Journal of Sustainable Civil Engineering and Technology
e-ISSN: 2948-4294 | Volume 3 Issue 2 (September 2024), 93-104
https://joscetech.uitm.edu.my

Studies on Research Methods and Factors Influencing the Urban Heat Island Effect: A Review

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Received: 15 May 2024 / Accepted: 05 August 2024 / Published online: 30 September 2024

Abstract

In view of the energy shortage and climate warming that are caused by rapid urbanization, the energy structure that relies on traditional fossil fuels brings serious ecological problems, such as the urban heat island effect, acid rain, fog, and haze. To promote urban carbon emission reduction, energy saving, and quality improvement, it is urgent to change the energy structure and develop more new energies. This study provides a systematic review of domestic and international research on the urban heat island effect, its resulting hazards, and related research methods. The correlations between heat island effect and anthropogenic activities as well as energy structure were elucidated. Simultaneously, the deficiencies of the promotion trend of new energy in recent studies were put forward to the point. To promote the "double carbon" orientation based on the natural non-loss method, it provides a valuable reference for further alleviating a series of ecological problems caused by urbanization.

Keywords: Urbanization; Energy structure; Heat Island effect; Double carbons

1. Introduction

As urbanization increases, more and more people are flocking to cities. Large populations make cities consume huge amounts of energy, and behind the rapid growth of cities is a serious imbalance in the urban environment. The most prominent of these is the urban heat island effect, which brings high summer temperatures that seriously affect the health of residents (“Spatial Evolution of the Effects of Urban Heat Island on Residents’ Health,” 2020). In July-August 2022 in the Shanghai metropolitan area, for example, the single-day maximum surface temperature was consistently above 37 °C, making about one-third of the heat stroke patients seen in major hospitals patients with pyrexia. The urban heat island effect is a climatic phenomenon caused by the concentration of reflective surfaces and lack of vegetation, whereby cities store heat during the day and release it at night, thereby increasing the overall temperature (Guindon & Nirupama, 2015) (Fig. 1).

Debbage and Shepherd (2015) reported that urban buildings are characterized by dense spreading. The high-density layout can amplify the impact of the urban heat island effect (Debbage & Shepherd, 2015). The severe urban heat island effect can bring heat waves (Anderson & Bell, 2011), and a very destructive and extreme climate, to the city (Zhao et al., 2018). It has also been shown that the urban heat island effect is closely related to energy consumption and greenhouse gas emissions in the progress of urbanization (Singh & Sharston, 2022; C. Li et al., 2014), which fundamentally resulted from urbanization and industrialization of human civilization and the irreversible and irrational use of energy to increase productivity, which greatly increases the burden on cities (Rizwan et al., 2008). For such a topic, which is closely related to the survival of human beings, most scholars worldwide have studied the heat island effect by using the methods of fixed-point observation (Sandvik et al., 2016), remote sensing measurement and analysis (Shi et al., 2018), and simulation and prediction (Sun et al., 2022).

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Although academics have been paying attention to the heat island effect as an environmental problem for a long time, most of the current research lies in analyzing the possible impacts of the heat island effect as well as the relevant factors that affect the heat island effect. Failure to reveal the correlation between human-induced energy consumption and the heat island effect, as well as to propose effective ways to mitigate the heat island effect. Based on the current research status, this review discusses the causes, research methods, and influence factors of the urban heat island effect and puts forward an outlook on its future development. To optimize the use of energy, rationalize the planning of urban resources, mitigate the urban heat island effect, promote "dual-carbon" based on a nature-based approach, and make recommendations to help reduce carbon emissions and save energy.

