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Thermal Discomfort and Its Impact on Urban Residential Electricity Use: A Case Study in Bandung, Indonesia

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Abstract. Urban energy demand in tropical highland settings is increasingly sensitive to climatic stressors, particularly the combined effects of temperature and humidity on thermal comfort. This study quantifies the influence of the Thermal Humidity Index (THI) on monthly electricity consumption in Bandung, Indonesia, between January 2012 and May 2024. Daily THI values were derived from 2-meter air temperature and relative humidity observations, aggregated into monthly means, and paired with utility records of residential electricity use. Spearman rank correlation analysis indicates a moderate positive association ($\rho = 0.35$, $p < 0.001$) between elevated heat-stress conditions and increased consumption. However, this relationship is partly obscured by concurrent growth in household electrification, appliance ownership, and urbanization.

Despite these confounding trends, the findings highlight a growing reliance on mechanical cooling in Bandung, a city historically known for its naturally temperate climate. The results underscore the importance of incorporating dynamic thermal stress and demographic shifts into future energy planning. While Spearman's correlation offers a valuable starting point, future research should adopt multivariate or time-series models to better isolate causal factors. Furthermore, the behavioral assumption linking THI to air conditioning use remains unvalidated in this study; incorporating user-level data or surveys would enhance the robustness of the conclusions. Overall, this study contributes to the broader understanding of climate-sensitive energy behavior and offers a transferable framework for urban energy forecasting in tropical regions.

Keywords: *Comfort Index, Electricity Consumption, Tropical Climate, Spearman Correlation.*

1 Introduction

In recent decades, climate change has emerged as a critical global concern, reflected in rising surface temperatures and increased humidity across many parts of the world.[1] These environmental changes not only affect natural ecosystems but also influence human activities, particularly in terms of energy consumption.[2] One of the most evident effects is the growing demand for electricity in residential areas, which is largely driven by the need to maintain indoor thermal comfort during periods of high heat and humidity.[3]

Electricity plays a vital role in urban households, supporting daily activities such as lighting, cooking, and operating home appliances including air conditioning units.[4] As temperatures increase, the dependence on cooling equipment also rises, leading to a noticeable surge in electricity use.[5] This behavioral shift has significant implications for energy management, particularly in tropical regions like Indonesia where high temperature and humidity are common throughout the year.[6]

To better understand how climate factors influence electricity usage, Riffelli, S from Department of Applied and Pure Sciences (DiSPeA), University of Urbino Carlo Bo have developed the Comfort Index.[7] This index combines several key variables, such as air temperature, relative humidity, and wind speed, into a single value that represents human thermal comfort.[8] Applying this index allows energy planners and policymakers to anticipate variations in electricity demand more accurately and to craft more responsive energy strategies.[9]

