

From Heat Demand to Engagement: Mapping Socio-Technical Conditions for Urban Energy Planning

An Exploratory, Multi-Scale Statistical Assessment of Heating System Age and Heat Demand Across Socio-Cultural Milieus

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Abstract. Understanding socio-spatial patterns of heating infrastructure is essential for designing effective strategies for the decarbonisation of urban residential energy systems. This paper investigates the relationship between socio-cultural milieus, heating system age, and heat demand using a multi-scale empirical analysis for the city of Bremen, Germany. The study integrates building-level Sinus-Milieu data with detailed heating system information and population statistics, enabling a comparative assessment at both the individual building level and a standardised 100 m × 100 m grid level.

Non-parametric statistical methods are applied to examine differences between Sinus-Milieus with respect to heating system age and heat demand. The results reveal robust and statistically significant differences in heating system age across milieus, with large effect sizes observed at both spatial aggregation levels. These differences can be meaningfully condensed into two stable groups, distinguishing milieus with predominantly moderate heating system ages from those with elevated renovation needs. In contrast, while absolute heat demand differs significantly between milieus, these differences largely disappear once heat demand is normalised by population at the grid level. Effect sizes for population-normalised heat demand are negligible, indicating that observed differences in absolute heat demand are primarily driven by structural factors such as building size, density, and population distribution rather than by milieu-specific heating behaviour.

By combining socio-cultural segmentation with spatially explicit energy data, the paper demonstrates the value of a multi-scale analytical approach for identifying structurally relevant patterns of renovation need. The findings highlight heating system age as a particularly robust indicator for targeting urban heat transition policies, while cautioning against the uncritical interpretation of absolute heat demand differences between socio-cultural groups.

Keywords: Urban Heat Transition, Spatial Energy Planning, Socio-Technical Integration, Sinus-Milieus, Citizen Engagement, GIS-Based Analysis

1. Introduction

The transition from fossil fuel-based heating systems to renewable and low-carbon alternatives represents a critical component of the broader energy transition. Urban areas, where the majority of residential heating demand is concentrated, face particular challenges in achieving

climate neutrality targets. While technical solutions for decarbonising heat supply, such as district heating networks, heat pumps, and building envelope improvements, are well established, their successful implementation depends not only on technical feasibility but also on the engagement, acceptance, and economic capacity of building owners and residents [1], [2].

Recent research and practical experience in urban energy planning have highlighted that socio-demographic characteristics significantly influence both the willingness and ability to participate in heating system transitions [3], [4], [5]. Different population segments exhibit varying levels of environmental awareness, financial resources for investment in heating infrastructure, readiness to adopt new technologies, and preferences for specific communication channels [6]. Traditional energy planning approaches, however, have largely focused on technical and spatial parameters, such as heat density, building age, and network infrastructure, while treating the residential population as a relatively homogeneous entity. This techno-centric perspective risks overlooking systematic differences in how various socio-demographic groups engage with heat transition measures.

Socio-demographic segmentation models, such as the Sinus-Milieu framework widely used in German-speaking (DACH) countries, offer a differentiated understanding of lifestyle-based population groups [7]. These milieus integrate social status, value orientations, and everyday practices, providing insights into renovation behaviour, technology acceptance, and communication preferences that may be relevant for targeted energy transition strategies [8]. If systematic differences exist between milieus in terms of heating infrastructure conditions, such as the age of existing heating systems or energy consumption patterns, this would suggest that differentiated approaches to planning, communication, and support mechanisms could enhance the effectiveness of urban heat transition efforts.

Despite the potential relevance of socio-demographic factors, empirical research linking milieu-specific characteristics to observable heating infrastructure conditions at the urban scale remains limited. Most existing studies either focus on attitudinal surveys [9] or aggregate technical assessments [10], but rarely integrate both dimensions at fine spatial resolution. This creates a knowledge gap regarding whether and to what extent different lifestyle segments actually differ in their current heating system age and energy demand, information that would be essential for prioritizing intervention areas and designing milieu-appropriate engagement strategies.

This study addresses this gap by examining the relationship between socio-demographic milieus and heating infrastructure characteristics in the city of Bremen, Germany. Specifically, it investigates: Do socio-demographic milieus differ systematically in heating system age and (specific) heat demand in urban residential areas, and which milieus exhibit distinct patterns? To answer this question, building-level and grid-level data on Sinus-Milieu distributions are integrated with heating system age and heat demand for approximately 95,000 residential buildings. Through comparative statistical analysis, milieus which show significantly older heating infrastructure or higher specific energy consumption are identified and possible meaningful clusters of milieus are distinguished. Bremen serves as a representative case study for medium-sized German cities, where milieu distributions have been regionally calibrated to reflect local socio-demographic compositions [11].

The findings contribute to a more socially informed approach to urban heat planning by demonstrating whether technical infrastructure conditions vary systematically across lifestyle segments, thereby providing an empirical foundation for subsequent spatial analysis and the development of differentiated transition strategies.

2. Methodology

2.1 Study Area and Data Sources

As outlined in the introduction, the empirical analysis is conducted for the city of Bremen, a medium-sized European city characterised by a heterogeneous building stock, pronounced socio-spatial differentiation, and diverse residential settlement structures. Bremen combines dense inner-city neighbourhoods, post-war housing estates, and suburban residential areas, providing a suitable context for analysing relationships between socio-cultural milieus, building characteristics, and energy-related indicators.

