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Impact of Atrium and Glazed balcony on residential building energy consumption in cold semi-arid climate: case study in Mashhad, Iran

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Abstract

Solar energy is one of the most important renewable sources and Iran is an ideal place for the use of solar energy. This form of renewable energy can be utilized through both active and passive systems. This research aimed to investigate the impact of the most common methods of using solar energy in passive ways, which are sunspaces (glazed balcony and atrium) on reducing energy consumption of two residential buildings in Iran-Mashhad city with cold semi-arid climate. The method of the research is descriptive, analytical and practical. The data collection was based on literature review, case study and climate data from meteorological station of Mashhad and reputable global web sites during a period of (2004-2018) for a short term and (1944-2020) for a long term. Also, a combination of the Echotect, Climate consultant and Autodesk Revit 2020 with insight 360 plug-in has been used. The Echotect software is used for optimum orientation analysis function and Climate Consultant is used for building design strategies appropriate for the unique characteristics of that climate of Mashhad. In this paper analyzed annual energy consumption in case A (with balcony and without balcony) and in case B (with atrium and without atrium). Results indicated that glazed balconies and atrium in two buildings could reduce the energy consumption by 41.33% in case A and by 26.28% in case B with respect to the reference building, respectively. Overall, using sunspaces can have a significant effect at city scale, by repetition in cold semi-arid climates. Thus, these systems can be considered by the designer in the first step of a designing project.

Keywords: Reducing energy consumption; Passive solar systems; Sunspaces; Atrium; Glazed balcony; Residential building

1. Introduction

Statistics indicate that while the world population growth is around 50% in the next forty years, the energy demand grows by about 80%. It is worth mentioning that about 40% of the worldwide energy consumption and 36% of the worldwide production of the carbon dioxide is attributed to the building sector, which has a significant contribution [1]. Iran's energy consumption statistic in 2017 shows that energy consumption in the residential sector is about 28%, which is more than energy consumption in industry by 25%, transportation by 24%, commercial by 6%, agriculture by 4% and non-energy consumptions by 13%. Therefore, residential sector is an important target for reducing the use of energy [2]. Sunspaces play a crucial role in building energy consumption under cold climate conditions. The addition of sunspaces can affect both daylight and energy performances in the adjacent living

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space. However, there are many previous researches about the influence of passive solar systems, especially sunspaces on building energy consumption. Mahar et al. showed that the most relevant passive design principles in cold semi-arid climates of Quetta are thermal control, passive solar heating, solar control, and passive cooling [3]. Zhao et al. stated that in the passive house system in cold areas, solar heat gain is of great significance and has equal status with the thermal insulation performance of envelopes, which has significant reference value for the early stages of passive house designing and the evaluation criteria [4]. Song et al. indicated that the indoor temperature of the condition without a balcony was 0.8 °C lower than that with a balcony. The heating and cooling load of the unit without the balcony space was 39% and 22% higher, respectively, than that of the unit with the balcony space [5]. Previous studies emphasized that usage of glazing framing around the balcony can reduce the energy demand in adjacent rooms up to 22%. It is caused by increased solar gains [6]. And also showed enclosed sunspaces with insulated walls and either low-E glazing or conventional double glazing provided any kind of energy savings up to 28%. The relatively large glazing areas in sunspaces can lead to overheating in the sunspace and adjacent rooms during summer, which can be prevented by naturally ventilating the sunspace and using shading devices. From the simulation results, the authors concluded that there were three most influential parameters for finding the optimum design solution for the sunspace, which were the glazing types and sizes, orientation and the sunspace occupancy profiles. The overall results showed that the highest energy savings for unheated sunspace in all cases were obtained by using low-E gas filled double-glazing for the sunspace glazing which provided up to 40% of energy savings [7].Yannas et al. revealed that the thermal impact of sunspaces on the heating energy demand is significant, accounting for a reduction of some 25-30%. As the depth of the sunspace increases, the thermal benefits diminish progressively, being reduced by 50% at a depth of 2.5m [8]. Liu et al. asserted that the sunspace's average temperature was higher and the thermal comfort level was better under the ratio of 45% or the depth of 1.5 m (depth/WWR), when only an individual factor in either ratio or depth was considered [9]. Eskandari et al. showed that the best position for using an Iwan (balcony) is the south direction and the use of balcony in temperate & humid, hot & humid, cold & mountainous and hot & dry climates could reduce the energy consumption in buildings by 32%, 26%, 14% and 29%, respectively [10]. Babaee et al. revealed that in a study in a cold region of Tabriz, Iran, reducing up to 46% of the heating load with an optimum design of sunspaces [11]. Owark et al. asserted that applying water tanks in the room with attached sunspace in Karaj (Iran) had a noticeable role in heat storing capacity. For example, the porous bed together with water tanks saved at least 37% (up to 87%) of energy cost compared to 10% (up to 15%) saved energy cost without water tanks [12]. Finocchiaro et al. stated that solar spaces make it possible to replace external environment conditions with a more favorable microclimate into which the living area can be extended. Atrium or greenhouses also become a tool for solving contradictions behind the optimization of morphological characteristics of energy-efficient buildings [13]. Laouadi et al. tested different atrium skylight forms in cold climate and concluded that the pyramidal/pitched skylights increased the solar heat gain ratio by up to 25% in the heating season compared to flat skylights. The effect of the skylight shape on the annual cooling and heating energy may be positive or negative, depending on the glazing U-value and SHGC ratios and the atrium type [14]. Other studies have declared that inappropriate glazing materials for skylights will cause undesired indoor conditions, since their optical and thermal properties are the dominant influencers of indoor lighting and thermal behavior [15, 16]. In a cold climate, another parameter that directly affects thermal comfort and energy performance is atrium geometry. For example, the problem with shallow atrium types is that during the summer time the atrium space becomes overheated in the vertical and horizontal directions, but throughout the winter time, this turns into an advantage [17]. Overall, this research reveal that passive solar systems have the potential to keep interior temperature within comfort zone and to reduce building energy demand.

1.1. Active and Passive solar energy systems

Increase in the world population has led to a sharp decrease in fossil fuel sources; and, therefore, substituting them with renewable sources as well as optimizing energy consumption could be considered ideal solutions [18]. Solar power consumption has increased exponentially for about a decade; another decade of similar growth will make the sun the world's dominant source of energy. There are several obstacles to continued growth, however, including political interference by companies in the fossil-fuel business. Nevertheless, solar power is the fastest growing source, and currently the most profitable energy investment [19]. Solar energy can be utilized through both active and passive systems. Active solar systems utilize mechanical and electrical devises to receive and transport energy. The term passive system is applied to buildings that collect and store solar energy without the use of energy-consuming devices and thus reduce the need for auxiliary energy for comfort heating. This causes the amount of energy consumption in different parts of a building to reach their point of minimum [20]. The design for a passive solar building has to take into account the amount and angle of solar gain throughout the seasons and during the course of each day. When these are combined, optimal building forms can be generated [21]. Passive technologies aim at maximizing the effect of this approach by choosing proper orientation of the building, size and location of windows, shading and ventilation devices, color of outer surfaces, thermal resistance and heat capacities of the building elements etc [22]. Sunspaces are passive systems often used in residential buildings due to their considerable energy conservation capability. They can significantly conserve the energy-generating products used for heating and cooling [23]. In this paper, the most common methods of using solar energy in passive ways, which are glazed balcony and atrium are investigated for reducing energy consumption.