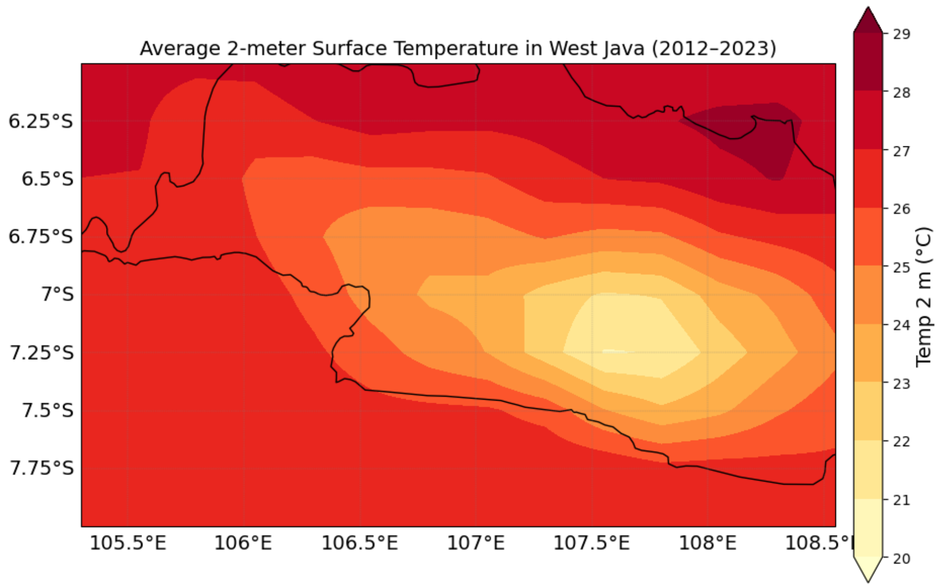


Figure 1 Average 2-meter Surface Temperature in West Java

This study aims to examine the relationship between the Comfort Index and household electricity consumption in Bandung, Indonesia.[10] Bandung was selected as the focus area due to its distinct thermal variability within the tropical region of West Java, as illustrated in the figure 1 above. The map of average 2-meter surface temperature from 2012 to 2023 shows that Bandung exhibits relatively lower surface temperatures compared to surrounding lowland areas, indicating a unique microclimate influenced by its elevation and urban structure. This thermal contrast makes Bandung an ideal case study for exploring how environmental discomfort affects household energy usage Through this analysis, the research seeks to offer valuable insights into how environmental discomfort shapes residential energy behavior, while also contributing to the formulation of more sustainable and climate-adaptive energy policies.[9]

2 Data and Method

2.1 Data

2.1.1 Non-Climate Data

The non-climate data used in this study consist of secondary data in the form of monthly household electricity consumption records for residential tariff customers. Data for business and industrial tariffs are excluded. The data were obtained from the Centralized Customer Service Application (AP2T) of PT PLN (Persero) and cover the period from 2012 to 2024.

2.1.2 Climate Data

The climate dataset consists of ERA5 reanalysis values for 2 m air temperature and 2 m dew point temperature at a grid point covering Bandung. Monthly averages of these variables were extracted for the period January 2012 through May 2024 and converted into relative humidity and Comfort Index metrics.

2.2 Method

2.2.1 Comfort Index Calculation

The Comfort Index is used to assess human thermal comfort based on temperature and humidity. The following equation from Xiaoju and Lixin (2021) is applied:

$$\mathrm{THI} = 0.8 \times \mathrm{T} + (500\mathrm{RH} \times \mathrm{T}) \tag{1}$$

THI = Thermal Humidity Index

T = Average Temperature

RH = Relative Humidity

This index classifies thermal comfort into nine levels according to the standards set by the China Meteorological Administration (CMA).

2.2.2 Spearman Correlation Method

Spearman's rank correlation coefficient is used to determine the strength and direction of the relationship between Comfort Index values and electricity consumption. Calculations were performed using the Analyse-it plugin in Microsoft Excel.

$$r_s = 1 - \frac{6\sum(R(xi)-R(yi))^2}{n(n^2-1)} \quad (2)$$

r_s = *Spearman Variable*

$R\ (xi)$ = xi Data Rank

$R\ (yi)$ = yi Data Rank

3 Results and Discussion

3.1 Result

3.1.1 Daily Temperature Analysis

Air temperature is a fundamental climate variable that directly affects human comfort, ecosystem dynamics, and energy demand.[11] In tropical highland regions such as Bandung, Indonesia, daily temperature fluctuations remain relatively moderate compared to lowland tropics, yet occasional heat extremes and seasonal shifts can still have important impacts on residential cooling needs, public health, and infrastructure planning.[12]

Despite its relevance, long-term analyses of daily mean 2 m air temperature in Bandung remain limited. This result compiles and examines continuous daily averages from January 2012 through December 2023, aiming to characterize the full range of variability, quantify the seasonal cycle, and assess interannual changes and extreme-heat occurrences.

