

Utilization of Solar Energy in Improving Energy Efficiency of Urban Households: A Bibliometric Review

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ABSTRACT

The utilization of solar energy has emerged as a critical solution for improving energy efficiency and achieving sustainability in urban households. This study conducts a bibliometric review to explore the research landscape on solar energy adoption, focusing on technological advancements, socio-economic implications, environmental benefits, and policy frameworks. The analysis identifies key themes such as photovoltaic innovations, smart grid integration, and energy storage technologies, as well as the influence of government incentives and community-based projects on adoption rates. While solar energy offers significant environmental and economic benefits, challenges such as high installation costs, energy variability, and aesthetic concerns remain. The findings highlight the need for interdisciplinary approaches and emerging technologies, including artificial intelligence and decentralized systems, to overcome these barriers. This review provides valuable insights for researchers, policymakers, and stakeholders to advance solar energy utilization and contribute to sustainable urban development.

Keywords: *Solar Energy, Energy Efficiency, Urban Households, Photovoltaic Systems, Smart Grids, Bibliometric Analysis*

1. INTRODUCTION

The use of solar energy to enhance energy efficiency in urban households has become a pivotal aspect of sustainable urban development. As the world grapples with the escalating challenges of climate change, urbanization, and energy security, renewable energy sources like solar power have emerged as viable solutions to mitigate these issues. This bibliometric review explores the evolving dynamics of solar energy utilization within urban settings, emphasizing the improvement of energy efficiency in households.

Solar energy, characterized by its renewability and minimal environmental impact, offers a significant advantage in reducing the carbon footprint of urban areas. The adoption of solar technologies in households not only addresses the environmental concerns but also enhances energy autonomy and reduces dependence on traditional fossil fuels. As urban populations continue to rise, the strain on energy resources amplifies, making the shift towards sustainable energy systems imperative. Solar panels, solar water heating systems, and integrated photovoltaic systems are among the technologies that urban households have adopted to harness the sun's energy efficiently [1].

The relevance of solar energy in urban energy strategies is underscored by its role in achieving the Sustainable Development Goals (SDGs), particularly Goal 7, which aims to "ensure access to affordable, reliable, sustainable, and modern energy for all" [2]. The transition to solar energy not only supports this goal but also contributes to tackling urban environmental challenges, such as air pollution and excessive greenhouse gas emissions [3].

Bibliometric analyses provide a quantitative approach to reviewing literature, allowing researchers to identify the most impactful studies, predominant research themes, and emerging trends within a specific field. This methodological approach helps in mapping out the landscape of research on the utilization of solar energy in urban households and its contribution to energy efficiency. By examining scholarly articles, conference papers, and patent data, this review aims to synthesize the body of knowledge accrued over the years and to highlight the trajectory of research developments in this area.

One significant area of focus in the existing literature is the economic viability of solar energy solutions in urban settings. Studies have frequently analyzed the cost implications of installing and maintaining solar energy systems in households and evaluated the long-term savings compared to conventional energy sources. Financial incentives, subsidies, and the declining cost of photovoltaic technology have also been crucial in driving the adoption of solar energy in urban households [4].

Technological advancements have played a critical role in the increased uptake of solar energy. Innovations in photovoltaic cells, battery storage systems, and smart energy management systems have progressively improved the efficiency and integration of solar systems in urban architectures. Furthermore, the role of policy frameworks and government initiatives cannot be overstated, as they provide the necessary support structures to facilitate the transition towards solar energy [1]. The socio-economic benefits associated with solar energy are also a vital area of research. Studies have demonstrated how solar energy reduces electricity bills, increases property values, and provides a reliable energy supply that contributes to the socio-economic upliftment of urban residents [5]. Additionally, the environmental benefits of reducing carbon emissions and other pollutants are well-documented, reinforcing the environmental justification for solar energy adoption in urban areas [1].

