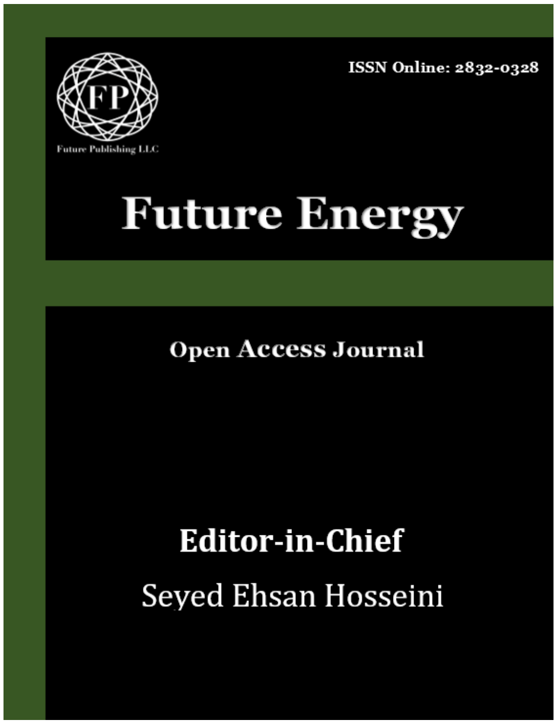
Journal Pre-proof

Evaluating zero-energy strategies in mixed-use buildings: a case study

Mahmood Abdoos, Mohammad Mahdi Mobaraki, Hossein Yousefi, Younes Noroollahi

DOI: https://doi.org/10.55670/fpll.fuen.4.1.2



ISSN Online: 2832-0328

Future Publishing LLC

Future Energy

Open Access Journal

Editor-in-Chief

Seyed Ehsan Hosseini

To appear in: Future Energy

Received date: 19 October 2024

Revised date: 24 November 2024

Accepted date: 04 December 2024

Please cite this article as:

Mahmood Abdoos, Mohammad Mahdi Mobaraki, Hossein Yousefi, Younes Noroollahi, “Evaluating zero-energy strategies in mixed-use buildings: a case study”, Future Energy 4(1), 8-18. DOI: https://doi.org/10.55670/fpll.fuen.4.1.2

Future Energy
Open Access Journal
ISSN 2832-0328

February 2024| Volume 04 | Issue 01 | Pages 08-18

Journal homepage: https://fupubco.com/fuen

https://doi.org/10.55670/fpll.fuen.4.1.2

Future Publishing LLC

Article

Evaluating zero-energy strategies in mixed-use buildings: a case study

Mahmood Abdoos, Mohammad Mahdi Mobaraki, Hossein Yousefi*, Younes Noroollahi

School of Energy Engineering and Sustainable Resources, College of Interdisciplinary Science and Technology, University of Tehran, Tehran, Iran

ARTICLE INFO

Article history:
Received 19 October 2024
Received in revised form
24 November 2024
Accepted 04 December 2024

Keywords:
Zero energy building, Mixed-use development, Energy efficiency, Thermal insulation, Sustainable design, HVAC systems

*Corresponding author
Email address:
hosseinyousefi@ut.ac.ir

DOI: 10.55670/fpll.fuen.4.1.2

ABSTRACT

The building sector is responsible for over 40% of global energy consumption, necessitating innovative strategies to minimize energy usage in both commercial and residential buildings, ultimately striving for zero-energy status. This study addresses the relatively overlooked area of zero-energy buildings within the context of a combined commercial-residential structure, utilizing Carrier (HAP) software for precise thermal and cooling load calculations. The research introduces a multifaceted approach, examining various scenarios that influence energy demand reduction, including wall color modifications, the application of noble gases for window insulation, shading effects, and technical innovations in window dimensions. Notably, this study emphasizes insulation as a cost-effective strategy for achieving zero-energy objectives, revealing that the optimal scenario incorporating krypton insulation, color adjustments, and effective shading achieves a significant 21.36% reduction in energy consumption. This research not only contributes novel insights into mixed-use building design but also provides a practical framework for future energy-efficient building projects.

1. Introduction

In numerous countries across the globe, residential buildings account for approximately 40% of the energy demand in residential areas, with an impressive 60% of the total energy consumption specifically allocated towards maintaining optimal heating conditions within living spaces [1, 2]. Moreover, it is worth noting that a predominant portion of this energy is consumed by air conditioning systems [3]. However, implementing thermal insulating materials in buildings yields a substantial reduction in energy load. Furthermore, there has been a notable surge in the adoption of innovative technologies within the realm of building construction in recent years. This technical advancement has consistently resulted in improved building management practices and has paved the way for the successful administration of building systems [4]. Implementing fundamental measures to conserve energy can result in a significant economic boost for the country. Within this arena, design and construction play crucial roles, as energy consumption can be substantially reduced by applying innovative design and construction techniques [5]. The global concerns of energy scarcity and environmental pollution invoke apprehension, and it is widely acknowledged that curtailing energy demand in buildings presents an efficacious solution to address this pressing issue [6, 7]. Researchers worldwide exhibit unwavering dedication in their endeavors to optimize the design and functionality of both buildings and energy systems [8-10]. Accurate thermal-cooling load assessments are fundamental for designing efficient HVAC systems. Studies utilizing advanced software tools have demonstrated that proper load analysis can lead to reductions in energy consumption by up to 20% in office buildings, emphasizing the importance of integrating technology into building design processes [11, 12]. Ramesh, G et al. [13] assert that buildings contribute to approximately thirty-eight percent of greenhouse gas emissions, with twenty percent attributed to residential buildings and eighteen percent to commercial structures, thereby placing them as significant contributors to global warming [14]. Implementing effective insulation strategies is crucial for reducing energy consumption in buildings. A study assessing various insulation scenarios found that buildings could achieve up to 30% reduction in heating and cooling loads when combined with renewable energy systems (e.g., solar photovoltaic panels). This synergy is vital for reaching net-zero targets, as highlighted in multiple building performance analyses [15, 16]. Consequently, research conducted by Felimban et al. [17] and colleagues posits that the demand for electricity in the residential sector of Saudi Arabia is projected to double by 2025, in comparison to the statistics recorded in 2009. In their research, Boemi et al. [18] contend that a pivotal advancement lies in the realm of sustainable design for residential and commercial buildings, coupled with the resilience of existing structures, all geared towards achieving reduced and optimized energy consumption. As elucidated by Baetens. in their research, harnessing renewable energy sources to meet the energy demands of buildings constitutes a noteworthy means of curbing energy consumption [19, 20]. Integrating solar panels in commercial properties has emerged as a transformative approach to achieving energy efficiency. A report noted that less than 3% of commercial buildings currently utilize solar panels; however, with over 8 billion square meters of suitable rooftops in the U.S., there is potential to generate approximately 1,400 terawatt-hours of electricity annually, nearly 40% of total utility sales. This transition from cost centers to profit centers underscores the financial viability of solar investments in commercial real estate [21, 22]. A comprehensive bibliometric analysis of renewable energy integration in zero-energy carbon buildings reveals critical gaps in research methodologies and implementation strategies. Machine learning techniques are increasingly being applied to forecast energy needs and optimize the integration of renewable technologies, which is essential for enhancing building performance and achieving sustainability goals [23]. Expounding on building energy modeling, Robertson J. J. and colleagues propose various approaches to enhance energy efficiency, including the optimization of passive resilience [24], refinement of building position geometry [25], optimization of cooling tower exergy [26], and optimization of control systems for variable refrigerant flow [27].

