Scientific Knowledge Group

ISSN: 3068-2789

Research Article

Journal of All Physics Research and Applications

Anthropogenic Heat and Urban Heat Island Research: A Bibliometric and Conceptual Assessment of Energy System Decay Heat from Spent Nuclear Fuel Storage

Hadis Allahyari[1], Bahman Zohuri[2*], and Esmaeel Salehi[1]

[1]*School of Environment, College of Engineering, University of Tehran, Tehran, Iran*

[2]*Ageno School of Business, Golden Gate University, San Francisco 94105, California, USA*

[*]Corresponding author:
Bahman Zohuri, Ph.D., Adjunct Professor, Artificial Intelligence Systems (ML/DL).

ABSTRACT

The rapid growth of urban centers today means that little attention is paid to the role of climate factors in maintaining the quality of life. Among the negative consequences of rapid urban growth is the spread of problems caused by urban heat islands (UHI), defined as areas within a city that are significantly warmer than other places, especially compared to rural areas. Human waste heat is increasingly recognized as a significant factor in exacerbating the UHI effect. While extensive research in recent years has focused on heat emissions from sources such as transport, buildings, and conventional energy systems, less attention has been given to the thermal consequences of nuclear energy infrastructure, particularly spent nuclear fuel storage. Despite reactor shutdown, spent nuclear fuel continues to decay heat from fission, and requires long-term cooling processes to release thermal energy into the surrounding environment. This study provides a comprehensive review of the sources of human waste heat in urban energy systems, with particular focus on the role of spent nuclear fuel storage. This paper explores the pathways of heat release from nuclear waste systems that affect microclimates by drawing on existing literature and developing a conceptual framework. In addition, a scenario-based assessment is conducted to compare the magnitude and spatial correlation of heat release from spent nuclear fuel storage with other anthropogenic sources. The results suggest that the direct contribution of spent fuel storage to the large-scale UHI effect may be limited, but it can create localized thermal anomalies near storage facilities, especially under specific environmental conditions. Therefore, diverse and novel heat sources should be included in urban climate assessments. This study, emphasizing the importance of accurate experimental data, encourages integrating energy system design and waste heat management into urban climate mitigation strategies to achieve a cohesive system.

Keywords: Urban Heat Island, Spent Nuclear Fuel, Decay Heat, Microclimate.

Received: June 16, 2026;
Accepted: June 25, 2026;
Published: July 10, 2026

Introduction

The Urban Heat Island (UHI) effect is marked by elevated temperatures in cities relative to their rural surroundings. UHI effect is a direct consequence of concentrated human activity, impervious surfaces, energy consumption, and sparse vegetation. As urbanization accelerates, UHI has emerged as a defining metric of anthropogenic climate disruption [1-3]. Understanding the factors influencing UHI has become crucial in light of the growing urbanization that has caused cities to expand both vertically and horizontally. This is because these factors have a direct impact on public health, energy efficiency, climatic resilience, and environmental sustainability [4,5]. In traditional sources, factors affecting UHI can be classified into surface and atmospheric factors, including changes in land use and land cover, urban geometry, reduced evapotranspiration, and increased heat storage in building materials [6]. However, anthropogenic heat release (AHR) has often been treated as a secondary

Citation: Hadis Allahyari, Bahman Zohuri, and Esmaeel Salehi (2026) Anthropogenic Heat and Urban Heat Island Research: A Bibliometric and Conceptual Assessment of Energy System Decay Heat from Spent Nuclear Fuel Storage. J All Phy Res Appli 2: 1-14.

component in the urban energy balance at large scales, although it can be locally significant in dense urban environments [4,7].

With a contribution ratio of 90–95%, energy use is the main source of atmospheric AHR emissions [8,9]. Based on energy use from industry, transportation, and other sectors, a great deal of research has been done since the 1970s on AHR emissions and their effects on the environment and climate in large cities like London, New York, and Vancouver, based on energy consumption from industry, transport, and other sectors [10-12]. The present global mean flux of AHR is roughly 0.03 W m -2. AHR is a small climatic influence when compared to the total radiative forcing (RF) caused by human activity, which is about 2.72 W m -2 [13,14]. AHR flux varies geographically and is correlated with economic activity; in densely populated urban areas like Tokyo, the flux can surpass 1000 W m -2, while in remote areas, it is nearly zero [15-18]. In recent years, the quantification and modeling of AHR in urban climate studies has increasingly increased. This adds to the urban heat island effect, which puts stress on the power grid and other urban infrastructure and can result in heat-related deaths and illnesses. Buildings, transportation, industrial operations, and human metabolism are the four main spatial causes of human-induced AHR and can significantly alter local thermal regimes, influencing UHI, especially in dense and congested urban environments [7,19,20]. AHR is heat generated by human energy consumption [21,22]. Human activity-related heat emissions vary not only in space but also in time (daily, weekly, seasonally, and annually). Therefore, the relationship between heat from human activity and urban temperature variability cannot be explained by research findings based on data from particular locations and specific periods [23]. Short-cycle operational heat sources and long-cycle residual heat processes are the two primary groups of AHR based on its temporal dynamics, according to the standard classification and what has been said. Buildings, transit networks, industrial processes, and human metabolism are examples of short-cycle sources. Strong diurnal and seasonal cycles, quick temporal fluctuation, and direct correlation with weather and human activity are characteristics of these sources. For instance, a positive feedback loop that raises urban temperatures and exacerbates heat stress occurs during heat waves when increased cooling demand results in higher energy consumption for ventilation [24]. Despite the growing body of research on anthropogenic heat release, existing studies overwhelmingly focus on operational anthropogenic heat sources, while persistent residual heat associated with energy infrastructures remains poorly explored. In particular, the long-term thermal contribution of energy system decay heat, such as that generated by spent nuclear fuel storage, has received limited attention within urban climate and UHI research. Given the rapid expansion of urban climate studies, bibliometric approaches provide an effective framework for identifying dominant research themes, emerging trends, and overlooked knowledge gaps in anthropogenic heat research. This study aims to investigate the overlooked role of long-cycle residual heat processes in Urban Heat Island intensification, with particular emphasis on decay heat generated by spent nuclear fuel storage systems. To achieve this, the study combines bibliometric network analysis using VOS viewer with a conceptual urban-energy framework to identify dominant anthropogenic heat research trends, reveal existing knowledge gaps, and evaluate the potential interaction between persistent decay heat and urban microclimate dynamics.

Methodology

Literature Data Collection

The bibliometric analysis was conducted using two complementary datasets retrieved from the Scopus database. The primary dataset focused on the broader literature related to Urban Heat Island (UHI), anthropogenic heat, waste heat, and urban thermal environments, while the secondary dataset targeted publications specifically associated with energy-system decay heat and spent nuclear fuel storage. The use of two datasets enabled both a comprehensive assessment of dominant anthropogenic heat research themes and a focused investigation of underrepresented long-cycle residual heat processes. VOS viewer software, which is widely used in bibliometric and scientometric research, was employed to analyze and visualize the acquired datasets [25]. The software was used to investigate relationships among keywords, citations, thematic clusters, and research patterns within the selected literature. In particular, keyword co-occurrence analysis, thematic clustering, and temporal overlay visualization were applied to identify dominant research themes, emerging topics, and knowledge gaps related to Urban Heat Island and anthropogenic heat studies. The search process concentrated on publications related to Urban Heat Island (UHI), anthropogenic heat release (AHR), waste heat, urban energy systems, thermal emissions, and energy-related heat processes. The primary search query was defined as follows: ("urban heat island" OR UHI OR "urban climate") AND ("anthropogenic heat" OR "waste heat" OR "urban energy balance" OR "urban warming" OR "thermal environment")
And then in the next step the query was defined as follows: ("spent nuclear fuel" OR "decay heat" OR "spent fuel storage" OR "nuclear waste heat") AND ("thermal emissions" OR "microclimate" OR "urban climate" OR "waste heat")

Table-1 summarizes the bibliometric datasets used in this study. The significant difference in document numbers between the two datasets highlights the limited representation of persistent energy-system decay heat within current urban climate studies.

Table 1: Summary of the bibliometric dataset used in this study

Dataset	Dataset 1	Dataset 2
Query Focus	UHI+ Anthropogenic Heat	SNF + Decay Heat
Database	Scopus	Scopus
Period	1990–2026	1990–2026
Documents	2850	59

The primary search query yielded 2,850 publications indexed in the Scopus database. The majority of the retrieved documents were peer-reviewed journal articles, followed by conference papers and a smaller number of review papers and book chapters and other documents. This distribution indicates that scientific production in anthropogenic heat and UHI research is predominantly driven by journal-based academic publications. The secondary dataset focused on literature associated with spent nuclear fuel decay heat and related thermal emissions. Compared with the primary dataset, the number of retrieved publications was substantially smaller, reflecting the limited representation of persistent residual heat processes within current urban climate literature. The comparatively low number of publications highlights the emerging and underexplored nature of energy-system decay heat research in relation to Urban Heat Island studies. Only peer-reviewed English-language publications published between 1990 and 2026 were considered. Conference papers, editorials, notes, and non-English publications were excluded to maintain consistency and scientific quality. After removing duplicate records and screening irrelevant studies, the final datasets were used for bibliometric network analysis and conceptual thematic interpretation.

