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Energy Efficiency in Dome Structures: An Examination of Thermal Performance in Iranian Architecture

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Abstract: This study investigates the energy efficiency of dome-shaped structures in traditional Iranian architecture in regions with cold winters and hot summers against the backdrop of rising energy consumption and environmental concerns. The present study employed Design Builder software to simulate three discrete models of Nowzari Caravanserai, featuring dome, flat, and sloping roofs. It was compared to the original model's dome-shaped roof in terms of energy consumption and internal temperature. The objective was to investigate the potential differences in thermal energy consumption across these distinct roof designs in all months of the year. The results indicate that the dome-shaped structures exhibit better efficacy in controlling indoor temperatures, as demonstrated by a marked increase in indoor temperatures during colder months and a decrease in indoor temperatures during hotter months, relative to alternative structures. Moreover, the results of the simulation of two domed-roof models with ventilation and without ventilation showed that in this climate zone, the ventilation holes built into the roof have a unique efficiency in adjusting the internal temperature. The implications of this research include that traditional architectural features such as domed structures can be incorporated into contemporary construction practices to foster energy-efficient buildings and sustainable urbanization. This holds true not only for hot and desert climate regions but also for areas characterized by both hot summers and cold winters. The integration of traditional expertise and modern technology can help create buildings that balance aesthetics and sustainability, creating a cleaner, more sustainable built environment.

Keywords: energy efficiency; dome-shaped structures; building simulation; traditional Iranian architecture; sustainable urban development

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1. Introduction

The incorporation of sustainable building design has become a crucial aspect of architectural practice due to increasing energy consumption and environmental issues [1]. The optimization of energy performance in buildings is a crucial factor in mitigating the impact of the built environment, as buildings account for a substantial proportion of global energy consumption and greenhouse gas emissions [2]. As per the findings of the International Energy Agency (2021), it can be inferred that buildings contribute to nearly 30% of worldwide energy consumption and 27% of carbon dioxide emissions related to energy usage [3]. Despite a doubling of investment and financing for clean energy in the past decade, the rate of progress has not been sufficient to surmount the resistance of energy-consuming systems. Hence, it is imperative to enhance the energy efficiency of constructions with the aim of curbing the discharge of greenhouse gases and alleviating the ecological ramifications of buildings [4]. In light of the contemporary era's focus on energy preservation and the implementation of passive systems to promote environmental cleanliness, it is deemed imperative to revisit the fundamental design principles and climatic regulations that underpin traditional architecture. Iranian architecture that adheres to traditional design principles is a prime illustration of climatic architecture. It showcases optimal solutions with regard to

environmental preservation, human comfort, and the efficient utilization of natural energy sources [5]. Hence, through the identification of the underlying principles and regulations that govern this particular architectural style, coupled with the presentation of a model that takes into account the scientific comprehension of novel materials as well as the climatic and functional implications arising from technological advancements, it is indeed possible to apply the traditional architectural knowledge and process in novel constructions while still maintaining a contemporary outlook. For centuries, Iran's native architecture has offered its residents comfortable living conditions while consuming less energy, similar to numerous ancient civilizations [6]. The implementation of a dual-layered dome ceiling and a domed roof with ventilation is a prominent feature of indigenous architectural design in the parched and sweltering regions of Iran. This technique has been widely utilized in the construction of diverse structures, including but not limited to mosques, mausoleums, bazaars, and residential dwellings. Certain regions have managed to preserve valuable examples of constructions that have maintained their stability to date, owing to their superior design and construction quality [7]. Mirzazadeh Akbarpoor conducted a study that demonstrated the potential of combining domed roofs with earth-to-air heat-exchanger systems to enhance their energy-saving capabilities. This study can be considered innovative. The integration of modern technologies with traditional architectural methods is a promising strategy for constructing environmentally friendly and energy-efficient structures, as evidenced by this innovative approach [8]. Studying the structural characteristics of dome elements in traditional architecture is a complex area with abundant design variations, offering ample research prospects due to Iran's diverse architectural heritage [9].

However, only a few studies can be found that use energy-simulation software to investigate the effect of the domed roof with ventilation as a bioclimatic element in reducing energy consumption.

The utilization of domed roofs—a traditional architectural element that is prevalent in the Middle East—has been observed to possess a noteworthy capacity to preserve energy and enhance the thermal comfort of occupants. The implementation of domed roofs in various settings, including bustling marketplaces, revered places of worship, and intimate residences, is notable due to their unique architectural features that contribute to efficient energy utilization and improved thermal comfort. According to Mahdavinejad's findings, the domes present on the historical mosques in Isfahan, Iran, served as thermal buffers that effectively reduced energy loss during the night. The architectural design and materials used in constructing the dome hindered the transfer of heat between the inside and outside of the structure, resulting in energy conservation and ensuring comfortable thermal conditions for the occupants [10]. The roof plays a crucial role in the building envelope as it is responsible for managing a significant amount of solar radiation. This can account for as much as 60% of the cooling energy used in a given space [6,11]. The significance of roof design cannot be overstated in mitigating the discomfort of inhabitants, particularly in severe weather conditions [12]. Several prominent researchers, such as Runsheng [13] and Fathy [14], have advocated for the use of domed roofs instead of flat ones due to their superior ability to receive solar radiation. This results in lower indoor temperatures and improved thermal comfort. Other researchers, including Faghih and Bahadori [15] and Olgyay [16], have also supported this approach. Research has demonstrated that the incorporation of the dome structure and traditional materials such as adobe results in outstanding insulation, reduces heat transfer, and promotes thermal comfort. Moreover, domes have the potential to function as thermal buffers, thereby impeding nocturnal energy dissipation [7,10]. Due to their unique configuration, domed roofs serve as effective self-shading mechanisms. This is because half of the structure is exposed to direct sunlight while the other half remains in the shade. In their study, Soleimani (2016) [17] investigated the effects of wind and buoyancy-driven ventilation in a geodesic structure that was equipped with roof vents and open windows in a hot climate. The research results indicate that roof vents have the potential to serve as a passive strategy for ensuring adequate indoor thermal comfort and air quality throughout all seasons.

Previous research has demonstrated the advantageous outcomes of employing dome roofs in conjunction with earth-to-air heat-exchanger systems, resulting in heightened energy-conservation capabilities. The aforementioned innovative methodology prioritizes the potential for amalgamating modern technologies with longstanding architectural traditions, thereby ushering in a novel epoch of environmentally conscious and power-conserving edifices [9].

Besides the aforementioned benefits highlighted in the research regarding domed roofs, certain studies have revealed the suitability of flat roofs when compared to domed roofs. The underlying reasons for these preferences will be elucidated below.

A few experts [18] have analyzed the thermal characteristics of curved roofs under hot and dry weather conditions using numerical calculations. They determined that the heat transfer and daily heat flow through curved roofs are hardly impacted by the roof's radius, thickness, and thermal properties. However, they are noticeably affected by the half-rim angle of both domed roofs (DRs) and vaulted roofs (VRs), as well as the ambient temperature. The findings also establish that domed roofs are unsuitable for regions with elevated air temperatures and high levels of diffuse sky radiation, which are commonly found in hot and humid areas. Another study [15] conducted numerical simulation on a simplified model of a domed roof in a paper titled "Evaluation of Thermal Performance in Domed Roofs". They demonstrated that the thermal performance of the investigated domed-roof building surpasses that of a building with a flat roof on hot days. However, in conditions where there is no wind flow, the flat-roof building outperforms the domed structure. In addition, while taking into account both convection and solar radiation on the roofs, [19] examined the thermal efficiency of vaulted roofs and compared their heat transfer with flat roofs. These investigators clarified that the heat transfer to the building, based on a specific ceiling-design temperature, is significantly influenced by different wind patterns and vault shapes. Upon comparing the outcomes with those of a flat roof, it was discovered that the daily average heat flux of all vaulted roofs, except the one with a rim angle of 180°, was lower than that of a flat roof, and it diminished further with higher wind speeds.

