International Journal of Economy, Energy and Environment
2024; Vol. 9, No. 2, pp. 51-58
https://doi.org/10.11648/j.ijeee.20240902.12

Research Article

Energy Performance and Life-Cycle Analysis of Building Retrofits: A Case Study in Abu Dhabi

Noura Alkaabi*, Ahmad Mayyas

Department of Industrial Engineering, Khalifa University, Abu Dhabi, UAE

Abstract

Highly developed nations worldwide encounter a notable energy demand as their main obstacle. Furthermore, the building sector plays a significant role in contributing to carbon emissions and climate change. In the UAE, buildings consume the largest portion of energy due to the improper selection of design parameters during the building's design phase, which are specifically tailored for the remarkably hot climate in the country. As a result, various studies, initiatives, and policies are focused on enhancing the energy efficiency of buildings. Additionally, retrofitting existing buildings has emerged as a crucial approach to achieving energy efficiency, resulting in several benefits such as reduced costs for operation and maintenance. This research performed an analysis of a commercial building in Abu Dhabi using DesignBuilder, based on energy modeling and simulation. Five main retrofits were examined, accompanied by a cost analysis to determine the most appropriate retrofit for future investments. The results demonstrate that increasing the cooling set point temperature by 4 degrees led to a 19.53% decrease in the annual cooling load. Additionally, retrofitting the chiller resulted in a 16.11% reduction in the annual cooling load, whereas wall insulation had the least impact as a retrofit. It was observed that improving the chiller's coefficient of performance (COP) offered significant advantages, with a payback period of around 5 years, making it the most favorable retrofit for investment. However, the glazing and wall insulation retrofits were considered less beneficial due to their high initial costs and long payback periods.

Keywords

Cost Analysis, Energy Consumption, Energy Efficiency, Retrofits

1. Introduction

The world has witnessed a substantial increase in energy demands over the past few decades, especially since the advent of the Industrial Revolution and the subsequent growth of the oil and gas sectors. Countries and cities consume crucial resources like electricity and water due to a multitude of factors, including economic expansion, urbanization, population growth, low energy expenses, and severe weather conditions. This has become a major concern for numerous nations, particularly those in the Gulf region. A prime example of this is the United Arab Emirates (UAE), which ranked among the top 10 countries worldwide in terms of per capita electricity consumption [1].

Moreover, the building sector exhibits the highest energy consumption and CO_2 emissions across all economic sectors. In most developed countries, buildings consume about 30% to 40% of the total energy output. Several factors contribute to this large

*Corresponding author: Nourah.alkaabi@ku.ac.ae (Noura Alkaabi)

Received: 28 February 2024; **Accepted:** 15 March 2024; **Published:** 30 May 2024

share, including the size and growth of the sector, the length of time individuals spend inside buildings, and the need for buildings to provide comfortable indoor environments regardless of outdoor weather patterns. The UAE building sector consumes approximately 70% of the generated electricity, making it even more energy-intensive than other sectors [2]. As a result, the substantial and increasing energy intensity of the building sector necessitates immediate attention to this matter. Addressing it can result in significant environmental, economic, and social benefits. To accomplish this, particular focus should be directed towards the operational phase of buildings. This phase accounts for 80-90% of their total energy consumption over their lifespan, while the remaining percentage is allocated to the construction and decommissioning stages [3]. In recent years, there has been a substantial amount of research, projects, and strategies that have been dedicated to enhancing the energy efficiency of building systems [4-6]. Energy efficiency refers to the process of minimizing a building's energy consumption while ensuring its functionality and providing a comfortable and healthy environment for its occupants [7]. Consequently, retrofitting existing buildings has emerged as a pivotal approach to improving energy efficiency and reducing energy usage in buildings. According to Fluhrer et al. [8] retrofitting the entire building can lead to energy savings of approximately 38 percent. Furthermore, a study conducted by Ernst and Young [9] disclosed additional advantages of retrofits, such as reduced maintenance requirements resulting in lower operational costs, improved occupant comfort, and heightened worker productivity.