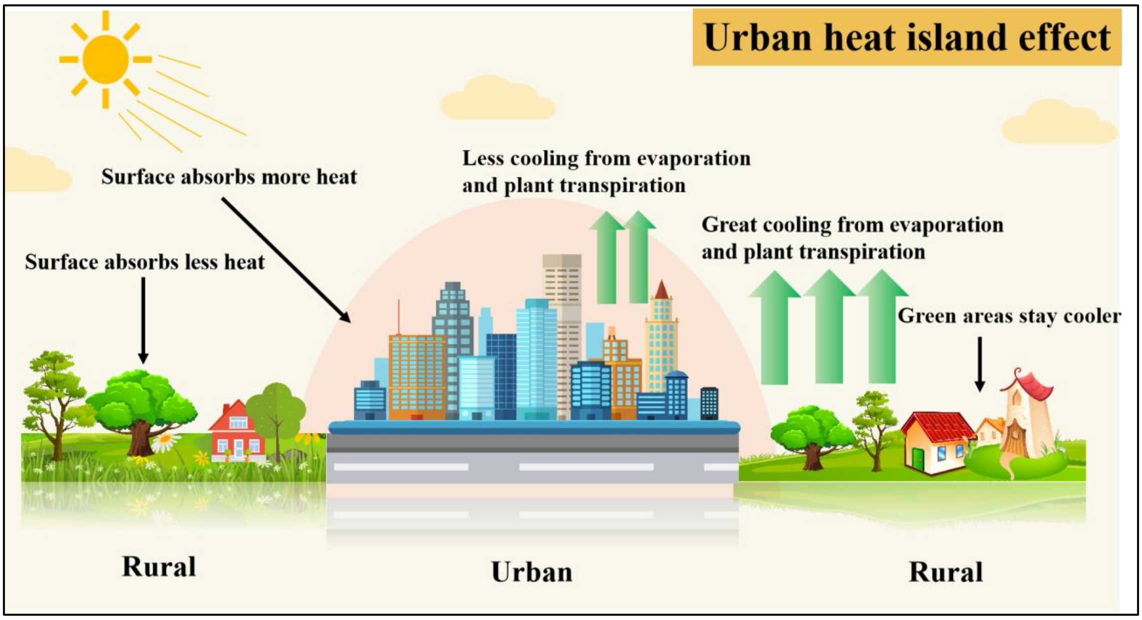

Figure 1. Urban heat island effect

In order to explore the research hotspots and research frontiers of urban heat island effect, this paper uses citespace software (V5. 7. R3) for visualization and analysis. In the China Knowledge Network database, with "Urban Heat Island Effect" as the title of the search, set the search time to January 1, 2014, and later, a total of 581 results. The retrieved articles were saved as plain text files, converted to executable format using the "Data Import/Export" function of citespace, and the time nodes were set to be from January 2014 to January 2024, with a time slice of one year, and the node type was "keywords". The top 10 most frequent keywords are as follows (Figure 1): "Urban Heat Island EFFect" (557), "Land surface temperature" (227), "Remote Sensing" (119), "urbanization" (92), "climate change" (85), "model" (80), "stragety" (62), "simulation" (59), "environment" (52), "expansion" (38). change" (85), "model" (80), "stragety" (62), "simulation" (59), "environment" (52), and "expansion" (38). In addition, the retrieved articles were performed cluster analysis and the current hot spots related to urban heat island effect research were acquired (see Figure 2). Synthesizing the keyword co-occurrence and clustering analysis, the following conclusions can be drawn. Urban heat island effect and landscape pattern, urban heat island effect and landscaping, urban heat island effect and urbanization are important research contents. In the current study, more attention has been paid to the spatial and temporal variability of the urban heat island effect and the intensity of the heat island. The more widely used methods in studying the urban heat island effect are numerical simulations, single-window algorithms, remote sensing, etc.