1.1.1. Balcony

Heating is most often needed in an occupied space in the seasonal cold climate regions of the world. Higher energy consumption and costs involved with meeting this need motivates us to find ways to improve the efficiency of the existing processes [24]. Balconies have been recognized as an environmental “buffer space”, with the capacity to mediate the outdoor conditions in dwellings and studied as a passive solution to reduce the energy consumption of contemporary buildings [25]. In this paper, two types of balcony spaces are compared and analyzed:

- **Open balcony:** has a roof and is not surrounded by glass. Open balconies play an important role in improving natural ventilation. Balcony as the open system to the outside and fixed shading construction can reduce overheating in a shaded room during the summer, as shown in Figure 1 [25].
- **Glazed balcony:** is closed by glass on the outside edge is known as sunspace or winter gardens. This space acts as a solar energy storage that can be applied in various ways to the building block. The adjacent space functions as a thermal buffer between the interior and exterior of the building and as a solar collector. This space could also be used as a ventilation pre-heating area using openable vents or windows to let the warm air flow into adjacent spaces, Fig. 1 [7].

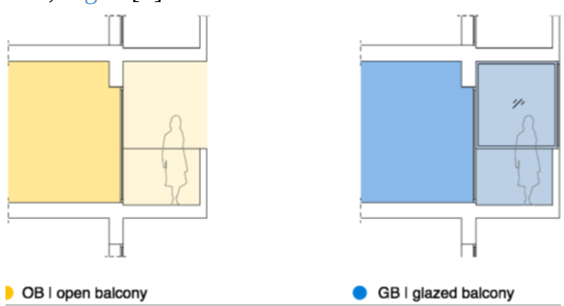


Fig. 1. Types of balcony spaces. Source: (Ribeiro, Ramos, & Colen, 2020)

1.1.2. Atrium

Solar gain and access to daylight are two main benefits of atrium in cold climates. In cold weather conditions and during sunny days, atrium is a pleasant sunspace, which also provides a buffer zone between undesirable outdoor conditions and indoor zones [26]. Atrium is a very large room, often with glass walls or roof, expose adjacent indoor spaces to daylight, maximize benefits from direct solar gain, and increase residents’ interactions. It also provides air circulation and communication among different stories of the building. The thermal mass of atrium external walls with external insulation provides better internal temperature variations in the winter so that the heat stored in walls could be useful for the nighttime buoyancy driven ventilation when there is no solar radiation. Table 1 [27].

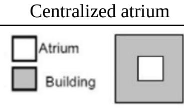
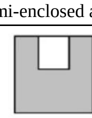
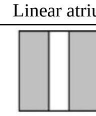
Atriums can be categorized into four general forms: [20].

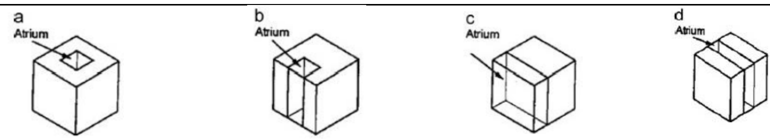
- The first type is the centralized atrium. This type of atrium has a centralized glass courtyard, which is located in the center of the building and is surrounded by a glass roof.
- The second type is the semi-enclosed atrium, in which the glass space is within the building but one of its sides is on the exterior surface of the building. In this type of atrium, the roof can be either made of glass or be open.
- The third type is the attached atrium, which is constructed outside the exterior walls of the building and is in contact with the outside space from three sides.
- The last type is the linear atrium, which is located in an area between two separated blocks with glass walls on two sides.

Overall, Sunspace can be a suitable and efficient system to reduce energy demand in the building if designed according to the local climate and passive design measures. The main purpose of a sunspace is to collect solar energy and reduce the need for other energy resources along with its energy demand [7]. Therefore, the objective of research is to investigate the impact of reducing energy consumption through sunspaces (glazed balcony and atrium) for two-selected buildings of residential complex in Iran-Mashhad city with cold semi-arid climate. In addition, the main research question of this study is as follow: How efficient are sunspaces especially glazed balcony and atrium on reducing energy consumption of residential building in cold semi-arid climate?

Table 1

Four general forms of the atrium in plan and volume. Source: (Modirrousta, 2016)

General forms of atrium	Centralized atrium	Semi-enclosed atrium	Attached atrium	Linear atrium
Atrium in plans				

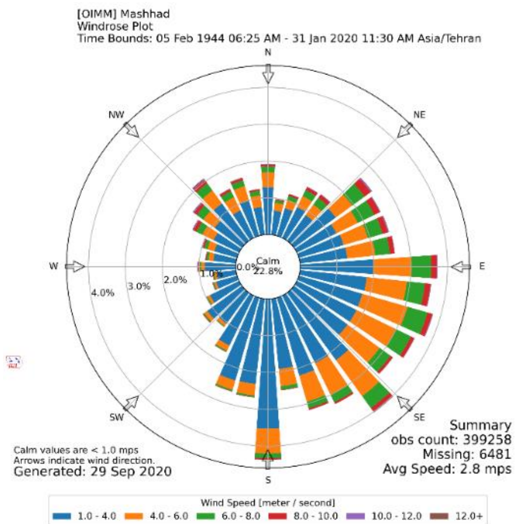
Atrium in Volume	

2. Methodology

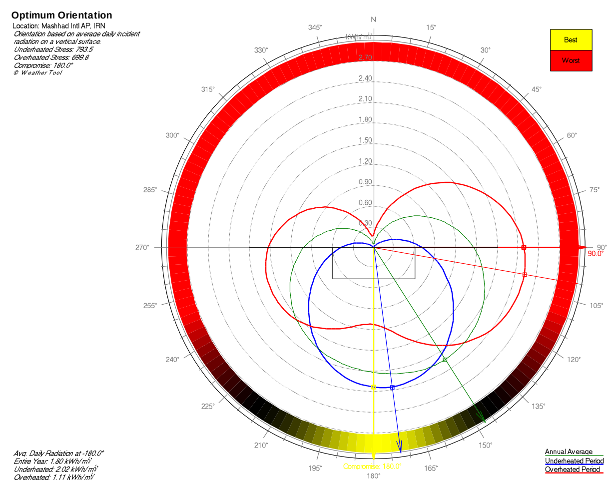
In all types of climates, designing a sunspace should always take into account the existing climatic conditions. The current paper was motivated by the convergence of recent weather data and building energy modelling techniques. From the previous studies and EPW data of the Iran meteorological organization, reputable global websites (globalsolaratlas, Iowa environment mesonet, weather underground and climate.onebuilding) during a period of (2004-2018) for a short term and (1944-2020) for a long term and computer simulation methods (Ecotect weather tool and Climate consultant), were extracted optimal orientation and climate responsive architecture solutions of Mashhad. Finally, the modeled building in Revit software was analyzed by Autodesk Revit 2020 with Insight 360 plug-in according to the type of passive systems to assess the annual energy consumption of the residential building in Mashhad.