The analysis is based on the integration of five main data sources:

Sinus-Milieu Data: Socio-demographic segmentation data were obtained from Michael Bauer Micromarketing GmbH (2025), specifically the "MBM Sinus-Milieus® Haus für das Land Bremen auf der Gebäudeebene inkl. OSM Koordinaten und Hausadressen" dataset. This dataset provides point-level information on the dominant Sinus-Milieu for residential locations, including the number of households represented by each point [11, pp. 135-136]. Sinus-Milieus represent a well-established sociological segmentation approach in German-speaking countries, grouping populations according to lifestyle, values, and social perspectives [12].

Heating System Data: Information on heating system age and annual heat demand was sourced from DBI Gas- und Umwelttechnik GmbH (2023, actual data-modelling: 2022). The DBI dataset contains point-level information with heating system age classified into five ordinal categories and (modelled) annual heat demand measured in kWh per year. The dataset distinguishes between different building types, allowing for the selective analysis of private residential buildings [13, pp. 8-10].

Building Footprint Data: Official building polygon geometries were obtained from the ALKIS (Amtliches Liegenschaftskatasterinformationssystem) dataset provided by Landesamt GeoInformation Bremen (2023) [14]. These standardised building footprints served as the spatial framework for aggregating point-based data.

Standardised Spatial Grid: Spatial grid cells at 100 m × 100 m resolution were obtained from the national geographic grid for Germany (GeoGitter national), provided by the Federal Agency for Cartography and Geodesy (Bundesamt für Kartographie und Geodäsie, BKG [15]). This official standardised grid system serves as the spatial framework for census data and other statistical products in Germany, ensuring temporal stability and spatial comparability of grid-based analyses. The regular geometry and uniform cell size enable consistent aggregation of statistical attributes across different datasets and time periods. Importantly, the same grid structure is used for Zensus 2022 population data, facilitating direct integration of demographic and energy-related information.

Population Data: Population counts at 100 m × 100 m grid resolution were derived from Zensus 2022, the national census of population, buildings, and housing with reference date May 15, 2022. The census provides official population figures and structured information on how people live, work, and reside in Germany [16]. The data collection is register-based (population registers), supplemented by household sampling and a comprehensive survey of buildings and dwellings. These gridded population data enable the calculation of specific heat demand normalised by the number of residents per spatial unit.

The combined use of building-level and grid-based data enables a multi-scale analysis of heating system age and heat demand patterns across socio-cultural milieus. This multi-level data structure forms the basis for the subsequent statistical analyses.

2.2 Data Processing and Integration

The methodology consisted of several sequential processing steps designed to integrate the heterogeneous data sources while maintaining statistical validity. To address the research questions from complementary spatial perspectives, two parallel analytical pathways were established: (1) a building-level analysis that preserves the fine-grained variation in heating system characteristics across individual structures, and (2) a grid-level analysis based on standardised 100 m × 100 m cells that enables the calculation of population-normalised metrics. The building-level approach focuses on heating system age distributions and absolute heat demand per structure, while the grid-level approach incorporates census population data to derive specific heat demand per capita. Both pathways follow analogous processing steps: aggregation of Sinus-Milieu and DBI data as well as filtering of district heating areas. They however differ in their spatial unit of analysis and derived indicators.

2.2.1 Sinus-Milieu Aggregation (Building and Grid Level)

Sinus-Milieu point data were first georeferenced using the address and coordinate information provided in the source dataset. These points were subsequently spatially joined to official ALKIS building polygons using a Python-based geoprocessing workflow adapted from an existing methodology [17, pp. 7-9]. This procedure enabled the assignment of socio-cultural milieu information to individual residential buildings.

In cases where multiple Sinus-Milieu points were associated with a single building, a weighted aggregation approach was applied. The dominant Sinus-Milieu for each building was determined based on the number of households represented by each point. This weighting ensures that the assigned milieu reflects the predominant socio-demographic characteristics of the building's residents rather than a simple count of point occurrences.

An analogous aggregation procedure was applied at the grid level. Sinus-Milieu point data were spatially joined to the standardised 100 m × 100 m grid cells, and the dominant milieu for each grid cell was determined using a weighted sum of households across all points located within the respective cell. Applying the same aggregation logic at both the building and grid levels ensures methodological consistency and comparability between the two analytical pathways.

2.2.2 Heating System Data Processing and Aggregation

The DBI heating system dataset underwent a multi-stage filtering and aggregation process to derive consistent indicators for both heating system age and annual heat demand at the building and grid levels. While both variables were processed in parallel, particular attention was given to heating system age due to its ordinal nature and the need to preserve the original classification scheme throughout the aggregation process.

Initial Filtering: Only data points classified as *private households* were retained for analysis, while commercial and industrial buildings were excluded. In addition, all data points located within existing district heating network areas were removed from the dataset. This exclusion was necessary because, in these areas, the recorded *heating system age* reflects the age of the connection to the district heating network rather than the age of an individual on-site heating system. Including such observations would therefore distort the analysis of decentralised heating infrastructure and compromise comparability across milieus.

Spatial Aggregation: At the building level, the filtered DBI point data were aggregated to ALKIS building polygons using a spatial join operation in ArcGIS Pro. To account for minor geocoding inaccuracies and points located close to building edges, a spatial tolerance of 3 metres was applied using a *Spatial Join (within a distance)* operation [18]. For each building

polygon, the mean heating system age and the sum of annual heat demand were calculated from all associated DBI points.

