three stages: title review, abstract review, and full-text analysis. This approach is in line with the methodology adopted by Dahiya and Laishram (2024).

In the third phase, the selected articles were analyzed for relevant applications of Life Cycle Assessment (LCA) in the context of social housing and residential buildings. Emphasis was placed on energy efficiency, building performance, and the influence of the electricity grid mix on carbon emissions and energy consumption. The initial search yielded 7,948 article titles. After removing duplicates, a structured filtering process resulted in a preliminary selection of 438 articles. After further refinement based on keywords and specific objectives, a final set of 67 articles was selected for detailed analysis.

Figure 1 presents a flowchart illustrating the step-by-step methodology of this systematic literature review.

4. *Results and discussion*

4.1. Bibliometric analysis

Table 1 provides a compilation of the 20 most frequently referenced articles from previous research, along with the associated journals of publication.

The data presented in Table 1 shows a significant concentration of publications in the journals Energy and Buildings and Journal of Building Engineering. This trend reflects both the preferences of the authors and the relevance of these journals in the field of building energy analysis. The prominence of these journals is consistent with the growing focus on the energy life cycle analysis of buildings and energy performance, which are central topics of the publications analyzed. As illustrated in Figure 2, most publications on the energy life cycle

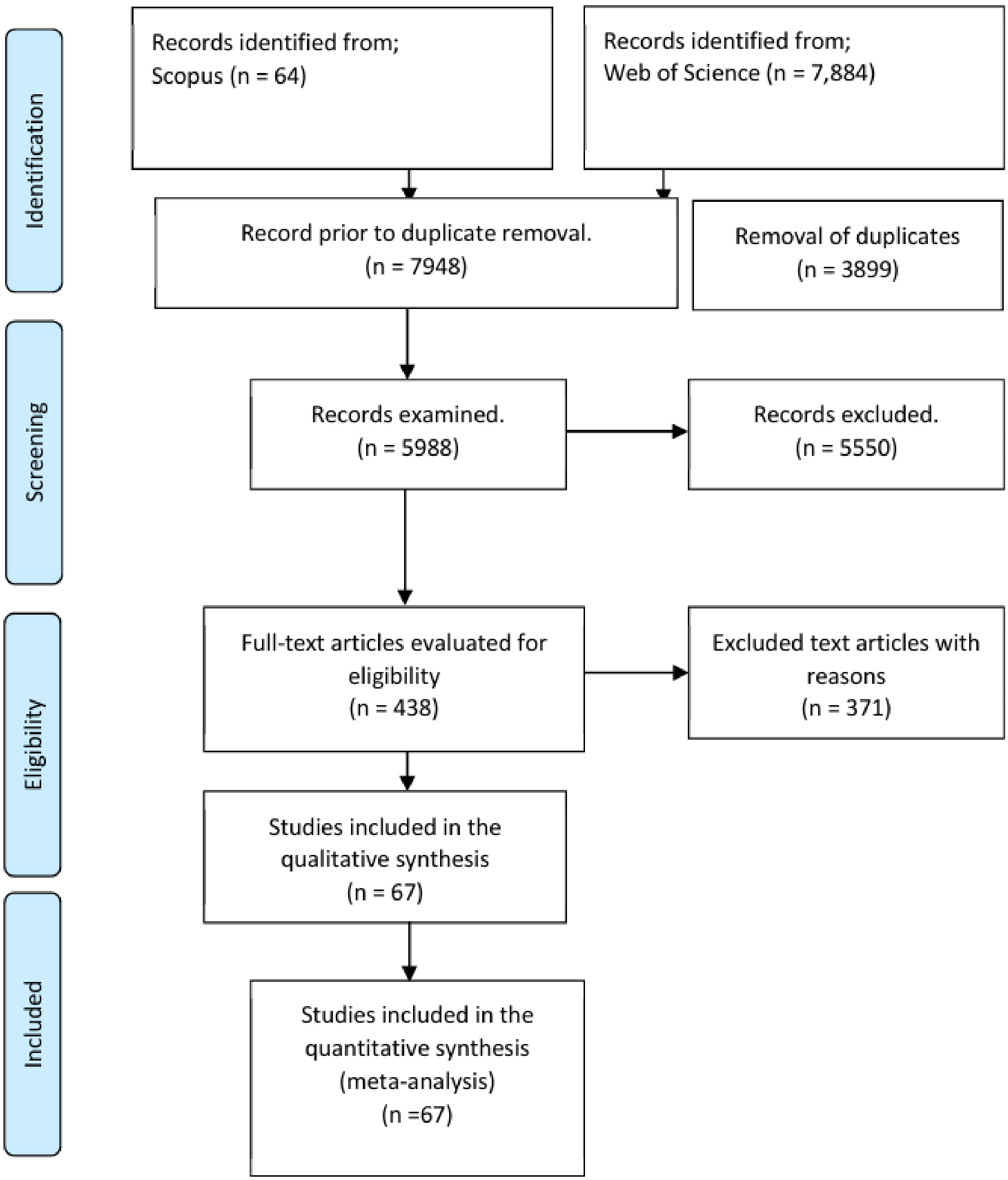

FIGURE 1 – PRISMA Method Diagram.

SOURCE: Prepared by the authors (2024).

TABLE 1 – Compilation of the 20 most frequently referenced articles in previous research.

Journal sources	Article title	Citations	Author reference
Construction and Environment	Life cycle assessment and life cycle cost of container-based single-family homes in Canada: a case study	46	Dara, Hachem-Vermette, & Assefa (2019)
Journal of Construction Engineering	Shifting meanings of embodied energy: A comparative study of building material and energy source specifications	47	Ajayi, Oyedele, & Ilori (2019)
Energy and Construction	What is the ideal robust and cost-effective environmental solution for building renovation? It is not the usual one.	47	Galimshina *et al.* (2021)
Energy and Construction	Life cycle analysis in building rehabilitation as an energy-saving intervention practice	49	Nicolae & George-Vlad (2015)
Applied Energy	Achieving zero greenhouse gas emissions and primary energy in the life cycle of apartment buildings in a Mediterranean climate	50	Stephan & Stephan (2020)
Resource conservation and recycling	Life cycle assessment (LCA) of a passive house in the subtropical climate zone	51	Kylili, Ilic, & Fokaides (2017)
Buildings	Strategies for improving the energy performance of buildings: A review of their impact on the life cycle	52	Mirabella *et al.* (2018)
Journal of Cleaner Production	Life cycle energy consumption and greenhouse gas emissions of urban residential buildings in Guangzhou City	57	Zhan *et al.* (2018)
Energy and Buildings	Life cycle assessment of urban buildings and neighborhoods comparing demolition and reconstruction with renovation	59	Weiler, Harter, & Eicker (2017)
Energy and Buildings	Quantification of embodied energy in buildings in China using a hybrid input-output-based LCA model	60	Guan, Zhang, & Chu (2016)
Construction and Environment	Life cycle assessment of external window shading in residential buildings in different climate zones	66	Babaizadeh *et al.* (2015)
Cleaner Production Journal	An integrated approach to LCA and energy simulation enabled by BIM: The optimized solution for sustainable development	70	Tushar *et al.* (2021)
Automation in Construction	Modular approach to multi-objective environmental optimization of buildings	86	Kiss & Szalay (2020)

Energy and Buildings	The impact of future scenarios on building renovation strategies for positive energy buildings	91	Passer *et al.* (2016)
Journal of Construction Engineering	Multi-objective optimization based on simulation of institutional building renovation considering energy consumption, life cycle cost, and life cycle assessment	101	Sharif & Hammad (2019a)
Applied Energy	Integrated optimization with building information modeling and life cycle assessment for the generation of energy-efficient buildings	105	Najjar *et al.* (2019)
Construction and Environment	Methodological challenges and developments in LCA of low-energy buildings: Application to biogenic carbon and global warming assessment	135	Fouquet *et al.* (2015)
Construction Engineering Journal	Development of a substitute ANN for selecting near-optimal building energy renovation methods, considering energy consumption, LCC, and LCA	142	Sharif & Hammad (2019b)
Cleaner Production Journal	How can life cycle thinking support building sustainability? Investigating life cycle assessment applications for energy efficiency and environmental performance	148	Ingrao *et al.* (2018)

SOURCE: Prepared by the authors (2024).

of buildings come from Europe, followed by Asia and North America.