2.1. Climate of Mashhad

The city of Mashhad with a latitude of 36.2605 ° N, 59.6168 ° E is the second most populous city in the country, which is located in northeastern Iran. Climate data of Mashhad show that June, July and August have the maximum average temperature (up to 35 °C) and December, January and February have the minimum average temperature (below to 0 °C). The lowest temperature recorded during the statistical period was on February 3, 2014 (-21 °C). This city does not receive heavy rainfall, the average annual rainfall is 234 mm. The maximum average wind speed is in June, July and August and the minimum average wind speed is in November, December and January. In other words, the maximum and minimum wind speed occurs in the warm months and the cold months of the year, respectively. Investigation of Mashhad's wind rose in the years (1944-2020) from the Iowa environmental mesonet (IEM) shows that the prevailing wind direction with a maximum average speed of 3 meters per second is east and southeast. Also, the study of the prevailing wind speed and direction of Mashhad in hot and cold seasons of the year according to the wind speed and temperature shows that summer cooling breezes from the south, warm summer wind from the northeast and with high speed, the prevailing cold winter wind blows from the east and southeast with high frequency and low speed up to 6 meters per second and from the northwest with low frequency and high speed, and warm winter wind from the west and southwest [28], Fig. 2(a). Furthermore, by using the website of climate.onebuilding.org contains climate data designed specifically to support building simulations according to Mashhad weather data in the years (2003-2017) and Ecotect weather tool software, the optimal orientation of the building is between 20° southeast and 15° southwest (160° to 195° from north). In addition, the best orientation is 180° from north (south-facing). This angle has the highest solar energy reception in the cold months and the lowest solar radiation energy in the hot months of the year, Fig. 2(b).



(a)



(b)

Fig. 2. Wind rose; (a) The best orientation = 180° from North; (b) in Mashhad, Source: https://mesonet.agron.iastate.edu/; (a) and output from Ecotect weather tool software; (b)

Determining thermal comfort conditions in different climatic zones minimize the need for mechanical heating and cooling and help save energy. Climate Consultant software is a tool for calculating the effectiveness of active and passive building design strategies, which means that it draws and calculates all the hours that are in the range of thermal comfort. This software receives the EPW (energy plus weather data) and after analyzing the climatic conditions of the place, offers recommendations for adapting the building to this climate. According to the psychrometric diagram and 15-year weather data of Mashhad (2004-2018), without implementing any energy efficient architectural solutions, two months of the year (May and September) are already within the comfort zone, three months from (June to August) are above the comfort zone and about 5 to 7 months from (November to April) are below the comfort zone and within the cold range. According to Climate Consultant software analysis without architectural solutions, 59.6% of the year needs heating and 27.6% of the year needs cooling in Mashhad with cold semi-arid climate. Also, natural ventilation is not necessary and night ventilation in summer can be used if needed. In general, the need for heating is necessary for more than half of the year, while the need for cooling is almost half of the need for heating during the year. In other words, the need for heating is higher in Iran-Mashhad and the cold period include most of the days of the year, Fig.

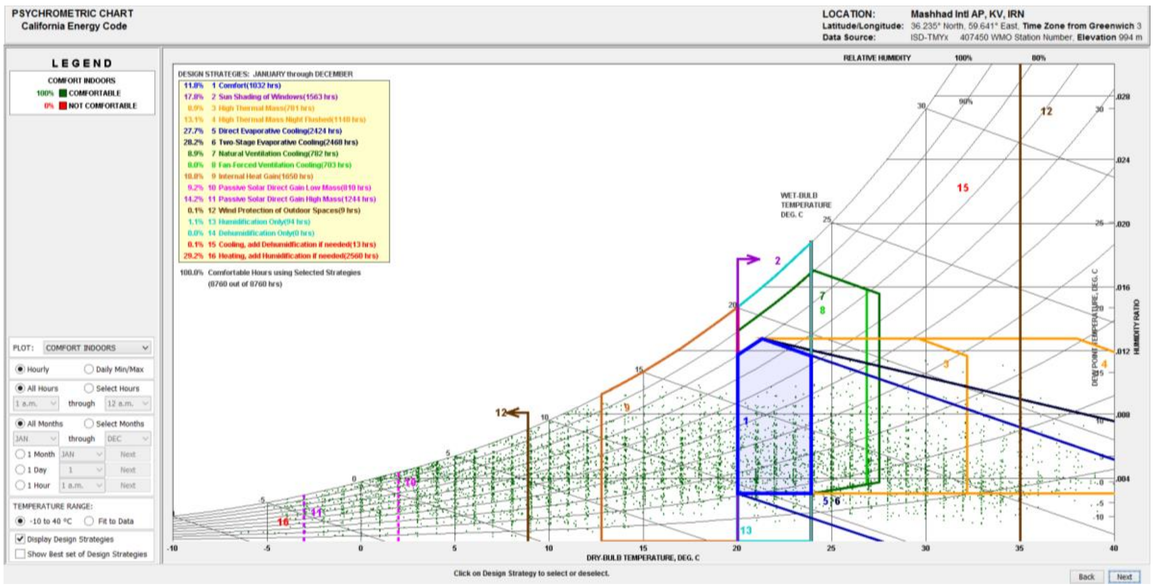


Fig. 3. Annual psychometric diagram of Mashhad based on climate data of the years (2004-2018). Source: Output from climate consultant 6.0 software.

