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Global Research Trends on Energy Efficient Retrofitting in Existing Buildings

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Abstract

Built environments have destructive effects on the natural environment as one of the responsible actors in increasing energy consumption and greenhouse gas emissions. Therefore, all types of energy-efficient and sustainable improvement studies for the existing building stock are pivotal in reducing the adverse effects on the environment. Although the measures taken and targets determined in line with the policy regulations implemented on a global scale are promising, the proliferation rate of these practices is relatively low. The retrofit process's complex nature, which requires multi-dimensional solutions involving several aspects, increases the significance of relevant studies. In this context, it is thought that it will be beneficial to monitor, analyse and assess contemporary studies in determining the areas that require further research. This study presents a comprehensive literature analysis using the science mapping method using bibliometric data of qualified academic studies published since 2000 when research on the energy-efficient retrofit of existing buildings gained momentum. It aims to contribute to the literature by determining the research areas in which the contemporary research concentrates and evaluating future studies on "energy efficient retrofit of existing buildings".

Keywords

energy efficient retrofit, bibliometric analysis, science mapping

1 Introduction

Cities and built environments are responsible for approximately 70% of global greenhouse gas emissions. Buildings, the most substantial component of built environments, are responsible for almost 40% of energy consumption and 36% of greenhouse gas emissions (GlobalABC, 2019). Therefore, increasing the energy performance of building stock and adopting an eco-friendly design approach should be a worldwide priority.

For this purpose, studies and research on "energy efficient" buildings can be defined through several concepts such as zero-energy, ecofriendly, green, sustainable, and ecological, in line with the increasing political regulations made in recent years and the decisions determined at the national/international level (Wuni et al., 2019). Although regulations for projected buildings are promising, the building stock is inadequately planned, equipped with old systems, and therefore has low energy performance (Heo et al., 2012); It maintains its large energy usage share on a global scale. Moreover, future predictions suggest an increase in this trend (IEA, 2020).

A costly way of retrofitting existing buildings is to replace the existing buildings with new green buildings. However, due to the high costs, the modification rate is meagre (Barlow and Fiala, 2007; Roberts, 2008). Therefore, "Energy Efficient Retrofitting" (EER), an alternative, emerges as a more convenient way to increase energy performance with less investment. Numerous projects and policies have been initiated worldwide to increase energy efficiency in this context. Governments have implemented retrofit initiatives and programs to promote energy savings in the construction industry. "Better Building Initiative" had a goal of reducing energy consumption by 20% in commercial buildings with cost-effective retrofit interventions in the United States by 2020 (Better Buildings, 2021; White House, 2011). The Energy Performance of Buildings Directive (EPBD-Recast, 2010/31/EU) and the Energy Efficiency Directive (EED,

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2012/27/EU) is published to set policies for promoting comprehensive retrofitting and renovation activities for the EU at a low cost (Asadi et al., 2012a).

Baek and Park (2012a) revealed that the main barriers to the energy performance retrofits of existing buildings as inadequate "awareness, financing, information, and regulatory systems". Overcoming such obstacles depend on policies and measures to be implemented in the light of successful practices adopted in developed countries.

In addition to all these policies, a comprehensive assessment of potential solutions is required to perform an efficient building retrofit.

It has been observed that EER studies with distinct scales and application areas significantly reduce greenhouse gas emissions and building energy consumption (Ardente et al., 2011; Mahlia et al., 2011; Moazzen et al., 2020). Considerable research on building retrofits revealed the significance of several factors such as efficiency level, retrofit cost, post-retrofit maintenance, and operating cost (Guardigli et al., 2018; Jakob, 2006; Liu et al., 2018), temporary repayment period (Biserni et al., 2018; Huang et al., 2012), features of the applied materials, functionality, comfort, alternative organisational solutions and their optimisation (Asadi et al., 2012b; Brunelli et al., 2016; Carratt et al., 2020; Pombo et al., 2016b; Schwartz et al., 2016) ecological, climatic (Carpino et al., 2018; Gómez Melgar et al., 2020; Sun et al., 2018a) social (Amini Toosi et al., 2020; Kivimaa and Martiskainen, 2018) legal, political conditions (Baek and Park, 2012a; Gonzalez Caceres, 2018; Gram-Hanssen, 2014; Sebi et al., 2019) and user requirements (Ascione et al., 2020; Miller et al., 2018; Thomas, 2010). Consequently, it is essential to analyse the literature to understand this complex process.

Several studies measure global energy issues and trends in the built environment. One by Wuni et al. (2019:p.69) analysed bibliometric data of "global research trends on green buildings in construction journals from 1992 to 2018". Det Udomsap and Hallinger (2020) documented "sustainable construction" research trends from 1994 to 2018. Olawumi and Chan (2018:p.231) applied similar methods to present "global research on sustainability and sustainable development". Darko et al. (2019) analysed and visualised the global green building research. Recently, Shukra and Zhou (2021) revealed a holistic approach through green BIM.

In parallel with those studies, this article aims to provide a holistic overview of research trends in the EER field. By conducting a comprehensive review of the existing EER literature, it attempts to create bibliometric maps and quantitative data. Thus, predictions on future trends were presented in the areas identified and focused on contemporary EER literature.

2 Research method

The research methods and tools used in the bibliometric analysis and the research method are presented comprehensively in Section 2. Fig. 1 illustrates the flow chart of this research method.

The software tool was decided primarily for the bibliometric analysis on the energy-efficient retrofit studies of existing buildings. The database that will provide the research was selected accordingly. Several searches were performed in the particular database with certain restrictions to obtain the bibliometric data. These data were handled in the context of "source journal, keyword, co-authorship, citations, and countries"; maps were then created for analysis. Afterwards, the main research areas for EER were determined by evaluating the analysis results. The trends and gaps in contemporary research were then assessed.

2.1 Science analysis and mapping

In this study, a technique that enables quantitatively mapping of patterns and networks with an extensive bibliometric data set is applied. This science mapping technique aims to generate science or bibliometric maps explaining how research fields are structured conceptually, intellectually, and socially (Cobo et al., 2011). This technique is applied to monitor a scientific discipline to determine its cognitive structure, evolution, and main subjects (Noyons et al., 1999). Science mapping (bibliometric mapping, in other words) enables researchers to make systematic discoveries in the literature by associating literature concepts

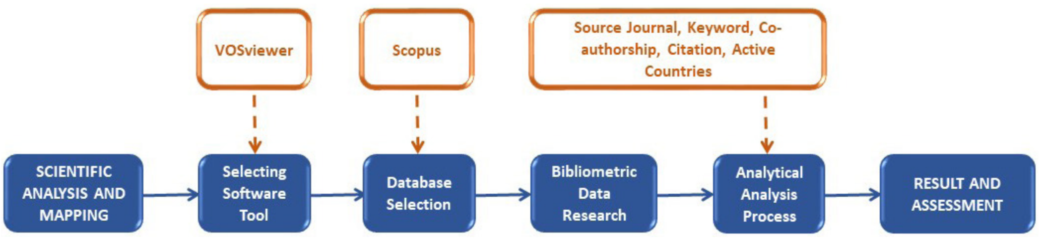

Fig. 1 Research method chart

(such as keywords, citations, study links of countries and research organisations) that may be omitted in manual review studies (Su and Lee, 2010). Moreover, using bibliometric data, science mapping facilitates tangible recommendations through the literature output (including the measurement and analysis of the network of researchers, institutions, and countries) (Hood and Wilson, 2001).

2.1.1 Selection of software tool and database

Numerous software tools (such as CiteSpace, VantagePoint, Gephi, CitNeTExplorer, BibExcel, VOSviewer) map and visualise bibliometric data sets have been developed to analyse the literature scientifically on a broader scope. As these tools were developed for general science mapping, they also have more specific applications. Moreover, these software tools differ from each other in terms of their capability, capacity, and limitations.

VOSviewer (version 1.6.15) was chosen as the tool within the scope of this study (van Eck and Waltman, 2022). VOSviewer is an open-source software tool specifically designed to generate and visualise bibliometric maps and, unlike most computer programs used, mainly focuses on the graphical representation of such maps (van Eck and Waltman, 2010). It is a very convenient tool for visualising large maps with features such as zoom function, custom labelling algorithms, and density representation (Cobo et al., 2011). Therefore, VOSviewer was the preferred choice for a systematic EER literature review.

Another critical step was the database selection through which the literature was reviewed. Web of Science and Scopus are two important databases that index publications on built environments and energy. However, the Scopus database was preferred since it contains more comprehensive publications and more recent bibliometric data (Meho and Rogers, 2008). Additionally, Scopus can import data in the file format (CSV) required for VOSviewer.

2.1.2 Generation of bibliometric data and analytical analysis process

To obtain an accurate and reliable bibliometric dataset for "Energy-efficient retrofit in an existing building," the most frequently used modifiable keywords were used to define the subject. In this context, Energy AND ("Existing Building" OR "Building Stock") AND (Retrofit* OR Renovation OR Refurbishment) was used as a keyword index to search. The flow shown in Fig. 2 was followed in the keyword selection.

