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Citation for the original published paper (version of record):
Camarasa, C., Nägeli, C., Ostermeyer, Y. et al (2019). Diffusion of energy efficiency technologies in European residential buildings: A bibliometric
analysis. Energy and Buildings, 202. http://dx.doi.org/10.1016/j.enbuild.2019.109339

Energy & Buildings 202 (2019) 109339

Contents lists available at ScienceDirect

Energy & Buildings

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

Diffusion of energy efficiency technologies in European residential buildings: A bibliometric analysis

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ARTICLE INFO

Article history:
Received 21 January 2019
Revised 12 June 2019
Accepted 24 July 2019
Available online 25 July 2019

Keywords:
Bibliometrics
Energy efficiency
Residential buildings
Technology diffusion
Multiple impacts
Europe

ABSTRACT

Many studies have investigated different aspects in the decarbonisation of the European housing stock. However, a comprehensive quantitative analysis of the literature on the diffusion of energy efficiency technologies is still missing. We conducted a bibliometric analysis to better understand the knowledge base in the field energy efficiency technology diffusion in the European residential building stock. After the scanning and screening process, we identified 954 scientific articles pertinent to this topic. Through a co-citation network analysis, we generated a visual knowledge structure of the field and by the further investigation of the bibliography we were able to synthesize the state-of-the-art and answer to our initial research questions. Results of the co-citation network show a scattered and fragmented field in many domains. The descriptive analysis highlights this fragmentation, especially on a cross-country level among EU country members. Findings from this study contribute to map the scientific knowledge base in relation to technology diffusion in European residential building projects, identify relevant topic areas, visualize the links between the topics, as well as to recognize research gaps and opportunities. The methodology utilized in this paper proved to be viable approach to map and characterize the knowledge base within a field and can, therefore, be replicated in upcoming studies with analogous ambitions.

1. Introduction

Residential buildings in Europe are responsible for approximately 40% of energy consumption and 36% of $CO_{2eq.}$ emissions [1]. Furthermore, about 35% of the residential building stock is over 50 years old and more than 75% is considered as energy inefficient [2]. To ensure the reduction of energy consumption and subsequent $CO_{2\ eq.}$ emissions in buildings, the European Union (EU) has developed two main decrees, the (1) Energy Efficiency Directive (EED) [3], and the (2) Energy Performance of Buildings Directive (EPBD) [4]. Among its requirements, the EPBD demands all new public buildings to be nearly zero-energy (nZEB) by 2018 and all new buildings by the end of 2020 [5].

Technology options to decrease building's energy demand to nZEB standards are readily available and, in many cases, economically viable [3,8,9]. The promising performance and economic potential of these technologies has also been acknowledged in residential buildings at an EU level [10–12]. Nevertheless, annual construction rates in the residential sector are still around 1%. Furthermore, most EU Member States suffered a decrease in the rate of new build in the recent years [13], echoing the impact of the financial crisis in the construction sector as well as the EU focus in refurbishment. In terms of retrofit activities, an average of 0.4–1.2% of the EU residential building stock is renovated each year [6], out of which less than 5% is reaching nZEB standards [7] – not even a third of what would be needed to reach the aforementioned EU's carbon ambitions [14]. This implies that, despite their availability and economic viability, energy efficient technologies are not being deployed at the required rate to meet EU's greenhouse gas emission reduction targets. This divergence between the technoeconomic potential and actual market behaviour has been coined as the 'energy efficiency gap' or 'energy paradox' and implies that non-technical market hurdles are preventing the large-scale diffusion of these solutions [15]. The 'energy efficiency gap' also suggests that, in the European housing context, the economic viability of energy efficiency technologies -specifically the cost of potential energy savings (commonly considered being the only financial benefit)- is

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https://doi.org/10.1016/j.enbuild.2019.109339

not sufficiently acknowledged or appealing to motivate the necessary investments [16].

In order to bridge the energy efficiency gap and favour the low-carbon transformation of residential buildings in Europe, policy measures need to be further developed. Policy instruments can be classified into push – (e.g. regulatory and control instruments), and pull-mechanisms, (e.g. economic or fiscal incentives and support tools for voluntary action) [17]. To ensure their effectiveness, these instruments should be selected and designed based on a solid comprehension of the current national market conditions and dynamics, particularly in relation to the uptake or diffusion of energy efficiency technology measures. However, [11,12] reveal a lack of national and cross-national understanding of the factors behind the low refurbishment rates and respective diffusion of energy efficiency technologies. Based on this knowledge gap and research need, the ambition of this study is to shed light on what research has been conducted in the diffusion of energy efficient technologies. More particularly, it aims at better understanding the knowledge base in the field of energy efficiency technology diffusion in the EU housing stock. By means of a bibliometric analysis, this paper provides an image of the research network structure, which helps us describe the state-of-the-art, as well as to identify emerging trends and future investigation needs.

To gather a general comprehension of the research landscape in the field, we conducted a preliminary literature review. This review consisted on the examination of grey literature, including open databases, European Union legislative and policy documents, technical data sheets and specifications, reports from non-governmental organizations (NGOs) and research projects datasheets and summary reports [19–30]. Findings from this process led us to identify three main topic areas and formulate the following research questions:

Technological measures for energy efficiency

Policy instruments, such as financial incentives and regulations, can increase the pace of energy efficiency measures [19]. To ensure their effectiveness, these instruments should be based on a solid comprehension of current market dynamics and technology diffusion rates. The Building Stock Observatory (BSO) is the main EU database generating and collecting data on buildings and their energy efficiency condition across Europe [20]. However, the database does not contain information for all data points and countries. It also lacks evidence as to what technology measures are taking place in these buildings.