2.2. The case study

Solar energy is one of the most reputable sources for providing future generations with sufficient energy. Given the average sun radiation in Iran, which is about 5 kilowatts per hour per square meter in sunny days, utilizing solar energy is easily achievable. To do so, there are several active and inactive systems which could be designed and installed, and as long as they are properly operated in architectural spaces, they can pave the way for reducing thermal loads [20]. In this study, the site was selected according to the height of adjacent buildings in order to gain solar energy, not to create the barrier of summer cooling breezes from the south, suitable land dimensions and homogeneous land uses. The site is located in the southwestern area of Mashhad, Fig. 4&5. According to the location of the building and information obtained from the Global Solar Atlas website [29], the highest average hours of solar irradiation in August, with a total of 7288 wh/m^2 and the lowest hours in January with a total of 3581 wh/m^2 and the annual average direct normal irradiance is 1843 kwh/m^2 in Iran-Mashhad, which indicates the importance of investing in this field to obtain radiant energy, Fig.6. The process of design formation according to the climate design parameters of Mashhad is as follows:

- Due to the priority of the need for heating in Mashhad and receiving appropriate solar radiation in winter, the buildings were arranged linearly and the parallel columns (east and west-facing) pattern was avoided due to reduced solar energy and unwanted heat gain in summer and increased passive solar heat gain in winter.
- To receive maximum solar energy in winter, the middle buildings of the site rotated to the south (south-facing). The complete rotation of the sidewalk buildings caused the street edge to be heterogeneous, so only part of the body of the blocks rotated towards the desired daylight and wind.
- By moving the blocks in the middle of the site was slightly approached the pattern of the central courtyard with the aim of creating a suitable green space and reducing shading of the buildings.

- By using the south-low, north-high pattern increased passive solar access in winter (the pattern of tall buildings in the north and low buildings in the south).
- By changing the height of the buildings (stepped building) reduced the shading of the buildings on top of each other.

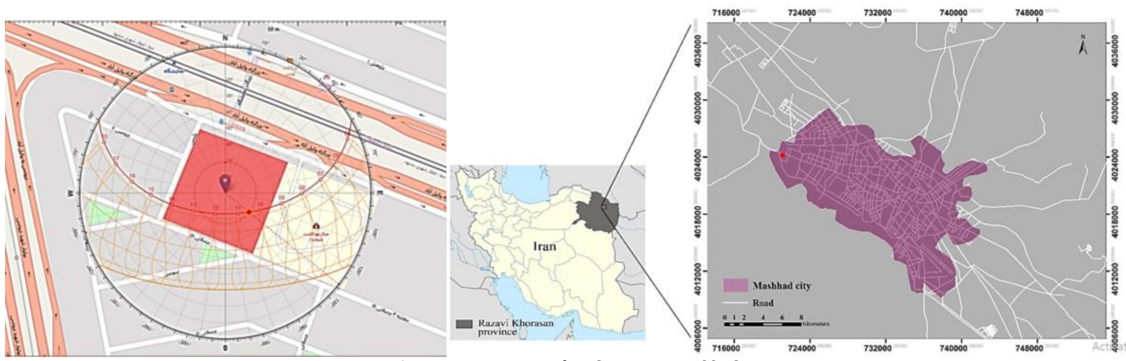


Fig. 4. Location map of study area in Mashhad.

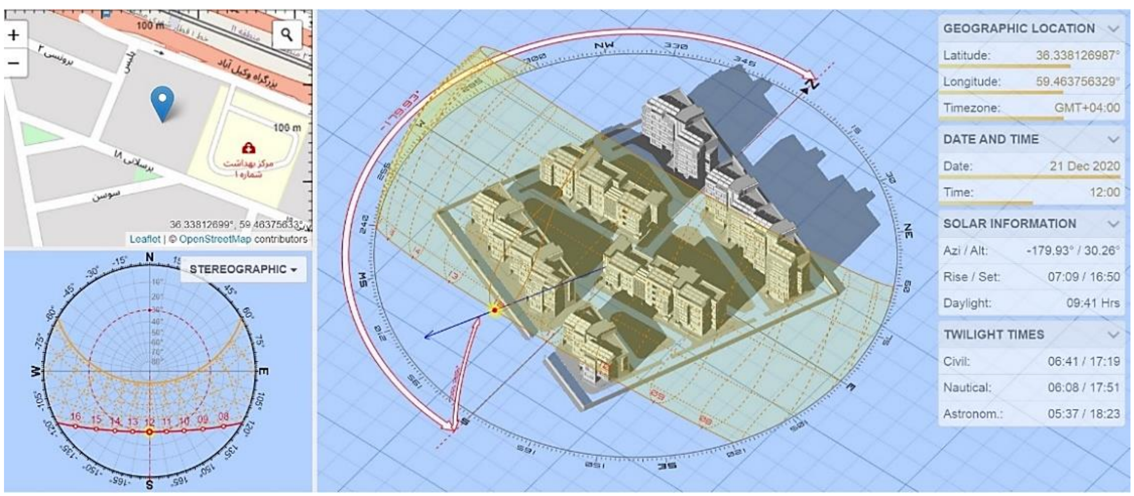
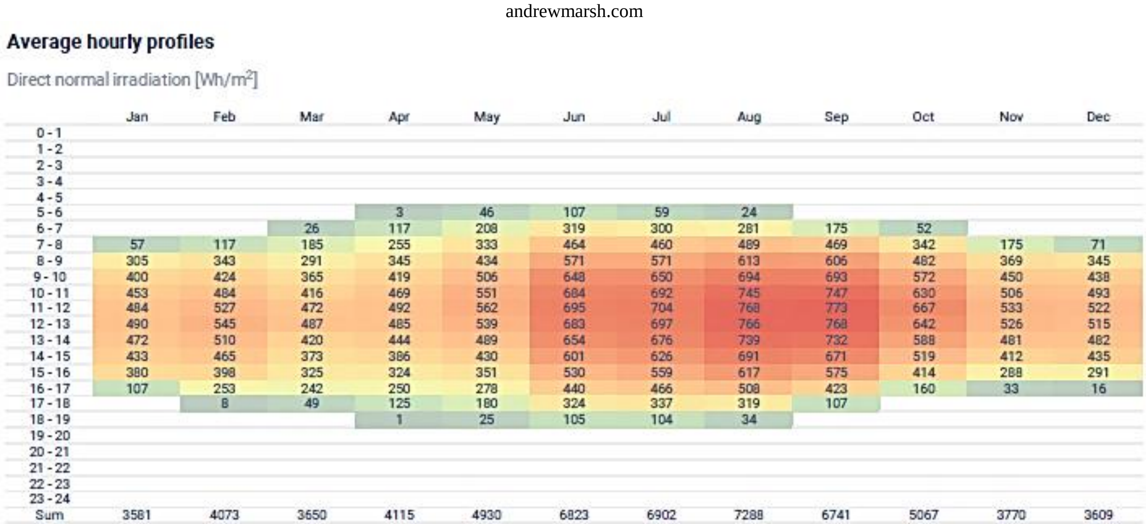


Fig. 5. Solar position, sun path and solar shading of buildings at the site during the winter solstice (December 21) at 12 noon. Source: Output from andrewmarsh.com



