Household energy consumption: state of the art, research gaps, and future prospects

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Abstract

Household energy consumption accounts for almost one third of global primary energy demand and significantly affects the environment. As such, it has served as a classic and compelling theme in the literature, with a range of studies having analyzed various aspects of household consumption, including energy conservation, energy poverty, and energy efficiency. Nonetheless, overall trends and frontiers in this research area have not been characterized and are poorly understood. This study aims to assess the current status, evolution, and emerging topics in this area through a bibliometric and network analysis of 1134 extracted publications from 1983 to 2018. This systematic review shows that nearly half the studies on household energy consumption were published in just three journals (namely, Energy Policy; Energy; and Energy Economics) with a focus on three areas (Environmental Sciences and Ecology; Energy and Fuels; Business and Economics). The findings also show that among contributing countries, the USA and China have the closest ties and wield the most academic influence. Furthermore, emerging and pioneering studies on behavioral interventions, energy conservation, and energy poverty and those pertaining to climate and electricity consumption may constitute the research frontier.

Keywords Household energy consumption · Energy conservation · Bibliometric analysis · Literature review

1 Introduction

It was in the 1970s that society first began to worry about fossil fuel depletion and the impending energy crisis. Adding to these concerns in the 1990s was a growing public awareness of the need for environmental protections and climate change mitigation. These shifts prompted more research on energy demand in various end-use sectors (Abrahamse et al. 2005; Amasyali and El-Gohary 2018; Stelmach et al. 2020). Among these sectors, it has been the household sector—which contributes to almost one third of global energy

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use—that has drawn major academic interest (Dahl and McDonald 1998; Granade et al. 2009; Sudhakara 2004; Wolfram et al. 2012; Wolske et al. 2020; Zhou and Yang 2016).

In the past 30 years, studies on household energy consumption have rapidly advanced, with researchers in this area successfully integrating concepts from economics, the environment, social development (Pachauri et al. 2004; Winkler et al. 2011; Xu et al. 2018; Yang and Cao 2018), sustainability, and other fields (Jin et al. 2006; Jurj et al. 2007; Xu and Chen 2019; Zhen et al. 2018), resulting in multiple interdisciplinary topics. Initially, studies focused on energy use or energy transition, a topic that has been around since the 1980s. Early examples of this research include studies by Zhu and Brambley (1983), Behrens (1986), Davis (1998), and Leach (1992). After Daniel Kahneman won the 2002 Nobel Prize in economics, field or experiment-based behavioral analysis was introduced to energy conservation intervention research (Darby 2006; Fischer 2008). In this thread of the literature, many studies reviewed applications of behavioral interventions to energy conservation (Abrahamse et al. 2005; Andor and Fels 2018; Fischer 2008; Karlin et al. 2014). In more recent studies, institutionally relevant variables such as cultural or social norms have been recognized as critical factors and have also been introduced into the analyses (Gifford and Nilsson 2014; Stephenson et al. 2015; Zhou et al.2018).

With the global energy shortage and climate change, energy efficiency has gradually become the focus of extensive research (Berg and Fuglseth 2018; Brounen et al. 2012; Chandel et al. 2016; Copiello 2017). In a pioneering study, Patterson (1996) defined energy efficiency, making it possible for researchers to measure and compare energy efficiency across individuals and years within a uniform framework. For example, researchers were able to benchmark the energy efficiency of buildings (Copiello 2017; Fossati et al. 2016; Modeste et al. 2015) and quantify the rebound effect of changes in energy efficiency (Gonzalez 2010; Sorrell et al. 2009; Wang et al. 2016). In energy conservation studies, researchers have observed an energy efficiency gap between actual and optimal energy use (Hirst and Brown 1990; Jaffe and Stavins 1994). Interest in this theme has grown gradually over the past two decades, and it has become one of the most popular topics in energy conservation studies (Allcott and Greenstone 2012; Bhardwaj and Gupta 2017; Freire-González 2011; Ouyang et al. 2010; Stadelmann and Schubert 2018).

In recent years, since energy use is known to affect human well-being and health and can result in harmful environmental emissions, studies in this area have been high on the research agenda. For example, some scholars have examined energy poverty (Betto et al. 2020; Mould and Baker 2017; Pachauri and Spreng 2011; Sanusi and Owoyele 2016). Others have quantified energy inequity in rural households (Carrion et al. 2018; Wu et al. 2017) and assessed health risks from biomass smoke exposure in indoor environments (Gibbs-Flournoy et al. 2018; Liu et al. 2018; Tigala et al. 2018). Moreover, emissions—especially greenhouse gas emissions, which result from combustion during energy consumption—have become a research hotspot (MacNaughton et al. 2018; Zahabi et al. 2012; Zhang et al. 2015). For literature reviews on these topics, refer to Kurmi et al. (2010) and Zhang et al. (2015).

In addition to the aforementioned main topics of household energy consumption, there are many other active topics (Ahmad et al. 2014; Axsen et al. 2012; Binita and Ruth 2017; Grimes et al. 2016; Jensen et al. 2018; Ouedraogo 2006). It is essential to explore the relationships among these topics to track the changing research trends, because all major changes in research direction must rely on previous research accumulation. However, no reviews have comprehensively covered the entire field to clarify these relationships; instead, they have focused on specific aspects such as energy conservation (Abrahamse et al. 2005; Andor and Fels 2018; Fischer 2008; Karlin et al. 2014), energy efficiency

(Ramos et al. 2015), the rebound effect (Gonzalez 2010; Malik et al. 2020; Sorrell et al. 2009), carbon emissions (Zhang et al. 2015) or energy poverty (Castaño-Rosa et al. 2019; Mould and Baker 2017; Roberts 2008). Their analyses focus on methods and contents, and the literature statistics are relatively straightforward, showing incomplete coverage of a number of topical areas (Sorrell et al. 2009). Although each study has provided insight into a specific sub-field, quantitative analysis of academic literature in all fields using bibliometric tools can provide further insights not previously fully grasped or evaluated. The time has come for a comprehensive review of the thousands of studies in this rich area. Such a review can help us uncover the inner nexuses between disciplines, depict development patterns and spectrums and identify research frontiers.

Accordingly, this study seeks to gain an impression of household energy consumption. One of our goals is to better appreciate the state of current research interests by considering the distribution characteristics of a great number of scholars' research results across the entire field of household energy consumption. Another, related goal is to explore directions for future research by identifying emerging topics and analyzing relational links between them.