- Research question I: What is the empirical evidence in relation to what energy efficiency technological measures are being implemented in residential buildings in Europe?

Decision-making behind the diffusion of energy efficiency technologies

There is a gap between techno-economic potential and actual market behaviour. This gap has been coined as the ‘energy efficiency gap’ or ‘energy paradox’ [21]. To reduce this ‘energy efficiency gap’ policy measures need to be implemented addressing behavioural factors, namely possible drivers pushing positive reaction towards energy saving measures [22]. In the European housing sector, several research studies have tried to better understand stakeholders’ decision-making processes and drivers [23–27]. However, these studies do not encompass all technologies, decision-makers, nor markets in an integrated manner.

- Research question II: What is the empirical evidence in relation to decisions behind the diffusion of energy efficiency technologies in residential buildings in Europe?

Multiple impacts of the diffusion of energy efficiency technologies

In the European housing market, the cost of potential energy savings, commonly considered as the only financial benefit, does not sufficiently motivate energy efficiency investments. However, the adoption of energy efficiency technologies offers a wide range of potential positive side-effects beyond the direct energy savings, such as: energy poverty alleviation, asset value increase, increase of disposable income, local job generation, among others [28,29]. Some sources argue that the quantification and monetization of these gains could support the adoption and/or prioritization of energy efficiency technologies [6,30]. Nevertheless, in practice these positive side-effects, so-called co-benefits, are seldomly quantified or taken into consideration [31].

- Research question III: What is the empirical evidence in relation to positive side-effects of technological measures for energy efficiency in residential buildings in Europe?

In this study a comprehensive literature review is conducted. The objective of this review is threefold:

1. Generate a visual knowledge structure of the intellectual base to define citation patterns, relationships and identify highly co-cited papers in the field
2. Review the papers and extract the main findings, to answer to our research questions.
3. Identify emerging trends and future research needs.

The remainder of this paper is organized as follows: in Section 2, we elaborate on the theoretical frameworks and methods used to collect, map and visualize the research. Section 3 presents the results of the study based on a co-citation network analysis. The paper concludes with Section 4, discussing key findings and conclusions.

2. Research method

As the goal of this study is to contribute to the understanding of the intellectual base in the field of technology diffusion, deductive research is considered as the most suitable approach. Deductive research approaches typically starts with theory-driven research questions or hypotheses, which guide the data collection and analysis [32]. In this case, deductive research is performed through a systematic literature review. This means a study with a (i) clear stated purpose, (ii) question, (iii) defined search approach, and (iv) exclusion criteria producing a characterization of articles. According to [33], the main steps in a systematic literature review are as follows: (1) identification of articles through the database, (2) screening, after the filtering and selection of papers, (3) assessing the articles for eligibility and, (4) data analysis and conclusions. Systematic literature reviews are based on a scientific, replicable and transparent protocol with the aim of minimizing human error and bias in the synthesis, and outlining of the analysis [34,35].

To further reduce the bias in the selection and mapping of the article titles, a bibliometric analysis was conducted. As stated by [36], bibliometrics is a powerful quantitative tool to explore knowledge networks based on published literature. It has been widely used for studying the structure and development of various research fields [37], including energy and climate change [36]. The method includes statistical analysis of published articles and citations to measure their impact [38]. Bibliometric analysis was found to be the most suitable approach for the scrutiny, as it enables us to perform an entire quantitative assessment of knowledge structures and research trends in the field, without having to select or dismiss any title for the selection and mapping or representation. Hence, reducing the potential bias in the analysis process.

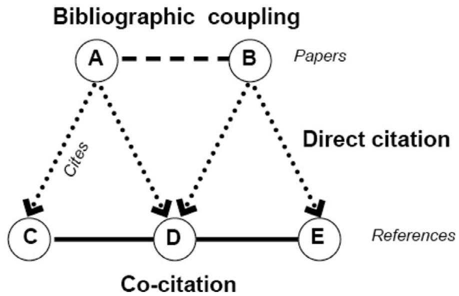

Fig. 1. Schematic overview of different approaches to citation network analysis; adapted from [45].

2.1. Approaches to citation network analysis

As described by [39], the system of networks provides additional information of the structures of the different themes within a topic. Furthermore, specific thematic clusters can be displayed by bringing together strongly interconnected authors. Within citation analysis, there are different approaches for analysing the network of citations in a group of publications [40]. They all construct a network that link documents, but the way of selecting and representing the edges and the nodes differs between the approaches [41,42]. The most common citation-based mapping approaches are described below:

Direct citation provides the straight references between cited documents. Following Fig. 1, paper A links C and D.

Introduced by M.M. Kessler in 1963, **bibliographic coupling** occurs when two works reference a common third work in their bibliographies. This method is used to extrapolate how similar the subject matter of the two works is [43]. Following Fig. 1, paper A and B would be connected due to the common citation of D.

Co-citation analysis gained recognition in the 1970s as a technique for "mapping" scientific literatures and finding latent semantic relationships among technical publications [44]. In 1973 H. Small concluded that co-citation analysis as a subject similarity indicator has two applications in information retrieval: firstly, to provide a list of new documents of highly co-cited articles based on the citation indexes and, secondly, to provide a list of more important "core" publications of earlier materials for a specific field, which may be a profile for that field and therefore, the basis of a selective dissemination of information (SDI) system. Following Fig. 1, references C and E would be linked through papers A and B, both citing D.