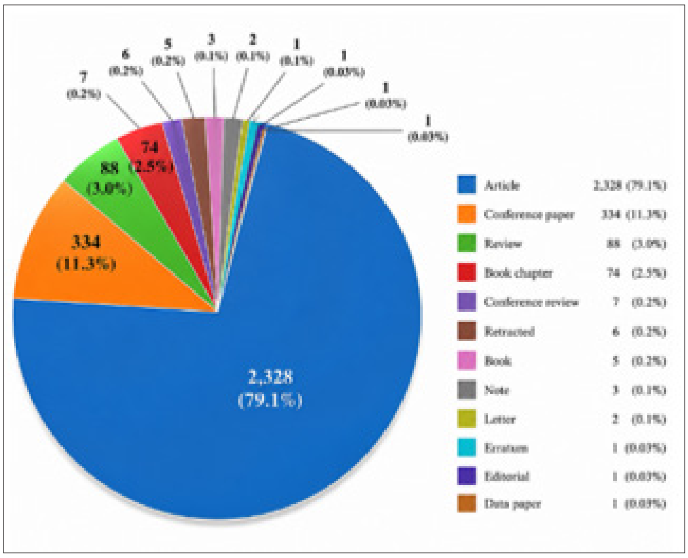

Figure 1: Distribution for Document Types for Query 1

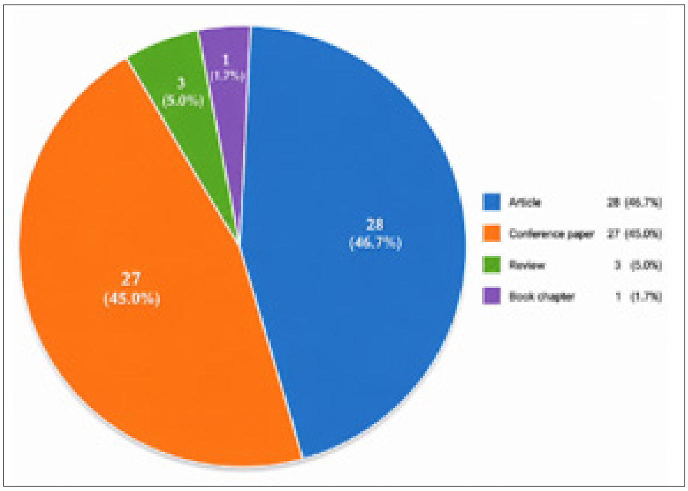

Figure 2: Distribution for Document Types for Query 2 1

Urban Heat Research Network

To identify the dominant research themes and thematic relationships within Urban Heat Island and anthropogenic heat studies, a keyword co-occurrence network was generated using VOS viewer based on the primary bibliometric dataset retrieved from Scopus. The visualization illustrates the major thematic clusters, keyword connectivity, and the structural organization of the existing research landscape. Node size represents keyword frequency, while link strength indicates the degree of association between research topics.

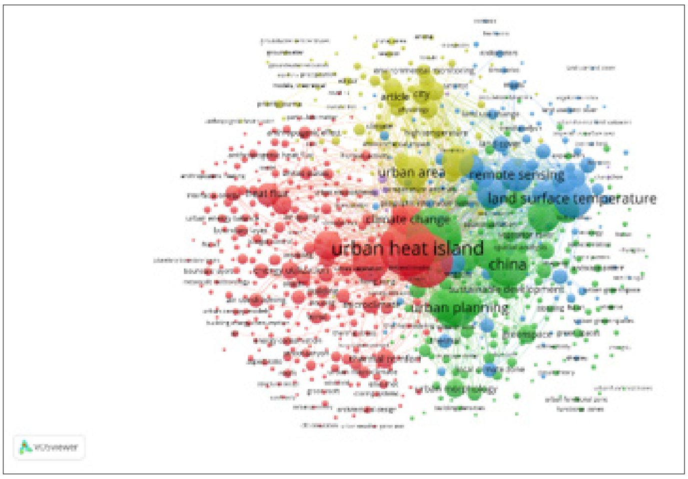

Figure 3: Bibliometric Keyword Co-occurrence Network of Urban Heat Island and Anthropogenic Heat Research

Table 2: Major Thematic Clusters Identified Through Keyword Co-occurrence Analysis

Cluster	Representative Keywords	Interpretation
Cluster 1 (Red)	urban heat island, heat flux, anthropogenic heat flux, energy utilization, air conditioning, thermal comfort, microclimate, urban energy balance	Operational anthropogenic heat dynamics and urban thermal processes
Cluster 2 (Green)	urban planning, urban morphology, sustainable development, urban green space, local climate zone, cooling systems	Urban morphology, planning strategies, and climate mitigation approaches
Cluster 3 (Blue)	remote sensing, land surface temperature, land cover, satellite image, spatial analysis, vegetation index	Remote sensing and spatial monitoring of urban thermal environments
Cluster 4 (Yellow)	climate change, environmental monitoring, urban area, high temperature, temperature anomaly, environmental impact	Climate-related environmental assessment and urban temperature studies

The keyword co-occurrence network based on figure 3 and table-2 reveals that current Urban Heat Island research is primarily structured around four dominant thematic clusters. The largest cluster is associated with operational anthropogenic heat dynamics, including thermal comfort, energy utilization, air conditioning, and heat flux studies. Additional major themes include urban planning and mitigation strategies, remote sensing-based thermal monitoring, and climate-related environmental assessment. The bibliometric structure indicates that existing research remains strongly focused on operational and morphology-related urban heat processes, while persistent residual heat associated with long-cycle energy infrastructures remains weakly represented within the dominant knowledge network.

Following the identification of the major thematic clusters, temporal overlay visualization was conducted to examine the evolution of research trends within the Urban Heat Island and anthropogenic heat literature in figure-4.

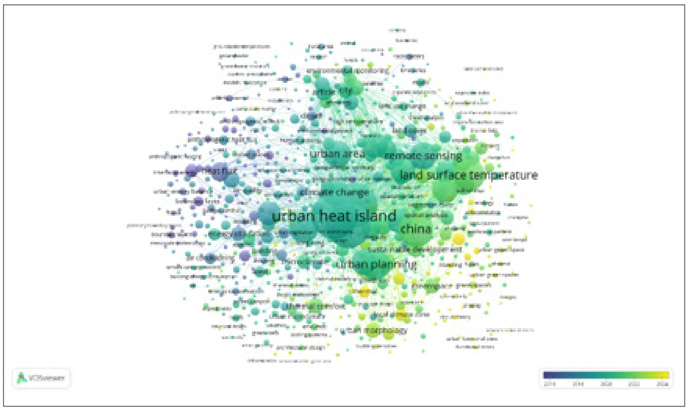

Figure 4: Temporal Overlay Visualization of Urban Heat Island and Anthropogenic Heat Research Generated Using VOSviewer

In this visualization, node colors represent the average publication year of keywords, allowing the identification of both mature and emerging research themes. The overlay analysis indicates that earlier studies were primarily concentrated on operational heat dynamics, atmospheric processes, and energy-related thermal emissions, including heat flux, anthropogenic heat flux, and boundary-layer interactions. More recent research trends increasingly emphasize urban planning, sustainable development, local climate zones, urban morphology, greenspace, and remote sensing-based thermal monitoring approaches. The strong emergence of terms associated with climate adaptation and urban sustainability reflects the growing interdisciplinary integration of urban climate research. Despite the expansion of research themes over time, persistent residual heat processes associated with long-cycle energy infrastructures remain weakly represented within the temporal structure of the literature. In particular, terms related to spent nuclear fuel storage and energy-system decay heat do not appear as dominant or emerging clusters, further confirming the limited integration of persistent anthropogenic residual heat processes within mainstream Urban Heat Island studies.

To further investigate the representation of persistent residual heat processes within the scientific literature, a secondary bibliometric analysis was conducted using a specialized dataset focused on spent nuclear fuel (SNF), radioactive waste, decay heat, and related thermal emissions. Unlike the broader Urban Heat Island dataset, the resulting network structure is substantially smaller and more fragmented, reflecting the limited integration of energy-system decay heat research within mainstream urban climate studies.