It is important to mention that the majority of studies exploring the advantages of domed roofs have primarily concentrated on hot and desert regions characterized by consistently warm weather year-round [20]. One such study was conducted within the arid and scorching areas of southern Egypt [21]. According to this research, domed-roof structures can have a significant impact on reducing the intensity of solar radiation received by maximizing the ratio between the height and radius of the dome. As a result, they decrease the energy required for cooling in hot climates and thereby enhance indoor thermal comfort.

Another study was carried out in Cairo, Riyadh, and Istanbul [22]. This study reveals that pointed double-dome roofs are effective in Cairo and Riyadh's climatic conditions, while cases of half-circular/pointed domes and vaults yield similar outcomes in Istanbul's climate.

In Iran, as well as in the hot and dry regions of Egypt, North Africa, and Istanbul, traditional dome roofs have been widely utilized for their notable impact on enhancing internal thermal conditions over time. However, since some structures with domed roofs in Iran are situated in areas experiencing hot summers and cold winters, this study aims to address the following inquiries:

Do domed roofs, like those found in hot and dry regions, affect energy consumption for heating in areas with cold and dry winters?

Furthermore, by comparing the gas and electricity energy consumption for heating and cooling between a dome roof and two flat and sloping roofs throughout the year and across different seasons in these regions, what will be the resulting findings?

Walls That Whisper: Tracing the Timeless Traditions and Unique Architecture of Arak Bazaar

As shown in Figure 1 the Arak Bazaar's primary axis, oriented in a north-south direction, spans approximately 722.52 m and accommodates roughly 320 stores and 22 caravanserai entrances throughout its expanse. The total area of the Bazaar amounts to 140,000 square meters. The principal marketplace is encompassed by a roofed edifice featuring a dome-shaped structure that incorporates apertures for ventilation. The architectural design of the caravanserais or passageways linked to this axis exhibits a distinctiveness that is noteworthy. In general, caravanserais are comprised of a centrally located courtyard that is encompassed by interconnected stores [23]. The majority of caravanserais are designed with a dual-level structure, featuring aesthetically pleasing brick and plaster roofs that are constructed with ribbed vaults, arches, and springs. The architect responsible for the design of the Arak Bazaar demonstrated a discerning approach by avoiding a monotonous and standardized layout for the 22 caravanserais. The arrangement of enclosed and open spaces in relation to the primary axis of the Bazaar exhibits remarkable diversity, resulting in a visually captivating and multifaceted Arak Bazaar. The Nowzari Caravanserai, situated within the Bazaar, is a notable example of a vast and complex structure. Covering an expansive area of roughly 5480.93 square meters, it stands as one of the largest caravanserais in the region. The caravanserai in question features a central courtyard, which is connected to three long, covered corridors (known as Timchehs) that are easily accessible. Additionally, there are three entrances leading to the main axis of the Bazaar, as well as one entrance from the Chahar Suq passage [24]. The paved flooring of the courtyard is adorned with stones, and a diminutive pool has been constructed at its focal point. Surrounding the area are multiple establishments featuring stone columns that uphold brick arches. A thoroughfare extends from the central shopping area to the adjacent corridors, facilitating seamless access between disparate sections. The entirety of the caravanserai is comprised of two levels. The retail establishments are involved in the sale of carpets, as well as the creation of carpet patterns [25].



(**a**) (**b**)

Figure 1. A view of Arak Bazaar and Nowzari Caravanserai (**a**) A section of the north-south view of the Nowzari Caravanserai; (**b**) Part of Arak Grand Bazaar's plan.

2. Materials and Methods

The primary research methodology employed in this study is simulation. Simulation studies employ computational models to replicate a given system or process, with the aim of forecasting outcomes under varying circumstances [26]. The present study employed Design Builder software V7.0.1.004 to conduct a simulation of the Arak market, utilizing varying roof forms (flat, sloped, and arched) and roof heights. The objective was to investigate the impact of these factors on the internal temperature and energy consumption for heating and cooling during the season. The seasonal variations in temperature were assessed.

The present study can also be categorized as quantitative in nature as it entails the collection and analysis of numerical data to comprehend the effects of alterations. Quantitative research employs statistical techniques to scrutinize data and typically entails impartial measurements and numerical outcomes [27]. This study involved the collection and analysis of data pertaining to indoor temperature and energy consumption across various scenarios. The aim was to draw conclusions regarding the impact of roof forms on these factors.

Thus, it can be posited that the methodology employed in this study is an experimental design conducted within a virtual environment. This methodology is frequently employed in domains such as architecture and construction, where conducting physical experiments can be prohibitively costly, time-intensive, or unfeasible. By means of this approach, it became feasible to employ a software application for the purpose of evaluating diverse architectural configurations and parameters, amassing relevant data, and deducing inferences from said data.

2.1. Design Builder Simulation Software Validation

In order to assess the accuracy and validity of energy-simulation software, researchers have introduced a range of methodologies. Broadly speaking, these methods can be classified into three overarching categories: analytical, comparative, and experimental methods. Within the realm of building-energy software-validation research, two prevalent types of validation studies are experimental methods, which involve comparing simulation outcomes with field measurements, and comparative methods, which involve comparing the results of various energy-simulation software with one another. The objective of these studies is to elucidate the factors that contribute to the disparity between projected energy consumption and observed consumption, as well as to validate the software inputs in accordance with their respective application platforms. In developed countries, where simulation software is designed in accordance with established regulations and standards, several software programs have undergone validation [28]. These include Ecotect Autodesk [29], Green Building Studio [30], IES [31], Energy Plus [32], E-Quest [33], and Design Builder [34]. The investigation of the validity of Design Builder software in Iran was conducted to align with the specific conditions and methodologies of construction and operation, as well as equipment and climatic factors. This investigation utilized two experimental and comparative approaches. The findings indicate that the Design Builder software exhibits favorable performance in accurately forecasting energy-consumption levels and internal temperature variations within spaces, considering factors such as construction conditions, equipment specifications, and climatic conditions [35].

In this research, to check the validity of the software in the study area (Arak City), we used the experimental method and compared the results of the simulation with field measurements.

2.1.1. Site Visit and Energy Survey of Sarai Nowzari

The desired information was collected through the utilization of existing maps of the Arak market, as well as the acquisition of additional information from the General Department of Cultural Heritage, Handicrafts and Tourism of Arak City; the Meteorological Organization of the province; and a field visit. Subsequently, a comprehensive and precise documentation process was conducted, encompassing the verification and quantification of various elements such as dimensional and architectural data, executive particulars, specifications pertaining to walls, ceilings, doors, and windows, as well as general specifications concerning the mechanical and electrical systems of the building, including lighting. Additionally, meticulous records were compiled regarding the comfort conditions within the spaces, encompassing temperature and humidity values, as well as the conditions governing the utilization of the building. The quantification of electricity and gas energy consumption was derived from monthly billing records over the course of one year.

The gas meter consumption indicated in the bills was determined in cubic meters, which was subsequently converted to kilowatt-hours. This value was then divided by the building's infrastructure, which is measured in kilowatt-hours per square meter, to calculate the final amount. Additionally, we measured the internal temperature of a store located in Sarai Nowzari on 15 December 2022 (representing the coldest month of the year) and on 15 July 2022 (representing the hottest month of the year). As shown in Table 1 the measurements were conducted over an 16 h period, starting from the early morning. During the cold season, the lighting and heating systems were turned off, and during the hot season, the cooling system was nonactivated. Furthermore, the windows were kept closed throughout the experiment. A TESTO DATA LOGGER device was utilized to record the temperature at specific time intervals. It is important to note that the first part of the experiment was conducted without the presence of users and customers, while the remaining hours involved the presence of residents and customers. The duration of one hour was measured at the central location within the store.