Moreover, the challenges and barriers to solar energy adoption are also a critical component of the literature. Issues such as the aesthetic impacts of solar installations, the need for technical expertise, maintenance requirements, and the variability of solar energy supply are frequently discussed. These challenges necessitate innovative solutions and adaptations in urban planning and policy-making to create an enabling environment for solar technologies [6]. This bibliometric review aims to provide a comprehensive overview of the utilization of solar energy in improving the energy efficiency of urban households. By exploring the multi-dimensional impacts and examining the breadth of research conducted in this field, the review will offer valuable insights into the potential pathways and strategies for optimizing the use of solar energy in urban environments.

2. LITERATURE REVIEW

2.1 *Technological Advancements and Integration*

A significant portion of the literature on solar energy focuses on the technological innovations that enhance the efficiency and integration of solar systems in urban households. The development of high-efficiency photovoltaic (PV) cells has been a major research theme, with studies such as those by [7] detailing advancements in PV cell materials that offer higher energy conversion rates under diverse environmental conditions. Moreover, the integration of solar energy into existing urban infrastructure poses both challenges and opportunities, as outlined by [8], who discuss modular and

flexible solar panels that can be integrated into building facades and rooftops without disrupting urban aesthetics.

2.2 *Economic Viability and Incentives*

Economic factors play a crucial role in the adoption of solar energy technologies. The literature reveals a strong emphasis on the cost-benefit analysis of installing solar energy systems in urban households. For instance, the work of [9] provides a comprehensive analysis of the payback period of residential solar systems across different urban regions, considering various federal and state incentives. These studies often highlight the importance of government subsidies and tax incentives in enhancing the economic attractiveness of solar investments for urban residents.

2.3 *Social Implications and Consumer Behavior*

The social dimensions of solar energy adoption are critically examined in several studies. Research by [3] explores the consumer behavior aspects of solar energy, identifying key factors such as environmental awareness, energy security concerns, and societal norms that influence homeowners' decisions to adopt solar energy. Additionally, the potential for solar energy to alleviate energy poverty in urban areas is discussed in the research by [10], which argues that targeted solar energy programs can significantly improve the quality of life in underprivileged urban communities by providing reliable and affordable energy.

2.4 *Environmental Impact*

The environmental benefits of solar energy, particularly in reducing carbon emissions and other pollutants in urban areas, are widely documented in the literature. [11] provide a meta-analysis of studies measuring the carbon footprint reduction achieved through residential solar systems, affirming the positive environmental impact of widespread solar adoption. These studies often serve as a basis for advocating for solar energy policies at the municipal and national levels.

2.5 *Policy Frameworks and Government Initiatives*

Policy and regulatory frameworks are pivotal in shaping the landscape of solar energy adoption. [3] review various policy models from around the world that have successfully promoted solar energy in urban areas, including feed-in tariffs, net metering, and solar mandates for new constructions. The study underscores the necessity of a supportive policy environment to overcome initial market barriers and stimulate investment in solar technologies.

2.6 *Barriers to Adoption*

Despite the advantages, the adoption of solar energy in urban households faces several barriers. Technical challenges, such as the integration of solar systems with existing electrical grids, are discussed in the study by [12], which also highlights the need for skilled workforce training. Additionally, aesthetic concerns and space constraints in dense urban areas pose unique challenges, as analyzed by [13], who suggest architectural innovations to address these issues.

3. METHODS

This bibliometric review was conducted using Scopus, targeting publications that focus on the utilization of solar energy in urban households and its impact on energy efficiency. The search criteria included keywords such as "solar energy", "urban households", "energy efficiency", and "sustainable energy solutions", spanning publications from 2000 to 2024 to capture both foundational theories and recent advancements. The inclusion criteria were set to filter peer-reviewed articles, conference proceedings, and patent documents written in English. Data extraction focused on authors, publication year, methodologies, findings, and citations to identify the most influential works and emerging trends. The bibliometric analysis was performed using VOSviewer software for keyword co-occurrence analysis, facilitating the mapping of knowledge domains and the identification of thematic clusters within the literature.

