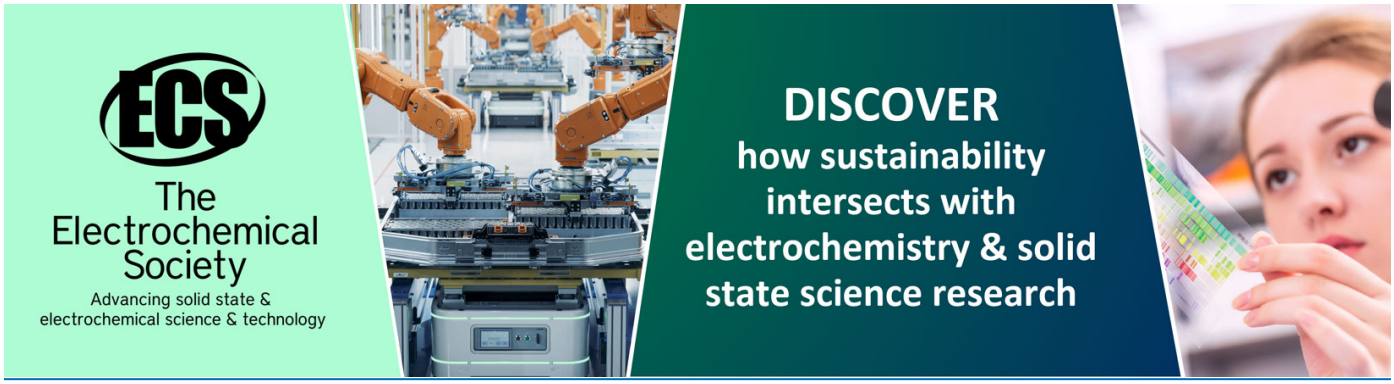
Zero carbon refurbishment for existing buildings: A literature review



Zero carbon refurbishment for existing buildings: A literature review

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Abstract. The need to mitigate climate change calls for the construction industry to achieve net-zero greenhouse gas (GHG) emissions for new and existing buildings by 2050. Zero carbon refurbishment (ZCR) for existing buildings is a significant area of interest, as many existing buildings will still be there in 2050. This paper investigates the global development, knowledge structure and gaps in the research field by conducting a systematic literature review. The final selection of 147 up-to-date journal articles was analysed using mixed-method data analysis, including quantitative (science mapping) and qualitative (thematic) analysis. Quantitative results reveal evolving research topics including energy performance and efficiency, life cycle environmental impacts, energy resources and policy, and decision-making with multi-objective optimisation. Research in ZCR is well-established in European countries and there is much interest and activity around the world. ZCR research on residential and office buildings provokes much consideration compared to other building types. The qualitative findings discuss the mainstream research areas (e.g. decision-making with multi-objective optimisation), determines research gaps (e.g. carbon impact), and recommends the future research agenda. The study offers academics a comprehensive understanding of ZCR research to link current research areas into future trends. It also provides construction professionals with current practices and an interdisciplinary guide to better deliver ZCR projects.

1. Introduction

Over the last few decades, climate change has presented many challenges [1]. The global carbon emissions have continuously increased, from 22.5 billion tons in 1998 to 34.04 billion tons in 2018 [2]. The Paris agreement in 2016 sought to limit the temperature increase from 2°C to 1.5°C above pre-industrial levels by 2050 [3]. Contributing to one-third of global GHG emissions, the construction sector is critical in alleviating carbon emissions. Compared to new buildings, refurbishing existing buildings offers a favourable opportunity to maximise carbon benefits. For example, Hasik et al. [4] compared the whole-building life cycle assessment (LCA) of refurbishment and new construction in the USA. The case study demonstrates 53–75% environmental impact reductions when refurbishing rather than constructing a new building.

