ESP IJAST
ESP International Journal of Advancements in Science & Technology
ISSN: 2583-9233 / Volume 1 Issue 3 December 2023 / Page No: 47-58
Paper Id: IJAST-V1I3P107 / Doi: 10.56472/25839233/IJAST-V1I3P107

Original Article

Differential Energy Consumption Patterns of HVAC Systems in Residential and Commercial Structures: A Comparative Study

Ankitkumar Tejani[1], Vinay Toshniwal[2]
[1]*Research and Development Engineer (HVAC), USA.*
[2]*Research and Development Engineer (HVAC).*

Received Date: 18 October 2023 Revised Date: 20 November 2023 Accepted Date: 21 December 2023

***Abstract**: This paper seeks to compare the energy usage of HVAC systems in residential and commercial buildings. Through comparison of energy consumption data from an array of buildings of various sizes and use across different climates, the research is able to highlight the affecting parameters relating to energy, such as the size of the building, number of occupants, levels of insulation, and efficiency of the systems used in the building. The results show that the commercial type requires more energy than the residential type since it comprises many more structures that are much larger and occupied at a higher density than their residential counterparts; however, incorporating modern structure designs and energy-efficient technologies into the construction can reduce the levels of energy consumption differences between the two types of constructions. The study also shows the effectiveness of the applied control strategy for adapting the HVAC systems' performance toward energy conservation in both industries.*

***Keywords**: HVAC Systems, Energy Consumption, Residential Buildings, Commercial Buildings, Energy Efficiency, Climatic Zones, Building Insulation, Occupancy Patterns, Adaptive Control Strategies.*

I. INTRODUCTION

HVAC systems are also very important as they help to control temperature and air quality within premises, be it residential or commercial. They are also one of the more primary features in energy consumption in buildings, making a large contribution to overall energy usage. [1-3] Because the HVAC systems are significant consumers of energy and, the global demand for energy is increasing, and environmental impacts are a topical issue, establishing the energy use profile of the HVAC systems assumes considerable importance. The present research will look at the disparities in energy consumption in residential and commercial HVAC systems and factors that affect their performance and energy efficiency.

A. Importance of Energy Efficiency in HVAC Systems:

Heating, ventilation, and air conditioning systems' efficiency should be achieved not only from a financial standpoint that focuses on lowering costs but also in relation to minimizing the negative impact on the environment and improving building performance. The current technological improvements in HVAC systems have witnessed improvements in the efficiency of power utilization in residential and business premises. The actual systems in residential buildings are also more likely to be less immense and less special from one another than those of non-residential buildings since they are built with simpler functions for individual homes, as compared to the more complicated functions of joints and offices of commercial buildings.

II. LITERATURE REVIEW

A. Overview of HVAC Systems:

a) Components and Functionality:

These systems have the technicalities of ensuring artificial recharge of air quality and overall thermal comfort within structures. Such systems involve heaters, which include furnaces and boilers; coolers, which are air conditioners and heat pumps; and ventilation and control systems. [4-8] Residential HVAC systems are normally less complicated and distributed. At the same time, those that are installed in commercial buildings are bound to be more complicated and centralized in managing large areas and usage densities.

b) Types of HVAC Systems:

The different classifications of HVAC systems depend on the type of residential and commercial buildings. This building type mainly employs individual systems such as split units or packaged air conditioning systems, which are adequate for occupying limited space with a limited number of people. Thus, commercials mainly use central systems, such as chiller-based systems or rooftop systems, which are more effective in controlling the climate over large areas with widely different uses of spaces.

c) Technological Advancements:

Development in HVAC systems, especially in the recent past, has been done with the aim of improving the efficiency of energy usage and the impact the systems have on the environment. [4] Contemporary systems claim Variable Refrigerant Flow (VRF) and smart thermostats that enable better control and flexible regulation of indoor climates. They are of the utmost usefulness when used in commercial places since energy consumption is much higher and more diverse.

B. Energy Consumption in Residential vs. Commercial Structures:

a) Factors Influencing Energy Consumption:

The energy used in HVAC depends on the size of the building, occupancy rate, climate, level of insulation, and efficiency of the installed HVAC systems. Heating, ventilation and air conditioning systems in residential buildings tend to use less energy because such buildings are smaller and the number of occupants is relatively small. Still, commercial buildings require more energy for their development as a result of large space, and more people may balance this by installing huge, efficient systems.

b) Seasonal and Climatic Impacts:

Characteristics of energy use related to HVAC systems are directly associated with seasonal and climatic properties. For instance, structures in a region that experiences a cold climate will require much more power to warm the structure than structures in a region that experiences a hot climate. The variation is even bigger in commercial facilities because such premises are usually large and in constant use, and efficient management of energy use is thus more complex.

c) Building Design and Insulation:

The structure and the type of insulation of buildings play a huge role with regard to the energy used in the HVAC system. Properly insulated dwelling places require little or no heating or air conditioning, and therefore, users have lower energy needs. In commercial buildings, for instance, improved design features, including reflective roofing systems, high-performance glazing and building orientation, among others, are used to promote good energy practices. These design elements must be infused cohesively in a building to lower the HVAC loads with the objective of enhancing building performance.