First, searches with the "retrofit" keyword were repeated after the reviews and assessments in the relevant database. It has been observed that relevant articles referred to "energy-efficient retrofit" with the words "retrofit-retrofitting" (Castleton et al., 2010; Ma et al., 2012; Mazzarella, 2015; Wu et al., 2017), "renovation" (Attia et al., 2017; Meijer et al., 2009; Pombo et al., 2016a;), and "refurbishment" (Carletti et al., 2014; Ficco et al., 2015; Lechtenböhmer and Schüring, 2011). To isolate the "retrofit" studies in different fields in the results, the search was narrowed by adding the words "existing building" and "energy."

As a result of the search, 2760 articles (as of October 2021) were viewed for these keywords using the "article title/abstract/keywords" function of the Scopus database without defining a time limit. Filtering functions are used to improve data results at this stage. The retrospective time limit was applied at the beginning of 2000 to narrow the research to when steady growth began (Fig. 3).

"Document type" was set to "Article or Review". Other types (such as conference papers, book or book chapters, short surveys) were omitted as they complicate the analysis process and contribute less to the results (Butler and Visser, 2006; Hosseini et al., 2018). Browsing was improved through setting the "Subject area" to "Engineering,

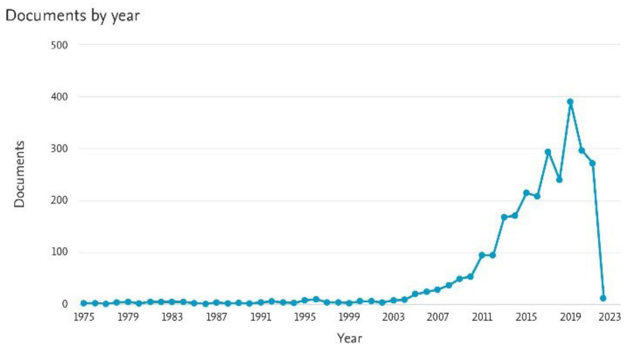

Fig. 3 Annual distribution of studies to time-limited scanning

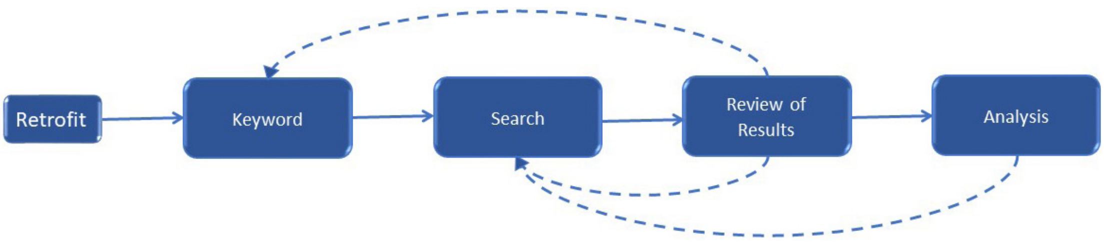

Fig. 2 The process of determining the keywords used in the subject

Energy, Environmental Science" and "Social Science". "Source type" was limited to "Journal" and language section to "English". With all these filters, 1416 research articles met all conditions. Bibliometric data was downloaded as a "Comma- Separated Values (CSV)" file, and the literature on energy-efficient retrofit in existing buildings was transferred to VOSviewer for science mapping.

After importing the bibliometric data to the software tool, first, the VOSviewer "create a map based on bibliometric data" function, the citations, co-authorship, co-occurrence keyword formation, and country citations networks have been created. The total, average, normalised, and average normalised number of citations, associations, and total link strengths of the articles, authors, and countries were coded. Tables summarising the numerical measurements of the networks were formed with maps to illustrate the networks. After that, VOSviewer's "create a map based on text data" function has been used to create a more comprehensive syntax map of terms. A map of the main EER research areas was created at this stage. The keywords in the generated network were analysed, and the main research areas became apparent.

2.2 Research findings

In Subsection 2.2, the bibliometric data set of the studies in the EER field has been processed through VOSviewer under "source journal, keyword, co-authorship, citation, and countries", and the maps are presented with relevant analyses.

2.2.1 Analysis of source journal data

Scientific journals constitute one of the leading publication platforms in promoting academic developments and innovations with articles within the specified scopes and limits. Identifying the high-impact journals would be a valid starting point to map research trends in energy-efficient retrofit literature systematically (Wuni et al., 2019). Fig. 4 visualises the citation network of 38 journals that publish research articles on the subject. Moreover, a detailed quantitative summary of the network is presented in Table 1. The journals reviewed have published at least five EER research articles and received at least 20 citations. These limitations were applied in VOSviewer during the network generating process, and as a result, 38 journals were suitable for the test. The search, which studied 1416 articles,

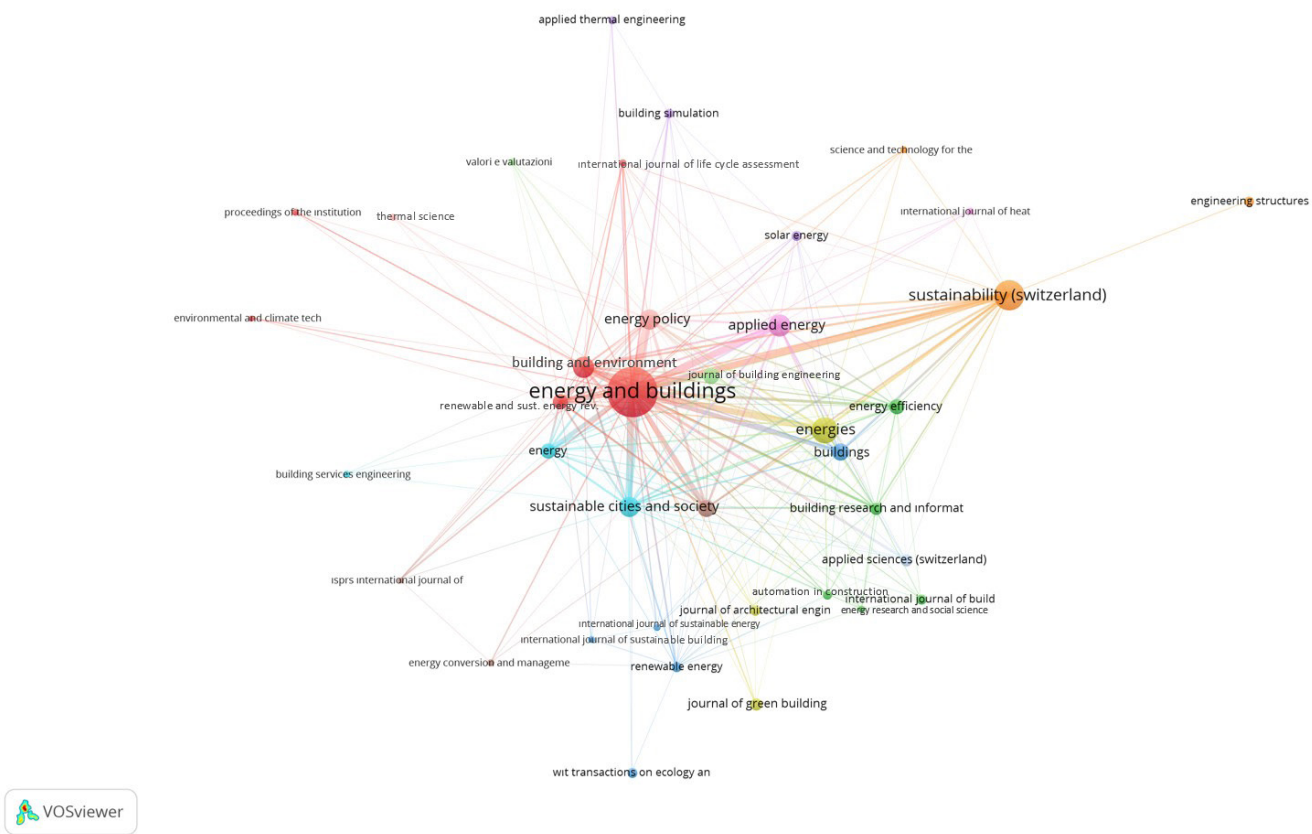

Fig. 4 The network of esteemed source journals in EER research

was limited to 38 journals that were more impactful in the field, and 1070 articles were viewed according to the new results obtained with an improved search. The data provided by these 1070 publications were used in the analyses.