Table 1. Comparison of measurement and simulation temperature results in a store in Sarai Nowzari on 15 July 2022.

Date/Time (July)	Relative Humidity %		Outdoor Dry-Bulb Temperature °C		Indoor Air Temperature °C	
	Simulation	Field Measurement	Simulation	Field Measurement	Simulation	Field Measurement
06:00:00	36.04403	35.0	23.002	23.2	26.03333	25.7
07:00:00	36.75922	36.5	23.407	23.9	25.3994	25.1
08:00:00	37.35827	37.0	24.35	24.6	24.62	24.3
09:00:00	38.39169	38.0	26.15	25.4	24.47424	24.0
10:00:00	39.72992	39.3	27.95	27.4	24.30419	23.6
11:00:00	40.81329	40.1	30.125	29.0	24.16153	23.4
12:00:00	41.35981	41.0	32.35	31.5	24.04242	23.0
13:00:00	41.7047	41.5	34.625	33.5	24.03182	22.6
14:00:00	41.94122	42.0	36.025	35.0	24.02612	22.3
15:00:00	42.48663	42.5	37.2	36.0	24.001	21.9
16:00:00	43.1832	43.0	38.325	37.0	24.0535	21.5
17:00:00	43.69019	43.5	37.325	36.0	24.40169	22.0
18:00:00	43.72846	43.8	35.55	34.6	25.02015	22.5
19:00:00	43.52163	43.2	33.825	33.3	25.76697	23.0
20:00:00	34.5239	35.9	33.025	32.2	26.41551	23.5
21:00:00	34.02543	33.1	32.45	31.5	27.34797	24.0

The results revealed a discrepancy between 1 and 3 percent between the temperature obtained from field measurements and the results obtained from simulation. According to other validation studies of the Design Builder simulation software [34,35], this discrepancy falls within the acceptable range, which is consistent with the reports reviewed in the previous sources.

In addition, Table 2 displays the internal temperature measurement of the Sarai Nowzari store on 15 December 2022 (the coolest month of the year) and the simulation data.

Table 2. Comparison of measurement and simulation temperature results in a store in Sarai Nowzari on 15 December 2022.

Date/Time (December)	Relative Humidity %		Outdoor Dry-Bulb Temperature °C		Indoor Air Temperature °C	
	Simulation	Field Measurement	Simulation	Field Measurement	Simulation	Field Measurement
6:00:00	20.2739	20.6	−2.87	−2.85	15.45966	15.28
7:00:00	19.34711	19.5	−2.075	−2.10	16.95825	16.48
8:00:00	17.93888	17.5	−1.875	−1.85	19.26227	18.87
9:00:00	17.75856	17.1	1.03	1.03	19.87473	19.63
10:00:00	18.33944	18.0	1.525	1.55	20.26867	19.78
11:00:00	18.96519	19.3	2.025	2.05	20.65415	20.21
12:00:00	19.42782	19.8	2.45	2.55	20.87272	21.13
13:00:00	19.61721	20.2	2.875	2.90	21.10908	21.49
14:00:00	19.79159	19.6	3.025	3.00	21.27316	21.10
15:00:00	20.12667	19.8	2.75	2.80	21.3349	20.90
16:00:00	20.296	20.4	0.825	0.82	21.44276	21.18
17:00:00	20.26794	20.3	0.25	0.25	21.511	21.77
18:00:00	19.53312	20.0	−1.85	−1.90	21.72228	21.43
19:00:00	18.79874	18.5	−2.45	−2.52	21.80025	21.40
20:00:00	21.59453	21.0	−3.975	−3.90	20.26762	20.69
21:00:00	22.26062	22.0	−4.55	−4.58	19.25935	19.45

The actual consumption of electricity and gas was extracted through monthly bills in a one-year period.

Using Equation (1), the information obtained from the monthly bills was compared to the results obtained from the case simulation.

$$\text{Difference Percentage} = |(\text{Actual Energy Consumption} - \text{Simulated Energy Consumption})| / \text{Actual Energy Consumption} + \text{Simulated Energy Consumption}/2) \times 100 \quad (1)$$

The simulation engine of this software is Energy Plus, which was developed by the US Department of Energy in 2011 and is known as one of the most reliable energy modeling software. The validity of Energy Plus software 9.4, which is the simulation engine of Design Builder, was confirmed based on BESTEST and ASHRAE-14 standards [36]. Energy Plus is among the dynamic energy software that have high flexibility, and the following factors are included within it:

- Geographic location and orientation of the structure;
- Specific local weather conditions;
- Intricate 3D geometry of the building, including shading from nearby structures and self-shading;
- Time lag in the response of the building envelope;
- Type and characteristics of utility systems (heating, ventilation, and air conditioning) installed in the building;
- Functioning of automated utility system controls during weather fluctuations;
- Building's operational schedule, accounting for varying usage throughout the day, week, month, and year;
- Nonlinear interconnection of utility system components within the building [37].

As can be seen in Table 3, the percentage difference between the actual consumption of electricity and gas and the results obtained from the simulation shows an average difference of 1.6%, which is consistent with the results obtained in similar studies [38].

Table 3. Comparison of the difference between predicted consumption with Design Builder software and actual consumption.

Date/Time Month	Dome Roof					
	Gas (kWh)			Electricity (kWh)		
	Simulation	Actual Consumption	Percentage Difference	Simulation	Actual Consumption	Percentage Difference
Jan	54,214.44	53,659.08	1.03%	219.5212	216.1801	1.53%
Feb	28,614.64	28,300.02	1.10%	576.7798	570.5030	1.09%
Mar	15,978.21	15,807.72	1.07%	2045.478	2016.1974	1.44%
Apr	5152.356	5078.193	1.45%	8003.493	7895.9567	1.35%
May	1370.026	1353.432	1.22%	22,415.59	22,041.8712	1.68%
Jun	0.0	0.0	0.0	37,432.63	36,912.6510	1.40%
Jul	0.0	0.0	0.0	56,717.68	56,127.1964	1.05%
Aug.	0.0	0.0	0.0	49,798.81	49,334.5298	0.94%
Sep	0.953908	0.935514	1.95%	31,352.17	31,038.2601	1.01%
Oct	1998.189	1973.200	1.26%	12,761.63	12,592.1292	1.34%
Nov	21,407.21	21,092.34	1.48%	852.084	842.6850	1.11%
Dec	40,989.13	40,489.30	1.23%	377.1165	372.4799	1.24%

2.1.2. Initial Settings of the Software for the Simulation Process

In order to acquire valid and reliable results from simulation, it is necessary to take certain factors into account. Therefore, the information gathered from the Bazaar's site visit was used as simulation input data and initial parameters in the software. Table 4 provides an example of input data.

Table 4. Input data and initial settings of Design Builder software.

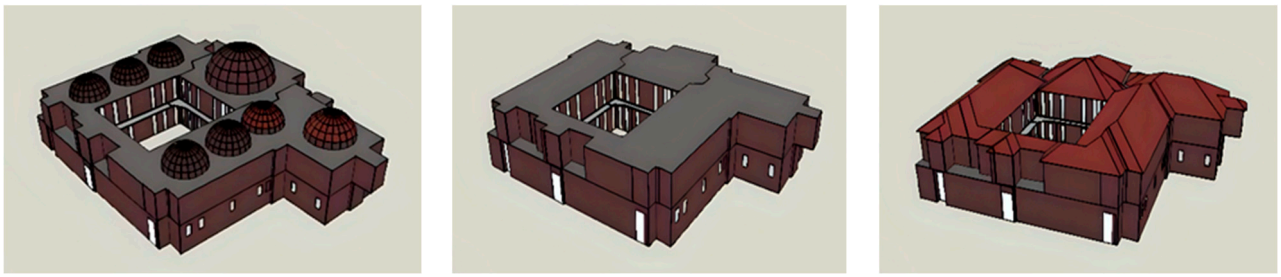
Wall 3 layers	**Outermost layer** Brickwork outer Thickness (m)	0.1000	
	Layer 2 Brickwork outer Thickness (m)	0.5000	
	Innermost layer Gypsum plastering	0.1000	
Roof 3 layers	**External layer** Thickness (m)	**Tile**	0.0200
		Brick	0.2000
	Air gap Thickness (m)	0.3000	
	Internal layer Thickness (m)	**Brick**	0.2000
		Plaster Board	0.0200
Convective heat transfer coefficient External Wall ($W/m^2/K$)		2.1000	
Convective heat transfer coefficient External Roof ($W/m^2/K$)		0.4900	

2.2. Simulation of Sarai Nowzari in Design Builder to Compare the Energy Consumption of Three Dome, Flat, and Sloped Roofs

In order to simulate the market conditions through the utilization of Design Builder software, it is imperative to initially establish the corresponding environment within the software.

