

Review

Residential Energy Consumption-A Computational Bibliometric Analysis

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Abstract: This paper conducted a systematic literature review (SLR) of peer-review documents focused on residential energy consumption. The main finding of this SLR derived from its computational implementation, filling a gap in the available literature. The paper had two main objectives: (i) the SLR itself; and (ii) to systematically identify the main policy measures oriented at reducing energy consumption recommended by the available literature and its related greenhouses gas emissions. A significant lack of a connection between scientific fields was identified. The fields of energy, engineering and environmental science are those that have addressed these topics the most. The sub-field with the largest presence is energy, with 29.5%, followed by engineering (23.9%) and the environment (21.3%). It is recommended that this gap be bridged because many of the main political measures in force to reduce residential energy consumption come from economics and need to be explored from a social science perspective to choose those measures that are more cost-effective.

Keywords: energy consumption; energy efficiency; residential building; greenhouse gases; energy utilization



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1. Introduction

In 2021, residential energy consumption accounted for 30% of global energy consumption and 27% of the energy sector's total greenhouse gas (GHG) emissions (International Energy Agency (IEA), 2022) [1]. Its global relevance has given rise to emerging scientific literature aimed at reducing both energy consumption requirements and the GHG emissions associated with such consumption. This literature has been produced in different scientific fields that address issues such as energy consumption itself, the optimal characteristics of buildings, improvements in their energy efficiency, the type of materials used in their construction, the fuels used for heating purposes, and indoor comfort standards.

Taking the beginning of the 21st century and the scientific paper database Scopus as a starting point, 2936 peer-reviewed papers published on energy consumption and GHG emissions in the residential sector were identified. The majority of the papers were published after 2014. To be more precise, the average number of annual publications as of 2014 is 146.8 (Figure 1).

Computational bibliometric analyses enable the identification of common areas in which researchers from different scientific fields work on the same topic. These analyses provide a comprehensive view of the developments aimed at reducing residential energy consumption. To the best of our knowledge, there is a gap in the literature on this type of bibliometric analysis.

The objective of this article is twofold. On the one hand, to fill the gap in the literature by conducting a systematic review of peer-reviewed papers published between 2000 and 2021. To do this, a novel computational bibliometric analysis of the literature related to

both topics (energy consumption and the residential sector) was conducted. This analysis was performed using bibliometric software and a rich database, analysing peer-reviewed scientific papers included in the Scopus, Web of Science (WOS), SciELO and Google Scholar databases. The second objective of this article is to present the most widely used policy measures aimed at reducing residential energy consumption derived from an SLR conducted in an orderly and systematic manner. Only scientific papers published in English were considered for the review.