There have been many attempts to compare the accuracies of these mapping approaches [34]. A study by Boyack and Klavans [44] concluded that direct citation network is the least accurate approach of all to map the research front. Co-citation can be a useful tool for mapping the structure of science [44] and a valuable approach for identifying key authors in a field [45]. Co-citation analysis can also map the structure of specialized research areas as well as science as a whole. Given that we aim to provide as accurate as possible picture of the research front in the field and collect information within specific research areas to answer to the research questions, we identified co-citation as the most suitable approach for our analysis. The steps in the implementation of the co-citation analysis and respective results are presented hereafter.

2.2. Document retrieval

Google Scholar, Scopus and Web of Science (WOS) are the most widespread databases on different scientific fields, thus frequently used for searching scientific literature [46]. Google Scholar is the academic bibliographic database provided by Google search engine. It covers a wide coverage of books, preprint, conference proceedings, non-English work, working papers, patents, institutional repositories. However [47], asserts that 'it lacks the quality control needed for its use as a bibliometric tool; the larger coverage it provides consists in some cases of items not comparable with those provided by other similar databases'. On the other hand, Scopus and Web of Science (WOS) are commercial repositories often used in bibliometric analyses due to their ability to provide citation lists and counts. Web of Science from Thomson Reuters (ISI) was the only citation database and publication which covers all domains of science for many years. However, Elsevier Science introduced the database Scopus in 2004, which rapidly became a suitable alternative [48]. As defined by [39], Scopus purportedly has lists some conference proceedings. Given that conference proceedings are out of scope in this study, the collection of publications was finally based on the literature source Web of Science Web of Science^{TM} Core Collection.

The search terms used to obtain the final results of this paper were: energy efficiency, residential building and technology diffusion. The selection of these terms was based on the findings from the preliminary study, as these appeared to be the most often mentioned keywords fitting our scope. The search was limited to the 28-member countries of the EU[1] and journal publications in the last ten years (2008–2018). Special attention was given in the screening and analysis process to studies published after the 30th of November 2016, date in which the European Commission proposed an update to the Energy Performance of Buildings Directive, to help promote the use of smart technologies in buildings [49]. English was selected as the language of the articles. Most cited articles were checked, and relevant studies were included in the review. Table 1 shows the synthesis of the search parameters in the paper retrieval.

2.3. Data collection

As a result of this paper recovery method, 1281 papers were identified, out of which 327 were dismissed after screening, due to duplication or lack of relevance within the scope of this study. The full final paper set consisted 954 peer-reviewed articles. To identify to what papers could be useful to answer each one of the research questions, a keyword search method was conducted. The search terms used for each of the research questions were those identified in the preliminary study as most often used in the titles of the grey literature. These were the following:

- **Research question I (Technological measures for energy efficiency):** *Technology, solution, measure, diffusion, uptake.*
- **Research question II (Decision-making behind the diffusion of energy efficiency technologies):** *drivers, barriers, motivations, decision, process.*
- **Research question III (Multiple impacts of the diffusion of energy efficiency technologies):** *impacts, benefits, effects, risks, adverse, detriments.*

The results from each of these searches generated a subset of papers, which we hereafter respectively refer to as subset 1 'Energy efficiency measures' (research question I), subset 2 'Decision-making' (research question II), and 'subset 3 'Multiple impacts' (research question III). The screened papers comprising the full paper set were subsequently classified and analysed in terms of the country, year published and subset.

[1] The United Kingdom was included in the study as for the time it was conducted the United Kingdom remained as a full member of the EU and rights and obligations continued to fully apply in and to the country.

Table 1
Search parameters for document retrieval.

Parameters	Selection
Search query	(((energy W/4 efficiency) OR (save W/4 energy) AND ((residential W/4 building) OR (dwelling OR home OR house)) AND (technology W/4 diffusion OR uptake)))
Document type	Articles
Time span	2008 - 2018
Citation Index	SCI-EXPANDED, SSCI and ESCI
Language	English
Countries	Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the UK.

2.4. Data analysis

The retrieved essays deriving from the data collection were then exported as a BibTeX format for further filter and analysis [50]. Following, the results were imported to RStudio for the bibliometric analysis [51]. RStudio v.3.51 was utilized as a tool to map and visualize the data and networks from the three established topic areas. Within RStudio, the Bibliometrix package was applied, as it is a useful R-tool for comprehensive science mapping analysis [52,53]. As described by [54], this package also provides various functions for facilitating the understanding and interpretation of network patterns, including analysing the different architectures of a bibliographic collection through conceptual, intellectual and social structures. Biblioshiny, a user-friendly web-interface for Bibliometrix, was later applied to customize the size of the labels and colour palette for better readability of the graphs. The distinct colours of the circles and lines correspond to the different clusters of papers. The clusters are generated by the Walktrap algorithm [55], which is very often used in bibliometrics with the aim of grouping or clustering, and can effectively cover over 80% of the links in the network [56]. The Walktrap algorithm proposes a new distance between vertices that quantify their structural similarity using random walks. According to [55], this method surpasses previously proposed ones concerning the quality of the obtained community structures and that it stands among. In the study, we inspected the results from the Walktrap algorithm and labelled the clusters by extracting and studying the titles and abstracts of the papers.