Many studies have investigated ways to enhance the energy efficiency of buildings in the UAE. These studies have focused on retrofitting both new and existing residential, commercial, and governmental buildings. To illustrate, Krarti and Dubey [10] conducted a comprehensive evaluation of various energy retrofit levels, such as incorporating programmable thermostats, utilizing LED lighting fixtures, implementing efficient cooling systems, and installing daylighting control systems. Their analysis, which employed building energy simulation and optimization-based bottom-up techniques, estimated that retrofitting the current stock of buildings in the UAE would result in significant cost-effectiveness. Additionally, it revealed potential energy savings of 7550 GWh/year from the total electricity consumption and a reduction of 4.5 million tons/year in carbon emissions. Moreover, the study emphasized the employment opportunities that retrofitting could generate in the fields of construction, manufacturing, and technical specialization. Different research conducted by Aldawoud et al. [11] focused on the renovation of a school structure in the UAE, utilizing DesignBuilder software as a tool for energy modeling and simulation. This research implemented retrofitting measures based on enhancements to the building envelope and A/C system in order to assess their influence on energy consumption. The examination revealed that replacing the existing air conditioning equipment was the most effective retrofitting measure, resulting in a 29% decrease in yearly electricity usage. Conversely, the addition of window insulation film was found to be the least effective measure, contributing to only a 5.8% reduction in annual energy consumption. Nevertheless, the optimal scenario emerged as a combination of improving A/C system efficiency and adding thermal insulation to walls, roofs, and windows, leading to a 57% reduction in yearly cooling energy usage. Another pertinent paper by Akhozheya et al. [12] examined the renovation of a housing complex in Al-Ain City, with a focus on the building envelope. The proposed retrofitting measures included upgrading the thermal insulation of external walls, roofs, and glazing to meet the minimum standards set by Estidama. The study discovered that implementing these measures could result in a significant reduction of up to 50% in annual energy consumption and carbon emissions, aligning with Estidama's objectives for building envelope insulation. Thus, the excessive energy consumption by buildings is attributed to insufficient understanding regarding the selection of design and operational features of buildings during the design phase, including the performance of the building envelope, chiller type, HVAC settings, and lighting usage. Consequently, researchers have turned towards retrofitting existing and new buildings to examine the impact of altering these design and operational features on the energy performance of buildings. However, such analysis has primarily focused on residential buildings and some commercial structures such as offices and schools, resulting in a lack of studies on retrofitting hotel buildings in the UAE. The objective of this study is to establish a modeling framework to quantify the impact of retrofitting a hotel building's parameters on its overall energy performance.

2. Method

The proposed methodology framework is shown in Figure 1 and detailed in the following subsections. It consists of developing a base case model of an existing Hotel in Abu Dhabi, UAE. The model is developed using the Design-Builder software. Five retrofits have been analyzed to study the effect of the parametric change on the building performance. Finally, parametric and cost analyses have been performed to select the most effective and suitable retrofit in term of the energy and cost savings.

2.1. Data Collection

The data on the hotel's geometric properties and material characteristics (Table 1) are obtained from various sources, including the hotel report from the Abu Dhabi City Municipality [13], the hotel's Engineering Department, and the Urban Planning Council study on typical building designs in Abu Dhabi, which provides specifications for different types of buildings. The hotel comprises 22 levels, which are assumed to have uniform heights. It is worth noting that there are 28 windows per exterior wall, resulting in a total of 2352 windows for 21 levels. This calculation takes into account the fact that each floor, except for the ground floor, has four exterior walls. Moreover, the shading effect has been taken into consideration. The hotel is shaded by two primary structures: one on the left side, measuring approximately 13.7m in distance and 50m in height, and another building located southeast of the hotel, with a distance of around 24.5m and a height of 84m. These measurements were extracted from a CAD file of district E3-Abu Dhabi.