This study makes two main contributions. First, to the best of our knowledge, this systematic analysis of 1134 studies from the past 35 years (incorporating all the major subtopics) is the first study to identify overall patterns and emerging topics in the literature on household energy consumption. Second, this study complements and improves the findings of other studies, which have approached the subject from a qualitative, specific perspective. For instance, we find that nearly half of the studies in household energy consumption have been published in *Energy Policy*, *Energy*, and *Energy Economics*, and that the research scope mostly relates to the fields of Environmental Sciences and Ecology, Energy and Fuels, and Business and Economics. In the most recent years, the topics of climate, behavioral intervention, and energy conservation have attracted increasing scholarly attention, while the topics of energy poverty and electricity consumption continue to be emerging.

The remainder of the paper is organized as follows. Section 2 introduces the bibliometric analysis methodology and data. Section 3 presents the research results and summarizes the trends in the evolution of the topics. Section 4 summarizes the main conclusions.

2 Materials and methods

2.1 Bibliometric analysis

Bibliometric analysis is the predominant method in quantitative literature reviews. As argued by Merigó and Yang (2017), using this powerful tool can provide a general overview of a field. Moreover, such an analysis can be further specialized along different dimensions, allowing a researcher to explore more complex relationships. For example, collaboration analysis can quantify the frequency and intensity of cooperation between different authors (Muñoz-Muñoz and Mirón-Valdivieso 2017). Author co-citation analysis (ACA) can reveal interrelationships between authors and identify influential authors (White and McCain 1998). Moreover, the co-occurrence tool enables a user to quantify the simultaneous frequency of two keywords in a document (Barberán et al. 2011). These network analyses are particularly helpful for identifying relationships between established and emerging topics (Fahimnia et al. 2015).

Several software tools have been developed to implement bibliometric analysis, such as BibExcel (Persson et al. 2009) and CiteSpace (Chen 2006). However, some of these tools cannot complete a bibliometric analysis alone, nor can they pretreat the original data in a precise way. Recently, Bibliometrix, an R package developed by Aria and Cuccurullo (2017), was designed to overcome these defects. This R tool follows a classic logical bibliometric workflow and allows researchers to artificially refine the initial search data to make the research scope more precise. In light of these merits, Bibliometrix has been applied in several recent bibliometric studies (Alonso et al. 2018; Bond et al. 2019; Li and Yan 2018; Nafade et al. 2018; Tani et al. 2018).

2.2 Data collection and processing

To review all the relevant fields, we use general keywords and apply topic search methods in the literature search stage. We use seven keywords for data collection: "household", "residential", "energy", "fuel", "consumption", "use", and "transition". Ten groups of keyword pairs were used: (1) household AND energy AND consumption; (2) household AND energy AND use; (3) household AND energy AND transition; (4) household AND fuel AND use; (5) household AND fuel AND transition; (6) residential AND energy AND consumption; (7) residential AND energy AND use; (8) residential AND energy AND transition; (9) residential AND fuel AND use; (10) residential AND fuel AND transition. We also exclude literature with unrelated keywords, such as "water", "food", "thermal", and "photovoltaic".

In the first search stage, these predefined keyword combinations are applied to probe documents from the Science Citation Index Expanded and the Social Science Citation Index in the Web of Science database for the years 1975 to 2018. Document types such as conference papers, data papers, books, and chapters of books are excluded. The initial search procedure yields a total of 4467 English articles. The records that have fully documented and cited references are stored for analysis.
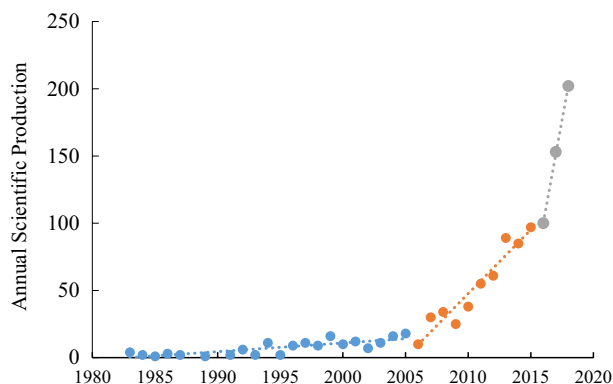
In the second stage, we apply three selection criteria as follows. First, we eliminate duplicate records, leaving 3505 documents. Second, we drop the records that are missing keywords or authors, leaving 2432 remaining documents. Third, we screen the abstracts to evaluate for topic relevance. This process results in 1134 publication records for our analysis. To avoid statistical bias resulting from duplicated abbreviated names of Chinese authors, we replace the abbreviated names with the authors' full names. Table 1 shows the results from this stage (note the absence of studies from before 1983).

Figure 1 shows the trend in the number of published articles. We divide the study period into three stages: the most recent years (2016–2018); the 10 years before 2016 (2006–2015); and finally, the 23 years before 2006 (1983–2005). With these divisions, we can more easily visualize evolutionary trends on the timeline. As shown, 2005 is a turning point in the evolution of household energy consumption literature. Before 2005, the number of related studies is small and development is very slow, while after 2005, the number of studies begins to show a significant upward trend. These results demonstrate geometric growth in publications.

Table 1 Main data characteristics

Indicator	Value
Documents	1134
Sources (journals)	70
Keywords Plus (ID)	1754
Authors' keywords (DE)	2668
Period[a]	1983–2018
Average citations per document	23.62
Authors	2705
Author appearances	3402
Authors of single-author documents	166
Authors of multi-author documents	2539
Single-author documents	181
Documents per author	0.419
Authors per document	2.39
Co-authors per document	3
Collaboration index	2.66

[a]There were no studies in the database before 1983 that met our search criteria

Fig. 1 Publication trends in the area of household energy consumption

3 Results and discussion

3.1 Statistics on journals and fields

Table 1 reveals that a total of 1134 papers were published in 70 journals, of which about 75% (833) were published in 10 journals (Table 2). The more striking revelation from Table 2 is that approximately half of these studies are from 3 major journals: *Energy Policy*, *Energy*, and *Energy Economics*. Table 2 also reveals an interesting trend in terms of timeline: the number of publications in the most recent 3 years is nearly equal to that from the previous 10 years. Clearly, the research on household energy consumption has expanded rapidly in recent years and has become a fruitful area of academic work.