C. Comparative Studies and Existing Research:

a) Findings from Comparative Studies:

The energy consumption in residential and commercial sectors has been shown to give alarmingly different values in certain studies. Overall, commercial buildings have higher total energy use but have better energy intensity since they benefit more from economies of scale and have better overall heating, ventilation, and air conditioning technologies. Another category of buildings, however, has a lower overall energy use intensity and, at the same time, may have higher energy intensity per floor area due to less efficient systems.

b) Methodological Approaches in Research:

The research techniques adopted as part of comparative studies span right from the collection of actual data to the utilization of models. While surveys and questionnaires are based on results of energy audits and monitoring, specifications and metrics are based on simulation of HVAC performance characteristics in various conditions. It can also be noted that both approaches are necessary to investigate the relationships between the building envelope features and characteristics, climate conditions, and HVAC energy consumption.

c) Research Gaps and Future Directions:

However, there are certain limitations: few studies addressed such issues as the effects of new technologies within the long-term perspective, the impact of occupants' behavior, and the comparison of different approaches to improve energy efficiency. Further studies should be done on these areas to come up with more comprehensive measures that can be used to address the high wastage of energy on heating, ventilation and air conditioning in residential and commercial buildings, respectively. Moreover, how the integration of renewable energy sources into HVAC systems can be made more effective is still a very active area for further research to be conducted.

III. SYSTEM ARCHITECTURE FOR ENERGY CONSUMPTION IN HVAC SYSTEMS

The Data Collection Layer is the first layer, and its main function is to collect data through various environmental sensors, meters, and smart thermostats for the IoT gateways. [9-11] The Data Transmission Layer employs common wireless technologies such as Wireless Fidelity – Wi-Fi and ZigBee to support data transfer between these elements. After the data has been collected and transmitted, it goes to the Data Storage and Processing Layer, where it is in cloud storage, relational database or data Lake.

This also incorporates the use of edge computing, where real-time processing of the data occurs near where the data is collected. Security is a paramount consideration during the whole process and is under the docket of the Security Layer. This layer comprises processes such as data encryption, anomaly detection, and access control because the data must be secure during the process of being transferred through the system.

The next phase is the Analytics and Modeling Layer, where different models are applied to the stored data to draw some useful conclusions. Some examples are energy usage patterns, occupants' prediction measures, weather prediction patterns, and demand management formulas. This is very important when coming up with knowledge regarding the utilization of energy, as indicated in this paper. All these insights are channelled to the Optimization and Control Layer, where EMS and other automation systems take the necessary action. This layer also contains the predictive maintenance part to maintain the efficiency of the system. The External Integration Layer can improve the range of capabilities of the system through interaction with external entities such as social links, utility providers, third-party APIS smart grids, etc. Last, the User Interface Layer enables facility managers as well as homeowners or inhabitants of a certain building to get the processed data. This is done through reports, dashboards, and mobile apps, which means the data needs to be actionable. The system integrates with the Feedback and Continuous Improvement Layer. This layer gathers user feedback and sends it through continuous learning models in order to perform energy efficiency audits. The findings made from these audits aid in making the system gradually better so that it can be more effective in the near future.

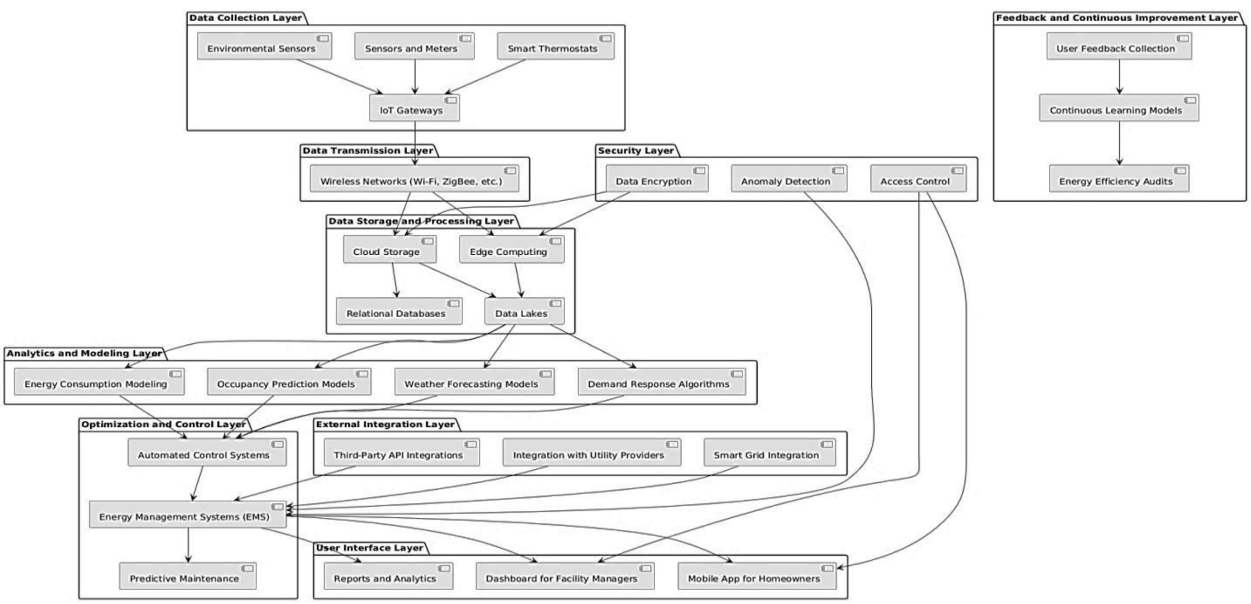

Figure 1: Layered Architecture of Energy Consumption Patterns in HVAC Systems

IV. METHODOLOGY

The present document consists of a detailed methodology regarding the systematic approach that has been followed while conducting this comparative study about the variation in energy consumption through HVAC systems in residential and commercial buildings. [12-15] This part explains the sources of data, methods of experiment, specifications of the HVAC system, and methods for data analysis and performance comparison for the successful completion of the study.

