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Article

A Critical Analysis of the Energy Requirements of a Commercial Building Based on Various Types of Glass Insulations

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Abstract: Heat loss through the building envelope comprises air leaks through the cracks and largely through the windows, which is the weakest link of the thermal envelope. Therefore, it is necessary to devise a systematic approach to analyze the rightful selection of glass for buildings. The investigation is to analyze the energy-saving potential of different glasses and their comparisons to the initial capital cost to find the payback time in terms of energy saving by using two different types of equipment. The quantitative simulation study was completed on the Hourly Analysis Program (HAP) to analyze the annual energy consumption of the HVAC system for seven glasses and two types of chilled water equipment. The results show that the performance glasses with a tint had better efficiency in terms of energy saving, with a payback time of 3–7 months. A comparison of all glasses illustrated that float glass contributes the most to the total cooling load among all glasses, which were 5.04%, 5.7%, 7.6%, and 8.9% for the N, S, E, and W orientations, respectively. Moreover, the lowest contribution of glass to the total cooling load was given by tinted double-glazed glass, which was 2%, 2.3%, 3.0%, and 3.01% for N, S, E, and W orientations, respectively.

Keywords: building energy; energy efficiency; HVAC; glass insulation

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1. Introduction

According to the report of the International Energy Agency, buildings use more than one-third of the total energy [1]. The vital demand for attaining thermal stability within buildings is growing, due to the exponential increase in population density at the global scale. In addition, the increase in living standards has also resulted in a further increase in energy demand. The energy that is used to fulfill the demand for thermal comfort in building facilities is usually a prominent proportion of the whole vitality requirement of the world [2]. A significant proportion of this energy is utilized by lighting, heating, ventilation, and air conditioning (HVAC), all of which have been impacted by the thermal and optical characteristics of a building's windows. Research into this subject has repeatedly stated that window thermal and optical features have a substantial influence on building energy usage, especially during hot conditions [3–5]. Such a requirement for energy is crucially important for both commercial as well as for domestic applications. Upon thorough consideration of the requirement and challenges of glass types or characteristics, it is undoubtedly necessary to devise a systematic approach to critically analyze the rightful selection of glass for buildings, with a particular interest in a localized environment.

According to the US Energy Information Administration (EIA), the recent advancement proportion shows that the world vitality requirement in 2040 will be 48% more than the demand in 2012 [6]. HVAC systems are essential to guarantee that building occupants have a suitable and healthy indoor environment. Buildings consume roughly one-third of the overall energy in developed countries. Regardless of the building's geometries, dimensions, suitable placements, and kinds of structure, the properties of facade materials should be analyzed to identify which of them will have a substantial effect on the building's overall effectiveness, and they may all be used to improve building energy efficiency [6]. While glazing is mandatory in the external façade of office buildings, it is crucial to employ nanotechnology-treated glazing within those frameworks in hot, dry areas, as it helps to minimize the heat transfer rate through all the outer envelope to the inside spaces and, moreover, promotes energy usage efficiency [7]. Widespread public awareness about carbon dioxide and nitrogen oxide (CO_2 and NOx) emissions, along with chlorofluorocarbons, has encouraged people to be continually interested in eco-friendly cooling and heating systems [8]. The recent advancement in the technology sector has a lot of means to find or calculate the energy usage throughout the year in the building, and find the impacts of architectural materials. Energy usage can be monitored while linking the Internet of things (IoT) with the building structure. Many physical objects may be connected to the Internet via the Industrial Internet of Things (IoT). To store all the data in this situation as effectively as possible, a coherent architecture is required. For the Internet of Things, several academics have put out numerous architectural models, but none of them have yet met all architectural requirements. Sensors are first positioned at the perception layer in order to generate and communicate information through wireless technologies into the network topology. The concept, networking, middleware, algorithms, and business layers make up the Internet of Things [9].

In several regions, optimum window dimensions are regulated to mitigate glare and warmth concerns [10,11]. This factor, though, eliminates various factors that have a significant effect on thermal loads, which includes orientation. The influence of window film on curtain wall glazing system stability varies substantially determined by the type of film used and how it is placed. If placed on the outside and inside of window frames, the layers can minimize the SC (Shading Coefficient) and solar heat gain factor by 44 and 22 percent, respectively. The building cooling load through the use of the glass on design day can be minimized by 27% and 2.2% for exterior and interior window films, correspondingly, for the double-pane, low-E glazing system [12]. The weather data are also very essential for the calculation of the cooling load and have a high impact on the solar load by glass. There is a CLIMWAT 2 module tool where the weather data of a specific region for a long period of time on a monthly average basis are available, which could be helpful in analyzing the climate of that region [13]. Whereas the ecological and financial consequences of energy efficiency might well be explained, in essence, incorporating that knowledge into the real estate management policy in order to create a consensus upon the standard for enhancing the thermal efficiency of operational facilities has been found to be problematic. This dilemma reflects a lack of mentioned features for managing and employing sustainable real estate buildings [14]. For energy conservation analysis, the selection of cooling/heating systems by analyzing their heat transfer method and efficiency is a very critical part. Many of the systems currently in use for the transfer of excessive heat rely on the two-phase heat exchange, i.e., capillary pump loops and loop heat pipes. The benefit of such methods is that they are able to transfer heat up to several meters at any position within the gravitational field. The loop fluid absorbs heat, and the vapors that are produced are evacuated to a condenser, where the heat is dispersed either by water cooling or air cooling. A wick construction often ensures the condensate's return. The heat transfer through the used source material can be enhanced by proper study of material specifications and can improve the efficiency of the equipment [15].

Jaber et al. [16] presented an evaluation of the ideal building orientations, window size, and thermal insulation thickness from such an energy, economical, and environmental perspective for a typical Mediterranean residential construction. The findings revealed that by selecting the optimal orientation, size of windows, shading devices, and insulation thicknesses, about 27.59 percent of yearly energy consumption could be reduced.

Alobeidi et al. [17] assessed the effects of the use of smart materials in contemporary building facades by the classification, different kinds, and significance in the architecture of smart materials, as well as the evaluation of a series of contemporary building facades and their technological and environmental consequences. Samy et al. [18,19] investigated the relationship between architectural and modern material science, particularly smart materials that can detect their environments, such as living systems, through analytical research of several types of smart materials. The study concluded that materials are a basic constituent with a technique that can be officially accepted and efficient for each phase of the design process, and the use of these materials improves building sustainability, so a comprehensive approach to a new model of innovative architectural design was proposed.

Cheong et al. [20] conducted a comparative simulation analysis to investigate the influence of glass type on the thermal environment and day lighting in a heavily glazed residential structure. According to the study, upgrading the glass type decreases cooling load and power cost. Stavrakakis et al. [21] introduced a unique computational technique for optimizing window design for indoor thermal comfort in naturally ventilated structures. They discovered that when the height of one of the apertures increases, the thermal feeling will be improved. Using dynamic simulations in an educational facility, Zomorodian and Tahsildoost [22] investigated the impact of window design on visual and thermal comfort. The study's findings showed that solar control laminated glass with low SHGC and strong visual transmission might be a substitute for solar shadings.

Lashgari et al.'s [23] work illustrates the energy demand forecast, which was built on metaheuristic algorithms in Taiwan. Three alternative models—linear, exponential, and quadratic—were used for the predictions, and the coefficients of each were optimized. The outcomes demonstrate that the suggested technique has more intricacy and requires a longer execution time due to the implementation of an upgraded metaheuristic algorithm. It is preferable to work on a more straightforward version of the provided solution to fix this issue. Future research will demonstrate a novel approach to offer a reasonable compromise between an effective solution and a dependable answer based on improved fuzzy systems.

Lee et al. [24] used regression analysis to analyze the influence of glazed windows on the electrical energy consumption in five typical Asian climate zones; the key finding of such research is that the Wall-to-Window ratio (WWR) should be minimized, excluding the north-facing opaque wall, and window location is highly dependent on climatic conditions [25]. Jin et al. [26] made a comparative analysis of 13 glazed window types on the exterior of a typical cellular office. The research shows that high-glazing techniques, such as photo-voltaic interconnected glazing, offer significant improvements in terms of both power consumption and indoor air quality over opaque shielded walls and traditional shielded glazed windows, including for substantial glazed envelopes.

