Energy Behavior and Smart Home Systems: A Bibliometric Analysis

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This study explores how households interact with smart systems for energy usage, providing insights into the field's trends, themes and evolution through a bibliometric analysis of 547 relevant literature from 2015 to 2025. Our findings discover: (1) Research activity has grown over the past decade, with leading journals recognizing several productive authors. Increased collaboration and interdisciplinary work are expected to expand; (2) Key research hotspots, identified through keyword co-occurrence, with two (exploration and development) stages, highlighting the interplay between technological, economic, environmental, and behavioral factors within the field; (3) Future research should place greater emphasis on understanding how emerging technologies interact with human, with a deeper understanding of users. Beyond the individual perspective, social dimensions also demand investigation. Finally, research should also aim to support policy development. To conclude, this study contributes to a broader perspective of this topic and highlights directions for future research development.

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1 Introduction

The global energy transition is accelerating as societies shift from fossil fuels to more sustainable energy sources, and it is aided by rapid digital and technological advancements (K. Khan & Su, 2023; Dekeyrel & Fessler, 2024). Among these technology innovations, smart home systems are practical tools that help optimize energy efficiency and reduce overall consumption for energy end users (Wilson et al., 2015). However, despite their potential, the social dimensions of smart energy systems have been largely neglected in mainstream energy transition agendas. Robison et al. (2023) argue that social sciences and humanities (SSH) should take a leading role in addressing this gap by examining how individuals interact with and benefit from technologies to fasten energy transition.

Understanding individual behavior is crucial for societal transitions such as the energy transition, where individuals serve as drivers, beneficiaries, and adaptors of change (Whitmarsh, 2011). We believe that digital technologies, particularly smart home systems, play an important role in shaping behavioral shifts by not only enhancing energy efficiency but also fostering pro-environmental behavior (PEB) (Froehlich, 2009; Nilsson et al., 2018; Stieglitz et al., 2023). Smart systems enable real-time behavior tracking, allowing for immediate adjustments, such as running a washer when energy prices are low either by households themselves or by automated system controls (Costanza et al., 2014; M. Khan et al., 2016). Smart systems also can enable the implementation of Just-in-Time Adaptive Interventions (JITAI) , such as sending real-time notifications about low energy availability or sharing social norms on neighborhood energy consumption to encourage adaptive user behavior (Nilsson et al., 2018). Finally, smart systems facilitate connection with others, fostering awareness that collective efforts are being made toward the energy transition – you are not alone (Froehlich, 2009). An often-heard problem in sustainability is the persistent belief that others may not feel as dearly about the environment as you yourself, which may diminish the likelihood for efficient or sustainable energy consumption (Gadenne et al., 2011). By making PEB visible, smart systems can reinforce social norms and encourage individuals to adopt energy-efficient practices. Additionally, users who share their energy usage online may feel social pressure to adopt energy-efficient behaviors (Froehlich, 2009).

Smart systems have also as benefit that they can be designed with more general (behavioral) rules, with the opportunity for its user to personalize the environment to meet his or her own preferences or needs. The latter is particularly important, as some users may greatly prefer high granulation of available data and options, whereas others want to keep it as simple as just seeing a price (Risteska Stojkoska & Trivodaliev, 2017). Moreover, visual design also influences household energy behavior to varying degrees, depending on individual preferences (Froehlich, 2009). Further, a great advantage is the ability to track behavior for a longer period. This does not only allow for measurement of lasting behavior change but also allows for follow-up interventions when effects seem to dissipate. Smart systems can incorporate framing and nudging strategies – such as demonstrating the specific impact of energy consumption reduction on CO_2 emissions or gamifying energy-saving goals with challenges and rewards – to educate end users, increase awareness, encourage desirable behaviors and serve as long-term interventions for behavior change (Kroll et al., 2019; Stieglitz et al., 2023). With the question in mind, *"What is the role of smart home systems in shaping household energy behavior?"* we conduct a literature analysis to explore the interaction between individuals and technology within the context of energy conservation at home. The following chapters outline our methodology, present the results, and propose directions for future research.