The present study involves the simulation of "Sarai Nowzari", a Caravanserai located in Arak Bazaar. The aforementioned caravanserai is characterized by an unroofed central area and enclosed compartments, featuring a sizable central dome and seven minor lateral domes. It is noteworthy that certain particulars have not been taken into account due to constraints in the software, which could potentially result in inaccuracies. The objective of this study was to examine the impact of different roof types on the reduction of energy consumption and enhancement of passive thermal comfort in Nowzari Caravanserai, which is situated in Arak Bazaar. In order to guarantee the precision of the investigation, the simulation was meticulously crafted to closely emulate the present Bazaar reality, and pivotal parameters such as dimensions and materials were meticulously chosen to correspond with the factual Bazaar.

The present investigation involved the creation of three distinct models of Nowzari Caravanserai, involving dome, flat, and sloped roofing designs (As depicted in Figure 2) In the simulated scenario involving a sloped roof, the angle of inclination for the roof was uniformly established at 30 degrees across all orientations. The selection of a 30° roof pitch was based on its recommendation in the literature for the purpose of facilitating maintenance and promoting enhanced air circulation, as compared to alternative pitches [39]. The objective was to conduct a comparative analysis of the parameters associated with thermal energy consumption (measured via gas consumption) and cooling (measured via electricity consumption) across the three distinct roof shapes. Furthermore, the present investigation was carried out with the objective of contrasting alterations in temperature during the warmest and coolest months of the calendar year within the interior and exterior settings of the marketplace. The average monthly temperature of Arak City over a 10-year period was obtained from the Meteorological Department for the purpose of temperature analysis. This study aims to offer valuable insights into the potential advantages of utilizing domed roofs as a means of reducing energy consumption and enhancing passive thermal comfort in conventional marketplaces, such as Arak Bazaar.



(**a**) (**b**) (**c**)

Figure 2. "Sarai Nowzari" is a part of Arak Grand Bazaar: (**a**) Simulation of the original dome roof; (**b**) Simulation of the flat roof; (**c**) Simulation of the sloping roof.

3. Results

3.1. Energy Analysis

In order to facilitate a meaningful comparison, it is necessary to first provide a summary of the aggregate simulated energy consumption for each category within every type of commercial structure for the given year.

A comparative analysis was conducted on the energy consumption of various types of roofs (For additional information, please consult Table 1). The annual energy consumption for heating (using gas) and cooling (using electricity) in a flat-roof structure were recorded

as 189,649.95 kWh and 297,761.24 kWh, respectively. The aggregate energy usage of the flat-roof configuration over the course of a year amounted to 567,909.30 kWh.

On the contrary, the employment of a dome-roof structure resulted in reduced energy consumption. The recorded heating energy consumption was 171,525.12 kWh, while the cooling energy consumption was 271,874.11 kWh. As a result, the aggregate energy consumption of the dome-shaped roofing system was significantly lower, totaling 515,539.93 kWh on a yearly basis.

The energy consumption of the sloping roof structure was moderate. A total of 183,309.95 kWh was utilized for heating purposes, while 284,792.92 kWh was consumed for cooling purposes. The aggregate energy consumption of a slanted-roof configuration throughout the course of a year amounted to 540,243.57 kWh.

According to the data in Table 5, the percentage difference in total energy consumption between roof types during the coldest and warmest months was analyzed.

Table 5. Variations in simulated energy consumption (over the course of one year) of Nowzari Caravanserai with three distinct rooftops.

Date/Time	Flat Roof		Dome Roof		Sloping Roof	
	Heating (Gas)	Cooling (Electricity)	Heating (Gas)	Cooling (Electricity)	Heating (Gas)	Cooling (Electricity)
Month	**kWh**	**kWh**	**kWh**	**kWh**	**kWh**	**kWh**
Jan	60,147.94	277.6499	54,214.44	219.5212	57,595.19	270.9657
Feb	31,765.94	771.796	28,614.64	576.7798	30,499.19	648.9638
Mar	17,657.38	2254.174	15,978.21	2045.478	16,742.15	2181.432
Apr	5451.338	8130.306	5152.356	8003.493	5383.951	8098.798
May	1425.126	23,978.4	1370.026	22,415.59	1400.365	23,161.36
Jun	0.0	40,649.91	0.0	37,432.63	0	38,801.34
Jul	0.0	61,990.3	0.0	56,717.68	0	59,805.05
Aug	0.0	54,601.4	0.0	49,798.81	0	52,211.26
Sep	1.454403	34,317.98	0.953908	31,352.17	1.1019	33,159.65
Oct	2048.211	13,820.44	1998.189	12,761.63	2025.542	13,182.91
Nov	23,408.87	1000.9152	21,407.21	852.084	22,795.53	978.3631
Dec	45,140.59	573.384	40,989.13	377.1165	41,367.28	466.3942

The mathematical expression used to calculate the percentage difference between two values is:

$$\text{Percentage Difference} = (|X - Y| / ((X + Y)/2)) \times 100 \quad (2)$$

The computations demonstrate the dissimilarity in energy usage across various architectural configurations, namely flat, dome, and sloping roofs, throughout the most frigid and sweltering periods of the year.

Highlighted by Table 6 during the month of December, the flat structure exhibits the greatest energy consumption, followed by the sloping roof and the dome, respectively. The flat type exhibits a notable dissimilarity from the other two variants, manifesting a higher energy-consumption rate of around 9.97% compared to the dome type and 8.95% in contrast to the sloping-roof type. Nonetheless, the energy usage of both the dome- and sloping-roof constructions exhibits a comparable pattern, with a marginal deviation of merely 0.97%.

Table 6. Variations in energy consumption (over the course of one year) of Nowzari Caravanserai with three distinct rooftops.

	Percentage Difference in December	Percentage Difference in July
Between Flat and Dome Roofs	9.97%	9.04%
Between Flat and Sloping Roofs	8.95%	4.26%
Between Dome and Sloping Roofs	0.97%	4.65%

During the month of July, which is typically characterized by high temperatures, it was observed that the flat structure consumed the highest amount of energy. However, the discrepancies in energy consumption between the various structures were comparatively smaller than those observed in the month of December. According to the data, the flat structure consumes 9.04% more energy compared to the dome, and a mere 4.26% more energy than the sloping roof. The energy consumption of the dome and the sloping roof exhibits a marginal variance of 4.65%.

Based on these findings, it can be deduced that:

The energy consumption of flat structures is higher for both heating and cooling, particularly during the coldest and hottest months, respectively. This implies that such structures may not be the optimal choice for extreme temperature conditions in terms of energy efficiency. This phenomenon may be attributed to various factors, such as an increased surface area that is subject to fluctuations in external temperature.

According to research, dome structures exhibit greater energy efficiency during colder months compared to flat- and sloping-roof structures, as they consume relatively lower amounts of energy. This phenomenon could potentially be attributed to the circular configuration of the object, resulting in a reduced surface area that is susceptible to colder temperatures and subsequently, a diminished amount of heat dissipation.