Stepan et al.'s [27] work related to energy saving due to the technical means which are used in construction. Energy conservation improves the quality of life for people worldwide by reducing pollution and reducing environmental impacts. Efficiency also provides employment opportunities and reduces running costs. All disruptive effects on the thermal regulation of a heated area or object should always be taken into consideration in order to design an energy-efficient system of autonomous heat delivery. Based on the results, it is essential to periodically evaluate the equipment, which necessitates further capital but can save costs.

Robert Hart et al.'s [28] research related to the thermal efficiency and potential of the annual energy impact of thin-glass triple-pane glazing in US residentials. Heat transfer through the use of the external walls and subsequent air leakage comprise the majority of HVAC loads in most regions, while windows, considered the weakest link in the thermal envelope, are accountable for roughly about 10 percent of the total building vitality usage. As a consequence, windows provide considerable potential for saving energy in dwellings. High-performing glass, such as triple glaze, accounted for less than two percent of the total US window revenue in 2016, which has remained the same since they usually required a thorough and exclusive redesign of the standard glass frame. Improving the glazing with such a slender triple-pane design that would not demand adjustments in the existing frame and sash is one low-operation, additional-cost option to kick start the market. This research initially gives a detailed description and performance of today's "average" residential windows by analyzing the National Fenestration Rating Council (NFRC) and Certified Products Directory (CPD) standards.

Considering the literature reported, it is highlighted that there is a need to improve the energy efficiency of the buildings to ensure long-term sustainability in terms of energy usage. This study is to analyze the thermal performance of seven various types of glasses and compare it at each orientation, e.g., north, south, east, and west (N, S, E, W). The bin method is employed to ascertain the annual energy consumption and cost savings by utilizing absorption and centrifugal chiller equipment. Such a comprehensive investigation, including various types of insulation glass, the effect of orientation, and HVAC equipment for the sake of improving the energy efficiency of buildings, is not hitherto reported in the literature.

2. Methodology

A supermarket building in Karachi, Pakistan, with different requirements, was categorized as an experimental setup on which the whole calculations and system were designed. The schematic of the supermarket is given in Figure 1. Total area of the supermarket was 4710 m^2, one side was exposed, and all other sides had existing buildings (two sides had partitions and one side was conditioned area). There were eight windows of dimensions 7.1 m $\times$ 4.3 m, which were situated on the exposed wall. The total area of the exposed wall was 298.2 m^2.

The simulation was performed by using the hourly analysis program (HAP), which is based on the heat balancing approach where surface's temperatures are the component of the calculations. The parameters that were used in the cooling load calculations were taken from the ASHRAE (American Society of Heating, Refrigerating, and Air-conditioning Engineers) Standards. Thermal comfort estimations were unachievable without details about the internal surface temperatures. The temperature that was to be achieved in the building was 24 °C. All the parameters except glass and orientations will remain same. The bin method was used for the analysis of the energy conservation of the building throughout the years.

The various parameters influencing the simulation or study are explained in the following sections.

2.1. Weather Data

Weather data that were used for the analysis or calculations are given in Table 1.

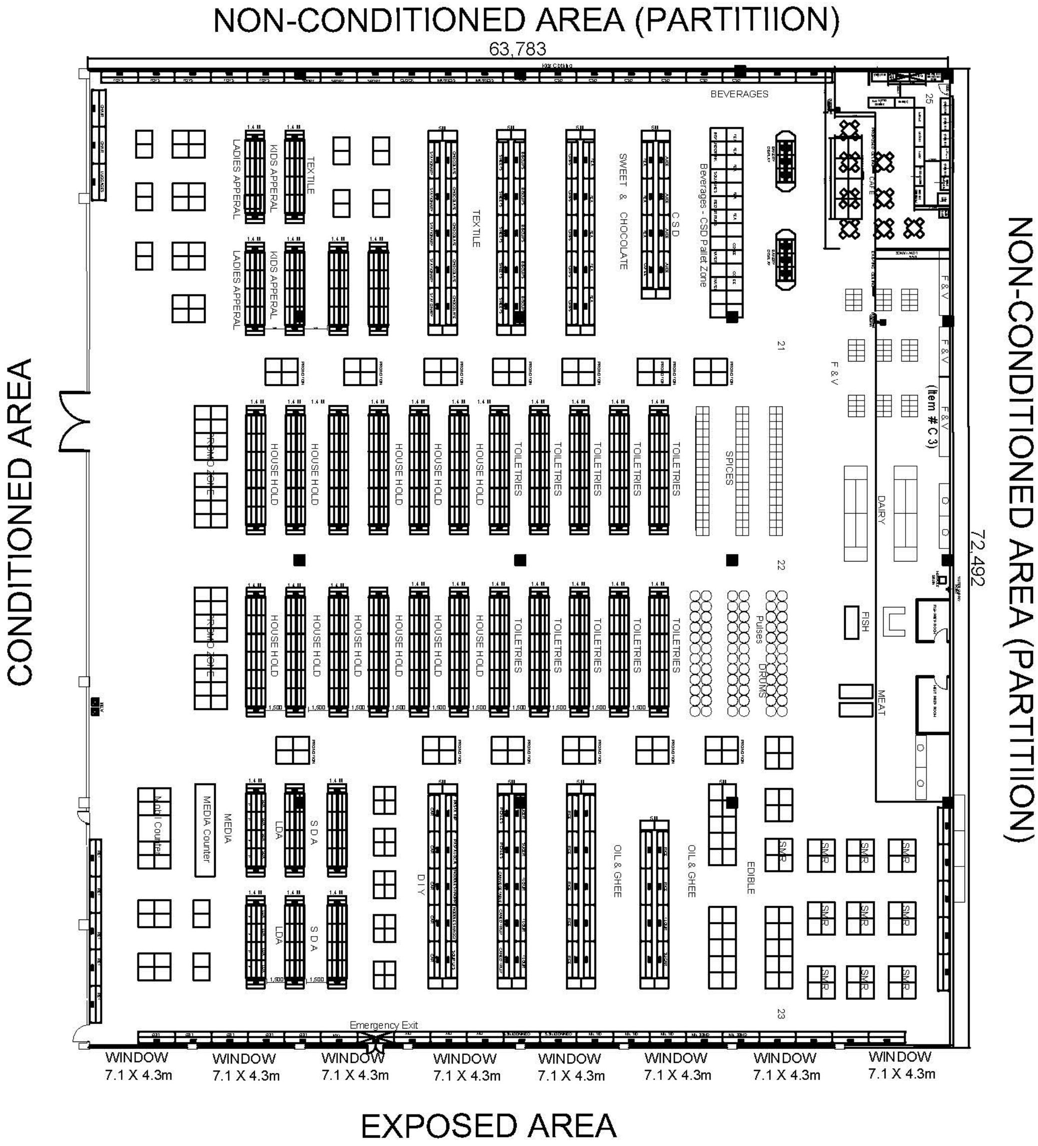

Figure 1. Schematic of commercial building.

Table 1. Weather data.

Location	Karachi, Pakistan
Latitude	24.9 N
Longitude	67.1 E
Elevation	22.0 m
Summer design db	38.9 °C
Summer coincident wb	22.6 °C
Summer daily range	6.2 k
Winter design db	10 °C
Winter coincident wb	5.5 °C
Time zone	+5.0 GMT

Weather data are essential for proper building load estimations as well as HVAC system assessments. The performance of primary and secondary HVAC systems is heavily influenced by outside air conditions such as dry and wet bulb temperatures, moisture, and solar radiation. Users of energy modeling software have access to a variety of meteorological data sources. The data ranges from local data obtained to data from preselected typical years. Such data sets contain a year's worth of hourly data synthesized to reflect long-term analytical correlations in meteorological data over a longer time period. According to one research, there is just a 5% variation across common meteorological data sets. The effective analysis of HVAC system configurations is ensured by the exact incorporation of the building load and meteorological profile with the system model. Building load profile and weather data are correctly linked to the total HVAC system model.

2.2. Types of Glasses

There are seven types of glass that were used in the calculation whose specifications VLT (Visual Light Transmittance), VLR_{ext} (Visual Light Reflectance Externally), VLR_{int} (Visual Light Reflectance Internally), U-Value (Thermal Transmittance), and SC (Shading Coefficient) are given in Table 2.

The frame is not included in the glass because topic of discussion in this paper is glass. The solar heat gain coefficient of glass is much greater than that of the conventional frame, which leads us to the fact that adding a frame will reduce the total heat gain of entire glazing (which also include the frame).