2 Data Acquisition and Bibliometric methods

We systematically retrieved relevant publications from the Web of Science (WOS) database, which is highly aligned with our research field through its SCI/SSCI indexing system, and conducted comprehensive bibliometric analyses, including descriptive statistics, word frequency analysis with cloud visualization, and keyword co-occurrence network mapping, to investigate the dynamic evolution of research hotspots in this field.

2. 1 Data Acquisition and Screening

To find all relevant articles, we defined the following search strategy. The keywords consist of a wide range of synonyms to ensure the inclusion of all records that might be relevant to the topic. Below is the complete search term:

(digit OR smart* OR ICT* OR tech* OR "Internet of Things") AND*

(energ OR resource* OR gas OR water OR electric* OR solar OR wind OR heat) AND*

(efficien OR conserv* OR consum* OR use OR usage OR using OR reduc* OR sav* OR curtail* or behavio?r* OR prod* OR invest*) AND*

(consumer OR house OR commun* OR collect* OR group OR citiz* OR pers* OR individual)*

We filtered only peer-reviewed articles to maintain an academic perspective, and they are written in English. The publication years were set between 2015 and 2025 to provide an overview of the last decade. Additionally, we focused on studies from the following fields, which we considered the most relevant: "environmental sciences ecology" or "water resources" or "business economics" or "psychology" or "urban studies" or "sociology" or "behavioral sciences" or "communication" or "public administration" or "social sciences other topics" or "social issues" or "demography". In total, 11,712 articles were retrieved from the Web of Science as of February 10, 2025.

Systematically screening 11,712 articles to identify publications relevant to the main subject of this review is a time-consuming and challenging task. Large language models, an emerging technology capable of automating language-related tasks, have been applied in literature reviews in some fields to screen titles and abstracts (Dennstädt et al., 2024). This paper adopted this approach, developing a prompt for screening titles and abstracts in line with the theme of this literature review. The process utilized Python to call the OpenAI ChatGPT-4o model via an API, helping to reduce labor costs. To refine the screening process, we conducted a self-scanning of 700 articles, iteratively improving the prompt to enhance accuracy and evaluation. The prompt incorporated inclusion criteria such as *"studies that explore smart devices, systems, meters, automation, or feedback mechanisms in home settings influencing energy-related human behavior"*. It also specified exclusion criteria such as *"if a study is mainly technical (>90% focused on engineering, algorithms, sensors, or optimization), and its discussion of human behavior is minimal, secondary, or incidental, it should be excluded"*. Additionally, we defined *human behavior refers to household energy consumption or production actions, behavioral interventions, lifestyle adjustments, or PEB influencing home energy use. It does not include technology adoption studies, policy evaluations, or studies focused solely on technical efficiency*. We compared the results of GPT-based screening with manual screening results and verified the feasibility of this approach. Using this approach, 547 papers related to energy behavior and smart home systems were selected for further analysis.

2. 2 Bibliometric Methods

Bibliometrics is a method for evaluating literature data, serving as a quantitative scientific assessment approach. It systematically collects, organizes, and analyzes academic literature data to reveal the development trajectory, research hotspots, and future trends of a discipline.

In this study, we conducted both external feature analysis and content analysis of the literature. External feature analysis forms the descriptive basics of bibliometric research, encompassing statistical analysis of data such as authors, institutions, countries, publication years, and journals. Content analysis, the core of bibliometric research, includes methods such as keyword co-occurrence analysis, and topic identification and evolution analysis. These approaches uncover research hotspots and provide critical insights into the evolving focus areas of energy behavior and smart home systems. We selected several analyses for this paper, and the details are outlined below:

(1) Descriptive Statistical Analysis:

We first conducted a systematic statistical analysis of the years, journals pf the publications to gain insights into their trend and their academic impact and relevance to our research topic. This involved a quantitative assessment of number of publications per year, journal, measuring the productivity. Additionally, we examine the distribution across different journals and check the top journals quality, considering factors such as impact factor and journal quartile rankings (Q1–Q4) to evaluate their academic influence. This approach allowed us to identify the most influential journals in the field and understand their role in shaping the discourse on the topic.

