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Review

Insights of Urban Density and Energy Consumption. A Bibliometric Correlation Analysis

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Abstract: Although impending urbanization is a well-acknowledged problem, there is a rising concern about how the urban forms will change and what can be the impacts on the global energy demand. As hubs of economic, social and cultural activities, cities are major energy consumers and GHG emissions. Energy consumption is a technical or a spatial problem? From Newman and Kenworthy to today, several studies have tried to shed light on this nexus. In this work, the controversial paradigm of urban density is discussed as a key component of the fight against climate change impacts. Concerning energy consumption, an in-depth bibliometric analysis is developed to identify the interdependencies of the terms. As a key 'promise' of an efficient urban configuration, density has been the core of diverse studies but with still under exploration arguments. This work provides a way forward for planners seeking to design strategies related to dense urban tissues exploring controversial paradigms as a key solution for energy-efficient problems.

Keywords: Bibliometric Analysis; Correlations; Energy consumption; Urban Density

1. Introduction

Given the climate change challenges and multifaced consequences, the literature reveals contrasts and debates respecting the concern of urban form and energy consumption. Urban areas account for more than 70% of global final energy consumption with the urban populations [1] with the global population to overcome the 2.5 billion between 2010-2050 [2] being hubs of Greenhouse Gases (GHG) productions and energy demand [3]. The most recent Intergovernmental Panel on Climate Change [4] identified the role of urban form as a key determinant of operational and embodied energy use [5]; nonetheless, the impact of spatial patterns of urbanization on energy consumption is still under investigation. Several studies (e.g. [6]–[9]) advocate the importance of high density resulting in reduced transport use, improvement of life quality or public health representing more efficient land use distribution, while others argued the effects on Urban Heat Island (UHI), the congestion and the elimination of green spaces, etc. (e.g. [10], [11] or [12]).

Over the last decades, energy efficiency has been the research interest on single buildings approaches rather than on urban systems [13]; nevertheless, numerous studies (e.g. [14]–[18]) stress the importance of a glance on urban configurations or mobility (e.g. [19], [20]), green spaces (e.g. [21]-[22]) or passive and active production (e.g. [23]-[24]) to enhance decarbonized and sustainable urban models.

Several studies (e.g. [20], [25]) proved the evidence of the interdependencies of energy demand and urban configurations. Controversial studies assert the correlation between 'high density' and 'energy consumption' advocating, as well as the European Green

Paper arguments (1990) [26] ([…] *'We, therefore, need a fundamental review of the town planning strategies to emphasize mixed-use and denser developments and people to live closer to workplaces making the car an option and not a necessity'* [27]). Higher levels of the population have been associated with economic benefits (e.g. [28]) or transportation reductions [29]. This tempting dilemma becomes a veritable challenge when the issue of energy efficiency is generated in communities as higher densities are said to enable economies of scale and enhance technological and economic viability.

This paper attempts to clarify the debate concerning the effects of urban density and energy consumption in urban areas along with a bibliometric analysis using CitySpace. The scope of the work lies in the analysis of historical research and debates being structured accordingly. Section 1 introduces and overviews previous studies respecting the controversial paradigm of dense configurations and its challenges to energy balances. Section 2 describes the methodological scheme and the analysis, Section 3 presents the results of the bibliometric analysis, while to end up, Section 4 the conclusions of the main findings.

1.2 Urban Configurations, Land-use and Energy Balances. Previous Observations

Over the last years, there has been a rising interest in the concepts of urban densification as part of spatial strategies against urban sprawl and growth. The logic of densifying originates from the perception that reversing from low density as dominated 60 years ago is feasible to embrace the mild transportation modes [55].

The controversial paradigm of a dense urban layout is cited in several studies, where the concentration of activities and populations is often perceived as a challenging issue due to intensified conflicts between urban land uses. A typical example of this problem is the lack of green spaces and amenities and hence the risk of permeable soils and the rise of the UHI effect with a worsening of the overall urban climate conditions and the quality of life (e.g. [56]-[57]). Nevertheless, despite some studies and empirical evidence, e.g. the case of Newman and Kenworthy in 1989 [30], there are no sufficiently conclusive outcomes proving the relationship between the urban form and the overall energy consumption (e.g. [31]). In this experimental study, the authors identified the correlation between urban density and transport energy consumption in 32 cities (Figure 1) arguing an intricate correlation between the two key parameters.

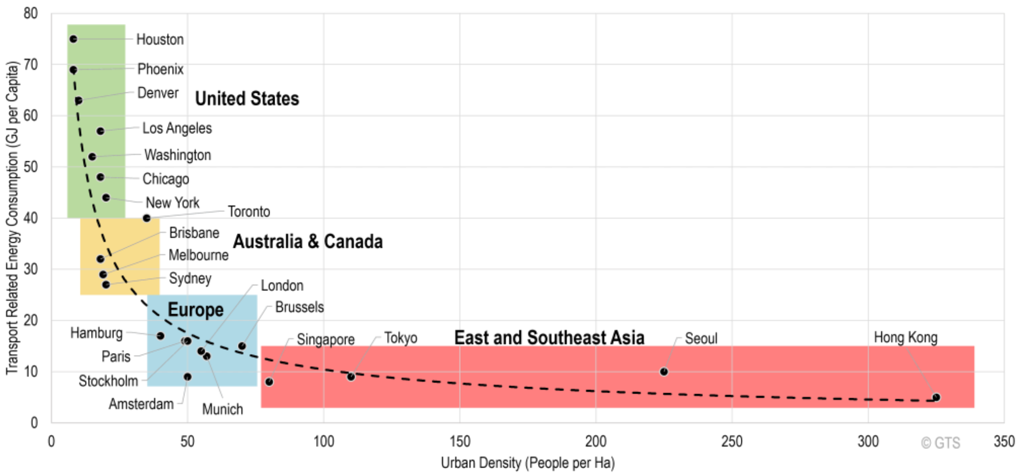

Figure 1. Correlation of urban density and transport-related energy consumption [30]

Between the '20s and '40s, few studies considered the relationship between land uses; urban morphology and energy consumption [32]. However, this problem has concerned scholars focused on for more than three decades (e.g. [33]-[34]). Owens [35] firstly investigated in 1986 the urban form and its implication for energy consumption, the energy supplies, the price, the RES use, etc. determine the energy demand and consumption in its spatial dimension and the most influential attributes of this correlation: compactness;

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integration of land uses, clustering of the trip ends and, at least to some degree, self-contained urban units of variable size and number (Figure 2).

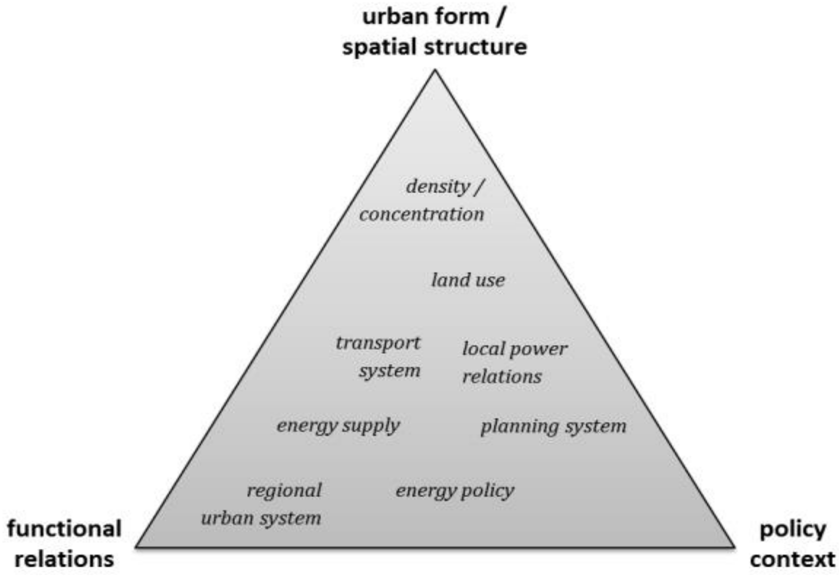

Figure 2. Urban form/spatial structure, functional relations and policy context as interrelated dimensions [35]

Owens [35] further attempts to quantify the magnitude of the key factors of the urban structure and their potential impacts and implications on energy consumption (Figure 3).

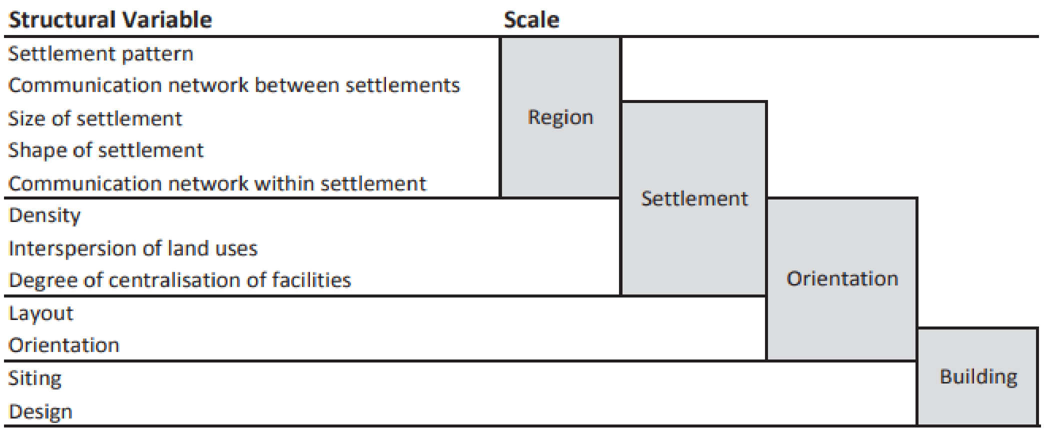

Figure 3. Urban structure variables affecting energy at diverse urban scales

In the literature, the urban form is defined as the physical qualities of the natural and urban environment in terms of geometry, configuration and **density**, which foster the interactions of people, activities and space (e.g. [36]-[37]). Burchell and Listokin [38] refer to a wide range of scientific works focusing on the connection between urban morphology and energy consumption. The most representative study on this issue is, however, the 'Costs of Sprawl' (1974) [39] representing the preliminary attempts the analysis the relationship between urban metabolism and the related energy costs along with other parameters.