There are many types of glass that are discussed here. Float glass is the most basic form of glass. It is formed by pouring the molten glass upon a bed of tin. This is a strip of untreated glass that is characterized just after the procedure of transforming molten glass into a larger panel, inside which molten glass floats on top of molten tin, resulting in a smooth yet slender glass panel. Low E glass is also the type of glass being used to diminish the influence of sun rays on the structures. As the names indicate, it has a low emissivity and serves to reflect the sun away from the structure in the summer. Laminated safety glass is a frequent choice for many people apprehensive regarding security or who demand heavier glass. To form a durable glass panel, two panes of glass are merged together through a film of polyvinyl butyl by employing a substantial amount of heat and pressure fusion. Tinted glasses are obtained by adding tint or color to the glass, generally for aesthetic reasons. Furthermore, it could also be used to minimize the intensity of solar radiation that travels through and, in some circumstances, to provide a shield against Ultraviolet radiation. Double-glazed glass is formed by connecting two layers of glasses together by a modest insulated spacer (such as air or inert gasses) to minimize heat transmission through the window [29,30].

Table 2. Types of glass and their technical perimeter [31].

Sr. No.	Description	Area of Glass	Price of Glass	Price of Glass	VLT	VLR_{ext}	VLR_{int}	U Value	SC
		m^2	PKR/m^2	PKR	%	%	%	(W/m^2 K)	
Type-1	Float 6 mm (clear glass)	244	721.16	175,963	88	—	—	5.7	0.94
Type-2	Single glaze 6 mm, (clear glass)	244	983.4	239,950	69	9	11	4.1	0.7
Type-3	Single glaze 6 mm, (blue glass)	244	1278.42	311,934	35	10	26	4.4	0.43
Type-4	Laminated, 6 mm clear 0.76 mm Clear PVB + 6 mm sunergy clear glass	244	1475.1	359,924	67	9	11	3.9	0.62

Table 2. *Cont.*

Sr. No.	Description	Area of Glass	Price of Glass	Price of Glass	VLT	VLR_{ext}	VLR_{int}	U Value	SC
		m^2	PKR/m^2	PKR	%	%	%	(W/m^2 K)	
Type-5	Laminated, 6 mm clear + 0.76 mm clear PVB + 6 mm sunergy blue glass	244	2032.36	495,896	34	10	26	4.2	0.4
Type-6	Double glazing unit 6-12-6, 6 mm sunergy + 12 mm 100% air + 6 mm clear (clear glass)	244	2982.98	727,847	62	13	17	2.1	0.6
Type-7	Double glazing unit 6-12-6, 6 mm sunergy + 12 mm 100% air + 6 mm clear (blue glass)	244	3212.44	783,835	32	11	19	2.3	0.33

2.3. Construction Material for the Exposed Wall and Roof

The construction of the exposed wall that was used while calculating the HVAC load of the building is given below in Table 3.

Table 3. Construction material of exposed wall.

Layers/Material	Thickness (mm)	Resistance Value m^2-K/W
Outside Surface Resistance	—	0.11975
Outside Plaster	13	0.01996
Concrete Block	203	0.17
Inside Plaster	20	0.0307
Outside Surface Resistance	—	0.04403

The construction of the exposed roof that was used while calculating the HVAC load of the building is given below in Table 4.

Table 4. Construction material of exposed Roof.

Layers/Material	Thickness (mm)	Resistance Value m^2-K/W
Outside Surface Resistance	—	0.16202
22 Gage Steel Deck	0.853	0.00002
PU	50	1.19
22 Gage Steel Deck	0.853	0.00002
Outside Surface Resistance	—	0.04403

2.4. Orientations

In the calculations of the cooling load, window type and the orientation of the building were the variables that helped to analyze the data at each selected orientation and the type of glass while considering all the remaining constant factors such as equipment heat, occupancy, exposed wall area, etc. Orientation has a substantial impact on the building due to the direction of the sun. Maximum solar heat gain is different for different orientations because it depends upon the movement of the sun across the building, which needs to be determined. Therefore, north, west, south, and east (N, W, S, and E) were the specified orientations that were considered for the calculations.

2.5. Time of Operations

The time of operation of the supermarket was 8 A.M. to 12 A.M. During this time span, the whole system was running, and the rest of the time supermarket remained closed. Time of operation helped in the calculation of the annual energy consumption analysis. The schedule or time of operation that was used in the HAP calculations is given in Figure 2.

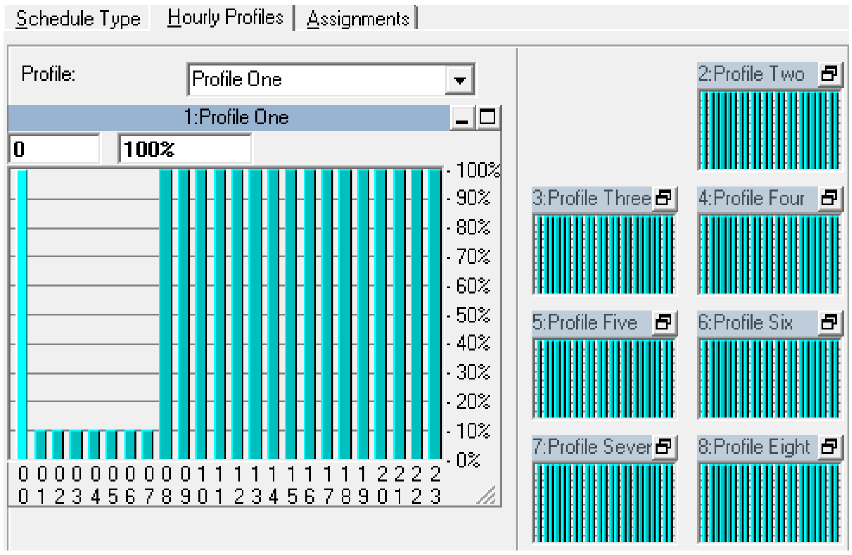

Figure 2. Time of operation set for the calculation in HAP.

2.6. Solar Irradiation

The solar heat gain is the summation of radiation emitted and absorbed that travels inward. Because energy is also transported through the glass anytime there is a temperature difference between the exterior and interior sides of the window, the total rate of heat admitted through the glass is as follows: first two parts are related to solar radiation, and the third part is related to the heat flow through the conduction that is the property of the material [32]. So, the relation of total heat admitted via glass becomes

Total heat admitted via glass = (Radiations Transmitted via glass) + (Inward flow of absorbed radiation) + (heat gain via conduction) (1)

2.7. Clear Sky Model

The total solar radiation incident on the surfaces is the summation of the direct radiation, diffused radiation, and reflected radiation, which is shown in the following equation.

$$G_t = G_D + G_d + G_R \tag{2}$$

$$G_t = [Max(\cos\theta, 0) + \frac{G_{dV}}{G_{dH}}C + \rho_g F_{wg}(\sin(\beta + C)]G_{ND} \tag{3}$$

where

G_D = direct irradiation = GND max (cosθ, 0)
G_d = Diffuse irradiation on the horizontal surface = $\frac{G_{dV}}{G_{dH}}CG_{ND}$
G_R = Reflected irradiation = $G_{ND}\rho_g F_{wg}(\sin(\beta + C)$

G_{ND} = Normal direct irradiation, Btu/(hr-ft2) or W/m2 = $\frac{A}{\exp\left(\frac{B}{\sin\beta}\right)} C_N$

C_N = Clearness number

θ = The angle of incidence between the sun's rays and the normal to the surface

β = Solar altitude

F_{wg} = Configuration or angle factor from wall to ground, which can be illustrated as the ratio of radiation leaving the wall of interest that hits the horizontal surfaces or the ground directly

ρ_g = Reflectance of ground or horizontal surface

$\frac{G_{dV}}{G_{dH}}$ = Fraction of diffused sky radiation incident on a vertical surface to that of the incident on a horizontal surface during clear days

2.8. Solar Heat Gain Coefficient

Heat gain, even for the smallest window, is illustrated by the fact that the windows are limited in size, they are enclosed, and rays hit them at different angles during the day. To completely account for all of the complications, spectrum techniques (using monochromatic radiation characteristics) must be used, as well as the angular radiation properties involved [9].