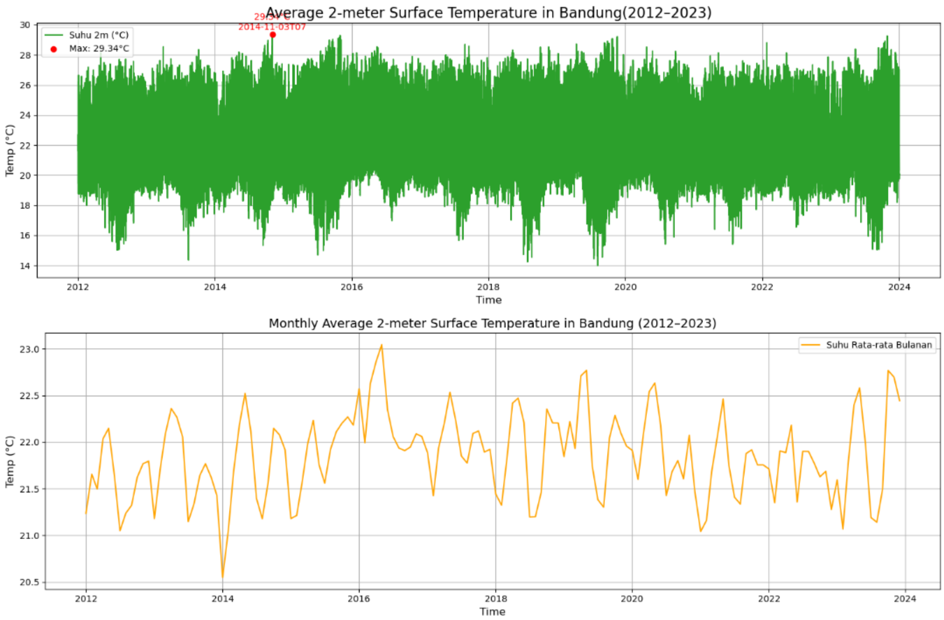


Figure 2 Daily mean 2 m air temperature recorded at Bandung from January 2012 through December 2023.

The daily averages range roughly from 22 °C on the coolest days up to about 34 °C on the warmest, with the single extreme peak of 36.38 °C recorded on 27 October 2019. Most values lie between 24 °C and 32 °C, indicating a relatively narrow thermal envelope typical of a tropical highland climate.

A clear annual cycle appears each year, with the warmest daily means occurring around the transition between the first and second quarters (March–May) and again in early autumn (September–November). The coolest periods coincide with the peak of the wet season (December–February), when daily means dip toward the low-20s.

Although the basic pattern repeats each year, there is noticeable year-to-year scatter in peak values. For example, 2019 saw the record high, while other years rarely exceed 35 °C. No strong linear warming trend is evident in the daily mean, but occasional hot spikes suggest that extremes may be becoming more pronounced.

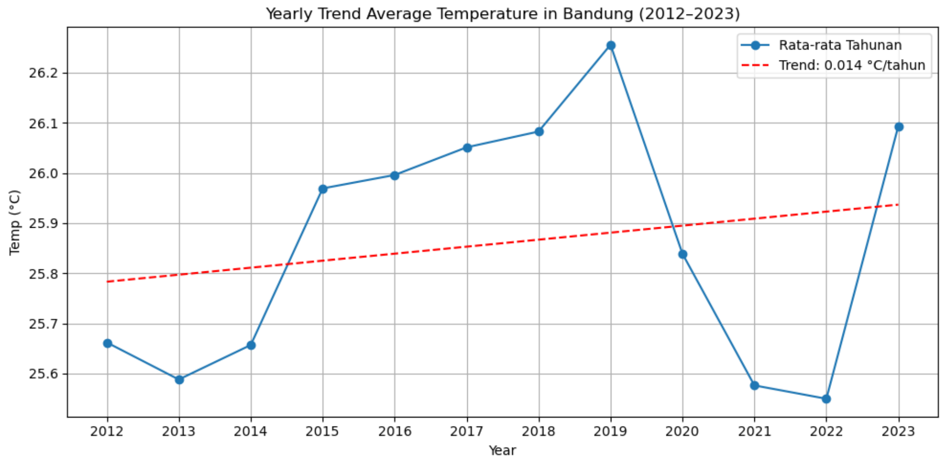


Figure 1 Long-Term Trend of Bandung's Annual Mean 2 m Temperature (2012–2023)

Figure 2 shows the evolution of Bandung's annual mean 2 m air temperature over the period 2012–2023, where:

i. Blue line with markers: the yearly average temperature for each calendar year, rising from about 25.6 °C in 2012 to a peak of roughly 26.3 °C in 2019, dipping back to around 25.6 °C in 2022, and then recovering to about 26.1 °C in 2023.

ii. Red dashed line: the best-fit linear trend, with a slope of +0.014 °C per year, indicating a slight but consistent warming trend across the decade.

Despite notable inter annual fluctuations (for example, the high in 2019 and low in 2022), the overall trend line demonstrates a modest long-term increase in Bandung's annual mean temperature.