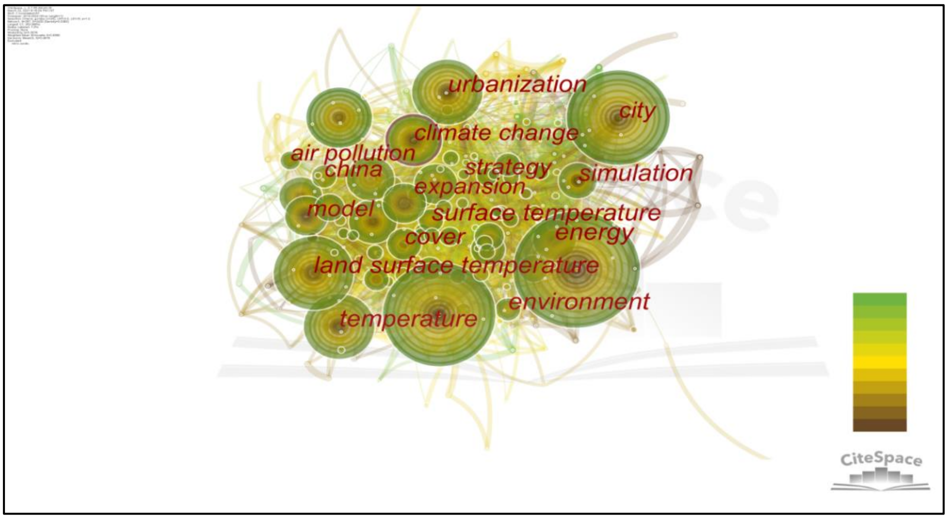

Figure 2. Keyword co-occurrence analysis

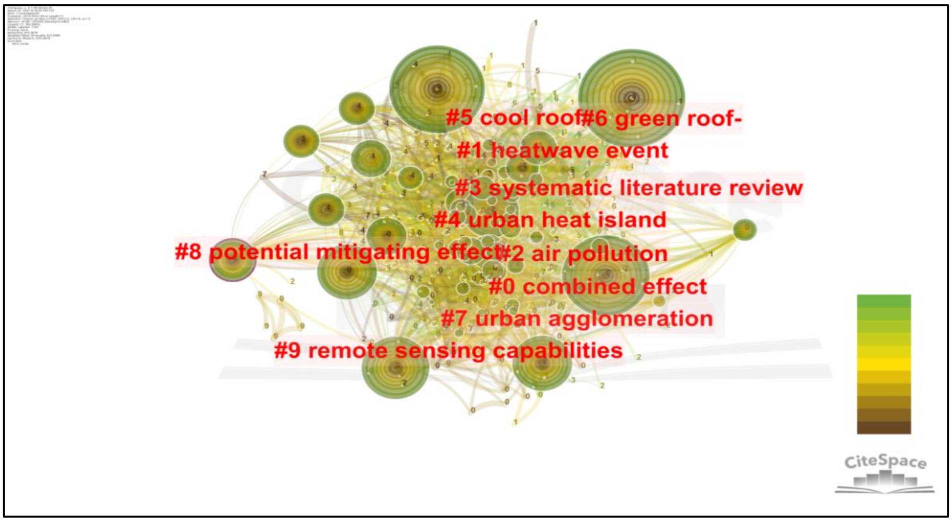

Figure 3. Cluster analysis

In addition, through the web of science database search results analysis function to analyze the number of articles in the field of urban heat island effect in the past 15 years, it is found that the number of articles in recent years is on the rise, with an average annual number of 38 articles. It can be seen that the study of urban heat island effect is still the research focus of many scholars.

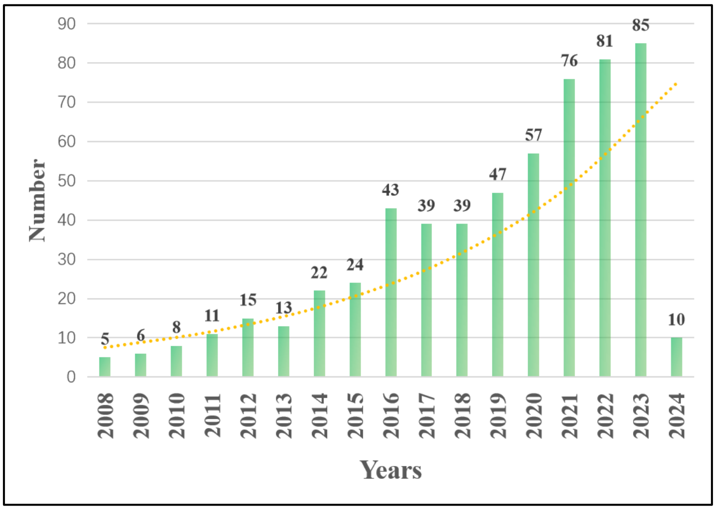

Figure 4. Number of articles published in the last 15 years on studies related to the heat island effect

2. Methodology

Through reviewing the literature, the following three methods, fixed-point observation method, remote sensing inversion method and simulation forecasting method, have been widely used in the study of urban heat island, so these three methods will be discussed in the following.