The structures with sloping roofs exhibit a commendable equilibrium in energy utilization under varying temperature conditions, consuming a lower quantum of energy than the flat structures but a marginally higher quantum of energy than the dome-shaped ones.

The data presented in Figure 3 indicate that:

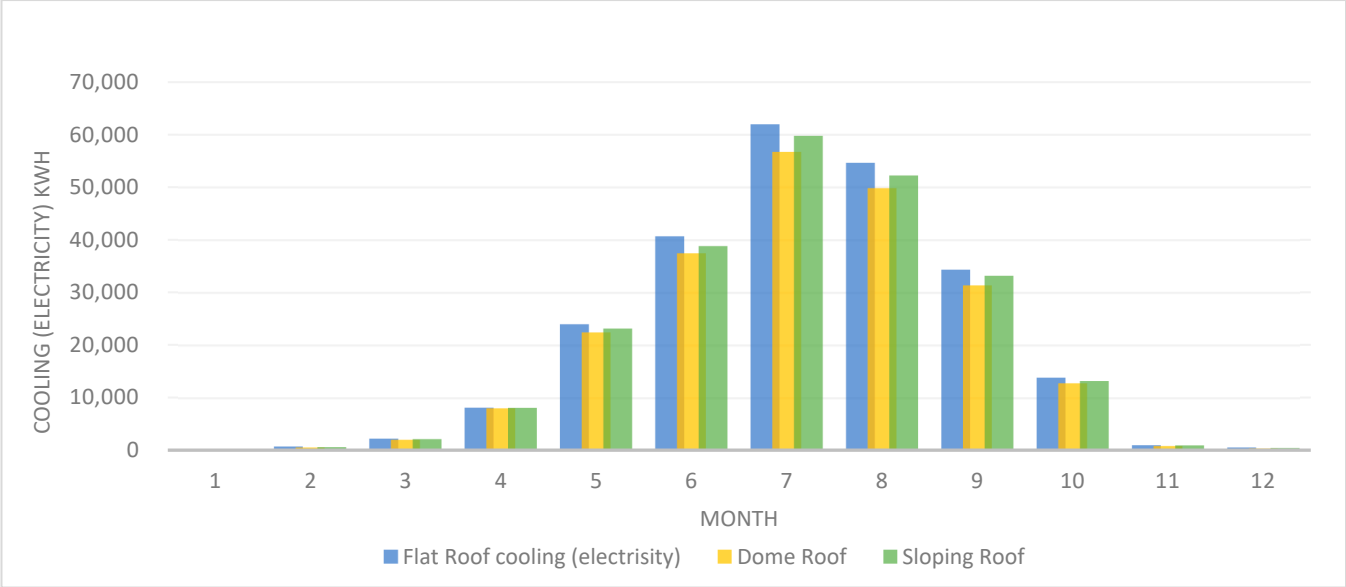


Figure 3. Comparison of electrical energy consumption for cooling purposes between two simulated roof models and the main dome-roof model of Nowzari Caravanserai during the hottest month of the year (July).

During the month with the highest temperatures (July), the flat roof exhibits the highest electrical energy to provide cooling inside, while the dome roof displays the lowest energy usage. The electrical energy of the sloping-roof commercial structure is marginally higher than that of the dome roof, yet lower than that of the flat roof.

The Arak Bazaar's dome roofs feature ventilation holes. Using Design Builder software, two scenarios were analyzed: one with the presence of ventilation holes and one without. The study aimed to determine the amount of electrical energy consumption required for cooling and the amount of gas energy consumption required for heating in both scenarios. An analysis was conducted on the months of the year to gather additional insights into the impact of ventilation apertures on energy usage (As depicted in Figure 4).

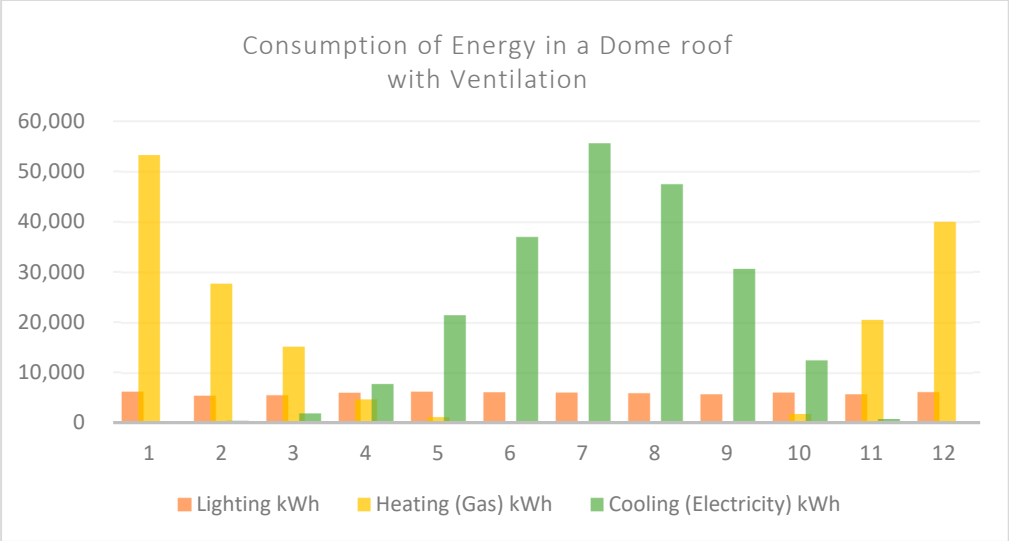


Figure 4. Diagram of consumption of energy in a dome roof with ventilation.

Upon comparing the data presented in Table 7 with those in Table 5, specifically in the domed-roof section, it is evident that the structure lacking ventilation exhibits higher energy consumption across all categories. The aforementioned statement suggests that the ventilation system within the edifice contributes to the mitigation of energy consumption by facilitating natural cooling and heating processes, thereby diminishing the necessity for artificial heating and cooling.

Upon analyzing the monthly data, discernible patterns can be observed.

In both configurations, the consumption of heating energy exhibits a peak during the colder months (January, February, November, and December) and diminishes to negligible levels during the warmer months (May through September).

The pattern of cooling energy consumption exhibits an inverse trend. The temperature exhibits a peak during the warmer months spanning from May to September and subsequently declines to a minimum during the colder months.

The energy usage for illumination appears to exhibit a degree of constancy over the course of the year in both edifices, with slight variations.

Typically, the energy consumption of a ventilated structure is lower than that of a non-ventilated structure.

Table 7. Energy consumption (over the course of one year) of Nowzari Caravanserai with ventilation.

Date/Time	Heating (Gas)	Cooling (Electricity)
Month	**kWh**	**kWh**
Jan	53,260.5	239.7364
Feb	27,724.76	479.9971
Mar	15,192.91	1943.613
Apr	4728.495	7786.682
May	1205.981	21,437.55
Jun	0	36,991.23
Jul	0	55,685.85
Aug.	0	47,481.87
Sep	0.385918	30,672.16
Oct	1816.613	12,478.89
Nov	20,505.58	820.495
Dec	39,980.93	301.8492

3.2. Thermal Comfort

The external weather information plays a crucial role in elucidating the internal temperature of spaces and determining the energy demand necessary to establish comfortable conditions. The climatic variables utilized in building-energy simulation, such as epw, wea, and TMY formats, are derived from meteorological station data and are employed while taking into account the environmental conditions surrounding the analyzed structure. The present study obtained weather data from the meteorological organization of Arak City, encompassing the average temperature, as well as the maximum and minimum temperatures, for the past decade. This information was subsequently utilized as input for the software, representing the weather conditions of the region. In accordance with the suggestions put forth by comparable scholarly articles [35,38], it is imperative to exercise control over various factors and parameters in order to enhance the dependability of predictions generated by simulation software. The relationship between the wind speed surrounding the market building and the level of radiation received is contingent upon the specific attributes of the surrounding area. Hence, the coefficients pertaining to wind and its reflection were regulated based on the market building's positioning relative to its surrounding context, in order to ensure that the software's outputs closely approximated the actual values.