4. RESULTS AND DISCUSSION

4.1 Keyword Co-Occurrence Network

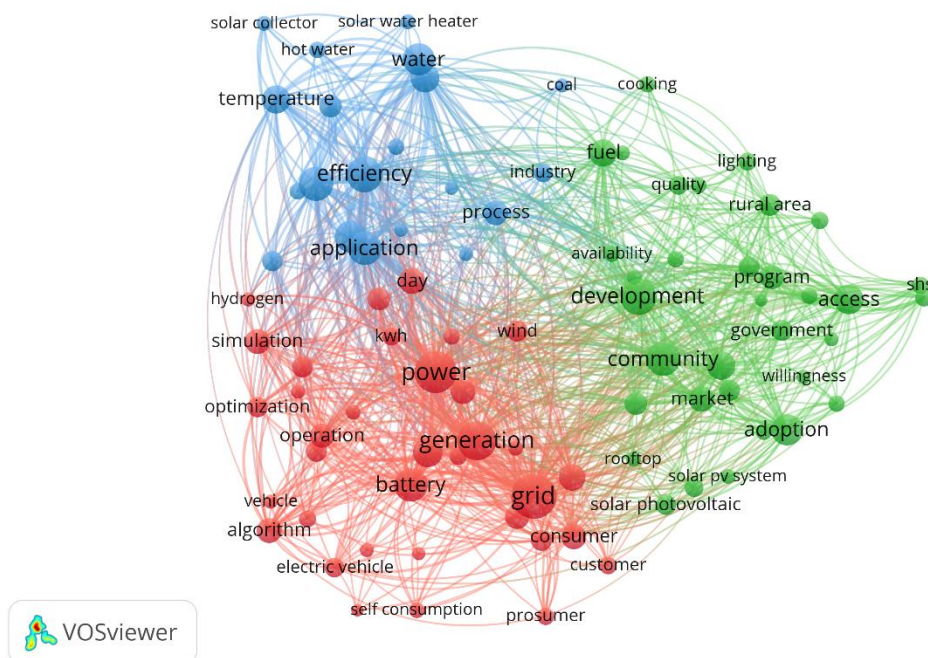


Figure 1. Network Visualization

Source: Data Analysis Result, 2024

This visualization illustrates a bibliometric network based on the co-occurrence of keywords in the field of solar energy utilization, with a focus on energy efficiency, grid integration, and rural development. The network is divided into distinct clusters, each represented by different colors, indicating the thematic groupings of research in this domain. The size of the nodes represents the frequency of keyword usage, while the proximity and connections between nodes indicate the strength of their co-occurrence in scholarly articles.

The red cluster prominently focuses on terms related to "power," "generation," "grid," and "battery," suggesting a thematic concentration on grid integration and the technical aspects of power generation and energy storage. Keywords like "algorithm," "optimization," and "operation" reflect the research emphasis on computational methods for enhancing the efficiency and reliability of energy systems. This cluster highlights the technological backbone of solar energy systems, such as optimizing battery storage and improving grid resilience, which are crucial for managing intermittent solar power.

The **blue cluster** centers around "efficiency," "application," "water," and "temperature," indicating a thematic focus on solar energy applications for water heating, solar collectors, and energy-efficient systems. The presence of terms like "simulation" and "process" points to the analytical and experimental studies that aim to improve system efficiency under varying environmental conditions. This cluster reflects the role of solar technologies in advancing energy efficiency, particularly in household and industrial applications, emphasizing innovation in solar water heating and other thermal systems.

The **green cluster** encompasses keywords such as "development," "community," "access," and "adoption," reflecting a socio-economic perspective on solar energy utilization. This cluster highlights the focus on market development, government programs, and community-based solar projects, particularly in rural and underserved areas. The emphasis on "willingness," "quality," and "adoption" suggests a significant research interest in understanding consumer behavior, policy interventions, and the socio-economic benefits of solar energy adoption. It underscores the critical role of policy frameworks and community engagement in scaling up solar energy utilization.

Overall, the visualization provides a comprehensive view of the interconnected research themes in the field of solar energy utilization. It reveals a balance between technological innovation, practical applications, and socio-economic considerations, reflecting the interdisciplinary nature of this research area. The strong interconnectivity among clusters suggests a growing recognition of the need to integrate technological, environmental, and social perspectives to address the challenges and unlock the full potential of solar energy in improving energy efficiency and fostering sustainable development.