Table 2 Top 10 most productive journals

Source	Publication period				Relative frequency (%)
	1983–2005	2006–2015	2016–2018	Total	
Energy policy	44	183	85	312	27.51
Energy	42	36	37	115	10.14
Energy Economics	24	51	29	104	9.17
Journal of cleaner production	1	22	51	74	6.53
Energy Research and Social Science	0	15	32	47	4.14
Energy efficiency	0	25	19	44	3.88
Sustainability	0	13	31	44	3.88
Ecological economics	3	23	16	42	3.70
Energies	0	6	22	28	2.47
Energy for sustainable development	0	15	8	23	2.03
Total	114	389	330	833	73.46

Figure 2 shows the trends and stack numbers of published articles for the top 10 most productive fields. The most obvious trend is that household energy consumption research is mainly distributed across three fields: *environmental sciences and ecology, energy and fuels, and business, and economics*. The number of articles in these three fields shows exponential growth, revealing that the current research is still focused on these three areas. It is worth noting that in recent years, Transportation and Meteorology and Atmospheric Science have entered the list of top 10 most productive fields. With the growing awareness of climate change and support for green travel, the number of publications in these two areas may continue to climb sharply.
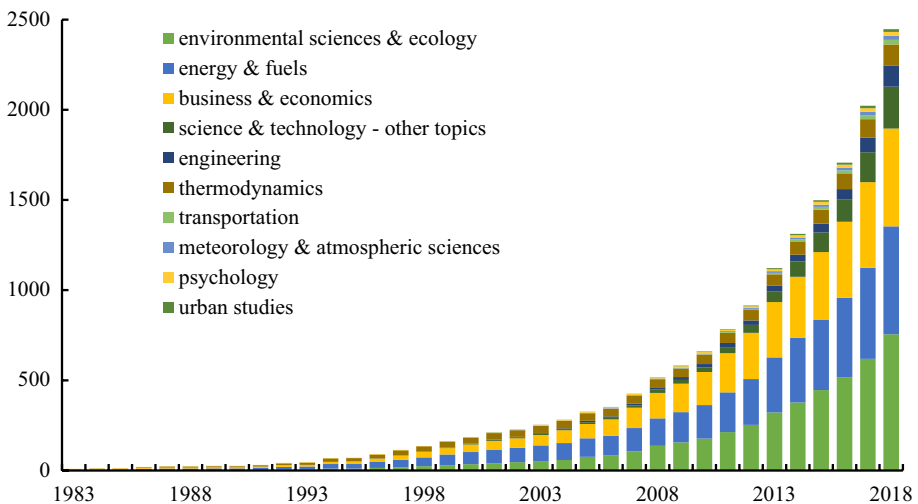

Fig. 2 Evolutionary trends in fields according to stack numbers of articles. *Note*: The research fields are categorized according to the Web of Science

3.2 Distribution and cooperation

3.2.1 Country distribution

Figure 3 shows the distribution of publications among the top ten most productive countries. The first three countries are the USA, China, and the UK, and the papers published by these three countries account for more than 38% of the total literature. Overall, the research on household energy consumption is dominated by developed countries, and approximately half of the most productive countries are in Europe. The level of international cooperation in this research area appears relatively low; on the contrary, it seems that most studies are produced by scholars within one country collaborating with each other. Chinese scholars have the highest degree of international cooperation in this field, with 33% of their publications as multiple-country publications.

3.2.2 International cooperation

Figure 4 shows collaboration among the top 25 most productive countries. The width of the line represents the strength of the cooperation. The minimum strength is set at 5, meaning that countries are connected only when the cooperation frequency between them is greater than 5. China and the USA are not only in the leading positions but also demonstrate the strongest connection; in other words, the cooperation frequency between these two countries is high, which may account for the fact that both countries have a large number of multiple-country publications, as shown in Fig. 3. We use six colors to identify the six cluster partner countries that cooperate most closely in the area of household energy consumption. In Fig. 4, the red cluster represents European countries, with Germany, the UK, and Switzerland as the three most active countries. Another salient cluster is the green one, representing the USA and China. The USA also frequently cooperates with European countries, while China cooperates more frequently with Australia and Japan. Interestingly, we found that among countries in a particular cluster, the frequency of cooperation may
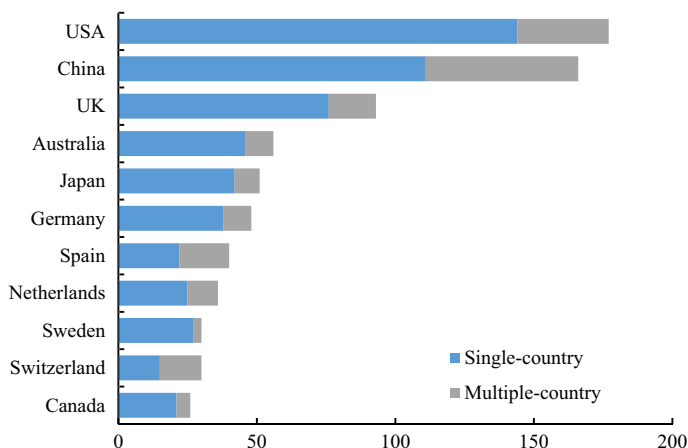

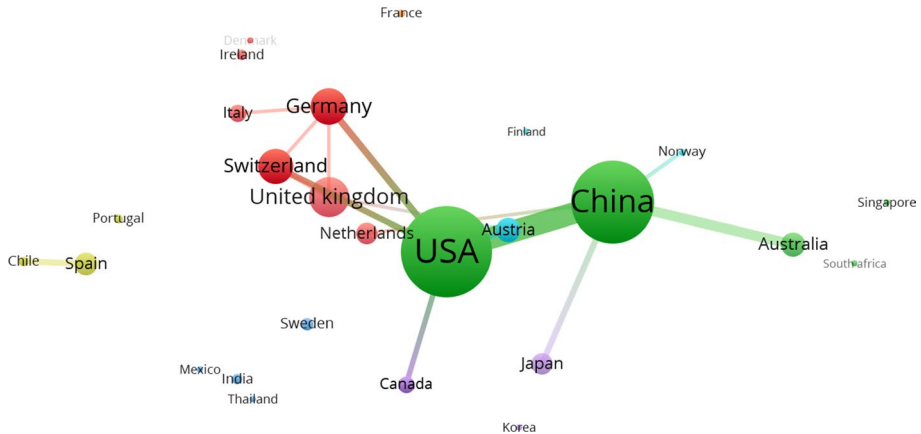**Fig. 3** Publication distribution among countries

Fig. 4 Collaboration network of the 25 most productive countries

still be very low (e.g., Mexico, India, Thailand, and Sweden). Apart from the USA and China, even the productive countries have relatively few instances of cooperation.