2.1 Fixed-Point Observation Method

The fixed-point observation method refers to the collection of updated meteorological data in the study area through the reasonable distribution of small meteorological observers. The meteorological data are collected by meteorological observers that arranged in the study area. The observed datasets are compared and analyzed to study the impact of the heat island effect on the study area. Using the fixed-point observation method can accurately reflect temperature changes at different locations at the same time or at different times at the same location, which can be clearly presented in horizontal or vertical form. Zhang Yiping et al. collected meteorological data from Kunming by means of fixed-point analysis. After comparative analysis, the maximum center of the urban heat island effect in Kunming shifted as the spatial height increased (Zhang et al., 2002). Ye Youhua et al. conducted fixed-point observations of various functional zones in the city. It is concluded that the heat island effect can be effectively mitigated by adjusting the rational planning of various functional zones in the city and mobilizing the interactions among them (Ye et al., 2008). Lucian Sfîcă (Sfîcă et al., 2018) and others selected eight sites in the city of Iasi for up to three years by means of the fixed-point observation method. Combined with the analysis of Yasi's characteristics and urban structure, the development and intensity of Yasi's urban heat island is derived. The city of Yasi was found with a classic urban cold pool in summer and two urban heat island centers in winter that are warm all day long. Similarly, Arifwidodo et al. (Ga et al., 2011) adopted a fixed-point observation method to investigate the urban heat island characteristics of Bangkok, Thailand. Using hourly temperature data from four weather stations scattered across Bangkok and combining it with data from the past five years, they found that the intensity of Bangkok's urban heat island was trending upward and that the maximum intensity at that time was 6-7℃. Ge Konan et al. (K. Ge et al., 2010) used the temperature fixed-point monitoring method to study the urban heat island effect in Nanjing. They selected seven representative geographic points from the city to the suburbs for real-time monitoring. After analyzing the temperature data and simulating the 3D images of the heat island, they found a general trend of higher and then lower temperatures in Nanjing, with highs reaching 25°C and lows reaching 21°C. Under the effect of solar radiation and anthropogenic factors and other aspects, there are multiple high temperature zones of heat island in Nanjing, and the center of heat island will be shifted. The heat island phenomenon is determined by a number of factors, including solar radiation and man-made heat dissipation, and when one of these factors is strong and dominant, the centre of the heat island is shifted towards that area.The fixed-point observation method requires the field to set up the corresponding instruments to collect data. It has the advantage of meteorological data collection in the field of the study area with high precision. However, the disadvantages of this method cannot be ignored. Easier to receive the influence of the interference of the external environment, its acquisition of data cycle is longer, time-consuming, labor-intensive, as well as difficult to obtain a wide range of monitoring area.

2.2 Remote sensing inversion method

Nowadays, with the rapid development of remote sensing satellites, many satellite constellations with different temporal, spatial and spectral resolutions have emerged to meet different demands (T. Zhou et al., 2016). Remote sensing inversion method(Fig.5) can effectively use the remote sensing satellites to collect different bands of radiation values of different subsurface, and use the corresponding thermal infrared sensors to collect the intensity of thermal radiation on the surface of the city, and then adopt the three common algorithms of radiative transfer equations (atmospheric correction method) (Sheng et al., 2016), single-window algorithms (J. Zhou et al., 2010), and single-channel algorithms (Zhu et al., 2008) to invert the surface temperatures of the study area, so as to effectively monitor the intensity of the heat island effect of the study area. Xie Qijiao used the remote sensing satellite image Landsat TM about the meteorological data of Wuhan city in the past two decades to analyze the relevant influencing factors that affect the urban heat island effect through algorithmic inversion and GIS spatial analysis techniques (Q. Xie, 2011). By using high-resolution remote sensing satellite data, Ge Yaning et al. took downtown Beijing as the study area and concluded that irrational building planning and high-density building groups in the city greatly enhanced the impact of urban heat island effect (Y. Ge et al., 2016). Jiang Zhangyan et al. (Jiang et al., 2006) used Landsat Landsat TM remote sensing image data to study the spatial distribution of surface temperature in Beijing city based on the inversion of the radiative transfer equation. It was found that the temperature in the urban area of Beijing is much higher than that in the suburban area, and the temperature in the urban area is lower than that in the area covered with vegetation, and it is also much lower than that in the water body in the city, which further highlights the importance of the green belt in the city. Chen Li et al. (C. Li et al., 1997) collected three remote sensing images of ChangZhuTan urban agglomeration, carried out surface temperature inversion, and analyzed the absolute bright temperature change and relative bright temperature change. They found that the strong heat island is mainly concentrated in the more developed areas of Changsha, Zhuzhou and Xiangtan cities. The overall temperature of the urban heat island in ChangZhuTan urban agglomeration has shown a decreasing and then increasing trend in the past two decades. Gongadu et al. (Gong et al., 2005) used Landsat TM thermal infrared band data from the Beijing area and employed the empirical formula proposed by Van to find the surface specific emissivity. Then they used a single-channel algorithm for atmospheric correction to obtain the surface temperature distribution map in Beijing. They concluded from the distribution map that the surface temperature in the urban area of Beijing is much higher than the surface temperature in the suburbs. And surface temperatures are higher in central and industrially developed areas, with the highest reaching 37℃. At the same time, they found that the average temperature of the water bodies was lower than the average temperature of the suburbs, highlighting the importance of water bodies for urban temperature regulation.