Salat [40] and Ewing and Rong [41] have analyzed the influence of density; architecture and structure on energy consumption. Ewing and Rong [41] propose three possible pathways through which the impacts of the urban morphology influence energy consumption: (a) losses through the transmission and energy distribution; (b) energy demand associated with the UHI effect and (c) the consumption variance through the size and the building typology in the urban areas. Papa et al. [42], nonetheless, concluded that despite

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the rising interest in a scientific review in questioning developing effective solutions for the reduction of energy consumption, there is no clear evidence of their interdependency. Urquizo et al. [43] at their works explain why we search for energy use in agglomerations considering the cities as a significant proportion of the world's (primary) energy consumption. However, the reduction in consumption is related to various morphological factors affecting the microclimate of the urban area, influencing the wind flows and the heat island effect, heating, cooling and artificial lighting needs and the percentage of solar radiation reaching the façade [44] (Figure 4):

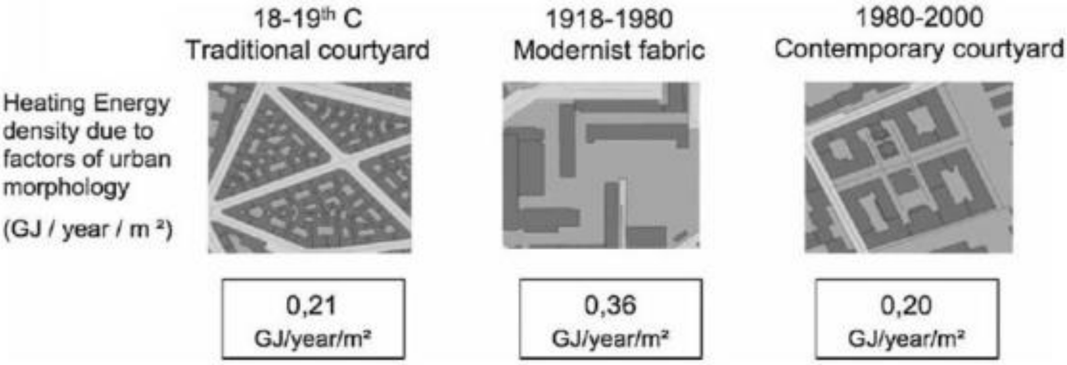

Figure 4. Effect of urban morphology on the energy need of building stock in Paris [44]

Mitchell [45] underlines eight key factors for building energy consumption including building consumption; users' activities; urban structure (geometry); etc. compared to the works of Salat et al. [46] and Ratti et al. [20] (Table 1).

Table 1. Factors influencing building energy consumption

Mitchell [45]	**Salat et al.** [46]	**Ratti et al.** [20]
Urban geometry	Urban structure	Urban geometry
Building morphology	Building performance	Building design
Thermal performance of materials	Equipment	Systems' efficiency
Efficiency of internal systems	Users'/Occupants' behavior	Occupants' behavior
Occupants' activities & behavior	Type of energy use	
Internal and external temperatures		

Baker and Steemers [47] consider the overall impacts of the urban form on building energy emphasizing the structure of individual buildings (Figure 5):

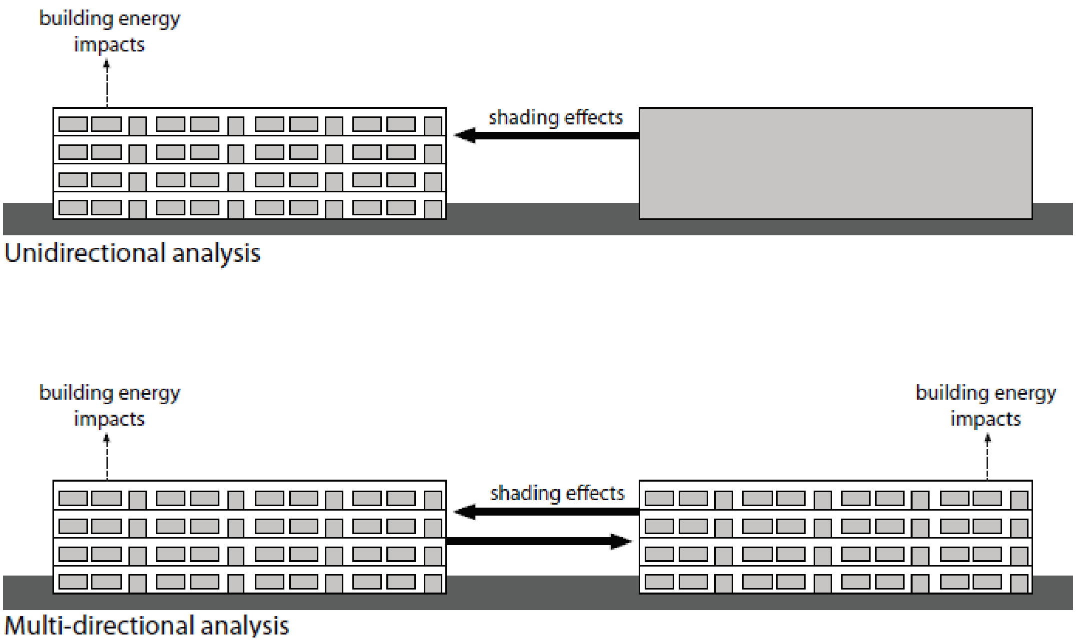

Figure 5. Unidirectional and multi-directional analysis of the urban structure

Miller [48] referring to 'building morphology' reflects the geometry, including the characteristics of its envelope, but also its design attributes (e.g. orientation, surface, etc.) [45]. Among the most interesting attributes to influence building, energy consumption is compactness [45] and building density [48]. Steemers [49] states a potential 50% of reduction in heating requirements by increasing the building density. Ewing and Rong [41] conclude in their works that households living in low-density, single-family homes, etc. consume more than 50% of energy for space heating and more than 20% for cooling comparing to multi-family or terraced houses.

Less frequently, studies of urban structures had a quantitative approach. Pont and Haupt [50] note that *'a quantitative analysis of the built form has not been applied thoroughly'*. Nonetheless, there is a growing recognition that the methods of the quantitative descriptions regarding the urban structures expand the qualitative approaches. They attempt to connect the spatial patterns to quantitative data and indicate the typical use of the criterion of **'density'** as an identifying concept of the building typology and the urban patterns of the agglomerations.

2. Materials and Methods

2.1 Data Sources

In this study, the first step was to determine the selection of reference journal articles from WoS and Scopus databases for unified analysis. WoS and Scopus are the primary data sources with authority and representativeness ([52]-[53]), complementing each other in this process to obtain a comprehensive view of the problem. For the WoS, the core collection consists of SCI-E, SSCI, A&HCI, etc. This study limited the search by creating a search string [54] and selecting "Topic" as the search type to retrieve the title, abstract, author keywords and Keywords Plus.

The second step was to choose journal articles using relevant keywords. As a result, "Urban Density (UD)" and "Energy Consumption (EC)" were chosen as key search keywords, and the search was conducted over an indefinite period (1900 to the present). The date of this search was July 20, 2022, and the search results were narrowed and filtered, yielding 964 initial relevant items. As a result of the correlation between attributes of UD and EC, cities have become centres of consumption and resource transformation as a nexus of human activities; urban population density, building form, urban morphology, and urban transportation are the concrete manifestations of the relationship between UD and EC [31], [55].

Moreover, as hubs of energy consumption, cities significantly impact the local, regional, and possibly global environment [56]. The keywords "building consumption", "carbon emissions", "urban energy efficiency" and "sustainable development" were chosen for artificial refining and screening of the first collected material. 698 papers were retrieved. Eventually, 581 were acquired using the Citespace 6.1 remove duplicates command. All records were transferred to CiteSpace version 6.1 R2 Advance for computation and analysis.

2.2 Method

Knowledge mapping, a cutting-edge technique of analysis in bibliometrics and scientometrics visually represents intuitively the findings of a quantitative study of a research topic [57]. CiteSpace is a popular Java platform-based knowledge mapping application that can do co-citation, co-occurrence, and cooperation network analysis of database literature and graphically and intuitively explain the evolutionary patterns, knowledge association status, and research horizons [58]. The results of this study focused on six areas: temporal distribution of publications, journal co-citation, country co-occurrence distribution, keyword co-occurrence, literature co-citation network, and landmark literature.

Reference co-citation analysis was initially proposed by Small [59] based on the specific principle that if two papers are co-cited by a third paper, the correspondence between the cited and cited papers represents the frontier of the literature in the field. In CiteSpace, the LLR algorithm is used to extract terminology from the titles of these papers to name the research content corresponding to the clusters [60]. The cluster analysis of citations provides a clear picture of the research framework of UD and EC, providing evidence for the development of the field. The different parameters in the results reflect each node's frequency and academic impact. Using CiteSpace 6.1 R2, 111 articles were duplicates [61]. In this study, the relationship maps obtained through CiteSpace for the different domains span the years 2001 to 2022, since the first mentions of UD and EC in the acquired database were articles from 1991. The software can also show the trend of UD and EC from 1991 to 2022 by calculating the relevant information; the development of the field is revealed.

An important statement to consider for the findings in CiteSpace analysis is the 'centrality' as a key indicator for analyzing the importance of keywords. If the centrality exceeds 0.1, the node is a central node in the research and has a more significant influence.

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3. Results

3.1. Results by Data Collection

3.1.1. Number of Publications

The number of publications is an important indicator of UD and EC research trends. The distribution of the number of papers published each year was examined using 581 articles on UD and EC. In particular, 2008 and 2017 are important years; the analysis reveals that the UD and EC research has undergone three distinct phases. The period 1991-2008 tended to plateau, with the less relevant research literature, and the topic had not yet attracted academic attention.