Among the countries analyzed, the United States leads in the number of studies published, followed by China and Australia. The growth in publications in Europe can be attributed to initiatives such as the *European Strategy for Construction Materials and Products*, which includes regulations, directives, and other actions aimed at sustainability in the construction sector (Kylili & Fokaides, 2017). This increase is consistent with the conclusions of previous reviews, such as that of Asdrubali *et al.* (2024), which highlighted the impact of European policies on academic production related to energy efficiency and sustainability in buildings.

4.2. Quantitative analysis

Based on the qualitative findings, the analysis performed with *VOSviewer* effectively demonstrates the main thematic schools of thought among authors, highlighting the interrelationships between the different topics addressed. This approach allows us to identify the structural connections between topics and provides a comprehensive view of trends in the use of Life Cycle Assessment (LCA) in buil-

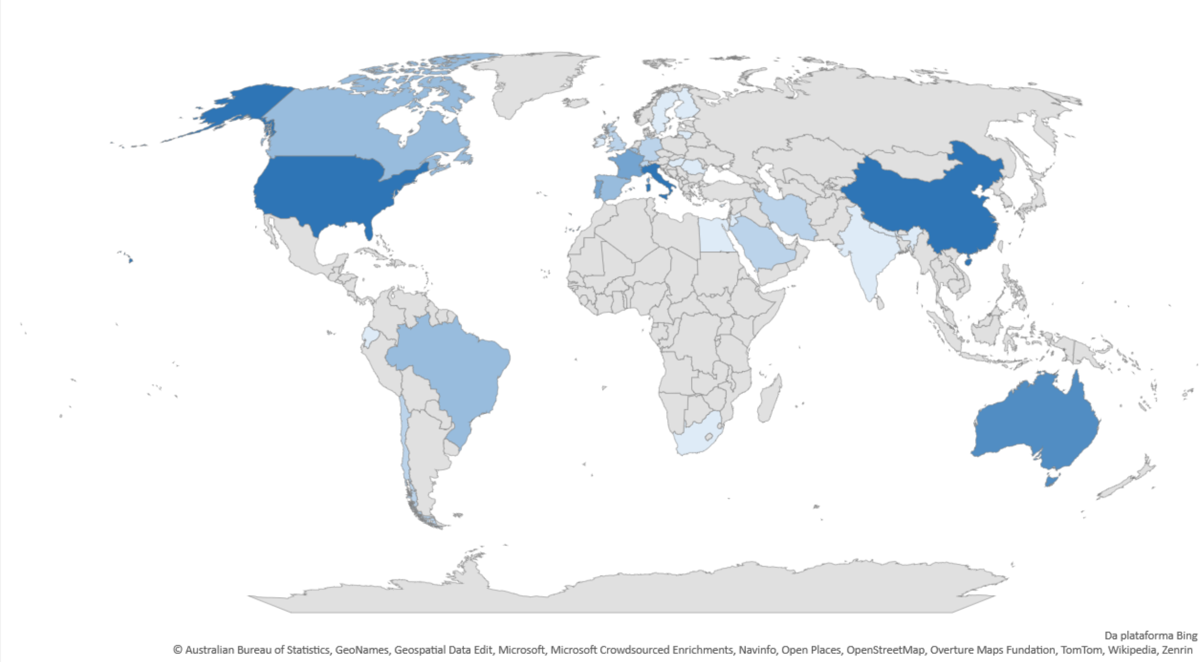

FIGURE 2 – Publications by country.
SOURCE: Prepared by the authors (2024).

dings. The results indicate that LCA is a dynamic and rapidly evolving field of knowledge with the potential to generate significant advances in a short period of time. Figure 3 illustrates the different perspectives adopted by the authors through a cluster classification structure, often associated with LCA applications in buildings, from 2015 to 2024. Each cluster reflects a distinct thematic core, including topics such as energy efficiency, environmental impact, building materials, *retrofitting*, and sustainability policies.

The analysis of the thematic clusters identified in *VOSviewer* allowed for the selection of the most relevant terms for each group, weighted according to their importance in the context of the research questions. This approach revealed three primary topics of discussion, represented by word clouds, in which the size of the words reflects their relevance within each cluster. The first cluster focuses on energy efficiency and includes key terms such as "embodied energy," "efficiency," "consumption," "carbon emissions," and "impacts". These terms indicate that academic research on Life Cycle Assessment (LCA) in buildings has focused on strategies to reduce embodied energy in order to mitigate adverse environmental and climate impacts. This