At the grid level, the filtered DBI point data were aggregated to 100 m × 100 m grid cells without applying a spatial tolerance buffer, as the regular grid geometry does not require adjustment for boundary inconsistencies. For each grid cell, the mean heating system age and the sum of annual heat demand were calculated from all associated DBI points. Grid cells that intersected with district heating network areas (even partially) were excluded entirely from the grid-based dataset. A partial exclusion approach, in which only DBI points located within district heating areas would be removed while retaining the grid cell, would have resulted in systematically underestimated heat demand values for affected cells. Such distortions would be particularly problematic for milieus concentrated in areas with partial district heating coverage. The complete exclusion of affected grid cells ensures an unbiased aggregation of heat demand across socio-cultural milieus.

Heating Age Classification: Aggregation of heating system age classes results in continuous values. These values were subsequently rounded to the nearest integer in order to restore the original ordinal classification scheme which was given by the DBI data. The five heating system age classes used throughout the analysis are defined as follows:

- Class 1: up to 5 years
- Class 2: 5 to 10 years
- Class 3: 10 to 15 years
- Class 4: 15 to 20 years
- Class 5: more than 20 years

2.2.3 Integration of Sinus-Milieu and Heating System Data

The processed Sinus-Milieu building dataset and the aggregated DBI heating system dataset were integrated based on their shared spatial reference to ALKIS building polygons. This integration resulted in a consolidated building-level dataset comprising approximately 95,300 residential buildings in the city of Bremen. Each building is characterised by the following attributes:

- Dominant Sinus-Milieu category
- Mean heating system age class (ordinal scale 1-5)
- Total annual heat demand (kWh/year)

The resulting building-level dataset forms the basis for analysing differences in heating system characteristics and heat demand across socio-cultural milieus at a fine spatial resolution.

In a second step, the building-level indicators were transferred to the standardised 100 m × 100 m spatial grid. For each grid cell, aggregated heating system age and heat demand indicators were derived from the underlying buildings following the procedures described in Sections 2.2.1 and 2.2.2. The grid-based dataset was subsequently merged with population data from Zensus 2022, enabling the calculation of population-normalised heat demand indicators. Specifically, absolute annual heat demand per grid cell was related to the corresponding number of residents, resulting in a specific heat demand measure expressed in kilowatt-hours per capita and year (kWh/cap·year).

The integration of Sinus-Milieu, heating system, and population data at both the building and grid levels establishes a coherent multi-scale analytical framework. This framework enables a systematic comparison of heating system age and heat demand patterns across socio-cultural milieus while accounting for differences in spatial aggregation and population distribution.

2.3 Statistical Analysis

The statistical analysis examines whether significant differences exist between Sinus-Milieus with respect to heating system age and heat demand indicators at both the building and grid levels. All statistical analyses and visualisations were conducted using Python-based workflows, while spatial data processing and map visualisation were performed in ArcGIS Pro.

Given the heterogeneous nature of the data and the large sample size, a robust, non-parametric analytical framework was adopted. Heating system age is measured on an ordinal scale, while heat demand indicators are metric but exhibit pronounced skewness, heavy tails, and substantial differences in variance across milieus. Under these conditions, classical parametric methods relying on distributional assumptions (e.g. normality and homoscedasticity) are of limited interpretability, particularly for large samples where normality tests tend to be overly sensitive.

To ensure methodological consistency and comparability across variables and spatial aggregation levels, rank-based non-parametric methods were therefore applied throughout the analysis. Global differences between milieus were assessed using the Kruskal-Wallis H-test, followed, where appropriate, by post-hoc pairwise comparisons. In addition to statistical significance, effect sizes were calculated to quantify the practical relevance of observed differences.

2.3.1 Analysis of Heating System Age (Ordinal Data)

Heating system age is represented by five ordered classes ranging from recently installed systems to installations older than 20 years. Owing to this ordinal measurement scale, non-parametric methods were employed for all comparative analyses.

Descriptive Statistics: For each Sinus-Milieu, the distribution of heating system age classes was summarised using median values and interquartile ranges (IQR). Box plots were used to visualise central tendency, dispersion, and distributional differences across milieus, allowing for an initial assessment of structural variation in heating system age profiles.

Global Comparison: A Kruskal-Wallis H-test was conducted to assess whether the distributions of heating system age classes differ significantly across the ten Sinus-Milieus. The null hypothesis (H_0) states that the distributions are identical across all milieus, while the alternative hypothesis (H_1) posits that at least one milieu exhibits a statistically different distribution. Statistical significance was evaluated at a significance level of $\alpha = 0.05$.

Effect Size: To complement the global test, epsilon-squared (ϵ^2) was calculated as a measure of effect size for the Kruskal-Wallis test. Epsilon-squared represents the proportion of variance in heating system age attributable to milieu membership and enables an assessment of practical relevance beyond statistical significance. Following common conventions, values of $\epsilon^2 \geq 0.14$ were interpreted as large effects.

Post-hoc Analysis: In cases where the global test indicated statistically significant differences, Dunn's post-hoc test with appropriate p-value adjustment was applied to identify specific pairwise differences between milieus. Given the large sample size, particular attention was paid to distinguishing statistically significant but potentially trivial differences from substantively meaningful contrasts.