There are various aspects that can be considered when analysing the results from a co-citation network. In this paper, we focus on whole-network features, by describing the overall density or tightness of the network; structural features, by naming main clusters (topics) within the network and, node-based features, by analysing characteristics from the nodes (papers), namely their centrality. In a network, three main conditions define its centrality: (i) degree, meaning the number of relationships from each node; (ii) closeness, as for the shortest paths among nodes; and (iii) betweenness; nodes that lie on shortest path between other nodes. According to [57,58], we can discover relevant sources in scientific knowledge by looking for cited references that both (a) accumulate abundant citations (in bibliometric terminology, ‘high in-degree’), and (b) are located in the centre of the network (in bibliometric terminology, ‘high betweenness-centrality’).

In this way, to characterize the intellectual structure of the full paper set, we developed a co-citation network. Through the analysis of the network we were also able to identify the most often cited papers and citation patterns that had taken place. All abstracts of the full paper set were studied. Then, we selected the papers with the highest ‘betweenness-centrality’ and ‘in-degree’ of each cluster, and analysed them in-depth. Based on these insights gained from these sources, we characterized and synthesized the state-of-the-art and answered to our research questions.

3. Results

The following section presents the outcome of the bibliometric analysis to evaluate our initial research questions. We start with presenting the descriptive analysis and co-citation network from the full paper set. Subsequently, we give an overview of findings arising for the different subsets.

3.1. Full paper set

3.1.1. Descriptive analysis

Results from the descriptive analysis show that, out of the 954 papers that compose the full paper set, 312 titles focus on technology solutions for energy efficiency measures, 105 of them are related to decision-making behind these measures, and 445 papers address the multiple impacts of the diffusion of these technologies. Fig. 2 shows the diagrammatic overview of the proportion each subset entails from the overall paper set and the overlap among the topics. As can be depicted from Fig. 2, the main overlap takes place between subset ‘Energy efficiency measures’ and ‘Multiple impacts’.

Table 2 shows the summary of the statistics of each subset and the full paper set. The highest citation index (an indicator of citations between publications) belongs to subset 3 ‘Multiple impacts’

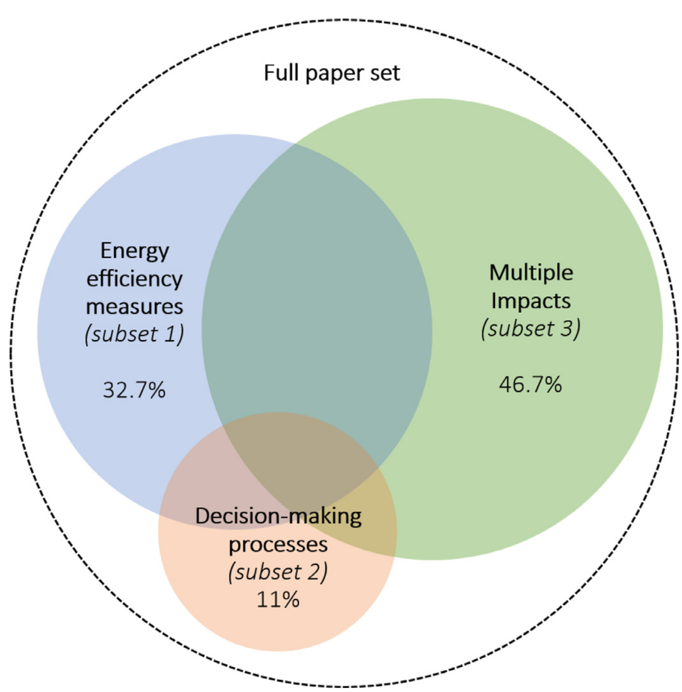

Fig. 2. Venn diagram of subsets percentages within the full paper set (n = 954 papers) and overlaps among them.

Table 2
Search statistics.

Set	No. of documents in the search	Total citations (without self-citations)	h-index	Average citation n per item	Highest number of publications per year no. (year)
Full set	*954*	*15,648*	*54*	*17.37*	*164 (2016)*
Subset 1 (energy-efficiency measures)	312	4861	37	16.32	60 (2016)
Subset 2 (decision-making)	105	1399	21	13.53	24 (2016)
Subset 3 (multiple impacts)	444	8744	42	20.34	77 (2016)