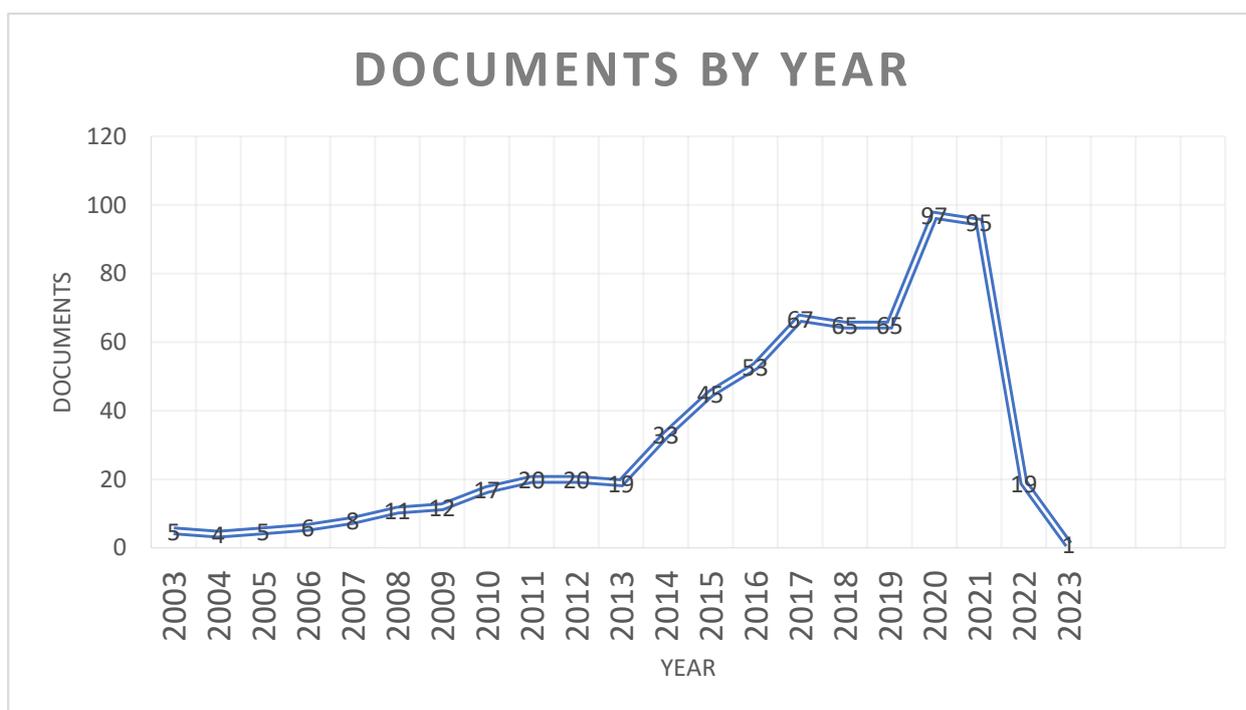


Figure 1. Number of documents published by year. Source: Own elaboration based on Scopus.

The structure of this paper is as follows: Following the Introduction, Section 2 outlines the methodology used. Section 3 describes the most relevant results. Lastly, Section 4 summarises the main conclusions, proposes further research and recognises some limitations.

2. Methodology

There are important reasons for conducting a scientific review of the literature on the determinants of energy consumption and the GHG emissions associated with said consumption in the residential sector. The first objective of this paper is to conduct a computational literature review. Following the review, it will be possible to answer the following questions:

1. How many peer-reviewed scientific papers on energy consumption and GHG emissions in the residential sector have been published, and in which countries have the main contributions been made? Which are the main journals and scientific disciplines that have taken an interest in the topic, and what are the connections between the topics and the scientific fields?
2. Based on the literature identified, what are the main recommended measures aimed at reducing residential energy consumption?

The answer to the latter will enable us to achieve the second objective of this paper.

Based on the above questions, a systematic literature review (SLR) is used as the methodological approach following pioneering recommendations [2–4]. The literature review is carried out by means of a computational bibliometric analysis structured in three steps: (1) justification of the interest in the scientific topic to be investigated; (2) selection of

peer-reviewed scientific papers on the topic of interest published between 2000 and 2021; and (3) identification of the main measures adopted to reduce energy consumption and GHG emissions in the residential sector.

As part of step (1) and to ensure that the review is performed correctly, scientific papers were researched using the appropriate keywords. Table 1 shows the keywords used for the SLR. These keywords were chosen based on [5]. These authors show that the specialised literature considers four main groups of factors to explain household energy consumption. These factors are the climate, equipment, technical characteristics of the dwelling, and socioeconomics. Column 1 of Table 1 details the search criteria. A keyword added to those proposed by [5] is economics. In this sense, for example, [6] approach energy poverty by cross-referencing data on economic vulnerability and household disposable income. Although the literature points to socioeconomic factors as determinants of energy consumption, it is possible to use a narrower keyword such as “Economics”. This makes it easier to identify relevant papers focused on aspects such as comfort and fuel poverty for our SLR.

Table 1. Keywords used in the systematic literature review.

Research	Type document	Number	Year of Publication																			
			2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Energy consumption in the residential sector + climate	article	252	3	6	5	2	1	3	2	6	5	4	9	11	12	9	22	22	25	35	36	34
	review	30							1	1		1			1	2	2	3	6	5	4	4
Energy consumption in the residential sector + equipment	article	90				1	1		2		6	1	6	4	3	7	3	6	11	12	17	10
	review	13			1					1		2	1	3			1			1	2	1
Energy consumption in the residential sector technical characteristics of the dwelling	article	1												1								
	review	1													1							
Energy consumption in the residential sector + socioeconomics	article	1																	1			
	review	0																				
Energy consumption in the residential sector + economics	article	135	3	2	2	1	3	2	2	3	2	4	5	5	3	7	9	17	13	16	15	21
	review	16								1		1		1	3			3	2	3		2

Source: Own elaboration based on Scopus, WOS, SciELO and Google Scholar.

From the documents in Table 1, the SLR enables the analysis of scientific fields, lines of research, authors, countries of residence, institutional affiliations and years of publication. All this information was properly categorised using two software tools: VOSviewer and CitNetExplorer [7,8]. Figure 2 shows the structure of the SLR performed.

Figure 2 describes how the documents analysed were selected. After filtering the total number of publications, taking into account the documents duplicated in the different search sources, the types of publications, the topics relevant to the research, and the years of publication considered, we obtained 685 publications, which were used to carry out the bibliometric analysis. Once the publications were obtained, the second research objective was then addressed by analysing and categorising the main recommended policy measures.