Due to a large volume of literature describing the role of ZCR, several systematic reviews exist in the ZCR research area to discover uncovered knowledge structures. Loli and Bertolin [5] presented a literature review towards ZCR of historic buildings, determining research gaps in the field and

highlighting the inconsistency in the Scandinavian countries. Hashempour et al.'s [6] review paper focuses on energy performance optimisation of existing buildings, while Lu and Lai's [7] study predominantly pays attention to the carbon emissions of commercial buildings. However, the generalisability of published reviews on this issue is problematic as they mostly concentrate on specific building types, locations and aspects. These results are also based upon data published until 2017-2018. Given the latest Paris agreement in 2016, the research interest in the global decarbonisation for the existing building stock is expected to increase. Thus, there is a need for an up-to-date evaluation of critical areas and emerging trends.

This paper aims to provide the latest comprehensive literature review in ZCR for existing buildings. The novelty of this study is performing mixed-method data analysis, including science mapping and thematic analysis, in reviewing the ZCR research area. The following objectives are (1) analysing the main research topics within ZCR; (2) identifying the current research gaps; and (3) proposing future research directions. The remaining part of the paper proceeds as follows: (1) describe the methodology used in the study; (2) report results from the science mapping approach; (3) discuss the main research topics with the research gaps and future research directions.

2. Research method

A systematic review was undertaken in this study to examine the state-of-the-art research on ZCR due to its organised, transparent, and reproducible way to synthesise research findings and discover future studies [8]. The paper adopted a mixed-method data analysis technique, including quantitative (science mapping) and qualitative (thematic) analysis. This approach has been extensively used in construction engineering and management to present knowledge domains and research topics [9, 10]. Science mapping was employed to analyse and visualise bibliometric networks [11], while thematic analysis was applied to describe data in rich detail, summarise and interpret various aspects of the research topic [12].

The research process consists of three stages. In stage 1, the bibliometric search strategy used the keywords: "zero carbon" OR "net zero carbon" OR "zero emission" OR "zero energy" OR "nearly zero energy" AND "refurbishment" OR "retrofit" OR "renovation" via Scopus to determine the relevant ZCR literature. Scopus was selected for document search because of its influential and all-inclusive database, covering more recent publications than other digital sources such as Web of Science [13]. To narrow the scope of the review, a set of selection criteria were considered, including (1) English journal articles published at the final stage in the last five years (2017-2021); (2) Relevant subjects in the construction research field; (3) Paper published in top-ranking journals in the construction field ranked by Scimago Journal and Country Rank (e.g. Energy and Building), publishing the largest number of papers in the research context. The final selection includes 147 up-to-date journal articles. In stage 2, VOSViewer – a comprehensive science mapping tool based on Visualisation of Similarities (VOS) technology was adopted. It has unique advantages in clustering fragmented knowledge from different domains according to their similarity and relatedness. Compared with other options, the viewing capabilities of VOSViewer are beneficial for maps containing at least a moderately large number of items (e.g. at least 100 items) and the tool displays such maps in a satisfactory way [14]. We employed VOSViewer to visualise and analyse three scientometric tests: (1) keywords/clusters co-occurrence analysis, (2) country-specific analysis, (3) document co-citation analysis. According to Van and Waltman [15], a node indicates a specific bibliographic item in the visualised networks, namely keyword, country, reference, etc. The node size signifies the counting of the appraised item, such as citation and occurrence. Link represents the co-citation and co-occurrence. The software automatically accomplishes the total link strength (TLS) to reflect the correlation between any two nodes in the created networks. The average normalised citation symbolises the normalised number of journal source, article, scholar, country, or organisation citations. The normalisation corrects the misinterpretation that older documents gain more time to receive citations than recent publications. In stage 3, a qualitative discussion was presented with a hierarchical knowledge structure of recent ZCR research. We summarised ongoing main research topics, identified the research gaps and proposed future research directions.