Using phase change materials has been shown to significantly enhance thermal comfort while reducing energy demands. Research indicates that buildings employing PCM can reduce cooling energy consumption by up to 25%, particularly in climates with high-temperature variability. This innovative approach allows buildings to maintain comfortable indoor conditions with minimal reliance on mechanical cooling systems [28, 29]. The innovation of this research is distinguished by its comprehensive analysis of a large-scale mixed-use building, integrating both commercial and residential elements to achieve zero-energy status. Unlike previous studies focusing on smaller, single-use structures, this research addresses the complexities associated with a 4072 square-meter facility, which presents unique thermal characteristics and energy management challenges. This study innovatively employs Carrier (HAP) software to model various scenarios that consider the impact of building colors, the use of noble gases like krypton for window insulation, and shading effects on energy consumption. By pioneering a comparative analysis between noble gases and traditional air insulation methods, this research provides valuable insights into enhancing energy efficiency in large buildings. Furthermore, it incorporates an economic perspective by evaluating cost-effective insulation strategies while ensuring that the commercial integrity of the building is maintained. It fills a critical gap in the literature regarding mixed-use developments and sets a precedent for future studies to optimize energy performance in large-scale buildings. The findings underscore the viability of achieving zero-energy status through innovative insulation techniques and strategic design modifications, reinforcing the importance of such approaches in sustainable urban development.

2. Mathematical expression

Building walls commonly comprise multiple layers composed of different materials, thereby transforming the wall into a composite structure. Consequently, the thermal resistance exhibited by a composite wall can be determined by summing the resistances of its constituent layers. The composite thermal resistance of the wall is expressed in equation (1):

$$\text{Thermal resistance composite wall: } \mathrm{R_1} + \mathrm{R_2} + \frac{\mathrm{X_1}}{\mathrm{K_1}} + \frac{\mathrm{X_2}}{\mathrm{K_2}} + \cdots \quad (1)$$

During the heat transfer process between the indoor and outdoor air of a building, a thin layer of air forms along the surface of the building wall, creating a thermal resistance that hinders the flow of heat. This layer, commonly referred to as the air film, exhibits a unit thermal coefficient denoted as F. The resistance of this air film, analogous to the resistance of the surrounding air, is represented by 1/f, where f is the value determined by the speed of the airflow.

$$\mathrm{U} = \frac{1}{\frac{1}{\mathrm{f_i}} + \mathrm{R_1} + \mathrm{R_2} + \cdots + \frac{1}{\mathrm{f_o}}} \quad (2)$$

U=The overall coefficient of thermal conductivity
$1/F_i$=Inner air film resistance
R_1, R_2=Thermal resistance of layers
$1/F_o$=Outdoor air film resistance

The calculation of heat transfer through various building components, including walls, ceilings, floors, windows, and glass, can be determined using the following equation (3):

$$Q = AU(t_1 - t_2) \quad (3)$$

Q=Heat transferred from the wall BTU/hr.
A=wall area ft^2
T_1=Temperature on the warmer side(F)
T_2=Temperature on the cooler side(F)

Every building has certain rooms or spaces that we intentionally do not desire to be heated or cooled to the same extent. If there exists an unheated room adjacent to the space where we are assessing the thermal load, and this adjacent room does not undergo cooling. The temperature of the adjacent uncooled room is expressed in equation (4):

$$\text{Adjacent uncooled room temperature} = \mathrm{t_i} + (\mathrm{t_o} - \mathrm{t_i}) * 0.667 \quad (4)$$

3. Methodology

3.1 Software

Hap software exemplifies the amalgamation of two formidable tools, offering a comprehensive package that encompasses the design of HVAC systems for commercial buildings, as well as robust energy analysis capabilities to ascertain energy consumption and operational costs for various design typologies. The fusion of these two tools yields substantial time savings, as input data and calculations from the System Design Calculation can seamlessly transition into energy studies, obviating the need for redundant input.

Furthermore, the carrier (HAP) hourly analysis software, an esteemed component of the Carrier (HAP) HVAC design software family, holds the distinction of being one of the oldest and most all-encompassing software solutions available for accurately computing the cold and heat load of buildings across diverse applications [30].

3.2 Case study

The average rainfall in Tehran varies from 230 mm to 500 mm annually. Tehran is one of the most climatic cities and four seasons in Iran. Precipitation is usually high in winter. The cold season starts in March but a little earlier in the mountains. Cold seasons last three or four months. In February, the cold decreases gradually, and in late February, the weather warms up more quickly, and in early May, the weather is relatively warm. The climate of Tehran province is warm and dry in the desert and South, in the cold and semi-humid basin areas, and in the cold Highlands with long winters. The warmest month of the Spring year is reported with an average maximum temperature of 37 ° C, and the coldest month of the year with an average minimum temperature of zero ° C. The temperature in Tehran is slightly cold in the mild winter and warm in the summer. For these reasons, this site was chosen over several other potential locations. The selection was primarily driven by two key factors. First, the site allows for the implementation and comparison of various scenarios, enabling the identification of the optimal option. Second, the region's unique climate contributes significantly to the natural cooling and heating of the building, which is crucial for sustainable design. Additionally, the study's scope is intentionally focused on facilitating the practical application of the best scenario.

The project is situated within Tehran, serving as a tangible real-world case study. It encompasses both commercial and residential functionalities, comprising six floors dedicated to residential use, four floors designated for parking, and an additional commercial floor supplemented by a half-floor extension. Spanning an area of 4072 m^2, this project represents a unique example not previously explored in the literature concerning the integration of commercial and residential spaces. Particularly noteworthy are the numerous thermal waste spaces inherent in the design, offering opportunities for mitigation through the implementation of existing strategies.

Given the considerable size of the project, the imperative of energy reduction is underscored. Table 1 provides insight into the climatic characteristics of the city, as elucidated within the carrier (HAP) software, further informing the project's development. In this modeling endeavor, the selection of air conditioning systems emerges as a pivotal consideration, given the thermal demands inherent in both the commercial and residential sectors. The convergence of energy supply and coordination poses a significant challenge in this context. The ventilation system adopted for the modeled building comprises a fan coil system supplemented with fresh air intake. Notably, the introduction of fresh air in the commercial sector plays a crucial role in alleviating thermal stress. Furthermore, the heating system chosen for this mixed-use project is a packaged system.

Table 1. Weather conditions in Tehran city

Region	Middle east	
location	Iran	
City	Tehran	
latitude	35.5	deg
longitude	51.4	deg
elevation	5418	ft
Summer design DB	104	F
Summer coincident WB	75	F
Summer daily range	25	F
Winter design DB	25	F
Winter coincident WB	18	F
Soil conductivity	1	Btu/hr/ft/F

The selection of air conditioning units is meticulously aligned with the climatic nuances of Tehran, where both cooling and heating functionalities are requisite owing to the climatic fluctuations. In this regard, neither system holds superiority over the other, and thus, they are not prioritized based on singular efficiency metrics. Instead, the choice of air conditioning systems is calibrated to ensure optimal performance under diverse climatic conditions prevalent in Tehran.