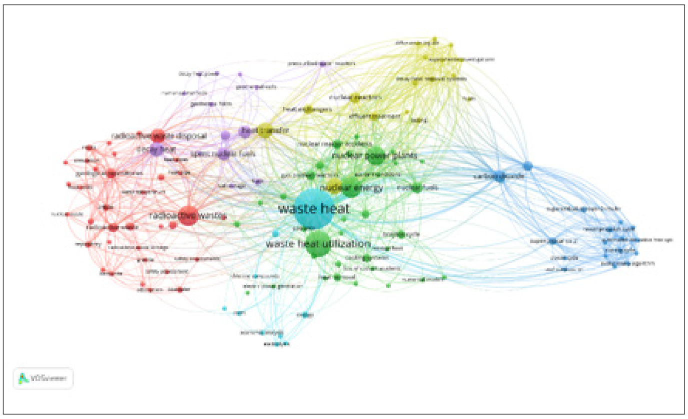

Figure 5: Bibliometric Keyword Co-occurrence Network of Spent Nuclear Fuel and Decay Heat Research

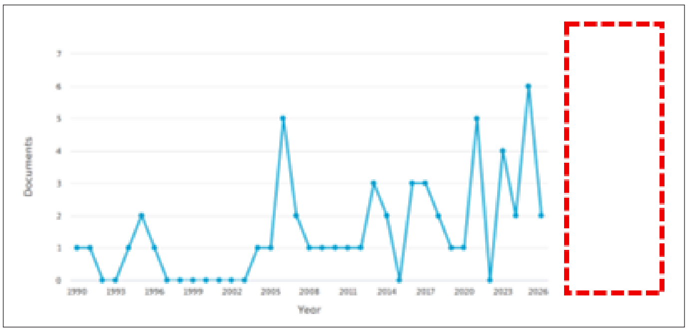

Figure 6: Annual Publication Trend for Query 2

The keyword co-occurrence network presented in Figure-5 reveals that the dominant themes within the secondary dataset are primarily associated with nuclear energy systems, radioactive waste disposal, heat transfer mechanisms, reactor cooling processes, and waste heat utilization. Keywords such as "radioactive wastes," "spent nuclear fuels," "decay heat," "heat transfer," and "nuclear reactors" form the central thematic structure of the network. However, direct connections to Urban Heat Island, urban climate, thermal comfort, or urban morphology themes remain weak or largely absent. This indicates that current research on decay heat is predominantly confined to nuclear engineering and thermal system management perspectives rather than urban climate applications. The annual publication trend shown in Figure 6 further confirms the emerging and underrepresented nature of this research field. Between 1990 and the early 2000s, publication activity remained extremely limited and discontinuous. A gradual increase in publication frequency can be observed after 2015, with the highest number of annual publications occurring in recent years. Nevertheless, the overall number of documents remains comparatively small relative to the broader anthropogenic heat literature, emphasizing the fragmented and still-developing status of persistent energy-system decay heat research. The combined interpretation of Figures 5 and 6 highlights a significant conceptual gap between conventional Urban Heat Island research and studies addressing long-cycle residual heat processes associated with nuclear energy infrastructures. This gap supports the need for a broader conceptual framework capable of integrating Persistent Anthropogenic Residual Heat (PARH) into future urban climate assessments and anthropogenic heat modeling approaches.

Findings

Conceptual Framework Development

Based on the thematic patterns and research gaps identified through bibliometric analysis, a conceptual framework was developed to classify anthropogenic heat sources according to their temporal dynamics and thermal persistence (See Figure-7).

The framework distinguishes between short-cycle operational heat sources and long-cycle residual heat processes. Particular emphasis was placed on the role of persistent decay heat generated by spent nuclear fuel (SNF) storage systems as a potentially overlooked component of urban thermal environments.

The conceptual model integrates heat transfer mechanisms, urban morphology interactions, and cumulative thermal loading processes in order to examine the possible contribution of energy system decay heat to localized Urban Heat Island intensification.

Short-cycle Operational Heat Sources: Over the past two decades, most research on AHR has focused on short-cycle operational heat sources in urban environments. More than half of all AHR is contributed by the building industry [26-29].

A. Dominant Research: Short-cycle Anthropogenic Heat Sources

A1. Buildings and HVAC Systems

Buildings and HVAC systems are widely recognized as major short-cycle sources of anthropogenic heat release (AHR) and important contributors to Urban Heat Island (UHI) intensification [30-35]. Anthropogenic heat flux (QF), defined as heat released into the atmosphere through human activities, represents a significant component of the urban energy balance and can be comparable to incoming solar radiation during summer periods [6]. Elevated QF increases urban air temperatures and subsequently raises building cooling demand [36,37].

Within buildings, heat generated by occupants and energy-consuming systems is initially released indoors through heating, ventilation, and air-conditioning (HVAC) operations. High-rise and high-density buildings are particularly important heat sources because their construction materials and operational requirements lead to substantial energy consumption for heating and cooling. This heat is transferred through building envelopes by conduction and subsequently released to the urban atmosphere through sensible heat flux and longwave radiation. As a result, internal heat generation alters the net storage heat flux (ΔQS) of buildings by increasing heat accumulation within construction materials [38,39].

Previous studies have shown that heat emitted from buildings and HVAC systems contributes directly to near-surface atmospheric warming and local UHI formation [7,18,40-45]. HVAC-related emissions exhibit strong diurnal and seasonal variability, with peak heat release typically occurring during hot daytime periods, creating feedback loops that intensify UHI effects, particularly in dense urban areas with limited ventilation [46].

A2. Transportation Systems

Transportation systems are a major short-cycle source of anthropogenic heat release (AHR) in urban environments. Heat is generated through internal combustion engines, vehicle exhaust, braking systems, and tire-road friction associated with vehicular movement [47-49]. Because only a portion of fuel energy is converted into useful mechanical work, a substantial fraction is released as waste heat into the urban atmosphere. Consequently, areas with high vehicle density often experience higher air temperatures than surrounding suburban regions, while traffic congestion can further intensify Urban Heat Island (UHI) effects [50,51].

Transportation-related heat emissions are strongly correlated with traffic volume, density, and commuting patterns [52]. In densely populated commercial and residential districts, prolonged engine operation, reduced airflow between vehicles, and limited ventilation within urban street canyons promote heat accumulation. Additional localized heating results from braking and tire-road friction processes near the ground surface. These emissions exhibit pronounced temporal variability, typically peaking during morning and evening rush hours and increasing during hot summer conditions. As a result, transportation-related AHR contributes to localized warming, transient increases in near-surface air temperature, and the intensification of UHI effects at neighborhood and district scales [53,54].

A3. Industrial Processes

Another significant category of short-cycle operational anthropogenic heat sources in urban and periurban settings is industrial activity. Fuel burning, manufacturing processes, the utilization of large machinery, and industrial processing systems all produce significant amounts of thermal energy. Only a small portion of the energy used in many industrial facilities is transformed into useful mechanical or manufacturing output; the remainder is emitted as waste heat into the surrounding environment [55-59]. Anthropogenic heat emissions are mostly caused by combustion-based industrial systems, such as boilers, furnaces, refineries, and power-intensive manufacturing processes. Additionally, throughout production cycles, friction, vibration, and motor action cause industrial machinery and mechanical equipment to continuously produce heat. Localized thermal emissions inside industrial zones can be further intensified by process heat related to metal processing, chemical reactions, material transformation, and high-temperature production [60].

A4. Human Metabolism

Human metabolism is a direct but often overlooked source of anthropogenic heat release (AHR) in urban environments. Thermal energy is continuously generated through respiration, circulation, thermoregulation, and physical activity, with much of the energy consumed by humans ultimately dissipated as heat through radiation, convection, conduction, and latent heat exchange [61,62]. Although individual heat emissions are relatively small compared with those from buildings, transportation systems, or industrial activities, their cumulative effect can become significant in densely populated urban areas. Metabolic heat is particularly concentrated in commercial districts, transportation hubs, office centers, shopping complexes, and public spaces where occupancy levels remain high. Studies have shown that population density is a major driver of spatial variability in anthropogenic heat intensity, and that metabolic heat can make a measurable contribution to urban heat fluxes [61,63,64]. Heat emissions vary according to activity levels, occupancy patterns, and land use, with peak values typically occurring during business hours, commuting periods, and large public gatherings.

Within the proposed framework, metabolic heat is classified as a short-cycle operational heat source because it depends directly on human presence and activity. Once occupancy decreases, heat emissions rapidly decline without significant thermal persistence. Consequently, metabolic heat contributes to localized and transient Urban Heat Island (UHI) intensification but has limited long-term influence compared with persistent residual heat sources [62].

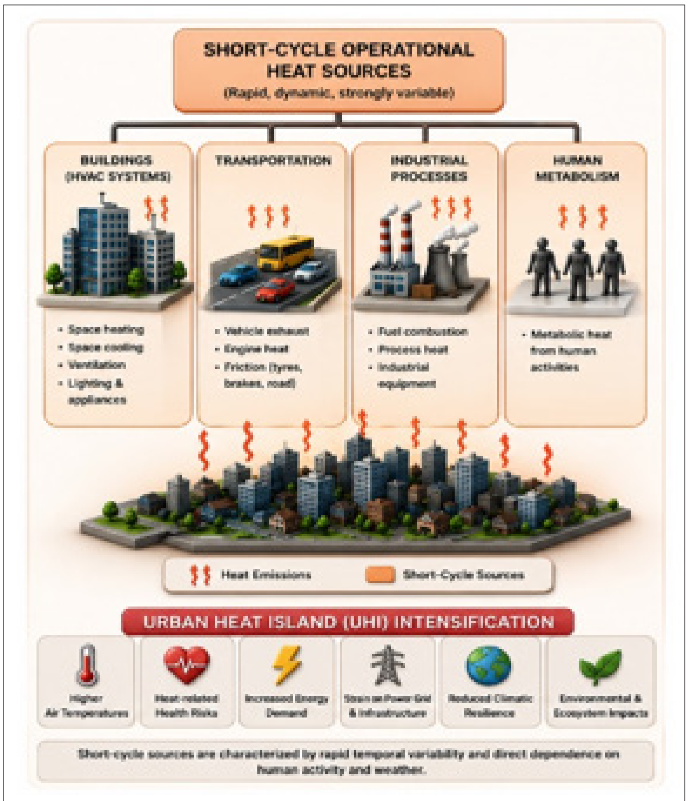

Figure 7A: Temporal Classification of Anthropogenic Heat Sources and Their Role in Urban Heat Island Intensification-Short cycle (Created by authors)

B. Long-Cycle Residual Heat Processes and Energy System Decay Heat

Thermal energy is stored and released gradually over long periods of time in long-cycle residual heat processes. These processes continue to release heat long after the initial energy-producing activity ceases, in contrast to traffic emissions, HVAC systems, or industrial operations that directly produce heat during operation. Their impact is cumulative, long-lasting, and unrelated to patterns of human activity [6].