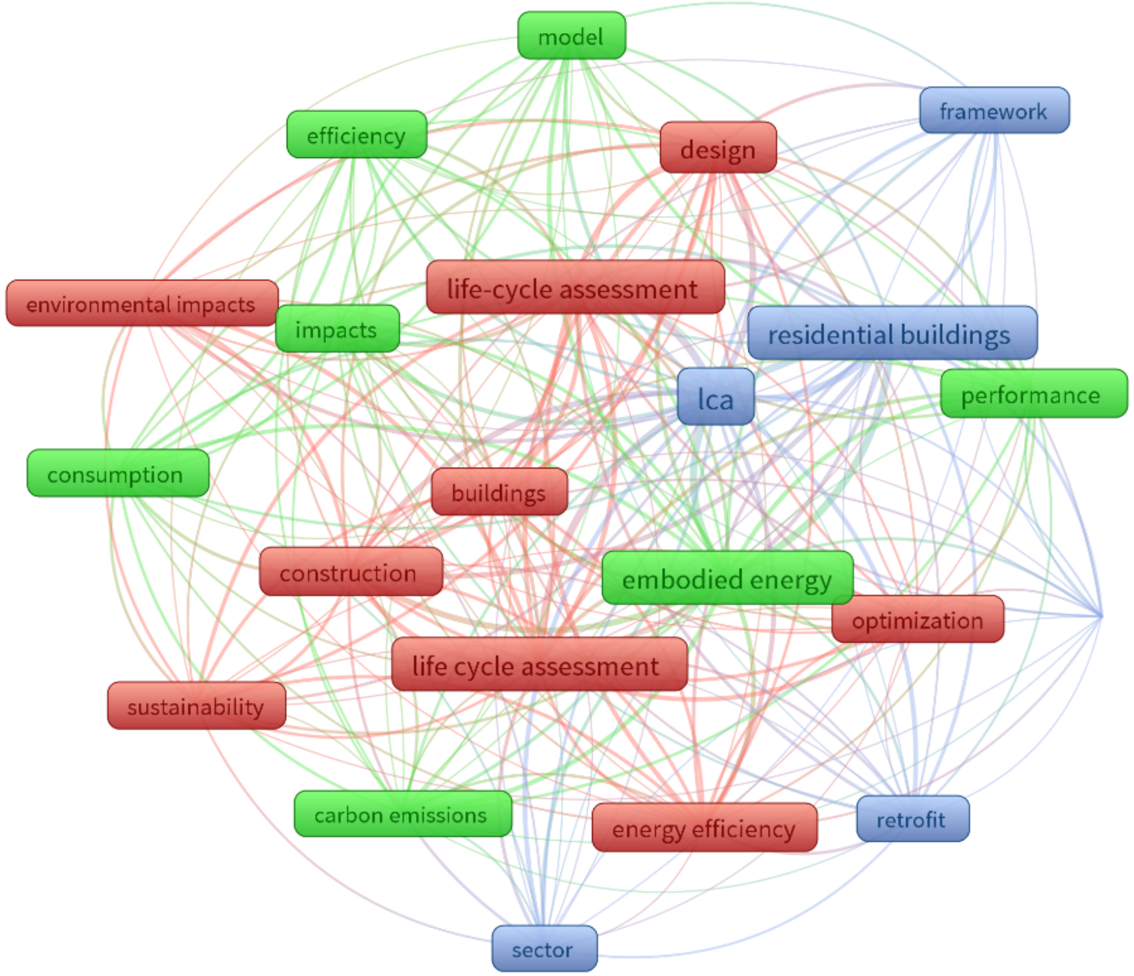

FIGURE 3 – Various applications commonly associated with LCA in buildings, based on bibliometric analysis.
SOURCE: Prepared by the authors (2024).

phenomenon can be attributed to the significant increase in annual material and energy consumption during the useful life of buildings, as pointed out by Song *et al.* (2018). The cluster reflects the growing importance of adopting practices that minimize negative environmental effects throughout the life cycle of buildings.

The second cluster directly addresses "life cycle assessment" and includes terms such as "optimization," "energy consumption," "sustainability," "construction," and "building." This group highlights the role of LCA in promoting sustainable development, especially through the assessment of the environmental performance of buildings (Asdrubali *et al.*, 2024). In addition, it highlights the need for optimization in the construction sector, which accounts for more than 40% of global energy consumption (Ata-Ali *et al.*, 2021), to improve energy efficiency and reduce environmental impacts (Kiss & Szalay, 2020; Najjar *et al.*, 2019). The intersection between sustainability, energy consumption, and construction reflects a focus on integrating environmentally responsible practices into the industry. The third cluster explores the areas of application and progress of scientific research related to LCA in civil construction. Terms such as "residential building", "design", "cost", "structure", "BIM", "simulation", and "environmental impacts" highlight the tools and methodologies employed in the sector. These terms point to the growing use of technologies such as *Building Information Modeling* (BIM) and simulations to assess and mitigate the environmental impacts of buildings (Dauletbek & Zhou, 2022; Nematchoua *et al.*, 2022). The emphasis on cost and structure analysis also reflects the relevance of LCA in guiding economic and sustainable decisions in building design and operation. As illustrated in Table 2, the bibliometric analysis reveals several groups. These three clusters reveal an interdisciplinary research structure that connects energy efficiency, sustainability, and technological innovation. Each cluster contributes to a more comprehensive understanding of LCA applications in civil construction and reinforces its relevance in the context of global policies aimed at mitigating climate change and the responsible use of natural resources.

TABLE 2 – Keywords identified through bibliometric analysis

Cluster 1	**Cluster 2**	**Cluster 3**
Keywords	Keywords	Keywords
Embedded energy	Life cycle assessment	Residential building
Efficiency	Optimization	Design
Consumption	Energy consumption	Cost
Carbon emissions	Sustainability	Structure and BIM
Impacts	Construction and building	Simulation and environmental impacts
Operational energy	Concrete	Emissions
Life cycle energy	Challenges	Life cycle assessment

SOURCE: Prepared by the authors (2024).

Table 2 illustrates the various clusters and keywords identified through bibliometric analysis, revealing several distinct groups.

4.2.1. Types of construction

Among the 67 publications analyzed, 52 case studies highlighted the application of Life Cycle Assessment (LCA) with a focus on energy efficiency in different countries and building types. Notably, more than three-quarters of these studies focused on multi-unit apartment buildings, highlighting a significant trend in the literature. This predominance is corroborated by works such as those by Kiss and Szalay (2020), Najjar *et al.* (2019), Pombo, Rivela, and Neila (2019), and Tettey, Dodoo, and Gustavsson (2019). The high representativeness of this typology reflects the predominant focus on European countries, as discussed in previous reviews, such as that by Mirabella *et al.* (2018). This pattern can be attributed to the relevance of multifamily buildings in densely populated urban areas, where energy efficiency strategies have a greater impact due to scale and concentrated consumption. Table 3 illustrates the various building typology studies and their respective authors. In addition, regulatory contexts and policies aimed at sustainable buildings in Europe reinforce the importance of investigating and optimizing the energy performance of these structures. These factors highlight the relevance of apartment buildings as a priority area for LCA-based energy efficiency studies.

The case studies reviewed present a wide range of technical solutions and strategies aimed at improving the energy efficiency of different types of buildings. These strategies cover interventions in materials, construction systems, and technologies applied to the life cycle of buildings. Table 4 summarizes twenty of these selected strategies, detailing the floor areas of the corresponding buildings, the useful life considered in the studies, and the materials evaluated. These strategies range from the use of materials with low embodied energy to the implementation of thermal insulation systems and renewable energy generation technologies. Improvements to building envelopes were also addressed, such as replacing windows with more efficient models, using solar panels, and applying retrofit techniques to reduce operational emissions.

In addition, the integration of methodologies such as *Building Information Modeling (BIM)* and computer simulations to predict energy performance over the lifetime of buildings was highlighted. The compilation in Table 4 demonstrates not only the diversity of technical approaches but also the interdependence between material choices and energy impact over the life cycle of buildings. The analysis of these strategies provides an overview of best practices and points to the potential for applying innovative solutions in the construction sector, aligned with global energy efficiency and sustainability goals.

Analysis of energy efficiency strategies reveals that most interventions are associated with buildings with heated floor areas greater than 100 m². However, smaller-scale studies, such as those by Song *et al.* (2018), indicate that housing units with areas of less than 50 m² represent about 39.41% of the total in Macau, while those between 50 and 99 m² constitute the largest share, corresponding to 44.58%. These data highlight the predominance of compact housing units in dense urban contexts. Macias *et al.* (2017) complement these observations,

TABLE 3 – Types of architectural typologies examined in the case studies.

Authors	Topologies	Floor areas
Pombo *et al*. (2019)	Residential – Building with several apartments	$49m^2$ and $64m^2$
Najjar *et al.* (2019)	Residential - Building with multiple apartments	$1558m^2$
Mahlan *et al.* (2024)	Residential - Building with multiple apartments	$154m^2$
Motalebi *et al.* (2022)	Residential - Building with multiple apartments	$776m^2$
Stephan & Stephan (2020)	Residential - Building with multiple apartments	$154m^2$
Bertoli *et al.* (2024)	Single-family residential building	46m
Fouquet *et al.* (2015)	Single-family residential building	$122m^2$
Dara *et al.* (2019)	Single-family residential building	$119m^2$
Kylili *et al.* (2017)	Single-family building	$185m^2$
Sartori & Calmon (2019)	Multi-family residential building	$59m^2$
Conci *et al.* (2019)	Multifamily residential building	$45m^2$
Tadeu *et al.* (2022)	Multi-family residential building	$100m^2$
Kylili *et al.* (2017)	Multifamily building	$185m^2$
Tushar *et al.* (2021)	Detached residential house	$230m^2$
Babaizadeh *et al.* (2015)	Detached residential housing	$130m^2$
Shrestha, (2021)	Detached houses	$52m^2$
Alsaqabi *et al.* (2023)	Residential houses	$49.8\ m^2$
Flamant *et al.* (2022)	Social housing	$67m^2$ and $76m^2$
Cusenza *et al.* (2022)	Semi-detached building	$152m^2$
Dauletbek & Zhou (2022)	Student residence	$3762m^2$
Pakdel *et al.* (2021)	Residential guest house	$66m^2$

SOURCE: Prepared by the authors (2024).

emphasizing that the residential category generally includes single-family and multi-family structures with up to four floors and areas greater than 60 m². In contrast, social housing often has areas smaller than 60 m², reflecting economic and design constraints. These topological differences are crucial for understanding the distribution of operational energy in different end uses (Li *et al*., 2021). Among the case studies reviewed, it was common to use 1 m² of heated or cooled floor area as a functional unit

TABLE 4 – Selected strategies adopted by the authors and corresponding buildings, floor areas, and materials evaluated.