(2) Word Frequency and Word Cloud

We used word frequency analysis to examine titles and abstracts, identifying the most frequently occurring terms in the research articles. This method helps highlight key themes that researchers focus on within the topic. By analyzing word frequency, we can determine the most researched concepts, emerging trends, and commonly discussed keywords, providing insights into the academic landscape.

To visually represent these findings, we generated word clouds, a widely used data visualization tool that displays words in different sizes based on their frequency of occurrence. The larger a word appears in the cloud, the more frequently it is mentioned in the dataset. This approach allows for an intuitive and immediate understanding of dominant research topics and their relative importance.

(3) Keyword Co-occurrence Analysis:

Using Python, we preprocessed the literature text data, including tokenization, stop-word removal, and lemmatization. The TF-IDF (Term Frequency-Inverse Document Frequency) algorithm was then applied to quantify keyword importance and filter core keywords for each article. By constructing a keyword co-occurrence matrix, we calculated the co-occurrence frequency and association strength between keywords, revealing the intrinsic connections among research themes. Moreover, we extracted latent topics from the titles and abstracts of publications across two distinct stages: exploration stage (2015-2020) and development stage (2021-2025). The topic identification for each stage highlights the evolution of the research agenda over the past decade.

Further, Gephi network analysis tools were used to transform the co-occurrence matrix into a keyword co-occurrence network graph. Through node size, edge weight, and community clustering visualization, we intuitively displayed the relationships and clustering characteristics of keywords.

3 Results

The research findings provide a detailed presentation of multiple analytical dimensions, including the timeline of publications, author productivity and collaboration patterns, journal statistics, word frequency and word cloud visualizations, as well as co-word and co-cited network analyses. Particularly noteworthy is the temporal segmentation into two distinct research phases: the Exploration Stage (2015-2020) and the Development Stage (2021-2025), through which the study systematically examines the shifting trajectories of research hotspots within the target domain. This phased analytical approach enables a nuanced understanding of the field's evolving research priorities and intellectual structure over time.

3.1 Timeline of Publications

We began by analyzing the number of publications per year. The following **Figure 1** illustrates the publication trend over the past decade.

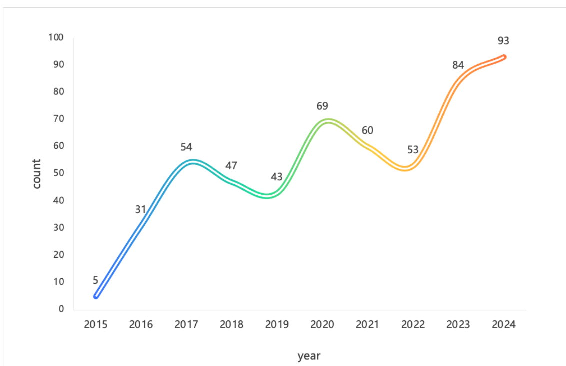

Figure 1: Publication Trend

The year 2025 (with a total of 8 publications) is excluded, as it is not a complete year and does not accurately reflect the total output. Overall, the research shows a steadily growing trend in interest and activity, increasing from just 5 publications in 2015 to 93 in 2024. The growth pattern also reflects some fluctuations. A slight decline in publication numbers in 2018 and 2019 may be linked to rising concerns over data privacy following the growing popularity of smart home systems, which could have temporarily slowed research momentum. Another dip in 2021 and 2022 may be attributed to the lingering impacts of the COVID-19 pandemic, which disrupted research activities and priorities across many fields.

3.2 Authors Productivity and Collaboration

We analyzed author statistics, focusing on the number of publications in the field and patterns of collaboration (**Figure 2**). The most productive author is Gram-Hansen, K, with eight publications, followed by Sovacool, B.K. with six publications, and Wang, B. and Skjolsvold, T.M. with five publications each. The co-authorship network diagram illustrates collaborative relationships among authors; however, the results indicate a scattered and loosely connected structure. This suggests that the field is currently at a stage where researchers are initiating their work independently. In the future, we expect to see increased collaboration, including more interdisciplinary partnerships and cross-institutional research efforts.