There are four distinct conceptual stages within this category:

B1. Thermal Storage in Materials

Heat retention in urban materials including concrete, brick, asphalt, steel, and building envelopes is the first level. These materials absorb both solar energy and human heat during the day. They retain energy and release it gradually at night because of their high thermal inertia [4,6].

It is commonly acknowledged that this process is one of the main ways that nighttime Urban Heat Islands (UHI) are preserved [31,65]. Warming effects are prolonged beyond the time of active energy input because the stored heat effectively serves as a transient thermal reservoir. Heat storage in constructed materials can considerably raise nighttime air temperatures when compared to nearby rural areas, according to studies of urban energy budgets [6,66].

Sensible heat storage and delayed release are its main mechanisms, and its time scale ranges from hours to days. The primary significance of UHI is warming during nighttime.

B2. Subsurface Heat Accumulation

When thermal energy seeps below the surface and builds up in soils, subterranean buildings, tunnels, utility networks, and foundations, the second step takes place.

Subsurface Urban Heat Islands (SUHIs), as defined by researchers, are becoming more common in urban environments [67,68]. Heat produced at the surface moves downhill and can be retained for months or even years underground. By releasing energy back toward the surface, this subterranean heat reservoir keeps temperatures high even while the surrounding air cools [68].

Stage 2 contains higher thermal masses and slower heat-transfer mechanisms than Stage 1, when heat is mostly stored in surface materials.

Time scales range from months to years, with conductive heat storage in soil and subsurface infrastructure serving as the major mechanism. The primary importance to UHI is long-term thermal persistence [67].

B3. Infrastructure-Based Residual Heat

The third stage is defined as heat retained and constantly emitted by energy infrastructure systems. Examples include Power generation facilities, District heating systems, Data centers, Electrical substations and industrial energy networks [7].

These systems convert an enormous amount of energy, with a significant portion finally appearing as waste heat. Even after peak demand have ended, infrastructure components frequently release residual heat due to thermal energy stored in machinery, fluids, and structural materials [7].

Infrastructure-based heat fills the gap between short-term operational heat emissions and true long-term decay heat processes.

Time scales range from days to year. The dominant process is waste heat retention and gradual release, with the main significance to UHI being continual background anthropogenic heating [4,7].

B4. Energy System Decay Heat from Spent Nuclear Fuel Storage

The main emphasis of this work is the fourth stage, which is theoretically unique.

The thermal energy produced by the radioactive decay of unstable isotopes in spent nuclear fuel following the shutdown of a reactor is known as decay heat [69,70]. When a reactor shuts down, nuclear fission immediately stops, but radioactive fission products and actinides continue to decay and release energy in the form of beta particles, gamma radiation, and other decay products. Heat is produced when the fuel absorbs this radiation [70].

Because decay heat persists long after reactor shutdown and requires continuous cooling, it is considered a major safety risk in nuclear engineering [70,71]. Compared to other man-made heat sources, this is distinct because

Most anthropogenic heat sources are directly related to ongoing human activities:

- Vehicles generate heat when in operation.
- When air conditioners are turned on, they emit heat.
- Heat is released by factories throughout the manufacturing process.

In contrast, spent nuclear fuel continues to emit heat even when: 1) Electricity production has halted. 2) Human operations have halted. 3)The reactor has been permanently shut down. As a result, decay heat is a residual anthropogenic heat source. The radioactive decay kinetics of the fuel stockpile regulate the heat release, rather than contemporary human activity [69].

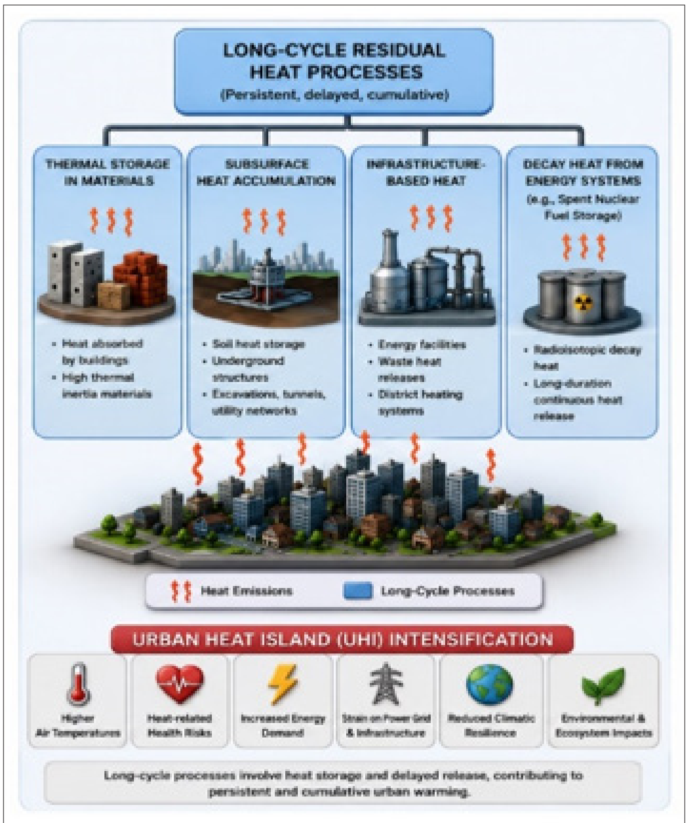

Figure 7B: Temporal Classification of Anthropogenic Heat Sources and Their Role in Urban Heat Island Intensification-Long cycle (Created by authors)

Temporal Persistence

Decay heat in spent nuclear fuel (SNF) originates from the radioactive decay of fission products and transuranic isotopes and remains a critical consideration for reactor safety, fuel handling, and long-term storage [70,71]. After reactor shutdown, SNF continues to generate heat, initially at several percent of reactor power and then gradually declining over time [69]. Although heat output decreases rapidly during the first years after discharge, significant residual heat can persist for decades or longer due to long-lived actinides [69,70]. Consequently, continuous cooling through spent fuel pools or dry cask systems is required [71]. While its direct urban-climate impact is generally limited, decay heat broadens the concept of anthropogenic heat beyond active energy consumption, representing a persistent residual heat source that can continue affecting thermal conditions long after energy production has ceased.

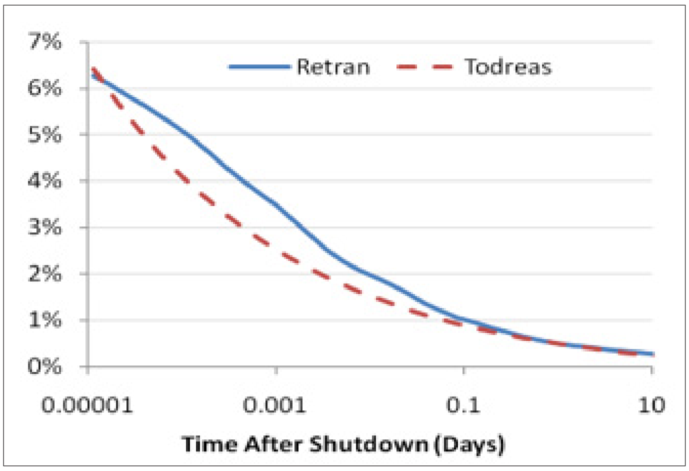

Figure 8: Decay heat as fraction of full power for a reactor SCRAMed from full power at time 0, using two different correlations

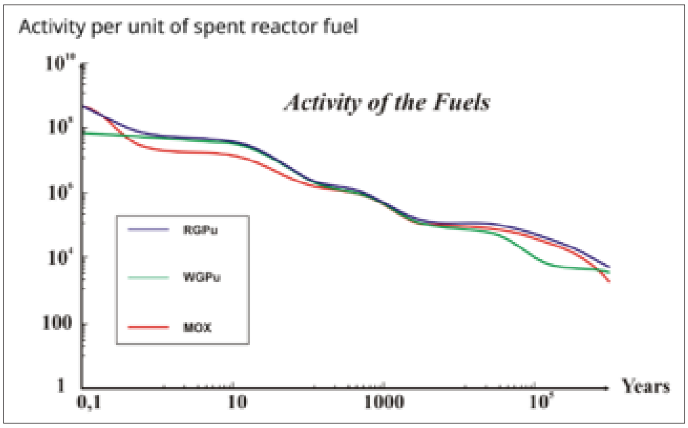

Figure 9: Total activity for three fuel types. In region 1 we have radiation from short-lived nuclides, and in region 2 from Sr-90 and Cs-137.

The composition of spent nuclear fuel depends on the initial fissile inventory and the energy extracted during reactor operation [72-

74]. A typical PWR fuel assembly enriched to 3.5% contains approximately 965 kg of U-238 and 35 kg of U-235 per tonne of fuel [72,73]. After irradiation, most U-238 remains, while only about 10 kg of U-235 is left. Consequently, spent fuel still contains around 1% fissile U-235, exceeding the natural uranium concentration of 0.7%, making uranium recovery and recycling potentially attractive [72-74].