3. Findings

3.1. Keywords co-occurrence analysis

A network of keywords was produced to exhibit the knowledge and rational organisation of the research themes. The options "All Keyword" and "Full Counting" in VOSViewer analysis were chosen to acquire a holistic academic knowledge of ZCR research. The minimum occurrence of a keyword was set at 4. Initially, 144 out of 1448 keywords met the threshold. After removing duplicates and general items such as "construction", "retrofitting", "building", etc., 69 keywords with 1212 links were selected for final consideration. In addition, using VOSViewer, the whole network could be automatically divided into clusters labelled with terms from keywords. Studies within the same cluster might be more similar than those from other clusters. Three clusters were identified in different colours, demonstrating latent semantic themes within the textual data, where the research patterns were perceived to uncover knowledge [9]. Cluster #1 (30 items) focused on energy performance, energy efficiency, and life-cycle environmental impacts. Cluster #2 contained 21 items centring on energy use, resources and policy, whereas Cluster #3 (18 items) emphasised decision-making with multi-objective optimisation, including economic trade-offs and renewable energy compensation. Figure 1 illustrates the mainstream of research keywords and their co-relationship.

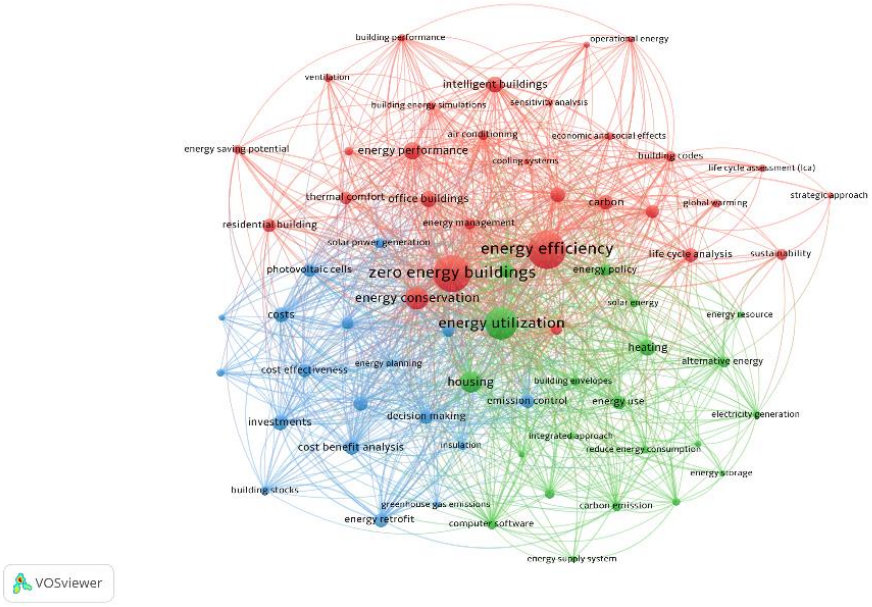

Figure 1. Mapping of co-occurred keywords

This network represented the boundaries and central tendency in the ZCR research area. The nodes sizes and the connection lines among keywords showed the most frequently studied and highly concerned terms, such as energy efficiency (Feq. =80, TLS=518), zero energy buildings (Feq. =79, TLS=418), energy utilisation (Feq. =61, TLS=407), energy conservation (Feq. =35, TLS=226), housing (Feq. =31, TLS=192), intelligent buildings (Feq. =19, TLS=146), costs (Feq. =16, TLS=136), investments (Feq. =17, TLS=135), cost-benefit analysis (Feq. =16, TLS=135), office buildings (Feq. =19, TLS=135). Residential and office building types have been given close and thoughtful attention. Further investigation in the average citations demonstrated that the following keywords including genetic algorithms (Avg. =34), building performance (Avg. =25), energy planning (Avg. =25), multi-objective optimisation (Avg. =23.5), energy management (Avg. =22.6) provoked much consideration.

3.2. Country-specific analysis

Keyword analysis specified several countries contributing to ZCR research, comprising developed and developing economies like the UK and India. The study further determined countries active in the global ZCR research. The minimum of number documents and citations for a country was set at 2 and 20, respectively. Finally, a shortlist of 22 countries and 62 links were generated. Figure 2 illustrates the map of countries contributing to ZCR research.

