RESEARCH PROGRESS ON CARBON EMISSIONS FROM HOUSEHOLD ENERGY CONSUMPTION: A GLOBAL PERSPECTIVE

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Abstract. Carbon emissions from household energy consumption have adverse effects on global warming and climate change. Therefore, research on carbon emissions from household energy consumption has become a key focus for scholars in various countries. We conducted an analysis of the progress and prospects of carbon emissions from household energy consumption based on the "Web of Science Core Collection Database". The development path for reducing carbon emissions from household energy consumption was proposed, with the aim of providing a reference for establishing carbon reduction in household energy consumption. (1) In terms of bibliometrics, statistics and analysis were conducted on the number of published papers and subject classification. Through keyword measurement, it is found that the research content mainly includes the study of driving mechanisms, energy saving consumption behaviors, and the characteristics of power emission reduction; (2) Through the review of calculation methods and model methods, it is found that the current research methods mainly include input–output method, life cycle method, carbon emission coefficient method and consumer lifestyle method. The research methods for influencing factors include Regression analysis, STIRPTA and LMDI, etc. The applicable scope, advantages and disadvantages of each research method are summarized. (3) Research on predictive scenarios has found that predictive scenarios are divided into machine prediction and model prediction. Predictive scenarios are mainly applied to architectural features, while there are relatively few predictions for household features. Research on carbon emissions from future household energy consumption can focus on the characteristics of predicted emission reduction in the future. This study presents the most recent and comprehensive overview of research progress and future prospects regarding carbon emissions from household energy consumption, offering valuable insights for global scholars.
Keywords: *bibliometric analysis, method summary, influence factor, prediction model, carbon emissions reduction path*

Introduction

The global energy system is the cornerstone of the modern economy and society. However, the production and consumption of energy also contribute to 75% of greenhouse gas emissions and are the main drivers of climate change. In accordance with the requirements of the Paris Agreement, global warming should be limited to 1.5°C or less address the adverse effects of by climate change. Households make a major contribution to global energy demand and carbon emissions. Targeted energy

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policies for households have become the key to the global energy transition. At present, the trend of increasing direct and indirect energy consumption and carbon emissions of households year by year is obvious. Also in every country, the household sector is the main consumer of energy and therefore the focus of efforts to reduce energy consumption emissions. Since 2014, the proportion of household energy consumption growth has surpassed that of the industrial sector, and the increasing household consumption has gradually become a key driving factor for the increase in CO_2 in various countries (IPCC, 2022). According to statistics, carbon emissions caused by household consumption account for approximately 17% of global carbon emissions. With the advancement of urbanization and rising in income levels, the importance of energy consumption in urban households will continue to increase. In rural areas, household carbon emissions have also increased significantly. How to promote the low-carbon transformation of energy consumption in urban and rural households has become an indispensable link in the process of building a modern energy system and achieving the "dual carbon" goals. Therefore, this paper takes the family as the unit and sorts out the direct and indirect carbon emissions of household and building energy consumption in urban and rural areas around the world. The research achievements and viewpoints over the past nearly 40 years are introduced, and the mainstream model methods, dynamics and future progress in this field are discussed.

Through bibliometrics and careful reading of the literature, the relevant literature on carbon emissions from household energy consumption from 1983 to 2024 was examined, with the aim of comprehensively understanding the current research status of carbon emissions from household energy consumption. Specifically, the basic characteristics of the output, the contributions of countries and institutions, the number of articles published by authors, and the development of research keywords were determined. Based on these results, more insights into current research and potential future research can be obtained, as well as a latest and comprehensive research review can be provided. The main contents of the article are as follows: The second part introduces the research methods and data sources; The third part describes the bibliometric analysis results from aspects such as journal contribution, disciplinary contribution, literature coupling, co-occurrence of keywords, and country/region. The fourth part summarizes and generalizes the mainstream research methods, influencing factors and predictions; The fifth part provides a summary of the full text and prospects for future research.

Research methods and data sources

Bibliometric analysis has flexible and powerful data processing capabilities and is an important tool for exploring quantitative analysis of a certain discipline or a certain research element at the present stage. This study conducted qualitative and quantitative research by combining bibliometric analysis with manual review. Firstly, a review and statistical analysis were conducted on the literature related to carbon emissions from household energy consumption published in domestic and foreign peer-reviewed journals in the past 40 years. Meanwhile, in this paper, VOSviewer is adopted as a literature information visualization software tool to construct a visual scientific knowledge graph in the field of carbon emissions from household energy consumption. VOSviewer is a bibliometric analysis software for drawing knowledge maps, jointly developed by scholars NEES Janvan Eck and LUDO Waltman from Leiden University (Wang et al., 2024).

The bibliometric literature retrieval of the literature Database was conducted on the "Web of Science Core Collection Database". The literature collection was completed by December 31, 2024, and the subsequent screening process of the literature was carried out. The key words include "energy consumption", "carbon emissions", "household" and "building". From 1983 to 2024. Through conditional retrieval, a total of 838 open access papers were obtained. Secondly, the search results were optimized using the filtering function of Web of Science, and the language was set to English for subsequent understanding. Select articles and reviews in the literature types. *Figure 1* shows the output process of the literature.