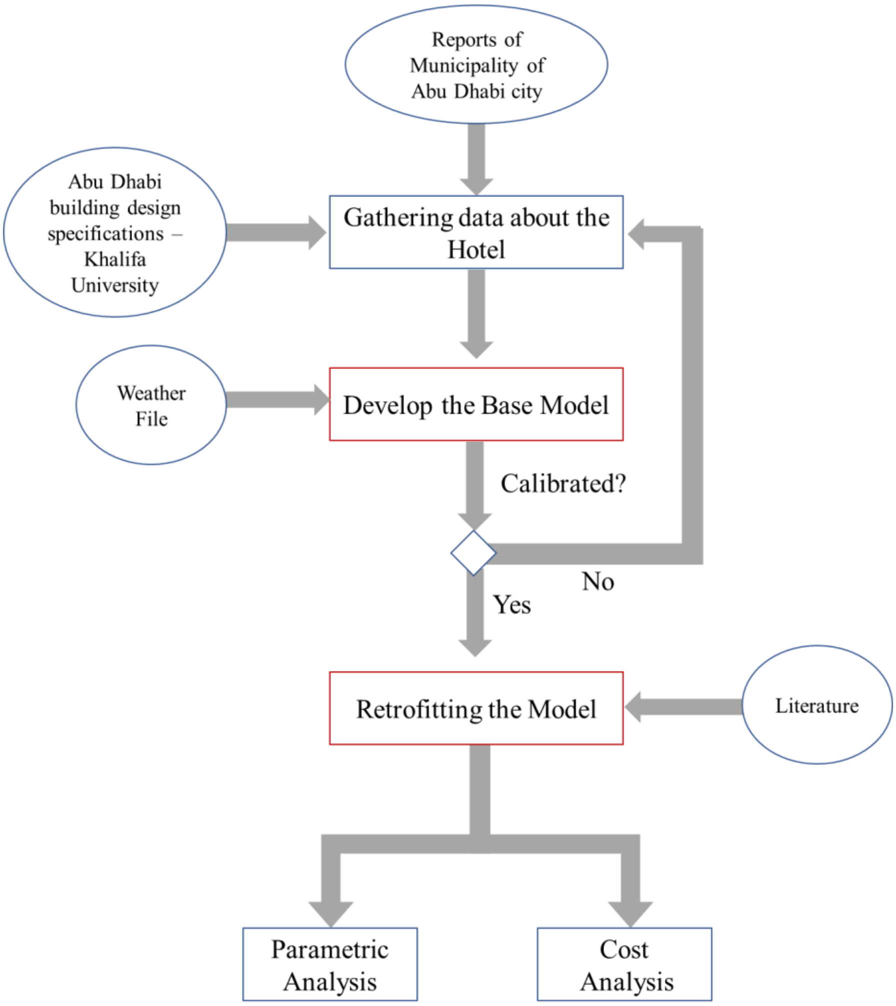

Figure 1. *Methodology of the research work.*

2.2. Building Energy Modelling Model

DesignBuilder, a simplified simulation tool for building energy performance, is used to build the model once real data had been collected for the building. Additionally, DesignBuilder offers users the possibility of comparing various buildings. The hotel's structural diagram is shown in Figure 2a before modeling, while the final layout of the hotel and the surrounding buildings, which have been constructed to create shading effects, is shown in Figure 2b.

Table 1. *The hotel's geometry and design data.*

Parameter	Value	Units	Parameter	Value	Units
Building Height	84	m	Windows U-value	3.88	W/m^2K
Width	35	m	SHGC	0.75	-
Length	35	m	Glazing emissivity	0.9	-

Parameter	Value	Units	Parameter	Value	Units
Area of the floor	1225	M^2	Thermostat setpoint	22 26	C
Height of the floors	3.82	m	Nominal COP	2.5	-
Window area	2.16	M^2	Infiltration	0.75	ACH
Number of windows per outer wall	28	windows	Indoor CHTC	5	W/Km^2
Roof/wall/floor density	750	kg/m^3	Roof-air CHTC	20	W/Km^2
Wall thickness	0.25	m	Wall-air CHTC	25	W/Km^2
Roof/floor thickness	0.35	m	Equipment intensity	12	W/m^2
WWR	51	%	Lighting intensity	8	W/m^2
Total wall U-value	1.15	W/m^2K	People density	0.04	$person/m^2$
Roof U-value	0.58	W/m^2K	Fresh air intake & vent	7.5	$ls/person$