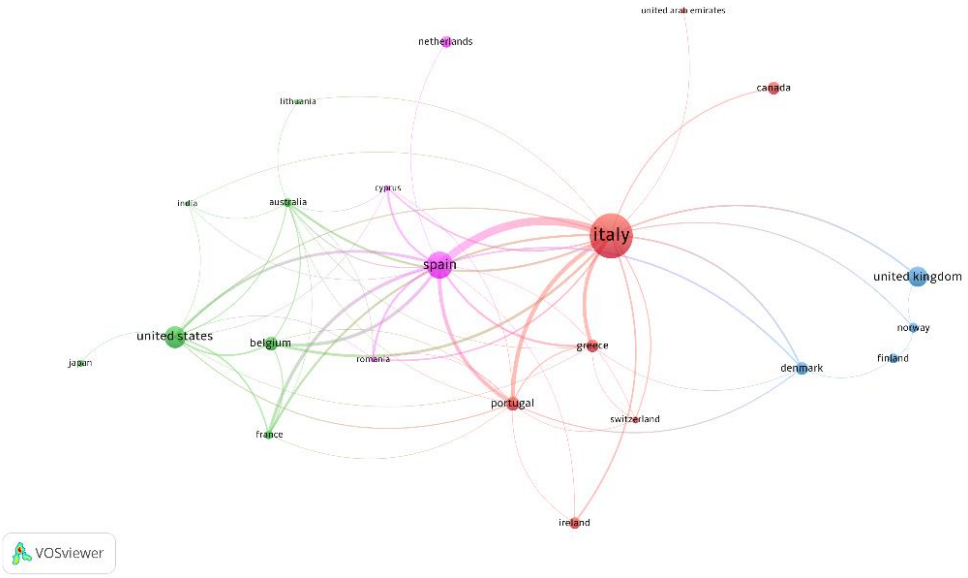

Figure 2. Mapping of countries contributing to ZCR research

According to the node sizes and connection lines, the following countries have contributed significantly to the global research: Italy, Spain, the USA, the UK, Belgium, Portugal, Canada. Other countries such as France and Norway offered fewer publications but strongly expressed their significant influence through the high average citation. Scholars from Europe took the lead in ZCR research, ranking the top in terms of the number of publications and total citations, followed by North America. This result might be explained that European nations have started implementing a long-term renovation strategy set out in the Energy Performance of Buildings Directive (2010/31/EU) over a decade. Research on ZCR has also been attentive in other parts of the world, e.g. Oceania (Australia) and Asia (India, Japan and UAE). Table 1 present the findings of the top-ten countries influencing ZCR research in the last five years.

Table 1. Summaries of country-specific leadership in ZCR research

Country	Numbers of publication	Number of citation	Average Norm. Citation	Country	Number of publication	Number of citation	Average Norm. Citation
Italy	46	868	1.13	Belgium	8	216	1.98
Spain	22	296	1.06	Greece	7	162	0.97
United States	16	159	0.70	Canada	7	136	1.01
United Kingdom	14	144	0.66	Denmark	7	64	0.94
Portugal	8	226	1.81	Netherlands	6	52	0.49

3.3. Document co-citation analysis

A document co-citation analysis could divulge the underlying intellectual structure of a knowledge domain [9]. Therefore, the most influential journal publications in the last five years were assessed with the co-citation network generated in VOSViewer. The minimum number of citations was set to 5. Of the 147 documents, 92 meet the threshold, resulting in a co-cited visual network map, as shown in Figure 3. The most extensive set of connected items consisted of 20 items. The nodes in the map denoted the documents, identified by the first author name and the publication year. The time of publication signified the colours of the nodes and the links.