From 2008 to 2016, when the Fourth World Urban Forum and the World Urbanization Prospects led to a historic global agreement, it arouses scholars' research on urban development trends, and the number of papers on UD and EC research increased to some extent. Still, the number was relatively stable each year, indicating that the field was beginning to attract academic attention.

In 2016, when the world reached a landmark consensus through the Paris Agreement, there have been a sharply increased number of articles, where a large number of keywords related to climate change appeared 2017. However, the number of article citations showed a fluctuating downward trend in 2018, indicating that after the emergence of the new issues, due to the uncertainty of the research and the diversity of new issues, the research has entered a phase of reflection and re-exploration. Then in 2019, it started to rise again, the number of papers shows a steep increase in the number of exploding literature, and the number of publications in only half a year in 2022 is the same as the number of publications in 2016, indicating that UD and EC research has attracted wide attention from and become a research hotspot (Figure 6).

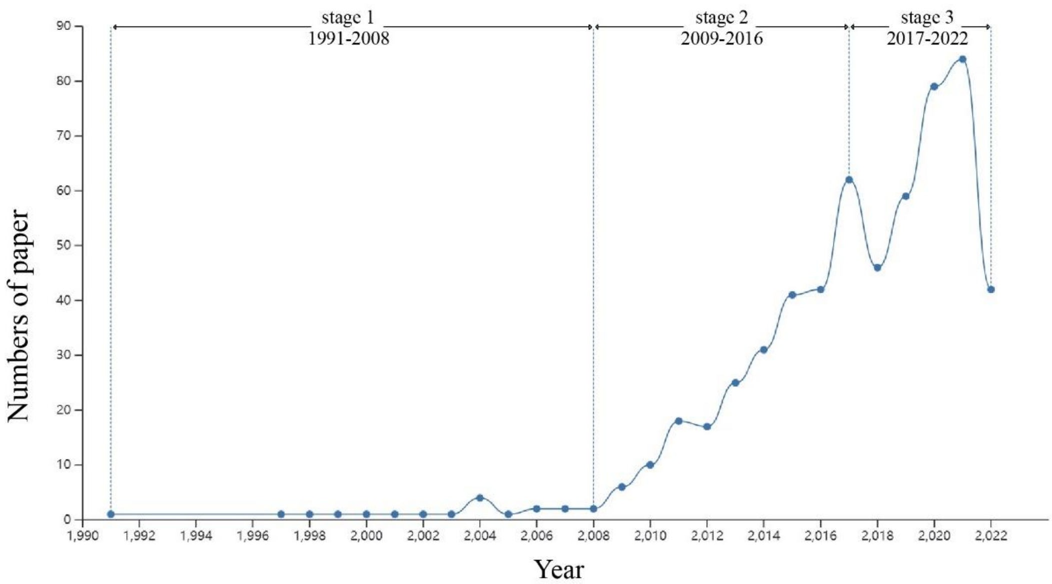

Figure 6. Distribution of annual publication outputs in the UD and EC field from 1991 to 2022

3.1.2. Major Journals Analysis

The node type was set to cited journals, and the time slice was set to 1 year to generate a graph of cited journal relationships [62]. In this research, the node value was 720, and the connection value was 4611, meaning that 720 journals were cited in this field and 4611 scholarly relationships were generated (density to 0.0178, Figure 7).

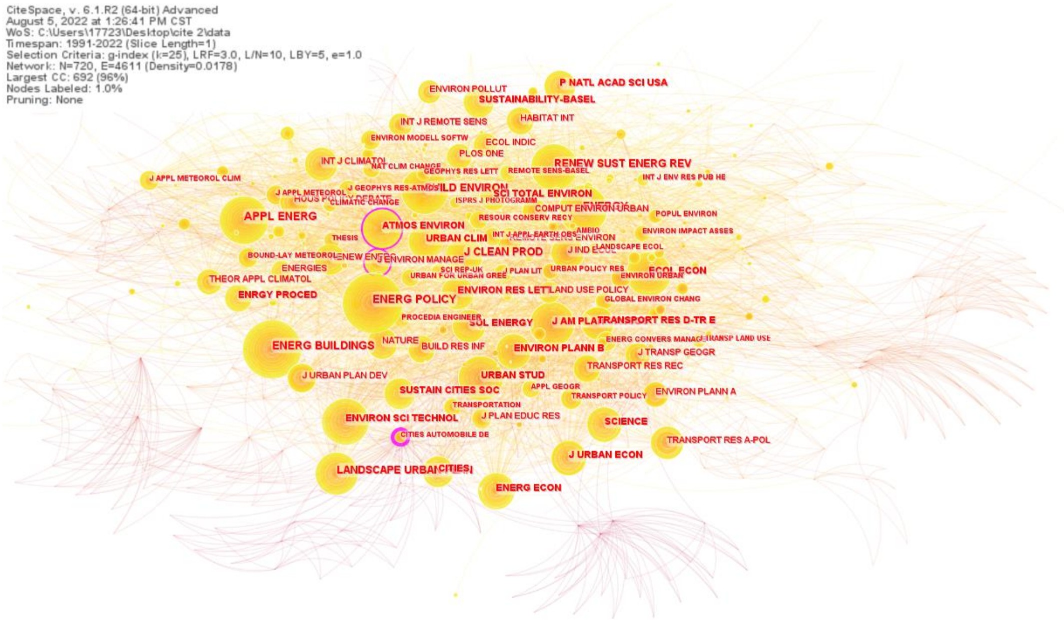

Figure 7. Knowledge map of co-journals of papers published on UD and EC from 1991–2022

The top five journals cited were energy and buildings, energy policy, applied energy, renewable & sustainable energy review, and energy (Table 2). The results shown in Figure 7 indicate that EC and emission reduction depend on technological innovation and industrial transformation and are closely linked to urban development patterns.

Table 2. List of cited journals and number of records contributed

Rank	Freq	Year	Cited Journal	Rank	Centrality	Year	Cited Journal
1	290	2001	Energy and building	1	0.21	1997	Cities automobile
2	289	2001	Energy policy	2	0.15	2002	Journal of environmental management
3	249	2005	Applied energy	3	0.11	2004	Atmosphere environment
4	227	2011	Renewable & sustainable energy reviews	4	0.08	2005	Applied energy
5	223	2001	Energy	5	0.08	2008	Environmental science & technology
6	199	2004	Building and environment	6	0.08	1997	Environment and planning B
7	166	2009	Landscape and urban planning	7	0.07	2001	Energy and buildings
8	166	2013	Journal of cleaner production	8	0.07	2004	Building and environment
9	148	1997	Journal of the American planning association	9	0.07	2007	Environment and planning A
10	145	2011	Ecology economics	10	0.06	2001	Energy

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4.1.3 Geographic Distribution

The analysis of the regional cooperation distribution of publications reflects the co-operation between the main countries [63] as well as the country's significance and impact on the research. The node type was set to country and the time slice to 1 year and sorted in the first release to generate a map and regional time zones in this field (Figure 8).

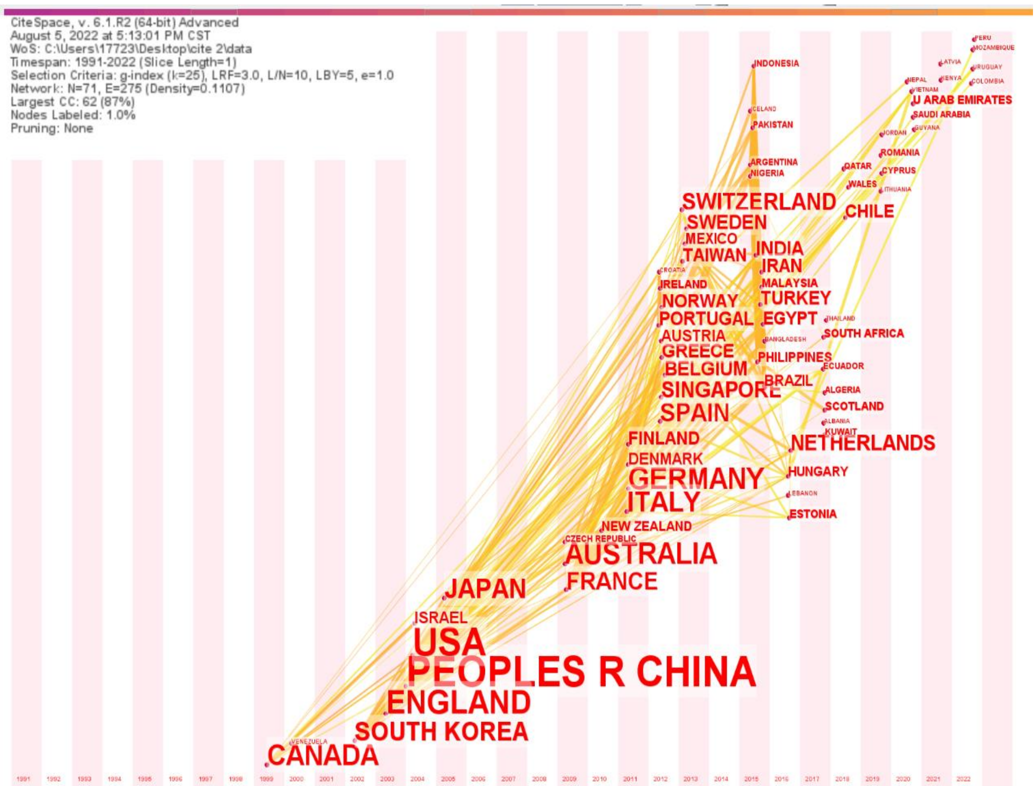

Figure 8. Time zooms of cooperative countries in the research on the UD and EC from 1991–2022

A total of 71 nodes and 275 data lines were obtained, representing 71 countries that have conducted relevant research in this field, resulting in 275 collaborations. From 1991 to 2022, 205 articles were published by Chinese institutions, 127 by US institutions and 55 by UK institutions. As shown in

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Table **3**, the USA is the leading country contributing to UD and EC, and it has the most collaborations and cross-citations with other countries (the centrality of 0.44). In addition, Canada was the first country to conduct research in this area in 1999, followed by Venezuela (2000) and South Korea (2002).