3.3 Scenarios used in modeling

3.3.1 Walls

Examining walls and their efficacy in mitigating energy consumption is a viable avenue for addressing energy and environmental concerns. According to Table 2, it is stated that according to previous research, choosing the most appropriate color can significantly reduce energy consumption throughout the year. This reduction manifests in a cooling effect of approximately 1.5 degrees Celsius during warm seasons and a corresponding increase in temperature of approximately one degree Celsius during colder periods. The analysis reveals that the wall's design is crucial in minimizing heat transfer between the interior and exterior environments. The high absorptivity (0.900) of the dark exterior surface color suggests that while it may absorb more heat from sunlight, effective insulation strategies can mitigate excessive heat gain during warmer months. The total R-value indicates how well the wall resists heat flow; higher values correlate with better-insulating properties, essential for achieving zero-energy goals. The U-value reflects the rate at which heat is transferred through the wall assembly; lower U-values are desirable as they signify reduced heat loss or gain. Incorporating advanced insulation techniques and understanding the thermal dynamics of building materials is vital for achieving zero-energy buildings. This analysis not only underscores the importance of selecting appropriate materials but also advocates for innovative design considerations—such as wall color and layered construction, that can lead to substantial energy savings. By focusing on these elements within a mixed-use context, this research provides valuable insights for future developments to enhance energy efficiency in large-scale buildings, thus contributing to sustainable urban development goals. Analysis of Table 3, The enhanced thermal performance of Wall Type Number 2 illustrates the importance of selecting appropriate materials and configurations for achieving zero-energy buildings. The higher R-value signifies better insulation against heat transfer, critical for maintaining comfortable indoor temperatures while minimizing energy consumption. The significantly lower U-value suggests that this wall type will reduce heating and cooling loads, contributing to overall energy savings and supporting zero-energy objectives. Including R-7 board insulation represents a strategic advancement in building design to enhance energy efficiency.

The shift to a lighter exterior color demonstrates an understanding of passive solar design principles, which can further optimize energy performance. In summary, the comparison between Wall Type Number 1 and Wall Type Number 2 underscores the critical role that material selection and design choices play in achieving zero-energy buildings. The advancements seen in Wall Type Number 2, particularly through integrating high-performance insulation and strategic color selection, demonstrate a clear pathway toward enhanced energy efficiency in mixed-use developments. These findings reinforce the necessity for continued exploration and implementation of innovative building strategies that align with sustainability goals in the construction industry.

According to Table 4, Wall 1's high absorption coefficient (0.9) implies it will absorb more solar heat, potentially leading to higher cooling loads in the summer months. In contrast, Walls 2 and 3 have lower absorption coefficients (0.45), making them more favorable for energy conservation as they reduce the heat gained from solar radiation. The U-value is a critical measure of thermal performance; Wall 1 has the highest U-value (0.225), indicating poorer insulation and greater heat loss or gain compared to Walls 2 and 3, which both have a much lower U-value (0.096). This substantial difference highlights the superior insulating properties of Walls 2 and 3. The choice of color significantly affects energy performance; the dark color of Wall 1 results in higher heat absorption and, consequently, increased cooling requirements. Walls 2 and 3 utilize a dark and light color, respectively, both contributing to lower energy consumption due to their reflective properties and reduced heat gain. In summary, the analysis of Table 4 reveals that Walls 2 and 3 are more advantageous for achieving energy efficiency in building designs aimed at zero-energy goals when compared to Wall 1. These walls' lower absorption coefficients and U-values indicate better thermal performance and reduced energy demands for heating and cooling. This analysis underscores the importance of material selection and color choice in optimizing building envelopes for enhanced energy efficiency, particularly in mixed-use developments where diverse thermal characteristics must be managed effectively.

Table 2. Details of wall type number 1

Outside surface color	dark		absorptivity	0.900	
Layers: inside to outside	thickness	density	Specific .HT.	R-Value	Weight
	in	lb/ft³	BTU/lb/F	HR-ft2-F/BTU	Lb/ft²
Inside surface resistance	0	0	0	0.68500	0
Gypsum board	0.625	50	0.26	0.56000	2.6
Air space	0.000	0.0	0.00	0.91000	0.0
LW concrete block	4.000	38.0	0.20	1.51500	12.7
Face brick	4.000	125.0	0.22	0.43300	41.7
Outside surface resistance	0.000	0.0	0.00	0.33300	0.0
Total	8.625			4.44	56.9
			Overall U-value	0.225	BTU/hr/ft²/F

Table 3. Details of wall type number 2

Outside surface color	Light		Absorptivity	0.450	
Layers: inside to outside	thickness	density	Specific.HT.	R-Value	Weight
	in	lb/ft³	BTU/lb/F	HR-ft2-F/BTU	Lb/ft²
Inside surface resistance	0	0	0	0.68500	0
5/8 -in gypsem board	0.625	50	0.26	0.56004	2.6
R-7 board insulation	1.000	2.0	0.22	6.94445	0.2
4-in LW concrete block	4.000	38.0	0.20	1.51515	12.7
Face brick	4.000	125.0	0.22	0.43300	41.7
Outside surface resistance	0.000	0.0	0.00	0.33300	0.0
Total	9.625			10.47	57.1
			Overall U-value	0.096	BTU/hr/ft²/F

Table 4. Technical specifications of walls defined in different scenarios

Different types of walls	Color	U-value	Absorption coefficient
Wall 1	dark	0.225	0.9
Wall2	dark	0.096	0.45
Wall3	light	0.096	0.45

3.3.2 Windows

The window plays a crucial role in reducing energy consumption as an integral component of a building. Widely regarded as a vital element in construction, the window serves multiple functions essential to the built environment. Among these functions, providing ventilation, natural light, and illumination to the interior space is paramount. Additionally, windows serve as filters, regulating the influx of sunlight and controlling the airflow to prevent excessive entry into the designated environment. When utilized effectively within a building, windows contribute significantly to enhancing the interior environment, thereby optimizing their impact on energy efficiency and overall comfort. According to Table 5, Window type number 1 features dimensions of 6.00 feet in height and 10.00 feet in width, constructed from aluminum without thermal breaks. This design choice may result in higher heat transfer compared to windows with thermal breaks, potentially leading to increased energy costs for heating and cooling. The overall U-value of 0.779 BTU/hr/ft^2/°F indicates a moderate level of thermal performance, suggesting that this window may allow more heat loss compared to more efficient alternatives. Furthermore, the overall shade coefficient of 0.827 signifies that the window provides a reasonable level of solar control, which can help mitigate excessive heat gain from sunlight. The absence of internal shading may enhance natural light entry but also necessitates careful temperature regulation within the space. In summary, while this window offers ample daylighting opportunities, its thermal performance may limit its effectiveness in energy-efficient building designs.

The properties outlined in Table 6 are critical for understanding how Window Type Number 1 will perform in various thermal scenarios. The high transmissivity coupled with low reflectivity means this window type will allow substantial solar heat gain. While this can be beneficial in colder months for passive heating, it may pose challenges during warmer months when cooling demands increase. The relatively low absorptivity indicates that only a minor amount of solar energy is retained by the glass, which helps mitigate excessive heat buildup within the window assembly.

Table 5. Details of window type number 1

Height	6.00 ft
Width	10.00ft
Frame type	Aluminum without thermal breaks
Internal shade type	None
Overall u-value	0.779 btu/hr/ft2/f
Overall shade coefficient	0.827

However, in combination with high transmissivity, it suggests that careful consideration must be given to shading strategies to manage heat gain effectively. When comparing Window Type Number 1 with other potential window configurations (not detailed here), several factors should be considered. Unlike more advanced window types that may utilize multiple glazing layers or low-emissivity coatings to enhance thermal performance, Window Type Number 1's simplicity may limit its effectiveness in extreme climates or high-performance applications. The gap type (¼-inch air space) provides some insulation; however, it may not be sufficient compared to windows employing argon or krypton gas fills or thicker air spaces that significantly improve thermal resistance. In practical terms, the characteristics of Window Type Number 1 suggest several applications and considerations for building design. Passive Solar Design: Given its high transmissivity, this window type could be effectively utilized in passive solar design strategies where maximizing natural light and heat gain during winter months is desired. Shading and Control Mechanisms: To counteract potential overheating during summer months, integrating external shading devices or using interior shading solutions will be essential to maintain comfort levels and reduce reliance on mechanical cooling systems. In summary, Table 6 highlights the fundamental thermal characteristics of Window Type Number 1, emphasizing its role in influencing energy efficiency within mixed-use buildings aimed at achieving zero-energy status. The balance between transmissivity, reflectivity, and absorptivity underscores the need for strategic design choices that optimize natural light while managing heat gain effectively. As part of a comprehensive energy strategy, this window type can contribute positively to overall building performance when integrated with appropriate shading and insulation techniques. According to Table 7, Window type number 2, with dimensions of 6.00 feet in height and 4.00 feet in width, is constructed from aluminum with thermal breaks, which aids in reducing heat transfer. This feature enhances energy efficiency and lowers heating and cooling costs. With an overall U-value of 0.557 BTU/hr/ft^2/°F, this window demonstrates relatively good performance in preventing heat loss.