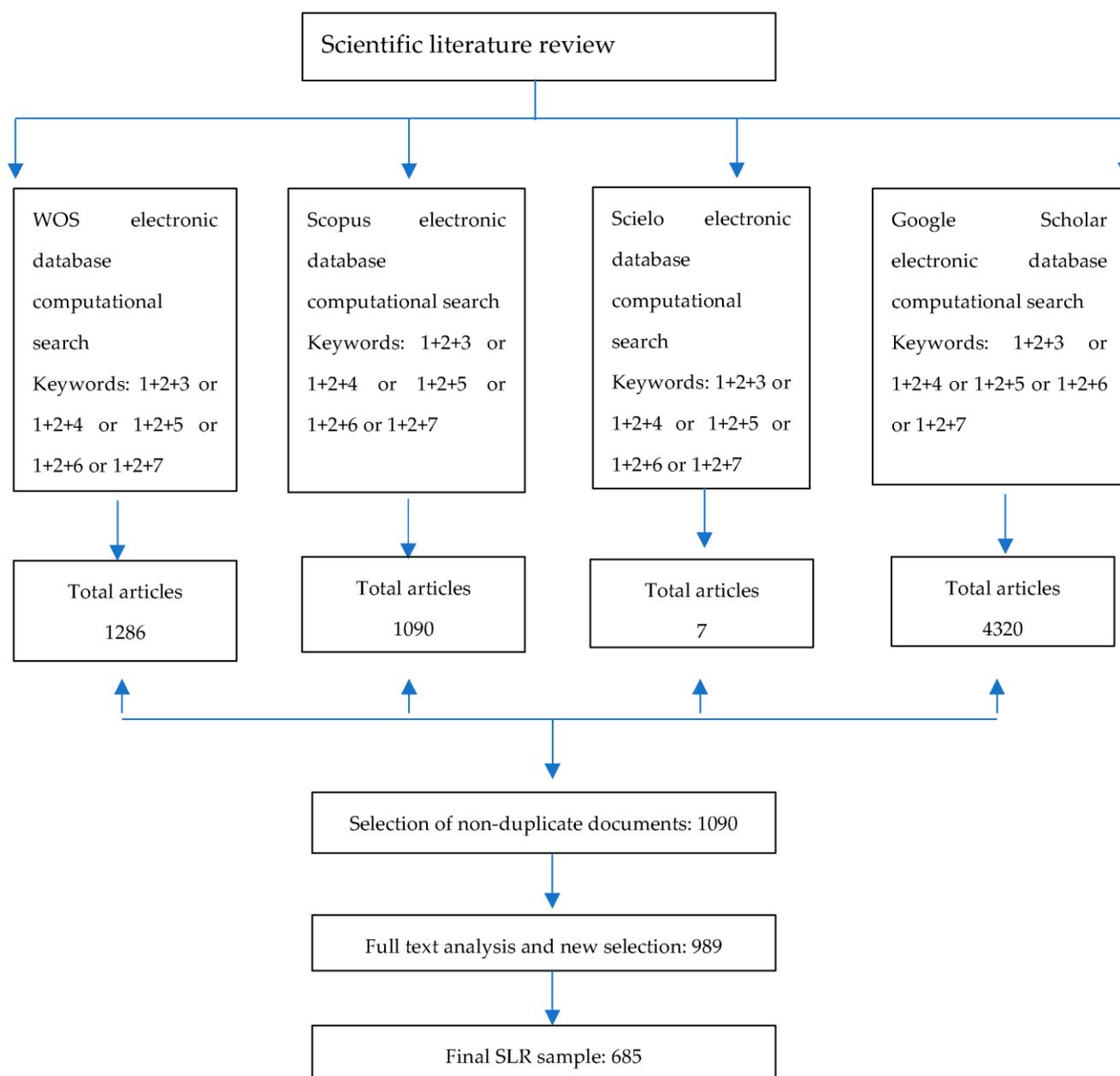


Figure 2. Criteria used and steps followed in the scientific literature review.

3. Results

3.1. Answer to Question 1. Systematic Literature Review

3.1.1. Keywords

The VOSviewer program was used to identify the main keywords in the selection of papers, regardless of whether they were identified as such by their authors (Table 1). The total number of valid publications was 685. Articles on topics unrelated to our focus of interest were excluded manually (end part of Figure 2). Figure 3 shows the keywords considered in the computational analysis and the map of connections between them.