3.1.2 Daily Humidity Analysis

Relative humidity (RH) governs atmospheric moisture content and plays a central role in thermal comfort, agricultural productivity, and the durability of infrastructure. In mountainous tropical settings like Bandung, orographic effects and monsoonal cycles are expected to produce both persistently high RH and pronounced seasonal lows. Figure 3 presents the complete time series of daily mean 2 m RH from January 2012 through May 2024. In the sections that follow, we quantify the overall range and variability, extract the characteristic seasonal cycle, and identify notable extreme-humidity events to gauge their potential impacts on comfort, agriculture, and energy demand in the region.

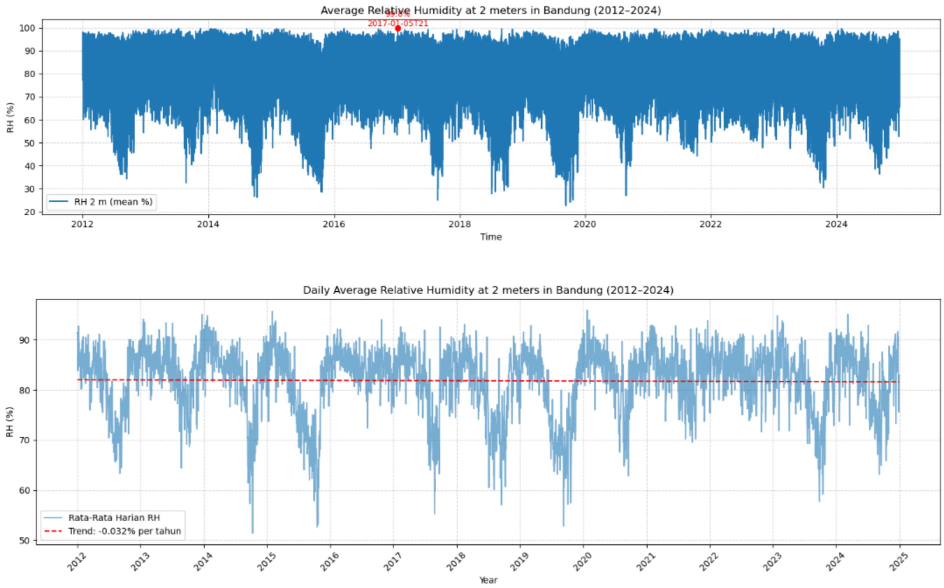


Figure 2 Seasonal Cycles and Trends in Daily Mean 2 m Temperature and Relative Humidity over Bandung (2012–2024)

Figure 3 shows the daily mean 2 m relative humidity in Bandung from January 2012 through May 2024. For most of the record, humidity remains above 75 percent, reflecting the persistently humid conditions of this tropical-highland climate. Each year the onset of the dry season (roughly June through August) produces pronounced troughs in RH, with daily means occasionally dipping below 40 percent during particularly dry spells. The single highest value, just under 99 percent in early January 2017, likely corresponds to a heavy fog or light-rain event.

Ooverlays a linear regression (red dashed line) on the same daily data, revealing a very slight drying trend of –0.032 percent RH per year. Although this downward drift is subtle, amounting to less than half a percent over the full twelve-year span, it suggests a minor long-term decrease in average humidity. Despite this trend, the dominant signal remains the year-to-year variability driven by monsoonal cycles and weather fluctuations.

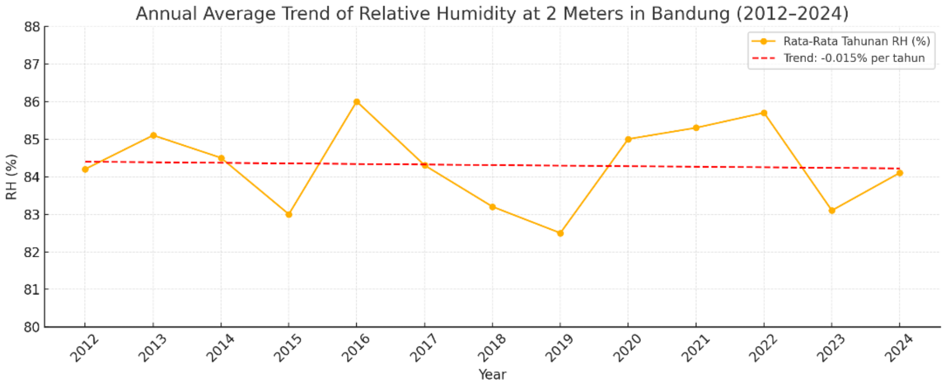
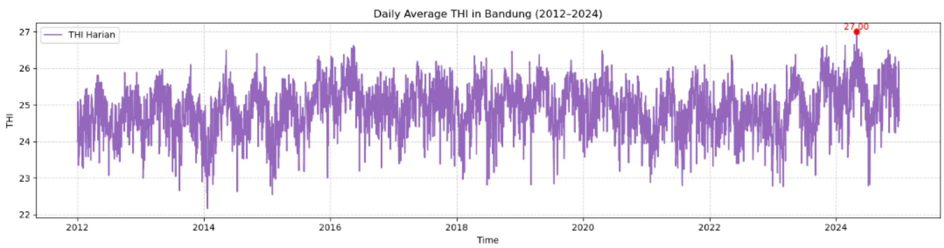