The portion of the incident irradiance (incident solar energy) that come in contact with the glass and become a part of the heat gain.

$$q_i = \dot{G_i}(SHGC) \tag{4}$$

where *SHGC* is the solar heat gain coefficient, and G_i is the incident irradiation that enters the glazing. The solar heat gain factor of the glazing may be calculated for a variety of sample windows. There are two solar heat gain coefficients of interest: one for direct sunlight at the actual incidence angle ($SHGC_{gD}$) and one for diffused radiation ($SHGC_{gd}$). Linear interpolation was used to calculate $SHGC_{gD}$.

After determining the values of $SHGC_f$, $SHGC_{gD}$, and $SHGC_{gd}$, the total solar heat gain of the window was calculated by applying direct radiation to the sunlit section of a fenestration and directed and diffused radiation to the whole fenestration:

$$q_{SHG} = \left[SHGC_{gD}A_{sl.g} + SHGC_f A_{sl.g}\right]\dot{G}_{D\theta} + \left[\,SHGC_{gd}A_g + SHGC_f A_f\,\right] G_{d\theta} \tag{5}$$

$$\dot{q}_{CHG} = \dot{U}(t_o - t_i) \tag{6}$$

where U is the thermal transmittance for the fenestration and $(t_o - t_i)$ is the difference between indoor and outdoor temperatures.

2.9. Bin Method

The bin approach [10] is a computer-aided or manual process used for determining power demands under a variety of outside temperature situations. Weather data in the form of five F bins with the hours of occurrence for each bin were used. The bin approach was built on the concept that almost all the hours in a month, season, or year when a specific temperature (bin) occurred may be collected together, and a power estimate can be produced for all those hours with the equipment running under those specific conditions. The procedure for finding the annual energy consumption using the bin method is given below in Figure 3:

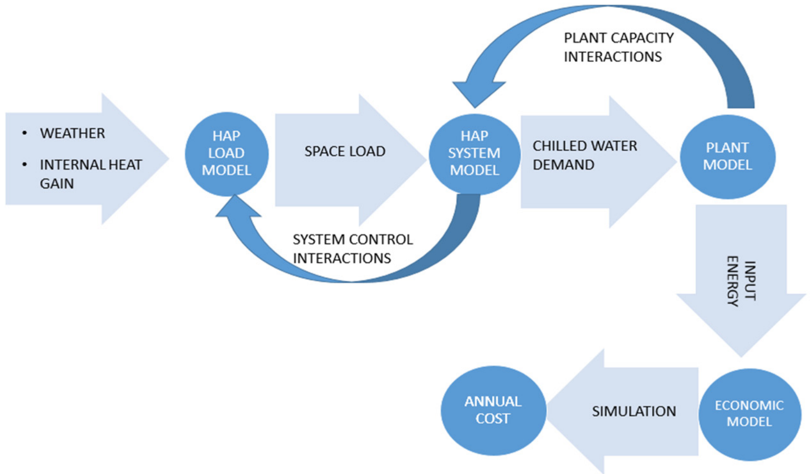

Figure 3. Schematic diagram of bin method.

First of all, the building load was calculated by using HAP. The unit capacities for specified regions or spaces were specified. The fraction of theoretical run time was determined, as it is the ratio of the building capacity to the unit or equipment capacity. Then, the partial load fraction and the fraction of actual run time were calculated by using Equations (6) and (7), respectively. The actual run time was calculated from the product of bin hours and the actual run-time fraction. Then, the total annual power used was deduced from the product of power input and actual run time of the system. According to the per unit rate of power for a specified region or building, the total running cost of the equipment was calculated. These steps were repeated for all bins.

$$PLF = 1 - D_c \left[1 - \frac{Building\ Load}{Unit\ Capacity}\right] \tag{7}$$

$$PLF = \frac{Theoretical\ Run\ Time}{Actual\ Run\ Time} \tag{8}$$

2.10. HVAC Equipment

There are different parameters of equipment, such as working temperatures, input power, coefficient of performance (COP), etc., required as an input for calculation purposes. Perimeters or values and the cost of the energy that was used for the calculation are given in the following Table 5.

2.11. Payback Time

The payback period (PBP) is the time taken for a consumer to reclaim the expected higher buying price of much more efficient equipment due to reduced running expenses. The PBP was measured as the proportion of the rise in purchasing expenditure (from the less effective system towards a more effective system) to reduce yearly operational expenses. This method is regarded as a "simple" payback period since it does not account for differences in operational expenses over time or the time value of money [33].

$$PBP = \frac{\Delta IC}{\Delta OC} \tag{9}$$

where ΔIC is the difference in the overall implemented cost between a more economical standard level and the base case design, and ΔOC represents the difference in yearly operational expense. *PBP*s are measured in years. *PBP*s larger than that of the product's life indicate that the higher total installation cost is really not repaid in lower operational expenses.

Table 5. Technical perimeters used for the energy analysis and cost of the energy.

Description	Value
Centrifugal Chiller	
Full load LCHWT (Leaving Chilled Water Temperature)	6.7 °C
Full load LCWT (Leaving Condenser Water Temperature)	29.4 °C
Input Power (ikW/kW)	0.171
Min ECWT (Entering Condenser Water Temperature) Set Point	15.6 °C
Chilled Water Supply Flow Rates	2.4 GPM
Condenser Water Supply Flow Rates	3.0 GPM
Absorption Chiller	
Full load LCHWT (Leaving Chilled Water Temperature)	6.7 °C
Full load LCWT (Leaving Condenser Water Temperature)	29.4 °C
Full Load Burner Input (ikW/kW)	0.715
Min ECWT (Entering Condenser Water Temperature) Set Point	15.6 °C
Chilled Water Supply Flow Rates	2.4 GPM
Condenser Water Supply Flow Rates	4.5 GPM
Fuel Rates	
Electricity (kWh)	23.00 PKR/Unit
Natural Gas (MMBtu) (1.0 MMBtu = 293.07 kWhr)	1283.0 KR/Unit

3. Results and Discussions

3.1. Contribution of Solar and Conduction Load

The total cooling load due to the window glass is the combination of solar radiation (transmittance, reflectance, and absorbance) and the conduction through the glass material. It can be seen from the results, which are shown in Figures 4–7, that the load occurring through conduction remains the same at every orientation for each glass separately because conduction depends only on the type of material and its properties. It can be observed from Figures 4–7 that the conduction load varies as the material changes due to the composition of each glass being different from the others. The conduction load is maximum at the float glass (Type-1), which is 19.07 kW, and minimum at the double-glazed clear glass (Type-6), which is 7.03 kW. The conduction load for the type-6 glass was slightly less than the Type-7 glass, which was 7.70 kW because Type-7 was colored glass and color absorbed more radiation than clear glass because of the blackbody radiation concept. On the other hand, the solar load depended on the solar transmittance, reflectance, and absorbance of the solar radiation through the glass, which was actually dependent on the type of glass, color, and direction of the sun. It can be observed from Figure 5 that being north facing has the least impact on the building, which is at maximum load (19.5 kW) for the clear float (Type-1) glass and at minimum load (6.85 kW) for the double-glazed (Type-7) glass with tint. The orientation which has shown the highest impact on the building with respect to the solar load was west. The maximum load occurred for Type-1 glass, which was 52.83 kW, and the minimum for the double-glazed glass with a tint, which was 14.57 kW. Although, the results of solar and conduction shown within this paper are for the buildings located between the equator and the 30th parallel north. If a building were located in the hemisphere below the 30th parallel south, the results of solar load on the southern and northern facing or orientation of a building would contribute a significant increase in the solar load to the building comparable to our building of discussion in this paper, where the results of solar on northern and southern orientations are minimal. Moreover, it was observed from the results that colored glass has shown good results against solar radiation but has more conduction load than clear glass, and vice versa.

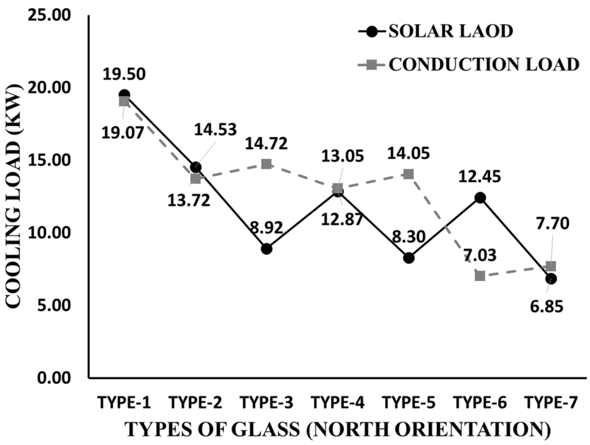

Figure 4. Contribution of conduction and solar load at north orientation.