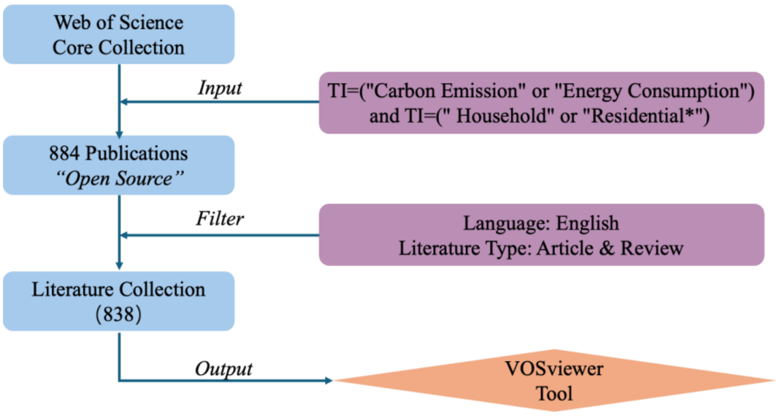

Figure 1. *Flowchart of literature screening*

Analysis of measurement results

Published number and contributions to disciplines

Analysis published articles

The statistical data of the article publication trend is shown in *Figure 2*. The number of annual publications on carbon emissions from household energy consumption is generally increasing. Especially since 2011, it has witnessed a period of rapid growth, with an average annual number of published articles of 53.35 and an average annual growth rate of 15.18%. Especially after 2018, the number of published articles has grown rapidly. This also indicates that in the post-industrial era, the proportion of household energy consumption growth rate has surpassed that of the industrial sector. The increasing household consumption has gradually become a key driving factor for the increase in CO_2 in various countries, and more and more scholars have begun to pay attention to the carbon emissions from household energy consumption. From the perspective of the scholars who first focused on the carbon emissions of household energy, in 1983 Zhu et al. (1983) analyzed the energy consumption and lifestyles of urban and rural households in China and found that the energy consumption of urban households was significantly higher than that of rural households. Secondly, in 1983 Ruggeri (1983) analyzed the patterns of household energy consumption in Canada during the periods of 1961-972 and 1973-1980. The results indicated that household energy consumption was significantly influenced by changes in economic and demographic trends. It can be seen from this that scholars from the two countries respectively studied the characteristics of household energy consumption in their own countries, laying a research foundation for later scholars.

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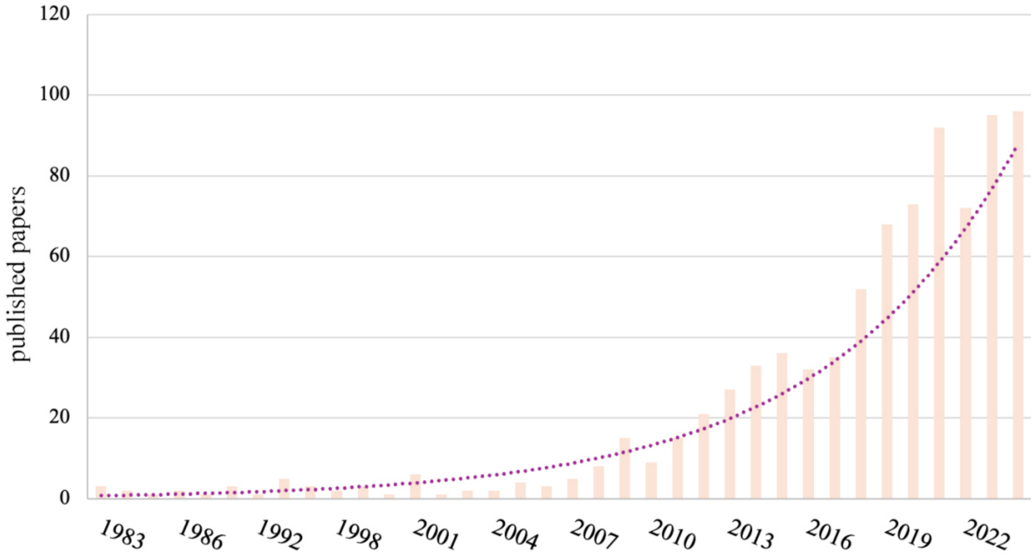

Figure 2. *The number of documents on carbon emissions from household energy consumption*

Disciplinary contribution

According to the research topics of Web of Science mainly involving 65 different disciplines, the results are detailed in *Figure 3*. Interdisciplinary integration has always been a common phenomenon in the research of carbon emissions from household energy consumption. Energy Fuels ranks first among all disciplines, accounting for approximately 22.95%. This indicates that conducting research on carbon emissions from household energy consumption from the perspective of energy transition is a key discipline, such as the development of renewable energy and how to reduce reliance on traditional energy (Quintana et al., 2023). Secondly, there are Environmental Sciences (10.94%) and Environmental Studies (9.05%). It can be seen that the research on carbon emissions from household energy consumption is the focus in the field of environmental science. Furthermore, building technology and building materials are the main contributors to carbon emissions from household energy consumption (Huo et al., 2021). These include Green Sustainable Science and Technology (9.97%), Engineering Civil (7.7%), Thermodynamics (4.42%), and Engineering Environmental (3.18%) and Engineering Chemical (2.59%). It is worth noting that Economics (5.87%) is also one of the indispensable disciplines in the research of carbon emissions from household energy consumption. The remaining disciplines combined accounted for 13.85%.

Analysis of research content on carbon emissions from household energy consumption

Keyword co-occurrence analysis provides the content of key research topics in a clear sense within a certain period. Using the Keywords plus function in VOSviewer, 1276 keywords were selected from the database. The minimum frequency of the keywords is set to 8, and finally a network graph containing 109 keywords is exported (*Fig. 4*). Classify the keywords into three clusters based on their frequency of occurrence. The correlation intensity of the key words, and there is a close relationship among the three clusters. Due to global concerns over climate change, research topics on carbon emissions from household energy consumption include studies on the driving mechanisms of geographical, economic and social factors, as well as strict energy policies and the

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improvement of energy efficiency, cleaner fuels (natural gas and solar energy), electricity consumption and the popularization of modern energy-saving technologies (Lin et al., 2023).