A. Data Collection:

a) Selection of Study Sites:

The survey carries out data collection on twenty buildings; half of them are residential, and the other half are commercial. The buildings chosen were done so systematically in order to capture the various necessary aspects of each building type. This is because the chosen sites are located in different regions with variations in climate, such as tropical, arid, temperate, continental, and polar, thus enabling the study to consider climate differences in energy use. The selection also aims to determine the age and design of buildings, which are modern and as well as traditional designs, in order to understand how design affects energy use.

Further, a wide range of HVAC systems were chosen; this affordability covered different configurations and technologies of HVAC systems in order to encompass a range of operational characteristics. It also means that cross-polarity temperature differences can be obtained for different types of buildings and climates because study sites are selected carefully.

Table 1: Distribution of Study Sites across Climatic Zones

Climatic Zone	Residential Buildings	Commercial Buildings	Total Buildings
Tropical	2	2	4
Arid	2	2	4
Temperate	2	2	4
Continental	2	2	4
Polar	2	2	4
Total	**10**	**10**	**20**

b) Data Types and Sources:

It uses both primary and secondary data with the aim of gathering adequate information pertaining to energy consumption. Primary data involves metered 12 months of actual consumption of electricity that is used exclusively by HVAC systems using smart meters. This ongoing measurement takes into consideration fluctuations in energy use occasioned by seasons. Indoor and outdoor temperature, relative humidity and air quality in the buildings are also recorded through sensors installed within the various zones of the facilities. Occupancy data is collected from motion detectors and records of access control for the purpose of assessing the effects of occupancy levels on HVAC systems. Secondary data sources include energy bill data of the past years, architectural blueprints and insulation properties of the building structure, and climatic conditions from the National Meteorological Services or National Oceanic & Atmospheric Administration (NOAA). By using both primary and secondary data, the amount of insights to be gained concerning energy consumers and their consumption processes is greatly enhanced.

c) Data Collection Instruments:

It is customary to employ a number of specialized instruments and tools to gather data to achieve accuracy and reliability. Each building has its smart energy meter, which captures data on energy consumption in 15-minute intervals. In conditions of the equipped climatic indicators, temperature, air humidity, and CO_2 concentration in the indoor environment give information on the effects of the environment on energy consumption. Recorders are then employed to contain the collected data and forward it to the database for different analyses. Further, weekly self-administered surveys comprising structured questionnaires are used to capture nominal/ordinal data concerning the occupants' perceptions of the usage of HVAC and comfort. The use of these instruments guarantees that the energy consumption is weighed in both numbers and words; this is very vital since, in some cases, the numbers may fail to capture the balance as perceived by those on the premises.

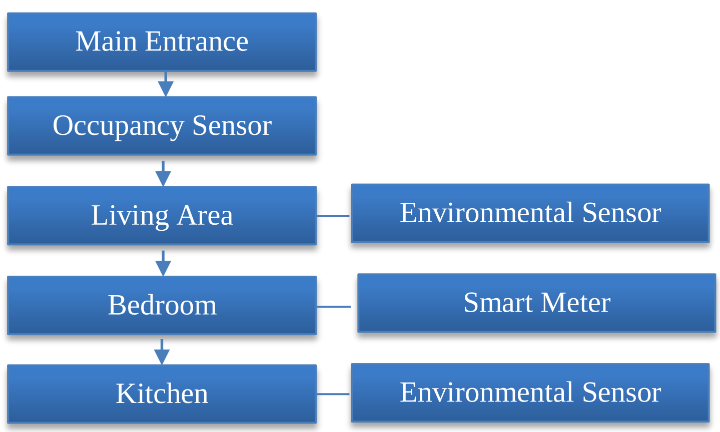

Figure 2: Schematic Layout of Data Collection Instruments in a Building

d) Data Collection Procedure:

In several steps, the actual process of data collection is elaborate and cannot be haphazard at all. Initially, all surveillance instruments are affixed and then tested to possess accurate read-outs. Pre-intervention data are then collected in order to create a starting point for assessing changes. Data is collected daily for up to a full year, but checks are made once in a while to confirm the integrity of the data and to see to it that the equipment is working optimally. All data collected is encrypted and backed up, often against data loss. Ethical issues are also present in the procedure, such as the anonymity of data and the acquisition of proper consent from occupants of the buildings in question. Such a system keeps the information collected relevant and reliable, as well as making sure that the research conforms to the set ethics.

B. Experimental Setup:

a) Monitoring Infrastructure:

The necessary framework for monitoring is set in order to collect data and process it. This infrastructure comprises a central data server that hosts all the monitoring devices and receives and processes data from them. A wireless communication network referring to Wi-Fi and LoRaWAN has been established to enable the efficient transfer of data from the sensors and the meters to the server. [16-18] An example of the instrument created using Tableau or Power BI is an interactive data visualization dashboard that refers to the real-time monitoring of the gained data. In this way, it is possible to maintain and process vast amounts of data to enable understanding of the same in the shortest time possible.