Authors	Energy efficiency strategies	Floor areas	Building topologies	Building lifespan (years)	Material evaluated
Pakdel, Aiatolá, & Sattary (2021)	Envelope improvement with terrestrial materials	$66m^2$	Residential guest house	35	Adobe, straw, mud, fired brick, and double glazing
Bertoli *et al.* (2024)	Envelope improvement	$46m^2$	Single-family residential building	50	Ceramic bricks, steel frames, ceramic tiles, and concrete slabs
Shrestha (2021)	Selection of materials and construction systems	$52m^2$	Detached houses	50	Reinforced concrete, interconnected blocks, and compressed stabilized earth blocks
Conci *et al.* (2019)	Integration of local energy generation from renewable sources	$45m^2$	Multifamily residential building	100	Insulated concrete and metal substructure wall, concrete block, reinforced concrete, rock wool, extruded polystyrene
Alsaqabi *et al.* (2023)	Improvement in insulation	$49.8\ m^2$	Residential housing		Extruded polystyrene, expanded polystyrene, rock wool, and glass wool
Sartori & Calmon (2019)	Envelope improvement	$59m^2$	Multifamily residential building	50	Green roof, reflective glass panel, concrete, ceramic bricks, PVC, ceramic tiles
Flamant *et al.* (2022)	Improved envelope insulation	$67m^2$ and $76m^2$	Social housing	50	Polyethylene, expanded polystyrene, ceramic tile, glass wool, steel structure, reinforcing steel
Pombo, Rivela, & Neila (2019)	Use of Passivhaus technique	$49m^2$ and $64m^2$	Multi-apartment residential building	50	Expanded polystyrene, extruded polystyrene, mineral wool, aluminum, and PVC
Najjar *et al.* (2019)	Optimization of exterior wall and window design	$1558m^2$	Multi-apartment residential building	30	Concrete block wall, double brick cavity wall, insulated brick, and lightweight plaster wall

Tushar *et al.* (2021)	Ceiling and wall optimization	230m^2	Detached residential dwelling	60	Concrete or clay tile roof, wooden roof, concrete block, plywood
Cusenza *et al.* (2022)	Use of cellulose fibers and battery storage systems	152m^2	Semi-detached building	60	Extruded expanded polystyrene, cellulose fibers, photovoltaic system
Motalebi, Rashidi, & Nasiri (2022)	Installation of solar panels, insulation of building envelopes, and replacement of inefficient appliances	776m^2	Multi-apartment residential building	50	Expanded polystyrene, rock wool, cellulose fiber, glass wool, fiberglass flat roof
Tadeu *et al.* (2022)	Replacement of existing low-efficiency energy systems	100m^2	Multifamily residential building	30	Ceramic tile, extruded polystyrene, ceramic block, perforated brick masonry
Babaizadeh *et al.* (2015)	Use of exterior shading systems	130m^2	Detached residential house	40	Wood, aluminum, and polyvinyl chloride (PVC)
Kylili, Ilic, & Fokaides (2017)	Incorporation of thick layers of insulating materials into the building's wall system	185m^2	Single-family multi-family building	50	Concrete, tiles, plywood, plasterboard, polystyrene, polyethylene, mineral wool, and steel
Fouquet *et al.* (2015)	Envelope enhancement and incorporation of renewable energies	122m^2	Single-family residential building	100	Wooden structure, cast concrete, and concrete block cavity
Dauletbek & Zhou (2022)	Reduction in insulation layer thickness using polyvinyl chloride (PVC) windows with movable sunshades	3762m^2	Student residence	50	Expanded polystyrene, extruded polystyrene board

Stephan & Stephan (2020)	Use of solar photovoltaic array, reducing the device's electricity demand	154m^2	Multi-apartment residential building	50	Expanded polystyrene insulation, solar thermal collector, use of LED lighting, and photovoltaic energy
Mahlan *et al.* (2024)	Improving wall system insulation	154m^2	Multi-apartment residential building	50	Extruded polystyrene, fly ash bricks, insulated cavity clay masonry, autoclaved aerated block
Dara, Hachem-Vermette, & Assefa (2019)	Envelope improvement	119m ^{2}	Single-family residential building	50	Container, lightweight wood container, improved container, and improved lightweight wood

SOURCE: Prepared by the authors (2024).

for comparative analyses. This approach allows for the evaluation of the energy and environmental performance of different energy efficiency strategies, as evidenced in the works of Najjar *et al.* (2019), Norouzi *et al.* (2022), Pakdel, Ayatollahi, and Sattary (2021), Pombo, Rivela, and Neila (2019), and Shrestha (2021). This standardized practice facilitates comparison between buildings of different types and scales, contributing to the development of optimized strategies that are adaptable to different climatic and socioeconomic contexts.

These findings underscore the influence of topological characteristics on energy efficiency and highlight the importance of considering the scale and function of built areas when designing solutions to improve the energy performance of buildings.

4.2.2. Building lifespan

The uncertainty associated with the useful life of buildings is widely documented in the literature, reflecting significant variations between building types and regional construction practices around the world. This variability was pointed out by Dahiya and Laishram (2024), who attributed these differences to regional contexts and the characteristics of the buildings analyzed. Most of the studies reviewed adopt 50 years as a reference for the useful life of buildings, as illustrated in the scatter plot shown in Figure 4. The useful life of buildings plays a key role in both operational energy consumption and embodied energy. As discussed by Pakdel, Ayatollahi, and Sattary (2021), in countries such as Iran, where the average service life of buildings is relatively short,