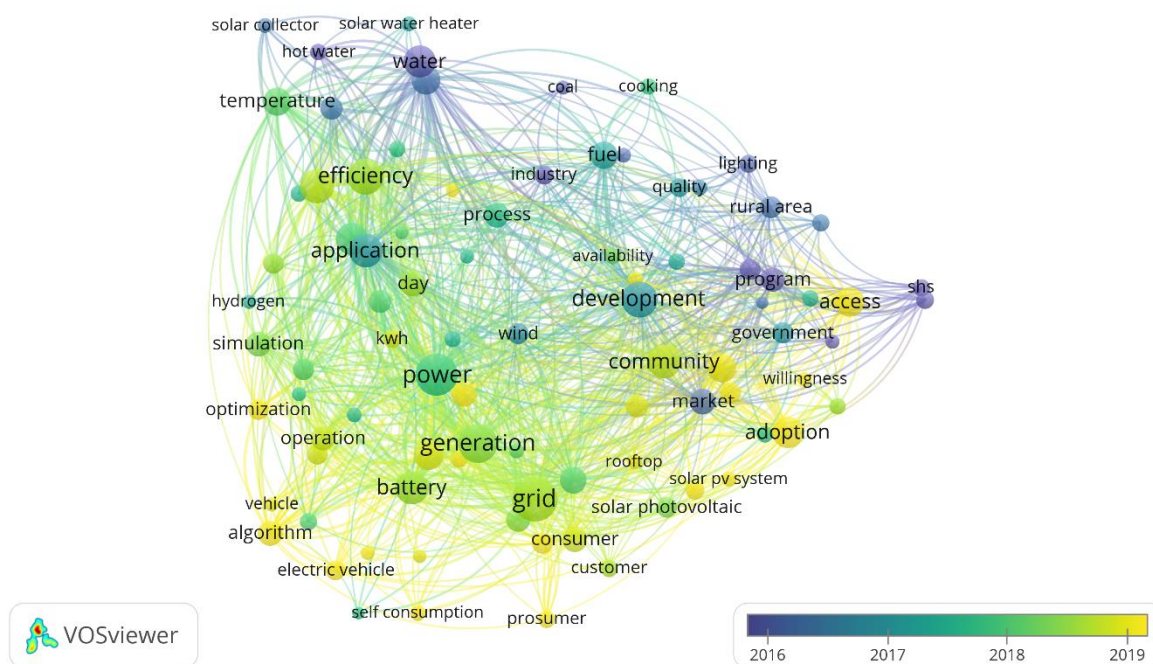


Figure 2. Overlay Visualization

Source: Data Analysis Result, 2024

This visualization depicts the evolution of research on solar energy utilization for energy efficiency in urban and rural contexts, with color gradients indicating the temporal progression of keywords' popularity. The timeline spans from 2016 (dark blue) to 2019 (yellow), showcasing how specific themes emerged, gained prominence, and integrated with broader discussions in the field.

The size of the nodes reflects the frequency of keyword usage, while the links and their density signify co-occurrence relationships.

The early focus (2016-2017), represented by dark blue nodes, centers around foundational concepts such as "water," "solar water heater," and "temperature." These keywords emphasize initial research into solar applications, particularly in water heating and thermal regulation systems. This phase primarily addresses the technical feasibility and efficiency of solar energy technologies in niche applications, setting the groundwork for more integrated solutions.

From 2018 to 2019 (green to yellow nodes), the research focus shifts toward broader adoption themes, such as "grid," "battery," "community," and "adoption." These keywords indicate an increasing interest in integrating solar energy into smart grids, exploring energy storage solutions, and addressing socio-economic dimensions like community engagement and market development. The rise in terms like "development" and "access" highlights efforts to expand solar energy applications to rural and underserved areas, reflecting a growing emphasis on equity and sustainability in energy transitions.