Milieu Grouping: To identify broader patterns beyond pairwise comparisons, a two-stage grouping strategy was employed. First, milieus were provisionally grouped based on descriptive characteristics, including median heating system age class and distributional spread. Second, this descriptive grouping was validated using hierarchical clustering (Ward linkage) applied to median and IQR values. The consistency between descriptive and clustering-based groupings was subsequently assessed using an additional Kruskal-Wallis test.

2.3.2 Analysis of Annual Heat Demand (Metric Data)

Heat demand was analysed in two forms: absolute annual heat demand at the building and grid levels, and population-normalised heat demand per capita at the grid level. Although these indicators are metric, exploratory analysis revealed strongly right-skewed distributions, substantial outliers, and heteroskedasticity across milieus.

Descriptive Statistics: For each Sinus-Milieu, heat demand distributions were summarised using means, medians, and interquartile ranges. Box plots were used to visualise distributional characteristics and to facilitate comparison between milieus and aggregation levels.

Global Comparison: Despite the metric nature of the heat demand variables, the Kruskal-Wallis H-test was applied to assess global differences between milieus. This choice reflects the non-normal distributional properties of the data and ensures methodological consistency with the analysis of heating system age. The null hypothesis (H_0) states that heat demand distributions are identical across all Sinus-Milieus, while the alternative hypothesis (H_1) posits that at least one milieu differs significantly. Statistical significance was evaluated at a significance level of $\alpha = 0.05$.

Effect Size and Interpretation: Epsilon-squared (ϵ^2) was again calculated to quantify the magnitude of observed differences. Comparing effect sizes between absolute and population-normalised heat demand allows for an assessment of the extent to which observed differences are driven by building size and density versus intensity-related factors linked to residential energy demand.

Post-hoc Analysis: Where the global Kruskal-Wallis test indicated both statistical significance and non-negligible effect sizes, Dunn's post-hoc test with p-value adjustment was applied to identify pairwise differences between Sinus-Milieus. For population-normalised heat demand, post-hoc comparisons were not pursued further, as the observed effect sizes were negligible, indicating limited practical relevance despite statistical significance.

3. Results

As laid out in the methodology section, non-parametric statistical methods were employed to examine differences between Sinus-Milieus due to the measurement scale and distributional properties of the dependent variables. Heating system age is measured on an ordinal scale, while heat demand exhibits strongly skewed, non-normal distributions. In addition, the large sample sizes involved increase the sensitivity of rank-based tests. In this context, high values of test statistics in procedures such as the Kruskal-Wallis test are a natural consequence of systematic rank differences and large sample sizes rather than an indication of methodological issues. Statistical inference is therefore based on the associated p-values, while substantive relevance is assessed using effect size measures. Accordingly, epsilon-squared (ϵ^2) is reported as a scale-independent measure of effect magnitude, quantifying the proportion of variance in ranked outcomes attributable to milieu membership.

3.1 Building-Level Results

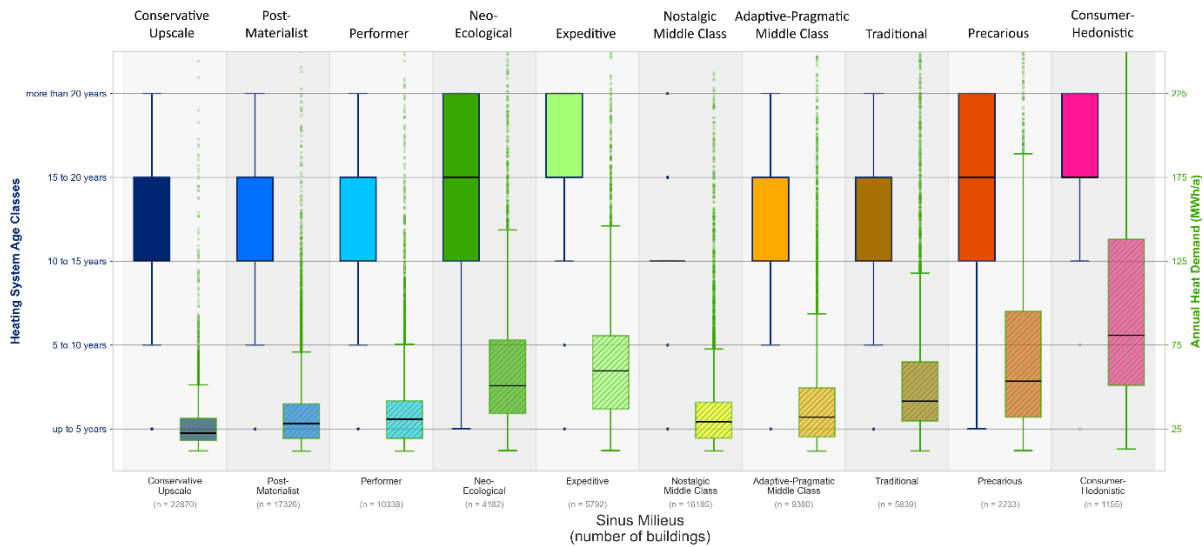


Figure 1. Heating system age classes and annual heat demand by Sinus Milieus (building level)

Figure 1 shows the distribution of heating system age classes and absolute annual heat demand across Sinus-Milieus at the building level. Pronounced differences between milieus are evident for both indicators. Several milieus exhibit median heating system age classes of 3, corresponding to installations predominantly between 10 and 15 years old, whereas other milieus display higher median values, indicating systematically older heating systems. Especially the Neo-Ecological, Expeditive, Precarious and Consumer-Hedonistic Milieus stand out.