Table 6. Details of window type number 1

Glazing	Glass type	Transmissivity	Reflectivity	Absorptivity
Outer glazing	1/8” clear	0.841	0.078	0.081
Glazing#2	1/8” clear	0.841	0.078	0.081
Glazing #3	Not used			
Gap type	¼” air space			

Table 7. Details of window type number 2

Height	6.00 ft
Width	4.00ft
Frame type	Aluminum with thermal breaks
Internal shade type	None
Overall u-value	0.557 btu/hr/ft^2/F
Overall shade coefficient	0.796

Additionally, the overall shade coefficient of 0.796 indicates that this window effectively controls solar radiation, helping to maintain indoor temperatures within a comfortable range. The absence of internal shading may contribute to increased natural light; however, it also raises the need for temperature management. Overall, this window presents a suitable option for spaces that require both natural light and energy efficiency.

The properties outlined in Table 8 are critical for understanding how Window Type Number 2 will perform in various thermal scenarios. The high transmissivity coupled with low reflectivity means that this window type will allow substantial solar heat gain. While beneficial for passive heating during colder months, effective shading strategies may be necessary during warmer months to mitigate excessive heat gain. The relatively low absorptivity indicates that only a minor amount of solar energy is retained by the glass itself, which helps mitigate excessive heat buildup within the window assembly. However, combined with high transmissivity, it suggests that careful consideration must be given to shading strategies to manage heat gain effectively.

The introduction of a ½-inch krypton gap is significant as krypton gas has a lower thermal conductivity compared to air. This enhances the overall insulation performance of the window assembly, reducing heat transfer through conduction and improving energy efficiency. When comparing Window Type Number 2 with Window Type Number 1 (previously analyzed), several key differences and improvements can be observed. While both window types utilize clear glass with similar transmissivity and reflectivity values, Window Type Number 2 benefits from using krypton gas in its gap, offering superior insulation properties compared to the air-filled gap in Window Type Number 1. Using krypton gas significantly lowers the U-value for Window Type Number 2 compared to Window Type Number 1. This reduces heat transfer rates and enhances thermal resistance, making it more effective in maintaining indoor temperatures and reducing energy consumption. Combining high transmissivity and improved insulation through krypton gas positions Window Type Number 2 as a more energy-efficient option than Window Type Number 1. This improvement is particularly relevant for buildings aiming for zero-energy status where minimizing energy loss is critical. Combining high transmissivity and improved insulation through krypton gas positions Window Type Number 2 as a more energy-efficient option than Window Type Number 1. This improvement is particularly relevant for buildings aiming for zero-energy status where minimizing energy loss is critical. In practical terms, the characteristics of Window Type Number 2 suggest several applications and considerations for building design. Given its high transmissivity, this window type could be effectively utilized in passive solar design strategies where maximizing natural light and heat gain during winter months is desired while ensuring adequate measures are in place to control heat gain during summer months.

To counteract potential overheating during summer months, integrating external shading devices or using interior shading solutions will be essential to maintain comfort levels and reduce reliance on mechanical cooling systems. In summary, Table 8 highlights the fundamental thermal characteristics of Window Type Number 2, emphasizing its role in influencing energy efficiency within mixed-use buildings aimed at achieving zero-energy status. The balance between transmissivity, reflectivity, absorptivity, and enhanced insulation through krypton gas underscores the need for strategic design choices that optimize natural light while managing heat gain effectively. As part of a comprehensive energy strategy, this window type can contribute positively to overall building performance when integrated with appropriate shading and insulation techniques.

According to Table 9, Window 1 has a higher U-value (0.779), indicating less insulation effectiveness compared to Windows 2 and 3 (both at 0.551). This suggests that Windows 2 and 3 will provide better energy efficiency by minimizing heat transfer. The use of krypton gas in Windows 2 and 3 enhances their thermal performance significantly compared to the air insulation used in Window 1. Krypton provides superior insulation properties due to its lower thermal conductivity. While all three windows have comparable Sh-coefficients, Windows 2 and 3 maintain a balance between solar heat gain reduction and thermal resistance, making them more suitable for energy-efficient designs in varying climates. The combination of lower U-values and effective solar heat gain management in Windows 2 and 3 positions them as favorable options for achieving zero-energy building goals, whereas Window 1 may require additional strategies to enhance its energy performance.

3.3.3 Roofs

The walls of a building serve as its outermost shell, exposed to direct air and temperature fluctuations, thus playing a pivotal role in heat exchange and energy regulation. Among these walls, the roof wall holds particular significance due to its expansive horizontal surface area. This orientation exposes it to prolonged periods of sunlight and other atmospheric elements, leading to heightened heat exchange compared to other walls of the building. Consequently, the heat exchange dynamics of the roof wall are accentuated, rendering it a critical focal point in building design and energy management considerations. This recognition underscores its importance as a key scenario warranting thorough analysis and optimization strategies. According to Table 10, The provided table details the specifications of Roof Type Number 1, including the outside surface color, thermal absorptivity, and characteristics of various roof layers. The dark outside surface color, with an absorptivity of 0.900, indicates a high capacity for heat absorption. The layers of the roof consist of inside surface resistance, steel deck, board insulation, and built-up roofing, each with specific thicknesses, densities, and thermal properties. The total thickness of the layers is 1.410 inches, with an R-value of 8.29 HR-ft^2-F/BTU, indicating effective insulation performance.

Table 8. Details of window type number 2

Glazing	Glass type	Transmissivity	Reflectivity	Absorptivity
Outer glazing	1/8” clear	0.841	0.078	0.081
Glazing#2	1/8” clear	0.841	0.078	0.081
Glazing #3	Not used			
Gap type	1/2” krypton			

Table 9. Technical specifications of windows defined in different scenarios

Types of windows	Insulation type	U-value	Sh-coefficient
Window1	air	0.779	0.827
Window2	krypton	0.551	0.796
Window3	krypton	0.551	0.796

Table10. Details of roof type number 1

Outside surface color	Dark		Absorptivity	0.900	
Layers: inside to outside	Thickness	Density	Specific.HT.	R-Value	Weight
	in	lb/ft^3	BTU/lb/F	HR-ft2-F/BTU	lb/ft^2
Inside surface resistance	0	0	0	0.68500	0
Steel deck	0.034	489.0	0.12	0.00011	1.4
Board insulation	1.000	2.0	0.22	6.94400	0.2
Built up roofing	0.376	70.0	0.35	0.33200	2.2
Outside surface resistance	0.000	0.0	0.00	0.33300	0.0
Total	1.410			8.29	3.7
			Overall U-value	0.121	BTU/hr/ft^2/F