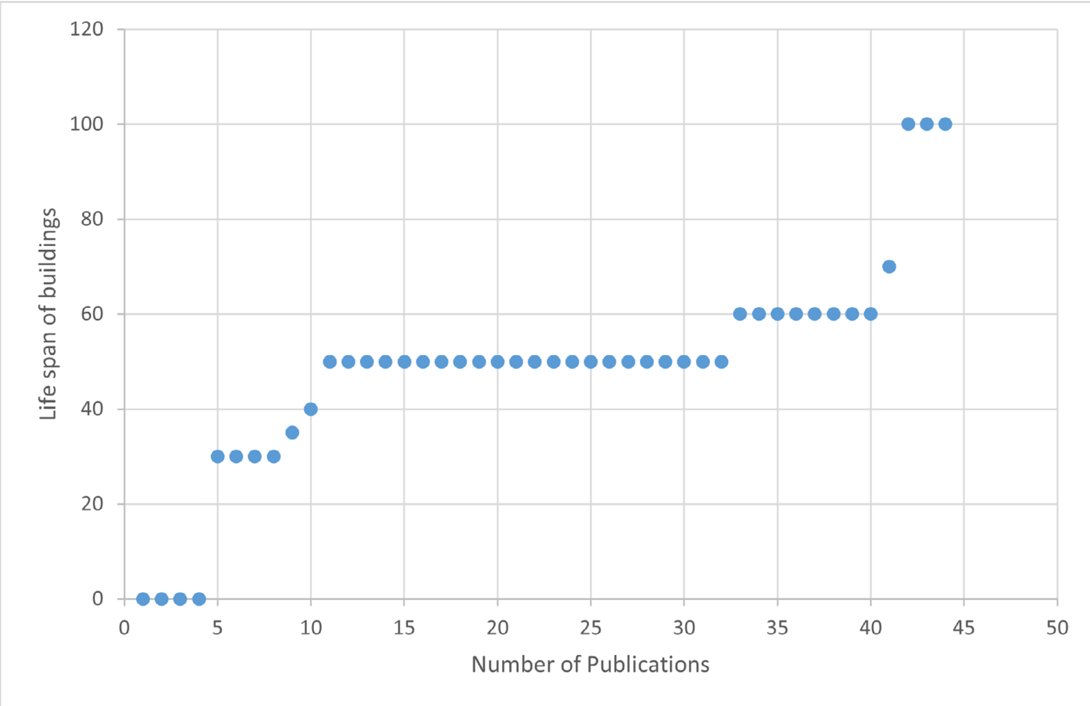

FIGURE 4 – Examined service life of buildings within the case studies analyzed.
SOURCE: Prepared by the authors (2024).

a more significant impact of embodied energy is observed. This is because lower durability tends to require more materials over time, increasing the energy and environmental impact of buildings.

Additionally, as energy efficiency strategies are implemented, the embodied energy in added materials and systems becomes a critical factor. Kneifel *et al*. (2018) point out that the pursuit of energy efficiency often results in greater use of materials, which can increase embodied energy, especially in contexts where building renovation or replacement is more frequent. These observations underscore the importance of considering the useful life as a key variable in life cycle analyses. It directly influences the ratio between operational energy and embodied energy, affecting the overall sustainability of buildings. Construction policies and practices should therefore seek to balance the durability of buildings with energy efficiency and environmental impact, promoting more resilient and sustainable solutions.

4.3. Research questions

4.3.1. What are the key strategies for energy efficiency in social housing?

This section addressed the challenges faced by social housing, especially in relation to energy efficiency, and the mitigation strategies discussed in the reviewed literature. Analysis of the different case studies revealed that the operational phase is, in fact, the most impactful in terms of energy consumption and environmental impact in the life cycle of buildings, with most of the energy consumed during the operation of buildings. Several studies offer a comprehensive view of how life cycle assessment (LCA) can be applied to mitigate the environmental impacts of this phase. Macias *et al.* (2017) analyzed construction methodologies in coastal and highland climates, noting that the operational phase of social housing accounts for 81.1% to 91.0% of total life cycle impacts. The researchers suggested the use of insulated concrete as a potential solution to reduce the impacts of this phase. Li *et al.* (2021), in turn, investigated the life cycle emissions of residential buildings in the Victoria region of Australia using a bottom-up approach. Their results showed a significant decrease in the operational energy of newly built housing, thanks to technological advances and energy-saving regulations. For older homes, embodied energy increased substantially, highlighting the need to consider both operational energy and embodied energy when assessing the life cycle of buildings. The study by Sartori and Calmon (2019), conducted in Brazil, focused on sustainable retrofit strategies for neighborhoods in Vitória, Espírito Santo. The research revealed that the main solutions for reducing energy use and greenhouse gas emissions were modifying absorption and implementing ventilated facades. These adjustments helped improve energy efficiency and reduce environmental impact. Flamant *et al.* (2022) evaluated energy retrofit solutions for mass social housing in Chile, considering three distinct performance scenarios (moderate, high, and extended) under different climatic conditions. The study concluded that improving the insulation of the building envelope, reducing air infiltration losses, and implementing controlled ventilation systems can lead to a substantial reduction in heating demand, with a decrease of up to 84% in some climatic cities.

Finally, Bertoli *et al*. (2024) conducted a thermal performance and environmental impact analysis on a single-family home in Brazil, comparing different construction scenarios. The study revealed that, regardless of the construction system used, the use phase accounts for more than 55% of total energy demand. The scenario that used a steel structure and thermoacoustic tiles had the lowest impact in terms of energy consumption and global warming potential (GWP), highlighting the importance of innovative solutions in the energy performance of social housing. These studies demonstrate that energy efficiency in social housing depends on an integrated approach that takes into account both embodied energy and operational energy, and that technological solutions to improve the thermal performance of buildings play a crucial role in mitigating environmental impacts throughout the life cycle of buildings.

4.3.2. What are the design alternatives for energy-efficient social housing?

Bertoli *et al*. (2024) highlight that improving the building envelope can significantly reduce energy consumption and greenhouse gas (GHG) emissions. Their findings indicate that improving the *envelope* can lead to a 20% reduction in annual energy consumption and a 12% reduction in Global Warming Potential (GWP) emissions. In addition, switching to a cleaner electricity grid can result in a 25% reduction in environmental impact. The study also suggests that, given the extended life cycle of buildings, it is essential to integrate potential future changes in the electricity grid during building assessments. Conci *et al.* (2019) conducted a similar analysis, focusing on multifamily buildings in Germany. Their results indicate that adopting conventional strategies has a limited impact on climate goals, suggesting that integrating local renewable energy may be more effective. The research revealed that adopting low environmental impact strategies, such as using renewable energy sources, has a significant effect on global warming potential, contributing to achieving climate goals. Newberry, Harper, and Norman (2023), through a case study in the United Kingdom, assessed the impact of embodied and operational carbon in a 60-year housing project, considering different insulation materials and different energy scenarios. The results highlight that embodied carbon accounts for the largest share of total emissions, ranging from 59% to 80%, while operational carbon accounts for 20% to 41%. The study suggests that design choices and the proportion of renewable energy in the electricity grid have a substantial impact on operational emissions, which can be challenging for design decisions. Kiss and Szalay (2020), in their study of a residential building in Hungary, used a parametric approach to optimize the design of an apartment building with a focus on various insulation materials.

They concluded that a compact shape, with large south-facing windows and adequate shading, combined with high levels of insulation, can result in a 60-80% reduction in environmental impacts. This study reinforces the importance of considering both operational and embodied impacts for an optimized energy-efficient solution. Monteiro, Freire, and Soares (2021), when evaluating a single-family home in Portugal, found that embodied energy exceeds operational energy, especially when the building shape is not compact and when there is a higher window-to-wall ratio (WWR). Reducing the window area can mitigate environmental impacts, especially in homes with lower operational standards, which underscores the importance of architectural design in energy efficiency. Norouzi *et al.* (2022), in their investigation of passive buildings in Northern Ireland, noted that the operational phase is primarily responsible for environmental impacts, surpassing other stages of the building life cycle.

The study indicated that the adoption of passive standards could significantly reduce environmental impacts, with a reduction of up to 50% when compared to low-energy buildings. Cusenza *et al.* (2022), when evaluating a net-zero energy building in Rome, observed that the use of cellulose fibers as thermal insulation material, together with an integrated photovoltaic system, led to an 18% reduction in overall energy demand and a 34% reduction in climate change emissions. The research showed that the use of environmentally friendly materials, such as cellulose fibers, can be an effective solution for reducing environmental impacts and improving energy efficiency. These studies show that, in order to improve energy efficiency and reduce environmental impacts in the life cycle of buildings, it is crucial to adopt an integrated approach that considers both operational efficiency and embodied energy. In addition, design choices, the use of sustainable materials, the adoption of renewable energy, and consideration of future changes in electrical grids play key roles in minimizing environmental impact and increasing the sustainability of buildings.