Differences in heating system age are statistically significant across milieus (Kruskal-Wallis $H = 15378.8$, $p < 0.001$), with a large effect size ($\epsilon^2 = 0.161$), suggesting that a substantial share of variance in heating system age is associated with milieu membership. Post-hoc comparisons indicate that these differences are not uniformly distributed across all milieu pairs but cluster into a limited number of structurally distinct groups characterised by similar heating system age profiles.

Absolute annual heat demand at the building level also varies markedly between milieus, as shown in Figure 1. Distributions are strongly right-skewed, with pronounced differences in both median values and dispersion. The Kruskal-Wallis test confirms statistically significant differences in absolute heat demand between milieus ($H = 18894.1$, $p < 0.001$), accompanied by a large effect size ($\epsilon^2 = 0.198$). These results indicate systematic variation in absolute heat demand across socio-cultural milieus at the building level.

3.2 Grid-Level Results

3.2.1 Heating System Age and Absolute Heat Demand

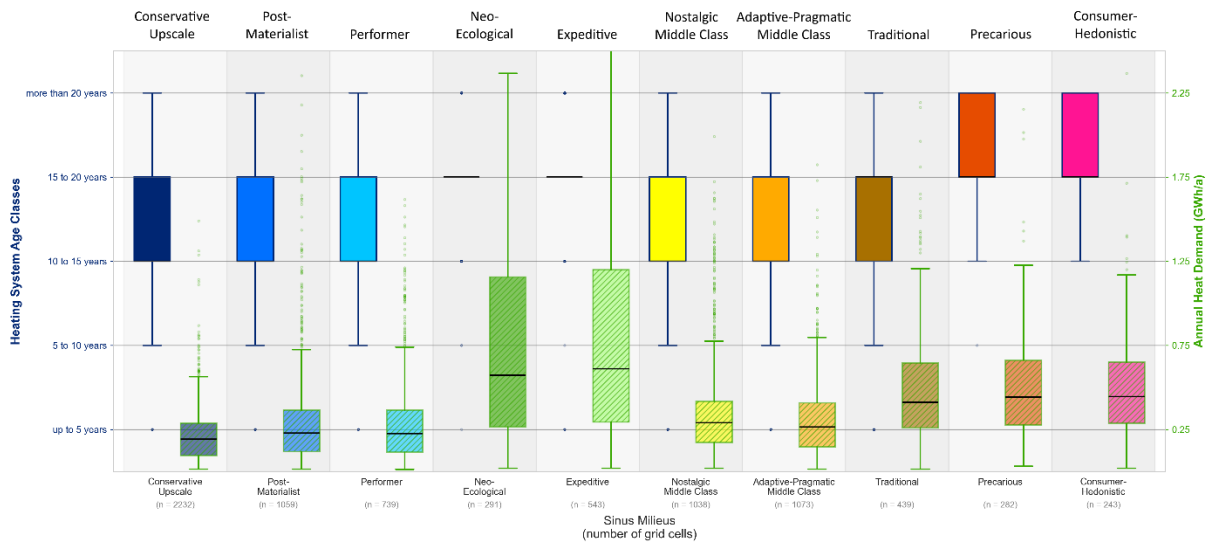


Figure 2. Heating system age classes and annual heat demand by Sinus Milieus (grid level)

Figure 2 presents heating system age classes and absolute heat demand aggregated to the 100 m × 100 m grid level. Compared to the building-level analysis, grid-level aggregation results in reduced within-milieu dispersion, while differences in median heating system age between milieus remain clearly visible. Several milieus exhibit median heating system age classes of 4 at the grid level, indicating spatial concentrations of older heating systems. Again, the Neo-Ecological, Expeditive, Precarious and Consumer-Hedonistic Milieus stand out.

Statistical testing confirms that differences in heating system age persist across spatial aggregation levels ($H = 1340.7$, $p < 0.001$), with a large effect size ($\epsilon^2 = 0.168$). Absolute heat demand aggregated to the grid level likewise shows pronounced differences between milieus ($H = 1376.3$, $p < 0.001$; $\epsilon^2 = 0.172$), demonstrating that variation in heat demand is robust to spatial aggregation.