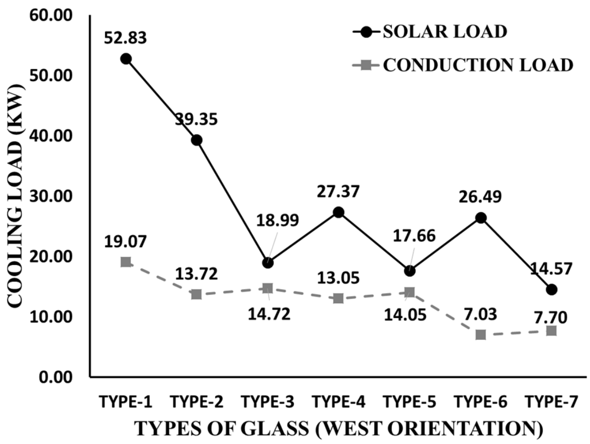

Figure 5. Contribution of conduction and solar load at west orientation.

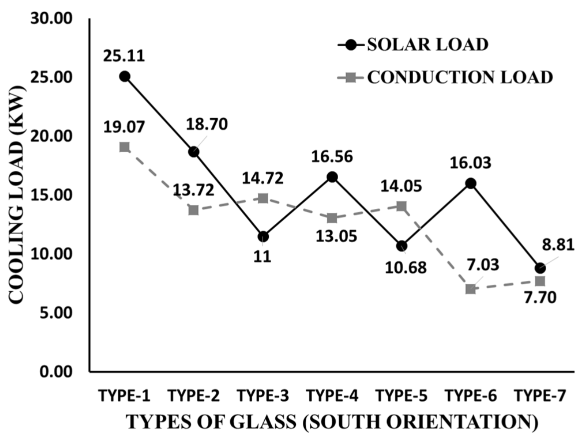

Figure 6. Contribution of conduction and solar load at south orientation.

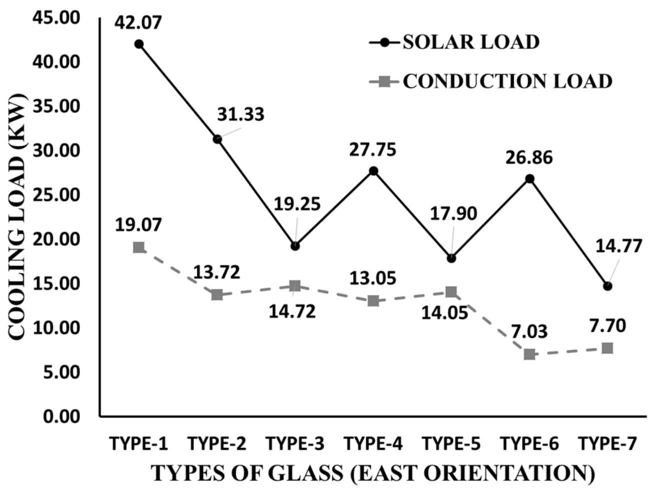

Figure 7. Contribution of conduction and solar load at east orientation.

3.2. Contribution of Glass Load in Total Cooling Load

The bar graph represents the peak cooling load of the building occurring at any one time within the year by keeping all the parameters constant except glass and orientation given in Figures 8–11, which was drawn from the hourly analysis program computational simulation tool at each orientation. Figures show that the contribution of glass occurs at the time of peak load in percentage at each facing of the building. A comparison of all glasses illustrated that the float glass (Type-1) contributes the most to the total cooling load among all glasses, which was 5.04%, 5.7%, 7.6%, and 8.9% for the N, S, E, and W orientations, respectively. Moreover, the lowest contribution of glass to the total cooling load was given by the double-glazed glass with tint (Type-7), which was 2%, 2.3%, 3.0%, and 3.01% for N, S, E, and W orientation, respectively. Lower SHGC and U values indicate the glass has less conduction of heat through the glass and less transmittance, absorbance, and reflectance through the glass. As can be seen from Figures 8–11, the maximum contribution of glass to the total cooling load was from the west side because the west direction has maximum solar flux, and the minimum load occurs from the north.

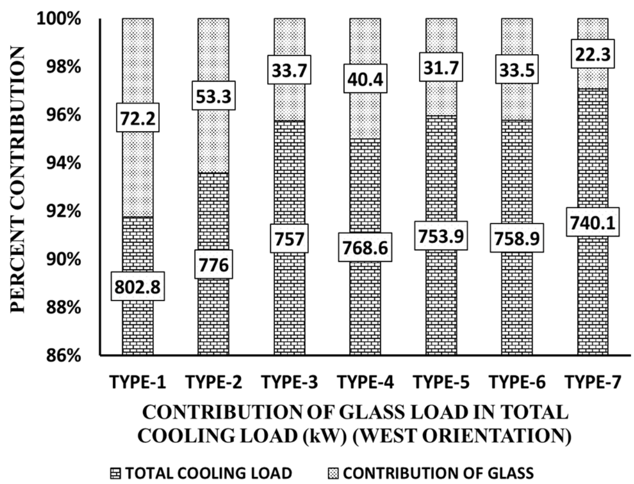

Figure 8. Contribution of glass load in total cooling load at west orientation.

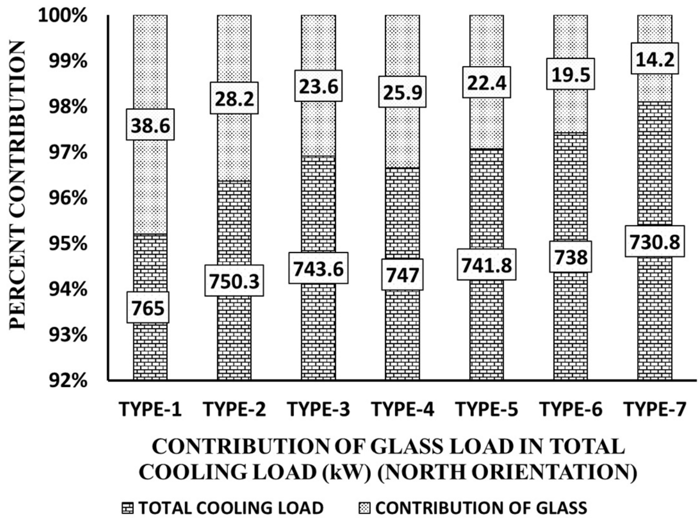

Figure 9. Contribution of glass load in total cooling load at north orientation.

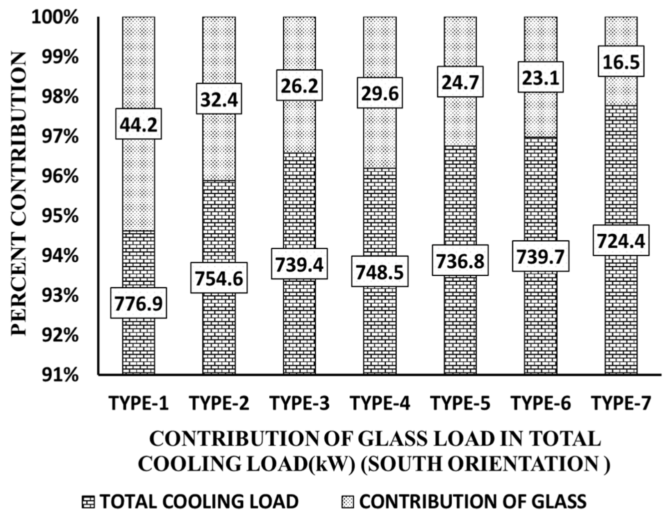

Figure 10. Contribution of glass load in total cooling load at south orientation.