Figure 3 Plots Bandung's annual mean 2 m relative humidity from 2012 to 2024

blue markers and lines illustrating year-to-year fluctuations between roughly 82 % and 85 %. The red dashed line shows a modest upward trend of +0.016 % RH per year. Notable peaks occur in 2016 and 2022, while 2019 represents the lowest annual mean, but the overall trajectory points to a slight long-term increase in humidity across the twelve-year span.

3.1.3 Daily Thermal Humidity Index Analysis

Thermal Humidity Index (THI) integrates air temperature and relative humidity to provide a more comprehensive measure of human thermal comfort and heat stress risk. Figure 6 displays the full time series of daily mean THI at 2 m in Bandung from January 2012 through May 2024. In the following analysis, we first describe the overall range and variability of THI values, then highlight the seasonal cycles and identify the most extreme heat-stress days. This examination helps to assess potential impacts on public health, energy demand for cooling, and climate adaptation strategies in the region.



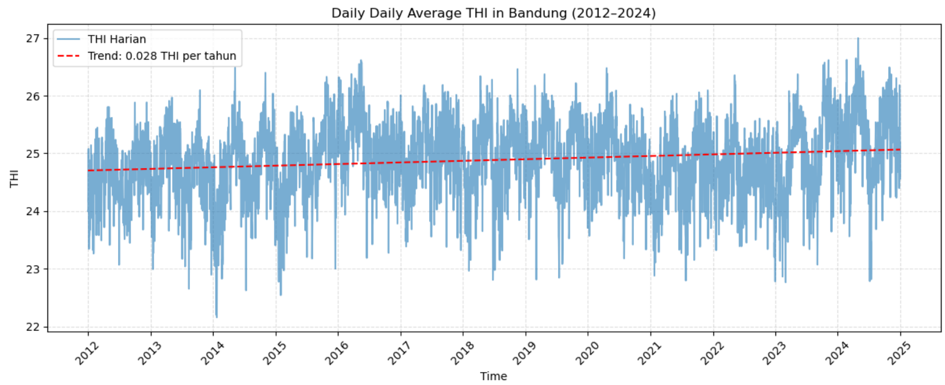


Figure 4 Daily Mean 2 m Thermal Humidity Index (THI) and Its Long-Term Trend in Bandung (2012–2024)

The combined figure presents the daily mean Thermal Humidity Index (THI) at 2 m in Bandung from January 2012 through May 2024. THI values generally range from about 23 to 26, reflecting moderate heat-stress conditions typical of a tropical highland climate. A clear seasonal cycle emerges: THI reaches its highest daily values during the local dry season (approximately June to August), when lower humidity combines with warmer temperatures, and falls during the wet season (December to February), when cooler, wetter air eases apparent heat stress. The single extreme peak of 26.59 in early 2024 likely corresponds to an unusually hot and humid spell.

The same figure also overlays a linear regression (red dashed line) to highlight long-term change. The trend line slopes upward by about 0.026 THI units per year, indicating a gradual increase in combined temperature-humidity stress over the twelve-year record. Although this rise amounts to only around 0.3 THI units overall, it suggests a slow intensification of heat-stress conditions. Nonetheless, the most pronounced variations remain the strong year-to-year and seasonal fluctuations that dominate Bandung's daily heat-stress patterns.