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Table 3. Major countries in the field of UD and EC from 1991–2022

Rank	Numbers of Articles	Centrality	Year of First Publication	Country
1	205	0.16	2004	China
2	127	0.44	2004	USA
3	55	0.13	2003	England
4	36	0.11	2009	Australia
5	36	0.07	2011	Germany
6	30	0.1	1999	Canada
7	27	0.11	2010	Italy
8	26	0.01	2005	Japan
9	22	0.04	2002	South Korea
10	20	0.13	2011	Spain

4.1.4. Research Subjects

Setting the node type to category and the time slice to 1 year will generate a co-concurrence mapping of subject categories, with a total of 62 nodes and 193 connections obtained. According to the publication time, energy & fuels, construction and building technology, and engineering civil were the first relevant studies in 1991, followed by environmental studies, environmental science & ecology (2002) (Figure 9).

Before 1997, the fields of energy fuels, building technology and civil engineering pioneered research, indicating that studies of UD and EC were the first to focus on the correlation between the construction industry and energy consumption. The period from 1997 to 2006 emphasized the impact of the environmental component on energy consumption and was supplemented by transportation and urban studies.

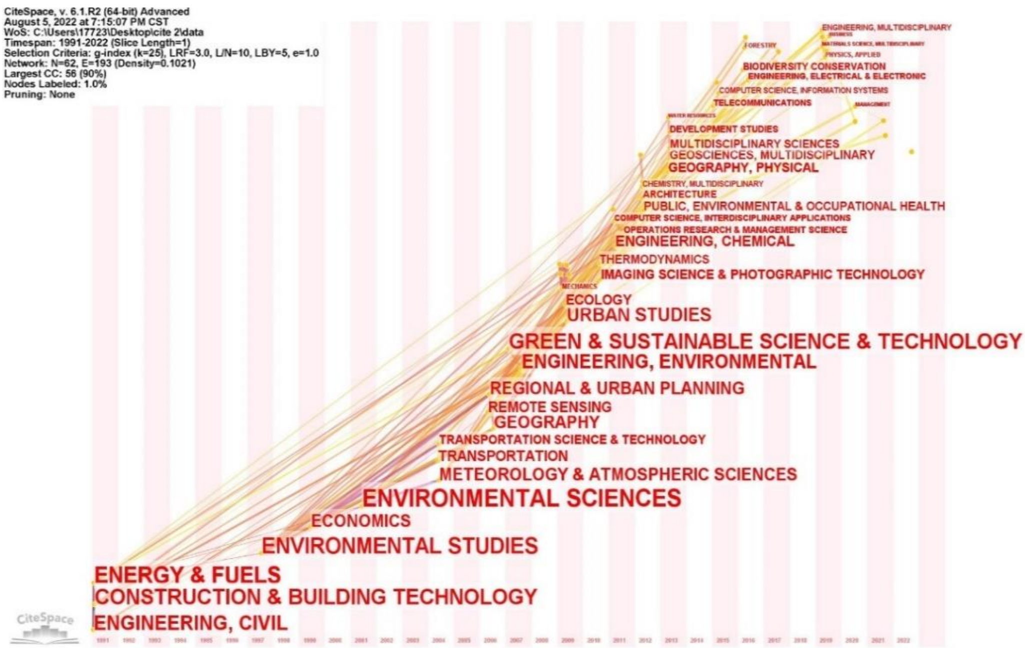

Figure 9. Time-zone view of research subjects

Table 4 presents the top 10 disciplinary categories of academic impact based on centrality.

Table 4. List of the most influential categories

Rank	Freq	Centrality	Year	WoS Categories
1	198	0.68	2001	Environmental science
2	153	0.46	1991	Energy & fuels
3	128	0.28	1997	Environmental studies
4	116	0.05	1991	Construction & building technology
5	114	0.02	2007	Green & sustainable science & technology
6	87	0.04	1991	Engineering, civil
7	69	0.07	2007	Engineering, environmental
8	61	0.08	2009	Urban studies
9	44	0.04	2006	Geography
10	42	0.12	2004	Meteorology & atmospheric sciences

The research areas are divided into three main directions, as shown in Figure 10: (1) energy fuels and technology, (2) construction and (3) building technology. Environmental and ecological studies link these two directions, indicating that this is a core discipline in the field of study, and environmental science has a centrality of 0.68, the most substantial citation explosion, indicating that it plays an essential role in this field. It is worth noting that among them, construction and building technology are directly linked to energy fuels and engineering civil and environment validating that the construction industry is one of the most energy-related consumers [64].

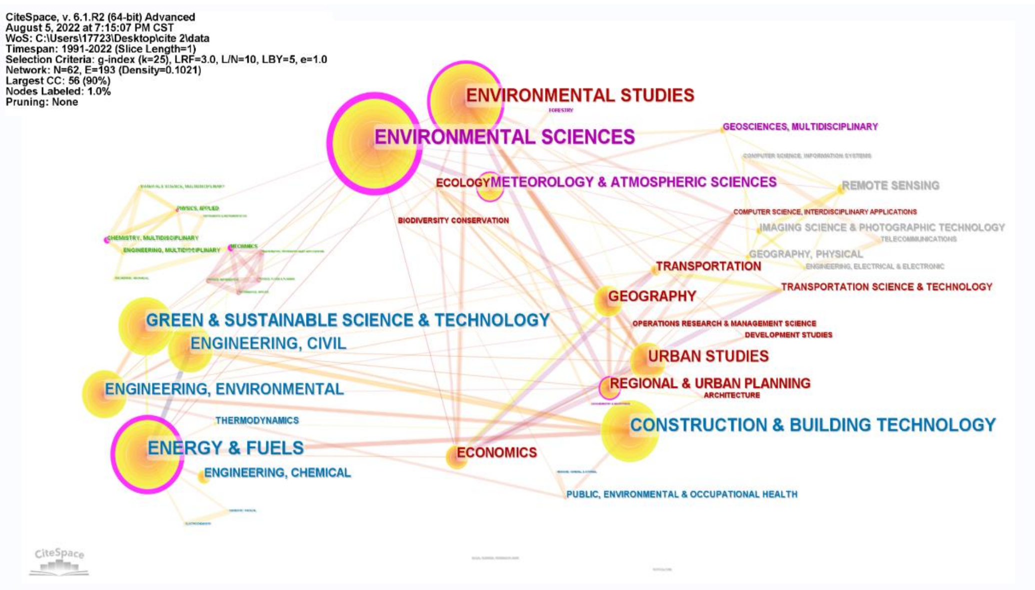

Figure 10. Co-occurrence network of research subjects

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4.1.5 Authors' Cooperation Distribution Analysis

Collaborative authorship analysis identifies the collaborative and cross-citation relationships among researchers [65]. A collaborative group of scholars can be analyzed to reveal the team effect of academic research [66]. In this section, the author's collaboration network graph contains 444 nodes, 426 connections and a density of 0.0043. Based on the topological analysis of the author cooperation network in Figure 11, this research field has formed a "K-core" model with Chen and Chiu as the nucleus, which enables adequate academic communication within the network, improves team cohesion, and serves as the foundation for knowledge growth. Researchers studying the field of UD and EC are mainly from China and USA.

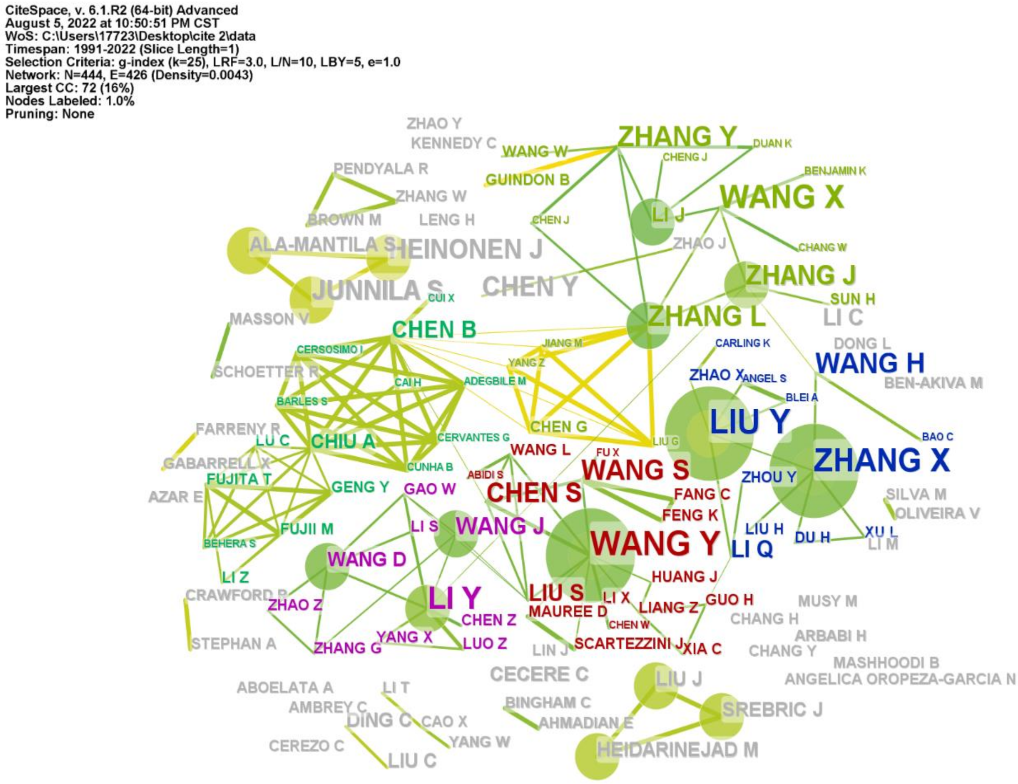

Figure 11. Knowledge map of co-authors of papers published on UD and EC from 1991–2022

4.1.6. Distribution of Contributing Institutions

The analysis of the distribution of collaboration between research institutions provided insights into this field's academic support and recognition [67]. This section presented a knowledge graph containing 328 nodes and 309 links with a density of 0.0058 (Figure 12).