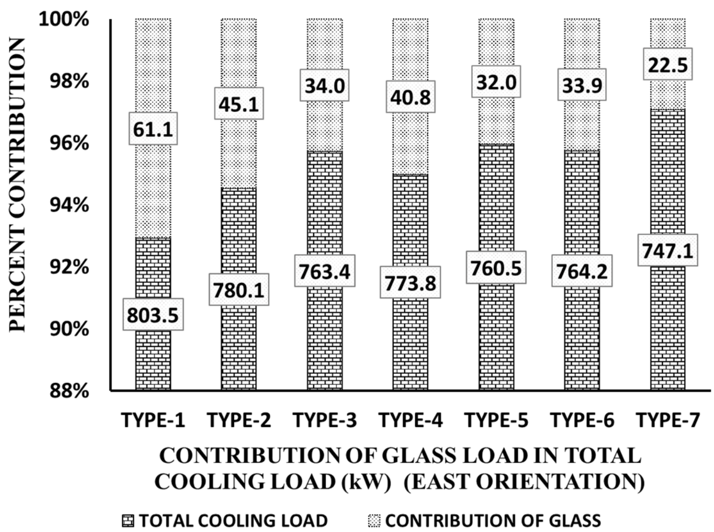

Figure 11. Contribution of glass load in total cooling load at east orientation.

3.3. Annual Energy Consumption and Running Cost

Equipment selection is very important because each piece of equipment has a different performance value and energy consumption. Additionally, two types of equipment (e.g., centrifugal chiller and absorption chiller), which are operated on different cycles, were selected to compute the energy consumption throughout the years. The annual energy consumption of the HVAC equipment was calculated from the hourly analysis program (HAP) computational tool by giving information about the equipment and software following the bin method for the calculation of annual energy consumption, which requires the performance values of the equipment. The annual energy consumption of both pieces of equipment is shown in Tables 6 and 7. Centrifugal chillers have a COP of 5.8, and absorption chillers are working on a COP of around 1.39. The fuel or input power required for the centrifugal chiller is only electricity. On the other hand, the absorption chiller uses both electricity and fuel (natural gas is used as a fuel). It can be seen from the result that the east and west sides have shown maximum results with minor differences, and the north side has shown minimum energy consumption.

Table 6. Annual energy consumption by using centrifugal chiller.

Types of Glass	Annual Energy Consumption in Kilowatt Hour (Centrifugal Chiller)			
	S	**N**	**W**	**E**
Type-1	1,220,024	1,168,957	1,215,013	1,211,717
Type-2	1,180,013	1,148,859	1,180,307	1,183,036
Type-3	1,147,631	1,138,555	1,153,551	1,162,538
Type-4	1,168,089	1,144,152	1,170,625	1,175,333
Type-5	1,143,121	1,136,058	1,149,516	1,158,924
Type-6	1,157,328	1,132,920	1,158,075	1,163,586
Type-7	1,125,477	1,122,001	1,131,779	1,142,489

Table 7. Annual energy consumption by using absorption chiller.

Types of Glass	Annual Energy Consumption (Absorption Chiller)							
	S		**N**		**W**		**E**	
	kWhr	**MMBTU**	**kWhr**	**MMBTU**	**kWhr**	**MMBTU**	**kWhr**	**MMBTU**
Type-1	774,365	8170	742,932	7848	775,568	8073	771,357	8090
Type-2	748,534	7941	730,770	7722	752,549	7883	752,939	7924
Type-3	727,929	7752	725,087	7648	734,872	7735	739,835	7801
Type-4	740,859	7874	728,020	7691	746,133	7830	747,991	7878
Type-5	725,061	7725	723,588	7632	732,276	7712	737,542	7780
Type-6	734,041	7810	720,796	7627	737,948	7760	740,404	7812
Type-7	713,899	7621	714,729	7550	720,764	7612	726,946	7686

It can be seen in Figures 12–15 that the centrifugal chiller equipment showed less energy consumption and annual running cost than the absorption chiller-based equipment. Although there was a minor difference in terms of the annual running cost of the equipment, the COP of the absorption chiller was 4.4 times less than the centrifugal chiller. This was because of the cost difference between natural gas and electricity. The cost of natural gas was much less compared to electricity, as shown in Table 5.

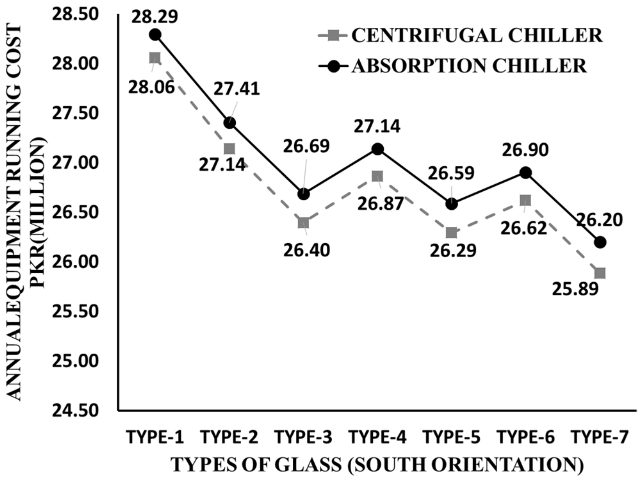

Figure 12. Annual equipment running cost at south orientation.

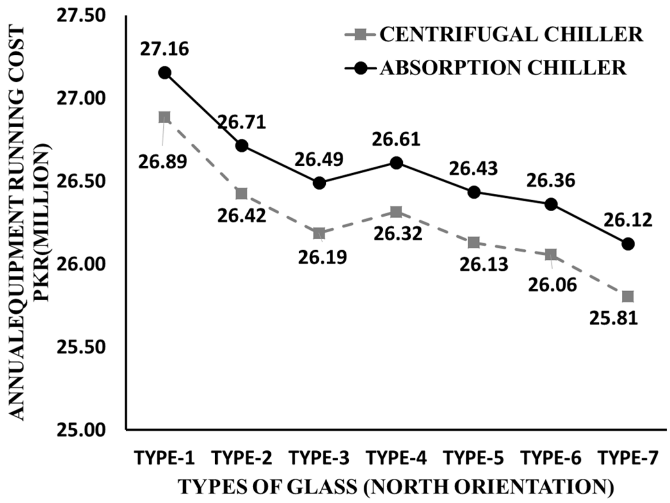

Figure 13. Annual equipment running cost at north orientation.

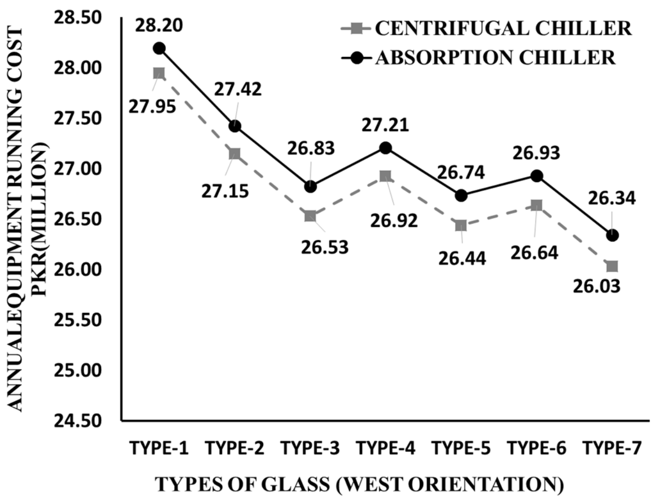

Figure 14. Annual equipment running cost at west orientation.

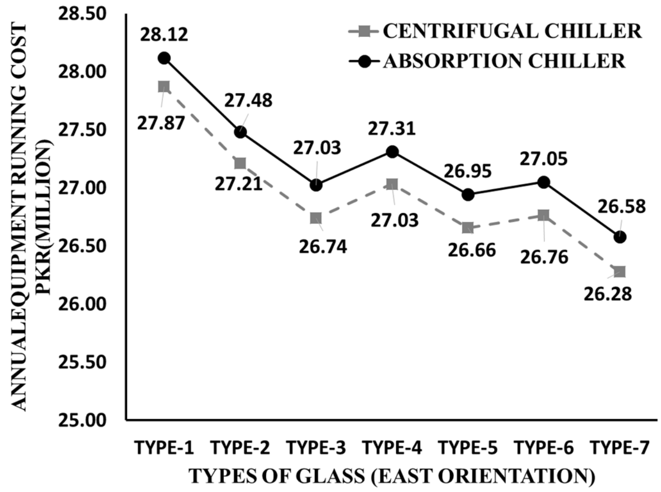

Figure 15. Annual equipment running cost at east orientation.