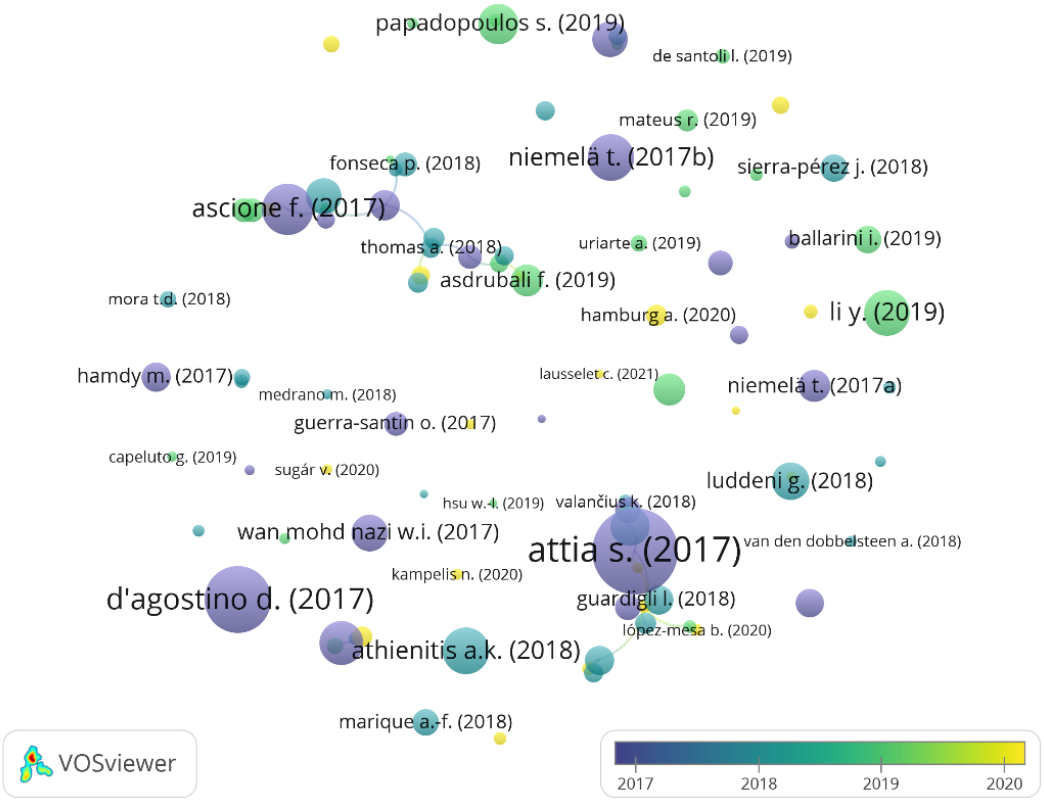

Figure 3. Mapping of co-citation analysis

The co-citation network showed an overall distribution, with only two large sets of connected items. This result indicated that the recent ZCR research directions went beyond common ideas and results. 2017 was a landmark year for ZCR research as the majority of high-citation papers were released. The latest ZCR research in the 2020s was expected to spread faster and more comprehensively. More details on the top-five most cited articles are demonstrated in Table 2.

Table 2. List of high-impact publications in ZCR

Scholars	Year	Title	Citations	Average Norm. Citation	Related topics
Attia *et al.* (2017)	2017	Overview and future challenges of nearly zero energy buildings (nZEB) design in Southern Europe	138	3.803	Operation and management research
D'agostino *et al.* (2017)	2017	Towards Nearly Zero Energy Buildings in Europe: A Focus on Retrofit in Non-Residential Buildings	95	2.618	Systematic evaluation
Ascione et *al.* (2017)	2017	Energy retrofit of educational buildings: Transient energy simulations, model calibration and multi-objective optimisation towards nearly zero-energy performance	64	1.764	Multi-objective optimisation
Athienitis *et al.* (2018)	2018	Assessing active and passive effects of façade building-integrated photovoltaic/thermal systems: Dynamic modelling and simulation	57	3.213	Environmental aspect
Niemelä *et al.* (2017)	2017	Cost-effectiveness of energy performance renovation measures in Finnish brick apartment buildings	56	1.543	Environmental and economic aspects

4. Discussion

Following the science mapping analysis, we carried out a qualitative discussion to summarise the growing research trend, identify research gaps and future work. An up-to-date ZCR knowledge map was developed, resulting from scientometric and thematic analysis (see Figure 4).