Average hourly profiles

Direct normal irradiation [Wh/m^2]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5												
5 - 6				3	46	107	59	24				
6 - 7			26	117	208	319	300	281	175	52		
7 - 8	57	117	185	255	333	464	460	489	469	342	175	71
8 - 9	305	343	291	345	434	571	571	613	606	482	369	345
9 - 10	400	424	365	419	506	648	650	694	693	572	450	438
10 - 11	453	484	416	469	551	684	692	745	747	630	506	493
11 - 12	484	527	472	492	562	695	704	768	773	667	533	522
12 - 13	490	545	487	485	539	683	697	766	768	642	526	515
13 - 14	472	510	420	444	489	654	676	739	732	588	481	482
14 - 15	433	465	373	386	430	601	626	691	671	519	412	435
15 - 16	380	398	325	324	351	530	559	617	575	414	288	291
16 - 17	107	253	242	250	278	440	466	508	423	160	33	16
17 - 18		8	49	125	180	324	337	319	107			
18 - 19				1	25	105	104	34				
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	3581	4073	3650	4115	4930	6823	6902	7288	6741	5067	3770	3609

Fig. 6. Average hourly profile of direct normal irradiation at the site in Mashhad. Source: Output from globalsolaratlas.info

3. Results and discussions

Sunspace is a particular typology of solar passive system. The addition of sunspaces can affect energy performances in the adjacent living space. To this end, the following analysis were conducted on them, which include the following: Fig. 7.

- Annual energy consumption in case A (with balcony and without balcony)
- Annual energy consumption in case B (with Atrium and without Atrium)

In this study, the buildings were evaluated according to the type of passive system in terms of annual energy consumption by using Autodesk Revit 2020 with Insight 360 plug-in. Energy simulation software tools are an important support used for a building designer to take cost-effective decisions that improve the performance and reduce the environmental impact of buildings. Insight 360 tool allows examining the energy and environmental performance of buildings taking into account variations of all building parameters specifications and its incidence to the total energy efficiency [30]. The ASHRAE method is used for building energy analysis, and HVAC systems include Central VAV, HW Heat, Chiller 5.96 COP and Boilers 84.5 eff. In addition, the schedule type (7/12) is considered for each day of the week and each month of the year. The building mode is selected (use building elements) and phase of the building project has been chosen (new construction).

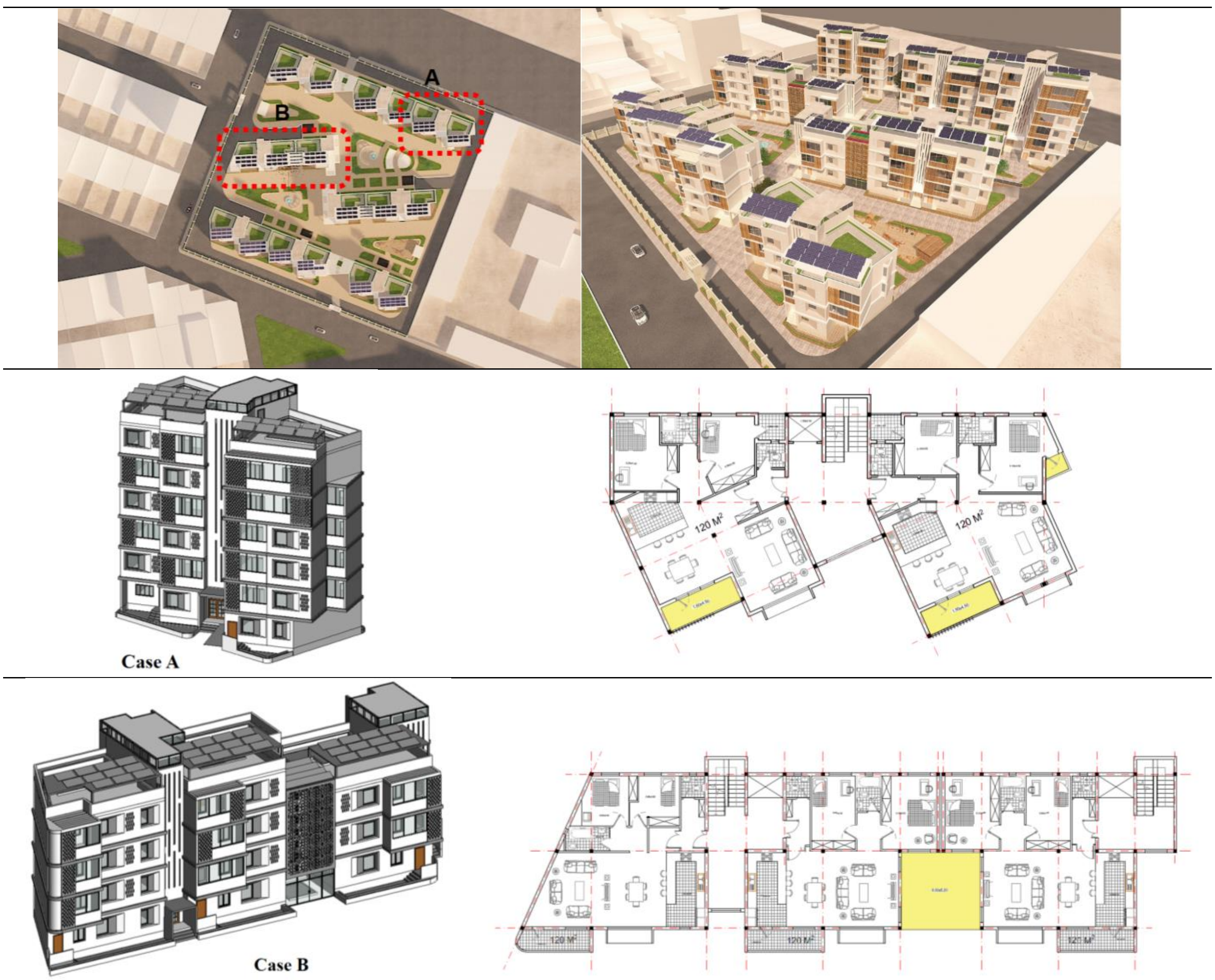


Fig. 7. Selection of two cases of residential complex for energy analysis with Autodesk Revit 2020 - Insight 360 plug-in.

The building envelope consists of all the building constructions, proper details and materials which separate the inside from outside; The role of thermal mass in sunspace buildings is to store heat distributed to the various rooms during diurnal periods without sunlight or during the night [23]. In case A with 5 floors and 12 units, the annual energy consumption was compared through computer simulations with Revit 2020. Results showed that a maximum of 31.5% of energy savings when compared to the reference case could be achieved through improvement of material parameters in construction Table 3. Increasing the thickness of external thermal insulation, AAC blocks and double glazing with Low-E coating have an effective role in reducing the U-value and maintaining heat storage in layers to save indoor thermal energy in Mashhad climate Table 2. These proposed materials were considered in all buildings of the residential complex and then was investigated the effect of balcony and atrium on energy consumption.

Table 2
Building construction design and U-value in Mashhad climate.