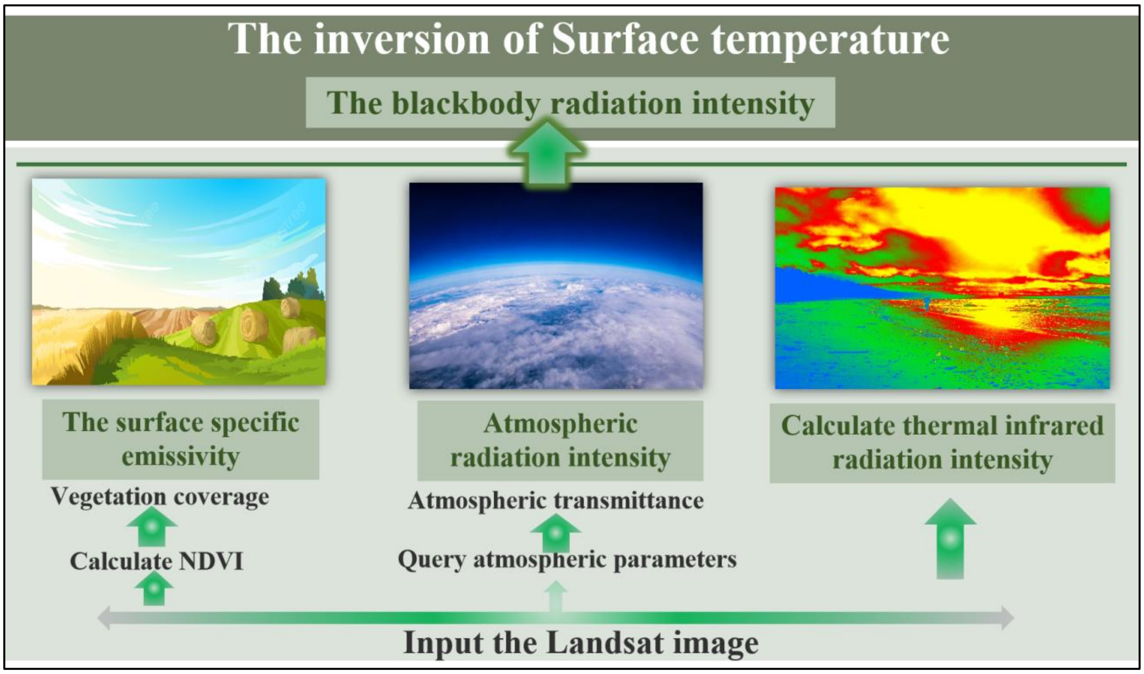

Figure 5. The process of Surface temperature inversion

The method of using remote sensing satellites to obtain data for inversion of surface temperature has the advantages of high resolution, wide coverage, and easy access to the data. However, it is often limited by the effect of different resolutions of different remote sensing satellites due to different research directions. First for spatial resolution. Satellites with high resolution can provide detailed surface temperature information and can distinguish small areas, buildings, or other details in a city. This is useful for studying the urban heat island effect, monitoring urban hotspots or for urban planning. Low-resolution satellites usually cover a larger geographic area but do not provide detail. Their data are suitable for wide-scale temperature distribution analyses, such as large-scale meteorological or climatological studies, but not for detailed analyses at the urban scale. Secondly, for spectral resolution. Multispectral satellites can provide data in different bands, including visible, infrared and thermal infrared bands. These bands allow temperature analysis of different features and surface characteristics. Multispectral data are commonly used for more accurate surface temperature inversion, especially in urban environments. Thermal infrared satellites focus on the thermal infrared band, which is useful for obtaining surface temperature information. However, they usually do not provide information in other bands, which may limit the range of applications in some cases. Therefore, the selection of the appropriate resolution of remote sensing satellite data should be weighed against specific research purposes, spatial scales, economic factors, and scientific objectives. Data of different resolutions have their unique application scenarios in surface temperature inversion. If detailed information on urban temperature distribution is required, high-resolution satellite data may be more suitable. If large-scale temperature distribution analysis is involved, low-resolution satellite data can be selected. At the same time, atmospheric conditions can have an impact on remote sensing measurements of surface temperature, and high-resolution data are more susceptible to atmospheric disturbances. Therefore, more accurate atmospheric corrections are required when using high-resolution data.

2.3 Simulation Forecasting Method

Simulation and prediction method based on computer technology has been widely adopted in urban heat island research because of its advantages of low cost and good applicability. At present, the main methods are:

i. using mature mathematical and physical models to quantitatively predict the current and future development trend of the urban heat island effect.
ii. combining geographic models and CFD virtual simulation technology, and simulating the evolution of the urban heat island phenomenon through the setting of various environmental parameters (Huang et al., 2017; Lv et al., 2022). Common prediction models include that time series method, fuzzy model, gray model, Markov chain model, BP artificial neural network model (Zhang, 2017).

Among them, the advantages and disadvantages of various prediction models are shown in the following table:

Table 1. Advantages and disadvantages of various forecasting models

Predictive Modeling	Advantages	Disadvantages
Time series approach	Simple and easy to use, high accuracy	Cannot reflect the inner connection of things