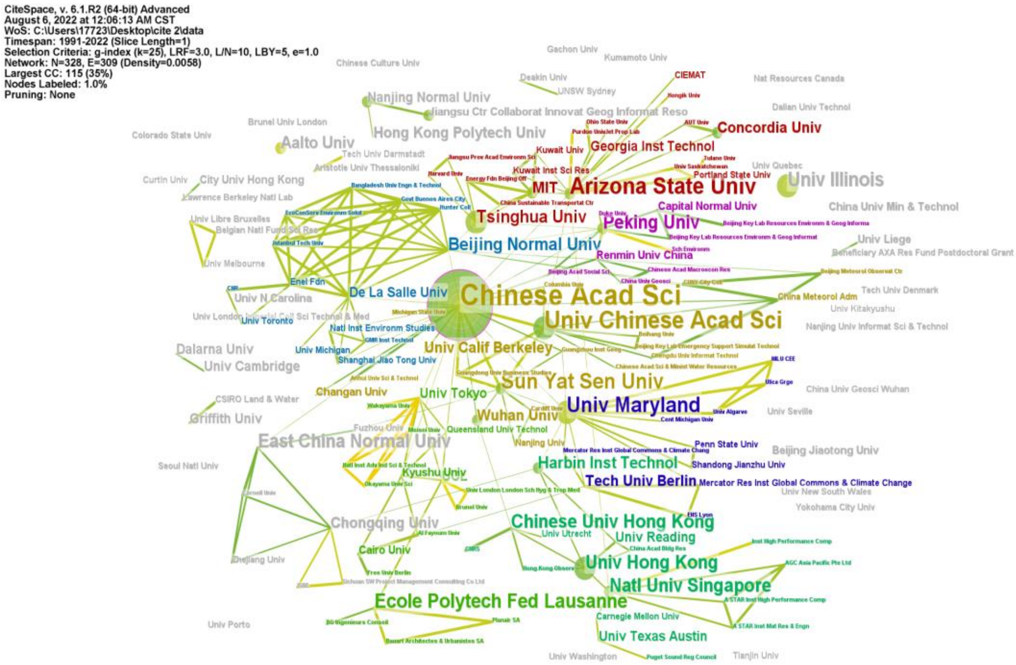

Figure 12. Knowledge map of cooperative institutions in the research on UD and EC from 1991–2022

Among the top 10 publishers from 1997-2022, the Chinese Academy of Science ranked first in the number of articles (33); the University of Chinese Academy of Science ranked second in the number of 16 articles, and Arizona State University ranked third in the number of 14 articles. Regarding collaborative centrality, among the top 10 research institutions, the Chinese Academy of Science ranked first (0.17) and Arizona State University ranked second (0.08).

As seen in Table 4 the volume and centrality rankings are not identical, indicating that there are research institutions that publish more articles, but the impact is not significant. Collaboration among research institutions, companies and universities worldwide is relatively fragmented. Although the Chinese Academy of Sciences has the broadest cooperation, they have not established a unified academic hub. Figure 12 conveys eight (8) decentralized academic research centres, with Arizona State University, Peking University, University of Chinese Academy of Sciences, Sun Yat-sen University, University of Maryland, East China Normal University, University of Tokyo, and the University of Hong Kong as research centres.

Table 5. Contributing institutions by frequency and centrality

Rank	Publication	Centrality	Year	Institution	Country
1	33	0.17	2011	Chinese Academy of Science	China
2	16	0.02	2013	University of Chinese Academy of Science	China
3	14	0.08	2010	Arizona State University	USA
4	12	0.01	2013	Sun Yat-Sen University	China
5	12	0.05	2011	University of Maryland	USA
6	9	0	2010	University of Illinois	USA
7	9	0.01	2013	Ecole Polytech Fed Lausanne	Switzerland
8	8	0.03	2011	National University of Singapore	Singapore
9	8	0.01	2017	University of Hong Kong	Hong Kong, China
10	8	0.03	2009	Peking University	China
10	8	0.02	2016	East China Normal University	China
10	8	0.01	2012	The Chinese University of Hong Kong	Hong Kong, China

4.2. Research Hotspots and Research Strategies

4.2.1 Reference Analysis

The cluster analysis of the co-citation network can visualize the main research contents that constitute the field's knowledge base [68]. The co-citation network was constructed by extracting the top 50 papers each year from 1991 to 2022, setting the pruning method to MST, clustering them according to the LLR and naming the clustering labels by extracting keywords. The clustering results of the literature are shown in Figure 13 except for “population density”, “economic agglomeration”, “residential development” and “building”. The impact of UD and EC, such as “greenhouse gas”, “land surface temperature”, "carbon dioxide emissions", and "microclimate", is also included.

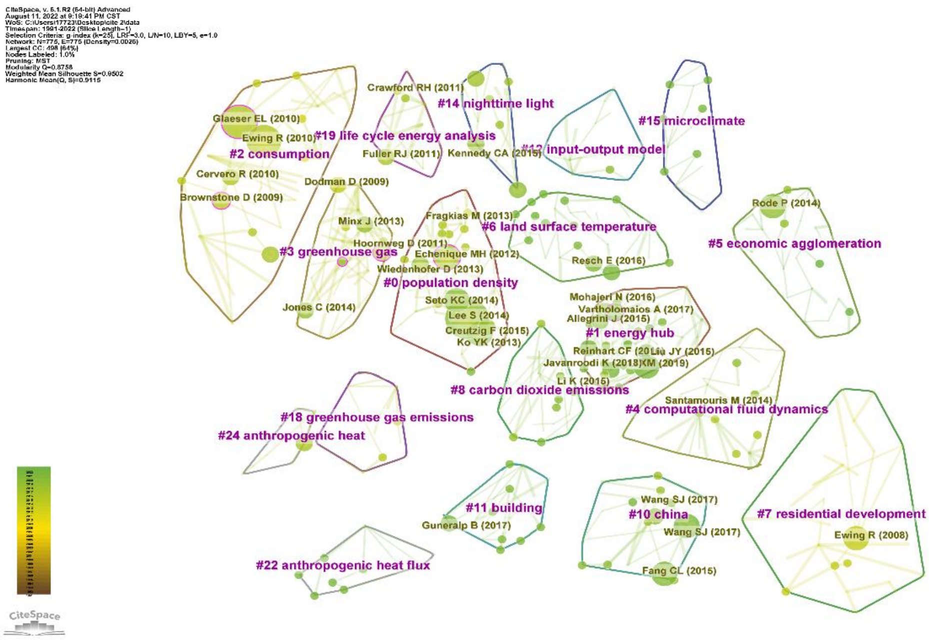

Figure 13. Knowledge map of cited references in the UD and EC research from 1991–2022

- UD and EC impact indicators

The urban built environment and transportation infrastructure have shaped energy consumption patterns for decades [69], and the analysis There is a strong correlation between UD and EC.

- Influence mechanism

The terms "greenhouse gas", "land surface temperature", "carbon dioxide emissions" and "microclimate" indicate that urban energy consumption exacerbates climate change. Population density influences household and transportation energy consumption, and the ensuing impacts are directly tied to GHG emissions ([70]-[71]).

4.2.2. Keyword Co-occurrence Network

Keywords can reveal the main direction of article content and its core ideas and detect the co-occurrence frequency and occurrence of keywords in related literature in UD and EC studies [72]. This study set the node type as keywords and the pruning method as MST. A total of 302 nodes and 508 links appeared, with a network density of 0.0112. According to the word frequency, sorting statistics are extracted. The top 20 basic keywords for each year from 1997-2022 are used as the content of the keyword co-occurrence network presentation. The centrality value can reflect the academic influence of a keyword. Based on the extracted top 20 keywords for each year, the top 20 central keywords are highlighted according to the centrality ranking.

- Research scope

The research scope mainly reflects the spatial and temporal distribution and research scale. According to Figure 14, “city density”, “urban form”, “energy”, “energy consumption”, and “energy efficiency’ are closely related, indicating a strong correlation between UD and EC.