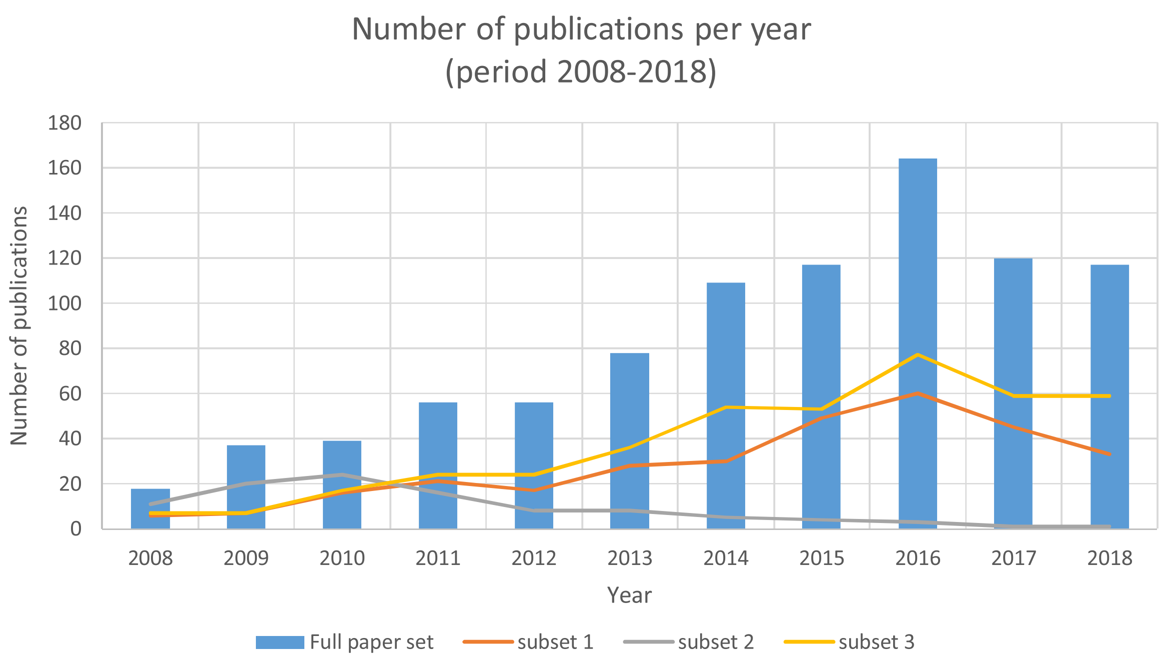

Fig. 3. Number of publications per year. Period 2008–2018.

with 20.34, with higher average than the one for the complete paper collection, which indicates that publications in this topic have been more cited than the others. Subset 2 'Decision-making' ranks last in terms of highest number of publications per year ($n = 24$), being less than half than subset 3. The average publication per item is also the lowest in 'Decision-making' ($n = 13.53$).

As can be depicted from Fig. 3, there has been a rapid development of publications in the field of technology diffusion from 2012 onwards, being subset 3 ('Multiple impacts'), the one with the highest increase. This trend has continued to grow until 2016, with a total of more than 160 publications. The only exception to this trend is subset 2 ('Decision-making'), which after 2010 started to decrease the number of publications per year, seeming of less interest now than in 2009/2010.

In terms of the European countries addressed[2] (see Fig. 4), the country with the highest number of publications for the whole paper set is the United Kingdom ($n = 135$), closely followed by Italy ($n = 130$). Spain and Sweden are the next countries with the highest number of publications ($n = 95$, $n = 71$, respectively), followed by Germany ($n = 57$). These values, however, vary when analysing the statistics of each subset individually. For instance, Italy is the country with the highest number of publications for subset 1 ($n = 50$) and scores very close to the UK in subset 3 and so does Spain and Sweden.

3.1.2. Co-citation network

The results of the co-citation network from the full paper set is displayed in Fig. 5. Within the network, each node or circle represents a paper. The lines connecting the circles are the links between the citations. The nodes with the highest number or links (in-degree) are the most cited ones. They also appear as more central within the graph. Each cluster is indicated with a colour and labelled with a title, based on the content of the papers.

The co-citation network of the full paper set consists of three main clusters (Fig. 5); 'Calculating energy consumption' (in green), 'Energy efficiency measures(in blue) and 'Definitions, methodologies and impacts of energy efficiency' (in red). 'Decision-making' matters are addressed both in 'Calculating energy consumption' and 'Energy-efficiency measures', constituting a fourth cluster in the network. Each main cluster has high density, although they are not highly interconnected among each other. The cluster with the highest betweenness-centrality is 'Energy efficiency measures, which means that it has the highest number of co-citations among authors. The biggest overlap takes place between 'Calculating energy consumption', 'Energy efficiency measures' and 'Decision-making', a logical link given the complementary understandings of the topics. 'Energy efficiency definitions, methodologies and impacts' is also linked with 'Calculating energy consumption'. The

[2] The country identification is based on the institutional affiliations of the authors.