Finally, the overall U-value of the roof is calculated to be 0.121 BTU/hr/ft^2/F, reflecting its adequate thermal efficiency and contributing to reduced heat transfer. These characteristics enhance energy efficiency and improve comfort within the building. Table 11 presents the specifications for Roof Type Number 2, characterized by a light outside surface color and a thermal absorptivity of 0.450, indicating a lower capacity for heat absorption compared to darker roofs. The roof layers include inside surface resistance, steel deck, board insulation, and built-up roofing, each with defined thicknesses, densities, and thermal properties. The total thickness of the roof assembly is 1.410 inches, with an R-value of 8.29 HR-ft^2-F/BTU, demonstrating effective insulation capabilities. The overall U-value is calculated at 0.121 BTU/hr/ft^2/F, suggesting efficient thermal performance and minimal heat transfer. These attributes contribute positively to energy efficiency and occupant comfort within the building structure. Table 12 analyzes roof types in the context of net zero energy buildings and reveals significant differences in thermal performance based on their absorptivity and color. Roof Type 1, characterized by a dark color and an absorptivity of 0.900, is likely to absorb a substantial amount of solar heat, which can benefit colder climates but may lead to increased cooling demands in warmer conditions. In contrast, Roof Type 2 features a light color with an absorptivity of 0.450, indicating a reduced capacity for heat absorption, which can enhance energy efficiency by minimizing cooling loads during hot weather.

Roof Type 3, also light in color with an absorptivity of 0.90, presents a unique case where, despite its light appearance, it retains a high absorptive capacity similar to Roof Type 1. These variations highlight the importance of selecting appropriate roofing materials and colors in the design of net zero energy buildings, as they directly influence energy consumption patterns and overall building performance. Effective roof design can significantly contribute to achieving the energy efficiency goals essential for net zero energy status, particularly by optimizing thermal comfort and reducing reliance on mechanical heating and cooling systems.

3.3.4 Shade

Another scenario involves the strategic deployment of shading to minimize sunlight penetration and optimize energy consumption within the building space. Harnessing sunlight and energy efficiently in buildings constitutes a fundamental principle for energy optimization, with shades in architecture serving as a viable solution. Awnings, in particular, represent an effective means of harnessing energy resources judiciously. The judicious utilization of solar energy within buildings plays a pivotal role in examining the impact of shading on reducing energy consumption. According to Figure 1, shading is exclusively implemented in Scenario 3, aimed at influencing the necessity for shading and its role in diminishing energy consumption. The introduction of shading in the form of a canopy has resulted in decreased energy usage attributable to the creation of a form of insulation and thermal barrier.

Table 11. Details of roof type number 2

Outside surface color	Light		Absorptivity	0.450	
Layers: inside to outside	Thickness	Density	Specific.HT.	R-Value	Weight
	in	lb/ft³	BTU/lb/F	HR-ft2-F/BTU	lb/ft²
Inside surface resistance	0	0	0	0.68500	0
Steel deck	0.034	489.0	0.12	0.00011	1.4
Board insulation	1.000	2.0	0.22	6.94400	0.2
Built up roofing	0.376	70.0	0.35	0.33200	2.2
Outside surface resistance	0.000	0.0	0.00	0.33300	0.0
Total	1.410			8.29	3.7
			Overall U-value	0.121	BTU/hr/ft²/F

Table 12. Specifications of technical ceilings defined in different scenarios

Types of roofs	The color of the modeled ceilings	Absorptivity
roof1	dark	0.900
roof2	light	0.450
roof3	light	0.90

The selection of an appropriate canopy is contingent upon factors such as location, climate, and the sun's angle, which fluctuates throughout the day. In a building, windows represent areas susceptible to high levels of light and heat ingress. Employing awnings for windows serves to deter the entry of heat and sunlight. Since glass has a greater propensity for heat absorption compared to walls, the strategic use of various types of canopies holds promise for reducing energy consumption and maintaining interior coolness. Shading windows or glass walls effectively curtails interior heat buildup, diminishing the reliance on cooling systems and reducing overall energy consumption.

4. Results and discussion

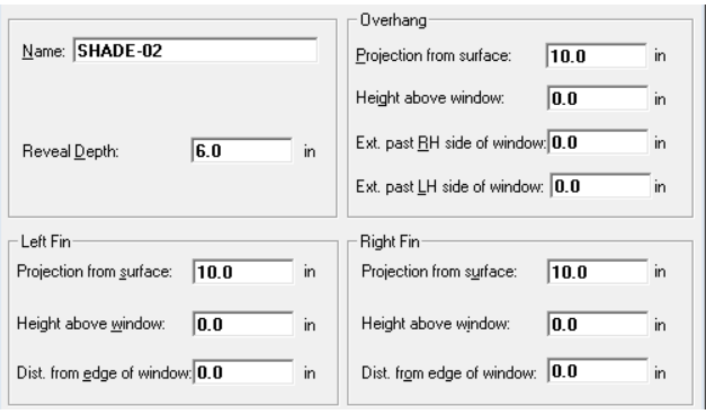
According to Table 13, in the Normal mode, the building spans an area of 4072 square meters. The walls are constructed using standard materials, while the glass features regular insulation with an air layer. The walls and ceiling are also dark in color, with an absorption coefficient of 0.9.

Notably, no shading elements are incorporated into the building design. In this Normal mode configuration, the thermal load of the building amounts to 1090681 BTU/hr. According to Table 14, the output from the Carrier (HAP) software for Scenario 2 is obtained under specific conditions. The wall incorporates R7 insulation, while the color of the wall remains dark. However, the ceiling color is light in this scenario. The absorption coefficient is maintained at 0.45. The space between the double-glazed window is filled with krypton gas for enhanced insulation compared to air. Notably, no shading elements are present. Additionally, the thermal load of the building has been recalculated to 916152 BTU per hour after implementing the specified scenarios. Based on Table 15, in this scenario, the color of the wall is lightened, and the absorption coefficient remains at 0.45. The specifications for the roof and window are consistent with those of Scenario 2. Additionally, all windows are equipped with shades. This configuration represents the optimal scenario, resulting in a thermal load calculated at 857610 BTU /hr.