The map is created using the VOSviewer's "source-citation network" function. The size of the nodes of each journal reflects the journal's impact in terms of receiving citations. For example, "Energy and Building" journal has

Table 1 Source journals prominent in Energy Efficient Retrofit Research

References	Total number of articles	Total citations	Avg. references	Links	Total link strength	Avg. normalised number of citations[1]
Energy and Buildings	280	10775	38	36	1108	1.42
Energy Policy	47	2394	51	26	342	1.60
Building and Environment	51	2185	43	26	236	1.63
Applied Energy	56	2039	36	23	258	1.77
Sustainable Cities and Society	47	1076	23	26	292	1.51
Journal of Cleaner Production	33	992	30	19	203	1.89
Renewable and Sustainable Energy Reviews	26	925	36	19	182	0.51
Building Research and Information	18	743	41	17	77	1.05
Energies	80	740	9	23	226	0.74
Energy	26	694	27	18	159	1.39
Automation in Construction	9	611	68	9	19	2.61
Sustainability (Switzerland)	104	592	6	21	250	0.69
Energy Efficiency	28	451	16	18	78	0.79
Journal of Building Engineering	29	445	15	21	121	1.83
Solar Energy	12	414	35	10	17	1.01
Buildings	33	290	9	16	134	0.57
Renewable Energy	11	218	20	18	37	1.09
Engineering Structures	13	198	15	1	3	0.74
Energy Conversion and Management	6	145	24	5	12	1.81
Applied Thermal Engineering	8	114	14	3	7	1.29
Building Simulation	9	104	12	9	20	0.66
International Journal of Life Cycle Assessment	7	104	15	9	30	0.82
Valori e Valutazioni	7	101	14	6	12	0.77
Applied Sciences (Switzerland)	16	82	5	12	47	0.88
Journal of Green Building	16	78	5	5	12	0.13
International Journal of Sustainable Energy	6	76	13	6	11	0.48
International Journal of Sust. Building Tech. and Urban of Dev.	6	66	11	5	8	0.35
Journal of Architectural Engineering	11	57	5	10	15	0.19
Environmental and Climate Technologies	5	54	11	3	7	0.49
Science and Technology for The Built Environment	7	52	7	6	11	0.35
Proceedings of the Institution of Civil Engineers: Engineering Sust.	7	49	7	4	9	0.30
International Journal of Building Pathology and Adaptation	13	47	4	7	10	0.33
International Journal of Heat and Technology	7	46	7	5	8	0.39
Building Services Engineering Research and Technology	6	41	7	4	4	0.22
ISPRS International Journal of Geo-Information	5	40	8	7	22	0.82
Thermal Science	7	23	3	4	7	0.12
WIT Transactions on Ecology and the Environment	12	21	2	3	3	0.06
Energy Research and Social Science	6	21	4	10	15	0.42

1 Normalized number of citations is a measure of the total number of citations an article is recorded in a year. Therefore, the normalization of citations standardizes the tendency for older articles to have better opportunities to get citations than recently (Hood and Wilson, 2001) the biggest knot. Journals of "Energy Policy", "Building and Environment", and "Applied Energy" appear to have relatively larger nodes than the rest of the sources. This situation highlights that EER publications in the journals listed have a higher impact.

The link lines between the node points indicate the citation network formed between journals - the frequency of these connection lines in the map increases in direct proportion to the number of citations.

It is observed that these 38 journals have strong citation links among themselves. Accordingly, it can be argued that most research articles refer to other EER articles published in all these journals. Moreover, research outputs were divided into 12 groups with distinct colour usage. The scope of the EER research areas or the frequency of common citations affects the formation of the groups.

The location and distance of the journals to each other also provide information about the relationship between them. Journals that are located closer within groups have stronger citation links than those that are further away. For example, although "Proceedings of the Institution of Civil Engineers: Engineering" journal is in the same cluster (red) with other journals such as "Building and Environment", "Energy and Buildings", "Environmental and Climate Technologies", "International Journal of Life Cycle Assessment", "Renewable and Sustainable Energy Reviews" it is positioned further away due to its weak citation link.

As observable in Table 1, there is a strong positive correlation, according to the correlation coefficient, calculated between the total number of articles, total citations, and total link strength (r) ($r > 0.9$). Therefore, each of these indicators can compare source journal results in terms of their productivity and contribution.

As the next step, the correlation between average citations and the rest of the indicators is calculated. There is a weak correlation between average citations and the total number of research articles in this context ($r = 0.27$). Also a weak correlation between average citations and total link strength ($r = 0.41$). However, a higher positive relationship exists between average citations and the average normalised number of citations ($r = 0.79$). Thus, it can be said that the average annual impact (normalised number of citations) of a journal is partially related to the average number of publications.

Based on the number of articles published and total citations they received, the journal with the most contribution to the subject is by far the "Energy and buildings" journal. This journal is followed by "Energy Policy," "Building and Environment," and "Applied Energy." Therefore, such information on the impact criteria regarding the resources will guide researchers in choosing which journal to submit their work.

2.2.2 Co-occurrence keyword analysis

Keywords that provide information about the main scope of research publications are used in indexing articles in databases. Therefore, analysing keywords in a number of publications is significant for researchers working in a particular field, as it provides a holistic map of the leading research areas (Wuni et al., 2019).

Fig. 5 illustrates the coexistence of author keywords used in 1070 articles. For the pre-set of VOSviewer, "co-occurrence" as an analysis type is used, and the search is limited with "author keywords" when creating the network. The minimum number of occurrences for a keyword was chosen as 10. Thus, the keywords strongly linked to the subject and selected by the article's author were included in the network to provide a substantive analysis. As a result, 75 keywords out of 3056 keywords were included.

The node size representing each keyword reflects the overall frequency of use across 1070 articles. Moreover, the keywords' proximity to each other indicates that these words are found together in articles. In this context, "energy efficiency" and "(building) (energy) retrofit" keywords have relatively larger nodes, meaning more common use, followed by "energy performance", "thermal comfort". Also, different keyword clusters are grouped by colour in the network. Each cluster indicates the most common keywords. For example, retrofitting in the green cluster is usually used with keywords such as thermal comfort, energy performance, payback period, energy simulation, residential building stock, social housing. This result shows that the studies focused on cost optimisation are directed towards retrofitting in residential buildings, particularly thermal comfort. Another example, retrofitting in the yellow cluster, is used with keywords such as multi-objective optimisation, building simulation, genetic algorithm, building envelope, district heating, heat pump. This result shows that the studies focused on multi-objective optimisation are directed towards retrofitting building envelope and heating systems. In addition, it is understood that genetic algorithms are mostly preferred as a method in these optimisation studies.

Based on the keywords co-occurrence network (Fig. 5), Table 2 extracts the 30 most frequently used keywords about the total usage and total link strength. Retrofit and