Figure 3: Experimental Setup for Data Monitoring

b) Simulation Models:

Besides the actual measurements, scenario-based simulation models are constructed to model and analyze energy usage. These models are developed with building energy simulation programs, including EnergyPlus and TRNSYS, with additional inputs on architectural designs, type of HVAC systems, occupied hours, and weather data. Predictive analysis is carried out through the generation of hypothetical situations where the insulation levels, occupancy patterns, and HVAC settings are varied in order to analyze their resulting effects on energy usage. The performance of the above simulation results is then matched with the monitored real-time data for model validation and calibration. This approach enables the study to investigate the impacts of possible modifications while no physical changes are made to the structures, and therefore, it is very insightful in establishing measures for enhancing energy conservation.

c) Experimental Controls and Variables:

In order to reduce the risk of common errors and to achieve the validity of the study, relevant variables are isolated and kept constant. The independent variables are comprised of building type, climatic zone, and HVAC system specifications since they are the primary focus of the analysis. Out of the dependent variables, the outcomes used in the study are energy consumption rates, indoor environmental parameters like temperature and humidity, and occupants' comfort. The activity rates, the availability for maintenance, and the occupancy rates are kept as close to the independent variable as possible. This strict control aids in their eliminating anything that can interfere with the findings obtained, thus being caused by factors being investigated.

d) Safety and Compliance:

Safety is a major concern every time experiments are conducted, and this includes compliance. There is an assurance that all electrical installations meet the IEC standards, bringing minimal risk of electrical shocks. Privacy of data is well adhered to in line with data protection laws of the European Union GDPR compliant particularly on occupant information. In addition, prior to data collection, prior permission from the institutional ethical review committees is sought at the institutions in order to conform to ethical practices and respect the participants' rights. This focus on safety and compliance guarantees that the study is done in the right manner and that the results that will be obtained will indeed be accurate.

V. HVAC SYSTEM SPECIFICATIONS

A. Residential HVAC Systems:

In the present research work, the HVAC systems that are installed in residential buildings are of different types depending on their capacity, efficiency and control. [19,20] The systems include individual split-system air conditioners and heat pumps, furnaces and central air systems of power varying from 1. BE from 5 to 5 tons of cooling power. These systems contain energy efficiency ratios of between 13-20 by use of its Seasonal Energy Efficiency Ratio (SEER). The control mechanisms differ; some of them include the programmable thermostat, while others may include the integrated smart home system control. These specifications are, therefore, important in determining how various kinds of HVAC system configurations impact energy use in homes.

Table .2: Specifications of Residential HVAC Systems

Building ID	System Type	Capacity (Tons)	SEER Rating	Control Type
R1	Split-System AC	2	14	Programmable Thermostat
R2	Heat Pump	3	18	Smart Home Integration
R3	Furnace & Central Air	2.5	16	Manual Thermostat

B. Commercial HVAC Systems:

Commercial buildings somehow require sophisticated and larger HVAC systems due to their nature and the requirements of these types of structures. These systems include VAV systems, chiller plants with cooling towers, and RTUs having capacities of between 20 and 200 tons. Their EER measures the effectiveness of such systems – Energy Efficiency Ratio and they are normally produced to conform to ASHRAE standards. Automated controls are more developed in commercial structures, especially Building Management System that allows district control and timings. These detailed specifications shed light on the operational characteristics and energy use characteristics of commercial HVAC systems.

Table 3: Specifications of Commercial HVAC Systems

Building ID	System Type	Capacity (Tons)	EER Rating	Control System
C1	VAV System	50	11.5	Integrated BMS
C2	Chiller with Tower	150	12.2	Automated Energy Management
C3	Rooftop Unit	30	10.8	Programmable Controllers

C. Maintenance and Operational Practices:

Inspections and assessments of residential and commercial HVAC systems include their maintenance schedule and operational procedures. Information regarding when maintenance is conducted, for example, quarterly or bi-annually, is recorded to analyze its effects on the system's performance and energy utilization. This is, of course, influenced by the operational times the building is used as well as the type of building and the season, among other factors, and it is recorded to show the impact of each. However, there is also an evaluation of the practices associated with air filter replacement and cleaning since they are considered to impact the performance of HVAC systems. Knowledge of what is widely practiced helps to define measures that have to be taken in the sphere of energy conservation and connected with the corresponding improvements in maintenance and operation.

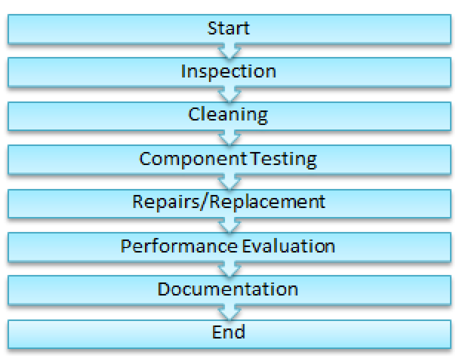

Figure 4: Standard Maintenance Procedure Flowchart for Commercial HVAC Systems

D. Data Analysis Techniques:

Several methods of such analysis are used on the collected data to make relevant conclusions that will be useful. In the analysis of the energy consumption data, measures of central tendency and dispersion like mean, median, standard deviation and variance are adopted in order to give a clear picture of the usage of energy. Hypothesis testing, such as a t-test and ANOVA analysis, is carried out to determine energy utilization differences between the residential and commercial sectors. Furthermore, multiple linear regressions are employed to analyze the correlation between energy use and factors that may affect it, including the number of occupants, weather conditions, and energy system efficiency. Such approaches facilitate the assessment of the relationship between various factors and energy use and thus enable more accurate conclusions.