$$\frac{1090681BTU/hr-916152BTU/hr}{1090681BTU/hr}*100=16\%$$

$$\frac{1090681BTU/hr-857610BTU/hr}{1090681BTU/hr}*100=21.36\ \%$$

$$\frac{916152BTU/hr-857610BTU/hr}{916152}*100=6.38\ \%$$



Name: SHADE-02

Reveal Depth: 6.0 in

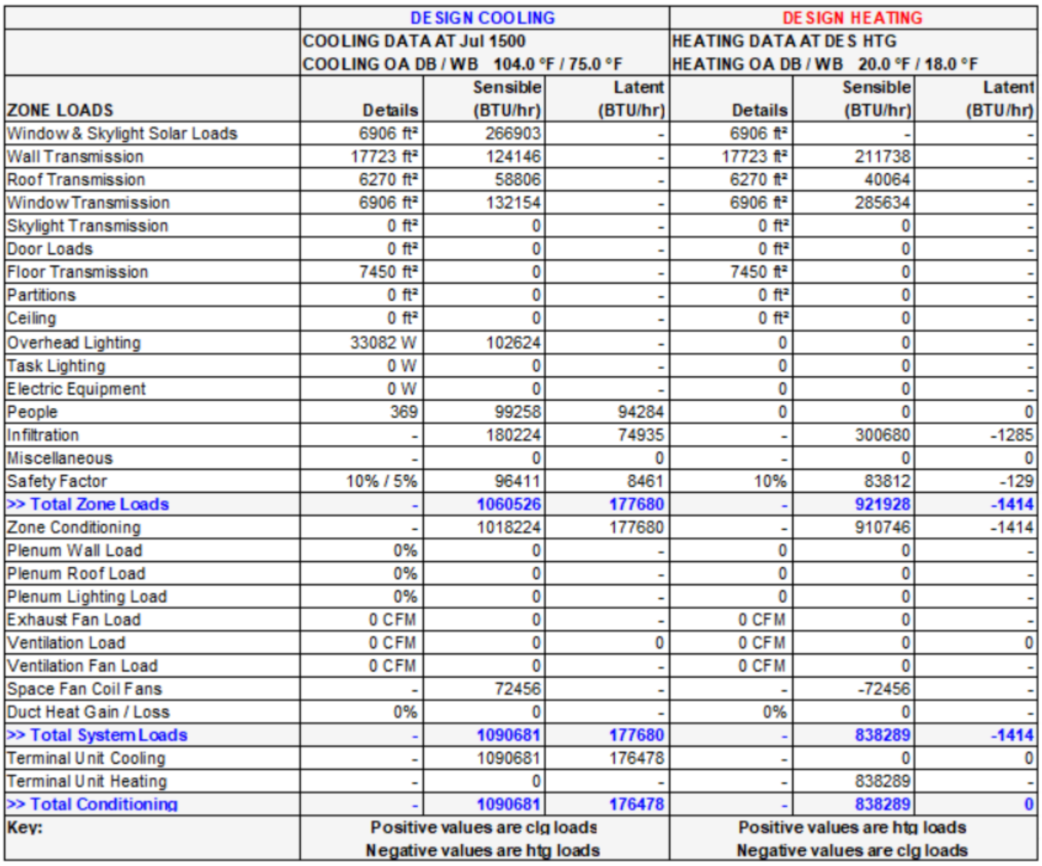
Overhang
Projection from surface: 10.0 in
Height above window: 0.0 in
Ext. past RH side of window: 0.0 in
Ext. past LH side of window: 0.0 in

Left Fin
Projection from surface: 10.0 in
Height above window: 0.0 in
Dist. from edge of window: 0.0 in

Right Fin
Projection from surface: 10.0 in
Height above window: 0.0 in
Dist. from edge of window: 0.0 in

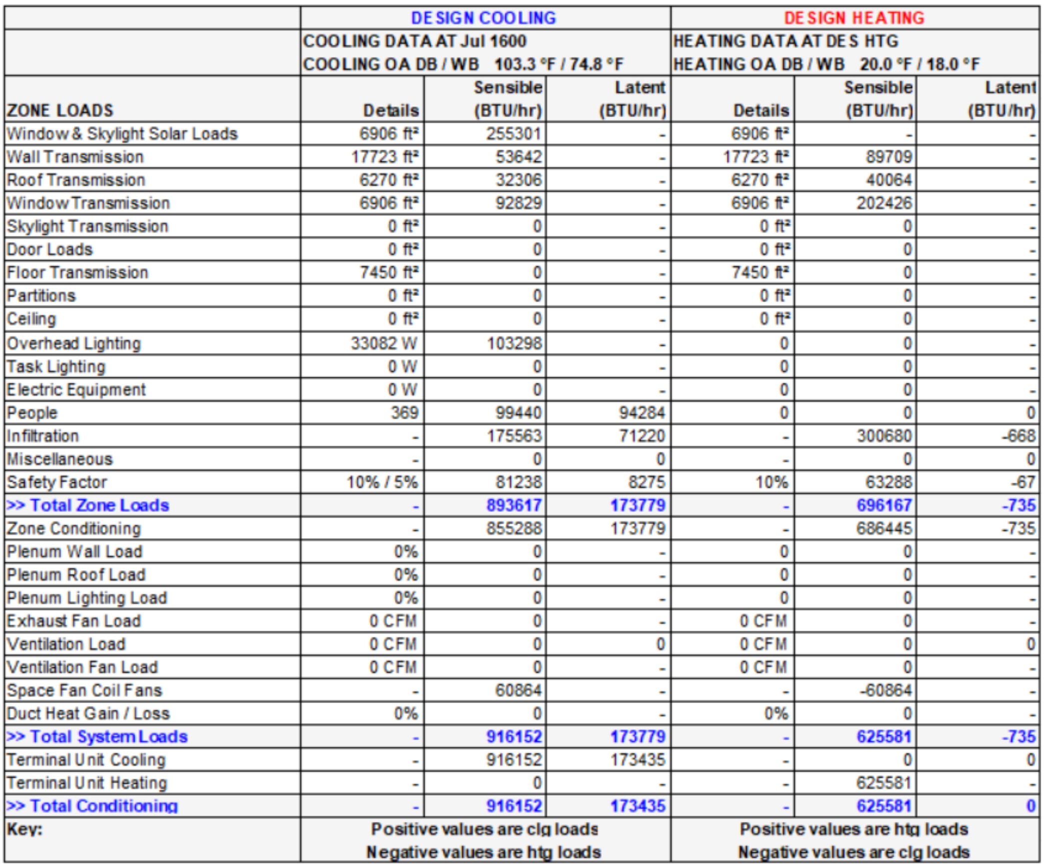
Figure 1. Details of shade type number 1