3.2.3 Organization distribution

Figure 5 shows the geographical locations of organizations that contribute to household energy consumption literature. The intensity of the color is proportional to the number of organizations. We find that research on household energy consumption demonstrates a trend toward globalization. Research institutions are distributed across five continents, indicating that research on household energy consumption has already spread across the globe. Not surprisingly, the USA and China have the most organizations, followed by the UK.
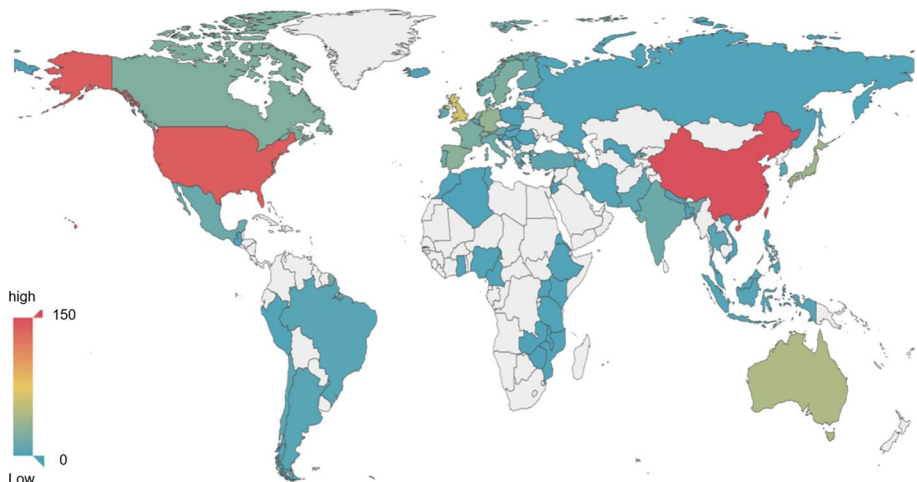

Fig. 5 Geographical locations of contributing organizations

Fig. 6 Cross-departmental distribution of contributing organizations
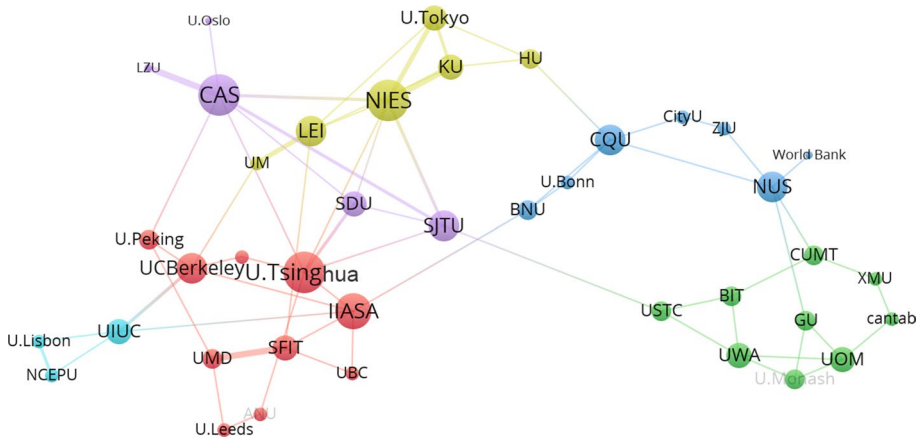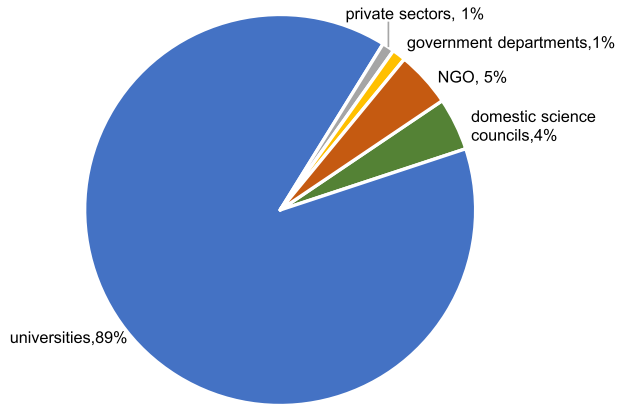

Fig. 7 Collaboration networks of the 40 most productive organizations

Figure 6 shows the cross-departmental distribution of the organizations. We find that this field is dominated by academic research institutions, with universities accounting for 89% and domestic science councils for 4%. Non-government organizations (NGOs) also play a relative important role in household energy consumption research, with some 41 NGOs participating in the study. In addition, the government and private sector are also involved in the study, but the proportion is very low, less than 1%, respectively. Overall, this field is dominated by the team of academics and lacks the voice of industry practitioners or policy makers.

3.2.4 Organizational cooperation

We analyze the collaboration patterns among organizations, and those of the top 40 most productive organizations are shown in Fig. 7. The minimum strength is set at 1. We mark each node with an abbreviation for the organization. (The full names and countries of these organizations are given in "Appendix 1".) As shown in Fig. 7, in the cooperative network, China has the most organizations (15), followed by Australia, the USA, and Japan (5, 4,

and 4 universities, respectively). The research organizations are mainly divided into six clusters, identified by six colors. Between each cluster, the tendency to cooperate is weak, often only one or two times. Within each cluster, collaboration is also weak even though the organizations may all come from the same country. Only three sets of organizations have cooperated more than 5 times: Lanzhou University (LZU) and the Chinese Academy of Sciences (CAS); the University of Maryland (UMD) and the Swiss Federal Institute of Technology (SFIT); and Kyushu University (KU) and the National Institute for Environmental Studies (NIES). In addition, the three organizations with the most partners are Tsinghua University (U.Tsinghua); the Chinese Academy of Sciences (CAS); and the National Environmental Research Institute (NIES). The three organizations with the most number of international collaborations are the International Institute for Applied Systems Analysis (IIASA); the University of California at Berkeley (UCBerkeley); and the University of Tsinghua (U.Tsinghua).

3.3 Influential authors and author collaborations

3.3.1 Identification of influential authors

Table 3 lists the top 16 authors in the area of household energy consumption based on total citations and h-index. These two indicators ensure that the researchers not only have conducted long-term research on household energy consumption but also that they have obtained high-quality results. We define influential authors as those whose citations are greater than 100 and whose h-index is greater than 5.