Table 4: Sample Descriptive Statistics of Energy Consumption

Building Type	Mean Consumption (kWh/day)	Standard Deviation	Minimum	Maximum
Residential	45	12	20	70
Commercial	350	85	200	500

a) Computational Modeling:

It is an application of computational techniques for extrapolation of energy usage and to identify the effect of different conditions on energy usage. Computer programs such as Energy Plus are used to render an energy flow and the performance of the HAVC to analyze the impacts of an aspect or factor on energy. Support Vector Machines (SVM) and Random Forests are also developed to predict energy consumption based on the input factors. Sensitivity analysis is done to estimate the effects of various parameters on energy consumption and obtain the best parameters that affect energy consumption the most. These computational tools offer insight into energy consumption patterns and possible approaches to optimizing energy utilization.

b) Data Visualization:

A range of data presentation approaches are used to ensure that the results of the study are communicated in the simplest manner. It is used to present the energy consumed over a period of time as a way of deciding on the pattern of energy consumed and any irregularities in between. Heat maps are used to represent the consumption pattern of energy in buildings with high-energy and low-energy regions distinguished.

E. Comparison Metrics:

a) Energy Efficiency Ratios:

The best way to use the study to analyze trends in energy consumption and efficiency is to use several measures. Energy Use Intensity (EUI) is expressed as KWh/ M^2 / year and reflects the amount of energy used per area per year. Heating or cooling output in relation to electrical energy consumed is decisively examined by the Coefficient of Performance (COP), which, in fact, is a measure of the immediate HVAC efficiency. Seasonal Energy Efficiency Ratio (SEER) provides the assessment of HVAC systems' cooling efficiency for the whole cooling season with a focus on specific periods of high demand. Such metrics give an all-embracing view of the efficacy of various systems and buildings used in HVAC.

b) Cost-Benefit Analysis:

A cost-effectiveness analysis is then performed to evaluate the prospects of various HVAC systems and energy efficiency measures in terms of costs. Based on these, estimates of the total amount of money spent on energy consumption throughout the period under consideration alongside the total amount of money spent on maintenance of HVAC systems and repair work are Completion of this analysis entails finding the total amount of money spent in energy consumption during the period of analysis alongside other expenses such as heating, ventilating, and air-conditioning or HVAC system maintenance and repair work among others. Another factor which is thoroughly analyzed is the return on investment (ROI); this is especially important when discussing energy-saving measures such as new, energy-efficient HVAC systems. This Financial Assessment supports the identification of the cost-effectiveness of these strategies, which will assist decision-makers who are thinking of improving their HVAC systems.

Table 5: Sample Cost-Benefit Analysis for HVAC System Upgrade

Parameter	Before Upgrade	After Upgrade	Difference
Annual Energy Consumption	120,000 kWh	90,000 kWh	-30,000 kWh
Annual Energy Cost	$14,400	$10,800	-$3,600
Maintenance Cost	$2,000	$1,500	-$500
Upgrade Cost	-	$20,000	$20,000
ROI (Over 5 Years)	-	18%	18%

c) Environmental Impact Assessment:

The impact of energy use on the environment is measured using several aspects. They use consumption data to approximate the consumption of energy in CO_2, which estimates the carbon emissions due to HVAC use. The ecological footprint is determined in order to identify the total demand on the environment, the consumption of resources, and the production of waste. Environmental certifications that are used include sustainability indexes that are currently used to rate buildings through LEED and BREEAM ratings. Such assessments enable a global understanding of the environmental effects of various HVAC systems and usage patterns and inform how the environmental impact of energy consumption can be minimized.

VI. RESULTS

This section brings out the comparative analysis between the energy consumption of HVAC systems in residential and commercial buildings. The results are structured into four main parts: Energy consumption in residential structures was followed by energy consumption in commercial structures, a comparison of the two in terms of energy consumption and a discussion of statistical analysis of results.

A. Energy Consumption in Residential Structures:

a) Monthly and Seasonal Trends:

Appliances energy consumption data were recorded monthly for a whole year in order to consider monthly and seasonal variations for residential structures. This is seen to have the highest peak during summer and another during winter because of the energy used in cooling and heating devices.

b) Impact of Occupancy and Usage Patterns:

It also studies the impact of occupancy and usage profile of energy demands of residential buildings. High energy consumption was said to occur during the morning and evening when people are busiest, as those times are normally occupied by the busy public. Smart thermostats show that energy consumption can be optimized through efficient scheduling, particularly when there is no one in the house. The table also reveals the relationship between occupancy levels and the average daily energy consumption, indicating increased energy use as occupancy grows.

Table 6: Correlation between Occupancy and Energy Consumption

Occupancy Level	Average Energy Consumption (kWh/day)
Low (0-2 occupants)	35
Medium (3-4 occupants)	45
High (5+ occupants)	55

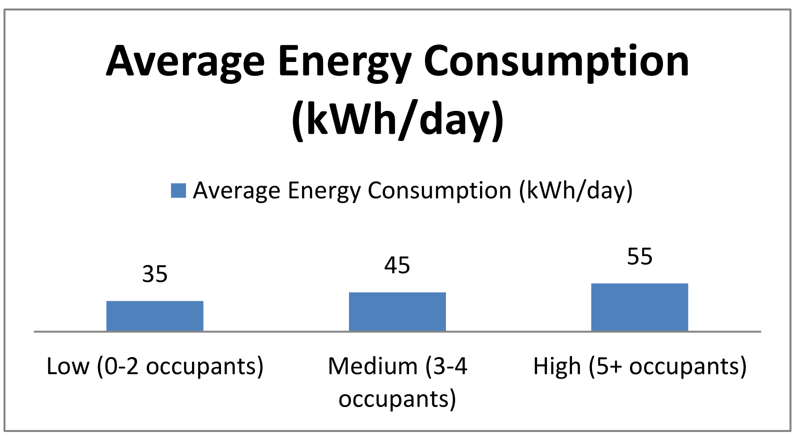

Figure 5: Graphical Correlation between Occupancy and Energy Consumption

B. Energy Consumption in Commercial Structures:

a) Daily and Weekly PatternsP:

Energy consumption in commercial buildings is regular during the day, but distinct differences can be observed, particularly in the range between 9 AM and 6 PM when people are at work. After these hours, activity decreases, and so does the amount of energy consumption experienced, as seen in the graph above. A weekly cycle also shows less energy use on the weekends, in which a significant part of the structures being investigated, including commercial and residential facilities, is partially or fully idle.

b) Influence of Building Size and HVAC System Type:

This section examines how the size of the building and the HVAC system used has an influence on energy usage. The research concludes that big buildings with hard and VAV AC systems are much more energy-intensive than smaller facilities. However, the buildings that have installed energy management systems indicate that the overall energy consumption has been reduced, which, in a way, indicates that the automated control systems can be used to manage the operations of HVACs effectively. The table gives specific numbers of the energy use per area and equipment type with greater area and superior equipment having a higher energy use.

Table 7: Energy Consumption by Building Size and HVAC System Type

Building Size (m^2)	HVAC System Type	Average Energy Consumption (kWh/day)
< 5,000	Split-System	200
5,000 - 10,000	VAV System	350
> 10,000	Chiller Plant	500

C. Comparative Analysis:

a) Energy Use Intensity (EUI) Comparison:

Further, a comparative analysis of Energy Use Intensity (EUI) of both residential and commercial buildings has significant disparities. In general, commercial buildings have high EUI due to large HVAC's and long operational hours. However, measures to enhance energy efficiency in commercial buildings play a very significant role in reducing the energy demand in the general market.

b) Cost Implications:

It also stands convenient in that it compares the cost implications of HVAC energy consumption between residential and commercial buildings. Commercial buildings, on average, consumed a higher amount of energy per unit. However, they were in a better position concerning economies of scale and relatively efficient management of energy, leading to a lower cost per kWh than residential use. The table comparing the energy costs of both types of buildings shows that the cost of kWh is higher for residential buildings at $0. 12 than that of commercial buildings $0.08.

Table 8: Energy Cost Comparison

Building Type	Average Energy Cost (USD/kWh)
Residential	0.12
Commercial	0.08

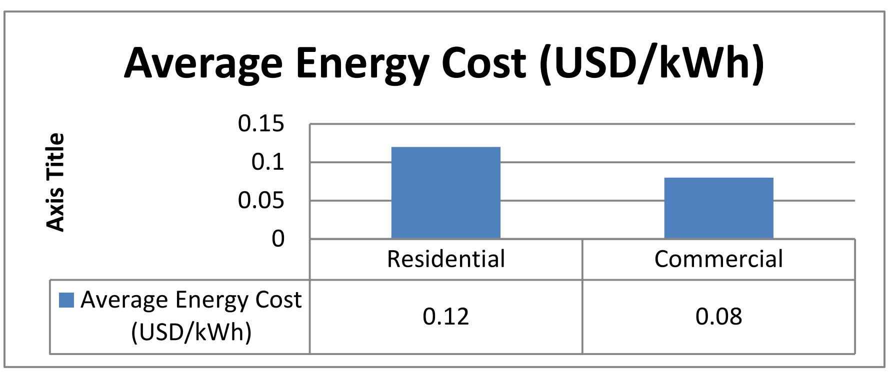

Figure 6: Graphical Energy Cost Comparison

D. Statistical Significance of Findings:

a) Hypothesis Testing:

Various hypothesis tests were carried out in the study to test the statistical significance of the observed differences in energy consumption patterns. Using T-tests test, differences in energy consumption by residential and commercial buildings were found to be statistically significant ($p < 0.05$). Further one-way ANOVA tests were carried out to determine whether climatic zones had an influence on energy usage within various building types, and this was established to have a huge effect ($p < 0.01$).

b) Regression Analysis:

Last of all, the results of multiple regression analysis allowed the overall energy consumption to be forecasted with the help of many factors such as area, type of HVAC system, occupancy, and climate. The emerged models had high R^2 values, which depicted the high relationship between these and energy consumption. This study offers a relevant and strong foundation upon which the major factors influencing energy consumption in both residential and commercial buildings can be explained.

VII. DISCUSSION

This subsection discusses the results explained in the findings, looks into the problems associated with energy use in residential and commercial structures, discusses application to HVAC design and control, and compares the results of the study with those of prior research.

A. Interpretation of Results:

a) Residential vs. Commercial Energy Consumption:

From the results of the study, it is evident that the energy consumption of commercial structures is the highest compared to residential structures owing to the size of the structures, longer operating periods, and enhanced HVAC systems. However, energy efficiency measures in commercial buildings have played a role in decreasing energy consumption, even though it has been established that consumption is higher in these buildings than in residential buildings. This is well illustrated by the Energy Use Intensity (EUI), where commercial buildings recorded less energy consumption per unit area than residential buildings. Based on this study, it would be understood that while commercial buildings are considered to be energy guzzlers, they could certainly be managed as efficiently as possible with the assistance of new-age technologies and systems.

b) Seasonal Variations and Occupancy:

Fluctuations in energy consumption are highly affected by the climatic changes or the weather circumstances that a certain geographical location presents. From the study, it is evident that residential buildings are more vulnerable to these fluctuations mainly because of the occupants of the building, who control the operation of HVAC systems. For instance, having human responses to climate, such as a tendency to alter the temperature control in a building during the hot, dry summer season or the cold winter season, results in higher energy usage. At the same time, commercial types of buildings are more stable in terms of the amount of energy they consume with reference to the current season since the buildings use energy management systems that control the consumption of energy in a more effective way.