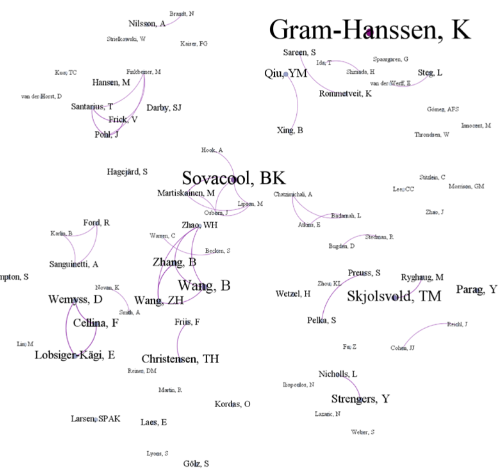

Figure 2: Co-authorship network

3.3 Journal Statistics

We conducted a descriptive analysis to identify the journals in which research on this topic has been published. The popularity of the top 10 journals is presented in the following **Table 1** and **Figure 3**. Energy Research & Social Science (88 publications), Sustainability (68 publications), and Energy Policy (62 publications) have the highest number of publications, and all three are Q1 journals. According to the latest available data as of 2025, the impact factors for the journals Energy Research & Social Science and Energy Policy are both notably high, at 6.9 and 9.3, respectively.

Table 1: Table of Journal Statistics

Source Title	Account	Percentage
Energy Research & Social Science	88	16.1%
Sustainability	68	12.4%
Energy Policy	62	11.3%
Journal Of Cleaner Production	37	6.8%
Energy Efficiency	31	5.7%
Energy Economics	15	2.7%
Environmental Research Letters	8	1.5%
Resources Conservation and Recycling	7	1.3%
Transportation Research Part D-Transport and Environment	7	1.3%
Environmental Innovation and Societal Transitions	6	1.1%

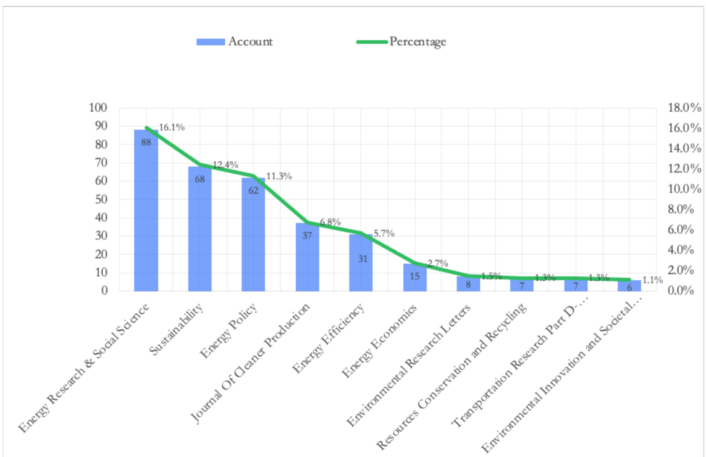

Figure 3: Journal Popularity

3.4 Word Frequency and Word Cloud

We analyzed word frequency in both titles and abstracts to identify the most researched terms. We generated word clouds for both, which appear similar. **Figure 4** is the word cloud for titles, which visually represents the most frequently occurring terms. As expected, "*energy*" is the most dominant term, reflecting the central focus of the research in this domain. Additionally, "*smart*" appears frequently, often in conjunction with "*meter*", *"system",* and *"consumption".* These keywords indicate that much of the research emphasizes smart energy systems, metering technologies, and consumption patterns. This distribution of terms confirms that our search strategy successfully captured relevant studies within the topic, as the retrieved articles focus on expected key areas. Furthermore, the absence of surprising or unrelated keywords suggests that the dataset is well-refined and accurately represents the research landscape in this field.