The size of the nodes in the map shown in Figure 3 represents the number of times the same keyword is repeated. The larger the node is, the more the keyword is repeated in the scientific papers analysed. The distance from the main nodes indicates the intensity of the linkage between the different keywords within the texts studied.

Figure 3 shows the grouping of data, which helps identify the document's keywords. Only the 200 most repeated keywords are mapped. Our analysis considered both the

Figure 4 shows that the Social Sciences are under-represented in the selection of publications.

The computational bibliometric analysis also allows the aggregation of keyword nodes with a certain degree of homogeneity by presenting them grouped in clusters. To facilitate the analysis, the clusters appear in different colours (Table 2).

Table 2. Grouping of keywords into clusters.

Number	Colour	Group According to Illustration
1	Red	Energy utilization, energy efficiency, heating, energy conservation, residential building, building and buildings
2	Green	Climate change, carbon dioxide, greenhouse gases
3	Blue	Housing
4	Lemon green	Economics, energy policy, residential energy, residential sector, electricity

Source: Own elaboration.

Table 2 shows the four clusters identified in the computational analysis.

The computational analysis yields interesting results. One of these results shows that the keywords identified as relevant in the analysis were not necessarily included by the authors in their list of keywords in their document summary; however, they are repeated in the main body text. This finding is shown in Table 3.

Table 3. Number of relevant keyword repetitions.

Keywords	Scopus Repetitions	Author Keywords	Index Keywords
Energy Utilization	567	0	567
Housing	437	34	229
Energy Efficiency	392	169	356
Residential Building	172	100	188
Energy Consumption	122	132	256
Buildings	119	113	250
Building	77	284	394
Climate Change	190	71	181

Source: Own elaboration.

The computational analysis was also performed by considering only the keywords chosen by the authors in the summary of their documents. Figure 5 maps this result. In this case, the terms “building” and “buildings” (singular and plural) are considered. Despite the lesser relevance of the term used in the plural (both when chosen by the authors and when it appears in the main text), we consider that it can enrich the analysis and, therefore, both plural and singular terms are considered.

Figure 5 considers only 50 keywords. “Energy efficiency” turned out to be the most relevant. It was classified in cluster 1 and in the keywords chosen by the authors (see Table 2).

In this research, the main focus will be on the results presented in Figure 2. Zooming in enables the different groups of words to be identified more clearly. To categorise the results obtained, we return to Figure 3. Separate maps for the keywords “energy utilization” and “energy efficiency” enable a more detailed analysis. These maps are shown in Figure 6.

It is worth noting the evolution of the Energies journal, as its publications date from 2016 to 2021 and it already has 80% of what has been achieved by Energy and Buildings.

Table 4. Number of publications by document type.

Document Type	Quantity
Article	624
Review	57
Conference paper	2
Data paper	1
Short survey	1

Source: Own elaboration.

Table 5. Top journals publishing on analysed topics.

Journal	Publisher	Document type						Total	%	Year
		Article	Conference paper	Review	Data Paper	Short survey	Empty			
Energy and Buildings	Elsevier	59	1					60	8.8	2004–2022
Energy Police	Elsevier	52	0					52	7.6	2000–2022
Energies	MPDI AG	43		5				48	7.0	2016–2021
Energy	Elsevier	43		1				44	6.4	2001–2021
Applied Energy	Elsevier	38						38	5.5	2011–2022
Renewable and Sustainable Energy Reviews	Elsevier	4		32				36	5.3	2003–2022
Journal of Cleaner Production	Elsevier	26		1				27	3.9	2014–2021
Sustainability (Switzerland)	MDPI	24						24	3.5	2015–2021
Energy Economics	Elsevier B.V.	15						15	2.2	2000–2021
Energy Efficiency	Springer	12		2				14	2.0	2009–2021
Other		304	1	17	1	1	3	327	47.7	
Total			2	58	1	1	3	685	100	

Source: Own elaboration.

Another relevant category is the relationship between publications and the authors' countries of residence. If we take the first author's country of residence as a criterion, the United States achieved the highest participation, followed by China, Spain, Italy and the United Kingdom. Figure 8 shows the 14 countries with 20 or more publications.

Finally, the SLR conducted enables the main research centres or universities leading the papers to be identified. For this purpose, the criterion of the first author is used to assign the document to an institution. It can be seen that the University of Tehran has the largest number of affiliated authors in these topics, followed by the University of Malaya and the University of Seville. Figure 9 shows the institutions with six or more affiliates.