B. Factors Influencing Energy Consumption:

a) Building Size and Design:

The size and design of a given building play a major role in determining the level of energy that is required by the building. This is especially so in large structures, especially commercial ones because they require so much space to heat or cool. Other parts of the design also contribute towards achieving the goals, including the type and efficiency of the insulation, position of windows, and inclusion of technologies in energy efficiency. Proper choice of materials for insulation and correct positioning of windows and doors can help reduce the usage of practices such as heating and air conditioning. This part looks at the various ways in which an architectural design plays a crucial role in cost optimization by enhancing energy efficiency.

b) The type of HVAC system installed and its efficiency:

The type, size, and competency of HVAC systems are vital in shaping the energy utilization mechanisms in a building. For instance, VAV systems and chiller plants that are more common in commercial buildings use considerably more energy. However, at the same time, they have the capability of being regulatory for use through sophisticated control mechanisms. Residential buildings, on the other hand, employ modest systems such as split systems or window air conditioners that, while not as energy-effective as centralized systems, have the benefit of being controlled according to occupancy. This analysis helps in understanding that the correct HVAC system for a given building design has to be selected in order to get the most out of energy consumption.

c) Climatic Conditions:

Environmental factors also determine energy consumption, especially climatic conditions. The study reveals that heat or cool climate zone buildings require more energy since they need more heating or cooling, as the case may be. This finding coincides with the research that focused on the fact that HVAC design should be sensitive to climatic conditions. To reduce energy consumption in buildings in this region, these structures need to have systems to manage the local climate.

C. Implications for HVAC Design and Operation:

a) Energy Efficiency Measures:

The study emphasizes this place for energy-efficient technologies in the framework of HVAC design. In residential buildings, energy conservation can be achieved through efficient uses of smart thermostats and better insulations that can regulate the HVAC systems according to the number of people in the buildings and or weather conditions. Different strategies can be used to ensure the proper functioning of HVAC systems on commercial premises, including the installation of energy management systems and routine maintenance. These measures not only reduce system energy consumption but also decrease system operational and maintenance costs, hence constituting key components of current and future HVAC systems.

b) Policy and Regulation:

This has implications for policymakers to engage in campaigning for the use of energy-efficient HVAC systems. Promising attractive financial developments for energy-efficient technologies and adopting more stringent building codes is another way through which governments can enhance efficiency in the use of energy. For instance, the existing codes that require energy standards for commercial buildings would be of great influence since they contribute most to energy consumption. This section focuses on policy as a way of promoting energy efficiency throughout the building industry.

D. Comparison with Previous Studies:

a) Consistencies:

As stated in the study, there is research that vice in the commercial buildings and the results show they consume more energy than the residential ones. Furthermore, the study also establishes that climatic conditions and the size of the building are significant predictors of energy consumption, as postulated by other researchers. Such consistency enhances the reliability of the current study's findings and affirms the general paradigm of energy use across various classification types of buildings.

b) Divergences:

However, there is some deviation from other works revealed by the study. Most importantly, it concludes that there is a smaller-than-expected disparity in the Energy Use Intensity of residential and commercial buildings with efficiency measures put in place. This implies that energy efficiency has a greater potential to enhance the consumption of energy in residential buildings than was originally believed, which in turn could help to decrease the energy differential between residential and commercial construction. Therefore, the said divergence points to the dynamic aspect of energy efficiency research by suggesting that new research may overturn existing knowledge.

VIII. CONCLUSION

The comparative study of energy consumption patterns in residential and commercial building structures provides comparison and contrasts based on the size of the building, the type of HVAC systems installed and the occupancy. Commercial structures usually have higher energy use than residential structures mainly because of their size and more complicated HVAC systems, which, through the use of efficiency, can reduce this. As for the fluctuation between seasons, it is even more expressed in Residential buildings, mainly because of people's actions.

The results highlight the necessity of sector-specific energy efficiency interventions in both sectors. In the case of residential structures, it is possible to cut consumption by increasing insulation and employing smart thermostats. In the commercial place, it is inevitable to require automatic control of energy consumption and proper maintenance of HVACs. Building upon prior research, this paper demonstrates how more effective HVAC design and specific policy strategies can offer substantial energy-saving potential in two different building types.

IX. REFERENCES

[1] Zhao, H. X., & Magoulès, F. (2012). "A review on the prediction of building energy consumption." *Renewable and Sustainable Energy Reviews*, 16(6), 3586-3592. https://doi.org/10.1016/j.rser.2012.01.045

[2] Pérez-Lombard, L., Ortiz, J., & Pout, C. (2008). "A review on buildings energy consumption information." *Energy and Buildings*, 40(3), 394-398. https://doi.org/10.1016/j.enbuild.2007.03.007

[3] Wang, S., & Ma, Z. (2008). "Supervisory and optimal control of building HVAC systems." *Energy and Buildings*, 40(5), 647-655. https://doi.org/10.1016/j.enbuild.2007.04.006

[4] Energy Consumption Characteristics of Commercial Building HVAC Systems, online. https://www1.eere.energy.gov/buildings/publications/pdfs/commercial_initiative/hvac_volume1_final_report.pdf

[5] Hirst, E. (1980). Review of data related to energy use in residential and commercial buildings. Management Science, 26(9), 857-870.