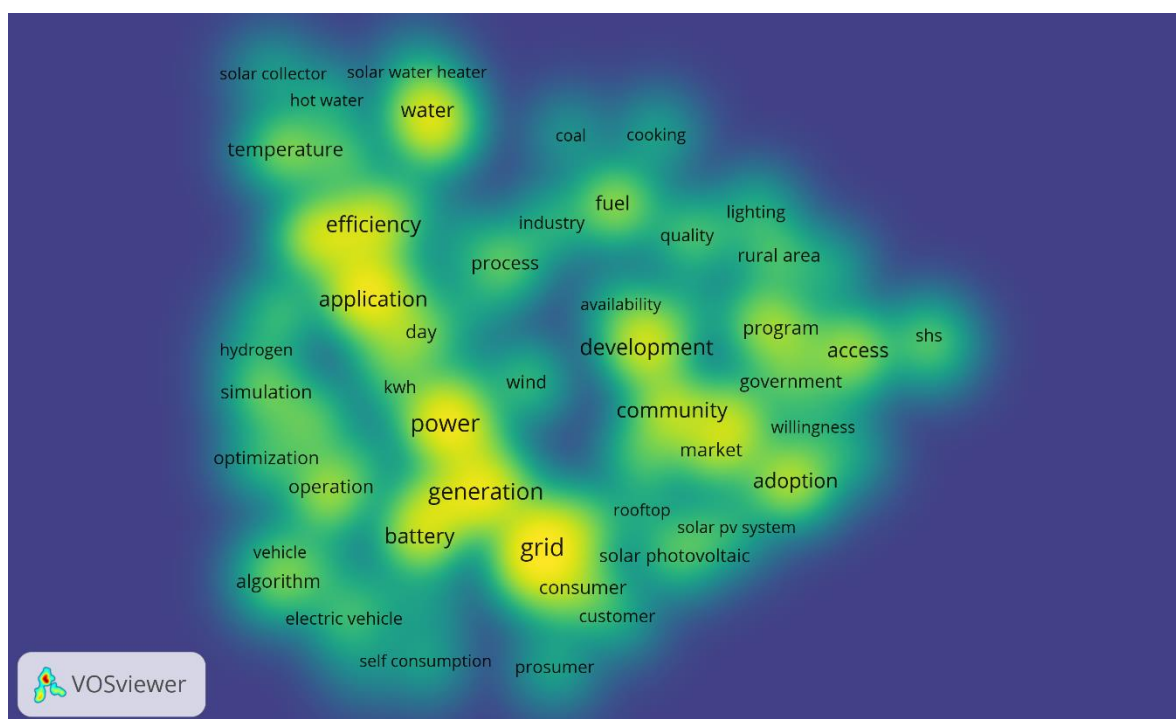


Figure 3. Density Visualization

Source: Data Analysis Result, 2024

This heatmap visualization highlights the frequency and prominence of keywords associated with solar energy utilization and energy efficiency research. Brighter regions (yellow) represent highly frequent keywords, while darker regions (green and blue) signify less frequent terms. Central to the heatmap are keywords such as "power," "generation," "grid," "efficiency," and "battery," which form the core focus of this research field. These terms reflect the technological emphasis on integrating solar energy into power grids, optimizing energy generation, and enhancing energy storage systems to address energy efficiency and sustainability challenges.

On the periphery, terms such as "water," "community," "adoption," and "access" represent emerging or context-specific themes. These highlight the broader societal and practical applications of solar energy, including water heating, rural electrification, and community-based solar initiatives. The diversity in keyword prominence across the map demonstrates the interdisciplinary nature of solar energy research, encompassing technological innovation, social engagement, and policy

considerations. This heatmap underscores the comprehensive scope of studies aimed at scaling solar energy solutions for both urban and rural energy needs.