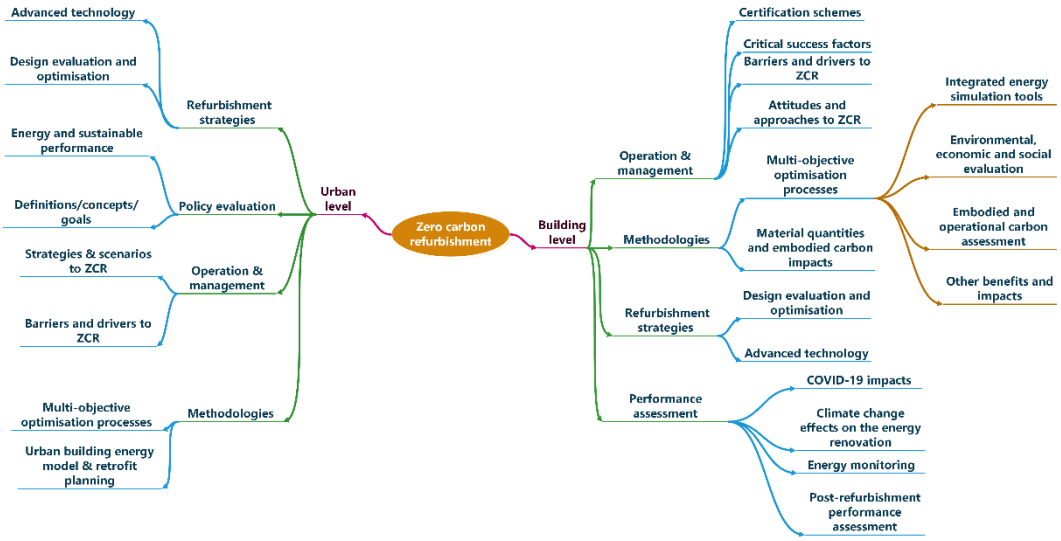

Figure 4. A mind map of ZCR research themes

Existing research has recognised the critical role of ZCR delivery methodology at the building level. The most highlighted finding is a continuous interest in using multi-objective optimisation processes, which support decision-making in selecting the best fit-for-purpose refurbishment options. Most studies

adopt at least two sustainability objectives focusing on environmental and economic factors [16]. However, carbon impact is not a common investigation focus compared to energy. Contemporary research [17] has preliminarily incorporated whole-of-life carbon consideration with energy and economy aspects. Mainly being overlooked in the past, the social objective ("co-benefits") has been recently well-established in multi-objective optimisation processes. An all-inclusive refurbishment to achieve the performance required by laws such as seismic regulations must also be considered. For instance, the methodology for comparing cost-optimality in building refurbishment developed in IEA Annex 56 project has been extended with: (1) an LCA including embodied primary energy and carbon emissions in the calculations [18], (2) an approach to integrate co-benefits in the evaluation of the refurbishment scenarios [19], and (3) a method for energy and structural upgrade [20]. These observations suggest that a holistic multi-objective methodology considering whole-of-life carbon, economic factors, co-benefits, and other impacts is necessary for the global ZCR development. Furthermore, multi-objective optimisation processes often incorporate various methods, tools and systems to support decision-making. Hu [21] proposed a novel building information model (BIM) – building performance model (BPM) – building environmental model (BEM) framework to identify the most energy-efficient and cost-effective refurbishment strategies. Rabani et al. [22] integrated an Indoor climate and energy simulation software (IDA-ICE) and a generic optimisation tool (GenOpt) through a Graphical Script interface to find the best combination of refurbishment measures. Nevertheless, empirical research reporting on how these methods, tools and systems are adopted to support decision-making in the current industry practice is of interest for future work.