3.2. Answer to Question 2. Main Measures Aimed at Reducing Residential Energy Consumption

The SLR conducted allows the second research question to be answered, and thus enables the second objective of this research to be achieved. In the past ten years, the number of publications analysing residential energy policies has increased significantly. There has been a notable increase since 2018, excluding the trend in 2020 due to the COVID-19 pandemic (Figure 10). The publishing work by the Renewable and Sustainable Energy Review journal should be highlighted, with 177,045 citations in 2021 (Figure 11).

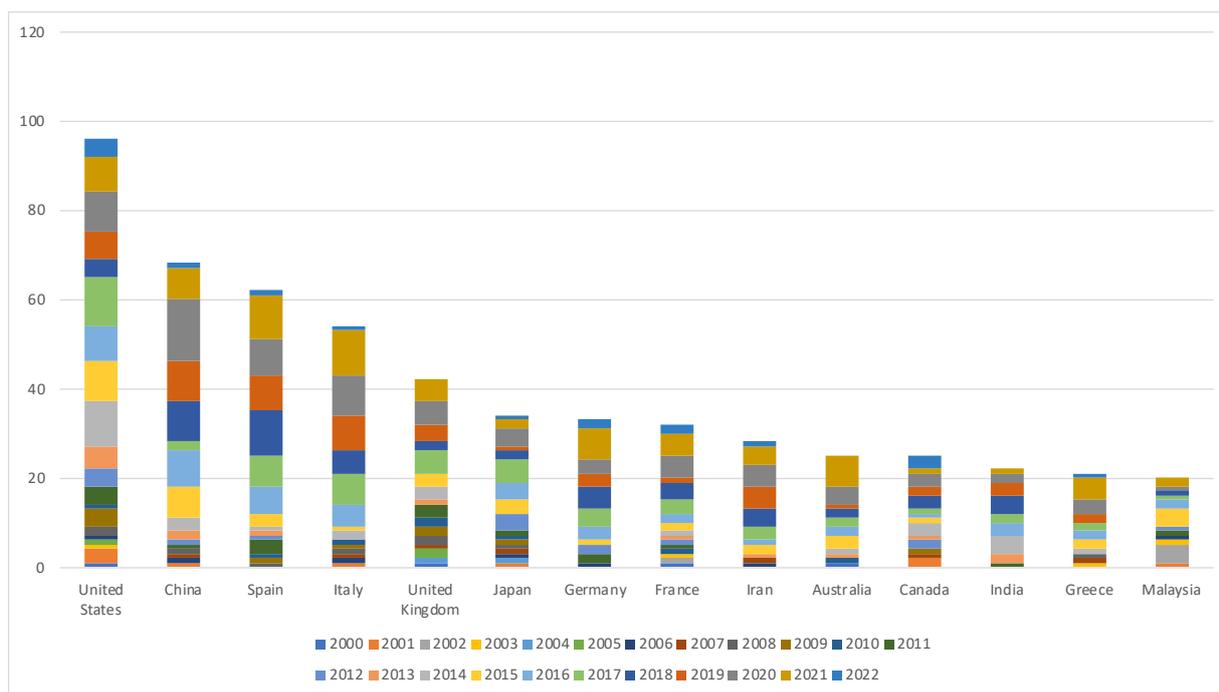


Figure 8. Countries with the highest number of publications. Source: Own elaboration based on the documents studied.

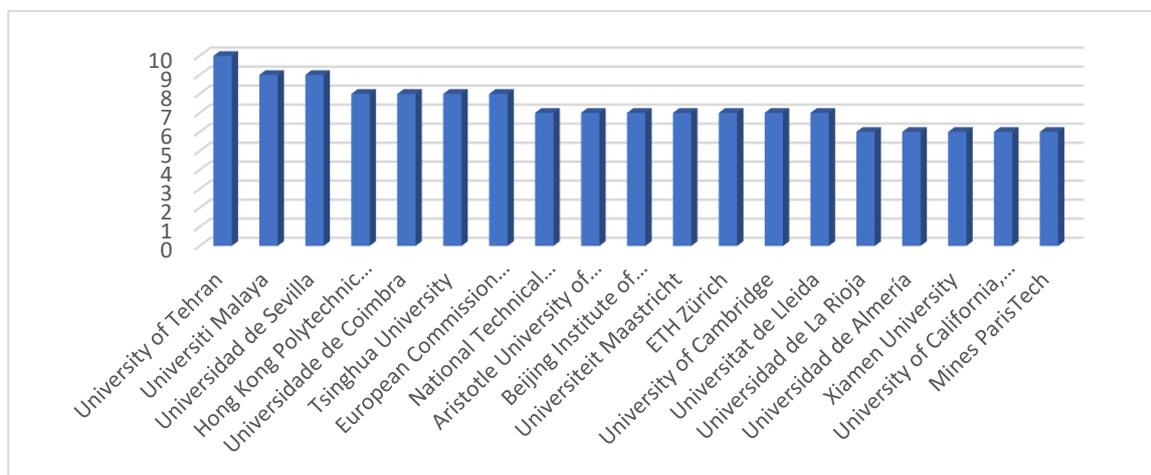


Figure 9. Institutions with the highest number of affiliates. Source: Own elaboration based on the documents studied.