Figure 5 presents data pertaining to the humidity, outdoor temperature, and indoor temperature of the warmest day of the warmest month in Nowzari Caravanserai, Arak Bazaar, for the purpose of comparison.

The outdoor dry-bulb temperature, measured in degrees Celsius, exhibits a diurnal pattern consistent with typical daily variations. The minimum temperature of 23.00 °C is recorded at 6 a.m., whereas the maximum temperature of 38.33 °C is recorded at 4 p.m. In this pattern, temperatures are at their lowest in the early hours of the morning prior to sunrise and at their highest during the afternoon.

The data suggest that there is a delay in the indoor air temperature in relation to the outdoor temperature. The indoor temperature reaches its minimum value of 24.00 °C at 3 p.m., which coincides with the outdoor temperature nearing its maximum value. Conversely, the indoor temperature reaches its maximum value of 31.34 °C at 1 a.m.

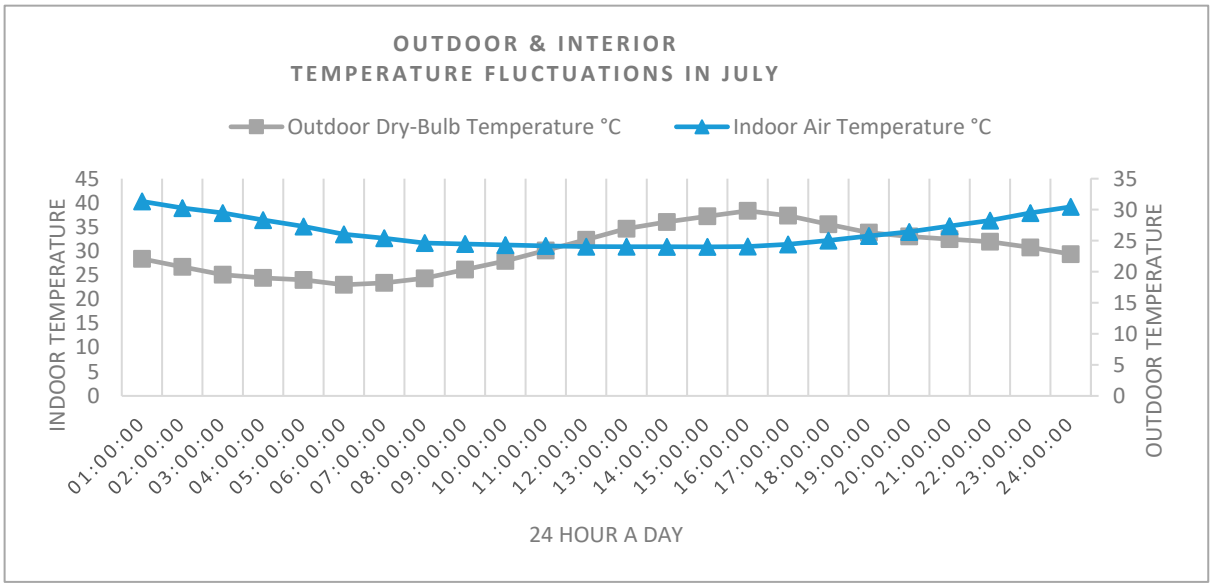


Figure 5. Diagram of outdoor and interior temperature fluctuations of Nowzari Caravanserai on the hottest day of July.

The mean absolute temperature difference between 6:00 a.m. and 6:00 p.m., as calculated from available data, is −6.44 °C.

The average absolute temperature difference during the nocturnal period, from 18:00 to 6:00, was found to be −1.54 °C. It should be noted that negative values indicate that the indoor temperature was lower than the outdoor temperature.

On average, the indoor temperature exhibits a decrease of 6.44 °C compared to the outdoor temperature during the day, and a decrease of 1.54 °C during the night.

Upon computation of the correlation coefficient, it was determined that the correlation between outdoor temperature and indoor temperature was −0.39534, which falls below the threshold of 0.5 and thus suggests a correlation that is weak to moderate in nature. This implies that the correlation between the ambient outdoor temperature and the indoor temperature is relatively weak.

Figure 6 displays information regarding the levels of humidity, outdoor temperature, and indoor temperature of the most frigid day of the chilliest month at Nowzari Caravanserai, Arak Bazaar, with the intention of facilitating a comparative analysis.

The minimum temperature of −5.925 °C is recorded at 1 a.m., whereas the maximum temperature of 3.025 °C is recorded at 2 p.m. The ambient temperature outdoors is subzero, whereas the indoor temperature is significantly elevated, maintaining a range of approximately 14 to 21 °C.

The diurnal temperature range exhibits an average absolute difference of approximately 19.32 °C, while the nocturnal temperature range displays an average absolute difference of around 21.94 °C. The aforementioned statement implies that the indoor temperature of the building maintains an average of being 19.32 °C higher during the daytime and 21.94 °C higher during the nighttime in comparison to the outdoor temperature.

The correlation coefficient calculation reveals that there exists a positive correlation of +0.704731 between the outdoor temperature and indoor temperature. This suggests that there is a positive correlation between outdoor temperature and indoor temperature, whereby an increase in one variable is accompanied by a corresponding increase in the other variable.

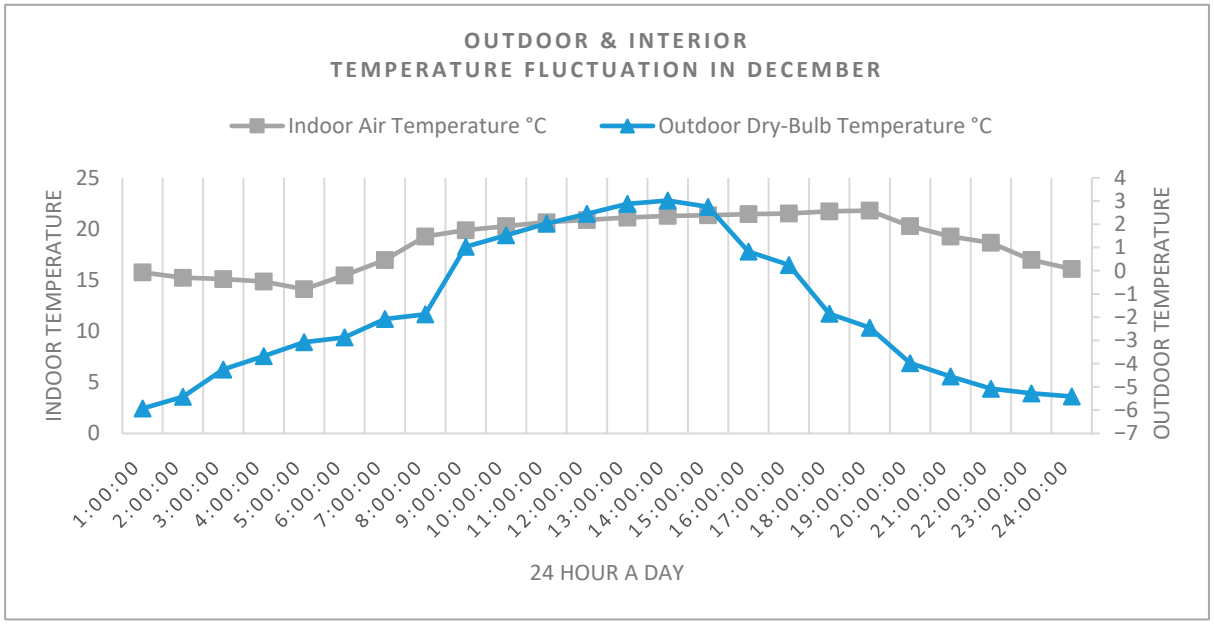


Figure 6. Diagram of outdoor and interior temperature fluctuations of Nowzari Caravanserai on the coldest day of December.