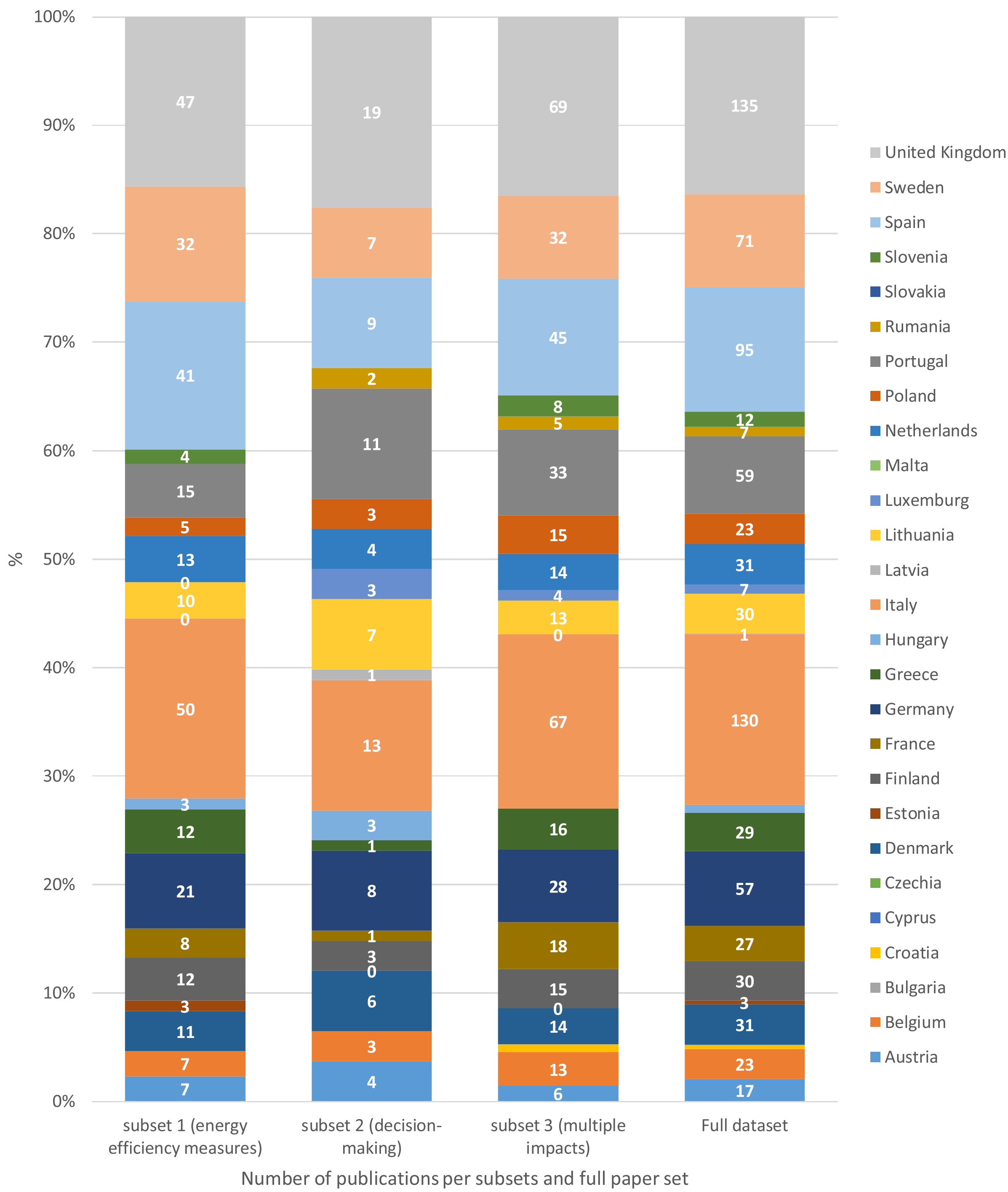

Fig. 4. Relative and total number of publications per country per country and full paper set.

densest cluster and, thus, the one with the highest number of betweenness centrality per paper is 'Calculating energy consumption'. Results from the network also indicate that, although topics arising from the research question are present, they are not the solely aspects contained in this field.

3.2. Technological measures for energy efficiency

Out of the subset 'Energy-efficiency measures', many studies present tools or simulations to support the development of zero-energy in buildings (NZEB), mostly on retrofit measures – a logic approach given the age profile of residential buildings in Europe [59]. Common technological options in this research field are: HVAC, lighting, insulation, glazing or building controls. One of the most often assessed technologies are the building envelope and lighting solutions. Among the most fast developing technologies are control automation and smart metering devices. As stated by [60], 'these devices allow the control of the energy demand/supply through ICT technologies considerably decreasing energy consumptions. Control systems relate to heating, cooling systems and ventilation, but are frequently applied to lighting (e.g. daylight and occupancy control). Furthermore, they allow data collection for performance calculations and dynamic simulation modelling'.

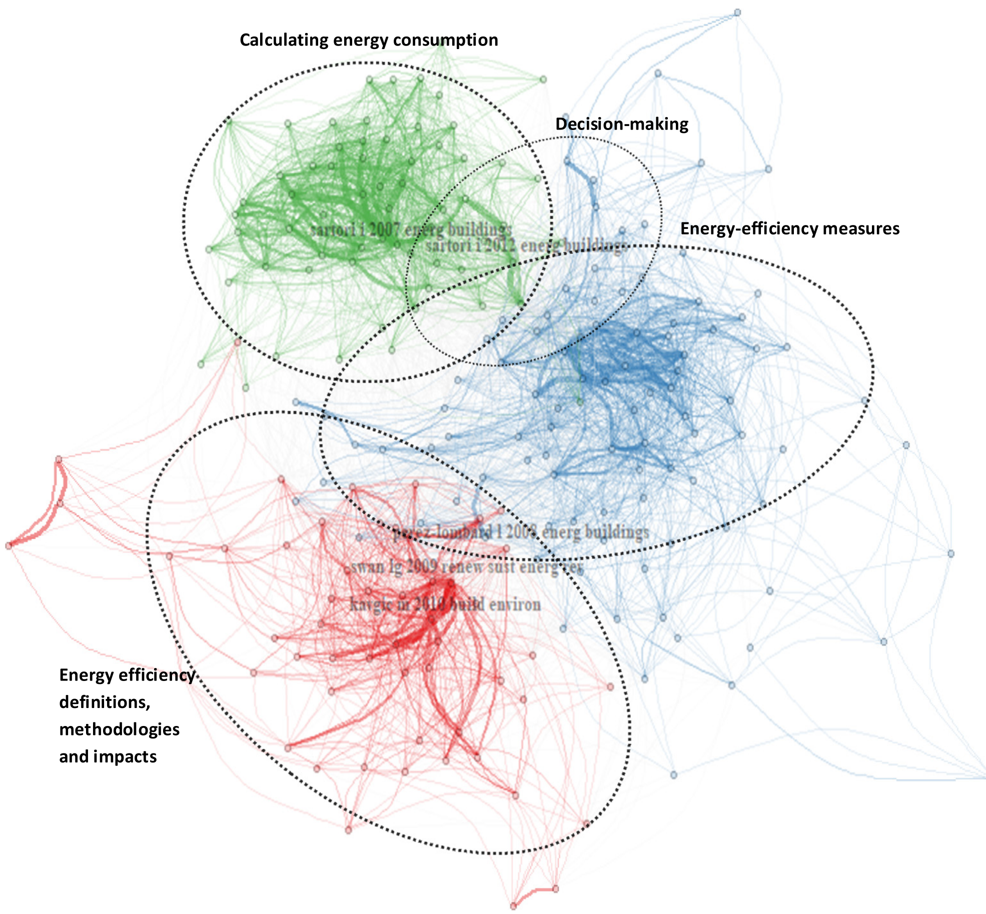

Fig. 5. Co-citation network of the full paper set: main clusters.