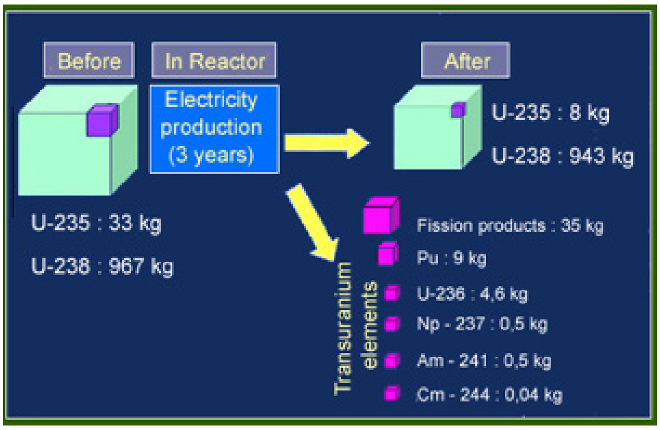

Figure 10: Distribution (in kg per ton of fuel) and mass produced by the principal radioactive elements present in fuel unloaded from a pressurized water reactor core. IPHC/IN2P3 (Source: Isabelle Billard)

fission products, actinides (such as neptunium, americium, and curium), and activation products formed by neutron irradiation of reactor materials, including cobalt-58, cobalt-60, manganese-54, antimony-124, tritium, and carbon-14 [70,72,73]. Most fission products decay relatively quickly, although isotopes such as cesium-137 and strontium-90 have half-lives of about 30 years, while actinides contribute to long-term radiological persistence [69,74].

By the end of 2022, the global spent nuclear fuel (SNF) inventory had reached approximately 430,000 tHM, with annual additions of about 10,000 tHM from operating reactors [72,73,75]. Because radioactive decay continuously generates heat, newly discharged fuel must be stored in cooling pools for several years before reprocessing or disposal. Consequently, decay heat management remains a key consideration in the safe handling and long-term storage of high-level radioactive waste [70,71].

A typical uranium oxide (UOX) fuel assembly weighs about 500 kg and continues to generate decay heat long after reactor discharge. Five years after removal from the reactor, a spent fuel assembly emits approximately the same heat as twelve 100-W lightbulbs, decreasing to about 85 W after 300 years [76]. Consequently, spent fuel must be cooled in storage pools or dry cask systems before disposal. Although vitrified waste generated after uranium and plutonium separation emits less heat and cools more rapidly, both waste forms continue to release thermal energy over long periods [74]. Repository designs must therefore limit temperatures to below 100°C to prevent water evaporation and maintain long-term safety. For this reason, high-level radioactive waste is stored and cooled for extended periods before final disposal [70,74].

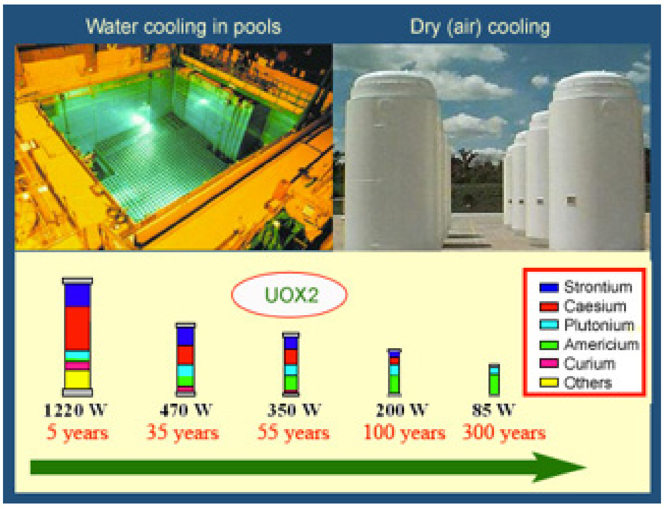

Figure 11: Heat released by a spent fuel assembly

Although the direct urban-climate impact of spent nuclear fuel (SNF) decay heat is generally limited due to the localized nature of storage facilities, it is conceptually important because it extends the definition of anthropogenic heat beyond active energy consumption [4,7,70]. Decay heat represents a residual anthropogenic heat source that persists long after energy production has ceased and may be the longest-lasting heat source associated with modern energy systems [69,70].

As illustrated in Figures 12–14, SNF storage systems continuously release decay heat through dry cask ventilation or wet-storage cooling systems [70,71]. With increasing urban expansion, some nuclear facilities and Independent Spent Fuel Storage Installations (ISFSIs) are located near populated areas, creating a persistent, though relatively small, thermal input to the local environment [75]. Unlike conventional anthropogenic heat sources that vary with human activity, decay heat is continuous and largely independent of daily or seasonal demand cycles. Consequently, localized thermal plumes may interact with urban morphology and microclimate processes, potentially contributing to cumulative heat loads and sustaining elevated nighttime temperatures, an important component of Urban Heat Island (UHI) intensity [4,6,65].

From an energy-systems perspective, spent nuclear fuel (SNF) decay heat is relevant to sustainability and life-cycle assessments. Although nuclear energy produces minimal greenhouse gas emissions during operation, its environmental evaluation must include back-end activities such as storage and waste management [74,77]. While decay heat decreases over time, it represents a continuous release of thermal energy that is rarely utilized [70]. In urban environments, this residual heat may marginally increase ambient thermal loads, highlighting the potential value of heat-recovery and integration strategies to improve overall system efficiency and reduce environmental impacts [74,77].

The passive cooling system of a dry cask spent nuclear fuel storage system is seen in Figure-12. The storage overpack's surrounding air channels receive residual decay heat produced by spent nuclear fuel via the multipurpose canister. Natural convection removes heat from the cask without the need for active cooling equipment or external electricity [70,71]. In the end, the released heated air releases decay heat into the atmosphere, which is a long-term residual human heat source [69,70].

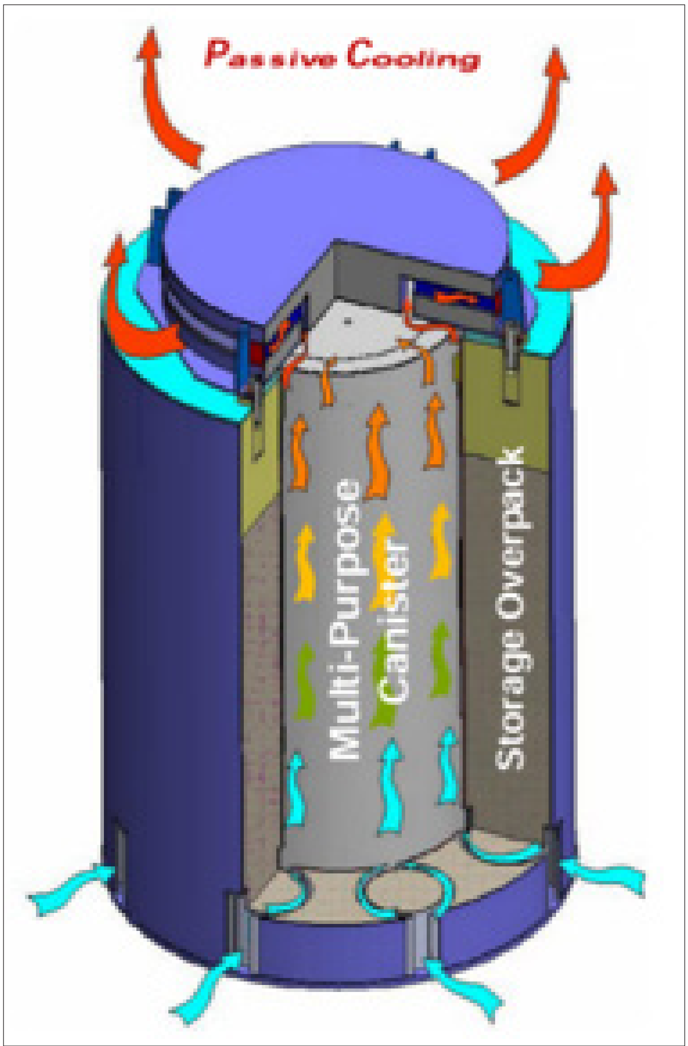

Figure 12: Heat Transfer Mechanisms

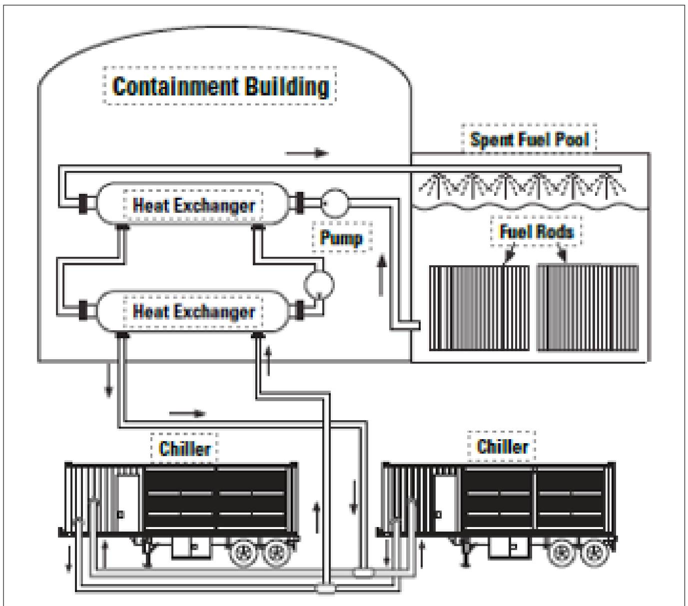

Figure 13: local thermal mechanism and urban heat island (UHI) effects in the vicinity of spent nuclear fuel facilities.