4.3.3. What are the material intervention strategies for energy-efficient social housing?

A systematic review of the literature reveals a diversity of studies focused on assessing the environmental and energy impact of different building systems and materials, with an emphasis on the Life Cycle Assessment (LCA) methodology. However, there is a notable lack of research addressing life cycle cost (LCC) in an integrated manner with environmental LCA, which represents an important gap in the literature, as pointed out in previous reviews (Mirabella *et al.*, 2018). Gulotta *et al.* (2021), in their analysis of 672 building archetypes representing 28 building stocks in the European Union, focused on both single-family and multi-family houses built before 2010. Using the *Bottom-up Harmonized Energy-Environmental Models for Europe* (BOHEEME) methodological approach, the research evaluated various insulation materials, such as cellulose fiber, rock wool, cork, and wood panels. The results indicated that older buildings, especially those built before 1970, account for approximately 72% of CO_2 emissions in the European Union. In addition, cellulose fiber stood out as the insulation material with the greatest capacity to mitigate environmental impacts throughout its life cycle, surpassing other materials, except in terms of human toxicity and depletion of non-renewable resources, where rock wool performed better. These findings suggest that the choice of insulation material can have a significant impact on the environmental sustainability of buildings, especially in relation to climate change mitigation. Alsaqabi *et al.* (2023) conducted an assessment of the performance of various insulation materials in the context of hot and arid climates, specifically in Saudi Arabia, using a case study at *Qassim* University, which comprises 288 residential villas.

The research followed a cradle-to-gate methodology and demonstrated that expanded polystyrene (EPS), with a thickness of 110 mm, resulted in the lowest cooling loads, while extruded polystyrene (XPS), with a thickness of 50 mm, had the highest. In addition, the study revealed that XPS had the highest global warming potential, with emissions of 5.28 kg of CO_2 equivalent, followed by glass wool (GW) with 3.2 kg of CO_2 equivalent, 63% lower. EPS was third, with emissions of 2.9 kg of CO_2 equivalent, while rock wool (RW) had the lowest emissions, with 1.3 kg of CO_2 equivalent, 123% lower than GW. These results highlight the importance of selecting insulation material for thermal performance and carbon emission reduction, especially in regions with extreme climates. Shrestha's (2021) study focused on comparing energy consumption and carbon emissions in different building systems, including reinforced concrete

(RCC), compressed stabilized earth block (CSEB), and interlocking block (IB).

The study covered the stages of material production, transportation, construction, operation, and end of life. The results showed that the fired brick masonry system generated the highest energy consumption and CO_2 emissions, with a total of 24,877 MJ-eq per m² and 1,560 kg of CO_2 equivalent per m², respectively. In contrast, the interlocking block system had the lowest impact, with 15,150 MJ-eq per m² of energy consumption and 931 kg of CO_2 equivalent per m² of emissions. These findings indicate that, when considering the entire life cycle, more efficient construction systems in terms of energy consumption and emissions can be chosen to reduce the environmental impact of buildings. The research by Pakdel, Ayatollahi, and Sattary (2021) compared the environmental impacts of a 66 m² guest house in *Yazd,* Iran, using two different construction systems: the conventional system and the sustainable system using traditional techniques and materials (TTM). The study revealed that TTM generated 43% less embodied energy and 48% less carbon emissions compared to the conventional system. Furthermore, operational energy consumption was 88% lower in TTM, resulting in an 81% reduction in carbon emissions. These results suggest that adopting sustainable construction techniques can significantly reduce both the environmental impacts and operational costs of buildings. Ata-Ali *et al.* (2021) conducted an analysis of the environmental impact of various ventilated facade materials, such as rock wool, natural cork, and recycled cork, in different climatic regions of Spain. Using a cradle-to-grave approach, the study revealed that recycled cork had the lowest environmental impact among the materials analyzed, standing out as a superior alternative in terms of thermal insulation and reduction of environmental impacts. In contrast, rock wool, although widely used in Spain, was shown to have a higher environmental impact, as well as posing health risks, suggesting that its replacement with more sustainable materials, such as recycled cork, could not only reduce environmental impacts but also improve public health.

Finally, Bertoli *et al*. (2024) conducted an assessment of the thermal performance and environmental impact of different construction systems in a single-family home located in the coldest climate region of Brazil. The study compared conventional and innovative systems, taking into account the electricity grid mix and using both cumulative energy demand and global warming potential. The findings indicated that the conventional system, with ceramic brick and concrete slab, generated the highest CO_2 emissions, while the innovative envelope, with a steel structure and thermoacoustic coating, showed a 17% reduction in carbon emissions. The analysis also showed that combining innovative systems can result in a significant reduction in operational energy consumption and carbon emissions, highlighting the importance of considering more sustainable solutions in building design.

In summary, the studies reviewed indicate that the choice of building materials and systems can substantially influence the environmental and energy impacts of buildings throughout their life cycle. Although life cycle assessment (LCA) is a valuable tool for measuring these impacts, the integration of life cycle cost (LCC) with LCA is still an under-explored area, but one that is essential for the development of more sustainable and economically viable construction solutions.

TABLE 5 – Main conclusions and implications observed in the study.

Key findings	Implications
There is no standardized methodology for assessing environmental impacts beyond emissions	This hinders comparability and the development of best practices
Operational energy is the dominant phase in the impact of the life cycle of social housing	Energy efficiency interventions should prioritize this phase
Building type, insulation, and climate strongly influence project performance	Encourages context-specific design strategies
Embedded energy becomes more relevant in highly efficient buildings	Requires smarter material selection and deeper integration of LCA
Circular economy principles are underutilized in current LCA applications	Integrating these factors contributes to the long-term sustainability of housing systems

SOURCE: Prepared by the authors (2024).

5. Conclusion

This article presents a detailed and structured overview of the scientific literature on the use of Life Cycle Assessment (LCA) in promoting energy efficiency in social housing, with a special focus on its integration with the electricity grid. The analysis reveals that, although there are many methodologies and case studies, comparing them is challenging due to the variety of parameters involved, such as building types, energy performance, climatic conditions, and different LCA methods.

An important finding is the lack of a standardized and comprehensive approach to assessing environmental impacts beyond energy use and carbon emissions. This methodological inconsistency makes it difficult to reach universal conclusions and highlights the need for a robust and integrated framework that considers all stages of a building's life cycle.

Regarding key strategies for energy efficiency (RQ1), the operational phase remains the main source of environmental impact, accounting for 81.1% of the total in some studies. This emphasizes the importance of prioritizing improvements in building operations.

Design alternatives (RQ2) are strongly influenced by climatic conditions, building typology, insulation systems, and building layout. Compact, well-designed buildings with high-performance envelopes perform better in terms of energy efficiency.

As for material intervention strategies (RQ3), although insulation materials play an important role, their embodied impacts are generally smaller compared to those of structural materials. Still, as buildings become more efficient, the relative weight of embodied energy increases, requiring greater attention to sustainable material choices.

Overall, the study highlights the urgent need for a more holistic and systemic approach to environmental assessment that goes beyond emissions and energy, encompassing other impact categories and circular economy principles. Table 5 presents a summary of the study's findings and implications, as well as the main conclusions.