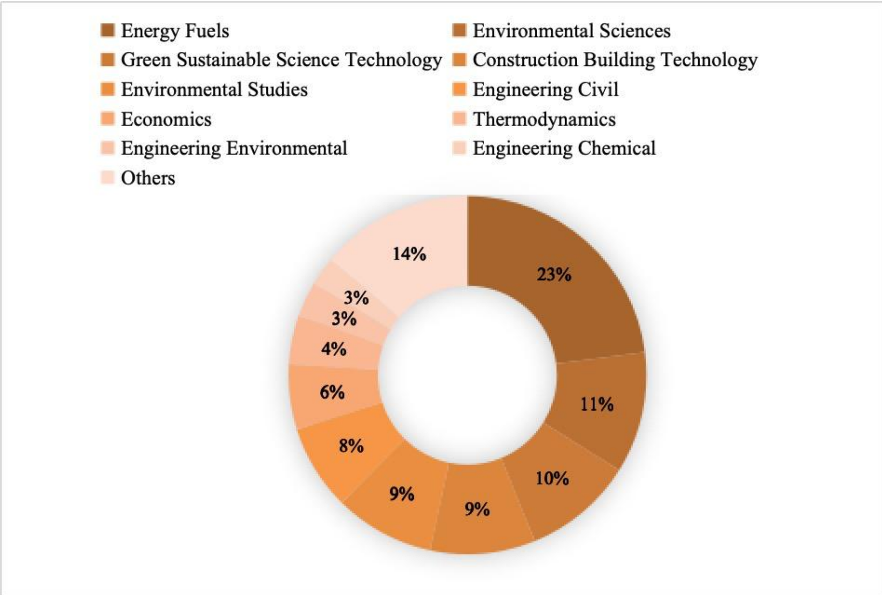

Figure 3. *Classification of discipline development*

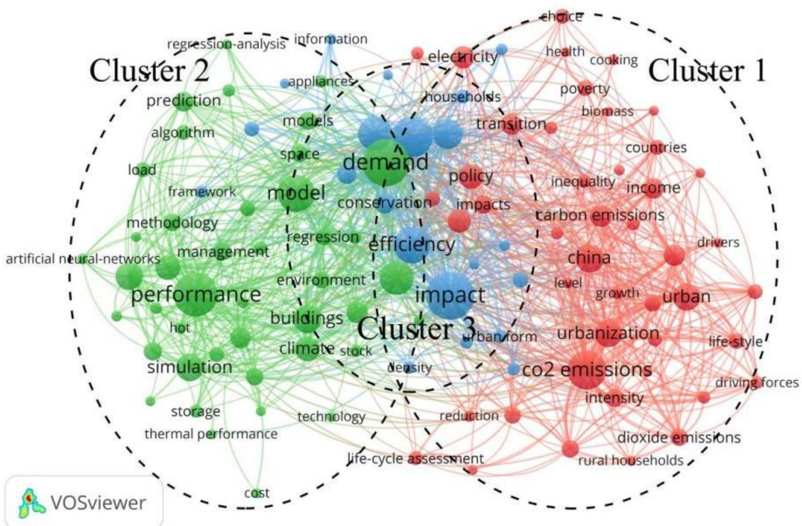

Figure 4. *Keyword co-occurrence analysis*

Research on driving mechanism

The research content of the first group (red) is divided into empirical analysis of the driving mechanism of energy consumption carbon emissions in urban and rural areas as well as different building types in cities (Kumar et al., 2024). The specific research topics include health, household income, policies, population, renewable energy, poverty and urbanization, etc. The countries studied are China and India. Firstly, a comparative study of carbon emissions from energy consumption between urban and rural households reveals a significant difference in such emissions (Li et al., 2023). The main research findings indicate that carbon emissions from urban households are higher than those from rural households, reflecting the inequality in energy consumption intensity and structure as well as the significant differences in quality of life between urban and rural areas (Eskander et al., 2024). Secondly, regarding health conditions, there are linear and nonlinear relationships among energy consumption, health, poverty and the quality of the living environment at the household level (Maya et al., 2024). The negative impact of health shocks on poor families is twice that of non-poor families. The main concern about household income is that income inequality among countries is the determining factor of household energy carbon emissions, and economic inequality in high-income countries has a decisive influence on the available choices of individual household energy behaviors (Olu-Ajayi et al., 2022). The impact of household energy consumption carbon emissions at different income levels. The research on family income inequality has always been the focus of scholars' attention (Yiran et al., 2023). Then in terms of policies Qi et al. (2020), some scholars believe that the understanding of energy-saving policies has significantly increased the energy consumption of households. But more importantly, policy support plays a crucial role in promoting the energy transition, including strategies such as quantity subsidies, price subsidies, coal reform, straw gasification and other biogas projects. Then in terms of population, population age, living area and family size have a significant impact on household energy consumption. A smaller family size will lead to an increase in per capita energy consumption and result in higher carbon emissions (Wang et al., 2020). Similarly, non-household population migration will also increase household carbon emissions. Research on renewable energy (Li et al., 2021) includes that green electricity is one of the most effective alternatives to traditional electricity. Like other technologies and energy-saving products, it can effectively reduce carbon emissions from household energy consumption. For instance, integrating photovoltaic systems with battery storage to achieve partial autonomous residential electricity consumption and production can effectively enhance self-consumption and self-productivity (Tang et al., 2022). Then, research on energy poverty indicates that the total direct energy consumption of the poor population is relatively high (Zhu et al., 2023), but modern energy usage is less, especially in cooking activities, and families with lower income, lower education level and smaller family size are more likely to experience energy poverty (Palaniappan et al., 2024). In terms of improving energy poverty, rural electrification is an important approach (Li et al., 2024). In terms of urbanization, at different stages of urbanization, the impact of urbanization on residents' energy consumption varies greatly in different regions (Xu et al., 2024). Finally, a comparison of the research on carbon emissions from household energy consumption in China and India reveals that income, energy prices, energy access, and local fuel supply are the key driving forces for energy transition in both countries, and urbanization is also a key factor (Jiang et al., 2021). It can be seen that scholars have explored global household energy consumption carbon emissions from the perspectives of different driving factors. Research has found that each factor has a significant impact on household energy consumption carbon emissions. In terms of urban-rural differences, urbanization is an important factor driving the increase in carbon emissions in urban areas. In rural areas, however, issues of energy poverty persist, such as the relatively high reliance on biomass energy and the associated health problems, while the utilization rates of clean energy and electricity remain low.