The papers identified by the SLR reveal that the main policies aimed at residential energy consumption can be classified into three groups: (i) policies aimed at reducing its environmental impact; (ii) policies based on the use of smart devices; and (iii) policies aimed at influencing the behaviour of agents through economic incentives. Up to 13 different measures have been identified. Table 6 shows the most relevant literature classified by groups of measures.

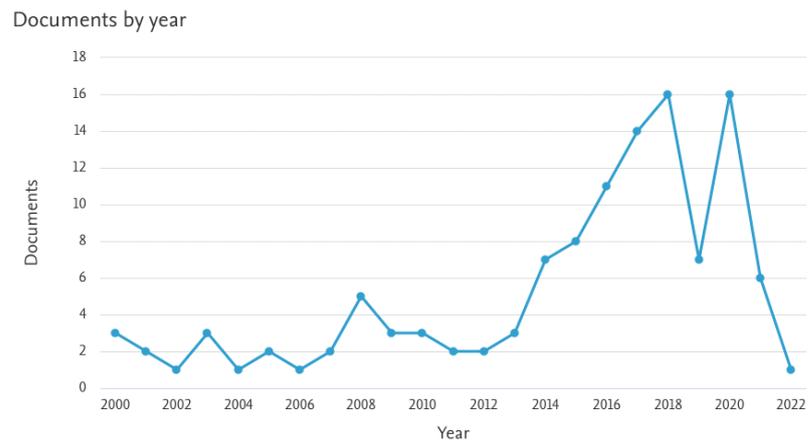


Figure 10. Publications by year. Source: Scopus.

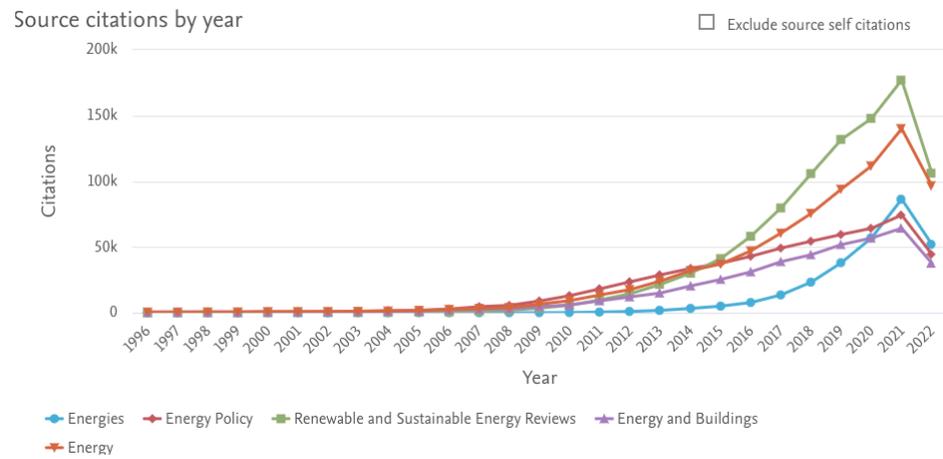


Figure 11. Source citations by year. Source: Scopus.

There are four countries whose residential sectors have been analysed the most: the United States, the United Kingdom, China and Italy (see Figure 12).

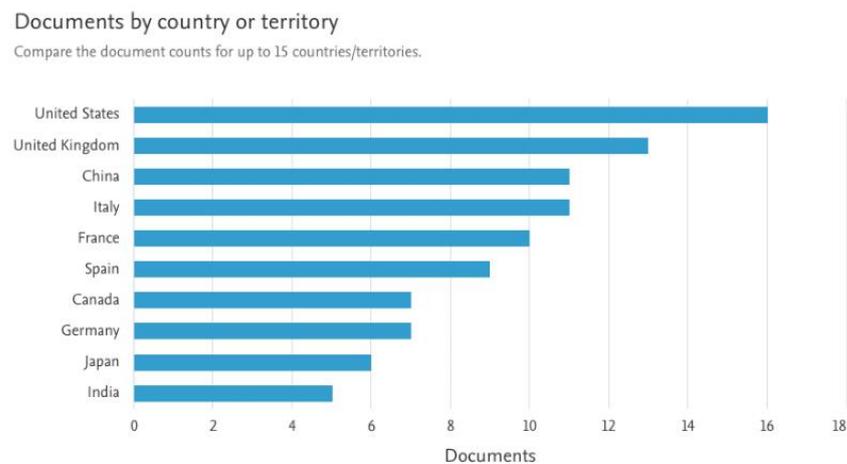


Figure 12. Number of publications by country. Source: Scopus.