Based on the responses to the research questions, the following conclusions are synthesized from the existing literature;

RQ1: What are the key strategies for an energy-efficient social housing project?

Mitigation strategies focus primarily on reducing operational energy use, which remains the main contributor to environmental impact. Key approaches include improving building envelopes, integrating passive design features, and applying *retrofit* solutions to reduce heating and cooling demands.

RQ2: What is the most appropriate design alternative for social housing, considering energy efficiency, environmental impacts, and integration with the electrical grid?

The most effective design alternatives are compact, climate-adapted buildings with improved insulation systems, optimized orientation, and passive strategies. The incorporation of renewable energy systems and the anticipation of changes in the electricity mix further strengthen their performance.

RQ3: How can we incorporate the best material interventions to build social housing with lower carbon emissions and greater energy efficiency?

Best practices involve the use of low-impact, locally sourced, and recyclable materials. In addition, assessing embodied impacts alongside operational efficiency is critical to avoid offsetting the energy savings benefits in highly efficient buildings. This is key to the transition to more sustainable, low-carbon housing solutions.

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References

Ajayi, S. O.; Oyedele, L. O.; Ilori, O. M. Change in the importance of embodied energy: A comparative study of building material specifications and energy sources. *Journal of Building Engineering*, 23, 324-333, 2019. doi: 10.1016/j.jobe.2019.02.008

Alsaqabi, Y. *et al.* Citation: Technical-environmental assessment of insulation materials in Saudi Arabia: Integrating thermal performance and LCA. 2023. Available at: https://doi.org/10.3390/buildings

Ascione, F. *et al.* Energy demand and air quality in social housing buildings: A novel critical review. *Energy and Buildings*, 319, 2024. doi: 10.1016/j.enbuild.2024.114542

Asdrubali, F. *et al.* LCA and energy efficiency in buildings: Mapping more than twenty years of research, *Energy and Buildings,* Elsevier Ltd, 15, 2024. doi: 10.1016/j.enbuild.2024.114684

Ata-Ali, N. *et al.* Recycled versus non-recycled insulation alternatives: LCA analysis for different climate conditions in Spain. *Resources, Conservation and Recycling*, 175, 2021. doi: 10.1016/j.resconrec.2021.105838

Babaizadeh, H. *et al.* Life cycle assessment of exterior window shadings in residential buildings in different climate zones. *Building and Environment*, 90, 168-177, 2015. doi: 10.1016/j.buildenv.2015.03.038

Bertoli, G. *et al.* Integrated life cycle analysis of the thermal, environmental, and cost performance of building envelope systems: Case study of a small house considering the change in network mix in Brazil. *Energy and Buildings*, 310, 2024. doi: 10.1016/j.enbuild.2024.114096

Conci, M. *et al.* Trade-off between the economic and environmental impact of different decarbonization strategies for residential buildings. *Building and Environment*, 155, 137-144, 2019. doi: 10.1016/j.buildenv.2019.03.051

Cusenza, M. A. *et al.* An integrated energy simulation and life cycle assessment to measure the operational and embodied energy of a net-zero energy Mediterranean building. *Energy and Buildings*, 254, 2022. doi: 10.1016/j.enbuild.2021.111558

Dahiya, D.; Laishram, B. Energy analysis of the life cycle of buildings: A systematic review. *Building and Environment* Elsevier Ltd, 15, 2024. doi: 10.1016/j.buildenv.2024.111160

Dalbem, R. *et al.* Optimization of social housing for southern Brazil: From basic performance standards to the passive house concept. *Energy*, 167, 1278-1296, 2019. doi: 10.1016/j.energy.2018.11.053

Dara, C.; Hachem-Vermette, C.; Assefa, G. Life cycle assessment and life cycle cost of container-based single-family homes in Canada: A case study. *Building and Environment*, 163, 2019. doi: 10.1016/j.buildenv.2019.106332

Dauletbek, A.; Zhou, P. BIM-based LCA as a comprehensive method for the refurbishment of existing dwellings considering environmental compatibility, energy efficiency, and profitability: A case study in China. *Journal of Building Engineering*, 46, 2022. doi: 10.1016/j.jobe.2021.103852

Dixit, M. K.; Singh, S. Embodied energy analysis of higher education buildings using an input-output-based hybrid method. *Energy and Buildings*, 161, 41-54, 2018. doi: 10.1016/j.enbuild.2017.12.022

Flamant, G. *et al.* Thermal and environmental evaluation of mid-rise social housing retrofit under different climate conditions. *Journal of Building Engineering*, 46, 2022. doi: 10.1016/j.jobe.2021.103724

Fouquet, M. *et al.* Methodological challenges and developments in LCA of low-energy buildings: Application to biogenic carbon and global warming assessment. *Building and Environment*, 90, 51-59, 2015. doi: 10.1016/j.buildenv.2015.03.022

Galimshina, A. *et al.* What is the best robust and cost-effective environmental solution for building renovation? It is not the usual one. *Energy and Buildings*, 251, 2021. doi: 10.1016/j.enbuild.2021.111329

Grainne Cuffe. *Inside Housing - Insight - Annual sector data returns for 2021-22: five key findings*. Available at: https://www.insidehousing.co.uk/insight/the-sectors-annual-data-returns-2021-22-five-key-takeaways-78707. Accessed on: Nov. 3, 2024.

Guan, J.; Zhang, Z.; Chu, C. Quantification of building embodied energy in China using an input-output-based hybrid LCA model. *Energy and Buildings*, 110, 443-452, 2016. doi: 10.1016/j.enbuild.2015.11.032

Gulotta, T. M. *et al.* A bottom-up harmonized energy--environmental models for Europe (BOHEEME): A case study on the thermal insulation of the EU-28 building stock. *Energy and Buildings*, 231, 2021. doi: 10.1016/j.enbuild.2020.110584

Hasik, V. *et al.* Whole building life cycle environmental impacts and costs: A sensitivity study of design and service decisions. *Building and Environment*, 163, 2019. doi: 10.1016/j.buildenv.2019.106316

Ingrao, C. *et al.* How can life cycle thinking support building sustainability? Investigating life cycle assessment applications for energy efficiency and environmental performance *Journal of Cleaner Production* Elsevier Ltd, 201, 556-569, 2018. doi: 10.1016/j.jclepro.2018.08.080

Kalangos, C. International Journal of Energy Economics and Policy Barriers and Policy Drivers to Energy Efficiency in Energy Intensive Turkish Industrial Sectors. *International Journal of Energy Economics and Policy*, 7(3), 110-120, 2017. Available at: http:www.econjournals.com

Kiss, B.; Szalay, Z. Modular approach to multi-objective environmental optimization of buildings. *Automation in Building*, 111, 2020. doi: 10.1016/j.autcon.2019.103044

Kneifel, J. *et al.* An exploration of the relationship between improvements in energy efficiency and life-cycle energy and carbon emissions using the BIRDS low-energy residential database. *Energy and Buildings*, 160, 19-33, 2018. doi: 10.1016/j.enbuild.2017.11.030

Kylili, A.; Fokaides, P. A. Policy trends for the sustainability assessment of construction materials: A review. *Sustainable Cities and Society*, 35, 280-288, 2017. doi: 10.1016/j.scs.2017.08.013

Kylili, A.; Ilic, M.; Fokaides, P. A. Whole-building Life Cycle Assessment (LCA) of a passive house of the sub-tropical climatic zone. *Resources, Conservation and Recycling*, 116, 169-177, 2017. doi: 10.1016/j.resconrec.2016.10.010

Li, S. *et al.* Multi-scale life cycle energy analysis of residential buildings in Victoria, Australia - A typology perspective. *Building and Environment*, 195, 2021. doi: 10.1016/j.buildenv.2021.107723

Macías, J. *et al.* Assessment of embodied and operational energy of different construction methods used in social housing in Ecuador. *Energy and Buildings*, 151, 107-120, 2017. doi: 10.1016/j.enbuild.2017.06.016

Mahlan, S. *et al.* An integrated life cycle assessment and energy simulation framework for residential building wall systems. *Building and Environment*, 257, 2024. doi: 10.1016/j.buildenv.2024.111542

MDR. Ministry of Regional Development (MDR) and João Pinheiro Foundation. *Housing deficit in Brazil,* 2013-2014, 2018. Available at: http://novosite.fjp.mg.gov.br/deficit-habitacional-no-brasil. Accessed on: Nov. 2024.