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Energy-saving consumption behavior

The research contents of the second group (green) include occupant behavior, thermal comfort, prediction and technology, etc. The research covers aspects such as household characteristics, green building features and energy conservation. Firstly, in terms of occupants' behaviors, the content to be explored includes the relationship between residents' energy behaviors and residential energy consumption (Tran et al., 2021). Iraganaboina et al. (2021) investigated high-rise residential buildings in Hong Kong. The results show that the behavior of the residents leads to a 26% higher monthly electricity bill for residents on the 20th floor and below than that of high-rise residents in spring, summer and autumn, while the electricity bill in winter is not much different from that of high-rise residents. The research on thermal comfort is mainly reflected in, on the one hand, the research on heating and cooling. Du et al. (2020) studied the preferences of Finnish residential properties in terms of heating systems. Kumar et al. (2024) evaluated the heating and cooling demands of typical detached houses in Finland. The report stated that when using predictive climate, the heating demand decreased by 20-40% and the cooling demand increased by 40-80%. On the other hand, research on thermal comfort has also been conducted in the performance of residential buildings. For instance, the design of building envelopes and green walls are also the most effective choices for reducing overall energy consumption. Finally, there are also relatively mature studies in the aspect of prediction (Sheng et al., 2021). It includes machine prediction and model prediction. Thus, a systematic review of occupant behavior research reveals that variations in resident behavior significantly shape the disparities in energy consumption for electrical, heating, and cooling purposes.

Characteristics of electricity emission reduction

The third group (blue) includes research on consumption behavior: household electricity consumption models, demand side energy management systems, electricity prices, feedback and efficiency, etc. Electricity price adjustment, time of use electricity pricing and the promotion of energy saving appliances have become important means to regulate residents' energy consumption (Akbari et al., 2021; Al-Shanableh et al., 2021). Osman et al. (2024) holds that demand side management refers to the plans aimed at optimizing power grid management, balancing supply and demand, and improving power grid efficiency. Ji et al. (2024) studied and investigated the willingness of Chinese households to participate in green electricity prices. Data analysis of smart electricity meters is conducive to better planning and operating the power system. Albatayneh et al. (2022) investigated the impact of energy subsidies on energy use and the consumption patterns in the residential sector. The analysis results show that, on average, ordinary homeowners consume approximately 297 kWh of electricity per month, while customers receiving electricity subsidies consume about 615 kWh of electricity per month. It can be seen that electricity is the most ubiquitous form of energy in household consumption. Therefore, research aimed at its decarbonization is of paramount importance for reducing the carbon footprint of the residential sector.

Co-citation analysis

Citation analysis is an activity and method based on the citation and reference relationships among literature, authors, journals and other sources. It involves studying the network or chain relationships among citations to reveal the developments and

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connections within a field. The more times an author or article is cited in other academic articles, the greater its influence in the discipline, and thus the importance of the article or researcher in any specific field can be judged (Rahimifar et al., 2023). As shown in *Figure 5,* the size of the midpoint represents TC, and the depth of the color represents the publication year. The top 10 articles and their performances in TC and AC/Y were selected. The one with the highest comprehensive score was Swan et al. (2009), which reviewed the overview of various emission reduction technologies for energy consumption modeling in the residential sector by applying top-down and bottom-up methods. The articles of Nejat et al. (2015) and Kim et al. (2024) ranked second and third respectively according to AC/Y. Nejat et al. studied the energy consumption, carbon dioxide emissions and energy policies of the residential sector in the top 10 countries around the world and found that population, urbanization and economic growth were the main driving factors. Kim et al. proposed a CNN-LSTM neural network capable of extracting spatio-temporal features, which can effectively predict housing energy consumption (*Table 1*).

Table 1. *Main citation manifestations*

	Author	Journal	TC	AC/Y
1	Swan et al. (2009)	Renewable & Sustainable Energy Reviews	1333	88.87
2	Nejat et al. (2015)	Renewable & Sustainable Energy Reviews	1314	146
3	Kim et al. (2019)	Energy	891	178.2
4	Kavgic et al. (2010)	Building and Environment	637	45.5
5	Jain et al. (2014)	Applied Energy	424	42.4
Total			4599	500.97

Research contents

Computing method

Regression analysis method

The input-output model was proposed by Slaffa in 1960 and was developed by Pasinetti, Deprez and Scazzieri et al. Human beings further develop. At present, this method is mostly applied in environmental research (Jiang et al., 2024). Extended input-output analysis can only calculate indirect energy consumption and not direct energy consumption of households. As for the application of the input-output model, it is mainly studied from the aspect of the driving mechanism. The input-output model has relatively mature applications in various countries (Messoudi et al., 2024; *Fig. 6*).

Life cycle assessment

The full life cycle refers to compiling and evaluating the inputs, outputs and potential environmental impacts of a product system throughout its entire life cycle (Luo et al., 2022). Yu et al. (2020) used Grasshopper and its plugins along the HypE algorithm to conduct multi-objective optimization of the life cycle energy consumption and life cycle cost of buildings in cold regions (Liu et al., 2022). The system boundary includes the production, transportation, construction, operation and disposal stages. The assessment results show that the operation stage is identified as the most significant contributor to carbon emissions, followed by the production stage. The impact of the transportation,

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construction and disposal stages on emissions is relatively small. Kavanagh et al. (2021) studied the life cycle assessment of high-rise residential buildings. It can be seen that scholars have mainly conducted research on the carbon emissions throughout the life cycle of different building types (*Fig. 6*).