Figure-13 shows how decay heat created by radioactive fuel is transported to cooling water, extracted via heat exchangers and chillers, and finally released into the atmosphere. Unlike conventional anthropogenic heat sources that require continuous energy consumption, this residual thermal emission persists for decades after reactor operation because it is governed by radioactive decay processes rather than ongoing energy production [69,70]. Consequently, spent nuclear fuel (SNF) storage may be considered a long-cycle residual anthropogenic heat source with potential implications for localized thermal environments and possible interactions with Urban Heat Island (UHI) processes [4,7].

Furthermore, assessing decay heat in connection to UHI intensification is consistent with the increased emphasis on integrated urban energy modeling and digital twin frameworks [78,79]. Advanced modeling technologies, such as Computational Fluid Dynamics (CFD), heat transfer analysis, and data-driven methodologies, allow for the full characterization of heat sources and their interactions in complex urban environment [6,80]. Incorporating SNF decay heat into such models can increase the accuracy of UHI projections, allowing for more informed urban planning and policy decisions. This is especially important for cities implementing climate adaption methods, because even small decreases in heat buildup may result in considerable benefits such as decreased cooling demand, lower peak electrical loads, and better public health outcomes [79].

This consideration is particularly relevant for cities pursuing climate adaptation and resilience strategies, where even modest reductions in accumulated heat loads may contribute to lower cooling-energy demand, reduced peak electricity consumption, and improved thermal comfort and public health outcomes [4,81]. Although the thermal contribution of SNF storage systems is expected to be small compared with major urban heat sources, evaluating their long-term and continuous heat release may help improve understanding of cumulative anthropogenic heat effects in urban environments [6,7].

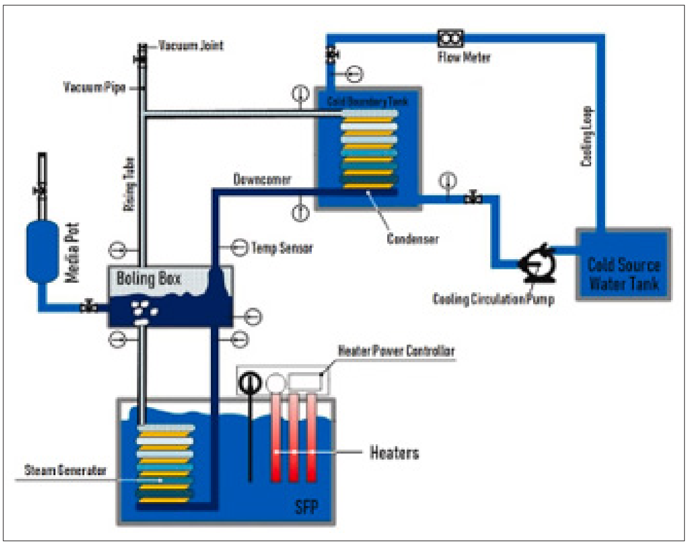

Figure 14: Experimental Schematic of a Spent Fuel Pool (SFP) Decay Heat Removal System Using a Two-Phase Natural Circulation Loop and Atmospheric Interaction

Figure-14 depicts an experimental thermohydraulic facility that removes decay heat from a spent fuel pool (SFP). Electrical heaters replicate residual heat generation from spent nuclear fuel, whereas a two-phase natural circulation loop distributes thermal energy via boiling, vapor movement, condensation, and secondary cooling [69,70]. The rejected heat is eventually released into the environment, demonstrating how spent nuclear fuel decay heat contributes to long-term residual anthropogenic heat emissions that are significant to urban heat island (UHI) studies [4,7].

Figures 12-14 are single-frame conceptual diagrams that graphically illustrate the relationship between spent nuclear fuel decay heat and Urban Heat Island (UHI) processes. Collectively, these figures show the generation, transport, removal, and eventual environmental release of decay heat from spent nuclear fuel storage systems. For clarity, the mechanisms represented in Figures 12–14 may be integrated into a unified conceptual framework, as illustrated in Figure-15, which summarizes the pathways through which decay heat is transferred from spent nuclear fuel storage systems to the surrounding urban environment and potentially contributes to cumulative anthropogenic heat loads [6,7].

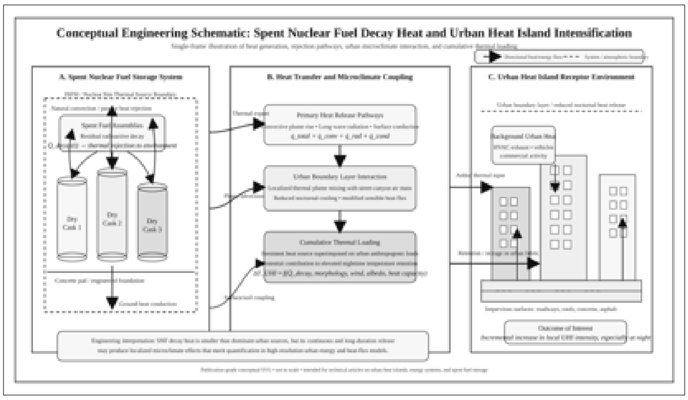

Figure 15: Conceptual Framework Linking Spent Nuclear Fuel Decay Heat to Urban Heat Island Intensification

The conceptual framework created in this study to show how the Urban Heat Island (UHI) phenomenon and spent nuclear fuel (SNF) decay heat are related is shown in Figur-15. The diagram illustrates how leftover thermal energy produced by SNF storage systems might interact with urban surroundings and perhaps contribute to localized warming by combining concepts from nuclear engineering, heat transmission, and urban climatology [6,7]. The framework is divided into three interrelated domains: the urban heat island receptor environment (C), heat transport and microclimate coupling mechanisms (B), and the SNF storage system as a continuous heat source (A).

The thermal energy source spent nuclear fuel storage facilities are seen in the left portion of Figure-15. Spent fuel continues to produce heat after being released from a nuclear reactor due to the radioactive decay of transuranic isotopes, fission products, and activation products [69,70]. Even while decay heat diminishes with time, it can still be measured decades or even centuries after reactor operation has stopped [74]. Because thermal energy is continuously released regardless of electricity demand, industrial activity, or human operating schedules, SNF storage systems represent a distinct category of anthropogenic heat source [70]. The thermal output from SNF storage comes from previously generated nuclear energy and continues long after power production has stopped [4,7] in contrast to traditional urban heat sources like transportation systems, commercial buildings, or industrial facilities. Although the conceptual framework is equally relevant to spent fuel pools and other interim storage configurations, dry storage casks are depicted in the graphic as exemplary storage methods. The main thermal driver in the system is the parameter $\dot{Q}$decay, which represents the rate of decay heat generation [69].

The middle section illustrates the mechanisms through which decay heat is transferred from storage systems to the surrounding environment. Three primary heat transfer pathways are identified: convection, radiation, and conduction [82]. Convective heat transfer occurs when air surrounding storage casks or cooling systems is heated and rises because of buoyancy effects, generating localized thermal plumes. These plumes transport energy upward into the atmospheric boundary layer and may influence local temperature distributions in the vicinity of the storage facility [6]. Radiative heat transfer occurs when heated storage surfaces emit long-wave thermal radiation to surrounding structures, ground surfaces, and the atmosphere [82]. Conductive heat transfer allows thermal energy to move into supporting foundations, surrounding soils, and nearby infrastructure, where it can be stored and subsequently released over extended periods [67,68]. Collectively, these mechanisms define the overall environmental heat release from the storage system, which is represented in the framework as:

$$\dot{Q}_{total}=\dot{Q}_{conv}+\dot{Q}_{rad}+\dot{Q}_{cond}$$

where $\dot{Q}_{conv}$, $\dot{Q}_{rad}$, and $\dot{Q}_{cond}$ represent convective, radiative, and conductive heat fluxes, respectively.

Thermal emissions in urban regions do not disperse uniformly because the built environment alters airflow patterns, radiation exchange, and heat storage behavior [6,65]. Buildings, streets, and other urban structures have an impact on turbulence production, wind speed, and atmospheric mixing, influencing how thermal energy released from SNF storage systems spreads throughout the surrounding microclimate [6,80]. As a result, the heat emitted by storage facilities may contribute to localized warming effects that extend beyond the facility's immediate boundaries [4,7].

The framework introduces a critical notion known as cumulative thermal loading. Urban thermal conditions are the result of the combined action of several heat sources, rather than any single source operating alone [6,7]. As a result, even if the thermal output of SNF storage is lower than that of transit networks, HVAC systems, industrial facilities, or commercial energy consumption, its continuous and long-duration character allows it to contribute to the overall metropolitan heat budget [4,70].

