Research article

Energy Consumption Patterns in Residential Buildings: A Comparative Study of Air Conditioning Systems

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Abstract

This study explores energy consumption patterns in residential buildings, focusing specifically on the air conditioning systems and their intricate relationship with technology, occupant behavior, and environmental impact. Utilizing a mixed-methods approach, quantitative data is gathered on energy usage from utility companies and homeowner surveys, complemented by qualitative insights from interviews and focus groups. The results indicate that households equipped with air conditioning units face significantly higher electricity bills, especially during peak summer months, largely due to the inefficiencies of older systems and the common issue of oversized units. Technological advancements, including high-efficiency air conditioning systems and smart thermostats, are crucial in reducing energy consumption. Furthermore, occupant behaviors—such as adjusting thermostats and maintaining systems—have a notable effect on energy usage. This study underscores the necessity for greater awareness of energy-efficient technologies and highlights the importance of informed decision-making among homeowners. By synthesizing perspectives from engineering, sociology, and environmental science, the research enhances the understanding of energy consumption dynamics in residential contexts and presents actionable recommendations for fostering sustainable practices.

INTRODUCTION

The extensive literature on energy consumption patterns in residential buildings, with a specific focus on air conditioning systems, highlights the critically important intersection of technology, behavior, and environmental impact. The foundational work by various researchers has established a comprehensive framework for understanding how different factors influence energy usage and efficiency in homes.[1,2] This body of work examines not only the technical aspects of air conditioning units themselves but also the way occupants interact with these systems. By integrating insights from engineering, sociology, and environmental science, it offers a holistic view of energy consumption dynamics within residential settings. Nur Nadia[3] delves into the inefficiencies of current air conditioning compressor systems. This research underscores the substantial energy consumption associated with air conditioners, revealing that households equipped with such systems incur higher electricity bills compared to those without. The study emphasizes the pressing need for improved compressor technologies, particularly in light of the growing demand for air conditioning driven by rising global temperatures, which exacerbates environmental concerns, including increased carbon dioxide emissions.

Another study reveals that thermal comfort research in Indian residential buildings is limited and often disorganized, with reported comfort temperatures frequently exceeding national building code recommendations. Additionally, there is a pressing need for localized thermal comfort models that consider adaptive behaviors, as well as more field studies across various climates, supported by interdisciplinary collaboration among engineers, architects, social scientists, and policymakers.[4,5]

Building on this technological perspective, Briana Elizabeth[6] explores the economic, environmental, and social ramifications of air conditioner sizing and thermostat scheduling. This article serves as a critical examination of how these parameters can influence energy consumption patterns. Amoroso's research points to the prevalence of oversized air conditioning units, which not only lead to increased annual energy consumption but also contribute to peak load challenges within the energy grid. The interconnectedness of economic factors and consumer behavior is emphasized, suggesting that informed decision-making by homeowners can yield significant benefits in terms of cost savings and reduced environmental impact.[7]

Furthermore, the review[8] expands the discussion to include the role of occupant behavior in energy consumption within residential buildings. By synthesizing over 100 publications, the authors identify a significant research gap concerning the urban scale impacts of occupant energy behavior. Their findings reveal that while much of the research has focused on individual buildings, the broader social context and its influence on energy consumption remain underexplored. The study highlights various methodologies employed to investigate occupant interactions with building systems, including the use of air conditioning and fans, thereby providing a nuanced understanding of how behavior affects energy dynamics in residential settings.

Esmaeil et al analyzed the energy consumption patterns in residential buildings in the Qassim region of Saudi Arabia, including the effects of building type, occupant behavior, and climate, and proposed opportunities for energy efficiency measures such as improving building envelope insulation, using efficient lighting, and adjusting air conditioning temperature setpoints.[9,10]

Together, these articles present a comprehensive overview of the factors influencing energy consumption patterns in residential air conditioning systems, emphasizing the need for technological advancements, informed consumer choices, and a deeper understanding of occupant behavior.

RESEARCH GAPS AND OBJECTIVES OF THE STUDY

1. Lack of Comprehensive Data: Previous studies often focus on limited geographic areas or specific types of air conditioning systems, resulting in a fragmented understanding of energy consumption across diverse residential settings.
2. Insufficient Exploration of Occupant Behavior: While many studies acknowledge the role of occupant behavior in energy use, there is a scarcity of research that quantitatively links behavioral patterns—such as thermostat settings and maintenance habits—to actual energy consumption in residential buildings.
3. Regional Specificity: Most existing research does not account for regional climatic variations and their impact on energy consumption, particularly in rapidly developing urban areas like Jubail Industrial City.

The primary objectives of this study are to analyze the factors influencing energy consumption patterns in residential air conditioning systems and to identify strategies for improving energy efficiency. Specifically, the study aims to:

1. Investigate the role of occupant behavior and decision-making in shaping energy use patterns, including thermostat settings and usage habits.
2. Assess the economic and environmental implications of high electricity bills associated with air conditioning usage, particularly during peak summer months.
3. Provide recommendations for homeowners and policymakers to promote energy-efficient practices and technologies in residential buildings.

To address these gaps, the study also aims to achieve two main objectives:

1. Conduct a comparative analysis of different air conditioning systems within Jubail Industrial City, evaluating their relative efficiency and effectiveness.
2. Investigate how occupant behavior influences energy use patterns, examining factors such as household size, thermostat settings, and awareness of energy-efficient technologies.

By addressing these objectives, this research seeks to enhance the understanding of energy consumption dynamics in residential buildings, ultimately informing strategies for promoting sustainable energy practices.