Table 6. Approaches classified by measures aimed at reducing residential energy consumption.

Approach	Energy Policy	Documents
Environmental	Net-zero buildings	[9–11]
	Construction materials	[12]
	Climate change mitigation	[13,14]
Use of smart devices	IoT	[15,16]
	Building modelling	[17–21]
	Theoretical calculation models	[22,23]
Economy	Financial instruments	[24]
	Energy subsidy	[25]
	Residential heating	[26,27]
	Energy efficiency	[28–30]
	Energy management	[16,31–33]
	Non-conventional renewable energies	[34]

Source: Own elaboration.

Measures aimed at reducing the environmental impact of residential energy consumption are mainly directed at improving the energy efficiency of dwellings. The ultimate goal is to make them net-zero buildings. [35] studied residential and non-residential construction in Austria with the goal of building near-zero energy consumption buildings. These authors recommend certification and construction under environmental standards but stress the importance of public policies on this issue. On the other hand, [22] use the quantile regression method, which permits us to find out which are the differentiating impacts for the study of energy performance gaps in different types of dwellings.

Building materials suitable for reducing energy consumption have also received considerable attention from public decision-makers [12,36]. Parts of the measures on materials are designed to ensure comfort while reducing energy consumption requirements. Efficient construction systems enable energy consumption to be reduced. For existing dwellings, solutions based on retrofitting buildings with thermal insulation that allows less temperature leakage to the outside have been proposed. This insulation includes the thermal envelope of walls and floors, changing window types and/or improving roof insulation [29,29]. In this vein, the author also highlights the importance of these solutions for historical buildings in Europe, considering that air-conditioning systems account for the highest energy consumption in dwellings (on heating and cooling degree-days). Other solutions for improving the air conditioning and thermal comfort of dwellings also emerge from this, such as ventilated façades [17,17] and eco-friendly walls and ceilings, inter alia.

According to data from the [37] Corporación de Desarrollo Tecnológico (Technological Development Corporation) (2018), in Chile, 53% of energy consumption is from heating, 20% from domestic hot water and the rest from lighting and daily home appliances. It is now worth pointing out that, as defined by [38], the building materials should be studied based on the area's climate to achieve more efficient construction solutions, especially for new buildings, preventing thermal bridging when making the building envelope and generating a thermal mass based on the climate characteristics. This issue is also connected to the architectural features of the dwelling, by considering the direction of the building for the use of solar energy and the necessary vents to prevent damp caused by condensation inside the dwellings.

The literature provides evidence to support this type of decision. Ref. [33] used the QGIS software to identify regional heating or cooling degree-days and their relationship with household energy consumption. Ref. [32] also analysed the climate variable by relating it to the conditions and size of dwellings and the household income level. Similarly, Ref. [24]

proposed a reduction in particulate matter when heating systems are based on the use of biomass.

Ref. [39] analysed urban areas in Tanzania where coal is the most commonly used fuel for heating in residential areas. Ref. [40] reported similar results after analysing 51 Japanese cities. These authors highlight the differences linked to the socioeconomic, demographic and climate levels of the population studied and the importance of incorporating these variables into new policies.

Regarding climate change mitigation, Ref. [41] identify the need to move towards energy transition in all sectors, including the residential sector. As regards the case of Italy, these authors argue that GHG emissions could be reduced by 68% by 2050 if measures and changes are implemented in the use of fuels for energy production.

China, Austria and the United Kingdom are the countries that have the most developed studies on the use of smart devices. One of the most discussed topics has been the need for energy-efficient buildings and energy-efficient appliances. In line with the above, Refs. [42,42] analysed policies that incentivise the consumer in processes related to building energy storage without the need for central coordination through smart metres and software applications that would enable the inhabitants to act as prosumers.

Regarding the case of Spain, Ref. [24] have analysed the use of financial instruments to promote both improvements in housing energy efficiency and the introduction of renewable energies. However, the latter objective is controversial in the literature.

Ref. [43] reach similar conclusions when addressing buildings in the U.S. state of California. The authors emphasise the importance of renewable energies, considering that current constructions require a greater use of electrical energy both for heating and cooling (in summer). In the same line but with regards to the state of New Jersey, Ref. [44] propose the use of heat pumps as a form of energy use for heating in the residential sectors, reducing the environmental impact of houses that only use electricity.