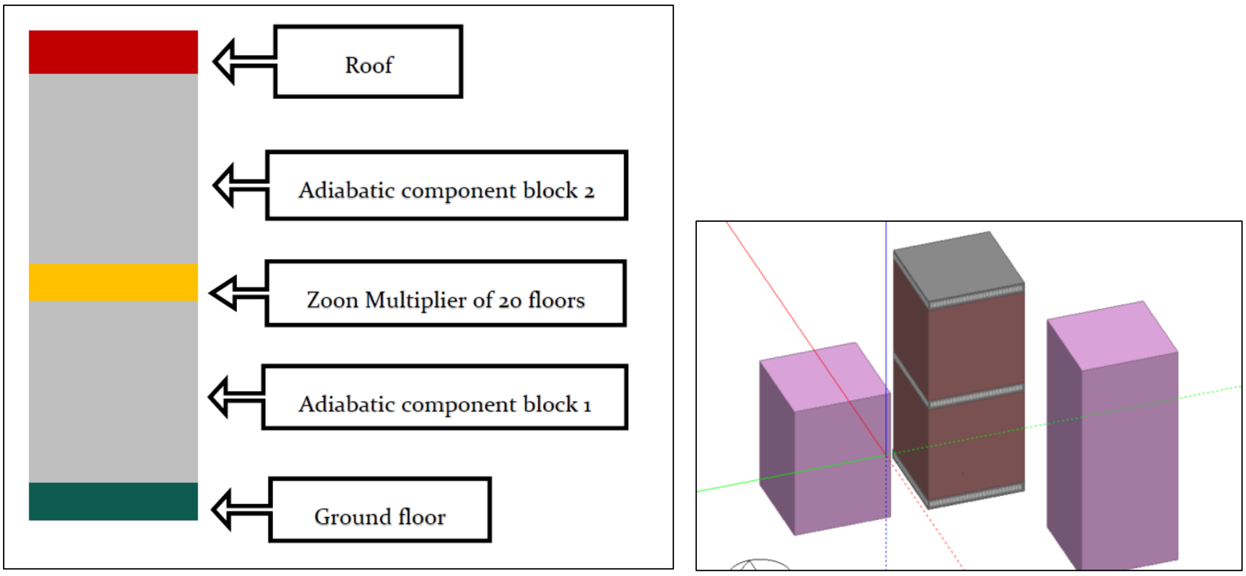

Figure 2. *(a) The model's structural diagram. (b) Final layout in DesignBuilder.*

2.3. Calibration

In the next step, the model is simulated to collect energy consumption readings, followed by calibration to compare the actual energy consumption with the model. NMBE (Normalized Mean Bias Error) and CvRMSE [14] are used to find the percentage of error between the actual energy output from the hotel and the simulated energy output from the hotel using Equation 1 and Equation 2, respectively.

$$NMBE = 100 * \frac{1}{\bar{y}} * \quad (1)$$

$$CvRMSE = 100 * \frac{1}{\bar{y}} * \sqrt{\frac{\sum_{i=1}^{n}(yi - xi)^2}{n-1}} \quad (2)$$

Where yi represents the actual energy values, xi represents the simulated energy values, and $\bar{y}$ represent the mean of the actual energy values.

2.4. Retrofits–Proposed Strategy

The analysis of the building model encompassed various retrofits aimed at investigating the effects of incorporating efficient building components on both total energy consumption and peak loads of the building. The objective behind these retrofits was to curtail electricity usage, cooling load, and internal gains by proposing more suitable values for the most energy-consuming components within the building. The current study puts forward five retrofits for consideration: The primary retrofit involves enhancing the air-tightness of the building. Air-tightness refers to the capacity of the building envelope to resist infiltration when the ventilation system is closed. The higher the airtightness at a given pressure difference across the envelope, the lower the infiltration. Consequently, reducing the airtightness of buildings can lead to reduced operating costs by minimizing heat loss, defects, condensation, and enhancing comfort levels [15]. The proposed modification focuses on the air changes per hour (ACH) value, aiming to change it from 0.75 to 0.50.

The second retrofit involves increasing the cooling set-point temperature. It has been found that "each degree increase in set point temperature can save up to 5% on AC consumption" [16]. Typically, the cooling set point for the hotel is adjusted to 26 ℃ (Table 1). A slight increase in the cooling set point by a few degrees is not expected to compromise thermal and human comfort. Therefore, the proposed retrofit suggests changing the temperature from 26 to 30 ℃, which is slightly higher than the range used in other UAE studies. The third retrofit focuses on enhancing the coefficient of performance (COP) of the chiller. Large buildings and multiple building campuses often utilize chiller plants to provide cooling, resulting in substantial electricity consumption by the chiller. In this study, the chiller efficiency (COP) has been improved from 2.5 to 3. Additionally, the fourth retrofit concentrates on improving the glazing system. Windows have long been utilized in buildings to provide natural light and ventilation. Moreover, well-ventilated indoor environments promote health, comfort, and productivity. However, windows also contribute significantly to heat loss, discomfort, and condensation issues. The rate of heat loss is quantified by the U-factor (U-value) of a window, where a lower U-factor indicates greater resistance to heat flow and better-insulating properties. Hence, the proposed change involves targeting the U-value and modifying it from 3.88 to 2.4. Lastly, the fifth retrofit entails enhancing wall insulation as a means to reduce electricity expenses by adding more insulation to the building. In this study, an insulation layer (R-15 XPS thickness 80mm layer) has been added to the external walls of the hotel. Since most of the external walls of the hotel are covered by glass, it is expected that the impact on energy consumption will be minimal.