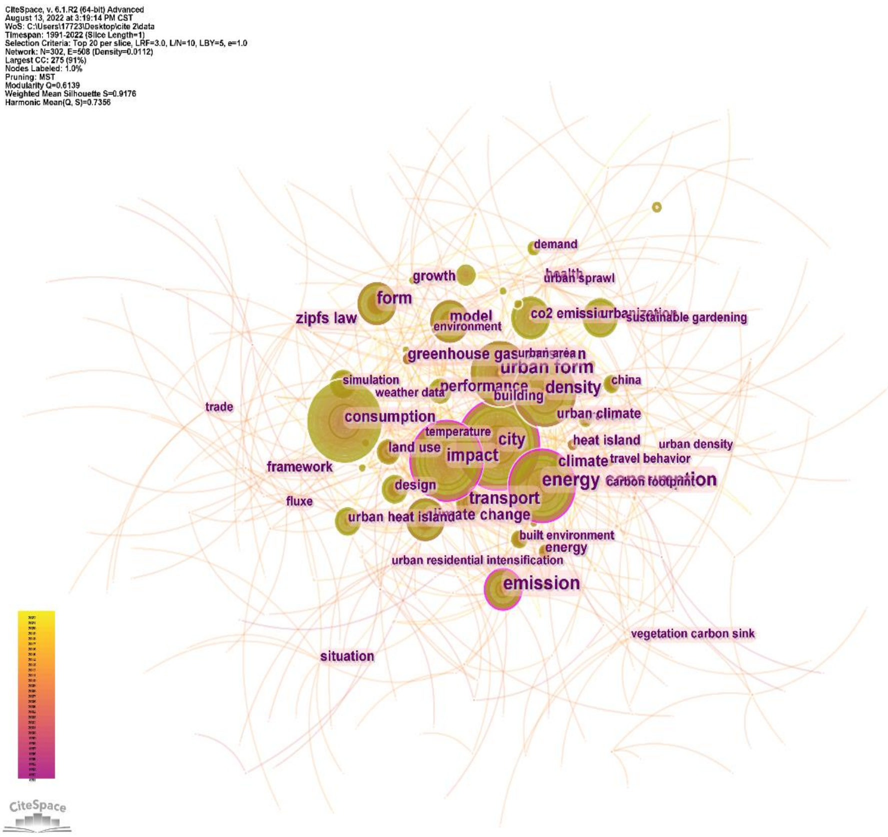

Figure 14. Clustering map of keywords of the papers

The keywords "co2 emission", "emission", "climate change", and "urban heat island" reflects the correlation between urban form, energy consumption and environmental change. In terms of centrality, 8 of the top 20 keywords are related to environmental change (Table 6), with "environment" having the greatest centrality (0.15), indicating that energy shortage, environmental pollution and climate change have become the core issues. Energy efficiency in an urban environment has become an important issue, and the most important reason is to solve the pollution problem in cities [73]. In addition, "consumption" and "behavior" reflect research on the psychology of human behavior under the process of urbanization. It demonstrates that the expansion of cities has a substantial effect on the work and daily lives of residents, as well as the energy consumption of cities by influencing residents' consumption habits and commute patterns [74]. It is worth noting that "China" appears 38 times among the first 20 keywords, indicating that the relationship between UD and EC in China has also been explored in the wider literature.

Table 6. List of keyword co-occurrence

Rank	Freq	Year	Keyword	Rank	Centrality	Year	Keyword
1	168	2005	impact	1	0.15	2004	environment
2	159	2004	city	2	0.14	2008	energy consumption
3	145	2008	energy consumption	3	0.14	2004	emission
4	143	2010	consumption	4	0.12	2011	design
5	102	2009	density	5	0.12	2002	climate change
6	98	2001	urban form	6	0.11	2004	transport
7	80	2009	co2 emission	7	0.11	2004	model
8	68	2004	model	8	0.11	2009	co2 emission
9	67	2004	emission	9	0.11	2004	climate
10	63	2002	climate change	10	0.1	2001	urban planning
11	59	2015	urbanization	11	0.1	2012	temperature
12	58	2013	form	12	0.1	2005	impact
13	50	2004	transport	13	0.1	2004	heat island
14	49	2011	design	14	0.08	2004	city
15	47	2004	land use	15	0.07	2000	energy efficiency
16	45	2015	simulation	16	0.07	2010	consumption
17	44	2007	energy	17	0.07	2010	behavior
18	43	2004	climate	18	0.06	2015	urban microclimate
19	41	2016	performance	19	0.06	2011	urban density
20	41	2005	urban heat island	20	0.06	2004	travel
21	38	2012	China	21	0.06	2013	pattern

- Strategy research

Research on mitigation strategies includes "impact", "design" and "urban planning". This research includes the impact and role of urban form-related strategies and technologies in improving energy consumption. According to a literature review, the current focus is on the relationship between urban energy consumption and urban density and city scale, with the mainstream view that cities should be compact and governments should increase urban density ([75]–[77]).

4.2.3. Keyword Co-occurrence Time-zone Analysis

The CiteSpace time zone map can visually reflect the highlight of research fields and their derivative relationships each year [78]. In this study, the keywords are filtered according to their occurrence and frequency and analyzed UD and EC research hotspots through keyword co-occurrence analysis. Timeline maps of UD and EC research from 1991 to 2008, 2008-2016, and 2017-2022 were obtained:

- Steady development phase (1991-2008)

This phase is the initial phase of UD and EC studies, which explored aspects such as energy balance and urban residential intensification (Figure 15), residential density and urban traffic consumption.

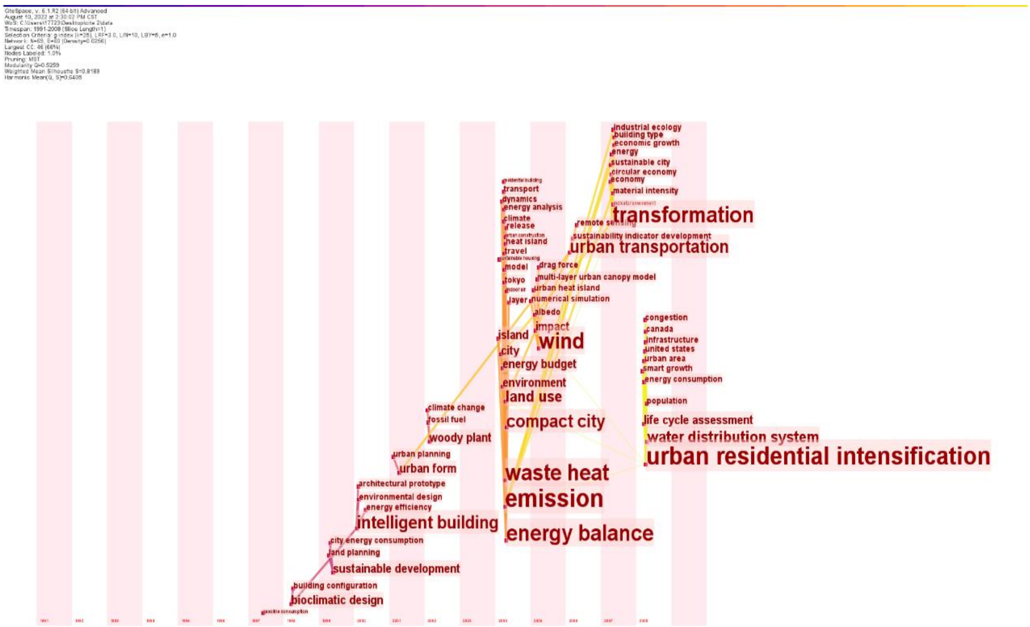

Figure 15. Annual variations of co-occurring keywords of the papers on UD and EC during 1991–2008

- Slow growth phase (2009-2016)

In this phase, UD and EC studies gradually received attention. This phase of research focused on the factors impacting urban energy consumption and studied the relationship between urbanization and energy consumption patterns, the terms "building", "transport", "travel", "population density" and "compact city" served as the main keywords (**Figure 16**). In addition, "greenhouse gas emissions" and "climate change" also indicate that this research phase has started focusing on UD and EC-related derivative areas and has turned to energy consumption and carbon emission reduction measures.

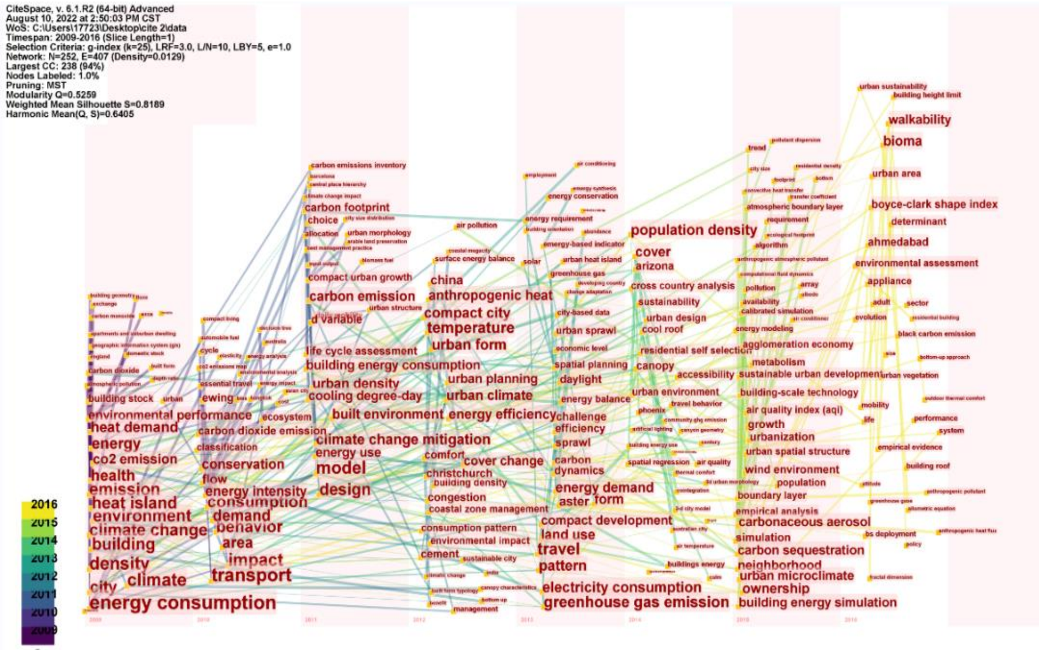

Figure 16. Annual variations of co-occurring keywords of the papers on UD and EC during 2009–2016

- Fluctuating upward phase (2017-present)

With globalization and the introduction of the concept of zero net carbon by the United Nations and the continuing Conference of the Parties. This research phase focuses on the access to achieve sustainable urbanization and decreased energy consumption to address the challenges posed by carbon reduction (**Figure 17**). Innovations in urban form, function, and energy efficiency provide new pathways for building low-carbon sustainable cities, exploring how cities can bring benefits to climate change. This phase contributes significantly to the process of sustainable urban development.