The relationship represents the cumulative effect:
$\Delta T_{UHI}=f\,(Q^{\cdot}_{decay}$, urban morphology, wind, albedo, heat capacity)

The resulting UHI intensity is determined not only by the magnitude of decay heat release, but also by urban geometric qualities, meteorological conditions, and the thermophysical properties of the urban fabric [4,6,65].

The right-hand section of the figure-15 depicts the urban environment, which receives and responds to thermal inputs. Urban regions are distinguished by dense building layouts, wide impervious surfaces, and substantial thermal storage capacity [6,65]. Roads, concrete buildings, asphalt pavements, and building materials absorb solar radiation during the day and release stored energy at night, resulting in the well-known UHI effect [4,31]. Additional anthropogenic heat sources, such as car exhaust, industrial activities, and air-conditioning systems, contribute to higher metropolitan temperatures [4,7]. Within this scenario, decay heat from SNF storage serves as a supplementary thermal input, supplementing current urban heat sources. The schematic shows how this additional thermal energy can be kept within the urban canopy layer, especially at night when air mixing is weaker and heat dissipation is reduced [6].

One of the most important implications of this concept is the identification of SNF decay heat as a type of long-cycle residual anthropogenic heat. Conventional anthropogenic heat sources are typically associated with ongoing human activity and show significant daily or seasonal variations. In contrast, SNF decay heat persists for decades [69,70]. This temporal characteristic distinguishes it from most other urban heat sources, implying that its cumulative environmental impact may be worth considering in long-term urban climate assessments, particularly in areas where nuclear facilities are located near urban or peri-urban development's [74].

In fact, Figure-15 represents a conceptual paradigm that connects nuclear energy systems with urban climate science. By describing the physical paths via which decay heat is transmitted from spent fuel storage systems into the urban environment, the framework provides a theoretical foundation for determining whether SNF storage facilities contribute measurable amounts to local UHI intensification [6,7].

Furthermore, it lays the groundwork for future quantitative studies aiming at calculating decay heat fluxes, determining their regional distribution, comparing them to traditional anthropogenic heat sources, and evaluating mitigating options [80,81]. This multidisciplinary approach tackles a hitherto unexplored area of urban energy balances and adds to a better understanding of the interplay between nuclear infrastructure and urban climate systems [6,77].

Conclusion

This study explored the relationship between anthropogenic heat release, Urban Heat Island (UHI) intensification, and long-cycle residual heat processes associated with spent nuclear fuel (SNF) storage systems. Through a combined bibliometric and conceptual assessment, it examined how anthropogenic heat sources are represented in current UHI research and whether energy-system decay heat is adequately considered within urban climate frameworks.

The bibliometric analysis revealed that UHI research is dominated by short-cycle operational heat sources, including buildings, HVAC systems, transportation, industrial activities, and urban morphology-related processes. Emerging themes increasingly focus on sustainability, urban planning, local climate zones, and remote sensing. In contrast, energy-system decay heat and SNF storage remain largely absent from mainstream research despite their continuous and long-term thermal characteristics, highlighting a significant knowledge gap.
To address this gap, a conceptual framework was developed that distinguishes between short-cycle operational heat emissions and long-cycle residual heat processes. Within this framework, SNF decay heat is introduced as a form of Persistent Anthropogenic Residual Heat (PARH), characterized by thermal emissions that continue long after electricity generation has ceased. This perspective expands the traditional understanding of anthropogenic heat and emphasizes the long-term thermal legacy of energy infrastructures.

The findings suggest that SNF storage is unlikely to be a major driver of large-scale UHI formation because of its limited spatial footprint. However, its continuous heat release may contribute to localized thermal anomalies and microclimatic warming when combined with urban morphology, meteorological conditions, and other anthropogenic heat sources. The significance of this work lies not in identifying SNF storage as a dominant UHI contributor, but in recognizing an overlooked category of anthropogenic heat. Future research should employ urban climate models, CFD simulations, digital twin frameworks, and experimental measurements to quantify the magnitude, spatial extent, and temporal behavior of decay-heat emissions and evaluate their role within comprehensive urban energy balance assessments.

References

1. Gaur A, Deb C (2026) Machine learning methods and approaches for Urban Heat Island (UHI) assessment: A comprehensive review. Renewable and Sustainable Energy Reviews 234: 116903.
2. Teixeira CP, Fernandes CO, Ahern J (2022) Adaptive planting design and management framework for urban climate change adaptation and mitigation. Urban Forestry & Urban Greening 70: 127548.
3. Santamouris M (2014) Cooling the cities–a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Solar energy 103: 682-703.
4. Santamouris M (2015) Regulating the damaged thermostat of the cities—Status, impacts and mitigation challenges. Energy and Buildings 91: 43-56.
5. IPCC (2021) Climate change 2021-the physical science basis. Interaction 49: 44-45.
6. Oke TR, Mills G, Christen A, Voogt JA (2017) Urban climates. Cambridge university press.
7. Sailor DJ (2011) A review of methods for estimating anthropogenic heat and moisture emissions in the urban

environment. International journal of climatology 31: 189-199.
8. Lu Y, Wang QG, Zhang Y, Sun P, Qian Y (2016) An estimate of anthropogenic heat emissions in China. International Journal of Climatology 36: 1134-1142.
9. Ferreira MJ, de Oliveira AP, Soares J (2011) Anthropogenic heat in the city of São Paulo, Brazil. Theoretical and Applied Climatology 104: 43-56.
10. Harrison R, McGoldrick B, Williams CGB (1984) Artificial heat release from Greater London, 1971–1976. Atmospheric Environment (1967) 18: 2291-2304.
11. Clark EC, Bornstein RD, Tam YT (1985) Current and potential anthropogenic moisture effects on the New York City planetary boundary layer. Journal of the Air Pollution Control Association 35: 831-835.
12. Grimmond CSB (1992) The suburban energy balance: Methodological considerations and results for a mid-latitude west coast city under winter and spring conditions. International Journal of Climatology 12: 481-497.
13. Chen B, Wu C, Liu X, Chen L, Wu J, et al. (2019) Seasonal climatic effects and feedbacks of anthropogenic heat release due to global energy consumption with CAM5. Climate Dynamics 52: 6377-6390.
14. Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, et al. (2021) Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change 2: 2391.
15. Chen B, Shi G, Wang B, Zhao J, Tan S (2012) Estimation of the anthropogenic heat release distribution in China from 1992 to 2009. Acta Meteorologica Sinica 26: 507-515.
16. Dong Y, Varquez ACG, Kanda M (2017) Global anthropogenic heat flux database with high spatial resolution. Atmospheric Environment 150: 276-294.
17. Varquez ACG, Kiyomoto S, Khanh DN, Kanda M (2021) Global 1-km present and future hourly anthropogenic heat flux. Scientific Data 8: 64.
18. Ichinose T, Shimodozono K, Hanaki K (1999) Impact of anthropogenic heat on urban climate in Tokyo. Atmospheric Environment 33: 3897-3909.
19. Allen L, Lindberg F, Grimmond CSB (2011) Global to city scale urban anthropogenic heat flux: model and variability. International Journal of Climatology 31: 1990.
20. Lu Y, Shao Z, Lu H (2024) Quantification of anthropogenic heat and simulation of its effects on environment and climate: A comprehensive review. Renewable and Sustainable Energy Reviews 204: 114802.
21. Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, et al. (2007) Changes in atmospheric constituents and in radiative forcing. Chapter 2.
22. Chen B, Wu C, Song X, Zheng Y, Lu M, et al. (2023) Anthropogenic heat release due to energy consumption exacerbates European summer extreme high temperature. Climate Dynamics 61: 3831-3843.
23. Sun R, Wang Y, Chen L (2018) A distributed model for quantifying temporal-spatial patterns of anthropogenic heat based on energy consumption. Journal of cleaner production 170: 601-609.
24. Vahmani P, Jones AD, Li D (2022) Will anthropogenic warming increase evapotranspiration? Examining irrigation water demand implications of climate change in California. Earth's Future 10: e2021EF002221.
25. Van Eck N, Waltman L (2010) Software survey: VOS viewer, a computer program for bibliometric mapping. scientometrics 84: 523-538.
26. Quah AK, Roth M (2012) Diurnal and weekly variation of anthropogenic heat emissions in a tropical city, Singapore. Atmospheric Environment 46: 92-103.
27. Smith C, Lindley S, Levermore G (2009) Estimating spatial and temporal patterns of urban anthropogenic heat fluxes for UK cities: the case of Manchester. Theoretical and Applied Climatology 98: 19-35.
28. Cao Z, Wu Z, Liu L, Chen Y, Zou Y (2019) Assessing the relationship between anthropogenic heat release warming and building characteristics in Guangzhou: A sustainable development perspective. Science of the Total Environment 695: 133759.
29. Wieser AA, Scherz M, Passer A, Kreiner H (2021) Challenges of a healthy built environment: Air pollution in construction industry. Sustainability 13: 10469.
30. Hwang RL, Lin CY, Huang KT (2017) Spatial and temporal analysis of urban heat island and global warming on residential thermal comfort and cooling energy in Taiwan. Energy and Buildings 152: 804-812.
31. Oke TR (1982) The energetic basis of the urban heat island. Quarterly journal of the royal meteorological society 108: 1-24.
32. Santamouris M (2015) Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions. Science of the Total Environment 512: 582-598.
33. Li X, Zhou Y, Asrar GR, Imhoff M, Li X (2017) The surface urban heat island response to urban expansion: A panel analysis for the conterminous United States. Science of the Total Environment 605: 426-435.
34. Peng S, Piao S, Ciais P, Friedlingstein P, Ottle C, et al. (2012) Surface urban heat island across 419 global big cities. Environmental science & technology 46: 696-703.
35. Li H, Zhou Y, Li X, Meng L, Wang X, et al. (2018) A new method to quantify surface urban heat island intensity. Science of the total environment 624: 262-272.
36. Santamouris M, Papanikolaou N, Livada I, Koronakis I, Georgakis C, et al. (2001) On the impact of urban climate on the energy consumption of buildings. Solar energy 70: 201-216.
37. Takane Y, Kikegawa Y, Hara M, Grimmond CSB (2019) Urban warming and future air-conditioning use in an Asian megacity: importance of positive feedback. npj Climate and Atmospheric Science 2: 39.
38. Li X, Zhou Y, Yu S, Jia G, Li H, et al. (2019) Urban heat island impacts on building energy consumption: A review of approaches and findings. Energy 174: 407-419.
39. Liu Y, Luo Z, Grimmond S (2022) Revising the definition of anthropogenic heat flux from buildings: role of human activities and building storage heat flux. Atmospheric Chemistry and Physics 22: 4721-4735.
40. Sailor DJ, Lu L (2004) A top–down methodology for developing diurnal and seasonal anthropogenic heating