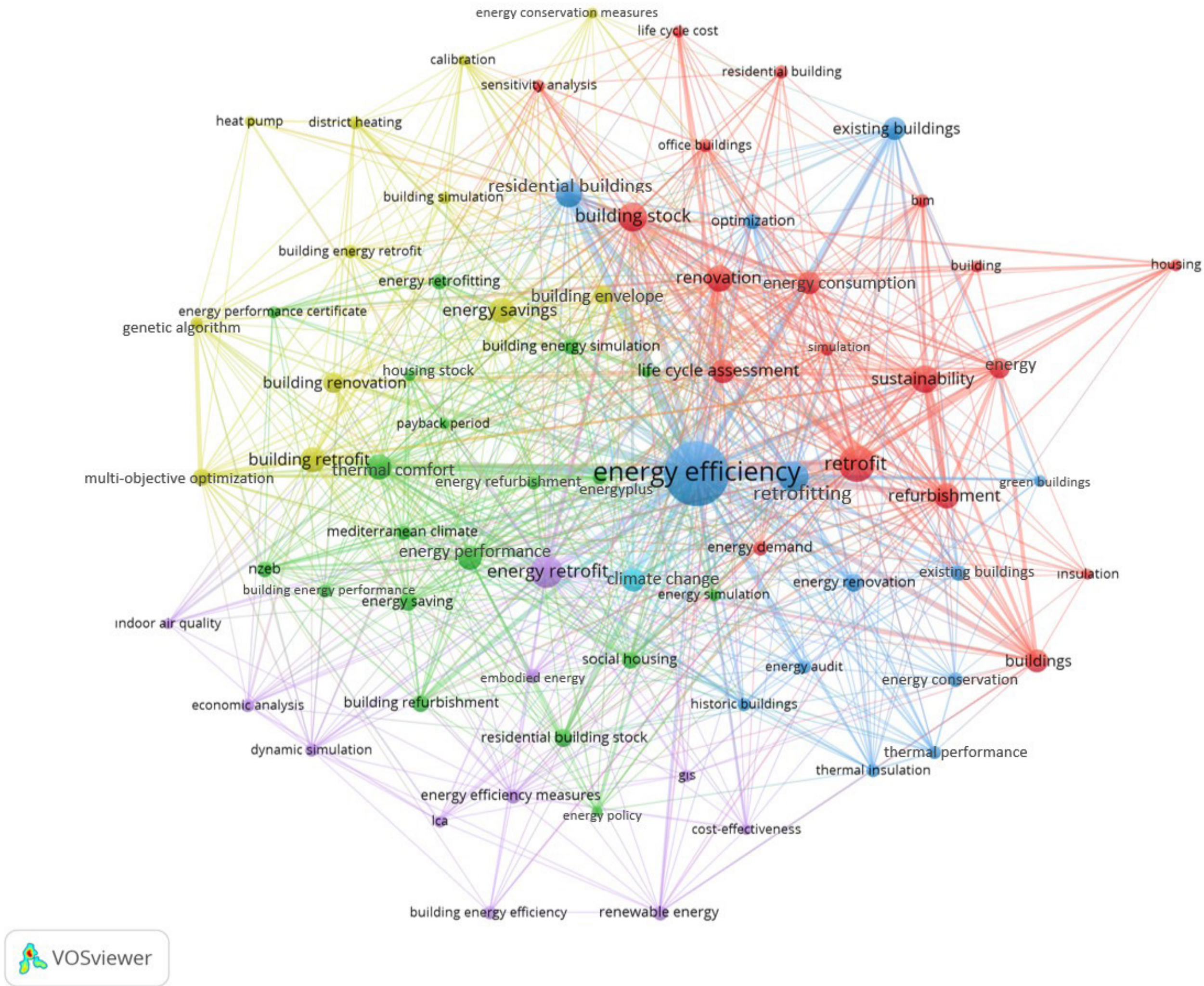

Fig. 5 The keyword co-occurrence network analysis

renovation keywords are also shared with different suffixes. To simplify repetitions with the same meaning, these uses are epitomised and shown in a single line.

The keyword usage correlation coefficient and total link strength calculation show a significant positive correlation (r = 1) between the two variables. Thus, the keyword occurrence frequency is directly proportional to the frequency of using frequency and other terms used in EER research. Numerical statistics of the changes in node sizes (using frequency) and total link strength (common use links) of keywords are presented in Table 2, which is a component of Fig. 5. In this context, 30 high-impact keywords that appeared together with other related terms at least ten times were found after analysing 3817 keywords in (1070) articles published from 2000 to 2021. This awareness is essential when guiding researchers in choosing appropriate keywords. An analysis of author keywords in research articles is summarised in Sub-subsection 2.2.2, as the holistic analysis of all keywords is presented in Section 3 to identify the main research areas in EER.

2.2.3 Co-authorship analysis

An awareness regarding scientific cooperation networks in a research area is important for contributing to scientific communication and collaborations. These collaborations increase productivity by facilitating access to areas of expertise and sharing ideas (Ding, 2011; Hosseini et al., 2018). Therefore, a network analysis of co-authored articles was conducted to determine the main collaborations in EER research. The minimum number of articles and citations were set at 7 and 50 in the VOSviewer pre-sets, respectively. Applying these thresholds generated 30 authors suitable for review among 2931 authors in 1070 articles.

Fig. 6 shows the collaboration of the highest contributing and most influential scholars of EER discourse under the selection criteria. Moreover, citations, normalised

Table 2 The most influential keywords in Energy-Efficient Retrofit Research

No	Keywords	Total usage	Total link strength
1	(building/energy) retrofit(s)(ing)	301	224
2	(building) energy efficiency	254	192
3	(building/energy) renovation	108	83
4	energy saving(s)	71	54
5	(building) refurbishment	70	56
6	building stock	59	51
7	existing building(s)	57	38
8	sustainability	52	44
9	residential buildings	48	38
10	thermal comfort	44	35
11	(multi-objective) optimization	43	35
12	energy performance	42	30
13	life cycle assessment	41	31
14	buildings	38	33
15	energy consumption	37	37
16	climate change	37	31
17	energy	33	30
18	building envelope	27	20
19	residential building stock	25	20
20	social housing	23	19
21	building energy simulation	20	19
22	nZEB	20	17
23	Mediterranean climate	18	18
24	energy conservation	18	13
25	energy efficiency measures	17	15
26	energy demand	17	15
27	simulation	16	14
28	thermal performance	16	14
29	thermal insulation	16	11
30	energy audit	15	14

number of citations, and total link strength are presented in detail in Table 3.

The analysis revealed six groups of productive and collaborative scholars. As for the network map in Fig. 6, the group with which Ascione F., Vanoli G. P. and Bianco N. are in close cooperation and De Masi R. F., Mauro G. M. also contribute to this cooperation (Ascione et al., 2014; Ascione et al., 2015b; Mauro et al., 2015). Another close collaborative group is Brattebø H., Sandberg N. H., Sartori (Sandberg et al., 2016) and I. Mata É., Wallbaum H., Österbring M. (Österbring et al., 2019) are also co-authors. Moreover, Ballarini I. Corrado V. (Ballarini et al., 2014), Almeida M. Ferreira M. (Attia et al., 2017), and Gasparella A. Krarti M. (Luddeni et al., 2018) are other clusters of collaborative scientists. Research has shown that these collaborations are mostly internal (within or between departments) and inter-institutional on a national scale (in-country).

Some collaborative authors do not appear on the network, although they meet the seven articles and 50 citation limitations because the authors they collaborate with do not meet these limitations. Therefore, a quantitative summary of the numerical indices of the co-authorship network within the clusters is presented in Table 3. For example, Papadopoulos A. M. (Papadopoulos et. al., 2002), Hong T. (Sun and Hong, 2017), Balaras C. A. (Droutsa et al., 2016), Dall'O' G. (Dall'O' et. al., 2012), Caputo P. (Caputo et al., 2013), Gagliano A. (Cascone et al., 2018a), He Q. (Zhou et al., 2016), Jokisalo J. (Tuominen et al., 2014), do not appear in Fig. 6 for this reason, although they meet the sampling standards. Additionally, although Krarti M. (Luddeni et al., 2018) is one of the authors with the most articles (12), it is presented that only one (total link strength) article is based on collaboration since the authors he collaborated with did not meet the sample criteria.

All articles published by Ascione F., Bianco N., and Vanoli G. P. were based on collaboration in their cluster. Thus, they seem like the most collaborative authors on the Table 3. Following these authors, Mauro G. M. is among the most collaborative authors with 11 and de Masi R. F. with ten link strengths.

Correlation analysis showed that the total number of articles positively correlated with citations ($r = 0.8$). Thus, an author's contribution (in terms of the citation or the average number of citations) to EER research is linearly related to the total number of articles produced by the author. There is also a moderately significant relationship between the total link strength and citation ($r = 0.65$). Accordingly, it can be said that publications produced through collaboration have a higher impact.

According to the sample criteria, the rankings have some differences. The overall impact (total citations) ranking among the top four authors is Vanoli G. P., Bianco N., Ascione F., Mauro G. M. However, the number of articles is Vanoli G. P. Ascione F., Bianco N., Krarti M. When the most influential authors are ranked based on the average normalised number of citations, the top four are Bianco N., Orehounig K., Ballarini I., Corrado V.

Surprisingly, although Orehounig K., Ballarini I., and Corrado V. produced relatively few publications, they had higher ranks than Vanoli G. P., Ascione F., Krarti M., Mauro G. M., de Masi R. F., Almeida M., Papadopoulos A. M., and Hong T. in terms of average annual effect (average normalised number of citations).

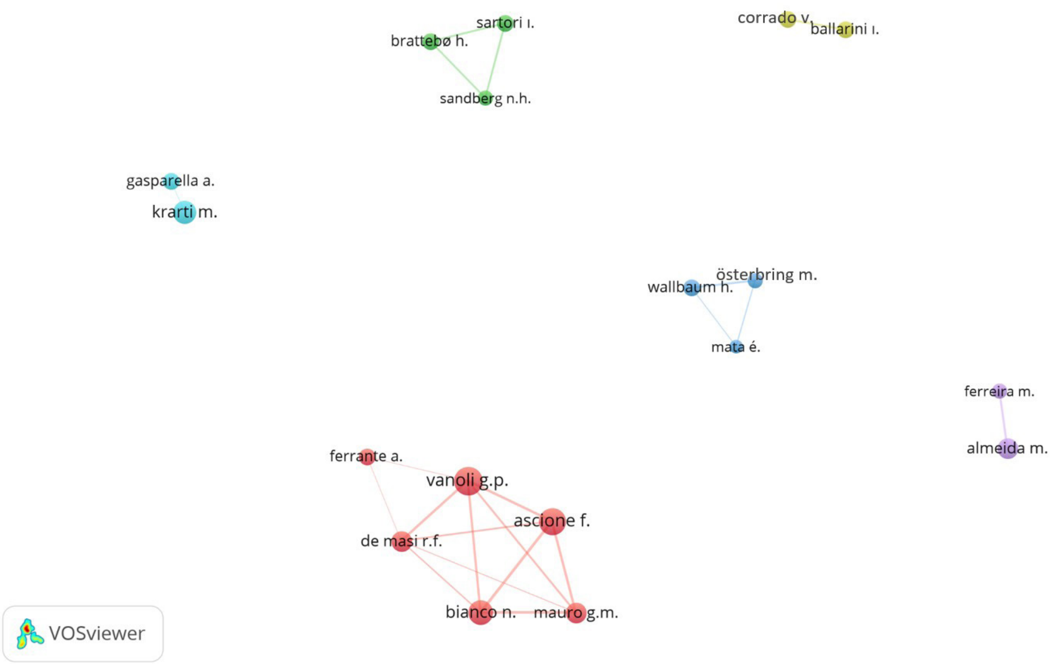

Fig. 6 The network of the coauthorship

2.2.4 Citation analysis of articles

The number of citations of an article is usually used as one of the impact measures of the publication. Therefore, articles with higher citations are generally accepted as pioneering publications on the subject. The citation analysis was conducted to identify qualified publications on the subject. First, the minimum number of citations for an article was set to 50 in VOSviewer pre-sets. Only 149 of 1070 research articles met these criteria, while only 118 of this number formed a linked cluster. The density map of these publications is shown in Fig. 7.