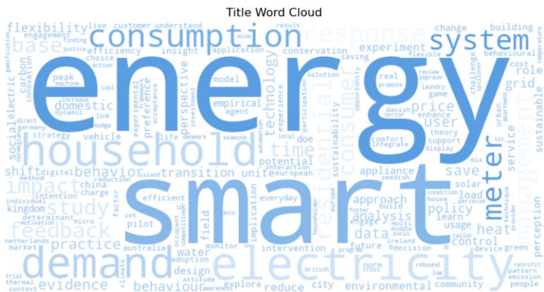

Figure 4: Title word frequency cloud

3.4 Co-Word and Co-Cited Analysis

From the 574 articles published between 2015 and 2025, we divided the research development into two stages: the exploration stage (2015–2020) and the development stage (2021–2025). The following figures and analyses present the co-word and co-citation patterns specific to each stage, highlighting key thematic clusters centered around the topic of energy. These clusters reflect interconnected research areas and reveal the dominant themes that have shaped the literature in each phase. In general, several distinct clusters emerge in the last decade clearly around Energy (illustrated from combining Figure 5 and 6):

Energy Sources: This cluster includes terms such as electricity, gas, water, and fuel, representing the types of energy sources discussed in the literature.

Home Technology: This cluster includes terms such as smart technology, meter, device, system, apps, and model etc., which are closely related to advancements in home energy management and digital innovations in energy efficiency.

Human-Centric: Another prominent group of terms focuses on people and their roles in energy consumption, including household, consumer, producer, and user. This indicates a strong research interest in how individuals and communities interact with energy systems.

Economic Factors: A separate cluster emphasizes monetary aspects, featuring terms like price, incentive, cost, bill, and tariff. This reflects the role of economic mechanisms in shaping energy consumption behaviors, such as pricing strategies and financial incentives.

Environmental Concerns: The importance of sustainability and climate impact is evident in terms like carbon and green, highlighting the connection between energy use and environmental policies.

Behavioral Aspects: Lastly, the behavioral dimension is captured through terms such as behavior (behaviour), usage, effectiveness, conservation, reduce, save, and practice. This cluster emphasizes research on energy-saving behaviors, decision-making processes, and the effectiveness of various interventions.

When comparing the two stages, several differences emerge, which are discussed in the following paragraphs.

Exploration stage (2015-2020): the thematic clusters from the first stage are illustrated in **Figure 5**. The clusters and keywords that distinguish this stage from stage two are:

1. Practice: practice, experience, lab, trial, theory, challenge.
2. Demand: peak, load, flexible, solution, control, efficiency.
3. Behavior: lifestyle, belief, characteristic, willingness.

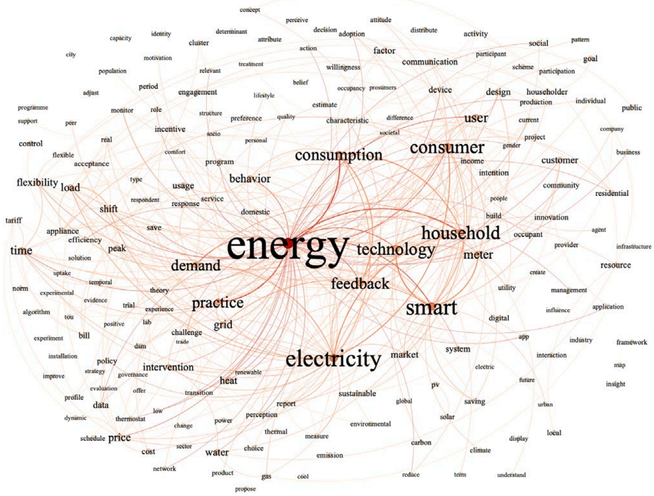

Figure 5: Co-Word and Co-Cited Analysis (2015-2020)

Development stage (2021-2025): the thematic clusters from the second stage are shown in **Figure 6**, and its noticeable that many new themes and keywords emerge:

1. Behavior: feature, share, perspective, motivation, attitude, social, agricultural, lifestyle, belief, characteristic, willingness.
2. Demand: service, resilience, justice, security, dynamic, explainable, responsible, efficiency, shift, peak, load, flexible.
3. Smart technology: digital, system, ai, device, innovation, hourly, future.
4. People: customer, residential, householder, government, customer, participant, enterprise, resident, supplier, stakeholder, citizen, company.
5. Environmental: sustainability, ghg, carbon, climate, green, transition, ecosystem, natural, co2, flood, cool.
6. Energy: electricity, power, renewable, resource, water, gas, heat, pv, solar.
7. Economic: economy, finance, cost, bill, tariff, price, rate, incentive, benefit, monetary.