2.5. Parametric and Cost Analysis

Parametric analysis has been conducted to assess how changes in specific parameters or input variables affect the performance and behaviour of a building. It tells the users how dependent the output energy consumption is on each building's parameter [17]. The parametric analysis was conducted after each retrofit using the below equation:

$$Parametric\ change = \frac{\Delta E/_{E0}}{\Delta P/_{p0}} \tag{3}$$

Where ΔE is the change in the total energy, and ΔP is the change in the retrofit parameters before and after th e parametric change, while $E0$ and $p0$ represent the energy output and the parameter value in the base case model. The cost analysis for each retrofit has been conducted through the utilization of the Net Present Value (NPV) by calculating the investment and saving costs of the proposed retrofits. The cost data for each retrofit have been sourced from the National Residential Efficiency Measures Database of the National Renewable Energy Laboratory.

3. Results and Discussion

3.1. Energy Consumption of the Original Model

According to the findings, the cooling load accounts for 47% of the total energy consumption, while the equipment load represents 31% and the lighting load represents 22%. In contrast, the heating load is negligible. It is worth noting that the cooling load is the primary contributor to electricity consumption in the hotel, particularly during the summer months, which is a line with the energy results from a typical Abu Dhabi building that was analyzed by Afshari et al [4]. On the other hand, the heating load remains at zero for most of the year making up a minimal percentage of the overall energy breakdown due to the extremely hot weather in the UAE, except for the beginning and end of the year.

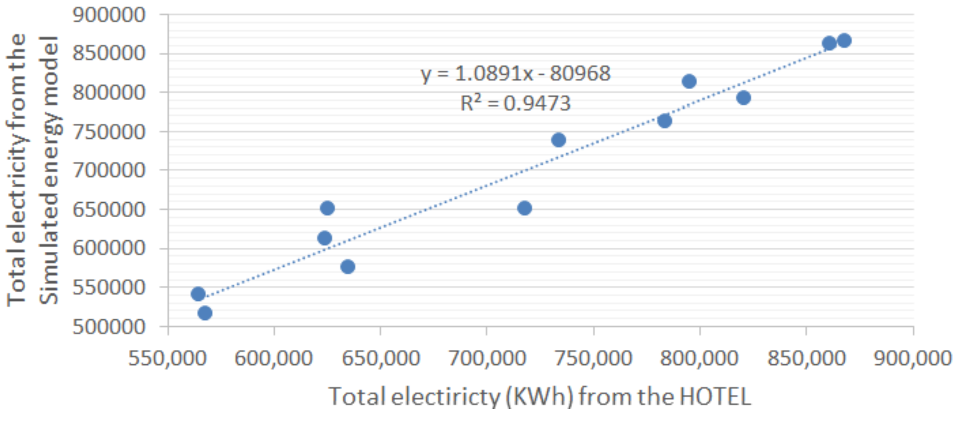

Figure 3. *Calibration Curve between the Simulated Model and the Actual data.*

3.2. Calibration

Figure 3 illustrates that the hotel's actual electricity consumption aligns closely with the electricity consumption predicted by the simulated energy model. Moreover, the calibration curve exhibits nearly linear behavior, with minimal deviation between the readings and the curve. This is further supported by a high regression coefficient (R2) of 0.94, which indicates a significant amount of variation in the outcome. Additionally, the Normalized Mean Bias Error is 2.612% (less than the desired threshold of 5%), while the Coefficient of variation of the Root Mean Square Error is 4.88% (below the desired threshold of 15%). These values indicate a relatively low percentage of error between the real and simulated energy output, suggesting that the model is validated [18].