Mirabella, N. *et al.* Strategies to improve the energy performance of buildings: A review of their impact on the life cycle. *Buildings* MDPI *AG*, 12, 2018. doi: 10.3390/buildings8080105

Monteiro, H.; Freire, F.; Soares, N. Life cycle assessment of a southern European house addressing construction design options for orientation, window sizing, and building shape. *Journal of Building Engineering*, 39, 2021. doi: 10.1016/j.jobe.2021.102276

Motalebi, M.; Rashidi, A.; Nasiri, M. M. Optimization and integration of BIM-based life cycle assessment for energy efficiency retrofitting of buildings. *Journal of Building Engineering*, 49, 2022. doi: 10.1016/j.jobe.2022.104022

Najjar, M. *et al.* Integrated optimization with building information modeling and life cycle assessment for generating energy-efficient buildings. *Applied Energy*, 250, 1366-1382, 2019. doi: 10.1016/j.apenergy.2019.05.101

Nematchoua, M. K. *et al.* Analysis of environmental impacts and costs of a residential building over its entire life cycle to achieve nearly zero energy and low emission objectives. *Journal of Cleaner Production*, 373, 2022. doi: 10.1016/j.jclepro.2022.133834

Newberry, P.; Harper, P.; Norman, J. Carbon assessment of building shell options for eco self-build community housing through the integration of building energy modeling and life cycle analysis tools. *Journal of Building Engineering*, 70, 2023. doi: 10.1016/j.jobe.2023.106356

Nicolae, B.; George-Vlad, B. Life cycle analysis in refurbishment of the buildings as intervention practices in energy saving. *Energy and Buildings*, 86, 74-85, 2015. doi: 10.1016/j.enbuild.2014.10.021

Norouzi, M. *et al.* Low-energy buildings in combination with grid decarbonization, life cycle assessment of passive house buildings in Northern Ireland. *Energy and Buildings*, 261, 2022. doi: 10.1016/j.enbuild.2022.111936

Pakdel, A.; Ayatollahi, H.; Sattary, S. Embodied energy and CO_2 emissions of life cycle assessment (LCA) in the traditional and contemporary Iranian construction systems. *Journal of Building Engineering*, 39, 2021. doi: 10.1016/j.jobe.2021.102310

Pannier, M. L. *et al.* Multidisciplinary post-occupancy evaluation of a multifamily house: An example combining sociological, energy, and LCA studies. *Journal of Building Engineering*, 37, 2021. doi: 10.1016/j.jobe.2020.102139

Passer, A. *et al.* The impact of future scenarios on building refurbishment strategies towards plus energy buildings. *Energy and Buildings*, 124, 153-163, 2016. doi: 10.1016/j.enbuild.2016.04.008

Pombo, O.; Rivela, B.; Neila, J. Life cycle thinking towards sustainable development policy-making: The case of energy retrofits. *Journal of Cleaner Production*, 206, 267-281, 2019. doi: 10.1016/j.jclepro.2018.09.173

Rosa, A. D. La *et al.* Environmental impacts and thermal insulation performance of innovative composite solutions for building applications. *Construction and Building Materials*, 55, 406-414, 2014. doi: 10.1016/j.conbuildmat.2014.01.054

Sartor, M. *et al.* International purchasing offices: Literature review and research directions. *Journal of Purchasing and Supply Management*, 20(1), 1-17, 2014. doi: 10.1016/j.pursup.2013.09.002

Sartori, T.; Calmon, J. L. Analysis of the impacts of retrofit actions on the life cycle energy consumption of typical neighborhood dwellings. *Journal of Building Engineering*, 21, 158-172, 2019. doi: 10.1016/j.jobe.2018.10.009

Sharif, S. A.; Hammad, A. Simulation-Based Multi-Objective Optimization of institutional building renovation considering energy consumption, Life-Cycle Cost, and Life-Cycle Assessment. *Journal of Building Engineering*, 21, 429-445, 2019a. doi: 10.1016/j.jobe.2018.11.006

Sharif, S.A. Development of a surrogate ANN to select near-optimal building energy renovation methods considering energy consumption, LCC, and LCA. *Journal of Building Engineering*, 25, 1, 2019b. doi: 10.1016/j.jobe.2019.100790

Shrestha, J. K. Assessment of energy demand and greenhouse gas emissions in low-rise building systems: A case study of five building systems constructed after the Gorkha earthquake in Nepal. *Journal of Building Engineering*, 34, 2021. doi: 10.1016/j.jobe.2020.101831

Song, Q. *et al.* Characterizing the essential materials and energy performance of city buildings: A Case study of Macau. *Journal of Cleaner Production*, 194, 263-276, 2018. doi: 10.1016/j.jclepro.2018.05.148

Soust-Verdaguer, B.; Llatas, C.; García-Martínez, A. Critical review of BIM-based LCA method for buildings. *Energy and Buildings*, 136, 110-120, 2017. doi: 10.1016/j.enbuild.2016.12.009

Stephan, A.; Stephan, L. Achieving net zero life cycle primary energy and greenhouse gas emissions apartment buildings in a Mediterranean climate. *Applied Energy*, 280, 2020. doi: 10.1016/j.apenergy.2020.115932

Tadeu, S. *et al.* Eco-efficiency to support the selection of energy conservation measures for buildings: A life cycle approach. *Journal of Building Engineering*, 61, 2022. doi: 10.1016/j.jobe.2022.105142

Tettey, U. Y. A.; Dodoo, A.; Gustavsson, L. Effect of different frame materials on the primary energy use of a multi-story residential building in a life cycle perspective. *Energy and Buildings*, 185, 259-271, 2019. doi: 10.1016/j.enbuild.2018.12.017

Tushar, Q. *et al.* An integrated BIM-enabled LCA and energy simulation approach: The optimized solution for sustainable development. *Journal of Cleaner Production*, 289, 2021. doi: 10.1016/j.jclepro.2020.125622

UNEP. United Nations Environmental Program. *UNEP SBCI, Sustainable Buildings & Climate Initiative*. Paris: Available at: https://www.unep.org/topics/cities/buildings-and-construction/sustainable-buildings. Accessed on: Dec. 2024

Weiler, V.; Harter, H.; Eicker, U. Life cycle assessment of buildings and city quarters comparing demolition and reconstruction with refurbishment. *Energy and Buildings*, 134, 319-328, 2017. doi: 10.1016/j.enbuild.2016.11.004

Zhan, J. *et al.* Life cycle energy consumption and greenhouse gas emissions of urban residential buildings in Guangzhou City. *Journal of Cleaner* Production, 194, 318-326, 2018. doi: 10.1016/j.jclepro.2018.05.124