Fuzzy model	Intuitive, concise conclusions	Not applicable when sample size is large
Gray model	Fewer parameters, less fault tolerance	Not suitable for long term observation
Markov chain model	Suitable for long-term prediction and prediction of data columns with high random volatility	No connection between the future and the past
BP artificial neural network model	Allow sample defects and distortions	Localized extremes, slow convergence

Wang et al., (2022) studied the heat island effect in Haikou city by using remote sensing inversion method and simulation prediction method. They used radiative transfer equation method to invert the surface temperature and classify the remote sensing data, and then used CA-Markov model to predict the development trend and spatial distribution of the urban heat island. It was concluded that the class of urban heat island effect in Haikou is increasing, but the growth trends is slow in the areas with strong heat island effect. It is predicted that the center of gravity of the heat island will be shifted to the southeast in 2024, which needs to be mitigated by artificial interventions. Huang Yuan et al. (Huang et al., 2017) also took remote sensing images as the basis for the study of urban heat island, analyzed the obtained data to derive the heat island simulation prediction and compared it with the CA-Markov model. Finally, they found that the introduction of CA model can improve the accuracy of heat island simulation. In recent years, Baotou city has been warming up significantly, and the reduction of the flow in the Yellow River Basin has made the warming more serious, there is an increase of 44.21km^2 in the Strong Heat Island Area in 2022 compared to 2016, which suggests that people need to increase the area of green space in the city to slow down the enhancement of the heat island effect. Lv Lina et al. (Lv et al., 2022) collected remote sensing image data of Shuangyuck City, a resource-based city, analyzed the land use of this city and carried out surface temperature inversion, surface cover index extraction, and predicted the evolution of the obtained analysis results based on the urban heat island pattern of artificial neural network. By 2024, the urban heat island effect in Shuangyashan City will obviously strengthen, and the medium-temperature zone and the sub-high-temperature zone will become the main types of the urban heat island, in which about 273km^2 of the low-temperature zone will flow into the medium-temperature zone, and the low-temperature zone will rapidly decrease, and the effect of the urban green island will be weakened; in the sub-high-temperature zone, there is a range of 511km^2 originating from the medium-temperature zone in 2017, and the area of it will increase from 20% to 46% in 2017, and become a major temperature zone in the urban heat environment. In the sub-high-temperature zone, 511km^2 of the range originated from the mesothermal zone in 2017, and its area increased from 20% to 46% in 2017, becoming the main temperature zone in the urban thermal environment, with a high transition intensity and a significant increase in the trend of the urban thermal environment. High temperature areas also increased from 3 percent in 2017 to 15 percent. In this analysis and prediction, they found that the heat island effect is closely related to endothermic activities and urban expansion, and different surface cover types also affect the degree and effect of the heat island effect.