As shown in Table 3, the number of published papers for the most influential authors ranges from 5 to 11, while the total number of citations varies widely, from around 100 to more than 2600. This difference stems mainly from the highly cited papers. The author

Table 3 Most influential authors in the area of household energy consumption

Rank	Author	h-index	Total citations	Total articles	Single-author	Multi-author
1	Linda Steg	8	2633	8	1	7
2	Tao Shu	6	200	7	0	7
3	Shonali Pachauri	6	676	9	1	8
4	Haji Hassan Masjuki	6	149	6	0	6
5	Zhang Junyi	5	108	7	0	7
6	Yu Biying	5	106	8	0	8
7	Wang Xiaohua	5	138	6	0	6
8	Steven Sorrell	5	900	6	0	6
9	Shen Guofeng	5	161	6	0	6
10	Rahman Saidur	5	142	5	0	5
11	TM Indra Mahlia	5	106	5	0	5
12	Seppo Junnila	5	106	5	0	5
13	Mikko Jalas	5	210	5	2	3
14	Jukka Heinonen	5	109	6	0	6
15	Massimo Filippini	5	306	11	0	11
16	Anna Alberini	5	180	7	1	6

with the highest number of highly cited papers is Linda Steg. We also found that this author has co-authored four papers with Wokje Abrahamse (Abrahamse and Steg 2009; Abrahamse et al. 2005, 2007; Steg et al. 2005), and all of these are highly cited papers in the field of energy use behavior. In addition, we found that all influential authors have had partners and that co-authored papers seem to be a mainstream trend. For example, Zhang Junyi and Yu Biying cooperated on a large number of papers, and Tao Shu and Shen Guofeng co-authored all their papers.

Figure 8 plots a co-citation network of 2705 authors based on the association strength similarity measure (van Eck and Waltman 2010). Typically, the co-citation map has two components: a set of nodes representing the authors and a set of edges representing the co-occurrence of these nodes in the references. In our study, since our goal is to identify who is the most influential author in the co-citation network, we only display nodes and do not display edges.

In Fig. 8, the size of each node is proportional to the total number of co-citations for the relevant authors. Interestingly, Linda Steg is cited more than 2600 times—much more frequently than Tao Shu—but her co-citation strength is relatively low. A likely explanation for this is that Steg focuses mainly on energy use behavior, which is a relatively new area. Thus, there may not be many scholars who can work and be cited together with Steg. Meanwhile Tao Shu is active in a wider variety of research topics and is more likely to be cited with others. Meanwhile the proximity of Filippini, Mitchell, and Pachauri, for instance, indicates that their research areas have a high degree of overlap. In general, a number of sub-field co-citation networks has emerged in household energy consumption,
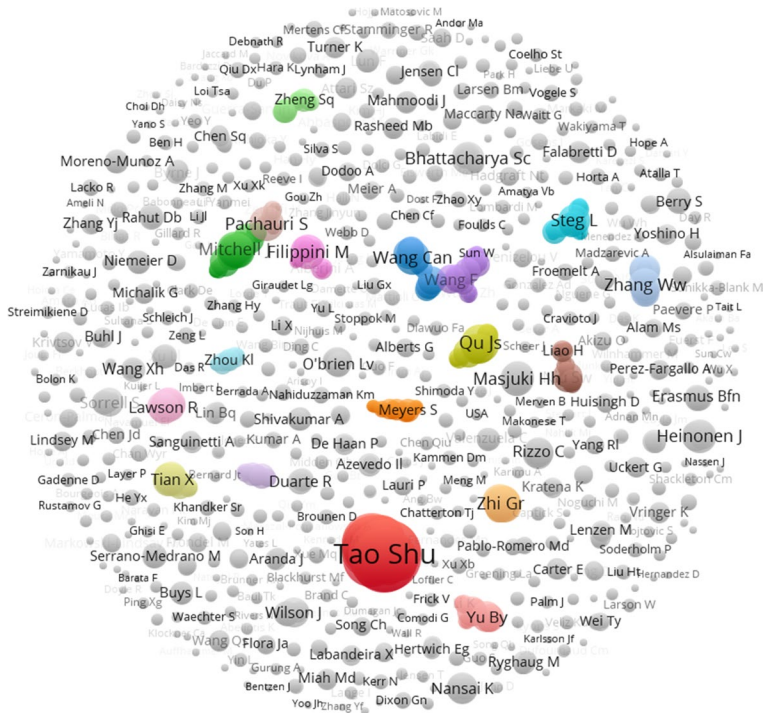

Fig. 8 Identification of the most influential authors by co-citation network

and in each of the smaller domains there are different core scholars who are the most frequently cited in the subnetworks.

3.3.2 Author cooperation

The collaboration of the top 50 authors is shown in Fig. 9. The size of the node represents the number of partners, so the larger the node, the more the collaborators. The width of the line between each node indicates the strength of cooperation, so the thicker the line, the stronger the cooperation. It can be noticed that there is a tendency for authors to cooperate in the field, generating several major clusters of authors, usually represented by two or more core authors. The two salient clusters in the figure are for two teams of Chinese scholars: a green group and a red one. In the green group, Tao Shu, Chen Yc, and Shen Gf are the key partners, whereas in the red group, Chen Han, Wang Xl, Liu Jf, Huang Ye, and Li Wei occupy similar positions. These results underscore our previous finding that China exhibits a high level of teamwork in household energy consumption research.

3.4 Evolutionary trends in topics

3.4.1 Identification of topics from influential papers

The method most commonly used to measure the significance of a paper is counting the number of citations (Ding and Cronin 2011). Some scholars believe, however, that total citations may not reflect the true impact of a paper. This is because older papers have had more time to garner citations (Fahimnia et al. 2015; Garfield 1979; Page et al. 1999), while more recently published papers clearly lack this advantage. To minimize the influence of the publication year and to better reflect more recent developments, we have listed the top twenty most significant papers based on numbers of citations from 2016 to 2018 (Table 4). Total citations and citations per year have also been calculated.
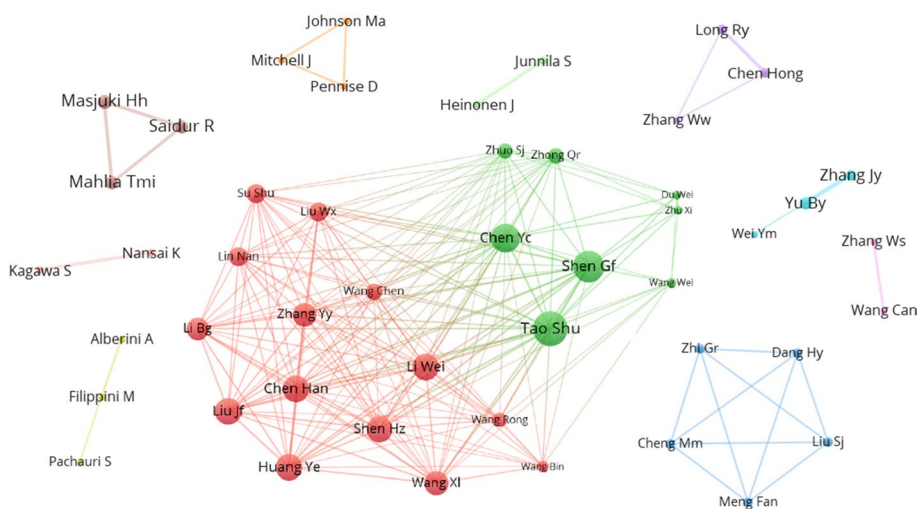