Most sources agree that NZEB solutions can achieve higher energy efficiency by taking a whole-building approach, hence, addressing many systems at once. This allows to save energy in a more cost-effective manner than with a single – system perspective approach, which they typically focus on isolated system upgraded (i.e. insulation or HVAC equipment). As a matter of fact, cost-effectiveness is one of the most common subjects of studies in this subset.

3.3. Decisions behind energy efficiency measures

According to [22], the main disciplinary approaches to decision making in the context of residential energy use are: conventional economics, behavioural economics, technology dissemination, social psychology and sociology. Most of the literature from subset 'Decision-making' focuses on conventional economics or social psychology. Within social psychology, most papers address a single technology and/or a specific stakeholder perspective. Demand-side actors (such as a property owners or tenants) are a key stakeholder group in these type of analyses [26,61]. Ástmarsson and Maslesa [62] investigates how regulatory changes and contractual solutions can help solve the landlord/tenant dilemma in relation to sustainable renovation of residential buildings, and how the general awareness of sustainable renovation can be increased. Results show that there are plenty of opportunities to overcome this issue. It also asserts it can only be done through integrated policy instruments, making use of tools like energy performance contracting and energy labelling (e.g. EPCs). Fouchal et al. [63], on the other hand, presents an approach for 'decision support tool to automatically generate building retrofit alternatives and rank them using energy performance analysis, user requirements, relevant benchmarks and regulations'. The model uses multi-criteria-based decision making with potential for approaching near optimum solution as it is intended to use dynamic databases for the components alternatives and genetic algorithms for the self-learning combined with fast computing.' The target groups of this tool are architects, project managers, building owners, facility managers and building contractors, aiming to support their decision-making process.

3.4. Multiple Impacts of energy efficiency measures

The scientific literature in the field presents a wide range of side-effects related energy efficiency measures in residential buildings, namely job creation, air pollution reduction, indoor air quality, energy poverty alleviation, among others [64]. These effects can be positive (so-called co-benefits or multiple benefits), or negative (so-called associated risks or detriments). Most studies, however, explore the positive effects of energy efficiency measures arguing that these surpass any potential adverse consequence [65,66]. Ürge-Vorsatz et al. [67] defines co-benefits as "the term co-benefits includes all effects of energy related renovation measures besides reduction of energy, CO_2 emissions and costs". It also classifies co-benefits into four main clusters: economic (e.g. job creation, increase of GDP, energy prices, etc.), social (e.g. energy poverty alleviation, reduction of health expenses, etc.), environmental (e.g. reduction of CO_2, reduction of local air pollution) and energy delivery (e.g. optimised utility services and energy security). Side-effects of energy efficiency measures can affect stakeholders directly involved in the residential buildings (e.g. through an increase in the value of the asset), as well as society (e.g. by decreasing local air pollution, increasing public budget or improving industrial productivity).

Ma et al. [68] asserts that reliable estimation and quantification of energy benefits are essential in a sustainable building retrofit decision-support system for the selection and prioritisation of retrofit measures. However, the identification and quantification of these ramifications is often complex as it is objected to uncertainty and depends on many variables such as local circumstances and implementation practices. As a consequence, in practice these effects are either ill assessed or not even considered in decision-making frameworks, such as public energy efficiency strategies or financing judgement schemes [69]. This might partially explain why we failed to find any study quantifying to what extent do these effects really impact the different stakeholder groups or how do they affect the investment decisions, on a country or cross-country scale.

4. Discussions and conclusions

In this study, we conducted a bibliometric analysis to better understand the intellectual base in the field of diffusion of energy efficiency technologies in European residential buildings. We reviewed a total of 954 scientific articles as well as their references. By analysing and comparing the co-citation structure of these papers we were able to generate a visual knowledge structure and identify relevant studies in the field (i.e. highest number of co-citations). Through the further investigation of the literature, we were also capable of synthesising the state-of-the-art to answer our initial research questions. What is more, it allowed us to find research gaps and opportunities.

Results from the descriptive analysis show a rapid increase in number of publications leading to an overall growth of the intellectual base. However, the network structure displays a scattered and fragmented field in many domains. This fragmentation is especially visible on a geographical level, that is among the EU member states. While countries such as Italy and UK show an active and comprehensive research activity in this front, other member states have few or no identified publications in some arenas.

4.1. Research question I – technological energy efficiency measures

The network structure of the subset 'Energy-efficiency measures' suggests it is a consolidated topic of research due to the high number of papers and co-citations. These results are validated by the statistical figures, showing a high number of publications per year with an increasing trend in the last decade. Most studies addressing this subject focus on the identification of what measures are most feasible for a specific building type/context, or in the development of methods to help identify the best possible options. Many publications focus on investigating technical and cost-effectiveness of these solutions as well as providing decision-making tools for stakeholders involved in the planning and construction of the building. The number of publications addressing cost-effectiveness as well as those related to control automation or smart metering, might continue to increase in the upcoming years due to the revised EPBD. Given the revised directive requires long-term national renovation strategies, as well as stronger rules on monitoring, metering and billing of thermal energy by giving consumers.