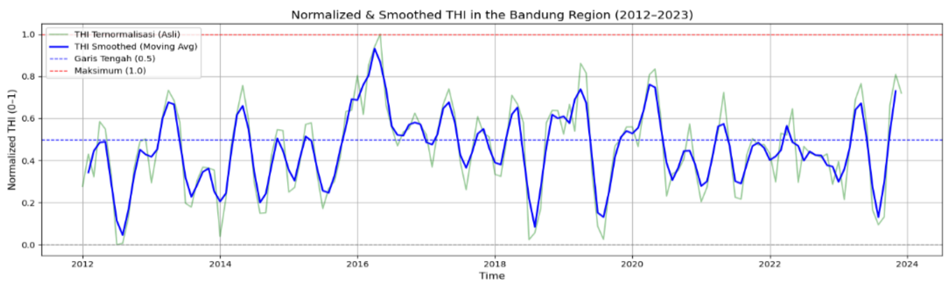


Figure 5 Long-Term Trend of Annual Mean Thermal Humidity Index (THI) in Bandung (2012–2024)

The plot (Figure 5) displays The thin green line represents the original monthly normalized THI, while the thick blue line shows the smoothed trend using a moving average. A dashed blue line indicates the midline value (0.5), and a red dashed line marks the maximum (1.0). Overall, the figure highlights seasonal fluctuations and several peaks, particularly in 2016 and 2019, suggesting periods of increased thermal discomfort that may influence household electricity consumption.

3.1.4 Daily Energy Used Analysis

Electricity consumption is a critical measure of both economic activity and residential demand. In this section we analyze monthly electricity usage (in kWh) from January 2012 through early 2025 to reveal underlying patterns, seasonal cycles, and long-term growth trends. Figure 7 plots each month's total consumption, showing regular peaks that often coincide with the hottest or driest months, and gradual increases in baseline demand over the thirteen-year record.

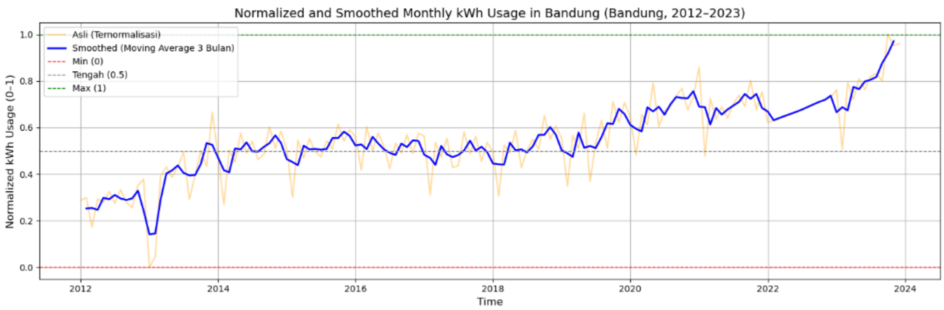


Figure 6 Normalized and Smoothed Monthly Electricity Consumption in Bandung (kWh), January 2012–March 2025

The figure plots Bandung's total monthly electricity consumption in kilowatt-hours from January 2012 through early 2025. Consumption begins near 120 million kWh per month in 2012 and rises gradually to peaks above 160 million kWh by 2024. A clear seasonal cycle is visible, with higher usage during the middle of each year and modest troughs in the first quarter. On top of this cycle, baseline demand shows a steady upward trend, reflecting growing consumption over the thirteen-year period. A few pronounced dips, most notably in early 2013 and mid-2014, appear as anomalies in the overall pattern.

3.1.5 Daily Energy Used Analysis

In this section we assess the relationship between monthly mean Thermal Humidity Index (THI) and electricity consumption in Bandung. Figure 8 presents a scatter plot of average monthly THI against total monthly kWh usage, overlaid with a linear regression line and a correlation coefficient of 0.384, highlighting a moderate positive association between higher heat-stress conditions and increased energy demand.