Fig. 9 Top 50 most productive author collaborations' network

Table 4 Top 20 most highly cited papers, 2016–2018. Source of category https://energy.stanford.edu/research/research–areas

Areas	Topics	Document cited	2016–2018 citations	Total citations	Total citation per year
Energy use/efficiency	Behavior intervention and energy-saving	Abrahamse et al. (2005)	393	832	64.00
		Fischer (2008)	199	453	45.30
		Abrahamse et al. (2007)	135	261	23.73
		Abrahamse and Steg (2009)	119	212	23.56
		Steg (2008)	116	206	20.60
		Attari et al. (2010)	88	201	25.13
	Rebound effect	Osbaldiston and Schott (2011)	103	161	26.83
		Poortinga et al. (2003b)	71	173	11.53
	Transportation	Sorrell et al. (2009)	155	319	35.44
Environmental Impact	Climate	Dietz et al. (2009)	208	428	47.55
		Isaac and Van Vuuren (2009)	173	282	31.33
		Sorrell and Dimitropoulos (2008)	141	253	25.30
		Weber and Matthews (2008)	75	209	20.90
		Brownstone and Golob (2009)	75	176	19.56
		Druckman and Jackson (2009)	73	204	22.67
	Resource and biodiversity	Liu et al. (2003)	54	308	20.53
Policy and Economics	Public opinion	Steg et al. (2005)	160	316	24.31
Others		Druckman and Jackson (2008)	84	177	19.67
		Holden and Norland (2005)	78	163	12.54
		Pachauri and Jiang (2008)	72	159	15.90

According to the energy research categories identified by Stanford University's Pre-court Institute, there are four clusters of research areas, and each area has several subtopics (Table 4). In Table 4, the block of energy use/efficiency clearly dominates the list. To be specific, four papers discuss behavior interventions and energy saving, two papers explore rebound effects, and one paper deals with transportation; another big block is concerned with environmental impact, with five papers on climate and one paper on resources and biodiversity. From the perspective of research clusters, the study on energy use/efficiency or environmental impact is still the main current research direction; from the perspective of subtopics, behavioral interventions, energy saving and climate change are the research hot spot. In terms of specific research content, psychological factors have been receiving increasing attention (Abrahamse and Steg 2009; Abrahamse et al. 2007; Osbaldiston and Schott 2011; Poortinga et al. 2003a). In addition, an interesting phenomenon is that none of the highly cited papers are from Chinese authors, even though we know that China has contributed the second highest number of papers.

3.4.2 Identification of topics from keywords

Authors' keywords represent the main themes of articles. Thus, analyzing keywords from a group of related studies can capture current research trends and predict future ones (Min et al. 2010). In this paper, a total of 2668 keywords were extracted from 1134 papers. We exclude some meaningless keywords, such as "energy consumption" and "household energy consumption", and then we list the top ten most frequently used keywords in the three time periods in Table 5.

As can be seen from Table 5, the term "energy efficiency" is not only the most frequently used word but also increases in use over time. The term "energy poverty", which was rarely used in the period 1983–2005, was among the top 10 keywords in 2006–2015 and has become the second most popular in recent years. The frequency of terms such as "China", "climate change" and "rebound effect" is stable, while the frequency of terms such as "energy conservation" and "energy demand" has declined slightly. In summary, from the timeline, energy efficiency, and energy poverty are the focus of future research and are drawing increasing attention. In terms of energy types, electricity is becoming the research focus. In terms of research regions, China is replacing India in terms of research

Table 5 Top 10 most frequently used keywords in each period

1983–2005	Freq	2006–2015	Freq	2016–2018	Freq
Energy efficiency	3	Energy efficiency	47	Energy efficiency	54
Energy demand	3	Rebound effect	28	Energy poverty	29
Electricity demand	3	China	20	Electricity consumption	22
Rebound effect	2	Energy conservation	16	Rebound effect	21
Energy conservation	2	Energy poverty	13	China	19
electricity Consumption	2	Climate change	13	Residential sector	14
Residential sector	2	Energy demand	12	Climate change	13
Energy policy	2	Sustainable consumption	12	Carbon footprint	11
Energy use	2	CO_2 emissions	11	Energy conservation	7
India	2	Consumer behavior	10	Energy demand	7

focus. Although energy conservation and energy demand are still concerns, the amount of attention is declining.

We apply co-word analysis to explore the relationships among the top twenty most frequently used keywords. The result is shown in Fig. 10. The largest cluster is shown in red, with the core keyword being "China". Research on household energy use in China mainly focuses on energy poverty, renewable energy, and energy policy. Fuelwood is also included in the red cluster, because fuelwood is highly associated with energy poverty. The yellow cluster is related to climate change. It shows that in the context of climate change, and the hot research topics are energy conservation and electricity consumption. In the green cluster, the line between "energy efficiency" and "rebound effect" is the thickest, as rebound effects are important to consider when studying energy efficiency. Studying energy consumption behavior in the household sector is likely to involve the study of energy efficiency and rebound effect. The blue cluster shows that input–output analysis is one of the most used methods for studying carbon footprints.

3.4.3 Identification of topics from leading journals

In order to analyze recent topics in prominent journals, we chose *Nature* journals as our target. *Nature* is the most well-known scientific journal in the world. Its content can tell us something about research trends and point to directions for future research. We selected studies from *Nature* and journals under the *Nature* brand in the period 2014–2018. After reading individual abstracts, we ultimately selected 37 papers related to household energy consumption (See "Appendix 2"). We classify these papers into 9 categories based on the authors' focus. The result is shown in Fig. 11.