Moreover, the impact of an article is evaluated by its total citations, normalised number of citations, and links with other articles. Table 4 presents the 20 most frequently cited articles in EER research. Correlation analysis shows a moderately positive relationship between total citations and the normalised number of citations (r = 0.54) in the highest-impact articles. Therefore, the annual contribution of an article to EER research is related to excerpts from it.

Table 4 shows that the top five articles with the highest citations were the studies belonging to Ballarini et al. (2014), Castleton et al. (2010), Heo et al. (2012), Ma et al. (2012), and Wei et al. (2018). Ma et al. (2012:p.889) provide "a systematic approach to the correct selection and definition of the best retrofit options for existing buildings". Castleton has revealed the energy conservation and costwise benefits of green roof applications on existing buildings with insulation in weak roofs (Castleton et al., 2010).

On the other hand, the normalised number of citation criteria revealed a relatively different sequence for ranking the most influential articles. Attia et al. (2017), Ballarini et al. (2014), Castleton et al. (2010), Ma et al. (2012), and Wei et al. (2018), respectively, created the top five article indices that are influential in the field with their studies. Wei et al. (2018) conducted a comprehensive review of the different approaches used to analyse energy use data of buildings. Analyses should be performed on "reference buildings" to identify appropriate remediation measures and measure the energy-saving potential of existing buildings. In this context, Ballarini et al. (2014) presented a methodology for the identification of reference buildings according to the IEE-TABULA (2009) project, which aimed at creating a harmonised structure for "European Building Typologies". The study focused on energy saving and CO_2 emission reduction potentials for the European residential building stock. Attia et al. (2017) summarised the findings of "a cross-comparative study of the societal and technical barriers of nZEB implementation in seven Southern European countries". The study analysed the current social and technical barriers to nZEB implementation in Southern Europe. As a result, suggestions for reducing the identified difficulties and barriers are presented.

2.2.5 Analysis of active countries in energy-efficient retrofitting research

Some countries differ in their contribution to the EER research discourse by region. Awareness regarding the

Table 3 Collaborative writers' analysis

Author	Number of articles	Number of citations	Avg. number of citations	Avg. norm. citations	Total link strength
Vanoli	15	845	56	1.99	15
Ascione	14	732	52	2.15	14
Bianco	13	777	60	2.43	13
Krarti	12	287	74	1.33	1
Mauro	11	468	43	2.10	11
de Masi	11	474	43	1.54	10
Almeida	11	332	30	1.23	8
Papadopoulos	11	527	48	1.13	0
Hong	10	423	42	1.93	0
Ballarini	9	494	55	2.17	9
Corrado	9	494	55	2.17	9
Sartori	9	393	44	1.36	8
Brattebø	9	333	37	1.73	7
Wallbaum	9	172	19	0.84	7
Ferrante	9	106	12	0.58	1
Gasparella	9	263	29	1.39	1
Ferreira	8	283	48	1.47	8
Österbring	8	99	12	0.69	8
Sandberg	8	293	37	1.36	7
Balaras	8	209	26	1.08	0
Dall'O'	8	437	55	1.12	0
Mata	7	123	18	0.85	3
Caputo	7	334	48	1.96	0
Gagliano	7	280	40	1.18	0
He	7	91	13	1.22	0
Jokisalo	7	152	22	1.30	0
Longo	7	50	7	0.30	0
Olofsson	7	119	17	1.13	0
Orehounig	7	336	48	2.41	0
Svendsen	7	351	50	1.01	0

most active countries in EER research can facilitate future collaboration, technology and idea exchange, and joint research funding programmes (Wuni et al., 2019). In this context, the country analysis of the contribution to EER research is visualised in Fig. 8.

The minimum number of documents and citations for a country was set as 10 and 20 when creating the network, respectively. Some 26 of 73 countries met the sample criteria in the EER research. Thus, approximately 38% of all countries in the world (73 out of 193) contribute to EER literature. The node size (country) in Fig. 8 elaborates on a country's contribution to EER research. For example, Italy, the United States, the United Kingdom, Spain, China, Germany are visualised by relatively larger nodes. It has been observed that EER research has a more significant impact on developed economies. Despite the geopolitical differences among the countries mentioned above, the scientific collaboration and citation rate are not surprising.

Moreover, four clusters regarding the most productive countries were revealed. For example, Italy, Germany, Greece, Ireland, Poland, Serbia, and South Korea, represented by red, belong to a single cluster. These clusters are formed based on cooperation, common citations, or similarity in research areas.

Table 5, where the country-specific contributions to the EER research are assessed with quantitative data, illustrates a different ranking regarding article and citation numbers. While Italy is the most productive country in

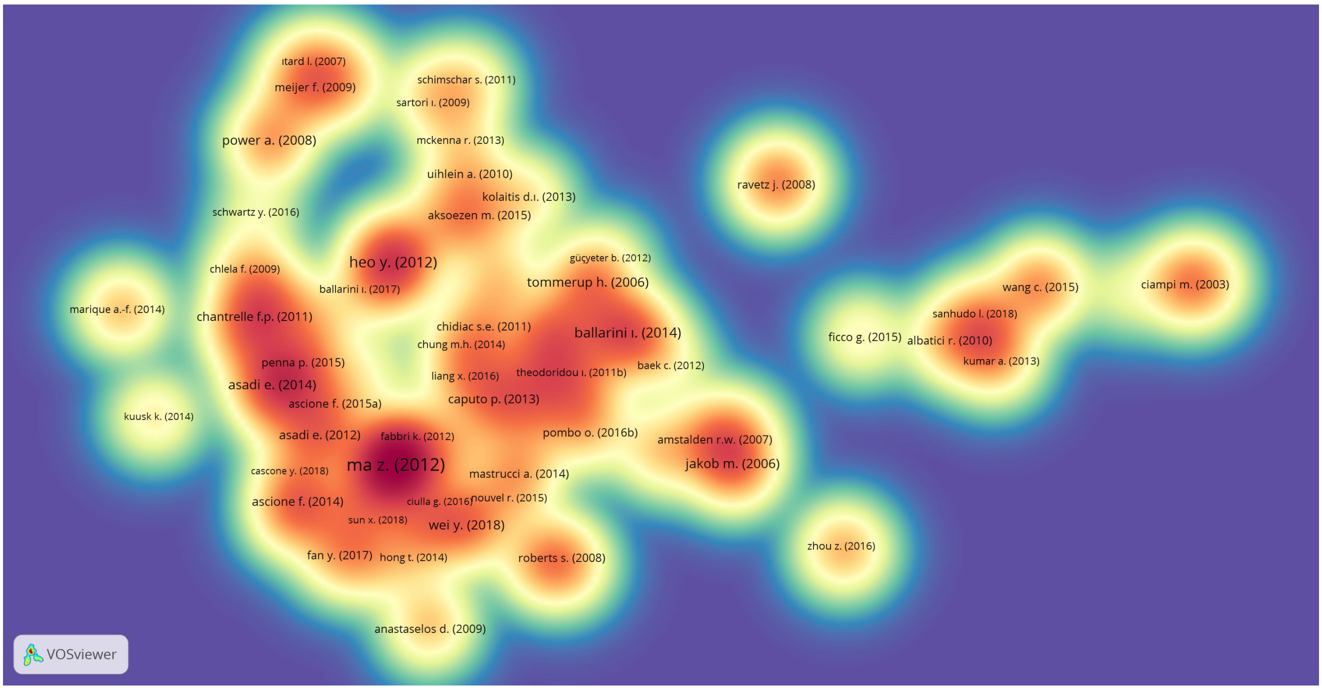

Fig. 7 The density map of the article citation network

both criteria, the ranking of the first four countries changes. By the number of citations top five countries are ranked as Italy, the United Kingdom, the United States, China, and Switzerland. Moreover, when the countries are ranked by normalised number of citations, the top five countries create an index consistent with the number of articles. In this context, it can be asserted that the most active contributors to the EER research discourse are Italy, the United States, the United Kingdom, Spain, and China, respectively.