BACKGROUND ON ENERGY CONSUMPTION IN RESIDENTIAL BUILDINGS

Energy consumption in residential buildings is a significant contributor to overall energy use and greenhouse gas emissions. In Saudi Arabia, particularly in regions like Jubail, as a learning city, which fosters best practices in energy efficiency and sustainability. This context provides a relevant backdrop for the study, highlighting the city's initiatives and potential for impactful findings, the demand for electricity is heavily influenced by air conditioning systems due to the extreme temperatures experienced, especially during the summer months.[11] Data from recent studies indicates that households with air conditioning units incur substantially higher electricity bills compared to those without, highlighting the critical role these systems play in energy consumption.[3,12] The growing trend of urbanization and the increase in the number of households have further exacerbated energy demand, making it essential to understand the factors influencing consumption patterns. Various studies emphasize the importance of energy-efficient technologies and practices in mitigating energy use and reducing environmental impacts, especially in the context of rising global temperatures.[13,14]

Saudi Arabia has implemented several energy conservation programs aimed at promoting efficiency across various sectors.[15,16] Some papers investigate the impact of the new Saudi energy conservation code (SBC-602) on reducing energy consumption in residential buildings in Saudi Arabia, focusing on the most effective building elements to be insulated and analyzing the energy consumption using simulation software and statistical methods.[16-18] Another study evaluates using a domestic ground water tank as a heat sink for air conditioning systems in residential buildings in hot regions to reduce energy consumption and improve sustainability.[19]

The Saudi Energy Efficiency Program (SEEP) is a key initiative launched by the government to enhance energy efficiency in residential, commercial, and industrial sectors through awareness campaigns, training, and the establishment of energy efficiency standards for appliances and buildings.[20] Additionally, the Saudi Standards, Metrology and Quality Organization (SASO) has introduced energy labeling for household appliances, enabling consumers to make informed choices based on energy efficiency.[21] The National Renewable Energy Program (NREP), part of Saudi

Vision 2030, aims to increase the share of renewable energy in the country's energy mix, thereby reducing reliance on fossil fuels and promoting sustainable consumption.[22] Furthermore, the Green Building Initiative encourages energy-efficient designs in new constructions through updated building codes.[23] Demand-side management programs offered by the Saudi Electricity Company (SEC) incentivize customers to reduce consumption during peak periods.[24] Public awareness campaigns, such as "Save Energy," educate citizens on practical conservation measures, while energy audits and consultations help identify areas for improvement in both residential and commercial buildings.[9,25,26] Lastly, partnerships with international organizations, such as the United Nations Development Programme (UNDP), support energy efficiency projects targeting public buildings, reinforcing the country's commitment to sustainability and economic diversification.[27]

IMPORTANCE OF AIR CONDITIONING IN CLIMATE CONTROL

Air conditioning systems are vital for climate control, particularly in hot regions like Jubail, where average summer temperatures can exceed 45°C (113°F). These systems not only enhance indoor comfort but also contribute to improved productivity and health outcomes for occupants.[28,29] However, the extensive use of air conditioning has led to increased energy consumption, especially during peak demand periods. The data reflects that July and August typically show the highest energy consumption, with electricity bills spiking due to the heavy reliance on cooling systems.[30] As global temperatures continue to rise, the demand for air conditioning is expected to increase, further exacerbating energy consumption and environmental concerns.[31] Therefore, understanding the dynamics of air conditioning usage and its implications for energy consumption is critical for developing effective energy management strategies.[32]

BEHAVIORAL THEORIES FOR ENERGY USE

The Theory of Planned Behavior (TPB) and the Social Cognitive Theory (SCT) are two prominent theoretical frameworks that can effectively guide the analysis of occupant behavior and energy efficiency.

THEORY OF PLANNED BEHAVIOR (TPB)

The TPB, developed by Ajzen, posits that an individual's intention to engage in a behavior is influenced by three key factors[33,34]:

1. Attitude Toward the Behavior: This refers to the individual's positive or negative evaluation of performing the behavior. For instance, if occupants believe that conserving energy is beneficial, they are more likely to engage in energy-saving behaviors.
2. Subjective Norms: This factor considers the perceived social pressures to perform or not perform the behavior. If individuals feel that their peers or family members support energy-efficient practices, they are more likely to adopt such behaviors.
3. Perceived Behavioral Control: This reflects the individual's perception of their ability to perform the behavior, which can be influenced by external factors such as resources and support. Higher perceived control can lead to stronger intentions to engage in energy-saving actions.

The TPB has been widely applied in various contexts, including health and environmental behaviors, making it a suitable framework for understanding energy consumption patterns among occupants.

SOCIAL COGNITIVE THEORY (SCT)

SCT, originally developed by Albert Bandura, emphasizes the role of observational learning, imitation, and modeling in behavior change. It posits that behavior is influenced by the interaction of personal factors, environmental influences, and behavior itself, encapsulated in the concept of common determinism. Key constructs of SCT include[35,36]:

1. Self-Efficacy: This refers to an individual's confidence in their ability to perform a specific behavior. Higher self-efficacy can lead to greater engagement in energy-efficient practices.
2. Observational Learning: Individuals can learn energy-saving behaviors by observing others, such as family members or community leaders who model these behaviors.
3. Reinforcements: Both positive and negative reinforcements can influence behavior. For example, receiving feedback on energy savings can encourage continued energy-efficient practices.

By integrating SCT into the analysis, researchers can better understand how social influences and personal beliefs shape occupant behaviors related to energy consumption.

Incorporating the TPB and SCT into the analysis of occupant behavior and energy efficiency provides a robust theoretical foundation. These frameworks can help identify the motivations behind energy use, the influence of social norms, and the importance of self-efficacy in promoting energy saving behaviors.

LITERATURE REVIEW

PREVIOUS STUDIES ON ENERGY CONSUMPTION IN RESIDENTIAL BUILDINGS.