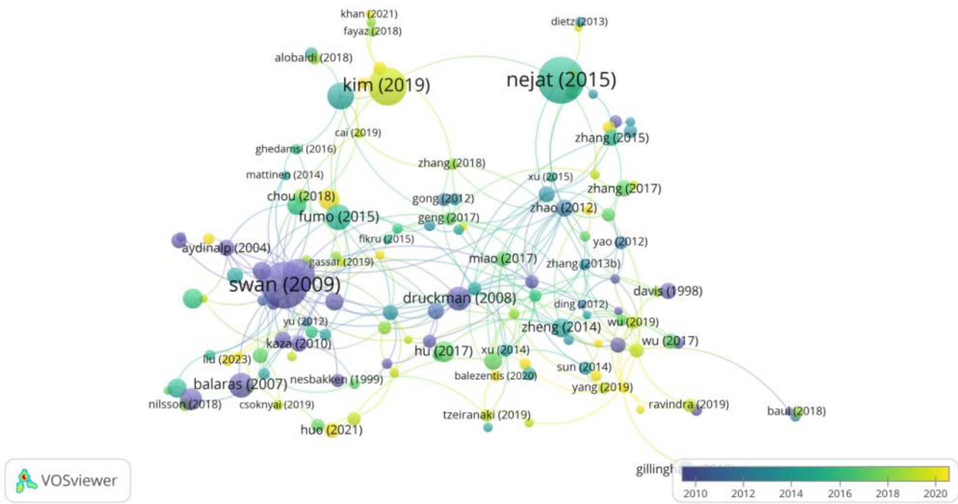

Figure 5. *Citation co-occurrence network*

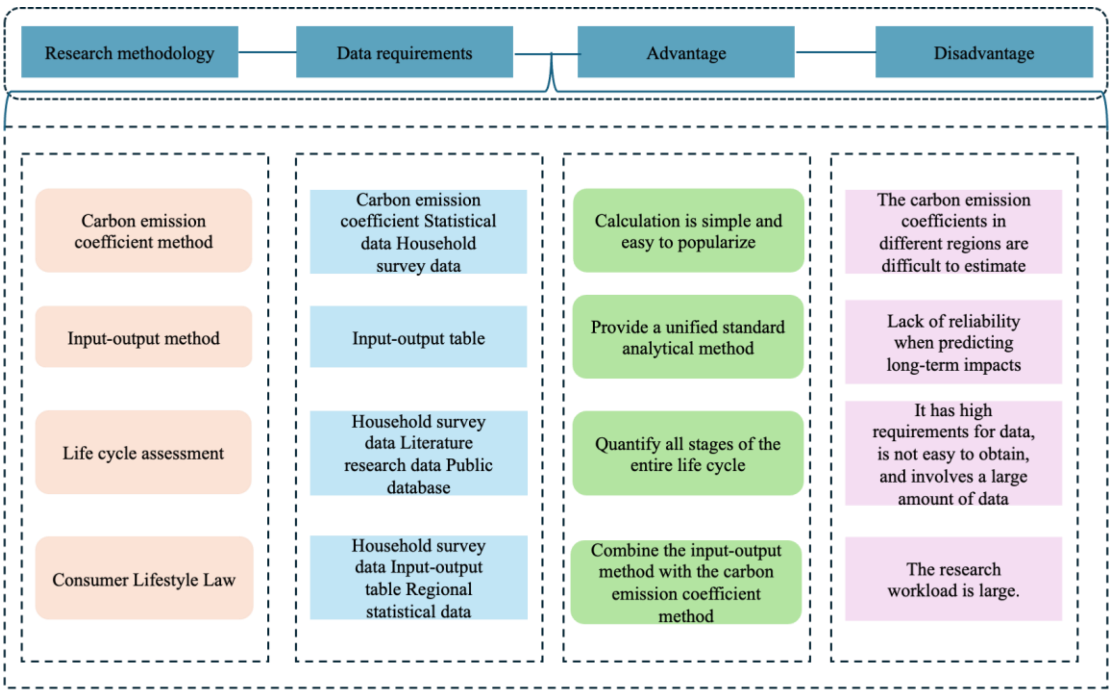

Figure 6. *Comparison of the advantages and disadvantages of research methods*

Carbon emission coefficient method

Based on the calculation method of carbon emissions from the power system of the Intergovernmental Panel on Climate Change (IPCC, 2006), using the terminal consumption of energy, the carbon emissions directly caused by residents' consumption

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were estimated (Luo et al., 2022). The content of household consumption is complex and diverse. Currently, the calculation of direct carbon emissions from household consumption is mostly based on multiplying the energy carbon emission coefficient by the corresponding energy consumption (*Fig. 6*).

Consumer lifestyle analysis

The carbon dioxide emissions are evaluated based on the direct or indirect energy consumption generated by individual consumption or overall household consumption in life. It regards household characteristics, individual determinants, external environmental variables, consumer choices and their outcomes as interacting factors (Cheng et al.,2024). (Tang et al.,2023) calculated the overall direct and indirect energy consumption of Chinese residents in recent years through the methods of energy classification and Consumer Lifestyle Analysis (CLA). Wang et al. (2022) studied the indirect energy consumption of rural households in China using CLA. The results show that the indirect energy consumption of rural residents in China has gradually declined. Wu et al. (2022) measured the energy consumption of Chinese residents using the CLA method and discussed that the impact of urbanization in China on household indirect energy consumption could be divided into stages and presented a U-shaped relationship. Wei et al. (2021) used CLA to estimate the direct and indirect impacts of the lifestyles of urban and rural residents on energy consumption and carbon dioxide emissions in China. Feng et al. (2020) used CLA to study the correlations among consumer activities, energy usage and related carbon dioxide emissions. The application of consumers' lifestyle methods has mainly been studied from both direct and indirect aspects. The Consumer Lifestyle Approach (CLA) assesses the carbon dioxide emissions from both direct and indirect energy consumption generated by personal or overall household spending. It views household characteristics, individual determinants, external environmental variables, and consumer choices along with their outcomes as interacting factors. While this method incorporates elements from other calculation methodologies, it is characterized by extensive survey requirements and a high demand for data accuracy (*Fig. 6*).

Influence factors methods

The carbon emissions from household energy consumption are influenced by household characteristics, technological and physical factors including climate variables, building features and service systems, etc. In order to gain an in-depth understanding of the changes in consumption carbon emissions in a country or region, it is necessary to analyze the influencing factors of carbon emissions (Alymani et al., 2023; *Fig. 7*).