Table 13. Implementation of base scenario



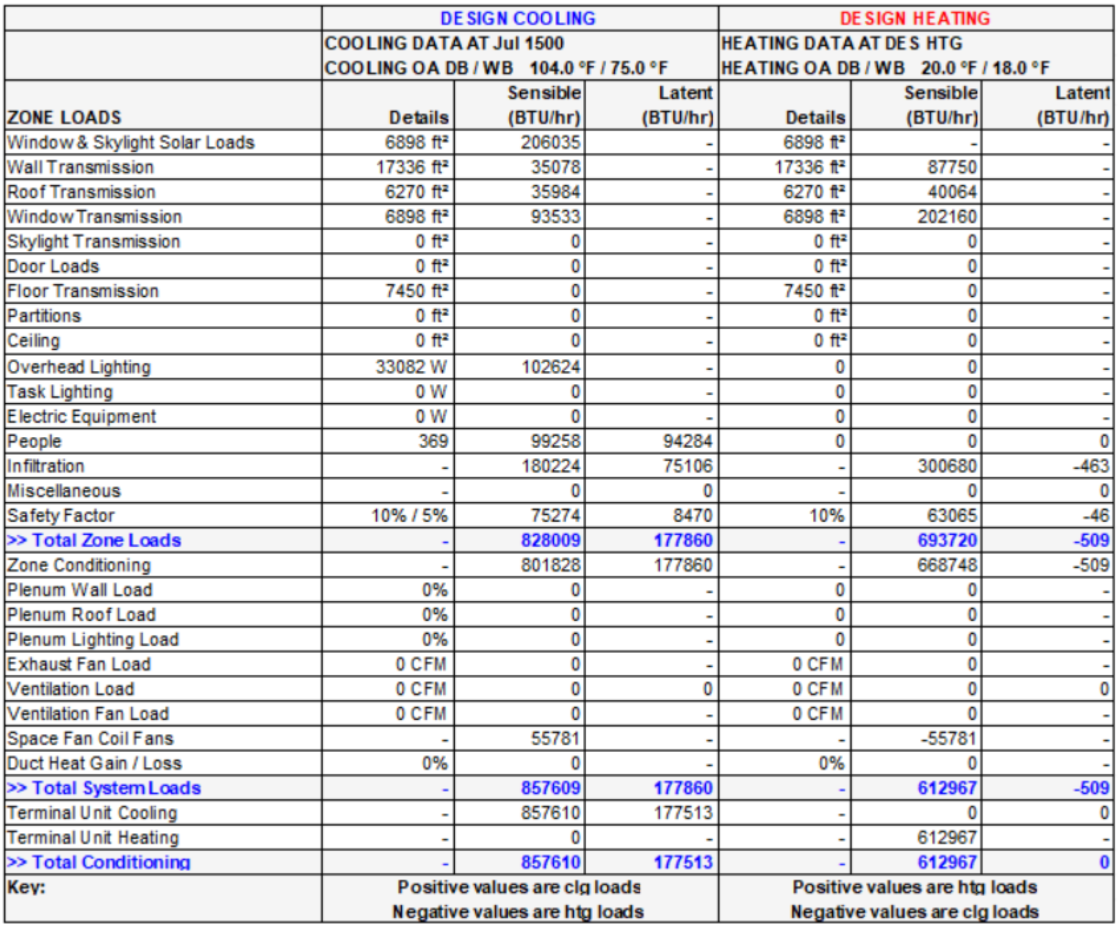
	DESIGN COOLING			DESIGN HEATING		
	COOLING DATA AT Jul 1500 COOLING OA DB / WB 104.0 °F / 75.0 °F			HEATING DATA AT DES HTG HEATING OA DB / WB 20.0 °F / 18.0 °F		
ZONE LOADS	Details	Sensible (BTU/hr)	Latent (BTU/hr)	Details	Sensible (BTU/hr)	Latent (BTU/hr)
Window & Skylight Solar Loads	6906 ft²	266903	-	6906 ft²	-	-
Wall Transmission	17723 ft²	124146	-	17723 ft²	211738	-
Roof Transmission	6270 ft²	58806	-	6270 ft²	40064	-
Window Transmission	6906 ft²	132154	-	6906 ft²	285634	-
Skylight Transmission	0 ft²	0	-	0 ft²	0	-
Door Loads	0 ft²	0	-	0 ft²	0	-
Floor Transmission	7450 ft²	0	-	7450 ft²	0	-
Partitions	0 ft²	0	-	0 ft²	0	-
Ceiling	0 ft²	0	-	0 ft²	0	-
Overhead Lighting	33082 W	102624	-	0	0	-
Task Lighting	0 W	0	-	0	0	-
Electric Equipment	0 W	0	-	0	0	-
People	369	99258	94284	0	0	0
Infiltration	-	180224	74935	-	300680	-1285
Miscellaneous	-	0	0	-	0	0
Safety Factor	10% / 5%	96411	8461	10%	83812	-129
>> Total Zone Loads	-	1060526	177680	-	921928	-1414
Zone Conditioning	-	1018224	177680	-	910746	-1414
Plenum Wall Load	0%	0	-	0	0	-
Plenum Roof Load	0%	0	-	0	0	-
Plenum Lighting Load	0%	0	-	0	0	-
Exhaust Fan Load	0 CFM	0	-	0 CFM	0	-
Ventilation Load	0 CFM	0	0	0 CFM	0	0
Ventilation Fan Load	0 CFM	0	-	0 CFM	0	-
Space Fan Coil Fans	-	72456	-	-	-72456	-
Duct Heat Gain / Loss	0%	0	-	0%	0	-
>> Total System Loads	-	1090681	177680	-	838289	-1414
Terminal Unit Cooling	-	1090681	176478	-	0	0
Terminal Unit Heating	-	0	-	-	838289	-
>> Total Conditioning	-	1090681	176478	-	838289	0
Key:	Positive values are clg loads Negative values are htg loads			Positive values are htg loads Negative values are clg loads		

Table 14. Implementation of the most balanced scenario



	DESIGN COOLING			DESIGN HEATING		
	COOLING DATA AT Jul 1600 COOLING OA DB / WB 103.3 °F / 74.8 °F			HEATING DATA AT DES HTG HEATING OA DB / WB 20.0 °F / 18.0 °F		
ZONE LOADS	Details	Sensible (BTU/hr)	Latent (BTU/hr)	Details	Sensible (BTU/hr)	Latent (BTU/hr)
Window & Skylight Solar Loads	6906 ft²	255301	-	6906 ft²	-	-
Wall Transmission	17723 ft²	53642	-	17723 ft²	89709	-
Roof Transmission	6270 ft²	32306	-	6270 ft²	40064	-
Window Transmission	6906 ft²	92829	-	6906 ft²	202426	-
Skylight Transmission	0 ft²	0	-	0 ft²	0	-
Door Loads	0 ft²	0	-	0 ft²	0	-
Floor Transmission	7450 ft²	0	-	7450 ft²	0	-
Partitions	0 ft²	0	-	0 ft²	0	-
Ceiling	0 ft²	0	-	0 ft²	0	-
Overhead Lighting	33082 W	103298	-	0	0	-
Task Lighting	0 W	0	-	0	0	-
Electric Equipment	0 W	0	-	0	0	-
People	369	99440	94284	0	0	0
Infiltration	-	175563	71220	-	300680	-668
Miscellaneous	-	0	0	-	0	0
Safety Factor	10% / 5%	81238	8275	10%	63288	-67
>> Total Zone Loads	-	893617	173779	-	696167	-735
Zone Conditioning	-	855288	173779	-	686445	-735
Plenum Wall Load	0%	0	-	0	0	-
Plenum Roof Load	0%	0	-	0	0	-
Plenum Lighting Load	0%	0	-	0	0	-
Exhaust Fan Load	0 CFM	0	-	0 CFM	0	-
Ventilation Load	0 CFM	0	0	0 CFM	0	0
Ventilation Fan Load	0 CFM	0	-	0 CFM	0	-
Space Fan Coil Fans	-	60864	-	-	-60864	-
Duct Heat Gain / Loss	0%	0	-	0%	0	-
>> Total System Loads	-	916152	173779	-	625581	-735
Terminal Unit Cooling	-	916152	173435	-	0	0
Terminal Unit Heating	-	0	-	-	625581	-
>> Total Conditioning	-	916152	173435	-	625581	0
Key:	Positive values are clg loads Negative values are htg loads			Positive values are htg loads Negative values are clg loads		

Table 15. Implementation of the best scenario



	DESIGN COOLING			DESIGN HEATING		
	COOLING DATA AT Jul 1500 COOLING OA DB / WB 104.0 °F / 75.0 °F			HEATING DATA AT DES HTG HEATING OA DB / WB 20.0 °F / 18.0 °F		
ZONE LOADS	Details	Sensible (BTU/hr)	Latent (BTU/hr)	Details	Sensible (BTU/hr)	Latent (BTU/hr)
Window & Skylight Solar Loads	6898 ft^2	206035	-	6898 ft^2	-	-
Wall Transmission	17336 ft^2	35078	-	17336 ft^2	87750	-
Roof Transmission	6270 ft^2	35984	-	6270 ft^2	40064	-
Window Transmission	6898 ft^2	93533	-	6898 ft^2	202160	-
Skylight Transmission	0 ft^2	0	-	0 ft^2	0	-
Door Loads	0 ft^2	0	-	0 ft^2	0	-
Floor Transmission	7450 ft^2	0	-	7450 ft^2	0	-
Partitions	0 ft^2	0	-	0 ft^2	0	-
Ceiling	0 ft^2	0	-	0 ft^2	0	-
Overhead Lighting	33082 W	102624	-	0	0	-
Task Lighting	0 W	0	-	0	0	-
Electric Equipment	0 W	0	-	0	0	-
People	369	99258	94284	0	0	0
Infiltration	-	180224	75106	-	300680	-463
Miscellaneous	-	0	0	-	0	0
Safety Factor	10% / 5%	75274	8470	10%	63065	-46
>> Total Zone Loads	-	828009	177860	-	693720	-509
Zone Conditioning	-	801828	177860	-	668748	-509
Plenum Wall Load	0%	0	-	0	0	-
Plenum Roof Load	0%	0	-	0	0	-
Plenum Lighting Load	0%	0	-	0	0	-
Exhaust Fan Load	0 CFM	0	-	0 CFM	0	-
Ventilation Load	0 CFM	0	0	0 CFM	0	0
Ventilation Fan Load	0 CFM	0	-	0 CFM	0	-
Space Fan Coil Fans	-	55781	-	-	-55781	-
Duct Heat Gain / Loss	0%	0	-	0%	0	-
>> Total System Loads	-	857609	177860	-	612967	-509
Terminal Unit Cooling	-	857610	177513	-	0	0
Terminal Unit Heating	-	0	-	-	612967	-
>> Total Conditioning	-	857610	177513	-	612967	0
Key:	Positive values are clg loads Negative values are htg loads			Positive values are htg loads Negative values are clg loads		