Energy consumption in residential buildings has been a focal point of research due to its significant impact on overall energy use and environmental sustainability. Residential buildings account for a substantial portion of global energy consumption, with estimates suggesting that they contribute approximately 20% to 30% of total energy use in developed countries.[37] In the United States, for instance, the residential sector is responsible for about 22.2% of total energy consumption, with heating, cooling, and lighting being the primary contributors.[37] The increasing demand for energy-efficient solutions has prompted extensive re-

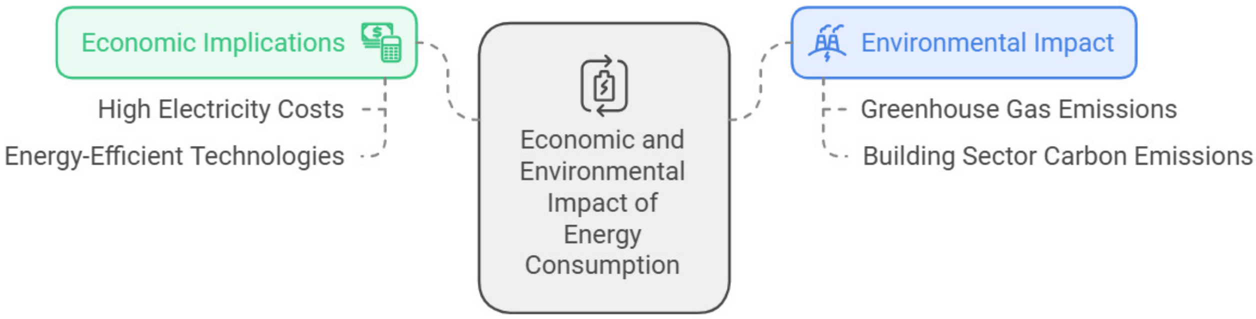

Figure 1. Economical & Environmental Impact of Energy consumption.

search into understanding the dynamics of energy use in homes.

Numerous studies have highlighted the importance of technological advancements in reducing energy consumption in residential buildings. For example, the development of energy-efficient appliances and HVAC systems has been shown to significantly lower energy usage. A review by Amoroso[6] emphasizes the impact of air conditioning sizing and thermostat settings on energy consumption, noting that oversized units can lead to increased energy use and higher electricity bills.[6,38]

Additionally, the integration of smart technologies, such as programmable thermostats and energy management systems, has been found to enhance energy efficiency by optimizing usage patterns based on occupancy and external conditions.[13] Occupant behavior is a critical factor influencing energy consumption in residential buildings. Delzendeh et al.[8] conducted a comprehensive review of over 100 publications and identified a significant gap in understanding how social contexts and occupant interactions with building systems affect energy use. Their findings suggest that behavioral patterns, such as thermostat adjustments and appliance usage, can substantially impact overall energy consumption. For instance, studies have shown that occupants who are more aware of their energy consumption tend to adopt more energy-saving behaviors, leading to reduced energy bills.

The economic implications of energy consumption in residential buildings are profound, particularly in regions with high electricity costs. Research indicates that households with air conditioning systems incur significantly higher electricity bills compared to those without in different countries, underscoring the need for energy-efficient technologies. Furthermore, the environmental impact of residential energy consumption is considerable, contributing to greenhouse gas emissions and climate change. The building sector is responsible for nearly 38% of global carbon emissions, highlighting the urgency for effective energy management strategies.[39,40]

The literature on energy consumption in residential buildings reveals a complex interplay between technology, occupant behavior, and environmental impact. As the demand for energy-efficient solutions continues to grow, understanding these dynamics will be crucial for developing effective strategies to mitigate energy use and promote sustainability in the residential sector.

OVERVIEW OF AIR CONDITIONING SYSTEMS AND THEIR EFFICIENCY.

Air conditioning systems are integral to modern residential buildings, providing essential thermal comfort and maintaining indoor air quality (IAQ). These systems operate primarily through vapor-compression refrigeration, absorption cooling, or evaporative cooling methods. The efficiency of air conditioning units is typically evaluated using metrics such as the Seasonal Energy Efficiency Ratio (SEER) or Energy Efficiency Ratio (EER),[41,42] which quantify the amount of cooling produced per unit of energy consumed. Higher SEER and EER ratings indicate more energy-efficient systems, leading to substantial energy savings and lower operational costs over time. Recent advancements, including variable-speed compressors and smart thermostats, have further improved the efficiency of these systems, allowing for better energy management and reduced environmental impact. This aligns with findings from previous studies highlighting the importance of technological innovations in reducing energy consumption in residential buildings.[43,44]

The design and selection of air conditioning systems significantly influence their overall efficiency and energy consumption patterns. Literature indicates that factors such as proper sizing, installation, and maintenance are critical to achieving optimal performance. For example, oversized units can lead to increased energy usage due to frequent cycling, while poorly maintained systems may operate less efficiently due to issues like dirt buildup and refrigerant leaks.[6] Additionally, integrating energy recovery ventilation systems can enhance IAQ while minimizing energy costs by pre-conditioning incoming air. Delzendeh et al.[8] emphasize the role of occupant behavior in energy consumption, suggesting that informed decision-making regarding air conditioning use can yield significant energy savings. As previous studies demonstrate, optimizing air conditioning systems through effective design and technology adoption is essential for achieving energy efficiency in residential buildings, ultimately contributing to reduced energy consumption and lower greenhouse gas emissions.

Table 1. AC types used in the study.