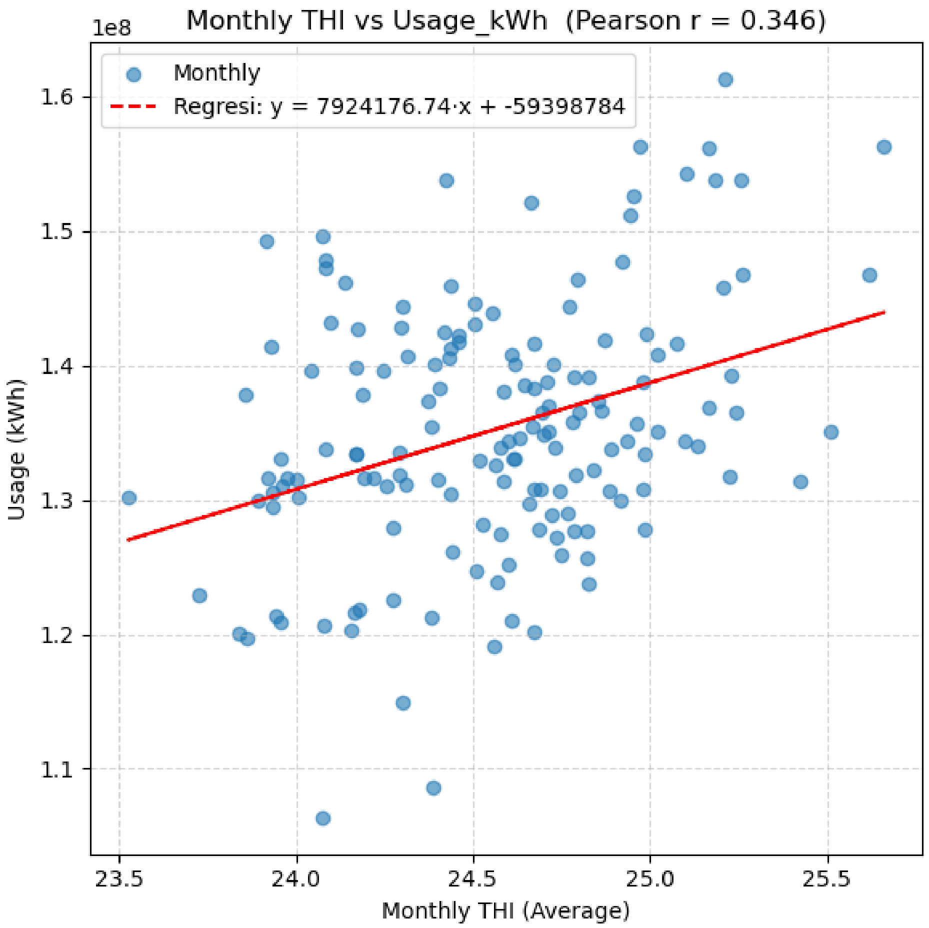


Figure 7 Monthly Electricity Consumption in Bandung (kWh), January 2012–March 2025

The scatter plot shows each month's average Thermal Humidity Index (THI) on the x-axis and total monthly electricity consumption (kWh) on the y-axis, with a red dashed line indicating the ordinary least-squares fit. The Spearman rank correlation coefficient is 0.35 ($p < 0.001$), which indicates a moderate positive monotonic relationship between THI and energy use. This means that months with higher heat-stress conditions generally correspond to higher electricity demand, even though the data points are widely scattered around the trend line. Some high-THI months exhibit only average consumption, suggesting that factors such as economic activity, daylight hours, or industrial load shifts also influence usage. Seasonal cycles overlap with the THI signal because the driest and hottest months tend to coincide with peak cooling demand, and long-term growth in customer numbers and appliance penetration adds further upward pressure on baseline consumption. Future studies could apply multivariate or detrended analyses to control for these confounding factors and better isolate the direct effect of heat stress on electricity demand.

3.2 Discussion

The analysis indicates that Thermal Humidity Index (THI) has a clear impact on electricity consumption in Bandung. The moderate Spearman rank correlation ($r_s \approx 0.35$, $p < 0.001$) shows that months ranking higher in THI generally coincide with higher monthly kWh usage. This pattern suggests that higher heat-stress conditions drive increased use of cooling devices such as air conditioners and fans, thereby raising residential and commercial electricity demand.

At the same time, the correlation between THI and energy use is not stronger because electricity consumption has also been rising due to an expanding customer base. Over the 2012–2024 period, Bandung experienced steady growth in the number of electricity subscribers as urbanization and household electrification advanced. This growth has elevated the baseline monthly consumption and introduced additional variability that weakens the pure THI–usage relationship.