Besides all this information, no scientific papers were found providing empirical data as to what measures are or have been implemented in residential buildings in the EU. Namely, broad statistical values on diffusion rates of energy efficient technologies, on a country or cross-country level. We assume that such studies exist, though have not necessarily been developed or published within the scientific community but rather by private companies such as technology suppliers. If addressed by technology suppliers, this information might address single technologies and not all available energy efficiency solutions.

4.2. Research question II – decision-making behind the diffusion of energy efficiency technologies

Decision-making behind the diffusion of energy efficiency technologies is the topic area with the lowest number of publications and co-citations, to the extent that the Walktrap algorithm does not even recognise it as an individual cluster. This is particularly startling given the importance of this information to trace knowledge-based policy instruments pushing positive reaction towards energy saving measures. Namely incentive schemes, market support instruments, professional capacity, communication campaigns and engagement of stakeholders.

Most of the literature resulting from the search addresses conventional economic factors (such as cost-benefit issues) or social psychology (such as drivers and barriers). Most papers address a single technology and/or a specific stakeholder perspective, being demand-side actors, such as a property owners or tenants, a key stakeholder group in these types of analyses. This said, we did not find any reference that offered a country or cross-country comparability of any of these parameters. As with the conclusions from research question I, we assume that such studies exist, though have not necessarily been developed or published within the scientific community.

4.3. Research question III – Multiple Impacts (MI) of the diffusion of energy efficiency technologies

The exponential growth in number of publications since 2008 recognises 'Multiple impacts' as a hot topic within the field. This can be partially attributed to the Energy Efficiency Directive demanding the integration of multiple impact assessment into long-term renovation and low-energy building strategies [3]. Also, to the numerous efforts of global organizations and initiatives such as IEA, WBCSD or IPCC, highlighting the importance of reliable quantification and monetization of energy efficiency measures to boost investments and foster the low carbon transformation of the built environment. However, most sources agree that further research is needed to quantify and monetize these impacts. Furthermore, additional efforts should be undertaken to integrate them into decision-making frameworks [70], such as investment scenarios or construction projects offering a decision-support system in the selection technology choices [18,71]. Further research could also try to broaden the understanding in this arena, by quantifying to what extent they impact the different stakeholder groups or how the monetization of these benefits impact investment decisions.

4.4. Research gaps and opportunities

In overall, this field has gained considerable momentum in the past decade but it still lacks a comprehensive cross-country understanding of most of the matters addressed. Hence, future research can be developed providing a cross-country pan-European overview of relevant topics. Specifically, it could provide empirical evidence of what energy efficiency measures are being implemented in the residential buildings in Europe, on a national and cross-national level. Likewise, a more holistic and consistent understanding behind the decisions leading to the implementation and selection of these technologies is needed, especially in the field of behavioural economics and sociology, targeting at possible drivers to energy saving measures. Thirdly, further assessment of multiple impacts of the large-scale diffusion of energy efficient technologies is needed-these being positive or negative. Additional efforts should be done to incorporate the assessment of wider benefits into the decision-making processes for stakeholders involved in the buildings' planning and construction process, including policy makers. Also, how the monetization of these benefits could impact energy efficiency investment decisions.

Another important aspect identified within this study is the mismatch between the scientific discourse and the development of EU or national policy instruments or marketing campaigns. Many studies in this field have as their ultimate goal support or advice policy instruments. However, it is often unclear to what extent these scientific contributions are being utilized in practice. This uncertainty can be partially attributed to the frequent lack of transparency on the information sources needed or being applied in policy design. More transparency on what information is needed or utilized on national as well EU policy making towards the decarbonisation of the building stock, would be beneficial to guide and harmonise research production. Leading to more effective efforts as well as to less fragmented datasets. It could also provide interested parties with an overview of the sources and reasoning of the articulation of certain measures.

4.5. Critical review of the methodology

The co-citation network analysis used in this study allowed an accurate mapping of the scientific basis. It identified key research topics and niches, proving to be a useful research tool to describe the knowledge base in the field of energy efficiency technology diffusion. However, this method entails several limitations that need to be considered. First, it is very much focused on a mapping the citations or links between the papers, not in the description of the content 'per se'. This means that, to assemble a comprehensive understanding of this field, the results from the co-citation analysis need to be complemented with qualitative descriptive analysis of the bibliography as well as further investigation of the papers that compose the study set. Second, it is based on co- citation between studies and, as such, it examines the links between the different papers in terms of what they have referenced. Some papers can be strongly linked in terms of content but not necessarily joint in the graph if the authors have not included among their sources. Finally, as much as this method is open and inclusive of the types of documents that it can contain (i.e. white and grey literature), it still very much focused on what the scientific community is publishing and, therefore, might not address all existing study or piece of information related to the diffusion of energy efficiency technologies in European residential buildings.

Despite these limitations, we hope that the results from this paper contribute to build-up a consistent pan-European overview of the current knowledge in the field. Appealing to a more integrated pan-European research, to support the development of effective policy instruments towards climate protection goals.

Declaration of Competing Interest

None.

Acknowledgements

This work has been financed by Climate-KIC, supported by the EIT – a body of the European Union TC_2.7.8_190515_P183-1B. The authors would like to thank Holger Wallbaum, head of the Sustainable Building research group at Chalmers University of Technology. As well as Ian Hamilton, for the insights gained from the work developed for the IEA-Annex70 have helped to shape and sharpen the focus of this study.

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