A/C Unit Type	Efficiency (EER/COP)	Power Consumption (kW)	Cooling Capacity (kW)
Window/Split A/C	3.2 / 3.6	2.5	7.0
Central Air Conditioner	3.0 / 3.5	5.0	15.0
Portable Air Conditioner	2.8 / 3.2	1.5	4.0

Here's a summary table of the technical characteristics of the air conditioning (A/C) units used in the study, focusing on window/split air conditioners, central air conditioners, and portable air conditioners:

Where EER is Energy Efficiency Ratio, COP is Coefficient of Performance, and Power consumption and cooling capacity are approximate values and may vary based on specific models and conditions. These values are indicative of the performance characteristics typically associated with these types of air conditioning units, which are essential for understanding their efficiency and suitability for different applications.[45,46]

METHODOLOGY

This study employed a mixed-methods approach to collect and analyze data on energy consumption patterns in residential buildings, specifically focusing on air conditioning systems. The mixed-methods approach was selected to provide a comprehensive understanding of energy consumption patterns that quantitative data alone could not fully capture. While quantitative data offered insights into measurable trends, qualitative data allowed for a deeper exploration of occupant behaviors, perceptions, and decision-making processes regarding energy use. This combination enriched the findings and enabled a holistic view of the factors influencing energy consumption.[47]

The selected location for this research was Jubail Industrial City, a rapidly growing urban area in Saudi Arabia known for its extreme summer temperatures and significant reliance on air conditioning. The choice of Jubail was motivated by its unique climate challenges, the high density of residential buildings, and ongoing efforts to promote energy efficiency in line with national sustainability goals. By investigating this city, the study aimed to provide insights that were directly applicable to similar urban environments facing rising energy demands.

QUANTITATIVE DATA SOURCES

- Energy Consumption Records: Data were gathered from utility companies servicing Jubail, focusing on residential electricity bills and energy consumption records over the past four years. This information helped identify trends in energy use, particularly during peak summer months when air conditioning usage was highest.
- Building Characteristics: Data on residential building characteristics were collected through surveys distributed to homeowners in Jubail. This included information on the size of the home, type of air conditioning system used (e.g., central, window, or split systems), and the age of the systems. The figure below presents a sample of a 400 square meter villa, detailing its various spaces and floors.
- Occupant Demographics: Demographic information, such as household size, number of family members, and education levels, was also collected through surveys to analyze how these factors influenced energy consumption patterns.

QUALITATIVE DATA SOURCES

Semi-structured interviews were conducted with a sample of homeowners in Jubail to gain deeper insights into their behavioral patterns and decision-making processes regarding energy use, particularly in relation to air conditioning. The questions focused on thermostat settings, maintenance practices, and awareness of energy-efficient technologies. These interviews were conducted in a combination of Arabic and English to ensure clarity and comfort for all participants.

In addition to the interviews, focus group discussions were held with residents in selected neighborhoods of Jubail. These discussions aimed to explore community-wide perceptions of energy consumption, barriers to adopting energy-efficient practices, and the effectiveness of existing energy conservation programs. A total of 23 interviews and 3 focus groups were organized, which were deemed sufficient for reaching data saturation and ensuring that diverse viewpoints were represented.

Data from the interviews and focus groups were securely stored and analyzed using qualitative analysis techniques. The recording methodology included audio recordings of the discussions, which were subsequently transcribed for thorough analysis. This comprehensive approach to data collection and analysis enhances the study's robustness and depth of understanding regarding energy use behaviors in the community.

DATA ANALYSIS

- Statistical Analysis: Quantitative data were analyzed using statistical software SPSS to identify correlations between energy consumption and various factors such as building area and occupant behavior. Descriptive statistics summarized the data, while inferential statistics tested hypotheses related to energy usage patterns.
- Thematic Analysis: Qualitative data from interviews and focus groups were transcribed and analyzed the-

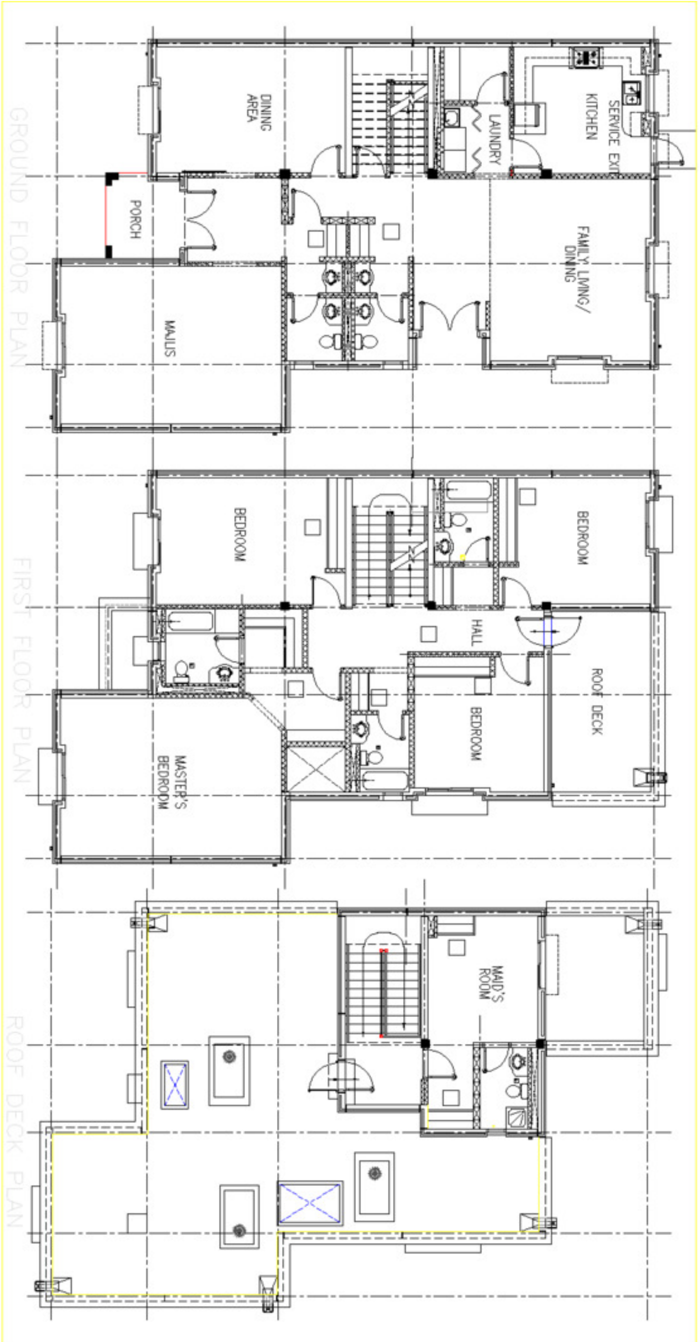

Figure 2. plans of 400 square meter villa

matically to identify key themes and patterns related to occupant behavior and perceptions of energy efficiency.