3.3. Retrofitting and Parametric Analysis

Based on Figure 4 and Table 2, it is evident that all the retrofits have resulted in a decrease in the overall energy consumption of the hotel model, although the extent of reduction varies. The adjustment of the cooling set point temperature has proven to be the most effective, leading to a minimum energy consumption of 451,000 KWh in February and a 19.53% reduction in annual cooling consumption. Conversely, the addition of wall insulation has shown the highest total energy consumption among the five retrofits, indicating its limited contribution to cooling energy reduction at only 0.07%. By increasing the chiller coefficient of performance (COP) from 2.5 to 3, a noticeable reduction of 16.11% in annual cooling has been achieved, particularly during the summer months when the cooling load is highest. Furthermore, changing the glazing material and reducing its U-value to 2.4 has resulted in energy savings of 8.25% in annual cooling load, while enhancing air tightness only yields a modest saving of approximately 4.29% in annual cooling energy.

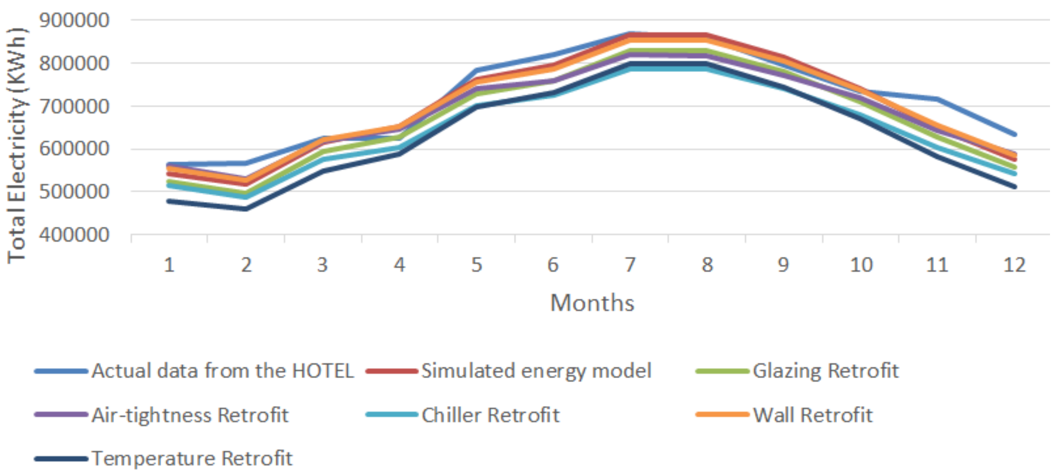

Figure 4. *Monthly Electricity Consumption for each retrofit Vs the Base-case Model and Actual data.*

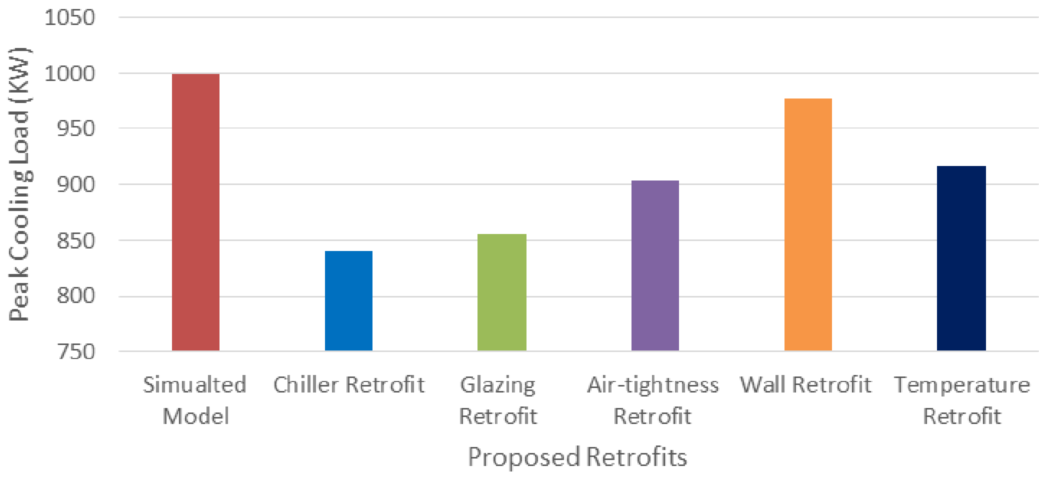

Figure 5. *Peak Cooling Load from the simulated Model Vs the Retrofits.*

On a separate note, Figure 5 demonstrates the peak cooling load of the base-case simulated model and the model after implementing the five retrofits. As expected, the base model exhibits the highest cooling load, whereas the proposed retrofits contribute to a reduction in the peak cooling load. The retrofit that significantly reduces the peak cooling is the enhancement of chiller COP. However, adding insulation to external walls does not provide any benefits to the building, as more than half of the hotel's façade is covered by glazing rather than walls, resulting in a negligible impact of insulation on the cooling load.