Another significant issue for upcoming research is relevant to the methodology for carbon quantification. Most LCA studies emphasise embodied carbon emissions of construction materials and rarely assess the carbon impacts of mechanical, electrical, and plumbing (MEP). The refurbishment often improves energy efficiency by upgrading building services, accounting for a considerable amount of embodied carbon emissions. To date, Rodriguez et al. [23] established a preliminary range of material quantities and embodied carbon impacts for MEP and tenant improvement (TI) components, focusing on commercial office buildings in the Pacific Northwest. Further work is required to establish the availability of embodied carbon quantities worldwide.

There is a large and growing body of literature regarding refurbishment strategies in advanced technologies, design evaluation and optimisation for ZCR. Examples include multi-disciplinary analysis of light shelves application [24], the evolution of double-skin and responsive façade [25], PV optimisation [26]. This finding shows that investigations on refurbishment technologies and strategies have been widely studied. Turning to performance assessment, many attempts have been made to evaluate the energy performance before and after refurbishment and the impacts of occupant behaviours [27, 28]. The current research trend evolves towards assessing the effects of long-term climate change and global pandemics such as the COVID-19 crisis on refurbishment actions [29, 30].

In terms of operation and management, understanding critical success factors, barriers and drivers to implement ZCR within the construction industry and the construction professionals' knowledge and attitudes towards ZCR are essential for a wide range of ZCR uptake [31, 32, 33]. For example, Alam et al. [34] argue that reducing embodied carbon emissions in the construction materials for refurbishment projects is less important than improving energy efficiency from Finish stakeholders' viewpoints. However, the transition to a 100% renewable energy system in many countries such as Denmark and New Zealand by 2050 may leave behind the primary focus on energy efficiency. This result, while preliminary, informs the formulation of policies to drive the whole-of-life carbon consideration for ZCR. So far, there has been little discussion about the stakeholder collaboration in the decision-making process towards delivering ZCR projects. Regarding energy and carbon performance certificate schemes, which often calculate energy savings and operational carbon reduction [35], the current schemes create a demand-driven market for energy efficiency, rather than looking at the carbon challenge holistically, such as the whole-of-life carbon performance assessment.

Due to a call for massive decarbonisation by 2050, the current research trend shifts from an individual building level to an urban level. As same as the building level, various studies have assessed the efficacy

of refurbishment strategies, operation and management and methodologies at the metropolitan level. The issue of ZCR-related policy has lately received considerable concentration. Cerezo-Narváez et al. [36] examined the energy, emissions and economic impact of the new nZEB regulatory framework and accomplished that the energy savings and carbon reduction objectives were greatly exceeded. Whereas, Approved Document L for existing British buildings was underperforming but could feasibly be revised to encompass contemporary sustainable design solutions [37]. Nonetheless, most studies are conducted in Europe, where research into building refurbishment has a long history. The challenges and opportunities to ZCR-related policy implementation in Europe indicate lessons learnt for other countries.

5. Conclusion

The study contributes to theoretical and practical knowledge by providing a holistic approach to an updated systematic literature review in ZCR for existing buildings. The science mapping analysis reveals main clusters of research around energy performance and efficiency, life-cycle environmental impacts, energy use, resources and policy, multi-objective decision-making. European nations take the lead, but other countries also actively contribute to the ZCR research. To specify the contribution from every country, future research should analyse the case studies and their implementation. Meticulous attention has been devoted to ZCR research on residential and office buildings. The recent ZCR research directions exceed common ideas and results. The most cited publications are relevant to operations and management, systematic evaluation, multi-objective optimisation, environmental and economic aspects. The follow-up qualitative analysis's results considerably align with the science mapping analysis. The most critical suggestions for future work are as follows: (1) a holistic multi-objective methodology considering whole-of-life carbon, economic factors, co-benefits and other impacts; (2) empirical research on how available methods, tools and systems regarding multi-objective optimisation processes are adopted to support decision-making in the current industry practice; (3) the investigation on stakeholder collaboration in the decision-making process towards delivering ZCR projects, (4) the availability of embodied carbon quantities; (5) whole-of-life carbon performance assessment. A limitation of this study is that the study scope is narrow, with published articles in the last five years and a set of selection criteria. Notwithstanding the relatively limited sample, this work offers new insights into the future ZCR directions.

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