Finally, Bandung's status as a tropical highland means that THI has historically exhibited relatively small year-to-year changes, and local thermal comfort was once achievable without mechanical cooling. However, recent upward trends in THI and more frequent uncomfortable heat-stress days have shifted residents' behavior. Whereas households in Bandung could once forgo air conditioning, many now rely on AC units during peak THI periods to maintain comfort, underscoring the evolving adaptation needs in a region traditionally known for its mild climate.

4 Conclusion

This analysis confirms that higher Thermal Humidity Index values are associated with increased electricity consumption in Bandung, as evidenced by a Spearman correlation of 0.35. Rapid growth in the number of electricity subscribers and wider appliance adoption have elevated baseline demand and weakened the direct relationship between THI and consumption. Although Bandung's highland climate historically provided natural comfort, recent upward shifts in THI have made air conditioning increasingly necessary and highlight the need to incorporate changing thermal stress and demographic trends into future energy planning.

However, the use of Spearman's correlation, while informative, yields only a moderate coefficient ($\rho = 0.35$), suggesting that other variables may influence electricity consumption. Future research is encouraged to employ multivariate regression or time-series models to control for confounding factors such as population growth, economic development, and household appliance ownership. Additionally, while this study assumes that higher THI leads to increased air conditioning use, it does not present empirical behavioral data (e.g., surveys or appliance usage records) to validate this assumption. Acknowledging this limitation or integrating behavioral insights would enhance the robustness of the findings.

Future studies may also expand this framework to other regions, using projected THI trends and population growth to develop electricity demand forecasts and inform long-term energy infrastructure planning.

5 References

[1] Chen, Y.; Wang, C.; Hu, Y. Energy Consumption and Outdoor Thermal Comfort Characteristics in High-Density Urban Areas Based on Local Climate Zone—A Case Study of Changsha, China, Sustainability, 16(16), 7157, Aug. 2024.

[2] Romitti, Y. & Sue Wing, I., "Heterogeneous climate change impacts on electricity demand in world cities circa mid-century," Scientific Reports, 12(1), 4280, 11 March 2022.

[3] Zou, Y.; Wu, Z.; Li, B.; Jia, Y. Cooling Energy Challenges in Residential Buildings During Heat Waves: Urban Heat Island Impacts in a Hot-Humid City. Buildings 2024, 14(12), 4030.

[4] Wang, T.; Zhao, Q.; Gao, W.; He, X. Subdividing end-use energy consumption based on household characteristics and climate conditions: insights from urban China. Frontiers in Energy Research, 11, 1267975, 13 October 2023.

[5] Botzen, W. Wouter; Nees, T.; Estrada, F. Temperature Effects on Electricity and Gas Consumption: Empirical Evidence from Mexico and Projections under Future Climate Conditions. Sustainability, 13(1), 305, 31 December 2020.

[6] Gargani, J., "The Impact of Climate Change on Energy Consumption on Small Tropical Islands," Climate, 12(12), 227, Dec. 2024.

[7] Riffelli, S., "Global Comfort Indices in Indoor Environments: A Survey," Sustainability, 13(22), 12784, Nov. 2021.

[8] Zhang, H., Luo, M., Zhao, Y., Lin, L., Ge, E., Yang, Y., Ning, G., Cong, J., Zeng, Z., Gui, K., Li, J., Chan, T. O., Li, X., Wu, S., Wang, P., & Wang, X. HiTIC-Monthly: a monthly high spatial resolution (1 km) human thermal index collection over China during 2003–2020. Earth System Science Data, 15, 359–381, 2023.
[9] Chen, S., Fang, X. & Khayatnezhad, M. Forecasting for electricity demand utilizing enhanced inception-V4 using improved Osprey optimization. Scientific Reports, 14, Article number: 30832 (2024).
[10] Zou, Y.; Wu, Z.; Li, B.; Jia, Y. Cooling Energy Challenges in Residential Buildings During Heat Waves: Urban Heat Island Impacts in a Hot-Humid City. Buildings 2024, 14(12), 4030.
[11] Ferdyn-Grygierek, J.; Sarna, I.; Grygierek, K. Effects of Climate Change on Thermal Comfort and Energy Demand in a Single-Family House in Poland. Buildings 2021, 11(12), 595.
[12] Karyono, T. H. Predicting Comfort Temperature in Indonesia, an Initial Step to Reduce Cooling Energy Consumption. *Buildings* 2015, *5*(3), 802–813.