Based on the parametric analysis (Figure 6), the building is sensitive to the variation of cooling set point temperature, chiller COP, and glazing U-value given a change in parameters of -0.603, -0.38, and 0.103, respectively. Negative values indicate that output decreases with an increase in input value (examples include temperature set point and chiller COP).

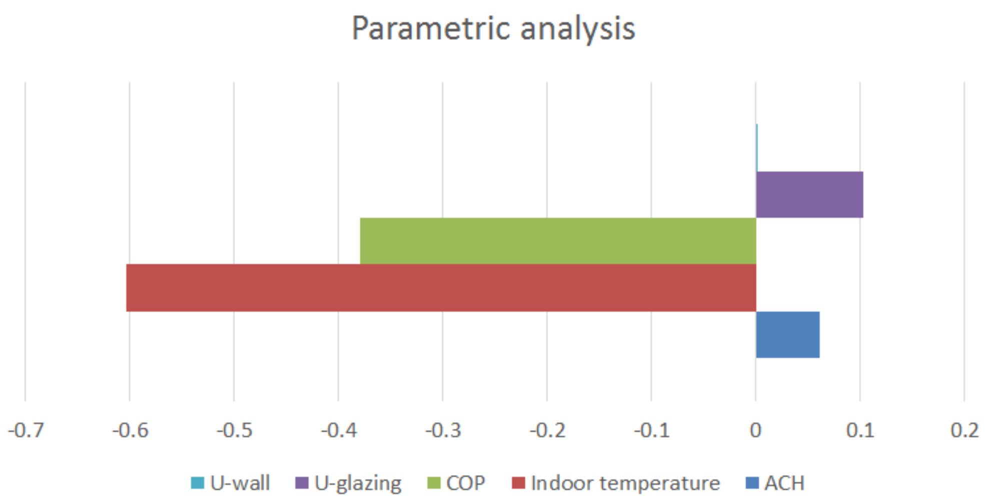

Figure 6. *Breakdown of Parametric sensitivity.*

Table 2. *Energy Reduction of the Proposed Retrofits.*

	Annual Cooling Consumption (KWh)	Energy Reduction (%)
Before Retrofit	3986727.5	-
Chiller Retrofit	3344603.6	16.11
Glazing Retrofit	3658016.9	8.25
Air-tightness Retrofit	3815514.2	4.29
Wall Retrofit	3983782.2	0.07
Temperature Retrofit	3208103	19.53

4. Conclusion

Energy consumption by buildings in the UAE is substantial. Retrofitting old residential and commercial buildings can be beneficial in terms of lowering energy usage and carbon emissions. The current study focuses on examining the energy usage and expenses associated with different retrofitting techniques for a hotel located in Abu Dhabi. Five main retrofits were assessed based on their potential to decrease the cooling load and overall electricity consumption of the building. The findings indicate that the cooling load is the main contributor to the hotel's electricity usage, accounting for almost half of the total consumption. Notably, raising the cooling set point temperature leads to a 9.28% decrease in total energy usage and a 19.53% decrease in annual cooling load, making it the most effective retrofit investment. Moreover, retrofitting the chiller system results in a 16.11% decrease in annual cooling load, such findings are in line with the work of Granderson et al. [19] and Barbosa et al. [20] who discover that inefficient building systems can result in elevated levels of energy consumption. In contrast, the retrofit involving wall insulation proves to be the least effective, exhibiting the highest energy usage among the five retrofits. The cost analysis demonstrates that enhancing the chiller coefficient of performance (COP) offers significant benefits, as it has a short payback period. However, retrofits like glazing and wall insulation do not provide any advantages to the building due to their high initial cost and long payback periods.

Abbreviations

COP	Coefficient of Performance
HVAC	Heating, Ventilation, and Air Conditioning
SHGC	Solar Heat Gain Coefficient
WWR	Window Wall Ration
CHTC	Convective Heat Transfer Coefficient
NMBE	Normalized Mean Bias Error
CvRMSE	Coefficient of variation of the Root Mean Square Error
ACH	Air Changes per Hour
NPV	Net Present Value

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] World Bank, "Energy Consumption by Country 2023," 2023. https://worldpopulationreview.com/country-rankings/energy-consumption-by-country (accessed May 26, 2023).