It is concluded from the results that the float glass was the cheapest glass of all but had the highest contribution in the load as well as in annual running cost. On the other hand, double-glazed glass was almost four times the price, but it saves almost more than PKR 1 to 2 million annually with respect to the orientation that the exterior wall faced. There is uncertainty between the results of the trend of the north-facing orientation graph, which is slightly different from the others because of the difference in the solar and conduction load. It can be seen in Figures 4–7 that the conduction load was the same for each material throughout each orientation, but the solar load changed. Solar load is very small on the north side, and the combined effect of solar and conduction load shows a small variation. The separate effect of solar and conduction load showed no variation in trend at each orientation.

3.4. Annual Cost Saving

It can be observed from Figures 16–19 that the total annual cost-saving potential of double-glazed glass with tint (Type-7) is the highest among all the glasses, as shown in the given results, and it could save PKR 1.08 to 2.17 million per annum with respect to the least efficient glass (Type-1), which was higher than the initial capital of the glass at PKR 0.784 million. Double-glazed blue color glass can easily pay back extra initial capital to buy highly efficient performance glass in 3 to 7 months in terms of a system running cost depending on the equipment load and directions, because the initial cost difference between the highly efficient glass and the least efficient glass was 4.45 times.

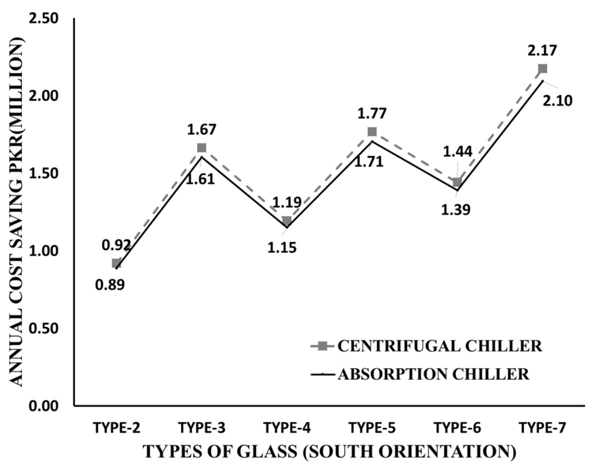

Figure 16. Annual cost saving at south orientation.

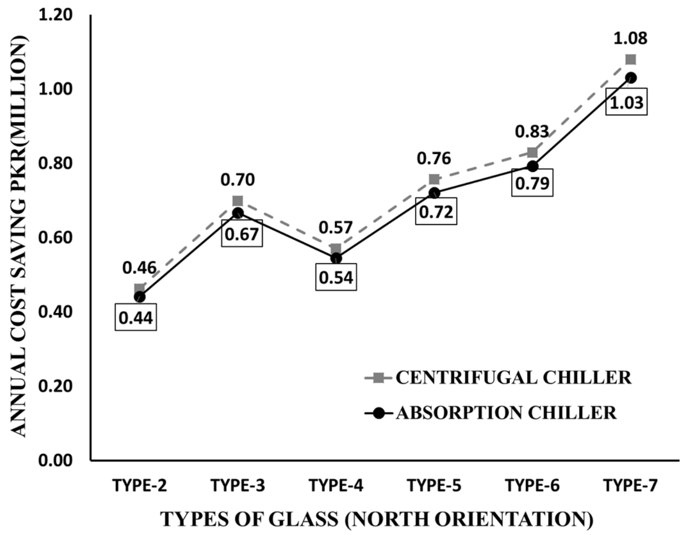

Figure 17. Annual cost saving at north orientation.

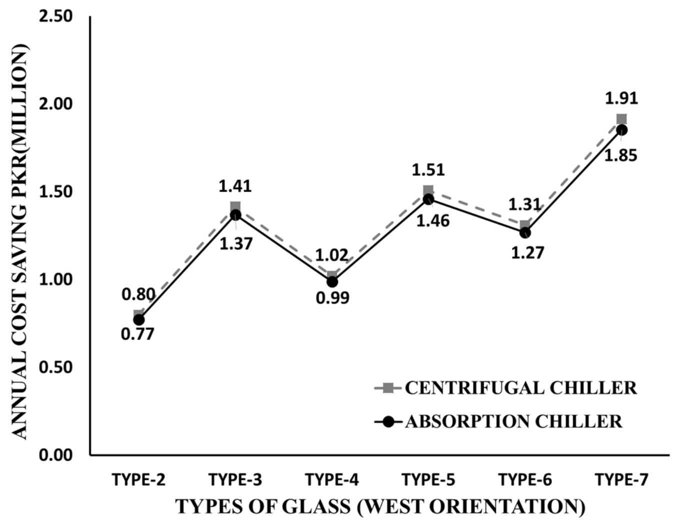

Figure 18. Annual cost saving at west orientation.

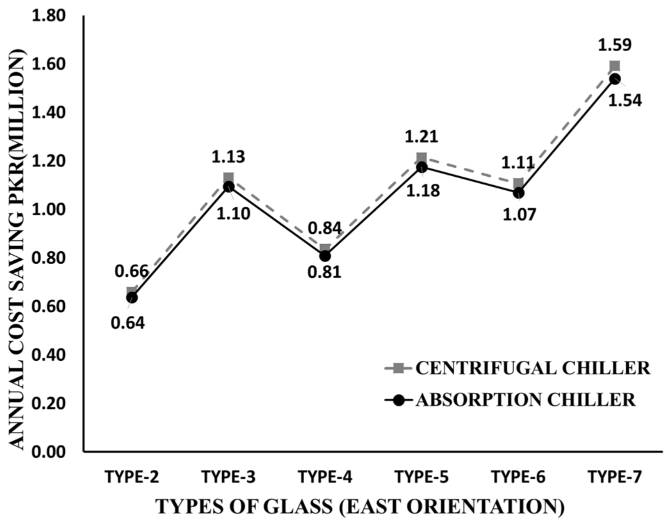

Figure 19. Annual cost saving at east orientation.

4. Conclusions

The current study concluded that performance glass (e.g., Type-6 and Type-7) with high efficiency and higher cost could save more energy as compared to cheap glass (e.g., Type-1). Although it can be seen from Table 1 that the capital cost of the double-glazed glass with blue tint is 4.45 times higher than the float glass, it can save PKR 1.03 to 2.17 million depending on the orientation of the building, which can easily pay back in 3 to 7 months depending on the orientation in terms of the running costs of the equipment, which can be seen from Figures 16–19.

It can also be seen from the results shown in Figures 4–7 that the E and W orientations show a higher impact on the building because of the solar flux or solar heat gain that was showing its maximum value at E and W orientation. Moreover, the conduction load of each glass remains the same at every orientation because it is the property of the material; however, the solar heat gain through the glass changes at every orientation because it depends on the direction of the solar radiation. It is realized that the west and east directions have the maximum solar load, and north sides have the least impact on the building. The comparison of all glasses illustrated that float glass (Type-1) contributes the most to the total cooling load among all glasses, which was 5.04%, 5.7%, 7.6%, and 8.9% for the N, S, E, and W orientation, respectively. Moreover, the lowest contribution of glass to the total cooling load was given by double-glazed glass with tint (Type-7), which was 2%, 2.3%, 3.0%, and 3.01% for N, S, E, and W orientation, respectively. However, it was used for the exposed wall on one side, which showed good results. If the building is exposed from all sides, then the selection of glass becomes the demand of the building as it can save 20% to 25% of the total cost.

All these results were based on just one side of the building being considered exposed. According to the findings, it is concluded that commercial buildings which use glass on the entire building on each orientation should minimize the area of the glass on eastern and western facings to minimize the cooling load, as the maximum load was shown on these orientations and the minimum load was shown on the northern and southern orientation. The performance glass (double-glazed or more) with significant color should be used instead of single-glazed or local glass that is used to save the initial capital cost. In reality, the developers increase the equipment maintenance and running costs of the building to save some chunks of the initial capital. However, efficient glass can easily pay back in less than a year, as described.

Additionally, the computed result reveals that equipment selection is very important in terms of the energy saving of the running equipment. The current study compares two pieces of equipment with different operating cycles: the centrifugal chiller that works on the vapor compression cycles and the absorption chiller that operates on vapor absorption cycles. Although both operating cycles have different operating efficiency or coefficients of performance, the annual running costs have less difference, which was almost 1% (PKR 0.3 to 0.6 million in different scenarios), which can be seen in Figures 12–15. It is because of the type of energy consumption and its cost; e.g., the cost of natural gas is very cheap in the local market. In Pakistan, it can compete with the centrifugal chiller or vapor compression cycle-operated chiller in terms of running cost because of the higher price of electricity and much lower price of gas, which can be seen in Table 5, which is 23 PKR/kWh for electricity and 1283 PKR/MMBtu for gas. However, overall results show that the centrifugal chiller equipment is better in terms of efficiency and running cost than the absorption chiller equipment.