3. Study on the Influencing Factors of Urban Heat Island Effect

3.1 Types of Energy Use and the Urban Heat Island Effect

With the advancement of science and technology, there is a serious imbalance in the use of energy to meet the increase in productivity as well as the improvement in the living conditions of human beings. It also has a serious impact on urban ecology in the long run. Li Mingcai et al. analyzed the relationship between climate change and outdoor meteorological parameters of heat island effect in a large city in northern China in recent years by collecting indoor heating conditions and air conditioning design temperatures of households in the city center and suburbs of the city. It is concluded that indoor heating conditions have a profound impact on the urban heat island effect (M. Li et al., n.d.). Climate change and UHI values have a significant effect on air conditioning design temperatures, with winter air conditioning design temperatures having the highest sensitivity and summer air conditioning design temperatures having the lowest sensitivity to UHI and climate change, so that reductions in heating loads will outweigh the increase in cooling compliance and will contribute to building energy efficiency. Li Chaosu et al. utilized a unique dataset using Ningbo city area as the study area. They found that the type of buildings as well as the density of the city causes variations in the electricity consumption, which also varies seasonally. Subsequent statistics of many years of data can be found that the heat island effect and electricity consumption show a relationship of mutual influence and increase year by year (C. Li et al., 2018). Yalcin Tolga et al. found that the long-term use of non-renewable fossil energy made the urban heat island effect becoming increasingly serious, not only the global temperature increases year by year, but also leads to the warming of the groundwater, which is all an early warning for human to optimize energy structure as soon as possible (Yalcin & Yetemen, 2009).

As the development and construction of major cities continue to advance, the increase of heat-absorbing subsurface in the city and the heat emission from industrial production exacerbate the urban heat island effect (Xu, 2015). Many cities are aware of the ecological problems caused by the heat island effect. It has also succeeded in mitigating the heat island effect by adopting measures such as renewable energy, improved building design and urban planning. This provides lessons and insights that other cities can learn from. For example, Singapore actively promotes the use of renewable energy, includingthe contruction of many solar panels and wind power facilities, the encouragement of green roofs and urban greening, which obviously mitigates the effects of the urban heat island effect. São Paulo, Brazil, has adopted a variety of renewable energy technologies, including bioenergy, hydroelectricity, and solar energy, which reduces the dependence on traditional energy sources and slows down the formation of the urban heat island effect. Shenzhen, China, is vigorously developing solar and wind energy and actively promoting the popularization of electric vehicles. It also focuses on greening and the rational use of water resources in urban planning to mitigate the heat island effect. Chicago, USA, encourages green roofs and green walls on buildings. Public green spaces and green corridors are also considered in urban planning to improve the thermal environment of the city.

3.2 Anthropogenic Activities and the Urban Heat Island Effect

With the process of urbanization, population moves towards cities and gathers. The heat generated by the metabolism of many people and the waste heat generated by the power consumption of buildings for economic construction or to meet the needs of their own quality of life greatly affect the process of the urban heat island effect. As an important factor for urban heat island effect, to investigate and analyze the relationship between heat that generated by human activities in cities and the urban heat island effect from the root causes is important for searching corresponding solutions. Peng Shaolin et al. (Peng et al., 2005) pointed out that urban anthropogenic heat emissions have a double impact on the urban heat island. On the one hand, it directly increases the heat in the city, especially in the summer and winter. On the other hand, many pollutants, such as coal ash, dust, and various greenhouse gases, are discharged into the atmosphere along with the anthropogenic heat, which forms the “dust mask” and “gas mask”" over the city and aggravates the intensity of the urban heat island.