Regression analysis method

Regression analysis is a method that allows for finding the relationship between a functional relationship (model or equation). For complex systems, regression analysis should be regarded as an iterative process; That is, the output is used for diagnosis, verification, criticism and possible modification input. Multivariate regression is a widely applicable method that is not limited by constants and other constraints. It can accurately measure the relationships and fitting degrees among various factors and is suitable for analyzing situations under the combined action of multiple factors (Zhao et al., 2024). Surahman et al. (2022) analyzed the factors influencing household energy consumption in major cities of Indonesia during the COVID-19 pandemic using the multiple regression

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method. Wang et al. (2022) analyzed the factors influencing residents' household energy consumption by using the multiple regression analysis method. The impact of household income on household carbon emissions under different savings levels was estimated using the panel threshold model. Deng et al. (2021) adopted the multiple linear regression analysis method to analyze the relationship between different building types and residential heating energy consumption.

STIRPAT model method

The IPAT (Environmental Impact of Population, Affluence and Technology) model is the most common decomposition method used for carbon emissions. The STIRPAT model is an empirical model used for analyzing environmental impacts, aiming to quantify the influence of population, economic development levels, and technological changes on environmental stress. This model was first proposed by Dietz and Rosa in 1994 and was later further developed and improved by York et al. (2021). Huo et al. (2021) adopted the STIRPAT model to investigate the multiple impacts of urbanization on building carbon emissions from three aspects: population, economy and space. Wang et al. (2023) used panel data and the STIRPAT model to study the relationship between global urbanization and household energy carbon emissions from 1990 to 2015.

LMDI decomposition method

LMDI was first proposed by Ang. It has the advantages of simple operation, strong adaptability and no residual decomposition, and is a method frequently used by scholars (Kertsmik et al., 2024). Wang et al. (2022) based on the kaya equation and the logarithmic mean Divisia index (LMDI) method, explored the key factors driving the changes in household energy consumption in China during the period from 2005 to 2017. Nie et al. (2014) found through the LMDI method that both the expenditure share and population size in household energy consumption in China have a positive impact on carbon emissions in the health and economic benefits of urban and rural areas. Ma et al. (2020) found using the LMDI model that per capita building area and the energy intensity of urban residential buildings are the most important factors affecting the uncertainty of emission peaks. Luo et al. (2023) combined with the Kaya–Theil decomposition, decomposed the differences in CO_2 emissions from urban and rural residents' consumption in China into four factors. The results show that from 2005 to 2020, the increase in per capita CO_2 emissions from rural residents' consumption was higher than that from urban residents' consumption, and the spatial difference was relatively large. Xu et al. (2023) applied IDA based on the logarithmic Mean Divisia Index (LMDI) to the energy consumption of Singaporean households. Different types of energy usage were analyzed. Kanemoto et al. (2020) analyzed the driving factors of carbon dioxide emissions in the residential sector of Japan using LMDI and regarded the number of households as the activity effect. Analyses were conducted at the prefectural level and the energy type level. Kurniawan et al. (2023) used LMDI to decompose CO_2 emissions from Indonesian households. In the studies mentioned later, population seems to be the driving variable, and both direct (i.e., fuel combustion) and indirect (i.e., power generation) emissions have been taken into account. Dennehey et al. (2024) took disposable income as the driving factor and applied the LMDI method to break down the heat energy usage of Irish households. In order to incorporate useful energy into the analysis. Obviously, most of the existing research focuses on developing countries. This is reasonable because

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the energy transition follows the economic development there (Guo et al., 2024). As can be seen, the LMDI modeling approach has been widely deployed by researchers in different countries. Meanwhile, findings from factor decomposition research overwhelmingly point to population and income as the principal factors affecting residential carbon emissions from energy consumption internationally.

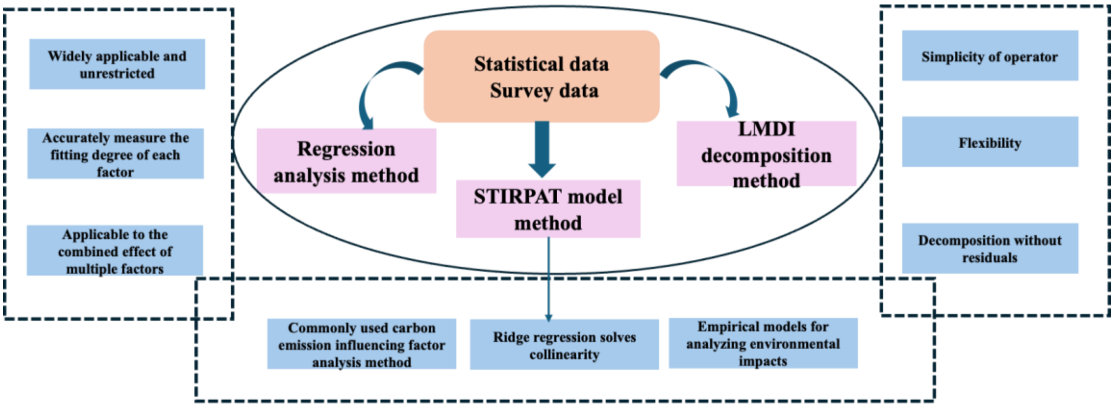

Figure 7. Analysis of influencing factors of carbon emissions from household energy consumption

Predictive scenario analysis

For the prediction of carbon emissions from household energy consumption, scholars mainly use two top-down and bottom-up models, and combine different scenarios to predict household energy consumption and carbon emissions. Among them, the top-down approach links the energy used by buildings to the reports of socio-economic metrics, technologies and physical drivers. The bottom-up approach is based on the calculation of energy consumption for each building, providing decision-makers with more detailed information to enable them to make more effective decisions based on regional patterns (Khanna et al., 2023). Most of these studies were conducted in the United States, mainly focusing on residential and commercial buildings. The prediction targets mainly include building energy consumption, such as electricity consumption for heating, ventilation and air conditioning, and on-site energy consumption intensity. Representative top-down models include several machine learning techniques, namely artificial neural Network (ANN), Gradient boosting (GB), deep Neural Network (DNN), Random Forest (RF), stack, K-nearest neighbor (KNN), Support vector Machine (SVM), decision tree (DT), linear regression (LR), and hybrid deep learning (DL) methods; The bottom-up models include the LEAP model, the SD model, the FIS model, the RF model and the STIRPIT model (Niu et al., 2023; *Fig. 8*).