3 Discussion on major energy-efficient retrofit areas

The contents of the articles are summarised mainly by the keywords used in the titles and abstracts. These keywords are primarily consistent with the content of the article and the research theme. Thus, holistically analysing keywords should reveal trends in the field of EER research (Wuni et al., 2019). Although the keywords co-occurrence network is presented in Fig. 5, the network was created using only the author keywords. All keywords in 1070 articles are analysed in Section 3. The "binary counting method" is selected, and the number of minimum occurrences is set to 10 in the VOSviewer pre-sets. As a result, 678 of the 22289 keywords met this criterion. The 407 most relevant terms (Fig. 9) were critically analysed and evaluated, and research areas were identified according to the clusters.

The main research areas (clusters), according to the analysis, are determined. The keywords that create the red cluster belong to the studies that can be grouped under the headline "Assessments on policies and stakeholders". Purple-green clusters are related to "Energy control and performance evaluation", the blue cluster is "Improvement technologies and optimisation". Lastly, yellow-purple clusters are related to the studies carried out within the scope of "post-implementation measurement and evaluation". Thus, the research areas related to the subject are categorised under four main headings.

In addition, the period in which the keywords appear, and the frequency of use are essential for giving information about the direction in which the research is improving. Based on the number of articles published in this context, four-time intervals were determined from 2000 to the present, as 2000-2010 (56 articles), 2011-2015 (222 articles), 2016-2018 (303 articles), and 2019-2021 (489 articles). The articles belonging to these periods were reanalysed over their keywords. The minimum number of views for keywords is set to five. Thus, trending keywords in each period have emerged. The graphical representation of the data is presented in Fig. 10.

In the first years (2000-2010), improvement studies focused on "energy efficiency." In the following years, it is seen that the subject has deepened with different parameters. After 2010, "building energy performance", "thermal comfort" and multi-objective optimisation", "life cycle assessment" were included. Since 2016, "building energy simulation", "nZEB", "social housing" have attracted

Table 4 The most cited articles

Author(s)	Title	Number of citations	Norm. number of citations	Link
Ma et al. (2012)	"Existing building retrofits: Methodology and state-of-the-art"	679	7.67	26
Castleton et al. (2010)	"Green roofs; Building energy savings and the potential for retrofit"	525	6.10	0
Heo et al. (2012)	"Calibration of building energy models for retrofit analysis under uncertainty"	370	4.18	6
Ballarini et al. (2014)	"Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of *TABULA* project"	301	5.97	12
Wei et al. (2018)	"A review of data-driven approaches for prediction and classification of building energy consumption"	257	10.78	4
Asadi et al. (2014)	"Multi-objective optimization for building retrofit: A model using genetic algorithm and artificial neural network and an application"	252	5.00	6
Tommerup and Svendsen (2006)	"Energy savings in Danish residential building stock"	221	1.58	12
Jakob (2006)	"Marginal costs and co-benefits of energy efficiency investments: The case of the Swiss residential sector"	221	1.58	4
Power (2008)	"Does demolition or refurbishment of old and inefficient homes help to increase our environmental, social and economic viability?"	213	2.35	2
Langston et al. (2008)	"Strategic assessment of building adaptive reuse opportunities in Hong Kong"	210	2.32	0
Ascione et al. (2014)	"Energy refurbishment of existing buildings through the use of phase change materials: Energy savings and indoor comfort in the cooling season"	206	4.08	6
Chantrelle et al. (2011)	"Development of a multicriteria tool for optimizing the renovation of buildings"	191	3.47	8
Asadi et al. (2012b)	"A multi-objective optimization model for building retrofit strategies using TRNSYS simulations, GenOpt and MATLAB"	182	2.05	6
Caputo et al. (2013)	"A supporting method for defining energy strategies in the building sector at urban scale"	163	3.93	14
Dall'O' et al. (2012)	"A methodology for the energy performance classification of residential building stock on an urban scale"	155	1.75	8
Wang et al. (2015)	"Automatic BIM component extraction from point clouds of existing buildings for sustainability applications"	149	3.47	2
Mastrucci et al. (2014)	"Estimating energy savings for the residential building stock of an entire city: A GIS-based statistical downscaling approach applied to Rotterdam"	148	2.93	6
Attia et al. (2017)	"Overview and future challenges of nearly zero energy buildings (nZEB) design in Southern Europe"	143	5.02	0
Amstalden et al. (2007)	"Economic potential of energy-efficient retrofitting in the Swiss residential building sector: The effects of policy instruments and energy price expectations"	141	2.24	9
Mazzarella (2015)	"Energy retrofit of historic and existing buildings. The legislative and regulatory point of view"	139	3.24	2

attention. In addition, "energy performance certificate" and "life cycle cost" became visible. Recently (2019-2021), it has been observed that the frequencies of the keywords "life cycle assessment" and "building energy simulation" have peaked. In addition, different methods such as BIM, machine learning, and "historic building", "renewable energy use" seem to be areas that tend to rise in the future.

3.1 Identification and assessment of main research areas

In Subsection 3.1, the four main research areas determined as a result of the analyses were defined and evaluated (Fig. 11):

1. Assessments on policies and stakeholders:
    - Policies and regulations have a function that guides the decision process related to EER to more rational

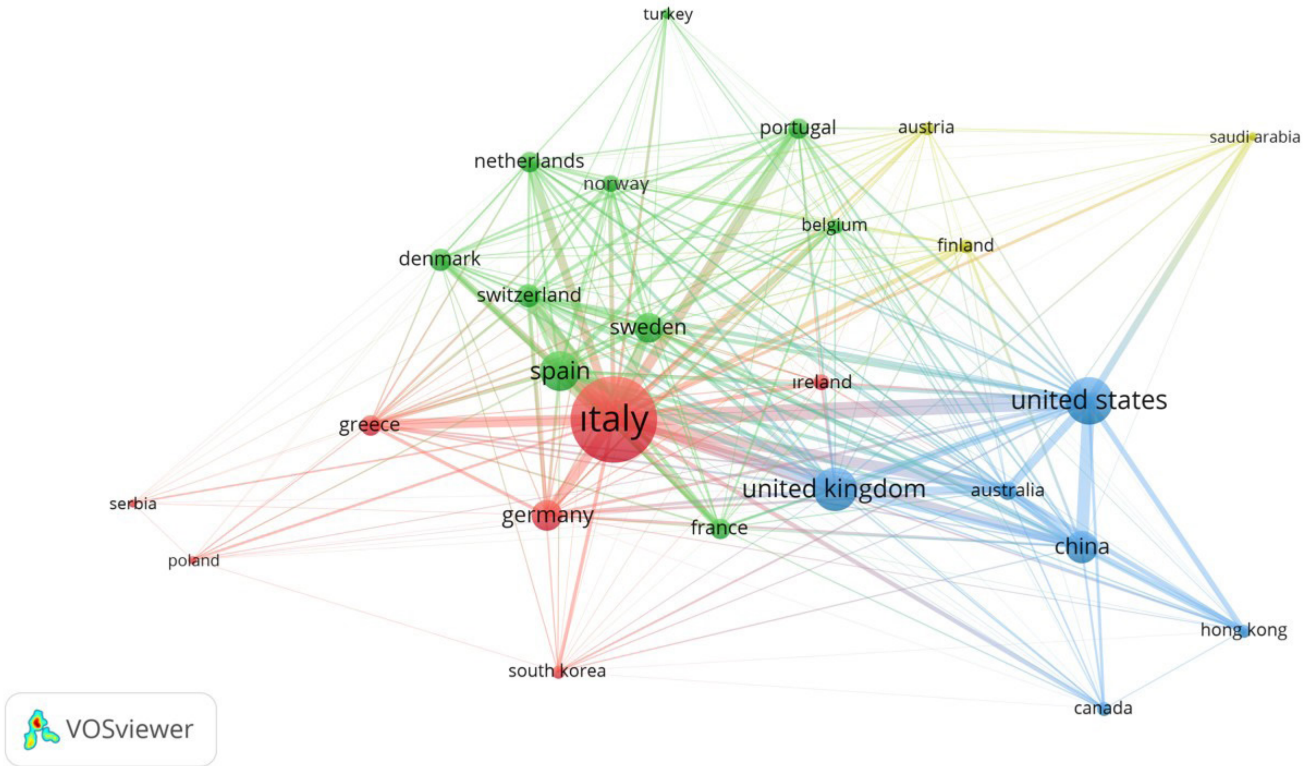

Fig. 8 Network analysis of countries contributing the most to EER research

and specific results (Wuni et al., 2019). The role of policies, incentives, and regulations developed in adopting and implementing EER is quite substantial.

In this regard, the Building Energy Performance Directive (EPBD) was published by the European Union (EU) in 2002 to increase the energy performance in buildings (EPBD, 2002/91/EC). According to the Directive (EPBD, 2002/91/EC), all EU member and candidate countries are obliged accordingly:

- development of national calculation methodology of energy performance in buildings,
- evaluation of energy performance of all new and existing buildings with developed methods,
- for the buildings to provide the minimum energy level determined by the standards and have an energy identity certificate. With this directive (EPBD-Recast, 2010/31/EU), which was renewed in 2010, the optimisation of global costs became obligatory along with new energy efficiency targets and requirements (Atmaca, 2017). Regulations and policies should include motivating implementation and assessment elements, ranging from raising awareness to determining goals and deficiencies and evaluating their performance for an effective retrofit. In this context, there are studies on political strategies that guide the development of retrofit policies and support retrofit (Baek and Park, 2012b).