Components	Material layer	Thermal conductivity (w/m.k)	Thickness (m)	U-value (w/m^2.k)
External wall	• Brick (outer) • Rear ventilated level • Extruded polystyrene • Aerated concrete block • Foil, EPDM • Gypsum plaster (inner)	- - 0.031 0.19 0.25 1.10	32 cm	0.364
Internal wall	• Gypsum (outer) • Gypsum plaster • Extruded polystyrene • Aerated concrete block • Foil, EPDM • Gypsum plaster (inner)	0.57 1.10 0.031 0.19 0.25 1.10	30 cm	0.338
External Floor	• Gypsum plaster (outer) • Quad-Deck • Light weight concrete • Roofing bitumen • Cement screed • Ceramic tiles (inner)	1.10 - 0.52 2.0 1.8 0.64	35 cm	0.758
Internal Floor	• Gypsum plaster (outer) • Quad-Deck • Light weight concrete • Roofing bitumen • Cement screed • Ceramic tiles (inner)	1.10 - 0.52 2.0 1.8 0.64	35 cm	0.694
Flat roof	• Tiles (outer) • Cement screed • Extruded polystyrene • Roofing bitumen • Light weight concrete • Quad-Deck • Gypsum plaster (inner)	0.64 1.8 0.031 2.0 0.52 - 1.10	40 cm	0.268
Window	• UPVC window frame + DblLoE Clr 12mm Arg	-		2
Door	• PVC coated MDF	-		0.9

Table 3
Monthly and annual energy consumption in case A with (suitable and unsuitable materials). Source: Output from Revit 2020 software.

Months of the year	energy consumption of case A before improvement with unsuitable materials (kwh)	energy consumption of case A after improvement with suitable materials (kwh)
January	12738.32	8724.52
February	9509.91	6513.39
March	5256.83	3600.43
April	3472.1	2378.06
May	3882.94	2659.45
June	6776.61	4641.34
July	7619.14	5218.39
August	7826.68	5360.54
September	5573.15	3817.08
October	3086.54	2113.99
November	4940.55	3383.81
December	10905.03	7468.92
Annual	81587.82	55879.90
Percentage of optimization	31.5%	

3.1. with balcony and without balcony in case A

Passive design, which has strong dependency of climate and areas, is the most economical effective strategy for reducing energy consumption inside residential buildings [31]. The sunspaces as the most common methods of using solar energy in passive ways are elements positioned to south, east and west facing facades. South glazed balconies are structures placed to the southern facade with the purpose of enhancing the effect of solar radiation on the adjacent internal spaces by providing a buffer zone. For the sunspace to be effective, the partition separating it from the adjacent space in the parent dwelling should be mostly glazed. The geometry of the east and west glazed balconies are based on the capture of southern winter solar radiation. They take the shape of angular protrusions, having the south facing wall glazed, while their other external surfaces are as insulated opaque elements. These elements create a buffer effect that leads to a better thermal performance [8]. In this section, building A of residential complex with balcony in two types of sunspaces (open balcony and glazed balcony) were compared to the reference (without balcony) for evaluating the annual energy consumption, Fig. 8 (a and b). Other parameters to be fixed such as materials, dimensions and height of the window. Adjustable solar shading by users placed outside the glazing to limit direct solar gains in summer period. The results in case A with 5 floors and 12 units (without balcony) show high annual energy consumption with the highest heating load in January (the coldest month) and the highest cooling load in August (the hottest month). In addition, the results reveal that using the south and east glazed balconies with the depth of 1.5m in case A with glazing on just one side at a rate of 41.33% and with open balcony save about 15.21% of annual energy consumption compared to the reference building, as shown in Table 4 & Fig. 9. This study shows that the use of solar glazed balcony as a buffer space will have an optimal effect on reducing annual energy consumption in cold semi-arid climate of Mashhad. In other words, an optimum designed sunspace is an efficient system for passive heating in cold periods of the year and the thermal conditions will be very attractive at the balcony and in the apartments as the temperatures in the balcony during the heating season will be very pleasant. There are overheating problems during the warmer seasons, which may be eliminated by adjustable solar shading devices (sliding louver screen) and night ventilation, so that the thermal comfort in the adjacent space can be achieved, Fig.8 (b and c).

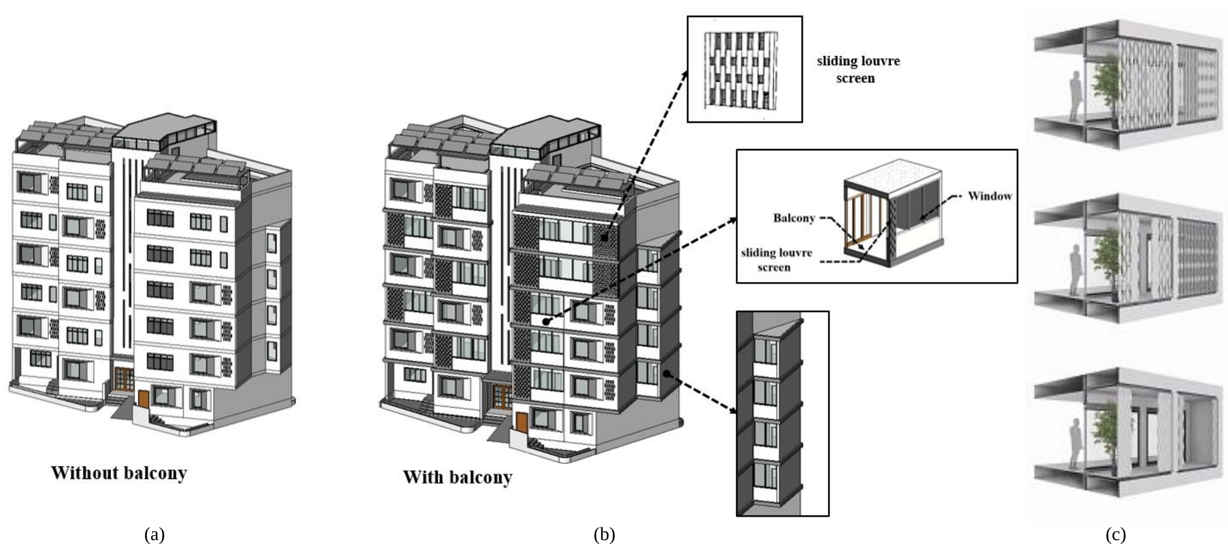


Fig. 8. Case A before improvement (without balcony); (a) and after improvement (with glazed balcony) in south and east view of the building; (b) source: author. Using adjustable shading devices to reduce heating load in summer and innovative use of natural light , source: (Saba apartment) (c).