profiles for urban areas. Atmospheric environment 38: 2737-2748.
41. Heiple S, Sailor DJ (2008) Using building energy simulation and geospatial modeling techniques to determine high resolution building sector energy consumption profiles. Energy and buildings 40: 1426-1436.
42. Fan H, Sailor DJ (2005) Modeling the impacts of anthropogenic heating on the urban climate of Philadelphia: a comparison of implementations in two PBL schemes. Atmospheric environment 39: 73-84.
43. Ouyang H, Xue Y, Lin Y, Zhang X, Xi L, et al. (2014) WNT7A and PAX6 define corneal epithelium homeostasis and pathogenesis. Nature 511: 358-361.
44. Ferrando M, Hong T, Causone F (2021) A simulation-based assessment of technologies to reduce heat emissions from buildings. Building and Environment 195: 107772.
45. Chen W, Zhou Y, Xie Y, Chen G, Ding KJ, et al. (2022) Estimating spatial and temporal patterns of urban building anthropogenic heat using a bottom-up city building heat emission model. Resources, Conservation and Recycling 177: 105996.
46. Xu Y, Vahmani P, Jones A, Hong T (2024) Anthropogenic heat from buildings in Los Angeles County: A simulation framework and assessment. Sustainable Cities and Society 107: 105468.
47. Costagliola MA, Marchitto L, Giuzio R, Casadei S, Rossi T, et al. (2024) Non-exhaust particulate emissions from road transport vehicles. Energies 17: 4079.
48. Costagliola MA, Marchitto L, Piras M, Mariani A, Giuzio R (2026) Measurements of brake and tire wear particulate emissions from light-duty vehicles under WLTC driving conditions. Science of The Total Environment 1016: 181462.
49. Fussell JC, Franklin M, Green DC, Gustafsson M, Harrison RM, et al. (2022) A review of road traffic-derived non-exhaust particles: emissions, physicochemical characteristics, health risks, and mitigation measures. Environmental science & technology 56: 6813-6835.
50. Husni E, Prayoga GA, Tamba JD, Retnowati Y, Fauzandi FI, et al. (2022) Microclimate investigation of vehicular traffic on the urban heat island through IoT-Based device. Heliyon 8: e11739.
51. Ding W, Yan W, Chang H, Xu H, Chen H (2026) Diurnal impacts of sectoral anthropogenic heat emissions on urban heat islands. Urban Climate 65: 102822.
52. Mishra MK, Mathew A (2022) Investigating the spatio-temporal correlation between urban heat island and atmospheric pollution island interaction over Delhi, India using geospatial techniques. Arabian Journal of Geosciences 15: 1591.
53. Lee J, Berkelhammer M (2025) Evaluating the influence of traffic congestion on surface urban heat island intensity. Geophysical Research Letters 52: e2025GL116651.
54. Kong J, Zhao Y, Strebel D, Gao K, Carmeliet J, et al. (2023) Understanding the impact of heatwave on urban heat in greater Sydney: temporal surface energy budget change with land types. Science of the Total Environment 903: 166374.
55. Salamanca F, Georgescu M, Mahalov A, Moustaoui M, Wang M (2014) Anthropogenic heating of the urban environment due to air conditioning. Journal of Geophysical Research: Atmospheres 119: 5949-5965.
56. Yang J, Tham KW, Lee SE, Santamouris M, Sekhar C, et al. (2017) Anthropogenic heat reduction through retrofitting strategies of campus buildings. Energy and buildings 152: 813-822.
57. Xia C, Yu Z, Huang JJ (2026) Effects of multi-source anthropogenic heat emissions on urban heat and cold stress across coastal megacities with contrasting energy-use patterns. Sustainable Cities and Society 145: 107452.
58. Brückner S, Liu S, Miró L, Radspieler M, Cabeza LF, et al. (2015) Industrial waste heat recovery technologies: An economic analysis of heat transformation technologies. Applied energy 151: 157-167.
59. Song J, Zhang H, Zhang Y, Ma Z, He M (2025) Research progress on industrial waste heat recycling and seasonal energy storage. AIMS Energy 13: 147-187.
60. Yu Y, Liu J, Shao W (2018) The estimation and effect of anthropogenic heat flux in Beijing. Energy Procedia 152: 302-306.
61. Mandal G, Subbaiyan G (2023) Spatial patterns of anthropogenic heat and urban density of an Indian metropolitan city. Environment and Urbanization ASIA 14: 55-71.
62. Takane Y, Kikegawa Y, Nakajima K, Kusaka H (2024) SLUCM+BEM (v1.0): a simple parameterisation for dynamic anthropogenic heat and electricity consumption in WRF-Urban.
63. Yang M, Cao S, Zhang D (2023) Spatially Explicit Modeling of Anthropogenic Heat Intensity in Beijing Center Area: An Investigation of Driving Factors with Urban Spatial Forms. Sensors 23: 7608.
64. Cui L, Chen Q (2024) Investigating Variations in Anthropogenic Heat Flux along Urban–Rural Gradients in 208 Cities in China during 2000–2016. Buildings 14: 2766.
65. Stewart ID, Oke TR (2012) Local climate zones for urban temperature studies. Bulletin of the American Meteorological Society 93: 1879–1900.
66. Grimmond CSB, Oke TR (1999) Heat storage in urban areas: Local-scale observations and evaluation of a simple model. Journal of Applied Meteorology 38: 922–940.
67. Menberg K, Bayer P, Zosseder K, Rumohr S, Blum P (2013) Subsurface urban heat islands in German cities. Science of the Total Environment 442: 123–133.
68. Benz SA, Bayer P, Blum P (2017) Identifying anthropogenic anomalies in air, surface, and groundwater temperatures in Germany. Science of the Total Environment 584–585: 145–153.
69. Todreas NE, Kazimi MS (2021) Nuclear systems volume I: Thermal hydraulic fundamentals (3rd ed.). CRC Press.
70. International Atomic Energy Agency (2018) Status and trends in spent fuel and radioactive waste management (IAEA Nuclear Energy Series No. NW-T-1.14). Vienna, Austria: International Atomic Energy Agency.
71. U.S. Nuclear Regulatory Commission (2024) Backgrounder on spent nuclear fuel storage. U.S. Nuclear Regulatory Commission. https://www.nrc.gov

72. World Nuclear Association (2024) Storage and disposal of radioactive waste. London, UK: World Nuclear Association.
73. World Nuclear Association (2024) The nuclear fuel cycle. London, UK: World Nuclear Association.
74. OECD Nuclear Energy Agency, & International Atomic Energy Agency (2022) Management and recycling of used nuclear fuel. Paris, France: OECD Publishing.
75. International Atomic Energy Agency (2024) Spent Fuel and Radioactive Waste Information System (SRIS). Vienna, Austria: International Atomic Energy Agency.
76. CNE (Commission Nationale d'Évaluation) (2004) Evaluation Report on Research Concerning Radioactive Waste Management in France. Paris, France.
77. International Energy Agency (2022) Nuclear power and secure energy transitions. Paris, France: International Energy Agency.
78. Batty M (2018) Digital twins. Environment and Planning B: Urban Analytics and City Science 45: 817–820.
79. Lu Q, Xie X, Heaton J, Parlikad AK (2020) From BIM towards digital twin: Strategy and future development for smart asset management. Automation in Construction 121: 103440.
80. Mirzaei PA, Haghighat F (2010) Approaches to study Urban Heat Island – Abilities and limitations. Building and Environment 45: 2192–2201.
81. Santamouris, M, Haddad S, Fiorito F, Osmond P, Ding L, et al. (2023) Urban heat island and overheating characteristics in a changing climate: Global trends and mitigation perspectives. Energy and Buildings 287: 112955.
82. Incropera FP, DeWitt DP, Bergman TL, Lavine AS (2017) Fundamentals of heat and mass transfer (8th ed.). Wiley.