3.2.2 Heating System Age and Population-Normalised Heat Demand

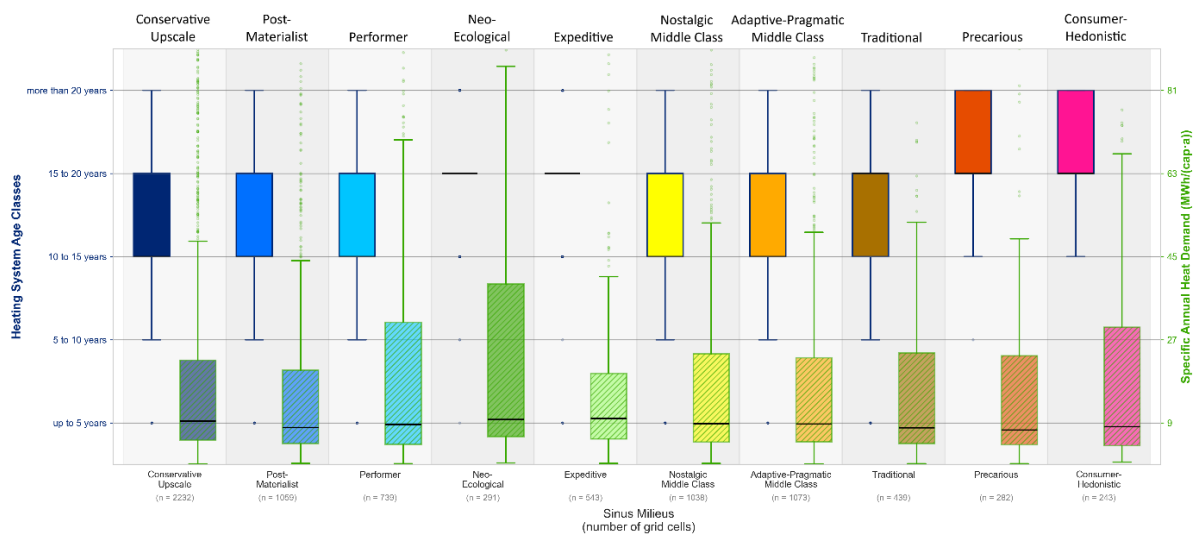


Figure 3. Heating system age classes and specific annual heat demand by Sinus Milieus (grid level)

Figure 3 contrasts heating system age classes with population-normalised heat demand per capita at the grid level. While differences in heating system age remain clearly discernible between milieus, the normalisation of heat demand by population substantially reduces between-milieu variation. Median values and interquartile ranges of population-normalised heat demand show considerable overlap across most milieus.

Although the Kruskal-Wallis test indicates statistically significant differences in population-normalised heat demand ($H = 24.9$, $p < 0.001$), the associated effect size is very small ($\epsilon^2 = 0.002$), pointing to negligible practical differences. This suggests that differences observed for absolute heat demand are largely attributable to variations in building size, density, and population distribution rather than to systematically different per-capita heat demand intensities across milieus.

3.3 Summary of Key Results

To synthesise the main findings across spatial scales and indicators, Table 1 provides an overview of heating system age and heat demand characteristics by Sinus-Milieu. The table summarises central tendencies and highlights milieus that consistently exhibit older heating systems and higher absolute heat demand, as well as those that remain close to the overall median. Population-normalised heat demand shows markedly fewer differences between milieus, indicating that variations in absolute heat demand are largely driven by building size, density, and population distribution rather than by per-capita consumption patterns.

Table 1. Summary of heating system age and heat demand patterns by Sinus-Milieu

Sinus-Milieu	Heating system age (building level)	Heating system age (grid level)	Absolute heat demand (both levels)	Population-normalised heat demand	Summary pattern
Conservative Upscale	Medium (median = 3)	Medium (median = 3)	Low to medium	Similar, medium level	Relatively modern systems, lower absolute demand
Post-Materialist	Medium (median = 3)	Medium (median = 3)	Medium	Similar, medium level	Close to overall median
Performer	Medium (median = 3)	Medium (median = 3)	Medium	Similar, medium level	Average heating age and demand
Neo-Ecological	High (median = 4)	High (median = 4)	High	Similar, medium level	Older systems, elevated absolute demand
Expeditive	Very high (median = 5)	High (median = 4)	High	Similar, medium level	Consistently old systems
Nostalgic Middle Class	Medium (median = 3)	Medium (median = 3)	Medium	Similar, medium level	Stable, moderate profile

Sinus-Milieu	Heating system age (building level)	Heating system age (grid level)	Absolute heat demand (both levels)	Population-normalised heat demand	Summary pattern
Adaptive-Pragmatic Middle Class	Medium (median = 3)	Medium (median = 3)	Medium	Similar, medium level	Near overall median
Traditional	Medium (median = 3)	High (median = 4)	High	Similar, medium level	Ageing systems at grid level
Precarious	High (median = 4)	High (median = 4)	High	Similar, medium level	Older systems, high absolute demand
Consumer-Hedonistic	High (median = 4)	High (median = 4)	Very high	Similar, medium level	Old systems, very high absolute demand

Table 1 summarises the main findings across spatial aggregation levels and heat demand indicators. Clear differences between Sinus-Milieus emerge for heating system age and absolute heat demand at both the building and grid levels. In contrast, population-normalised heat demand shows no pronounced differences between milieus, indicating that variations in absolute heat demand are largely driven by building size, density, and population distribution rather than by per-capita consumption patterns.

4. Discussion

4.1 Robust Milieu Differences in Heating System Age

The analysis reveals robust and substantial differences in heating system age across Sinus-Milieus. The Kruskal-Wallis test indicates statistically significant differences with a large effect size ($\epsilon^2 \approx 0.16$), demonstrating that a considerable share of variance in heating system age is associated with socio-cultural milieu membership. While post-hoc pairwise comparisons yield a large number of statistically significant differences, this result is largely attributable to the very large sample size and small but systematic shifts in the ordinal distributions.

From a substantive perspective, however, the observed differences can be meaningfully condensed into a limited number of distinct groups with similar heating system age profiles (Table 1). This indicates that the multitude of significant pairwise contrasts reflects gradual distributional shifts rather than fundamentally different heating system regimes across all milieus.