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References

1. Qiu, S.; Li, S.; Wang, F.; Wen, Y.; Li, Z.; Li, Z.; Guo, J. An energy exchange efficiency prediction approach based on multivariate polynomial regression for membrane-based air-to-air energy recovery ventilator core. *Build. Environ.* **2019**, *149*, 490–500. [CrossRef]
2. Saaly, M.; Maghoul, P.; Kavgic, M.; Polyzois, D. Performance analysis of a proposed geothermal pile system for heating and cooling energy demand for a building in cold regions. *Sustain. Cities Soc.* **2019**, *45*, 669–682. [CrossRef]
3. DeForest, N.; Shehabi, A.; Selkowitz, S.; Milliron, D.J. A comparative energy analysis of three electrochromic glazing technologies in commercial and residential buildings. *Appl. Energy* **2017**, *192*, 95–109. [CrossRef]
4. Omrany, H.; Marsono, A.K. Optimization of building energy performance through passive design strategies. *Br. J. Appl. Sci. Technol.* **2016**, *13*, 1–16. [CrossRef]
5. Fasi, M.A.; Budaiwi, I.M. Energy performance of windows in office buildings considering daylight integration and visual comfort in hot climates. *Energy Build.* **2015**, *108*, 307–316. [CrossRef]
6. Kho, N.; Huynha, H.L.; Soh, Y.C.; Cai, W. Performance characterization of the membrane-based energy recovery system. *Procedia Eng.* **2017**, *214*, 50–58. [CrossRef]
7. Abdin, A.R.; El Bakery, A.R.; Mohamed, M.A. The role of nanotechnology in improving the efficiency of energy use with a special reference to glass treated with nanotechnology in office buildings. *Ain Shams Eng. J.* **2018**, *9*, 2671–2682. [CrossRef]
8. Janssen, J. Ventilation for acceptable indoor air quality. *ASHRAE J.* **1989**, *31*, 40–48.
9. Mehbodniya, A.; Webber, J.L.; Rani, R.; Ahmad, S.S.; Wattar, I.; Ali, L.; Nuagah, S.J. Energy-Aware Routing Protocol with Fuzzy Logic in Industrial Internet of Things with Blockchain Tech-nology. In *Wireless Communications and Mobile Computing*; Hindawi: London, UK, 2022.
10. Ashrae, A. *Ashrae Handbook 2019: Heating, Ventilating, and Air-Conditioning Applications, Si Edition*; ASHRAE: Atlanta, GA, USA, 2019.
11. Mebarki, C.; Djakab, E.; El Hassar, S.M.K.; Slimani, M.E.-A. Impact of glazing type and orientation on the optimum dimension of windows for office room in hot climate. *J. Arch. Environ. Struct. Eng. Res.* **2018**, *1*, 10–15. [CrossRef]
12. Li, C.; Tan, J.; Chow, T.-T.; Qiu, Z. Experimental and theoretical study on the effect of window films on building energy consumption. *Energy Build.* **2015**, *102*, 129–138. [CrossRef]
13. Khan, Z.A.; Imran, M.; Umer, J.; Ahmed, S.; Diemuodeke, O.E.; Abdelatif, A.O. Assessing Crop Water Requirements and a Case for Renewable-Energy-Powered Pumping System for Wheat, Cotton, and Sorghum Crops in Sudan. *Energies* **2021**, *14*, 8133. [CrossRef]
14. Beusker, E.; Stoy, C.; Pollalis, S.N. Estimation model and benchmarks for heating energy consumption of schools and sport facilities in Germany. *Build. Environ.* **2012**, *49*, 324–335. [CrossRef]
15. Kamran, M.S.; Naz, K.; Umer, J.; Sajjad, M.; Saleem, M.W.; Zeinelabdeen, M.I.M. Experimental Evaluation of Performance Characteristics of a Horizontal Copper Mesh Wick-Based Miniature Loop Heat Pipe. *Arab. J. Sci. Eng.* **2021**, *46*, 2121–2132. [CrossRef]
16. Jaber, S.; Ajib, S. Optimum, technical and energy efficiency design of residential building in Mediterranean region. *Energy Build.* **2011**, *43*, 1829–1834. [CrossRef]
17. Alobeidi, M.M.; Alsarraf, A.A. The Impact of the use of Smart Materials on the Facades of Contemporary Buildings. *Int. J. Eng. Technol.* **2019**, *8*, 308–315. [CrossRef]
18. Alobeidi, M.M.; Alsarraf, A.A. The Impact of the use of Smart Materials on the Facades of Contemporary Buildings. *Int. J. Eng. Technol.* **2018**, *7*, 744–750. [CrossRef]
19. Taha, H.S.; Hassan, S.A. The Effect of Smart Low Emission Glass Material on Reducing Energy Consumption for Office Building in Hot Arid Climate. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2020; Volume 881, p. 012017.
20. Cheong, C.H.; Kim, T.; Leigh, S.B. Thermal and daylighting performance of en-ergy-efficient windows in highly glazed residential buildings: Case study in Korea. *Sustainability* **2014**, *6*, 7311–7333. [CrossRef]
21. Stavrakakis, G.M.; Zervas, P.L.; Sarimveis, H.; Markatos, N.C. Optimization of window-openings de-sign for thermal comfort in naturally ventilated buildings. *Appl. Math. Model.* **2012**, *36*, 193–211. [CrossRef]
22. Zomorodian, Z.S.; Tahsildoost, M. Assessment of window performance in classrooms by long term spatial comfort metrics. *Energy Build.* **2017**, *134*, 80–93. [CrossRef]

23. Lashgari, A.; Hosseinzadeh, H.; Khalilzadeh, M.; Milani, B.; Ahmadisharaf, A.; Rashidi, S. Transportation energy demand forecasting in Taiwan based on metaheuristic algorithms. *Energy Sources Part A Recover. Util. Environ. Eff.* **2022**, *44*, 2782–2800. [CrossRef]
24. Lee, J.W.; Jung, H.J.; Park, J.Y.; Lee, J.B.; Yoon, Y. Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements. *Renew. Energy* **2013**, *50*, 522–531. [CrossRef]
25. Hawila, A.A.-W.; Merabtine, A.; Troussier, N.; Bennacer, R. Combined use of dynamic building simulation and metamodeling to optimize glass facades for thermal comfort. *Build. Environ.* **2019**, *157*, 47–63. [CrossRef]
26. Jin, Q.; Overend, M. A comparative study on high-performance glazing for office buildings. *Intell. Build. Int.* **2017**, *9*, 181–203. [CrossRef]
27. Panfilov, S.A.; Kabanov, O.V.; Starostina, J.E.; Terenteva, A.V.; Sadunova, A.G.; Kandalova, M.A.; Egorov, P.N.; Matveev, S.V. Problems with construction of technical means for energy saving and pollution mitigation. *Procedia Environ. Sci. Eng. Manag.* **2021**, *8*, 725–731.
28. Hart, R.; Selkowitz, S.; Curcija, C. Thermal performance and potential annual energy impact of retrofit thin-glass triple-pane glazing in US residential buildings. *Build. Simul.* **2019**, *12*, 79–86. [CrossRef]
29. Glass, B. 6 Common Types of Glass for Windows. Available online: https://www.bobsglass.com/6-common-types-of-glass-for-windows (accessed on 1 August 2022).
30. Windows, V. Different Types of Window Glass. Available online: https://www.valleywindows.com.au/different-types-window-glass/ (accessed on 1 August 2022).
31. Glass, A. AGC Architectural Brochure. Available online: https://pdf.archiexpo.com/pdf/agc-glass-europe-49576.html (accessed on 10 October 2022).
32. ASHRAE. *Ashrae Fundamentals*; American Society of Heating, Refrigerating and Air-conditioning Engineers: Atlanta, GA, USA, 2009.
33. Rosenquist, G.; Coughlin, K.; Dale, L.; McMahon, J.; Meyers, S. *Life-Cycle Cost and Payback Period Analysis for Commercial Unitary Air Conditioners*; University of California: Oakland, CA, USA, 2004. [CrossRef]