While the use of photovoltaic panels can reduce non-emission-free energy consumption by up to 54% in multifamily dwellings, controversy in the literature arises because total energy consumption may end up increasing. Such is the case of Japan, where there is evidence that in houses with photovoltaic panels, total electricity consumption increased by 3.02% [45]. In these situations, policies aimed at replacing residential energy sources may be inducing a rebound effect on total energy consumption if a life-cycle analysis perspective is adopted, which includes the emissions associated with the manufacture and distribution of the devices used in the houses as a result of the replacement of conventional energy sources.

Finally, the results of energy subsidies granted to certain families have also been controversial. Ref. [25] showed that households that received energy subsidies consumed twice as many kWh/month as households that did not.

In any case, the measures listed above can be expanded by including an analysis of CO₂ emissions in the residential sector that encompasses the role played by the cement industry. Although this goes beyond the focus of this article, it is worth discussing due to the concerns expressed by both technical and academic communities. Two research topics can be highlighted: (i) Substituting a percentage of conventional cement with other materials, such as nanomaterials, to reduce CO₂ emissions by decreasing the production of Portland cement and enhancing the resilience of Portland cement-based concretes against hazards such as fire, earthquakes, and aggressive industrial environments (e.g., [46]); (ii) Making efforts to properly rehabilitate existing reinforced concrete (RC) buildings in terms of seismic performance (e.g., [47,48]) and considering the use of more efficient and thinner concrete jackets (e.g., [49–52]).

4. Discussion and Main Conclusions

4.1. Conclusions

The computational bibliometric review (SLR) performed in this research is a useful tool to achieve the two intended objectives: (i) To fill the gap in the existing literature on this

type of review; and (ii) to present a systematic and orderly overview of the main measures implemented to reduce residential energy consumption.

Despite the emerging number of publications, the connection between the different scientific approaches to the topic is weak. Interdisciplinary approaches are scarce. This weak connection between disciplines poses a barrier to finding effective measures to reduce energy consumption. Therefore, one of the main conclusions is that there is a significant lack of connection between scientific fields. More specifically, the fields of energy, engineering and environmental science are those that have addressed these topics the most. The sub-field with the largest presence is energy, with 29.5%, followed by engineering (23.9%) and the environment (21.3%).

A second conclusion is the lack of contributions from the field of social sciences. This is a particular concern when we analyse the most frequent keywords in research and the most widely used measures aimed at reducing residential energy consumption. The reason is that a significant part of these measures is related to the use of financial instruments or subsidies, and their correct design requires further results from the field of social sciences.

The previous conclusion is reinforced when we analyse the importance of the keywords “energy utilization” and “energy efficiency” in the research documents. In the first case, the influence of household income has been highlighted by the literature; however, it is beyond the scope of papers published in the predominant scientific fields such as energy, engineering or environmental science.

In the second case, it should be noted that advances in energy efficiency depend not only on the improvement in building materials but also on the efficiency with which the measures allow households to make changes in the equipment or construction of their homes. This reinforces our recommendation for greater cooperation between researchers from different scientific fields.

4.2. Recommendations and Further Research

The analysis leads to the conclusion that the weak connection between the scientific disciplines that analyse residential energy consumption acts as a barrier to scientific progress. Based on the results obtained, our recommendation is to increase the publication of scientific papers in the area of social sciences. An interesting focus for future research would be the evaluation of the good results obtained in the main countries and journals publishing on the topic under analysis.

It is also recommended to extend the analysis of the GHG emissions residential sector related with those related with the cement plants activity since a large proportion of GHG emissions comes from the industry of the production of cement, which is the main ingredient for producing concrete. Focus might be put on two research topics: (i) To substitute a percentage of cement with other low carbon emissions materials and (ii) to properly seismically rehabilitate existing reinforced concrete buildings.

4.3. Limitations

The exclusive use of scientific papers published in English is a limitation of the conclusions obtained. Documents published in Spanish were used only in the specific case of Chile. Future research should overcome this limitation. However, the most influential scientific publications are in English. The limitation of establishing a link between a publication and the country behind it based solely on the criterion of the first author should also be considered.

Finally, it is possible to conclude that the main measures implemented that have been aimed at reducing household energy consumption and associated GHG emissions are environmental in nature, focus on the use of smart applications, and frequently use economic incentives to promote them. It is recommended that future analyses consider a behavioural economics approach to better understand the reaction of agents to the available incentives so that the most cost-effective ones are chosen.

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