The urban heat island effect is closely related to the population density, the degree of social development, and the degree of industrial system development. Highly populated cities usually have more buildings, transportation, population, and economic activity. It is therefore more susceptible to the heat island effect. This is because dense buildings and population activities lead to more energy consumption and heat release, thus increasing the temperature of the city. A large population also means more energy consumption, which can exacerbate the heat island effect in cities. Cities with higher levels of social development tend to have more industrial activities and transportation. These lead to the increased energy consumption and heat release, and in turn increases the impact of the heat island effect. At the same time, a more developed society means more buildings, roads, and population. This also leads to higher heat release and energy consumption, which in turn increases the heat island effect in the city. The development of industrial systems leads to more energy consumption and industrial emissions, all of which contribute to higher urban temperatures. Particularly if there is an over-concentration of industrial activity, this will have a greater impact on temperatures around the city. The development of an industrial system may also create the need for more buildings and transportation, which in turn will increase energy consumption and heat release, exacerbating the heat island effect.

Zheng Jofang et al. (Zheng et al., 2005) found that the center of the urban heat island in Beijing is mostly located in the densely populated areas, such as large urban stadiums, industrial and commercial agglomerations, and densely populated areas, by analyzing the time-by-time temperature observation data from applied automatic weather stations in Beijing. It can be concluded that the formation of the urban heat island has a great relationship with the large amount of anthropogenic heat released by human activities. Rajapaksha Shehani et al. estimate the total Anthropogenic Heat Emissions (AHE) based on the contribution of three major sources of waste heat generation in an urban environment, i.e., buildings, vehicular traffic, and human metabolism. Furthermore, a comparison of the dominating anthropogenic heat factor of Darwin with that of other major international cities was carried out. Field measurements of microclimate (temperatures, humidity, solar radiation, and other factors of climate measures) were conducted along Smith Street, Darwin City. Then, surveys were conducted to collect information regarding the buildings, vehicle traffic and Human population (metabolism) in the study area. Each individual component of AHE was calculated based on a conceptual framework of the anthropogenic heat model developed within this study. The results showed that AHE from buildings is the most dominant factor influencing the total AHE in Darwin, contributing to about 87% to 95% of total AHE. This is followed by vehicular traffic (4–13%) and lastly, human metabolism (0.1–0.8%). They concluded that anthropogenic heat plays a major influence on the heat island effect (Rajapaksha et al., 2022). Meng Qingyan et al. took the industrial park as the investigation block, analyzed the relationship between large urban building groups and the urban heat island effect from the time scale and space scale, and defined the IHI benefits more finely, to better analyze the relationship between the two and put forward the solution to alleviate the excessive waste heat generated by large building groups (Meng et al., 2022). Xu Ling et al. analyzed the phenomenon of heat reflection from the urban pavement and proposed the cold pavement technology combined with the principle of solar collectors, which has positive significance to alleviate the urban heat island effect and the use of renewable energy (Xu et al., 2021).

4. Research Outlook

In the context of urbanization, the fossil fuel-based energy structure and irrational urban planning have brought great pressure on energy security and carbon reduction policies (H. Xie et al., 2017). With various ecological problems caused by the heat island effect, the new-energy industry is rapidly developing and fiercely competing (Xue et al., 2021). As the world’s largest energy consumer and carbon emitter, it is urgent to change the energy structure. For example, automobile, the amount of carbon dioxide emissions accounted for about sixty percent of the total emissions, so electric car has become the trend of future development of China's automobile industry (Yuan et al., 2015). At present, in order to convert energy structure, electrolysis hydrogen technology was expected to be an effective solution to energy consumption. To accelerate the process of hydrogen industrialization, the transition to low-carbon clean energy of China can be expected soon. Cang Dingbang et al. found that new energy has the advantage of being sustainable and non-polluting, while the consumption of traditional fossil energy in short term is still increasing with the introduction of new energy into the market. Therefore, the efficiency of new energy as well as its cost-effectiveness should be further improved with the popularization of new energy (Dingbang et al., 2021). Combining with current hotspots, to find a high-precision method to study the influence of energy utilization structure and urban heat island effect for pursuing more scientific and appropriate countermeasures to mitigate the urban heat island effect is significant. Meanwhile, reducing energy consumption and take "dual carbon" goal as important guide to improve the efficiency of energy utilization and to reduce carbon emissions is also of great urgency.

Acknowledgements

I would like to thank the School of Life and Environmental Sciences, Shaoxing College of Arts and Sciences for providing facilities and financial support for this study.

Declaration of Conflicting Interests

I agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

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