2. Energy audit and performance assessment:
   - Energy audits cover energy use assessments in a particular area or site. Energy audits cover analysing building energy data, understanding building energy use, determining areas with energy-saving potential, and cost-free and low-cost energy conservation measures/suggestions (Mata et al., 2015). Energy audits play a vital role in the energy retrofitting process to provide the information necessary for building performance assessment. Numerous studies highlight the importance of energy audits in energy-efficient building retrofits.

Ascione et al. (2015a:p.172) propose "a method for reliable energy diagnostics aimed at the integrated energy regeneration design of existing buildings concerning historical architectures". Beccali et al. (2017) conducted an audit study to provide information on the public buildings' energy performance and select more appropriate actions. Dall'O' et al. (2013) used the infrared scanning method for energy control regarding retrofitting in residential buildings (Rakha and Gorodetsky, 2018). Rakha and Gorodetsky (2018) applied this method to a group of campus buildings.

It is essential to perform energy audits with reliable tools and obtain accurate results because, according to these results, retrofit measures are determined, and energy-saving estimates and performance assessments are

Table 5 Most productive countries in EER research

Country	Number of articles	Number of citations	Avg. number of citations	Norm. number of citations	Total link strength
Italy	269	6989	25	296.95	1082
United States	117	3364	28	123.31	555
United Kingdom	106	3688	34	110.84	392
Spain	93	1471	15	101.93	408
China	71	1772	24	97.48	411
Germany	65	1510	23	50.04	250
Sweden	62	1434	23	62.96	306
Switzerland	43	1519	35	66.35	375
Denmark	42	862	20	34.28	183
Portugal	38	1190	31	52.54	234
Greece	37	1288	34	40.48	224
Netherlands	37	1140	30	48.21	211
France	37	1091	29	50.96	196
Australia	32	1300	40	42.53	381
Norway	28	785	28	24.85	203
Ireland	27	342	12	20.87	100
Belgium	25	729	29	39.62	172
Canada	23	675	29	27.62	96
Finland	22	576	26	22.63	131
South Korea	21	473	22	16.87	74
Hong Kong	20	673	33	20.97	147
Austria	20	139	6	18.21	94
Turkey	15	422	28	12.41	56
Serbia	12	65	5	1.65	22
Saudi Arabia	11	189	17	12.69	91
Poland	11	179	16	8.99	42

completed. The simulation models' parameters for these assessments are obtained from energy control data.

Studies focusing on developing and implementing suitable models and strategies for performance assessment and diagnosis are performed in this context. These evaluation and diagnosis processes are based on comparisons according to the criteria of various rating tools (such as LEED, BREAM, CASBEE) (Dall'O' et al., 2015; Li et al., 2019) or with computational measurements and models based on input data from energy audits (Bruno et al., 2018; Caputo et al., 2013; Laetitia et al., 2020; Zhang and Hong, 2017).

3. Retrofitting technologies and optimisation:
   - There are various available retrofit technologies and measures to operationally implement to reduce the energy need and consumption and meet the requirements from renewable and efficient sources. In this context, the heating and cooling demand can be reduced by using other advanced technologies such as retrofitting the building envelope and airtightness and window shading. Moreover, technologies including advanced control schemes, natural ventilation, lighting retrofit, heat recovery, use of energy-efficient equipment and devices, and thermal storage systems are also utilised for this purpose (Barlow and Fiala, 2007; Krarti, 2016; Xing et al., 2011). Additional measures can support the electricity and thermal energy load with renewable energies such as solar energy, wind energy, geothermal energy.

The most crucial step towards a building retrofit is determining the most effective long-term measures among these many options. The dependence on the different factors and their combinations in the retrofit process reveals the necessity of multi-purpose optimisation techniques (Diakaki et al., 2008). The criteria set in the solution of this multi-purpose optimisation problem are combined with simulation to enable a final decision between a defined set of alternative actions (Fan and Xia, 2017). There are several studies

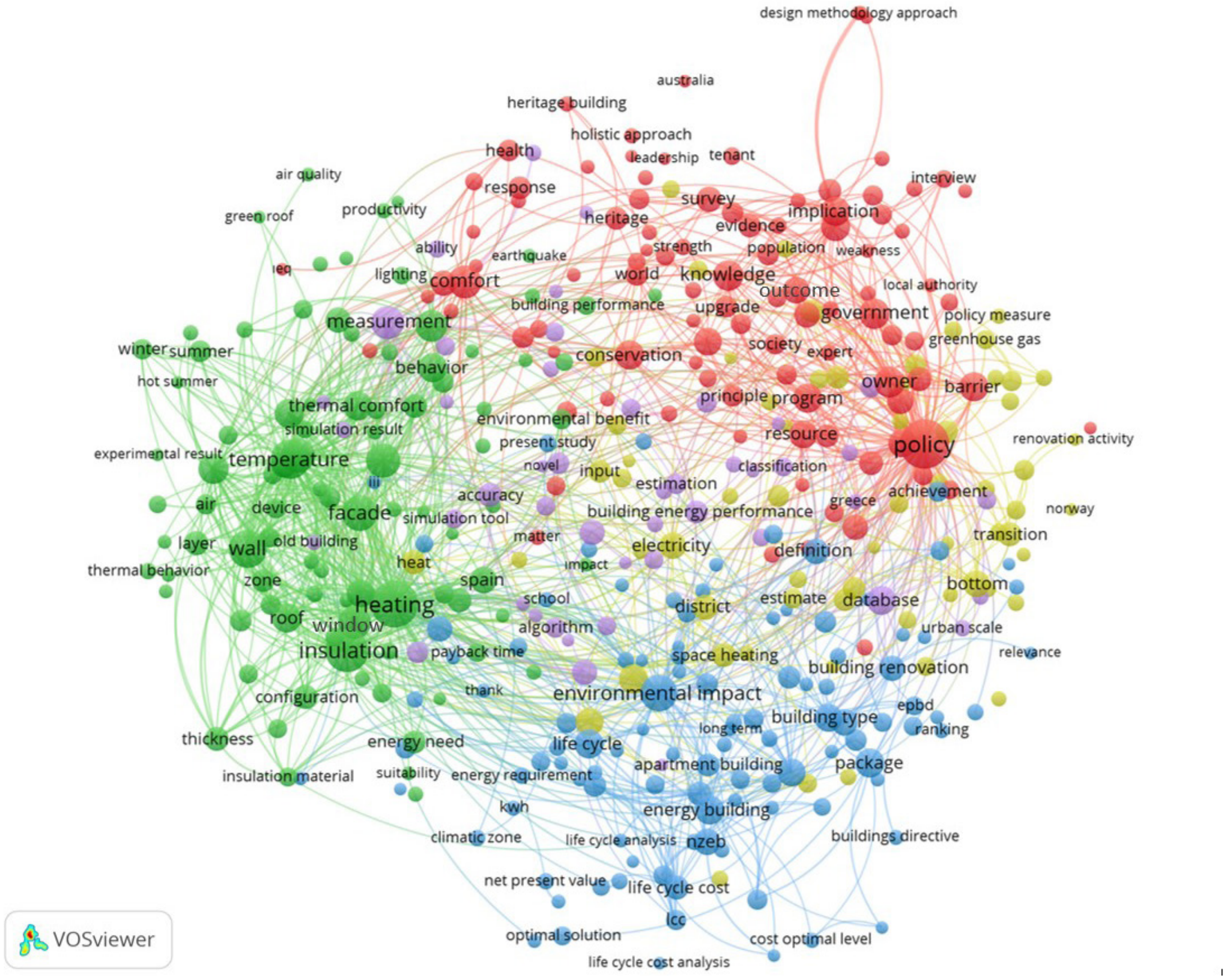

Fig. 9 Clusters of main research areas

and evaluations made by combining different criteria, measures, simulations, and programs (Ascione et al., 2017; Cascone et al., 2018b; Stazi et al., 2013).

Asadi et al. (2012b:p.370) used "a simulation-based multi-purpose optimisation scheme (a combination of TRNSYS, GenOpt and a Tchebycheff optimization technique developed in MATLAB) is employed to optimise the retrofit cost, energy savings and thermal comfort of a residential building". Many decision areas have been studied, including building envelope insulation and alternative materials for mounting a solar collector in the existing building (Asadi et al., 2012b). Similarly, other studies include the search for optimum solutions on building envelope retrofits and thermal comfort to maximise energy savings and economic benefits (Fan and Xia, 2017; Gustafsson, 2000; Güçyeter and Günaydın, 2012). Chidiac et al. (2011) and Wu et al. (2017) conducted a case study in residential buildings to apply an optimal ECM set to the large building stock. There are also optimisation studies focusing on retrofitting "existing buildings to minimise their environmental impact" by using Life Cycle Assessment (LCA) and Life Cycle Cost (LCC), which should be considered in optimising energy consumption.