4.2 Dichotomisation of Heating System Age and Validation by Clustering

Based on the median heating system age classes, the Sinus-Milieus were grouped into two analytically and substantively meaningful categories: milieus with moderate heating system age (median = 3) and milieus with elevated renovation need (median ≥ 4). This threshold-based dichotomisation follows a clear technical interpretation, as median values of 4 and above

correspond to heating systems predominantly older than 15 years and thus approaching or exceeding typical renovation cycles.

The robustness of this grouping was independently confirmed using hierarchical clustering at the milieu level. Clustering based on median and interquartile range values resulted in two clearly separated clusters that closely match the descriptively defined groups. As expected, the dichotomisation leads to a modest reduction in explained variance; however, the effect size remains substantial ($\epsilon^2 \approx 0.14$), confirming a strong and stable association between socio-cultural milieu and heating system age.

This finding implies that while fine-grained distinctions between individual milieus exist, the dominant pattern is a structural divide between milieus characterised by predominantly younger versus older heating infrastructures.

4.3 Absolute versus Population-Normalised Heat Demand

Differences between Sinus-Milieus are also evident for absolute heat demand at both the building and grid levels (*Figure 1* and *Figure 2*). These differences are statistically significant and associated with large effect sizes ($\epsilon^2 \approx 0.17$), indicating pronounced variation in total heat demand across milieus. However, absolute heat demand primarily reflects structural characteristics such as building size, dwelling density, and population concentration, limiting its suitability for assessing milieu-specific energy efficiency or heating behaviour.

To enhance structural comparability, heat demand was therefore analysed at the grid level and normalised by population. This adjustment fundamentally alters the interpretation of the results: once heat demand is expressed on a per-capita basis, differences between milieus largely disappear (*Figure 3*). Although formal statistical tests remain significant due to the large sample size, the associated effect size is negligible ($\epsilon^2 \approx 0.002$), indicating minimal practical relevance.

This finding demonstrates that observed differences in absolute heat demand are driven predominantly by spatial and structural factors rather than by systematic differences in per-capita heating demand between socio-cultural milieus. Consequently, combining heating system age and heat demand into a multidimensional typology does not yield additional explanatory power, as the second dimension collapses after appropriate normalisation.

4.4 Spatial Aggregation Effects and Added Value of the Grid Perspective

Comparing building-level and grid-level results highlights the importance of spatial aggregation. Differences in heating system age remain robust across both levels; however, the grid-based analysis reveals shifts in the classification of certain milieus. In particular, the Traditional milieu exhibits a median heating system age of 4 at the grid level, while remaining below this threshold at the building level.

This shift reflects the spatial concentration of traditional milieus in neighbourhoods characterised by homogeneous building stocks with consistently older heating systems. Grid-level aggregation emphasises these typical residential environments rather than individual buildings, thereby providing a complementary perspective on spatially concentrated renovation needs.

Notably, milieus exhibiting higher median heating system ages at the grid level are represented by comparatively smaller numbers of grid cells. This does not indicate reduced analytical robustness but rather points to spatial clustering in specific neighbourhood types. In these concentrated milieu cores, older heating systems occur particularly consistently, as reflected by stable medians and, in some cases, very small interquartile ranges.

Taken together, the building-level analysis identifies milieu-specific differences in heating system age, while the grid-level analysis highlights spatial concentrations of elevated renovation demand. Both perspectives are therefore complementary rather than redundant.

4.5 Synthesis of Effects across Indicators and Scales

To summarise the relative strength of observed effects across indicators and spatial scales, *Table 2* provides an overview of effect sizes derived from the Kruskal-Wallis tests.

Table 2. Summary of effect sizes across analysis levels

Analysis level	Heating system age	Absolute heat demand	Population-normalised heat demand
Building level	Large ($\epsilon^2 \approx 0.16$)	Large ($\epsilon^2 \approx 0.17$)	–
Grid level (100 m × 100 m)	Large ($\epsilon^2 \approx 0.17$)	Large ($\epsilon^2 \approx 0.17$)	Negligible ($\epsilon^2 = 0.002$)

This synthesis underscores that heating system age constitutes the most robust and policy-relevant dimension of milieu differentiation, while differences in heat demand largely vanish after accounting for population distribution.

4.6 Limitations and Uncertainty

Several limitations of the present study should be acknowledged. First, the analysis relies on proprietary data sources, particularly the Sinus-Milieu classification and the DBI heating system dataset. While both datasets are widely used in applied socio-spatial and energy research, their underlying modelling assumptions, weighting schemes, and potential imputation procedures are not fully transparent. Consequently, the analysis treats these inputs as empirically robust but methodologically opaque, which limits the reproducibility of the exact classification process.

Second, the integrated datasets differ with respect to their reference years. Sinus-Milieu data refer to 2025, heating system data to 2023, building geometries to 2023, and population data to the 2022 census. Although major structural changes in the building stock and heating infrastructure typically occur gradually, temporal mismatches may introduce uncertainty, particularly in areas affected by recent renovations, demolitions, or socio-demographic change.

Third, several aggregation-related limitations apply. Heating system age is analysed using an ordinal classification scheme, which restricts the resolution of age differences and necessitates non-parametric statistical methods. In addition, the assignment of a single dominant Sinus-Milieu to buildings and grid cells inevitably smooths intra-building and intra-cell heterogeneity. While this approach is appropriate for identifying prevailing socio-cultural patterns, it may mask more fine-grained variation within mixed residential contexts.