Top-down model method

Top-down models are used to explore the interaction between the energy consumption sector and macroeconomic factors in an overall manner to predict future energy consumption or carbon emissions. Zmeureanu et al. (2023) reviewed the application of artificial neural networks in predicting the hourly energy consumption of buildings in 2019 and concluded that artificial neural network algorithms achieved good results in both single-step and multi-step predictions. Dostmohammadi et al. (2024) utilized three

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discrete algorithms, namely Artificial Neural Network (ANN), K-Nearest Neighbor (KNN), and Decision Tree (DT). In addition, this application also adopts three other machine learning algorithms: Random Forest (RF), Extreme Gradient Boosting (XGB), and Gradient Boosting Tree (GBT). In order to improve the accuracy of the forecast, the superimposed ensemble method was adopted, in which the forecasts generated by many algorithms were combined to predict the energy consumption of buildings. Mohan et al. (2024) proposed a stacked ensemble model, which combines Extreme Gradient boosting (XGB), Decision Tree (DT), and Random Forest (RF) algorithms to predict the energy consumption of heating and cooling loads (HL and CL) in buildings. Alymani et al. (2023) introduced a new IMFO-WVEL method for energy consumption prediction of residential buildings. The IMFO-WVEL model is mainly used to predict the energy utilization of residential buildings. Elbeltagi et al. (2021) predicted the energy consumption in the early design stage of residential buildings based on the method of artificial neural networks. Cui et al. (2024) used the residential energy consumption survey dataset and three tree-based machine learning algorithms to develop separate energy usage intensity prediction models for two typical types of residential buildings in the United States. The results show that the prediction model based on LightGBM has the best prediction effect on apartment houses, while the prediction model based on CatBoost has the best prediction effect on single-family houses. Finally, the SHAPLEY additive theory is applied to the analysis of the influence of residential characteristics on energy consumption. Wang et al. (2024) applied and evaluated the combination of evolutionary algorithms and traditional neural networks to predict building energy consumption in the residential sector. In the deployment of bottom-up models, researchers apply a variety of models to generate forecasts. The selection of a specific model is often contingent upon both data adaptability and the investigators' entrenched preferences. In their predictive exercises, scholars perform simulations across multiple scenarios with the objective of determining which scenario is paramount for facilitating carbon emission reductions in residential energy consumption.

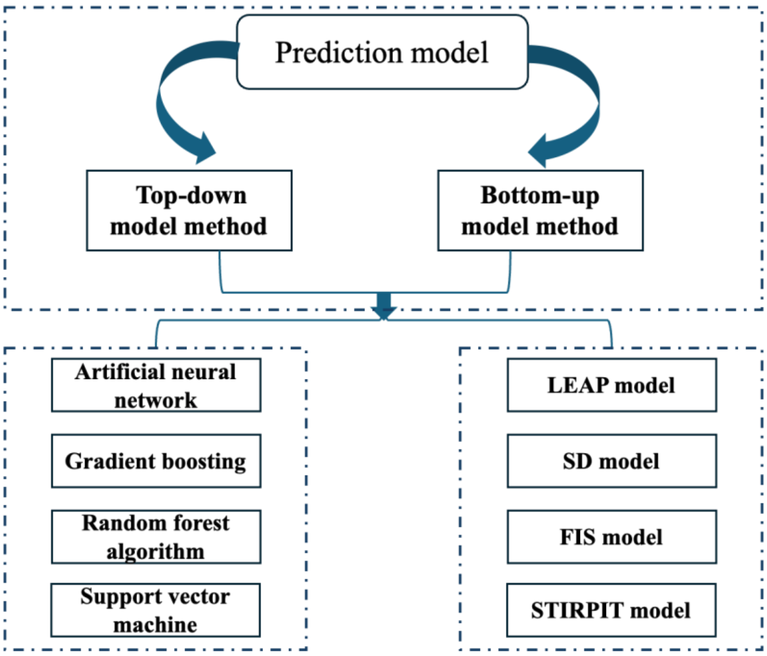

Figure 8. *Prediction model of carbon emissions from household energy consumption*

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Bottom-up model method

The bottom-up model summarizes the building energy consumption and carbon emissions at the regional or national level through the accumulation of end-user energy consumption from the bottom up. The main models included are the LEAP model, SD model, FIS model, RF model and STIRPIT model. Then, combined with scenario analysis, predict or analyze the carbon emission peak of the building (Jiang et al., 2020). Huo et al. (2021) embedded the bottom-up terminal energy decomposition LEAP model into the system dynamics model and constructed a complete dynamic simulation model. It reveals the dynamic interaction and feedback mechanism between macro and micro factors. Tang et al. (2023) adopted the SD model to simulate the flow and stock changes, CO_2 trends and peak times of urban residential buildings, and conducted a predictive analysis of the CO_2 emission trends and emission reduction potential of urban residential buildings in China. Tan et al. (2024) established the STIRPAT–Ridge model and predicted the peak of carbon emissions in China. Finally, a combination of static and dynamic methods was adopted to predict the carbon emission peaks under the low-carbon scenario, the benchmark scenario and the high-carbon scenario. Shanableh et al. (2024) aims to explore the potential of the Fuzzy Interference System (FIS) in estimating the energy consumption of various residential buildings in northern Cyprus. Liu et al. (2024) established an RF model to predict the energy consumption of buildings, ranked the importance of building envelope parameters, and compared the performance of RF with that of ANN and SVM. Duan et al. (2023) achieved energy consumption prediction through principal component data by applying the principal component analysis model, which is of great significance for energy conservation and emission reduction in buildings.