To construct the psychometric diagram representing ASHRAE's comfort conditions, it is essential to consider six primary factors that influence thermal comfort. The parameters to be considered in this study are as follows: air temperature (°C), mean radiant temperature (MRT—°C), air speed (m/s), relative humidity (%), metabolic rate (met), and clothing level (col).

The aforementioned parameters are evaluated based on the climatic conditions prevailing in the region during the peak heat of the warmest month and the extreme cold of the coldest month, as indicated in Table 8.

Table 8. Psychometric factors that affect thermal comfort of Nowzari Caravanserai.

Month	Mean Air Temperature (°C)	Mean Radiant Temperature (°C)	Air Speed (m/s)	Relative Humidity (%)	Metabolic Rate (met)	Clothing Level (col)
July	26.37	26	0.15	35.23	1.7	0.5
December	18.74	18	0.2	21.17	1.7	1

As is evident from the data in Table 8, the air temperature parameter encompasses the calculation of the average temperature on both the hottest and coldest days. During the peak of July, the prevailing atmospheric conditions are characterized by an average air humidity of 35.23% and an air speed of 0.15 m/s. The investigation of the comfort temperature within the market premises primarily focused on the activities commonly performed by its users, such as walking, passing through the market, and engaging in shopping activities. Consequently, a metabolic rate of 1.7 (met) (representing the standard for walking) was taken into account. The value of 0.5 (col) is commonly used to represent the clothing level parameter in the context of typical summer clothing.

Furthermore, on the coldest day of December, the average humidity is recorded as 21.17%. The air speed during this time is measured at 0.2 m/s, while the metabolic rate is estimated to be 1.7 (met). Additionally, the clothing level factor is assigned a value of 1 (col), representing typical winter clothing.

In order to generate the thermal comfort diagram for ASHRAE Standard 55-2020 [40] during the month of July, the six factors listed in the first row of Table 8 were utilized. Similarly, for the comfort temperature diagram in accordance with ASHRAE Standard

55-2020 during the month of December, the settings were configured based on the second row of Table 8.

The data depicted in Figures 7 and 8, which include relative humidity, were acquired via simulations conducted using the Design Builder software. The software was utilized to create an accurate model of the intended building, considering multiple parameters and conditions. Following this, the software generated results pertaining to relative humidity.

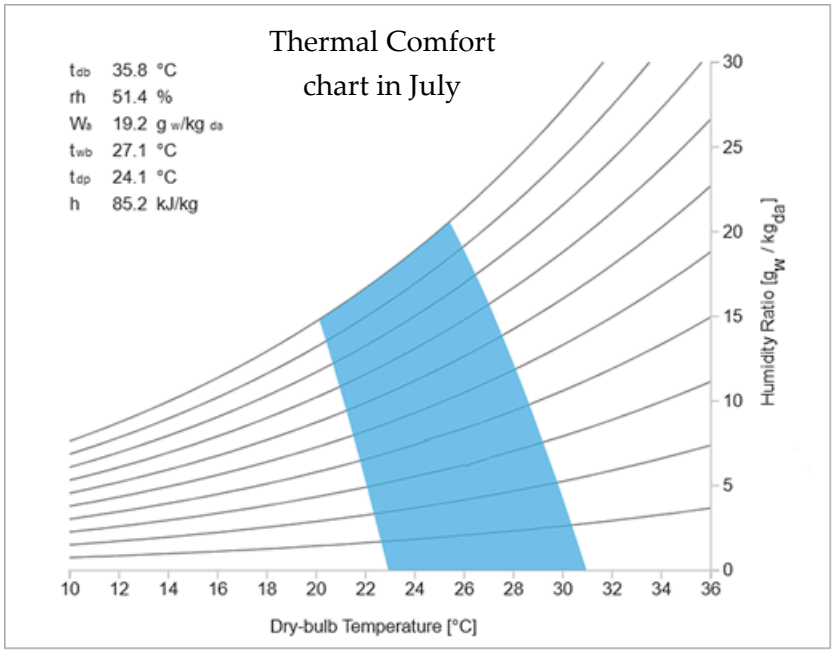


Figure 7. Thermal comfort chart [41] of Nowzari Caravanserai on the hottest day of July.

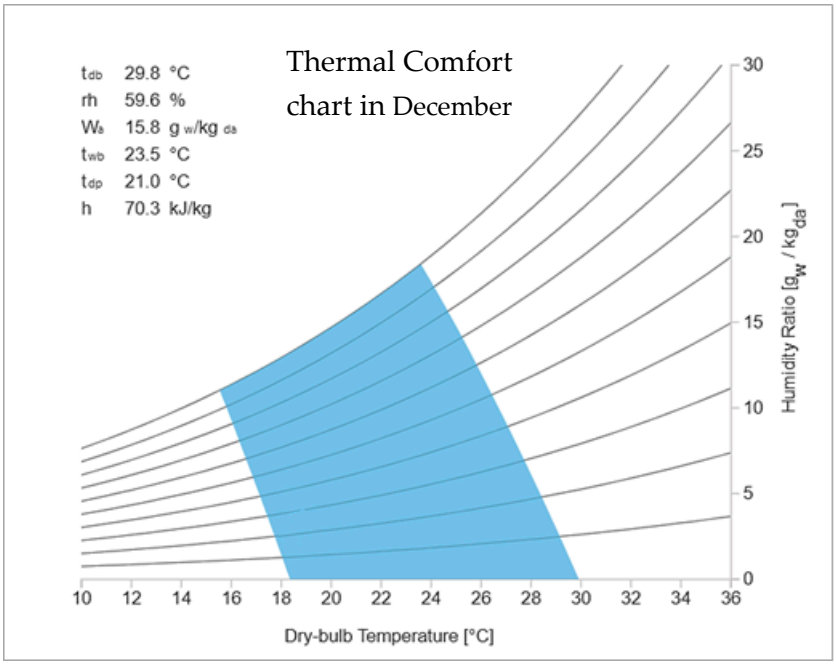


Figure 8. Thermal comfort chart [41] of Nowzari Caravanserai on the coldest day of December.

The temperature data provided are derived from the report obtained from the local meteorological institution.

The blue area depicted in Figures 7 and 8 represents the comfort zone, which signifies the range of dry-bulb temperature and humidity values deemed acceptable according to

the established standard. This interpretation assumes that the remaining four parameters remain unchanged.

Figure 7 presents thermal comfort charts that illustrate a spectrum of conditions in which individuals would experience thermal comfort, taking into account variables such as temperature, humidity, and other environmental factors. The provided chart illustrates the environmental conditions experienced at the Nowzari Caravanserai on the peak of July's hottest day and their implications for human comfort.

The thermal comfort chart depicted in Figure 8, similar to the July chart, illustrates the spectrum of conditions within which individuals would experience thermal comfort on the coldest day of December at the Nowzari Caravanserai.

4. Discussion

The results obtained from this investigation validate and broaden the scope of prior research activities that have investigated energy usage in various architectural configurations. The energy consumption of the flat-, dome-, and sloping-roof structures exhibited notable dissimilarities, particularly in the months with high temperature peaks.

During the month of December, it was observed that flat structures exhibited the highest energy consumption. This observation is consistent with the research conducted by Jimin et al. (2020), which indicated that flat roofs, as they have larger surface areas exposed to the cold, tend to require more energy for heating purposes [13,42]. By comparison, dome structures were observed to consume less energy as they have smaller surface areas exposed to temperature fluctuations. This observation is consistent with the findings of Abraham et al. (2016), who suggested that the energy-efficient characteristics of dome structures could be attributed to their geometric shape [43].