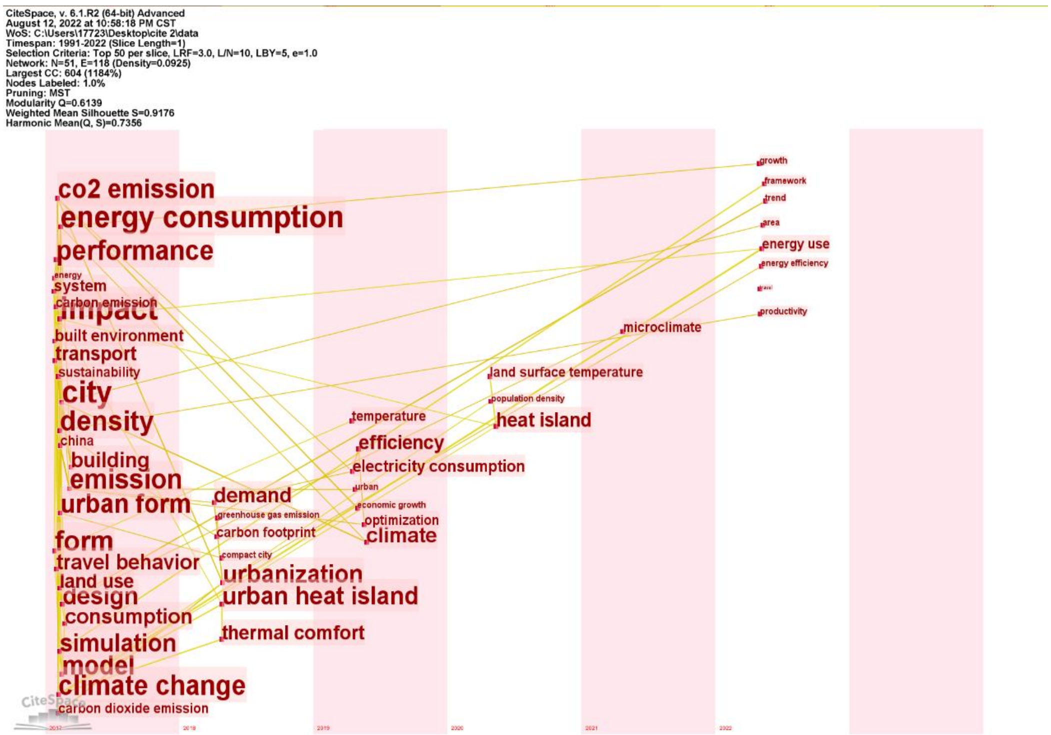

Figure 17. Annual variations of co-occurring keywords of the papers on UD and EC during 2017–2022

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4.2.4. Keyword Clustering Analysis

This study clustered and analyzed keyword knowledge graphs to explore research themes and evolutionary trends in UD and EC development over different periods. The period is from 1991 to 2022. The 50 most cited articles were selected for each piece. After running the analysis in CiteSpace, we obtained the map shown in Figure 13. The clustering function was used as the labelling source, and the log-likelihood ratio was used as the method. Modularity Q is a value ranging from 0–1, and values close to 1 reveal closer relationships and connections within clusters. The average profile should have a value between -1 and 1. A value close to 1 indicates that the articles within the cluster are highly consistent or similar in content [79]. Figure 15 shows that the modularity Q value is 0.6364, and the average silhouette value is 0.9332. In 18 major clusters, the silhouette value is greater than 0.7. this indicates that the knowledge mapping has a high quality of cluster analysis. According to the CiteSpace naming system, the cluster sizes were sorted from #0 to #18 (Figure 18), with the largest cluster named #0. After screening, 15 effective clusters were obtained (Table 7), representing a wide range of topics, except for the #0 stirpat model, which represents the specific simulation method used in the study.

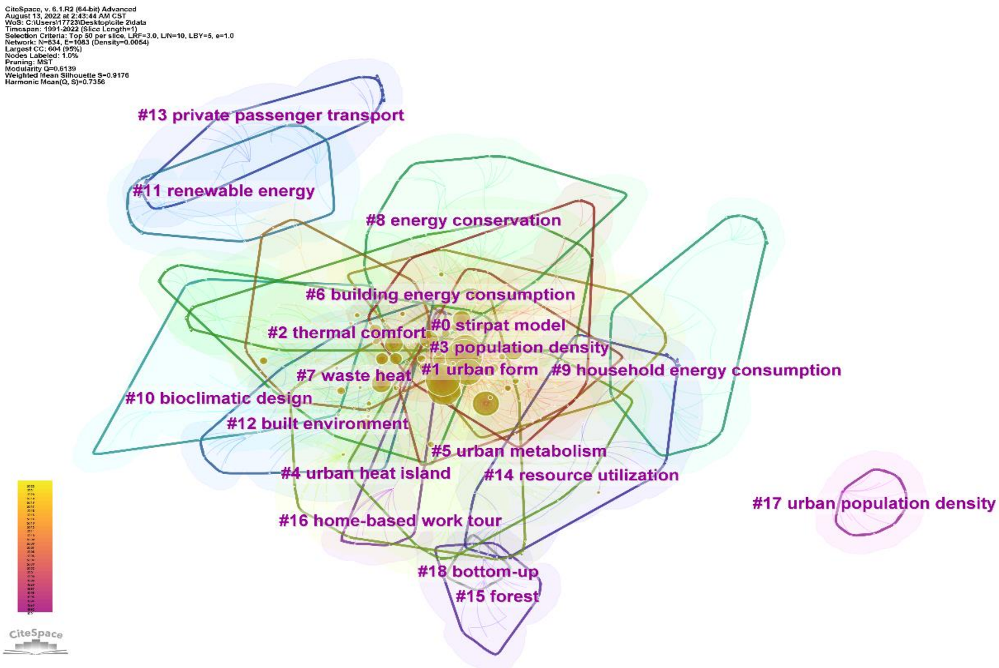

Figure 18. Co-citation network and clusters of the papers on UD and EC during 1991–2022

Table 7. List of cited clusters and number of records contributed

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Cluster ID	Size	Silhouette	Year	Label（LLR）
#0	64	0.86	2014	stirpat model
#1	52	0.907	2009	urban form
#2	48	0.794	2013	thermal comfort
#3	48	0.832	2012	population density
#4	46	0.927	2011	urban heat island
#5	39	0.949	2011	urban metabolism
#6	37	0.975	2012	building energy consumption
#7	33	0.953	2009	waste heat
#8	32	0.935	2012	energy conservation
#9	30	0.934	2011	household energy consumption
#10	28	0.925	2009	bioclimatic design
#11	26	0.968	2011	renewable energy
#12	25	0.912	2012	built environment
#13	25	0.984	2012	private passenger transport
#14	22	0.99	2011	resource utilization
#16	14	0.998	2012	home-based work
#18	7	0.997	2012	residential building stock

There is a strong link between group 1 and group 2, and there is a causal link between group 1 and group 2, and group 3. Combined with the clustering timeline view in Figure 19, the active years of different topics were analyzed.

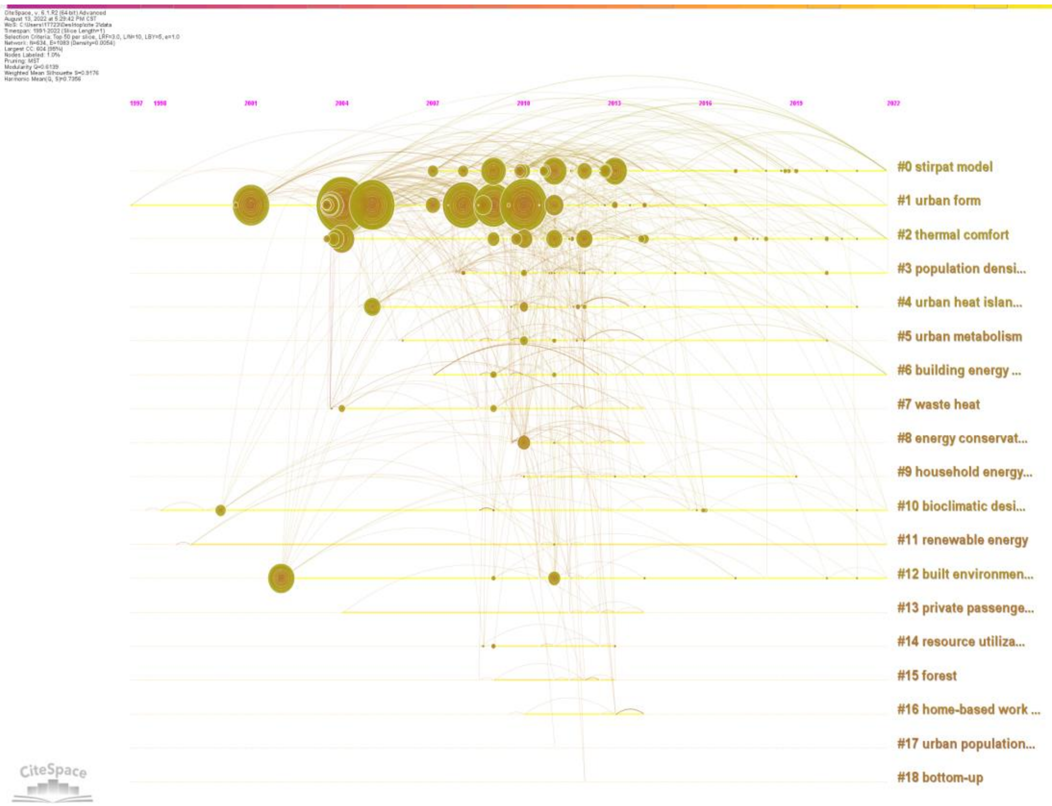

Figure 19. Timeline view of research topics

- Group 1: Urban Spatial Structure

The theme of the first group is urban spatial structure, which contains 5 clusters. #1: urban form, #3: population density, #12: built environment, #18: residential building stock, reflecting the urban spatial structure change in urbanization. With the process of urbanization, high-density development and comprehensive utilization will unavoidably lead to the concentration of enterprises and population and the expansion of building density. The expanding urban scale effect accompanied by economic development, urbanization and population growth will lead to more energy consumption, inevitably leading to energy consumption in group 2 and reflection on environmental changes in group 3. The overall study represented by #1: urban form examined the dichotomous relationship between urban form and energy consumption, exploring the scale and rate of urban growth, making sustainable urban development a key issue for global sustainability [80],[81]. Secondly, the density and intensity of activities such as transportation and industry are the main factors that influence energy consumption [82]. #3: population density presents a study linking urban energy to population density, using population density as a study variable, thus obtaining area-specific access to information. In this way, it allows a more detailed analysis from a country [83] to a city [84] and is more suitable for smaller regions. #12 and #18 focus on building energy consumption and prediction ([85]-[86]), while #18 focuses on the purpose, advantages and disadvantages of a residential energy model based mainly on bottom-up building physics ([87]–[89]).