4.2 Citation Analysis

Table 2. The Most Impactful Literatures

Citations	Authors and year	Title	Contributions
657	[14]	Methodology for optimal sizing of stand-alone photovoltaic/wind-generator systems using genetic algorithms	Introduced a genetic algorithm-based methodology for the optimal sizing of standalone photovoltaic and wind generator systems, enhancing the efficiency and cost-effectiveness of renewable energy installations in remote areas.
478	[15]	Regression analysis for prediction of residential energy consumption	Developed a regression model to predict residential energy consumption, providing a tool for energy planners and policymakers to forecast energy demands and tailor energy-saving strategies accordingly.
460	[16]	Optimal operation of residential energy hubs in smart grids	Explored the optimal operational strategies for residential energy hubs within smart grids, focusing on the integration of multiple energy sources and technologies to maximize efficiency and sustainability.
448	[17]	Optimal electrical and thermal energy management of a residential energy hub, integrating demand response and energy storage system	Proposed an integrated approach for managing both electrical and thermal energy in residential energy hubs, incorporating demand response and energy storage systems to improve energy efficiency and reliability.
371	[18]	Nanophotonics-enabled solar membrane distillation for off-grid water purification	Introduced a novel nanophotonic solar membrane distillation technique for off-grid water purification, leveraging solar energy to provide clean water in underserved regions without relying on external energy sources.
360	[19]	Willingness-to-pay for renewable energy: Primary and discretionary choice of British households' for micro-generation technologies	Analyzed British households' willingness to pay for renewable energy, particularly micro-generation technologies, shedding light on consumer preferences and potential barriers to adoption.
350	[20]	Renewable energy markets in developing countries	Reviewed the status and prospects of renewable energy markets in developing countries, identifying challenges and opportunities for scaling up renewable energy to meet local and global energy demands.
336	[21]	Temperature-adaptive radiative coating for all-season household thermal regulation	Developed a temperature-adaptive radiative coating that improves household thermal regulation by reflecting solar heat in summer and

Citations	Authors and year	Title	Contributions
			retaining internal heat in winter, contributing to energy savings and comfort.
336	[22]	Water desalination system using solar heat: A review	Provided a comprehensive review of water desalination systems powered by solar heat, discussing different technologies and their effectiveness in providing sustainable access to potable water.
315	[23]	Biochar-based water treatment systems as a potential low-cost and sustainable technology for clean water provision	Examined the potential of biochar-based water treatment systems as a low-cost, sustainable solution for clean water provision, especially in areas lacking conventional water treatment facilities.

Source: *Publish or Perish Output, 2024*

Discussion

1. Technological Advancements and Energy Efficiency

The prominence of keywords such as "efficiency," "power," "generation," and "grid" highlights the central role of technological innovation in solar energy research. The evolution of photovoltaic (PV) technologies, including advancements in efficiency, cost reduction, and integration into urban infrastructure, has significantly shaped the field. Studies, such as those by [22], emphasize the importance of optimizing PV materials and improving energy conversion rates. Similarly, innovations in energy storage systems, such as batteries, address one of the key challenges in solar energy—its intermittency. Research by [24] underscores the growing importance of advanced storage technologies, including lithium-ion and solid-state batteries, in ensuring a reliable energy supply for urban households.

The integration of solar energy into smart grids also represents a significant area of focus. The ability to manage and distribute energy efficiently using smart grid technologies is critical for maximizing the benefits of solar energy. Research by [23] has demonstrated the potential of energy hubs and smart grid solutions in improving energy efficiency and reducing wastage. These innovations align with the broader goals of sustainable urban development, ensuring that urban households can transition to renewable energy sources without compromising energy reliability or affordability.

2. Socio-Economic Dimensions of Solar Energy Adoption

The socio-economic implications of solar energy adoption are another critical dimension of this research field. Keywords such as "community," "adoption," "market," and "access" indicate a growing recognition of the need to address social and economic barriers to solar energy utilization. For urban households, the decision to adopt solar energy is influenced by factors such as upfront costs, access to financing, and government incentives. Studies by [20] highlight the effectiveness of financial subsidies and tax incentives in reducing the economic burden on households and encouraging widespread adoption.

The willingness of consumers to invest in solar technologies also depends on their awareness of the environmental and financial benefits. Research by [17] has shown that consumer education campaigns can play a vital role in increasing adoption rates by addressing misconceptions and highlighting the long-term benefits of solar energy systems. Moreover, community-based solar projects, as explored by [22], offer an innovative approach to expanding access to solar energy, particularly in densely populated urban areas where private installations may not be feasible. These

projects leverage economies of scale and shared resources to reduce costs and make solar energy more accessible.