In addition, the aggregation of Sinus-Milieu data to both building polygons and grid cells follows a dominant-milieu principle. For spatial units containing multiple milieus, only the milieu with the highest aggregated household weight is retained. While this “winner-takes-all” approach is well suited for identifying dominant socio-cultural structures and spatial concentrations, it systematically underrepresents milieus that are weakly represented or spatially dispersed within individual buildings or grid cells. As a result, the analysis emphasises dominant milieu configurations while potentially underestimating the presence of minority or mixed milieu constellations city-wide.

Fourth, spatial aggregation itself influences the interpretation of results. Differences observed at the building level and the grid level reflect not only analytical scale but also the modifiable areal unit problem (MAUP). The grid-based analysis emphasises spatial concentrations and typical neighbourhood structures, whereas the building-level analysis captures individual variation. Both perspectives are complementary, but neither can be considered scale-neutral.

Finally, the analysis focuses exclusively on private residential buildings. This restriction is necessary to ensure conceptual consistency of heating system age and heat demand indicators, but it limits the transferability of results to mixed-use or non-residential urban areas.

Taken together, these limitations do not undermine the core findings of the study but highlight the importance of cautious interpretation, particularly when translating socio-spatial patterns into policy recommendations.

5. Conclusion and Outlook

5.1 Conclusion

This study set out to examine whether and to what extent socio-cultural milieus are associated with differences in heating system age and heat demand, and how these relationships change across spatial aggregation levels. By combining Sinus-Milieu data with detailed heating system information and population statistics, the analysis provides a multi-scale perspective on structural differences in residential heating infrastructure.

The results demonstrate that **heating system age differs robustly between Sinus-Milieus**. Across both spatial aggregation levels, statistically significant differences with **large effect sizes** were observed, indicating a strong association between socio-cultural milieu and the age structure of heating systems. While post-hoc analyses revealed numerous significant pairwise differences, these differences can be meaningfully condensed into a limited number of stable groups. In particular, a dichotomisation into milieus with moderate heating system age (median = 3) and milieus with elevated renovation need (median ≥ 4) captures the dominant pattern and remains associated with a substantial proportion of explained variance.

In contrast, **absolute heat demand**, although significantly different between milieus, was shown to be largely driven by **structural factors** such as building size, density, and population concentration. Once heat demand was normalised by population at the grid level, differences between milieus nearly vanished, and effect sizes dropped to negligible levels. This finding indicates that socio-cultural milieu membership is not associated with systematically different per-capita heat demand, and that observed differences in absolute heat demand primarily reflect the spatial distribution of buildings and residents rather than distinct heating behaviours.

The comparison of building-level and grid-level analyses further highlights the importance of spatial scale. While both levels reveal consistent milieu-specific patterns in heating system age, the grid-based perspective emphasises **spatial concentrations of older heating infrastructure**, particularly in neighbourhoods characterised by homogeneous building stocks. Together, the two analytical levels provide complementary insights: the building level captures fine-grained variation, while the grid level identifies structurally relevant spatial clusters of needs for retrofitting older heating systems.

5.2 Outlook

Beyond the statistical analysis, the findings underline the value of **integrating socio-cultural and spatial perspectives** in urban energy research. Heating system age emerges as a particularly robust indicator for identifying milieu-specific and spatially concentrated renovation

needs, whereas heat demand metrics require careful normalisation to avoid misleading interpretations.



Figure 4. Example of building polygons, extruded by heating system age classes

As an illustrative extension of the quantitative results, three-dimensional visualisations of selected neighbourhoods may support the communication of spatial patterns identified in this study. *Figure 4* serves as an example: In such visualisations, building or grid geometries can be coloured by Sinus-Milieu affiliation and extruded according to heating system age classes. Rather than serving as additional evidence, these representations provide an intuitive depiction of how milieu-specific heating infrastructure characteristics manifest spatially and cluster within the urban fabric. This approach may be particularly useful for exploratory analysis, stakeholder communication, and urban energy planning contexts.

Future research could build on the present framework in several ways. First, the integration of additional building characteristics, such as construction period, renovation status, or energy performance indicators, would allow for a more differentiated assessment of renovation potential. Second, extending the analysis to other cities would enable comparative insights into the generalisability of milieu-specific patterns. Finally, linking the identified spatial clusters of older heating systems to policy instruments and targeted renovation programmes could help translate socio-spatial analysis into actionable strategies for the decarbonisation of urban heating systems.

Data availability statement

The study is based on a combination of proprietary third-party data and publicly available datasets. Sinus-Milieu data were obtained from Michael Bauer Micromarketing GmbH, and heating system data were provided by DBI Gas- und Umwelttechnik GmbH under licence agreements that restrict public redistribution. These data cannot be made publicly available due to contractual and legal constraints.

Publicly available datasets used in this study include official building footprint data (ALKIS) provided by the State Office for Geoinformation Bremen and population data from the 2022 German Census, both accessible through the respective data providers.

Derived datasets and aggregated results presented in this article were generated solely for analytical purposes and do not contain original third-party data. Access to the proprietary

input data may be granted by the respective data providers upon reasonable request and subject to their licensing conditions.

The data processing and analysis scripts used in this study are available from the author upon reasonable request.

Author contributions

The author is the sole contributor to this work. All stages of the research, including conceptualization, methodology, data analysis, and manuscript preparation, were performed independently by the author.

Competing interests

The author declares that he has no competing interests.

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