Conclusion and policy suggestion

Conclusion

Household sector is a major contributor to national energy consumption and rising carbon emissions. A comprehensive review of global carbon emissions from household energy consumption helps clarify the current research landscape and future trends. This study employs bibliometric methods to conduct macro and micro, qualitative and quantitative, holistic and detailed analyses of 838 selected papers. It reviews research hotspots, calculation methods, influencing factor research methods, and prediction models, discussing the evolving trends, research priorities, content, and countermeasures in household energy carbon emissions. The findings are summarized as follows:

(1) Analysis of publication volume and disciplinary contributions reveals a rapid growth in publications after 2018. This surge is primarily attributed to global recognition of the adverse impacts of excessive carbon emissions on sustainable development, leading to concerted efforts towards decarbonization across sectors, including significant attention to the household sector. Disciplinary focus has centered on energy transition and the environmental impacts of carbon emissions. Reviewing publication trends and disciplinary contributions provides a macro-level understanding of household energy carbon emissions. Future research should prioritize renewable energy development and the adverse environmental effects of carbon emissions.

(2) Regarding research hotspots, key factors in driving mechanisms include health, household income, policy, population, renewable energy, poverty, and urbanization. In

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energy-saving consumption behaviors, different behaviors significantly impact energy demands such as electricity bills, cooling, and heating. Electricity consumption is the most prevalent and widespread form of household energy use, making it a critical focus for emission reduction. Therefore, current research hotspots will remain central to future research directions and problem-solving.

(3) Primary calculation methods include the carbon emission coefficient method, currently the most applied approach. Other methods, such as input-output analysis and life cycle assessment, have gained traction recently but require extensive data. The consumer lifestyle approach is mainly used for calculating direct and indirect carbon emissions. Future calculations could integrate multiple methods for comprehensive direct and indirect emission accounting.

(4) In modeling influencing factors, methods are mainly categorized into regression analysis, the STIRPAT model, and LMDI decomposition. Each has its applications: regression analysis is widely used and allows precise measurement of individual factors; the STIRPAT model, common in carbon emission studies, effectively addresses collinearity issues and is often combined with panel models; LMDI offers simplicity, strong applicability, and no residual error.

(5) Predictions primarily target building energy consumption, such as heating, ventilation, air conditioning electricity use, and on-site energy intensity. Models are divided into top-down and bottom-up approaches. Representative top-down models include various machine learning techniques: Artificial Neural Networks (ANN), Gradient Boosting (GB), Deep Neural Networks (DNN), Random Forest (RF), Stacking, K-Nearest Neighbors (KNN), Support Vector Machines (SVM), Decision Trees (DT), Linear Regression (LR), and hybrid Deep Learning (DL) methods. Bottom-up models include the LEAP model, SD model, FIS model, RF model, and STIRPAT model. Consequently, energy conservation and emission reduction in buildings should be a key focus for future research.

Suggestion

(1) Transition to smart energy. We should vigorously develop intelligent energy technologies and promote breakthroughs in key areas first. Promote the in-depth integration of emerging technologies such as the Internet, artificial intelligence and big data with traditional manufacturing industries, and build a green manufacturing system. In addition, smart meters and applications are also good ways to help households sense changes in energy efficiency and lead to more efficient energy usage. Sustainable strategies and goals for phasing out fossil fuels in urban power supply systems are crucial for building climate-resilient cities. Especially in rural areas, subsidies should be encouraged for families to upgrade outdated household appliances such as traditional overburning stoves and fireplaces to modern energy-saving devices in order to reduce energy waste and improve living conditions. In terms of residential buildings, measures to improve the building envelope, such as the adoption of innovative materials, the improvement of insulation and building structure of new buildings, and the renovation of existing buildings to reduce energy consumption of buildings.

(2) Transition to renewable energy. We should focus on accelerating the development of wind power and solar power generation, develop nuclear power safely and orderly, develop hydropower and other renewable energy sources in accordance with local conditions, and enhance the utilization capacity of clean energy. Therefore, clean power generation systems require climate policies to comprehensively promote renewable

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energy power generation projects in the household sector in both urban and rural areas. Encourage high energy-consuming industries to replace coal with high-quality energy sources such as renewable energy and electricity.

(3) Improve energy policies. Climate policies should focus on how to address the spatial shift and regional inequality of carbon emissions from electricity consumption. The government should formulate differentiated energy pricing policies to reduce inequality while restricting the energy consumption of some high-income groups. Such policies are currently implemented in the field of electricity and should be extended to fields such as natural gas and oil. The government should formulate standards for green building construction and green home appliances, promote green construction methods, offer preferential treatment or price discounts for green building materials and other structural buildings, and facilitate the purchase of low-carbon residences and home appliances. Encourage energy-saving renovations of old residential buildings; Encourage the public to buy fewer private cars or promote energy-saving and environmentally friendly cars, vigorously develop public transportation, and advance the creation of a “bus metropolis”. Therefore, when formulating national energy policies, these issues should be carefully considered. Developing countries cannot simply copy the policies of developed countries. Instead, they must modify and adjust these policy design models to suit their own national conditions.

(4) Enhance energy conservation awareness. For residents, turn off unused electrical appliances, reduce the use of electrical appliances, dim the lights, make good use of electrical appliances during periods of low electricity bills, lower the indoor temperature, transition to more cost-effective heating energy sources, and use computer-controlled heating schedules. Try to choose public transportation for travel.

(5) Regarding calculation methods, the selection of carbon emission factors should not blindly adhere to international standards; instead, country-specific emission factors tailored to national conditions should be developed. Furthermore, integrating multiple calculation approaches during the process will yield more comprehensive results.

(6) In terms of model selection for analyzing influencing factors, each model has its applicable scope. It is hoped that scholars can choose models that align with both data suitability and their specific research needs when conducting studies. This will enable objective assessments and practical solutions for reducing carbon emissions from household energy consumption.

(7) In predictive modeling research, previous scholars have paid relatively limited attention to this area. Therefore, energy conservation and emission reduction in the building sector should become a key focus for future studies.

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