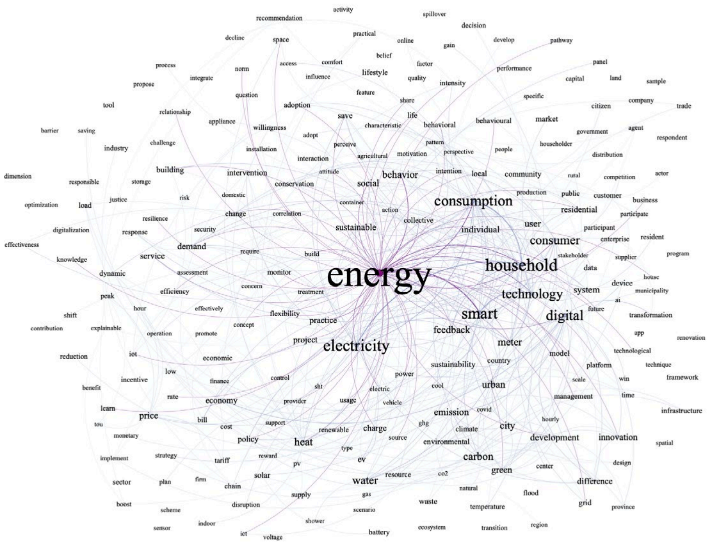

Figure 6: **Co-Word and Co-Cited Analysis (2021-2025)**

These clusters, along with their associated themes and keywords, offer a comprehensive overview of the key areas in energy research, highlighting the interplay between technological, economic, environmental, and behavioral factors within the field.

4 Conclusion and Future Research

This study presents an exploratory analysis of research on energy behavior and smart systems using bibliometric methods. First, it reveals descriptive insights, including productive years, authors, and journals. Second, it identifies key topics across two distinct stages—the exploratory stage (2015–2020) and the development stage (2021–2025)—highlighting the evolution of the field. The findings reveal a thematic focus on, and interplay among, smart technology, human behavior, economic factors, climate considerations, and energy conservation.

The findings highlight the multidisciplinary nature of energy research, where technological advancements and behavioral dynamics intersect to shape the evolving landscape of energy consumption and management. The number of the publication for the last decade shows the need of more research in this area with a particular emphasis on user-centric solutions, and behavior change approaches in the energy sector.

There are several avenues for future research. Based on thematic analysis, we examined multiple studies in detail and identified key directions for further exploration. Future studies could investigate the role of Artificial Intelligence (AI), blockchain, and Internet of Things (IoT) not only in optimizing energy efficiency and demand-side management but also in understanding how these technologies interact with human behavior to enhance practical applications (Froehlich, 2009; Nilsson et al., 2018; Stieglitz et al., 2023). Additionally, a deeper understanding of users is lacking. It is important to understand who the users of smart home technologies are and how they interact with and engage with these systems. Gram-Hanssen & Darby (2018) argued that the home represents a place of safety and control, raising questions about the boundaries of control and cooperation in smart home systems. Moreover, improving energy efficiency could lead to a rebound effect, where consumers use more energy than necessary (Kroll et al., 2019). Future research should examine this phenomenon through the lens of digital nudging in smart home applications to better motivate and foster deeply ingrained, intrinsic sustainable behavior that persists. However, it is also crucial to consider the trade-offs between comfort, value, and cost, as these vary among users. People could prioritize warmth and comfort at home over others (Sovacool et al., 2020). Moreover, the impact of social influence and peer pressure on encouraging PEB warrants further investigation, as these factors might be rather effective than focusing solely on individual motivations (Froehlich, 2009; Gadenne et al., 2011). Furthermore, research should also aim at providing policy recommendations, such as strategies to support vulnerable groups (Sovacool et al., 2017) and approaches to promote the adoption of smart home systems (Froehlich, 2009; M. Khan et al., 2016; Robison et al., 2023).

By addressing these research gaps, future studies can further enhance the understanding of energy users' behavior in relation with energy systems, improve policy effectiveness, and drive innovation in sustainable energy solutions.

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