3. Environmental Benefits and Sustainability

The environmental benefits of solar energy are well-documented, with a strong focus on reducing carbon emissions and mitigating climate change. The inclusion of keywords like "water," "temperature," and "solar collector" highlights specific applications of solar energy that contribute to sustainability. For instance, solar water heating systems reduce reliance on fossil fuels for domestic hot water, contributing to lower greenhouse gas emissions. Research by [15] provides evidence of the significant carbon footprint reductions achieved through widespread adoption of solar water heating technologies. In addition to direct environmental benefits, solar energy also contributes to broader sustainability goals by enhancing energy resilience and reducing dependency on non-renewable energy sources. This aligns with the United Nations' Sustainable Development Goals (SDGs), particularly Goal 7, which focuses on ensuring access to affordable, reliable, and sustainable energy for all [25]. The dual benefits of solar energy in improving energy efficiency and reducing environmental impact make it a critical component of urban sustainability strategies.

Challenges in Solar Energy Utilization

Despite the numerous benefits, several challenges remain in the widespread adoption and integration of solar energy in urban households. One of the most significant barriers is the upfront cost of installation, which can deter households from transitioning to solar energy. Although the cost of PV panels has decreased significantly over the years, the total cost, including installation and maintenance, remains a concern for many households. Research by [26] emphasizes the importance of innovative financing models, such as pay-as-you-go systems and green loans, to address this issue.

Another challenge is the aesthetic impact of solar panels in urban areas. The integration of solar technologies into urban landscapes requires careful planning to ensure that they do not compromise the aesthetic appeal of residential buildings. Architectural innovations, such as building-integrated photovoltaics (BIPV), offer potential solutions to this challenge by incorporating solar panels seamlessly into building designs. Additionally, the variability of solar energy supply, influenced by weather conditions and seasonal changes, underscores the need for advanced energy storage solutions and hybrid systems that can complement solar energy with other renewable sources.

Policy and regulatory frameworks also play a crucial role in addressing these challenges. Research by [1] highlights the importance of supportive policies, such as net metering, feed-in tariffs, and renewable energy mandates, in driving solar energy adoption. Policymakers must also address issues related to grid integration and energy distribution to ensure that solar energy systems can operate efficiently within existing energy infrastructures.

Emerging Trends and Future Directions

The bibliometric analysis reveals several emerging trends in solar energy research, including the role of smart grids, energy management systems, and community-based solar projects. The increasing interest in integrating solar energy with other technologies, such as artificial intelligence (AI) and the Internet of Things (IoT), represents a promising direction for future research. These technologies can enhance the efficiency of solar energy systems by enabling real-time monitoring, predictive maintenance, and optimized energy distribution. Another emerging trend is the focus on decentralized energy systems, which empower households and communities to generate and manage their energy. Decentralized systems reduce dependency on centralized power grids and enhance energy resilience, particularly in the face of natural disasters and grid failures. Research by [5] suggests that decentralized solar energy systems can also contribute to energy equity by

expanding access to renewable energy in underserved urban areas. Finally, the intersection of solar energy with water and food security presents an exciting avenue for future research. Technologies such as solar desalination and solar-powered irrigation systems have the potential to address critical resource challenges while promoting sustainable development. The work of [4] on solar membrane distillation for off-grid water purification highlights the potential of these technologies to provide clean water in urban and peri-urban areas.

CONCLUSION

This bibliometric review highlights the critical role of solar energy in enhancing energy efficiency and promoting sustainability in urban households. The findings underscore significant advancements in photovoltaic technologies, energy storage systems, and smart grid integration, which have collectively driven the adoption of solar energy solutions. Furthermore, socio-economic factors, including government incentives, community-based projects, and consumer education, have emerged as pivotal in overcoming adoption barriers and ensuring equitable access to renewable energy. While the environmental benefits of solar energy are well-documented, challenges such as high installation costs, aesthetic concerns, and energy variability require innovative solutions and supportive policies. Future research must focus on integrating emerging technologies, such as artificial intelligence and decentralized energy systems, to address these challenges and expand the potential of solar energy. By addressing these multifaceted issues, solar energy can significantly contribute to sustainable urban development, energy resilience, and the broader global effort to mitigate climate change.

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