Table 4
Monthly and annual energy consumption of case A before improvement (without balcony) and after improvement (with south and east balconies). Source: Output from Revit 2020 software

Months of the year	energy consumption of case A before improvement (without balcony) , kwh	energy consumption of case A with open balcony + solar shading (kwh)	energy consumption of case A with glazed balcony + solar shading (kwh)
January	14871.38	12706.77	8724.52
February	11102.39	9580.64	6513.39
March	6137.11	5431.06	3600.43
April	4053.52	3484.19	2378.06
May	4533.16	3776.94	2659.45
June	7911.39	6535.46	4641.34
July	8895.00	7337.96	5218.39
August	9137.30	7569.81	5360.54
September	6506.40	5318.92	3817.08
October	3603.40	3020.73	2113.99
November	5767.87	5049.32	3383.81
December	12731.13	10943.37	7468.92
Annual total energy	95250.05	80755.23	55879.90
Percentage of optimization		15.21%	41.33%

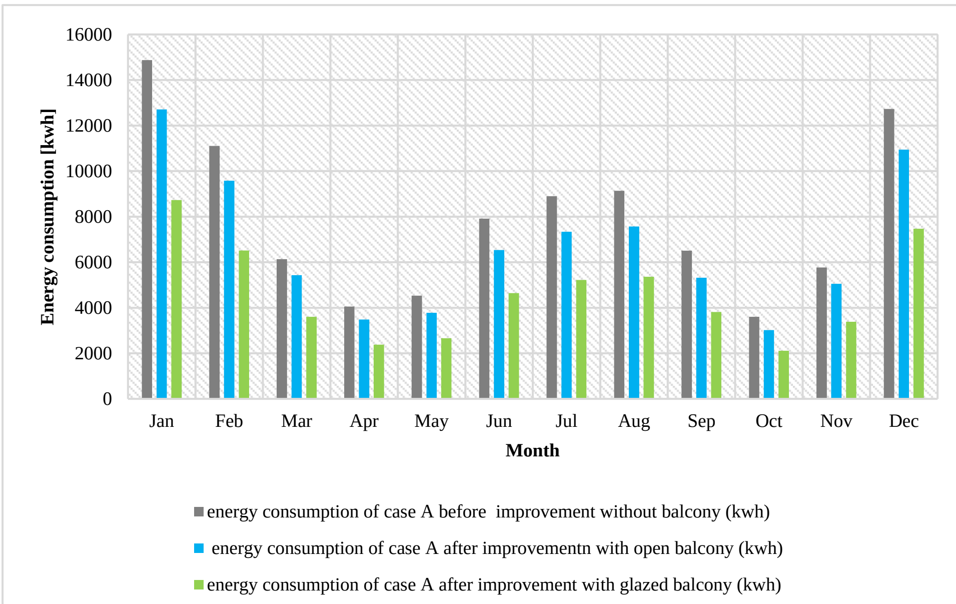


Fig. 9. Comparison chart of monthly energy consumption of case A (with balcony and no balcony).

3.2. with Atrium and without Atrium in case B

Atrium adjusts the indoor climate environment through "greenhouse effect" and "chimney effect". A greenhouse space reduce the heating load of the building in cold seasons and solar chimney effect and natural ventilation reduce the cooling load in hot seasons. Proper use of these two effects can effectively save energy consumption of air-conditioning [32], as shown in Fig. 11. In this section, building B of residential complex with Semi-enclosed atrium in two types of closed skylight and open skylight were compared to the reference (without atrium) for evaluating the annual energy consumption, Fig. 10. A Semi-enclosed atrium is a glazed space that is positioned in the building such that only one side faces the exterior. It may or may not have a glazed roof. The results indicate that the annual energy consumption would be reduced in a building with atrium in two types of closed skylight by 26.68% and open skylight by 23.07% in cold semi-arid climate of Mashhad, as shown in Table 5 & Fig. 12. Furthermore, this depends on the solar shading and glass types used in the building. The relatively large glazing areas in sunspaces can lead to overheating in the sunspace and adjacent rooms during summer, which can be prevented by night ventilating the sunspace, using shading devices and colored glass (a sense of traditional Iranian architecture). Fig. 13.

(a) (b)

Fig. 10. Before improvement (without Atrium); (a) and after improvement (with Atrium); (b)

(a) (b)

Fig. 11. Atrium (greenhouse effect) as a heating source and insulating the indoor space from the outside in winter; (a) and Atrium (solar chimney effect); (b)

Table 5
Monthly and annual energy consumption of case B before improvement (without atrium) and after improvement (with atrium). Source: Output from Revit 2020 software

Months of the year	energy consumption of case B before optimization (Kwh)	Atrium with open skylight + solar shading (kwh)	Atrium with closed skylight (flat glazed roof) + solar shading (kwh)
January	21794.77	16765.21	15978.99
February	16271.13	12516.26	11929.29
March	8994.254	6918.66	6594.20
April	5940.644	4569.73	4355.42
May	6643.585	5110.45	4870.79
June	11594.55	8918.89	8500.63
July	13036.09	10027.76	9557.50
August	13391.19	10300.92	9817.84
September	9535.472	7334.98	6991.00
October	5280.965	4062.28	3871.78
November	8453.118	6502.40	6197.46
December	18658.14	14352.42	13679.35
Annual total energy	139593.9	107379.96	102344.31
Percentage of optimization		23.07%	26.68%

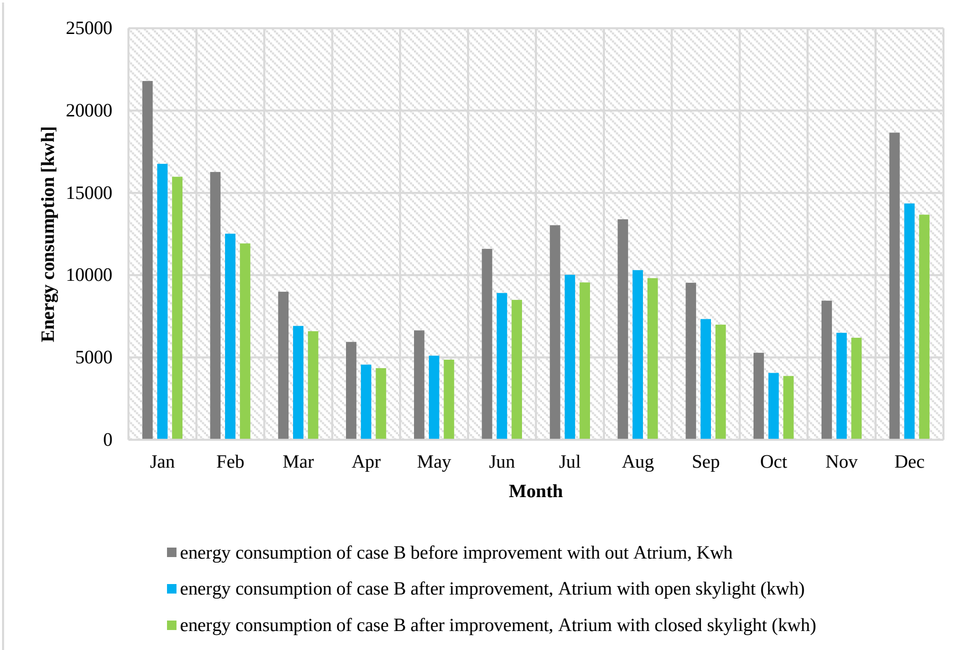


Fig. 12. Comparison chart of monthly energy consumption of case B (with atrium and no atrium).