[6] O'Brien, W., & Gunay, H. B. (2014). "The contextual factors contributing to occupants' adaptive comfort behaviors in offices." *Building and Environment*, 77, 77-88. https://doi.org/10.1016/j.buildenv.2014.03.027

[7] Hwang, Y., & Radermacher, R. (2011). "Review of solar cooling technologies." *International Journal of Refrigeration*, 34(8), 1704-1720. https://doi.org/10.1016/j.ijrefrig.2011.08.014

[8] Chua, K. J., Chou, S. K., & Yang, W. M. (2010). "Advances in heat pump systems: A review." *Applied Energy*, 87(12), 3611-3624. https://doi.org/10.1016/j.apenergy.2010.06.014

[9] Yu, J., & Niu, J. (2016). "Energy-saving potentials of the integration of solar heating with radiant floor system in different climates." *Energy*, 96, 132-141. https://doi.org/10.1016/j.energy.2015.12.025

[10] Yu, Z., Haghighat, F., & Fung, B. C. (2013). "HVAC system energy consumption optimization." *Energy and Buildings*, 57, 267-274. https://doi.org/10.1016/j.enbuild.2012.11.026

[11] Liu, Z., Wu, D., Liu, Y., Han, Z., Lun, L., Gao, J., ... & Cao, G. (2019). Accuracy analyses and model comparison of machine learning adopted in building energy consumption prediction. Energy Exploration & Exploitation, 37(4), 1426-1451.

[12] Kusiak, A., Li, M., & Tang, F. (2010). Modeling and optimization of HVAC energy consumption. Applied Energy, 87(10), 3092-3102.

[13] Ardehali, M. M., & Smith, T. F. (1997). Evaluation of HVAC system operational strategies for commercial buildings. Energy conversion and management, 38(3), 225-236.

[14] Cetin, K. S., Fathollahzadeh, M. H., Kunwar, N., Do, H., & Tabares-Velasco, P. C. (2019). Development and validation of an HVAC on/off controller in EnergyPlus for energy simulation of residential and small commercial buildings. Energy and Buildings, 183, 467-483.

[15] Trčka, M., & Hensen, J. L. (2010). Overview of HVAC system simulation. Automation in construction, 19(2), 93-99.

[16] Pérez-Lombard, L., Ortiz, J., Coronel, J. F., & Maestre, I. R. (2011). A review of HVAC systems requirements in building energy regulations. Energy and buildings, 43(2-3), 255-268.

[17] Jazizadeh, F., Joshi, V., & Battaglia, F. (2020). Adaptive and distributed operation of HVAC systems: Energy and comfort implications of active diffusers as new adaptation capacities. Building and Environment, 186, 107089.

[18] Shin, M., & Haberl, J. S. (2019). Thermal zoning for building HVAC design and energy simulation: A literature review. Energy and Buildings, 203, 109429.

[19] Pourhosseini, O. (2016). Availability based maintenance scheduling in Domestic Hot water of HVAC system (Doctoral dissertation, Concordia University).

[20] Belhadj, C. A., Hamanah, W. M., & Kassas, M. (2017, June). LabVIEW based real time Monitoring of HVAC System for Residential Load. In 2017 IEEE International Conference on Computational Intelligence and Virtual Environments for Measurement Systems and Applications (CIVEMSA) (pp. 66-71). IEEE.

[21] Ankitkumar Tejani, 2021. "*Assessing the Efficiency of Heat Pumps in Cold Climates: A Study Focused on Performance Metrics*", ESP Journal of Engineering & Technology Advancements 1(1): 47-56. [Link]

[22] Ankitkumar Tejani, 2021. "*Integrating Energy-Efficient HVAC Systems into Historical Buildings: Challenges and Solutions for Balancing Preservation and Modernization*", ESP Journal of Engineering & Technology Advancements 1(1): 83-97. [Link]

[23] Ankitkumar Tejani, Jyoti Yadav, Vinay Toshniwal, Rashi Kandelwal, 2021. "*Detailed Cost-Benefit Analysis of Geothermal HVAC Systems for Residential Applications: Assessing Economic and Performance Factors*", ESP Journal of Engineering & Technology Advancements, 1(2): 101-115. [Link]

[24] Ankitkumar Tejani, Jyoti Yadav, Vinay Toshniwal, Harsha Gajjar, 2022. "*Achieving Net-Zero Energy Buildings: The Strategic Role of HVAC Systems in Design and Implementation*", ESP Journal of Engineering & Technology Advancements, 2(1): 39-55. [Link]

[25] Ankitkumar Tejani, Harsh Gajjar, Vinay Toshniwal, Rashi Kandelwal, 2022. "The Impact of Low-GWP Refrigerants on Environmental Sustainability: An Examination of Recent Advances in Refrigeration Systems" ESP Journal of Engineering & Technology Advancements 2(2): 62-77. [Link]

[26] Ankitkumar Tejani, Jyoti Yadav, Vinay Toshniwal, Harsha Gajjar, 2022. "*Natural Refrigerants in the Future of Refrigeration: Strategies for Eco-Friendly Cooling Transitions*", ESP Journal of Engineering & Technology Advancements, 2(1): 80-91. [Link]

[27] Ankitkumar Tejani, Vinoy Toshniwal, 2023. "Enhancing Urban Sustainability: Effective Strategies for Combining Renewable Energy with HVAC Systems" ESP International Journal of Advancements in Science & Technology (ESP-IJAST) Volume 1, Issue 1: 47-60. [Link]

[28] Ankitkumar Tejani, Rashi Khandelwal, 2023. "Enhancing Indoor Air Quality through Innovative Ventilation Designs: A Study of Contemporary HVAC Solutions" ESP International Journal of Advancements in Science & Technology (ESP-IJAST) Volume 1, Issue 2: 35-48. [Link]