5. Conclusion

The significance of zero-energy buildings (ZEBs) is increasingly recognized as a crucial strategy in addressing the building sector's substantial contribution to global energy consumption, which exceeds 40%. This study highlights the potential of ZEBs in mixed-use developments, particularly focusing on a unique case involving a large-scale commercial residential structure. By employing advanced modeling techniques with Carrier (HAP)software, this research not only identifies effective energy-saving strategies but also emphasizes the need for innovative approaches tailored to complex building types. The findings reveal that implementing a combination of advanced insulation methods, such as krypton gas for window treatments, alongside strategic design modifications like wall color optimization and shading techniques, can lead to significant reductions in energy consumption up to 21.36% in the most effective scenario. The exploration of diverse thermal characteristics and the integration of commercial and residential functionalities present new challenges and opportunities that have been insufficiently addressed in prior studies. As such, this article serves as a vital contribution to the field, advocating for the adoption of zero-energy principles in large mixed-use buildings. Future efforts should focus on refining these strategies across various climates and building types, reinforcing the role of ZEBs as a cornerstone in sustainable urban development and energy management practices.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

References

[1] Chwieduk, D., Towards sustainable-energy buildings. Applied energy, 2003. 76(1-3): p. 211-217.

[2] Saeed Ahmadi, Hadi Nezhadayni, Mohsen Asvad, Mahmood Abdoos, Reducing the share of electricity generation from fossil fuels by replacing renewable energies in rainy areas, Journal of Sustainable Energy Systems (2023). Volume 2, Issue 3, July 2023, Pages 299-312.

[3] Al-Homoud, M.S., The effectiveness of thermal insulation in different types of buildings in hot

climates. Journal of Thermal Envelope and Building Science, 2004. 27(3): p. 235-247.

[4] Kazemi Pouran Badr, S., et al., Impact of insulation and building management systems on reducing energy consumption and Energy analysis of residential buildings. Journal of Structural and Construction Engineering, 2020. 7(2): p. 5-23.

[5] Cao, X., X. Dai, and J. Liu, Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. Energy and buildings, 2016. 128: p. 198-213.

[6] Cuce, P.M. and S. Riffat, A comprehensive review of heat recovery systems for building applications. Renewable and Sustainable Energy Reviews, 2015. 47: p. 665-682.

[7] Svobodová, H. and P. Hlaváčková, Forest as a source of renewable material to reduce the environmental impact of buildings. Journal of Forest Science, 2023.

[8] Radhi, H., A comparison of the accuracy of building energy analysis in Bahrain using data from different weather periods. Renewable Energy, 2009. 34(3): p. 869-875.

[9] Wynn, M. and O. Olayinka, E-business strategy in developing countries: A framework and checklist for the small business sector. Sustainability, 2021. 13(13): p. 7356.

[10] Wang, H., X. Xue, and C. Zhao, Performance Analysis on Combined Energy Supply System Based on Carnot Battery with Packed-Bed Thermal Energy Storage. Available at SSRN 4712077.

[11] Zahedi, R. and S. Gitifar, TRNSYS simulation of water heating system based on flat plate solar collector in Iranian climate. Journal of Renewable and New Energy, 2024. 11(2): p. 1-8.

[12] Aboutorabi, R.S.S., H. Yousefi, and M. Abdoos, A comparative analysis of the carbon footprint in green building materials: a case study of Norway. Environmental Science and Pollution Research, 2024: p. 1-22.

[13] Ramesh, G., Study on Mechanical Properties of Polyurethane Foam Concrete. Indian Journal of Structure Engineering (IJSE) Volume-1 Issue-1, 2021: p. 1-3.

[14] Ghoniem, A. and L. Aboul Nour, Experimental investigation into the properties of crumb rubberized concrete incorporating corrugated round steel fibers. Archives of Civil and Mechanical Engineering, 2024. 24(2): p. 1-16.

[15] Shahee, A., et al., Reducing the energy consumption of buildings by implementing insulation scenarios and using renewable energies. Energy Informatics, 2024. 7(1): p. 18.

[16] Zahedi, R., et al., Technical, economic and environmental assessment of carbon capture from thermal power plants and convert it into value added concrete material. Emergent Materials, 2024: p. 1-12.

[17] Felimban, A., et al., Assessment of current energy consumption in residential buildings in Jeddah, Saudi Arabia. Buildings, 2019. 9(7): p. 163.

[18] Boemi, S.-N. and O. Irulegi, The Hotel Industry: Current Situation and Its Steps Beyond Sustainability. Energy Performance of Buildings: Energy Efficiency and Built Environment in Temperate Climates, 2015: p. 235-250.

[19] Baetens, R., et al., Assessing electrical bottlenecks at feeder level for residential net zero-energy buildings by integrated system simulation. Applied Energy, 2012. 96: p. 74-83.

[20] Nielsen, S. and B. Möller, Excess heat production of future net zero energy buildings within district heating areas in Denmark. Energy, 2012. 48(1): p. 23-31.

[21] Zahedi, R., et al., Thermal analysis model of a building equipped with green roof and its energy optimization. Nature-Based Solutions, 2023. 3: p. 100053.

[22] Abdous, M., et al., Design and analysis of zero-energy and carbon buildings with renewable energy supply and recycled materials. Energy and Buildings, 2024. 324: p. 114922.

[23] Zahedi, R., et al., Feasibility study for designing and building a zero-energy house in new cities. Solar Energy, 2022. 240: p. 168-175.

[24] Robertson, J.J., B.J. Polly, and J.M. Collis, Reduced-order modeling and simulated annealing optimization for efficient residential building utility bill calibration. Applied Energy, 2015. 148: p. 169-177.

[25] Hiyama, K. and L. Wen, Rapid response surface creation method to optimize window geometry using dynamic daylighting simulation and energy simulation. Energy and Buildings, 2015. 107: p. 417-423.

[26] Singh, K. and R. Das, Exergy optimization of cooling tower for HGSHP and HVAC applications. Energy conversion and management, 2017. 136: p. 418-430.

[27] Kim, W., S.W. Jeon, and Y. Kim, Model-based multi-objective optimal control of a VRF (variable refrigerant flow) combined system with DOAS (dedicated outdoor air system) using genetic algorithm under heating conditions. Energy, 2016. 107: p. 196-204.

[28] Shaghaghi, A., et al., Energy consumption reduction in a building by free cooling using phase change material (PCM). Future Energy, 2024. 3(2): p. 31-36.

[29] Kassim, M., A. Aslani, and R. Zahedi, Energy performance analysis of thermal insulating plaster in the different climate zones. Thermal Science and Engineering Progress, 2024. 47: p. 102294.

[30] Zahedi, R., et al., Analysis and evaluation of thermal-cooling loads of office buildings using carrier software in Iran. Journal of Smart Buildings and Construction Technology, 2022. 4(2): p. 61-74.