[2] H. Radhi, "Evaluating the potential impact of global warming on the UAE residential buildings – A contribution to reduce the CO 2 emissions," *Build Environ*, vol. 44, no. 12, pp. 2451–2462, 2009, https://doi.org/10.1016/j.buildenv.2009.04.006

[3] E. Asadi, M. Gameiro, C. Henggeler, and L. Dias, "Multi-objective optimization for building retrofit strategies: A model and an application," *Energy Build*, vol. 44, pp. 81–87, 2012, https://doi.org/10.1016/j.enbuild.2011.10.016

[4] A. Afshari, C. Nikolopoulou, and M. Martin, "Life-cycle analysis of building retrofits at the urban scale-a case study in United Arab Emirates," *Sustainability (Switzerland)*, vol. 6, no. 1, pp. 453–473, 2014, https://doi.org/10.3390/su6010453

[5] Lal. Jayamaha, *Energy-efficient building systems: green strategies for operation and maintenance*. McGraw-Hill, 2007.

[6] University of New South Wales., International Academy for Production Engineering., Engineers Australia., and Informit., *LCE 2008: 15th CIRP International Conference on Life Cycle Engineering; conference proceedings.* [CIRP], 2008.

[7] L. F. Xiao, S. Wang, C. Yan, and F. Xiao, "Quantitative energy performance assessment methods for existing buildings," *Energy Build*, vol. 55, no. December, pp. 873–888, 2012, https://doi.org/10.1016/j.enbuild.2012.08.037

[8] C. Fluhrer, "Achieving Radically Energy Efficient Retrofits: The Empire State Building Example," vol. 116, p. 2010, 2010.

[9] I. Nsw, "Business opportunities in a low carbon economy Final report Industry and Investment NSW," no. September, 2010.

[10] M. Krarti and K. Dubey, "Review analysis of economic and environmental benefits of improving energy efficiency for UAE building stock," *Renewable and Sustainable Energy Reviews*, vol. 82. Elsevier Ltd, pp. 14–24, 2018. https://doi.org/10.1016/j.rser.2017.09.013

[11] A. Aldawoud, F. E. Hosny, and R. Mdkhana, "Energy retrofitting of school buildings in UAE," *Energy Engineering: Journal of the Association of Energy Engineering*, vol. 117, no. 6, pp. 381–395, 2020, https://doi.org/10.32604/EE.2020.011863

[12] B. Akhozheya, M. Syam, R. Abdelghani, and K. A. T. Aoul, "Retrofit evaluation of a residential building in UAE: Energy efficiency and renewable energy," in *5th International Conference on Renewable Energy: Generation and Application, ICREGA 2018*, Institute of Electrical and Electronics Engineers Inc., Apr. 2018, pp. 238–242. https://doi.org/10.1109/ICREGA.2018.8337615

[13] Abu Dhabi Municipality, "Energy Efficiency Project for Sector E3-02," 2010.

[14] Advanced Instruments, "The Importance of Calibration." https://www.aicompanies.com/education-training/calibration/why-is-calibration-important/ (accessed May 13, 2023).

[15] Designing Buildings, "Air tightness in buildings," 2022. https://www.designingbuildings.co.uk/wiki/Air_tightness_in_buildings (accessed May 13, 2023).

[16] "Dubai Electricity & Water Authority (DEWA)," 2015. https://www.dewa.gov.ae/en/about-us/sustainability/lets-make-this-summer-green/set-your-ac-to-24 (accessed May 26, 2023).

[17] O. Jan, "Sensitivity Analysis," 2019. https://xplaind.com/167040/sensitivity-analysis (accessed May 13, 2023).

[18] K. Grygierek and I. Sarna, "Impact of passive cooling on thermal comfort in a single-family building for current and future climate conditions," Energies (Basel), vol. 13, no. 20, Oct. 2020, https://doi.org/10.3390/en13205332

[19] P. Reviewed, L. Berkeley, and B. Cancer, "Energy Information Handbook: Applications for Energy-Efficient Building Operations," no. July, pp. 35–43, 2010.

[20] J. D. Barbosa and E. Azar, "Modeling and implementing human-based energy retrofits in a green building in desert climate," Energy Build, vol. 173, pp. 71–80, 2018, https://doi.org/10.1016/j.enbuild.2018.05.024