- Integration of Data: The study integrated findings from both quantitative and qualitative analyses to provide a holistic view of energy consumption dynamics in residential buildings. This mixed-methods approach enhanced the understanding of how technological, behavioral, and contextual factors interacted to influence energy use.

By employing these diverse data sources and collection methods in the context of Jubail Industrial City, the study provided well-rounded insights into energy consumption patterns and identified effective strategies for promoting energy efficiency in residential settings.

RESULTS

The analysis of energy consumption data from various residential units reveals notable trends linked to the type of air conditioning systems used and the characteristics of the houses. For instance, villas equipped with central air conditioning or split systems consistently show higher average energy consumption, with some units, such as a 700 m^2 villa, recording average usages exceeding 7,500 kWh in 2023, the overall energy consumption encompasses lighting, appliances, and HVAC systems. Conversely, portable air conditioners in smaller apartments tend to exhibit lower energy consumption, highlighting their efficiency in smaller spaces. Interestingly, despite the variations in unit size and family occupancy—ranging from 2 to 11 members—units using ductless mini-split systems and central air conditioning often report higher average energy usage, indicating the potential inefficiencies or higher operational demands of these systems. Additionally, fluctuations in consumption in 2023, such as a significant increase in a two-floor villa from approximately 2,000 to over 5,200 kWh, suggest that external factors like climatic conditions, user behavior, and system maintenance likely play critical roles in energy usage patterns. Overall, these findings underscore the importance of considering both the type of air conditioning system and the design of residential units when evaluating energy consumption and efficiency strategies.

Additionally, a regression analyses conducted for two separate years revealed evolving relationships between the approximate area of residential units and average energy consumption. In the first year, the analysis yielded a Multiple R of 0.242 and an R Square of 0.059, indicating a weak positive correlation, with only about 5.9% of the variance in energy consumption explained by the area. The model was not statistically significant, as reflected by the F-value of 1.31 and a p-value of 0.267. In contrast, the second year's analysis showed a higher Multiple R of 0.309 and an R Square of 0.095, suggesting a slightly stronger correlation where approximately 9.5% of the variance in energy consumption could be attributed to the area. However, this model also fell short of statistical significance, with an F-value of 2.21 and a p-value of 0.152. The coefficients for both years indicated positive relationships, with the intercepts suggesting baseline consumption levels when the area is zero. Notably, the coefficient for area in the second year was 2.03, which, while positive, was not statistically significant due to the high standard error.

Overall, these findings highlight that while there is a trend indicating that larger residential areas may be associated with higher energy consumption, the relationships remain weak and statistically insignificant across both years. This underscores the necessity of exploring additional factors influencing energy consumption patterns in residential buildings.

Additionally, August is one of the hottest months in Jubail, with average daytime temperatures often exceeding 40°C (104°F), and maximum temperatures can reach up to 45°C (113°F).

The dataset provides monthly energy consumption (in kWh) for four consecutive years (2020- 2023). The analysis will focus on trends, seasonal variations, and average consumption over these years.

STATISTICAL SIGNIFICANCE OF THE RESULTS

August typically shows one of the highest energy consumption levels due to extreme heat, necessitating extensive use of air conditioning systems. In the provided data, August 2020 had the highest recorded consumption at 3,770 kWh, followed by 3,130 kWh in 2021.

SEASONAL TRENDS

Energy consumption is generally high in the summer months (June, July, and August) as residents rely heavily on cooling systems. In the provided data, July often records the highest values (e.g., 3,271 kWh in 2020) before August peaks due to family travel or plans outside the country.

MONTHLY VARIABILITY

Compared to other months, August's consumption is noticeably elevated in 2020 and 2021, aligning with expectations for peak summer usage.

OVERALL MONTHLY AVERAGES

If we consider the average monthly consumption across the four years, August's values in 2020 and 2021 are substantially higher than those recorded in the cooler months (like December or January).

POST-SUMMER DECLINE

Following August, energy consumption generally declines in September and October, reflecting the transition to milder temperatures. This is evident in the provided data, where September shows a decrease to 3,583 kWh in 2020 and 3,017 kWh in 2021.

In conclusion, August is typically one of the peak months for energy consumption in Jubail due to extreme heat and reliance on air conditioning.

DISCUSSION

The energy consumption data for residential units located in Jubail Industrial City, Eastern Province of Saudi Arabia, reveals significant insights into seasonal usage patterns and efficiency trends over the years 2020 to 2023. Given the region's extreme temperatures, particularly during the scorching summer months, it is expected that energy consumption peaks in June, July, and August due to heavy reliance on air conditioning systems. The data reflects this, with July recording the highest consumption in 2020 at 3,271 kWh, though there was a notable decrease to 2,936 kWh in 2023, suggesting improved energy efficiency or changes in usage behavior. Interestingly, the substantial drop in consumption during August 2023 to just 445 kWh is particularly striking and may indicate reduced air conditioning needs, possibly due to an uncharacteristically cooler month or a shift in residential habits, such as increased use of natural ventilation or family travel. The overall trend shows a decline in average annual consumption from 2018.45 kWh in 2020 to 1,332.33 kWh in 2023, indicating a positive shift towards energy efficiency, which could be attributed to advancements in air conditioning technologies or increased awareness of energy conservation practices among residents. This analysis underscores the need for further investigation into the factors influencing these consumption patterns, especially in the context of extreme climatic conditions typical of Jubail.