Pombo et al. (2016a) proposed a multi-criteria method for comparative analysis of retrofit solutions. Environmental impacts are combined by expressing monetary values through Life Cycle Assessment and Life Cycle Cost. A Pareto optimisation was used to select preferred strategies. The methodology demonstrated how the current renovation strategies of a residential block implemented in Madrid for a case study are far from optimal solutions. Sharif and Hammad (2019) aimed to find "the most suitable scenario for the renovation of buildings considering energy consumption and LCA while providing an efficient method to deal with a limited budget".

4. Post-implementation measurements and assessment:
   - Measurement and verification operations are performed to reliably determine the savings realised thanks to an energy management programme in

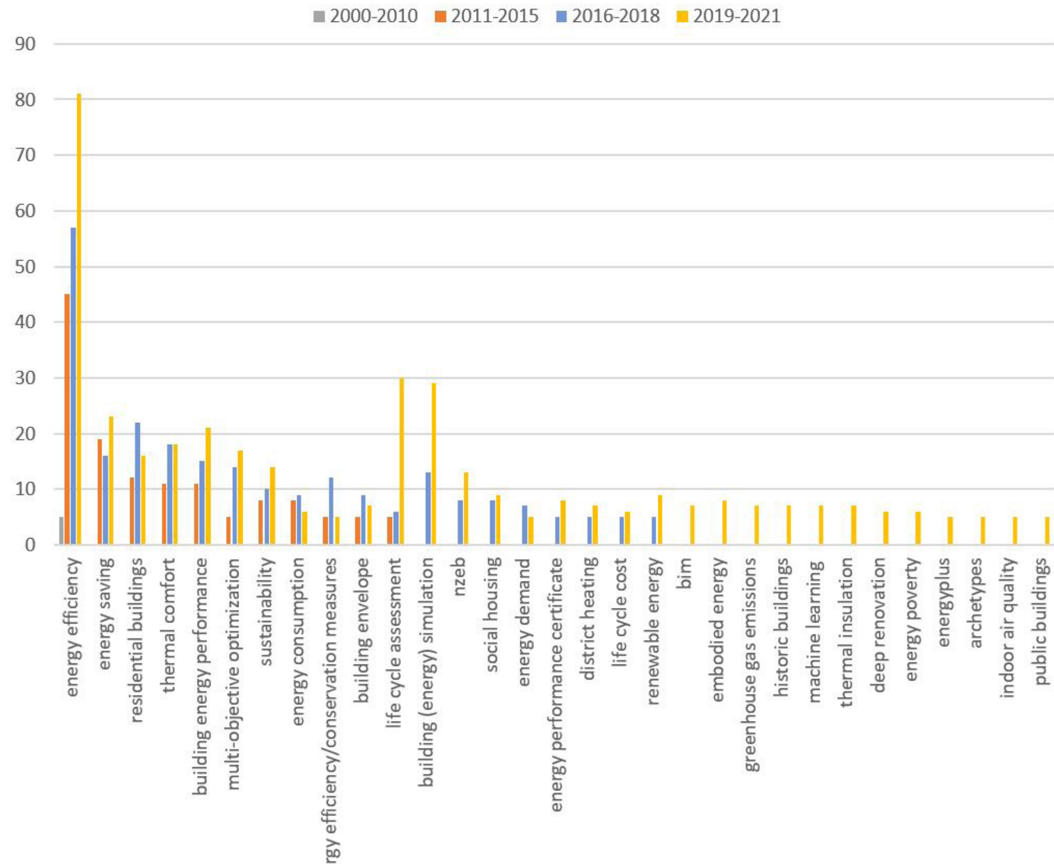

Fig. 10 Frequency of use of keywords by years

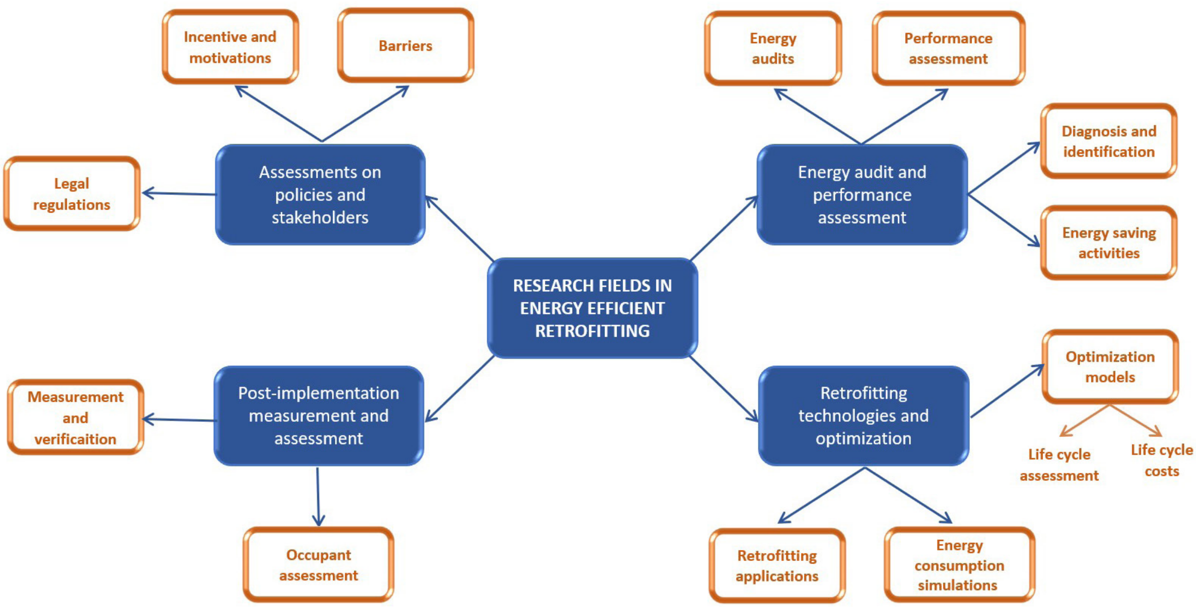

Fig. 11 Main areas of EER research

existing buildings. These assessments are pivotal in the sustainability of EER programs since EER investment strategies are dependent on quantitative results of energy savings through "measurement and validation" that compares actual energy consumption with pre-retrofit energy consumption (Liang et al., 2016). The results obtained from the M&V studies suggest that improving energy baseline estimates by including the user factor to understand the effect of users on energy consumption (Sun et al., 2018b) can help reduce M&V risks and thus facilitate energy efficiency retrofitting investment strategies (Liang et al., 2016).

In the studies on energy audit and performance assessment, some deviations are observed between the actual measurements and the values expected from the audits. Sun et al. (2018b) reached approximately 50% less than expected energy saving measures applied to improve energy performance. Authors attributed this result to uncertainties caused by errors and user influence in the building performance simulation. Ham and Golparvar-Fard (2013) proposed augmented reality energy performance models to minimise the deviation in this regard.

It was indicated that economic consumption could be reduced, on average, by 37% in buildings with the same installation depending on the user factor. Therefore, there is great potential to reduce demand by influencing behaviour. Desmedt et al. (2009) discussed the effect of user behaviour on energy consumption in their study. They examined the socio-economic factors affecting the energy consumption in houses. They have developed tools that include suggestions on energy-saving measures to help raise awareness of homeowners' energy behaviour, then tested and analysed these tools in a range of houses.

4 Conclusions

Research trends related to energy-efficient retrofits in existing buildings were analysed by the scientific analysis method. The bibliometric data of 1070 studies published since 2000, when an increase was observed in studies on EER, have been evaluated. Inferences have been made about where the research is and where it can head, and the main research areas related to EER have been determined. Studies on EER have shown that appropriate retrofits can significantly increase existing buildings' energy and environmental performance. Considering the results of the qualified studies, numerous specific and uncertain factors that affect the retrofit process and efficiency assessments come to the fore.

The most important are inadequate political regulations and economic and user-centred social factors. However, the number of studies that holistically consider these factors in retrofit projects is quite insufficient. Comprehensive multiple optimisation models offer a practical approach for the best retrofitting solutions in which economic analyses are not omitted. Cost-effectiveness is a good incentive for EER, hence the need for further studies in this context. Most studies have been conducted using numerical simulations with different energy results predicted in practical case studies and measurements. It has been observed that the human factor directly affects building energy use. Therefore, more comprehensive studies on the user factor in EER studies are necessary. Moreover, the ratification of the policy and regulations developed in the international arena on the national scale, increasing the incentives and motivations by removing the related problems, have become fundamental.

As a result, more work is necessary, both in theory and in practice, to make the existing building stock more energy-efficient and environmentally sustainable. It is vital to increase practical case studies to help strengthen confidence in the potential retrofit benefits.

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