We can find that articles on behavior/intervention are most likely to be published in *Nature*, followed by those related to energy poverty/justice/equality. Research on electricity that mainly focuses on users' willingness to pay and on electricity policy is also favored by *Nature* journals. In addition, the roles of institutionally related factors in household energy use (such as social norms, culture, etc.) are relatively hot topics in *Nature*. Although the
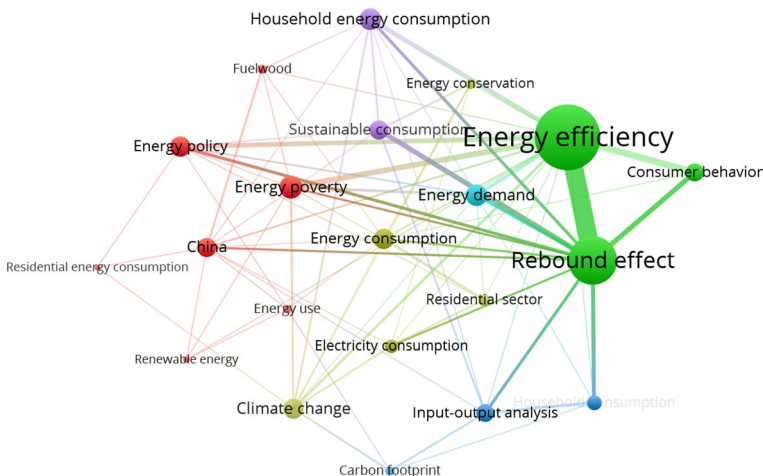

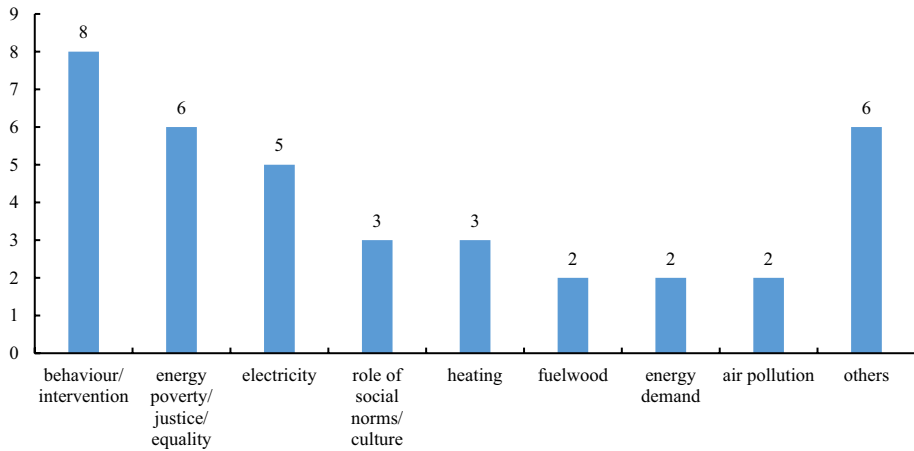**Fig. 10** Relationships among the top 20 most frequently used keywords

Fig. 11 The number of articles in each category (articles are from Nature)

number of published papers is small, the research topics that are still worth paying attention to include heating, fuelwood, and air pollution.

4 Conclusion, recommendations, and future research

This study conducts a bibliometric analysis of 1134 articles on household energy consumption. Several literature reviews have already been published on the subtopic of household energy consumption. However, a comprehensive bibliometric and network analysis to pinpoint influential authors, author teams, and emerging research directions has not been undertaken until now. The study's preliminary exploration of journal publications and research teams characterizes the current status of research across the entire field. Moreover, through additional analyses of papers and keywords, our study traces the evolution of research topics and predicts directions for future research. Our findings lead to the following conclusions.

Research on household energy consumption is in a stage of rapid development. The number of publications in recent three years accounted for 85% of the total published papers in the past decade. Nearly half of the studies in this area have been published in *Energy Policy*, *Energy*, and *Energy Economics*. The research mainly covers the fields of environmental sciences and ecology, energy and fuels, and business and economics.

The geographical distribution of the works does show a global trend, but it is mainly concentrated in Europe, the USA, and China. This result is not surprising since energy and the environment has become a topic of global concern and authors in many countries have joined this sub-discipline, expanding the work in a variety of areas. Consistent with common sense, most of the research institutions are located in China, Europe, the USA and other developed countries. Among these countries, China and the USA have the strongest partnership. The USA also frequently cooperates with European countries, while China cooperates more frequently with Australia and Japan.

For those seeking to do research in this area, we have identified the most influential authors and some of the latest works that can be utilized to identify potential research

topics. Awareness of who the influential scholars are in this area is important because they may lay the foundation for the future research, and careful monitoring of their work and that of their co-authors could provide some guidance for further research. In addition, we found that the most influential scholars tended to be those with the most collaborators. This finding highlights the importance of teamwork in this field.

Through our research, some insights and future research directions for household energy consumption have been identified. These major outstanding research concerns can be summarized as follows:

First, the topics of energy efficiency and environmental impact will remain the main research directions in the future. Not only did topics related to energy efficiency and environmental impact account for more than half of the highly cited papers, but also keywords related to them were also the most frequently used in recent years. Given the urgency of solving environmental resource problems, these two topics should occupy the most important position in future research.

Second, the research on energy poverty and electricity consumption will continue to develop. We found that the number of works related to energy poverty and electricity consumption is growing rapidly, and these two topics are also favored by *Nature* journals. The lack of commercially available energy, especially electricity, often has a number of adverse effects on households and societies, including increased poverty, lack of development opportunities, and migration to large cities (Kaygusuz 2011). Tackling this problem during transition to a zero-carbon and sustainable economy is one of the most important challenges for policy makers. Therefore, more and more scholars have shifted their attention to this field (Adusah-Poku and Takeuchi 2019; Middlemiss et al. 2019; Sánchez-Guevara Sánchez et al. 2020; Thomson et al. 2019).

Third, the roles of social, cultural, and psychological factors are increasingly attracting scholars' attention. In terms of specific research content, we have noticed that the papers related to these factors have high citations and tend to be published in leading journals. To develop effective policy intervention to promote energy transition and energy savings, it is crucial to understand household energy use behavior (Jürisoo et al. 2019). Given the rise and vigorous development of experimental methods, a growing body of research has begun to use experimental intervention to study the impact of irrational factors on residents' energy use behavior (Jachimowicz et al. 2018; Jürisoo et al. 2019; Lynham et al. 2016; Matsui et al. 2014).

Based on our research, we can also summarize some deficiencies or gaps in the research on household energy consumption overall.

First, the lack of non-Western, non-China research is a problem. Energy transition and climate change are global trends; it is necessary to broaden the number and location of countries where household energy consumption is being investigated. Without the voice of less developed countries, it is difficult to assess whether we are meeting the United Nations Sustainable Development Goals on energy and the environment (SDG7, SDG13).