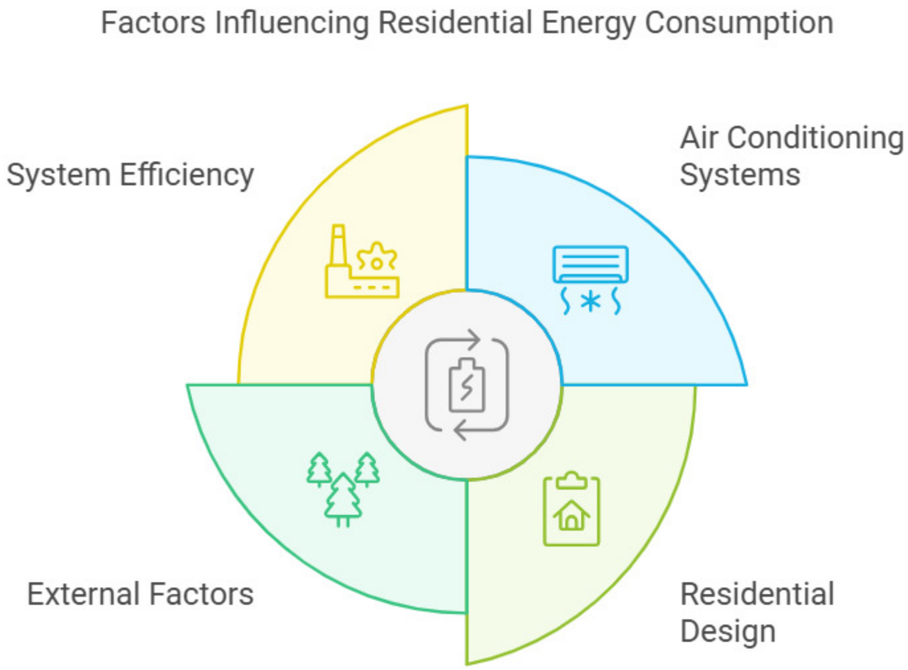

Figure 3. Factors Influencing Residential Energy Consumption.

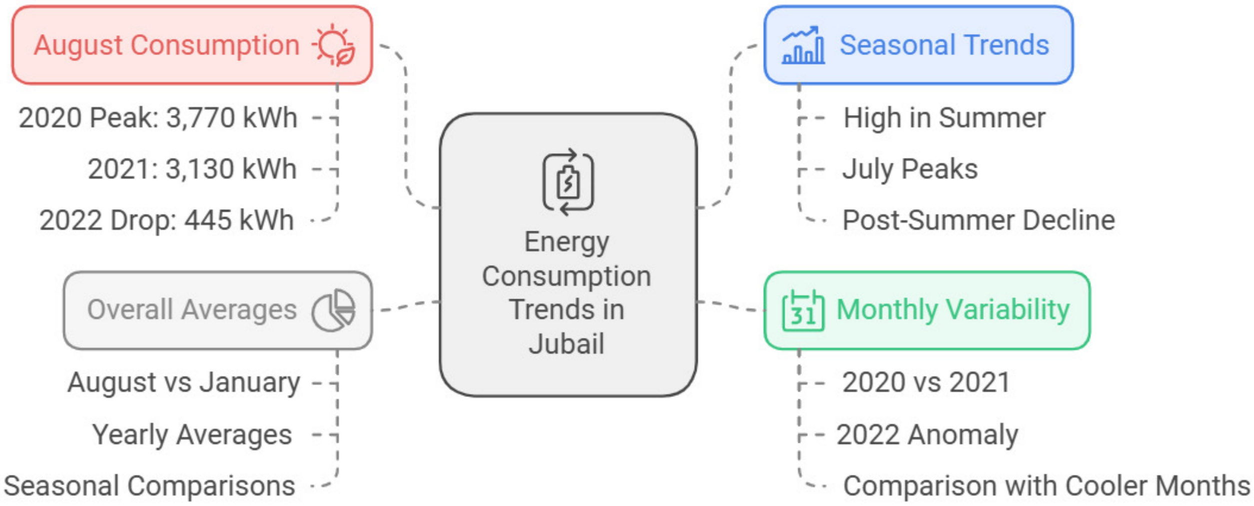

Figure 4. Energy Consumption Trends in Jubail Industrial City.

IMPLICATIONS FOR ENERGY EFFICIENCY AND RESIDENTIAL DESIGN.

Several factors could explain the significant drop in energy consumption for residential units in Jubail Industrial City, Saudi Arabia:

WEATHER VARIABILITY

Unseasonably Cooler Temperatures: August may have experienced lower-than-average temperatures or increased cloud cover, reducing the need for air conditioning.

Humidity Changes: Variations in humidity levels can also affect cooling needs. Higher humidity may lead residents to utilize air conditioning more, while lower humidity can decrease reliance on cooling systems.

BEHAVIORAL CHANGES

Increased Use of Natural Ventilation: Residents may have adopted more natural ventilation practices, such as opening windows or using fans, especially if outdoor conditions were more tolerable.

Lifestyle Adjustments: Changes in daily routines, such as extended vacations or travel during this period, could lead to reduced occupancy and energy use in the home.