In the month of July, which is typically characterized by high temperatures, there was a decrease in the energy-consumption discrepancy among various architectural designs. However, it is noteworthy that flat structures continued to exhibit the highest energy-consumption levels. The dome structures exhibited commendable energy efficiency by consuming relatively low energy, as confirmed by the findings of [10,15,44], particularly during temperature extremes.

Regarding the temporal discrepancy between outdoor and indoor temperatures, the warm season of the year also plays a role in enhancing energy efficiency. Improved insulation can result in decreased energy consumption, as evidenced by a delayed indoor response to outdoor temperatures. The correlation coefficient of -0.39534 observed between outdoor and indoor temperature suggests a moderate association between these variables. This finding implies that changes in outdoor temperature do not necessarily result in corresponding changes in indoor temperature. These results are consistent with the research carried out by [6,45–47].

The supplementary discoveries serve to underscore the variations in thermal regulation and energy expenditure among diverse architectural arrangements, with particular emphasis on the dome-shaped edifices situated in Arak Bazaar.

During the month with the lowest temperatures, the minimum temperature of -5.925 °C was documented at 1 a.m., while the maximum temperature of 3.025 °C was recorded at 2 p.m. The aforementioned fluctuations were found to be uniform, as the indoor temperature levels displayed a mean absolute deviation of roughly 19.32 °C during daytime hours and 21.94 °C during nighttime hours, relative to the corresponding outdoor temperature levels. The significant contrast highlights the insulating capabilities of dome-shaped structures, which aligns with the research conducted by [7,48], demonstrating that dome structures demonstrate better thermal efficiency in comparison to alternative designs.

Furthermore, a statistically significant positive correlation coefficient of +0.704731 was observed between the outdoor and indoor temperatures. This represents a deviation from previous discoveries that indicated a feeble adverse association. The alteration in temperature regulation within the dome structures at Arak Bazaar can potentially be ascribed to

their distinct characteristics, including the presence of ventilation apertures. These features may have contributed to a heightened sensitivity to fluctuations in external temperature.

The Design Builder software was utilized to conduct a comprehensive assessment of the ventilation apertures present in the dome roofs. The study aimed to compare the energy consumption of two scenarios—one with ventilation holes and the other without—in order to determine their respective impacts. The findings indicate that structures featuring apertures for ventilation exhibit reduced energy consumption, corroborating prior scholarship that underscores the significance of passive ventilation in augmenting energy efficacy. The studies conducted by [17,48,49] are of academic interest.

This study revealed that the energy consumption pertaining to heating experienced a surge during the colder months, whereas the energy consumption for cooling reached its peak during the warmer months. The observed trends were in line with prevailing assumptions and align with the outcomes of prior research activities [8,50]. Additionally, the utilization of illumination exhibited consistency throughout the annual period, indicating that fluctuations in energy usage were predominantly attributable to the requirements for heating and cooling.

5. Conclusions

The current study conducted a comprehensive investigation into architectural configurations, focusing specifically on the energy efficiency and thermal comfort of various roofing structures. The study conducted a thorough analysis of the "Sarai Nowzari" Caravanserai in Arak Bazaar, with a specific focus on three different roofing designs: dome, flat, and sloped. This analysis was carried out using the Design Builder simulation software.

The results of this study emphasize the importance of architectural configuration in achieving energy efficiency, particularly in the context of dome-shaped buildings that integrate ventilation features. The Nowzari Caravanserai, situated in Arak Bazaar, serves as a prime example of how architectural design can effectively minimize energy usage by harnessing natural cooling and heating mechanisms.

Based on the findings of this study, it has been observed that dome structures demonstrate superior efficacy in the regulation of indoor temperature when compared to flat- and sloping-roof structures, particularly during periods characterized by extreme temperature conditions. The findings of the research demonstrate that the dome structures displayed enhanced thermal efficiency, as indicated by notably higher indoor temperatures in colder months and lower indoor temperatures in hotter months, in contrast to outdoor temperatures. Significant variations were observed in energy consumption across different roof types during the comparative analysis. The dome-shaped roofing system exhibited a decrease in energy consumption, amounting to 515,539.93 kWh per year, in comparison to flat- and sloping-roof structures. This discovery highlights the potential benefits of incorporating domed roofs into traditional marketplaces as a means to decrease energy usage.

A thorough evaluation of ventilation apertures in a dome roof was undertaken. The results of the study revealed that buildings with ventilation openings demonstrated lower energy consumption, providing further evidence for the importance of passive ventilation in enhancing energy efficiency.

The aforementioned findings highlight the notable advantages of incorporating traditional architectural elements, as exemplified by the Nowzari Caravanserai, into contemporary building designs. The achievement of energy efficiency is often a significant factor to be taken into account, particularly within the realm of commercial buildings.

The findings of the study indicate that there was a significant increase in energy consumption for heating purposes during colder months, whereas energy consumption for cooling purposes reached its maximum during warmer months. This observation is consistent with prevailing assumptions and previous research, suggesting that energy consumption is influenced by seasonal demands.

The current study emphasizes the importance of incorporating the inherent benefits of traditional architecture into modern constructions. Through the application of these principles and their adaptation to meet contemporary needs, it is possible to pave the way for the construction of buildings that are more sustainable and energy efficient. The integration of traditional knowledge and modern technology has the potential to address the challenge of constructing buildings that are environmentally sustainable and economically viable.

The integration of conventional architectural principles into contemporary construction methodologies holds the capacity to construct buildings that efficiently mitigate energy consumption, thereby fostering sustainable urban development.

The dome roof is a notable feature of traditional Iranian architecture and has been found to exhibit unique thermal properties that enable effective energy management, thermal comfort, and the optimal utilization of natural resources. Previous research has demonstrated the advantages of employing dome roofs in mitigating energy consumption and promoting energy conservation in various settings, including residential structures and places of worship, such as mosques. This study contributes further evidence to support the efficacy of dome roofs in enhancing energy efficiency, highlighting their importance within the realm of sustainable architectural principles.

In conclusion, the prioritization of improving energy efficiency in the construction sector is crucial for reducing the impact of built environments on global energy consumption and greenhouse gas emissions. This study highlights the significance of traditional Iranian architecture and its ability to provide a comfortable living environment for residents while minimizing energy consumption over a prolonged period. The proposition is that by discerning the principles and regulations that govern architecture, alongside the integration of new materials and technological advancements, it becomes feasible to employ the knowledge and methodology of traditional architecture in the development of groundbreaking structures that communicate a unique aesthetic. The findings of this research possess the capacity to make noteworthy advancements in the domains of architecture, engineering, and policymaking through the provision of valuable insights that can guide the development of sustainable and energy-efficient buildings. Consequently, this can facilitate the development of a more sustainable and ecologically conscious constructed environment.

The software limitations prevented the consideration of certain specific details, which may have led to potential inaccuracies. Subsequent investigations could further investigate these dimensions by examining supplementary factors and employing experimental methodologies to authenticate the simulation results.

In summary, this study adds to the expanding corpus of knowledge regarding energy-efficient architectural design, specifically within the framework of traditional marketplaces. Through an examination of the complex relationship between architectural configurations, energy consumption, and thermal comfort, this study provides valuable insights that can inform decision-making processes in the realm of sustainable building design and urban planning.

Author Contributions: Conceptualization, A.H. and F.O.; methodology, F.O.; software, A.H.; validation, F.O. and A.H.; formal analysis, A.H.; investigation, A.H.; resources, A.H. and F.O.; data curation, A.H. and F.O.; writing—original draft preparation, A.H.; writing—review and editing, A.H.; visualization, A.H.; supervision, F.O.; project administration, A.H.; funding acquisition, A.H. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: For this study, the data has not yet been uploaded to a public repository. We recognize the significance of data transparency in the research community. Currently, we are in the process of identifying suitable platforms where our data can be shared while upholding any relevant privacy and ethical guidelines.

Conflicts of Interest: The authors declare no conflict of interest.

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