Second, not only is there a relative lack of diversity in the authorship and location of the work, but also the lack of cross-country cooperation limits multiculturally and globally relevant viewpoints. We hope future research will encourage more cross-border collaboration, contributing to and influencing this area in innovative and interesting directions.

Third, the field is dominated by academic scholars and lacks the perspective of policymakers and industry practitioners. Integrating real industry data and policy-makers' perspectives into academic research are likely to be beneficial for both practical and theoretical development.

This study has a few important limitations that should be mentioned. For example, extending keyword searches to include building methodologies, energy selection, transportation, and so on could allow for a more detailed review of the field. However, adding keywords (and, thus, expanding the dataset) could compromise the effectiveness of the bibliometric tool and lead to deviations in the statistical results and network visualizations. Moreover, additional content analysis could have been conducted on specific emerging topics, allowing us to further refine our research methods and analytical frameworks.

Appendix 1

Organization	Abb	Country	Organization	Abb	Country
Chinese Academy of Sciences	CAS	China	Australian National University	ANU	Australia
Beijing Institute of Technology	BIT	China	University of Melbourne	UOM	Australia
Beijing Normal University	BNU	China	Griffith University	GU	Australia
City University of Hong Kong	CityU	China	Monash University	U.Monash	Australia
Chongqing University	CQU	China	University of Western Australia	UWA	Australia
Lanzhou University	LZU	China	National Institute for Environmental Studies	NIES	Japan
Shandong University	SDU	China	Hiroshima University	HU	Japan
Zhejiang University	ZJU	China	Kyushu University	KU	Japan
University of Science and Technology of China	USTC	China	University of Tokyo	U.Tokyo	Japan
china university of mining and technology	CUMT	China	University of Cambridge	Cantab	UK
North China Electric Power University	NCEPU	China	University of Leeds	U.Leeds	UK
Shanghai Jiaotong University	SJTU	China	University of British Columbia	UBC	UK
Peking University	U.Peking	China	Leiden University	LEI	Netherlands
Tsinghua University	U.Tsinghua	China	Maastricht University	UM	Netherlands
Xiamen University	XMU	China	Swiss Federal Institute of Technology	SFIT	Switzerland
Uiversity of California,Berkey	LBNL	USA	Università della Svizzera italiana	SUI	Switzerland
Harvard University	U.harvard	USA	University of Bonn	U.Bonn	Germany
University of Illinois	UIUC	USA	University of Oslo	U.Oslo	Norway
University of Maryland	UMD	USA	University of Lisbon	U.Lisbon	Portugal
International Institute for Applied Systems Analysis	IIASA	–	National University of Singapore	NUS	Singapore

Appendix 2

Literature	Author	Year	Journal	Topics
Air pollution: clean up our skies	J Schmale, etc	2014	Nature	Air pollution
Extreme air pollution from residential solid fuel burning	C Lin, etc	2018	Nature	
Behaviour: Seeing heat saves energy	L Steg	2016	Nature Energy	Behavior/Intervention
Household behaviour crowds out support for climate change policy when sufficient progress is perceived	SH Werfel	2017	Nature Climate Change	
Energy use behaviour: A window of opportunity	D Roy	2017	Nature Energy	
Solar PV adoption: Incentives and behaviour	J Richler	2017	Nature	
Energy Saving behaviour: Negative spillover to policy	KT Raimi	2017	Nature Climate Change	
Efficacy of interventions targeting household air pollution from residential wood stoves	TJ Ward, etc	2017	Nature	
Feel the nudge	N Dean	2018	Nature Energy	
Renewable energy policy: Enumerating costs reduces support	D Evensen	2017	Nature Energy	

Literature	Author	Year	Journal	Topics
Household electricity access a trivial contributor to CO_2 emissions growth in India	S Pachauri	2014	Nature Climate Change	Electricity
Factors affecting household satisfaction with electricity supply in rural India	M Aklin, etc	2016	Nature Energy	
Electricity reliability: Willingness to pay in Nigeria	A Rubino	2017	Nature Energy	
Exploring the impact of network tariffs on household electricity expenditures using load profiles and socio-economic characteristics	V Azarova, etc	2018	Nature Energy	
Inaccurate consumer perceptions of monetary savings in a demand-side response programme predict programme acceptance	LV White, ND Sintov	2018	Nature Energy	
Energy decisions reframed as justice and ethical concerns	BK Sovacool, etc	2016	Nature Energy	Energy poverty/justice/equality
An index of inequality in China	D Guan	2017	Nature Energy	
Energy poverty: Electrification and well-being	KR Sharma, etc	2016	Nature Energy	
Measurement of inequality using household energy consumption data in rural China	S Wu, etc	2017	Nature Energy	
Young, transient and cold	J Richler	2017	Nature Energy	
Rethink fuel poverty as a complex problem	KJ Baker, etc	2018	Nature Energy	
A penny for your preferences	F Khan	2017	Nature Energy	Fuelwood
The carbon footprint of traditional woodfuels	R Bailis, etc	2015	Nature Climate Change	

Literature	Author	Year	Journal	Topics
Impacts of global warming on residential heating and cooling degree-days in the United States	Y Petri, etc	2015	Scientific reports	Heating
Quantifying the economic impact of changes in energy demand for space heating and cooling systems under varying climatic scenarios	T Hasegawa, etc	2016	Palgrave Communications	
Residential heating: What it takes to go green	E De Ranieri	2016	Nature Energy	
The significance of relationships	K Burningham	2017	Nature Energy	The role of social norms/ culture
Behavioral Science: Culture and climate action	L Zaval	2016	Nature Climate Change	
The critical role of second-order normative beliefs in predicting energy conservation	JM Jachimowicz	2018	Nature Human Behavior	
Public perceptions of demand-side management and a smarter energy future	A Spence	2015	Nature Climate Change	Energy demand
Residential energy demand: Consumption unzipped	N Dean	2016	Nature Energy	

Literature	Author	Year	Journal	Topics
Making savings count	F Khan	2018	Nature Energy	Others
Quantifying the rural residential energy transition in China from 1992 to 2012 through a representative national survey	S Tao, etc	2018	Nature Energy	
Healthy privilege	F Khan	2018	Nature Energy	
Unequal household carbon footprints in China	D Wiedenhofer, etc	2017	Nature Climate Change	
Energy efficiency to reduce residential electricity and natural gas use under climate change	JL Reyna, etc	2017	Nature Communications	
Improving poverty and inequality modeling in climate research	ND Rao, etc	2017	Nature Climate Change	

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