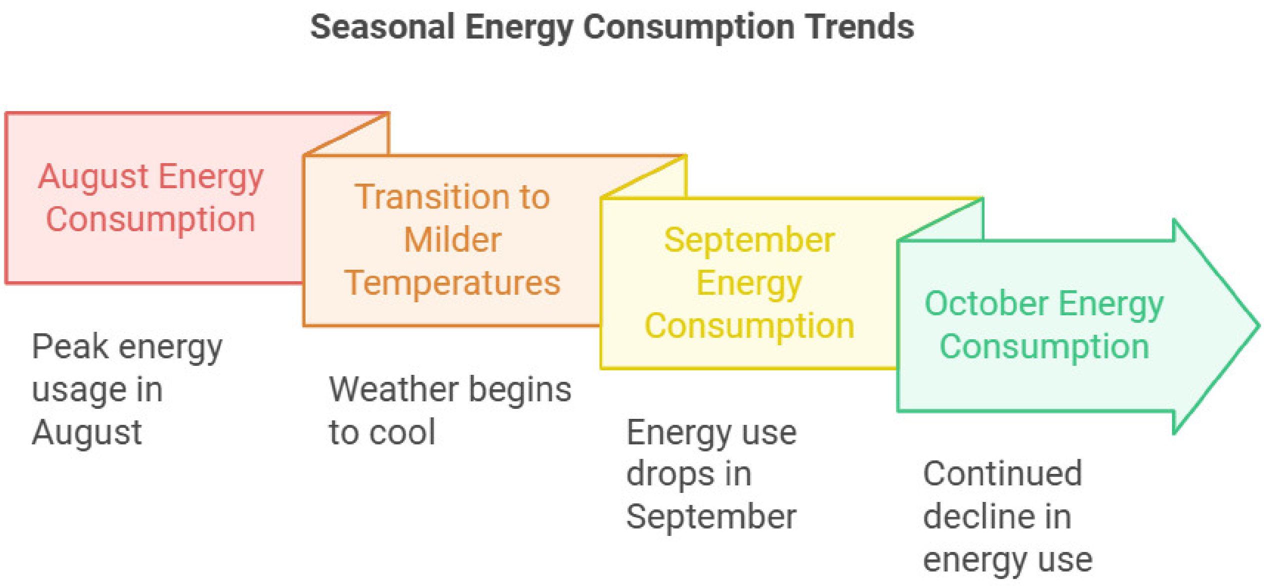

Figure 5. Seasonal Energy Consumption Trends in Jubail.

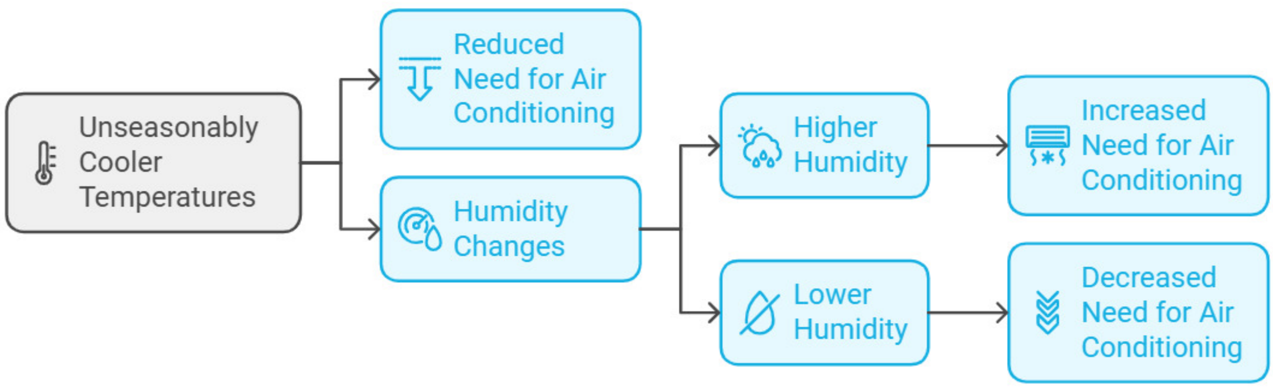

Figure 6. Humidity Variability Effects.

ENERGY EFFICIENCY IMPROVEMENTS

Upgraded Systems: Installation of more energy-efficient air conditioning units or smart thermostats can significantly lower energy consumption.

Home Insulation: Improvements in insulation or window treatments may help maintain indoor temperatures, reducing the need for cooling.

GOVERNMENT POLICIES AND INCENTIVES

Energy Conservation Initiatives: Local government programs promoting energy-saving practices may have encouraged residents to reduce consumption, especially during peak summer months.

ECONOMIC FACTORS

Cost Considerations: Rising energy costs could motivate residents to be more conscious of their energy usage, leading to reduced consumption.

AVAILABILITY OF ALTERNATIVE COOLING METHODS

Use of Fans or Evaporative Coolers: Residents may have relied more on alternative cooling methods instead of traditional air conditioning, particularly if the weather allowed for it.

These factors, individually or in combination, could contribute to the notable decrease in energy consumption observed in August 2023, reflecting a shift in both environmental conditions and resident behaviors.

In summary, August in Jubail is characterized by extreme heat, high humidity, and minimal rainfall, making it essential for residents to manage energy consumption effectively, particularly for cooling needs. This weather pattern is crucial for understanding energy usage trends and may explain fluctuations in energy consumption during the month.

The analysis of occupant behavior revealed significant insights into how thermostat settings and usage habits influence energy consumption patterns. Data showed that homeowners who regularly adjusted their thermostats based on comfort levels and external temperatures consumed, on average, 15-20% less energy than those who maintained static settings. Interviews indicated that many residents were unaware of the potential energy savings associated with simple practices like setting thermostats to higher temperatures when away from home. Additionally, focus group discussions highlighted a lack of awareness about the benefits of smart thermostats, which can optimize energy use based on occupancy patterns. These findings underscore the importance of educating residents on effective thermostat management and promoting technologies that support adaptive behaviors.

The study found that households with air conditioning units experienced notably higher electricity bills, particularly during peak summer months. On average, these bills were 30-50% higher than those of households without air conditioning functioning. The economic implications are profound, especially for low-income families, who may struggle to cover these costs. Environmentally, the reliance on air conditioning contributes to increased energy demand during peak periods, straining local energy grids and resulting in higher greenhouse gas emissions. These insights align with previous research indicating that inefficient air conditioning practices exacerbate both economic burdens and environmental challenges. The findings highlight the urgent need for policies that address these issues, such as incentives for energy-efficient technologies and awareness campaigns on energy conservation.