Fig. 13. Using shading devices and colored glass to reduce heating load in summer, innovative use of natural light and creating sense of traditional Iranian architecture.

3.3. Comparison of two systems

This study shows that glazed balcony is better when compared to open balcony and much better than without balcony. It builds up a buffer space between the exterior and the interior. On a sunny cool day, the buffer heats up the balcony and can help reduce heat consumption and provide remarkable energy savings in the building. While at the same time offering a pleasant space for the people living in the apartment to spend time on the balcony. In addition, atrium with closed skylight is better than atrium with open skylight and much better than without atrium in Mashhad climate. Atrium has aesthetical, environmental, and economic benefits; the appropriate atrium design can enhance an atrium's thermal performance and the adjacent spaces temperatures, but during the summer period it can cause overheating and using shading devices shrinks the lighting intensity and temperature. In addition, the surface exposed to excessive heating is smaller, so less protection from overheating is needed. Overall, sunspaces are a source of auxiliary heat, a place to grow plants and innovative use of natural light and pleasant living area. Summer cooling breezes from the south provide natural ventilation in the balcony and solar chimney effect in the atrium to reduce the cooling load in hot seasons. In addition, balconies and atrium closed by glass on the outside edge protect from the cold winter wind from the east and southeast to reduce the heating load of the building in cold seasons, Fig. 14. Furthermore, using double-glazing with Low-E coating, insulation by adding 0.05 mm of EPS (Extruded polystyrene) to external walls and Autoclaved Aerated Concrete (AAC blocks) had almost effect on average energy consumption.

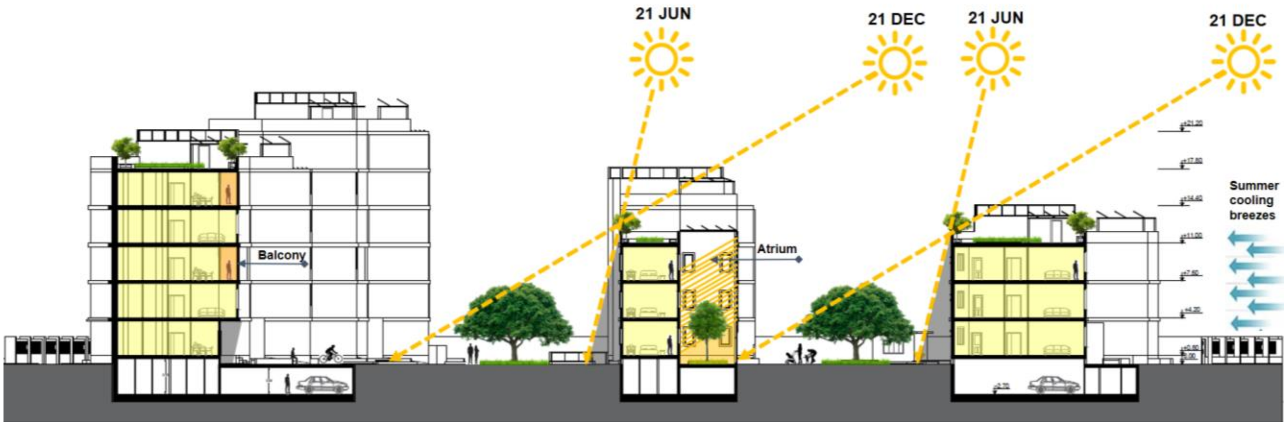


Fig. 14. Summer cooling breezes and angle of radiation on 21 June and 22 December.

4. Conclusions

There are different methods for the utilization of the solar energy in an inactive way namely solar windows, solar greenhouse method, Trombe wall and aqua wall, atriums, and pools on the rooftops. In this paper, the most common methods of using solar energy, which are glazed balcony and atrium are analyzed. Two buildings of residential complex were selected for investigation of energy consumption in Iran-Mashhad. The main objective was to evaluate the impact of passive solar systems (sunspaces) on reducing energy consumption in the buildings of Mashhad's cold semi-arid climate. The results from recent research show that passive solar design with optimum designed sunspaces presents various advantages in cold periods of the year, so that atrium and glazed balcony have a potential to save energy without using active systems. In this investigation, glazed balconies in case A with glazing on just one side at a rate of 41.33% and Semi-enclosed atrium in case B with closed skylight by 26.68% reduced energy consumption in two selected residential buildings. Overall, using sunspace systems include the glazed balcony and atrium and an integration of these two systems are essential to diminish energy consumption of residential building. So that these systems can be considered by the designer in the first stages of the designing a project. Using sunspaces can have a significant effect at city scale, by repetition. Many areas along this latitude, cold climate, strong sunshine and low cloud cover generate incentive for their extensive use around the world. An optimum designed sunspace is an efficient system for passive heating in cold periods of the year. Conducting this research has brought recommendations for optimal sunspaces design in cold climate. Some of these recommendations are:

4.1. Glazed balcony

- Glazed balcony is more beneficial for colder climates, because having a sunspace can raise the indoor temperature in the building. So that heating the balcony will offer significant energy savings for space heating and ventilation.
- To achieve a better thermal performance, in most cases sunspaces will be beneficial if oriented towards south.
- The position, angle and materials used in the balcony affect the amount of daylight capture.
- Sunspaces with insulated walls, roofs and floors and either Low-E double-glazing provide any kind of energy savings.
- Night ventilation strategy, adjustable solar shading devices or kinetic shading systems and sufficient thermal insulation in combination with the sunspaces can reduce overheating in sunspaces during the summer period. The effectiveness of the night ventilation is related to the relative difference between indoor and outdoor air temperatures.

4.2. Atrium

- Semi-enclosed atrium with a fully or partially integrated sunspace is a larger contact surface with the building interior than with the exterior, which makes it more comfortable during wintertime. Furthermore, due to the smaller surface exposed to excessive heating, less protection from overheating is needed during the summer.
- During summer months when there is maximum energy consumption, the roof openings remain closed due to unsatisfactory external climatic conditions.
- A vent opening profile can be used in the skylight/glazed roof of atrium that is opened automatically only under favorable climatic conditions.
- Adjustable solar shading or kinetic shading systems in the atrium's faced and skylight, Low-E double glazing and colored glass reduce heating load in summer and create a sense of traditional Iranian architecture

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