- Group 2: Energy consumption

This group contains types of urban energy consumption, including #6 "building energy consumption" and #9 household energy consumption—both span from 2007 to 2022, indicating the need for continued attention to related research. The study in #6 focuses on predicting energy consumption in urban buildings, which is greatly valued in energy efficiency and sustainability studies [90]. Representative article #9 predicts household energy consumption in terms of income and demographic characteristics. Understanding and changing household energy consumption behavior is an effective way to improve energy efficiency and promote energy conservation [91].

- Group 3: Impacts on the environment

This group covers environmental impacts and includes two clusters, #2 Thermal Comfort and #4 Urban Heat Island, with the #2 Thermal Comfort cluster active from 2009-2022. Representative articles are Yang's review of human thermal comfort in the built environment, which reviews thermal comfort research work and discusses its impact on building energy efficiency [92].

- Group 4: Mitigation strategies

The regrouping contains the main coping strategies for urban energy consumption, mainly #5 urban metabolism, #7 waste heat, #10 bioclimatic design, #11 renewable energy, and #14 resource utilization. The #5 and #10 studies focus on coping strategies for urban spatial structure. The cluster analysis of #5 shows that urban metabolic analysis has become an important tool for studying urban ecosystems ([93]-[94]). #7 shows that a bioclimatic approach can create comfortable building conditions, including natural ventilation, lighting, and passive heating and cooling, thereby improving building energy efficiency ([95]-[96]).

#7, #11 and #14 are analyzed mainly in terms of energy savings. #7 and #14 focus mainly on the reuse of urban energy. Through the analysis of the representative literature, waste heat recovery is considered an effective way to increase the utilization of carbon-free green energy and reduce greenhouse gas emissions [97], especially in urban areas, from several sources such as sewage, industrial processes, and waste incineration plants [98]. In addition, representative article #11 analyzed the need to reduce urban energy consumption to build low-carbon, resilient and livable cities, as well as the options to provide robust, decentralized and renewable energy sources to build sustainable energy systems.

4.2.5 Highly Cited Articles

A co-citation network is generated by extracting highly cited landmark references from the WoS based on citation frequency. Highly cited articles indicate the level of disciplinary activity within the UD and EC fields, and high citations can identify the most active disciplines and research directions. According to the clustering framework in Figure 11, most of the research topics in these 17 papers belong to academic group 1 (Figure 20).

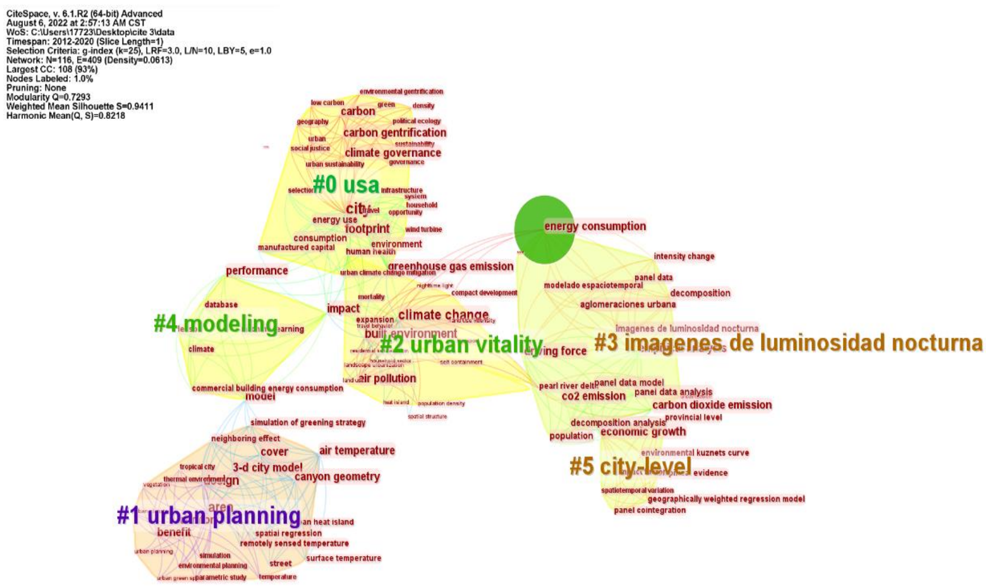

Figure 20. Timeline view of research topics

Their studies mainly concentrate on the impact of urban form on energy consumption. This reflects the fact that this grouping is the focus of this field. Combined with the main content of research in the highly cited articles, 13 of the top 17 highly cited references belong to group 1, 7 articles belong to group 3, and 2 articles belong to group 4 (**Table 8**).

Table 8. Highly cited references on UD and EC

Author	Times Cited, WoS Core	Year	Research Content	Cited reference
Ng, et al.	489	2012	The cooling effects of greening in a high-density city	[99]
Creutzig, et al.	252	2015	Economic activity, transport costs, geographic factors, and urban form influence urban energy use.	[69]
Zhang, et al.	243	2013	Vegetation Adjusted NTL Urban Index urban structure, energy use, and carbon emissions.	[100]
Kammen, et al.	234	2016	The options for establishing sustainable energy systems by reducing energy consumption;	[70]
Zhang, et al.	210	2017	Urbanization affects carbon dioxide emissions	[71]
Wang, et al.	192	2017	Examining the combined impacts of socioeconomic and spatial planning factors on CO2 emissions;	[101]
Chun, et al.	186	2014	UHI in high-density areas	[102]
Robinson, et al.	178	2017	Machine learning approaches for estimating commercial building energy consumption	[103]
Lee, et al.	152	2014	Urban form influences an individual households' CO2	[104]
Aflaki, et al.	141	2017	Urban heat island mitigation strategies	[105]
Shen, et al.	130	2017	Migration increased urban residential and transportation emissions	[106]
Lin and Zhu	113	2018	Changes in urban air quality during urbanization	[107]
Wang, et al.	105	2019	Examining the spatial variations of determinants of energy-related CO2 emissions	[108]
Xia, et al.	91	2020	Analyzing spatial relationships between urban land use intensity and urban vitality at the street block level	[109]
Xie, et al.	55	2019	The influencing mechanism of traffic density on smog pollution from the perspectives of direct emissions, spatial agglomeration, and technology spillover effects.	[110]
Rice, et al.	53	2020	Larger carbon footprints and reductions in transportation or building energy emissions.	[111]
Wang, et al.	49	2019	Energy consumption and carbon dioxide emissions at the city level	[112]

4. Conclusions

Planners continue to discuss the importance of density as a promising concept for responding to the challenge of reducing energy consumption and meeting the decarbonization ambition. Nevertheless, the dilemma overlooks the question of spatial organization and the efficient strategies of resource distribution. A portfolio of approaches is identified and established in different works presented in this paper.

The research in this paper investigates the relationship between the selected urban form characteristics and energy consumption, to understand how one influences the other in a bibliometric analysis using CitySpace. To aid planners to design cities and redesign existing ones to achieve energy efficiency, the study explores, in a theoretical-methodological approach the correlations of the terms.

The research outlines the relationships and trends between operational energy consumption and urban density and developed a comprehensive understanding using an approach based on correlations.

"Urban Density (UD)" and "Energy Consumption (EC)" were chosen as key search keywords, and the search was conducted over an indefinite period (1900 to the present).

As a result of the correlation between attributes of UD and EC, cities have become centres of consumption and resource transformation as a nexus of human activities; urban population density, building form, urban morphology, and urban transportation are the concrete manifestations of the relationship between UD and EC.

The analysis is developed by:

- The number of publications is an index important to identify the research trends. The study examined more than 500 articles for the period 2008-2017 in three distinct research periods (1991-2008, 2008-2016 and 2017-2022);
- Journal analysis: conducted research in more than 700 journals and generation of more than 4500 relationships;
- The geographic distribution reflects the cooperation of diverse countries related to the research fields representing more than 70 countries and 250 collaborations.
- Research subjects investigating more than 190 connections of related research zones.
- The authors' cooperation analysis revealed more than 400 connections with the most coming from USA and China.
- Distribution and collaboration of institutions with more than 300 interconnections.

A keyword and reference analysis is also developed for the period 1991 to 2022, but also a time-zone analysis respecting the relevant research hotspots.

Ultimately, the findings in this paper provide a way forward for researchers, urban policy-makers and planners seeking to design strategies related to dense urban tissues. Exploring the controversial paradigm of urban density as a key solution for energy-efficient urban configurations is not a new topic, however, still there are unexplored fields and answers to be given. It is only by understanding the role of these factors within dynamic processes that city designers will foster efficient frames to conceptualize the recursive relations of planning and energy demand, which will foster sustainable and livable cities.

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NOMENCLATURE	
Acronym	Description
GHG	Greenhouse Gas Emissions
UHI	Urban Heat Island
RES	Renewable Energy Sources
WoS	Web of Science
SCI-E	Science Citation Index Expanded
SSCI	Social Science Citation Index
A&HCI	Arts & Humanities Citation Index
UD	Urban Density
EC	Energy Consumption
LLR	Log-Likelihood Ratio

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