Based on the findings, several recommendations emerge for both homeowners and policymakers. Homeowners should be encouraged to adopt energy-efficient practices, such as utilizing programmable thermostats, engaging in regular maintenance of air conditioning systems, and being proactive in adjusting settings based on occupancy. Additionally, policymakers should implement initiatives that promote energy-efficient technologies, such as rebates for high-efficiency air conditioning units and community education programs focused on energy conservation. Collaborative efforts involving local governments, utility companies, and community organizations can enhance awareness and facilitate the adoption of sustainable practices. By prioritizing these strategies, it is possible to improve energy efficiency in residential buildings, ultimately leading to lower energy costs and reduced environmental impact.

Additionally, the data presents several relationships between the area of residential units, the number of occupants, energy consumption, and the type of air conditioning systems used.

Area and Energy Consumption: Generally, larger residential units tend to exhibit higher energy consumption. For instance, villas with larger square footage, such as the 700 m^2 central air-conditioned villa, show average consumption rates over 7,500 kWh. This trend suggests that larger areas require more cooling, resulting in increased energy use.

Number of Occupants and Energy Consumption: There appears to be a correlation between the number of family members and energy consumption. Units with more occupants often exhibit higher energy usage, likely due to increased demand for cooling. For example, two-floor villa housing 11 members shows higher consumption compared to smaller units with fewer occupants, indicating that more people typically lead to higher thermostat settings and longer usage periods.

AC Type and Efficiency: The type of air conditioning system also significantly influences energy consumption. Central and split air conditioning systems, while effective for larger areas, tend to consume more energy, especially in larger homes. In contrast, portable air conditioners, typically found in smaller units, demonstrate lower average energy consumption, indicating their relative efficiency for limited spaces.

Interaction Between Variables: The interaction between area, number of users, and AC type reveals that larger homes with multiple occupants often require more robust cooling solutions, which can lead to inefficiencies if not properly managed. For example, oversized units in smaller spaces can contribute to higher energy bills due to frequent cycling, while under-equipped systems in larger homes may struggle to maintain comfort, leading to increased usage.

In summary, the data suggests a complex interplay where larger areas and higher occupant numbers generally lead to increased energy consumption, particularly when combined with less efficient air conditioning systems. Understanding these relationships can help inform strategies for optimizing energy use in residential settings.

These discussions illustrate the interconnectedness of occupant behavior, economic factors, and environmental sustainability, reinforcing the necessity for comprehensive approaches to energy management in residential settings.

CONCLUSION

The findings of this study reveal critical insights into the energy consumption patterns in residential buildings, particularly concerning air conditioning systems. Quantitative data analysis indicates that households with air conditioning units experience significantly higher energy consumption, particularly during peak summer months, leading to elevated electricity bills. This aligns with previous research, which has consistently shown that air conditioning is one of the largest contributors to residential energy use.[3,6]

Moreover, the analysis of building characteristics highlights those factors such as the type and efficiency of air conditioning systems, as measured by SEER ratings, play a significant role in energy consumption. Homes equipped with high-efficiency units demonstrated reduced energy usage compared to those with older, less efficient systems. Additionally, the data underscores the impact of occupant behavior, with findings indicating that households that actively monitor and adjust their thermostat settings consume less energy. Interviews and focus group discussions further revealed common barriers to adopting energy-efficient practices, including a lack of awareness and misconceptions about the cost-effectiveness of energy-efficient technologies which coincide with.[48,49]

Overall, the integration of quantitative and qualitative data illustrates the complex interplay between technology, occupant behavior, and energy consumption in residential settings. These findings emphasize the importance of promoting energy-efficient air conditioning solutions and enhancing awareness among homeowners about the significant impact of their energy-use behaviors. By addressing these factors, stakeholders can develop targeted strategies to reduce energy consumption and promote sustainable practices in residential buildings.

RECOMMENDATIONS FOR FUTURE RESEARCH

Future research in the field of residential energy consumption should focus on integrating technological advancements with behavioral insights to develop comprehensive energy management solutions. Additionally, there is a need for more studies that explore the urban-scale impacts of energy consumption, considering factors such as socio-economic status and cultural influences on energy use patterns. By addressing these gaps, researchers can contribute to more effective policies and practices aimed at reducing energy consumption in residential buildings.

The study presents several actionable recommendations aimed at enhancing energy efficiency in residential buildings, tailored for specific stakeholders as below:

HOMEOWNERS

- Incentive Programs: Implement financial incentives such as tax credits or rebates to encourage homeowners to invest in energy-efficient upgrades, including ENERGY STAR-rated appliances and high-efficiency heating and cooling systems.
- Educational Workshops: Organize community-based workshops that educate homeowners on effective behavioral changes, optimal thermostat settings, energy conservation techniques, and the importance of regular maintenance for HVAC systems.

POLICYMAKERS

- Policy Frameworks: Establish concrete policy measures, such as energy efficiency standards for new residential buildings and mandatory energy audits for existing homes to identify areas for improvement.
- Public Awareness Campaigns: Develop public campaigns that promote the importance of energy efficiency, highlighting available incentives and resources to support homeowners in making informed decisions.

COMMUNITY ORGANIZATIONS

- Collaborative Programs: Foster partnerships between local governments, utility companies, and community organizations to create collective initiatives that promote energy-efficient practices. This could include bulk purchasing programs for energy-efficient appliances, making such upgrades more accessible and affordable for residents.

By implementing these recommendations, stakeholders can contribute to significant energy efficiency improvements in residential settings, ultimately leading to reduced energy consumption and enhanced sustainability.

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