

# Impact of combining windcatchers with an atrium on energy consumption in the hot-dry climate

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## ABSTRACT

*Using passive systems as a non-mechanical method is an effective way to address energy waste in the environment. Therefore, efforts should be made to reduce these impacts by using sustainable technologies. Atrium, as a passive heating system, provides heating and natural light, while windcatcher, as a passive cooling system, offers natural ventilation and cooling in buildings. Passive systems, despite their advantages, also have disadvantages that ignoring them will result in inefficiency. In this study, for the first time, both atrium and windcatcher systems are used simultaneously to combine them to eliminate each other's disadvantages and reduce building energy consumption. The case study example in two scenarios, with and without a windcatcher, was designed and simulated using EnergyPlus software. The simulation results showed that adding a windcatcher to the atrium reduced cooling consumption by 67%. Implementing water spray at the windcatcher's entrance further improved its efficiency, increasing humidity and lowering cooling consumption by 7-17% compared to a windcatcher without water spray. These strategies resulted in significant energy savings for the building.*

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## 1. Introduction

The excessive use of fossil fuels, the rise of pollutants, and the growing population have led to global warming, posing a threat to the Earth and the health of its inhabitants [1]. The

building sector is a significant producer of greenhouse gases and accounts for over one-third of global energy consumption, including a large amount of waste from construction and demolition activities [2-3]. Iran's share in this field is five times the global average [4]. Therefore, optimizing energy consumption and utilizing renewable energy sources to achieve sustainable buildings has become a priority for designers, building owners, and policymakers

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today. It's worth noting that sustainable building practices not only benefit the environment but also offer significant cost savings, making them an attractive option for policymakers [5]. Building occupants and users expect the availability of natural ventilation, thermal comfort, and visual comfort to enhance their interaction with the environment [6]. Therefore, providing comfortable conditions is very important, considering that people spend most of their time indoors [7]. The demand for cooling energy plays the most significant role in energy consumption, and many studies have been conducted to reduce the energy demand for building ventilation and cooling [8]. On the other hand, thermal comfort and air conditioning in large buildings require significant expenses [9]. The provision of visual comfort through daylight management and control [10], as well as thermal comfort by maintaining indoor air quality, is an important and influential factor in occupants' health, alertness, and well-being. This subject, in turn, leads to reduced energy consumption and contributes to achieving sustainable development in the building industry. [11]

Environmental controls and cooling systems are passive strategies to prevent energy loss and excessive heat [12]. One design strategy that can reduce energy consumption and provide residents' comfort through natural ventilation is integrating passive heating and cooling systems such as windcatchers and atriums, which directly harness energy from renewable sources [13]. The innovative use of passive design strategies, which means that the collection, storage, and distribution of energy in buildings is done with the help of the natural movement of air, heat, and light from the sun and natural cooling methods, can significantly reduce energy consumption and address environmental problems [14]. This innovative approach to design can inspire architects and builders to create more energy-efficient and sustainable buildings [15].

Atriums can be a practical strategy in sustainable architecture, preventing energy loss. In the past, atriums were defined as the central open courtyard of a Roman house, a courtyard in front of medieval churches, and, in ancient Roman architecture, an internal courtyard or central courtyard of a building [16]. Today, the

atrium is one of the architectural elements used to harness sunlight in buildings. As a transparent space, the atrium allows sunlight to penetrate the building and can lead to energy savings [17]. On the other hand, the atrium provides visual connections, fosters interaction between the building and its surroundings, and creates a sense of focus and cohesion among individuals [18]. Since natural light performance in an atrium is heavily influenced by the climate, if not correctly designed, it can lead to excessive energy consumption and a resulting loss of visual and thermal comfort [19-20]. However, research has shown that correctly designing atriums using strategies such as 'external louvers' and 'perforated screens' as shading devices, and 'fixed or adjustable horizontal or vertical fins' as sunshades, and considering climate-responsive design principles can effectively enhance sunlight penetration into various climates [21].

Wind towers were used as a passive cooling system on the central Iranian plateau. Their purpose was to provide natural ventilation and thermal comfort for inhabitants during the hot months in both hot and dry, as well as hot and humid climates [22]. Today, using wind towers in the same way as in the past is considered an obsolete method. However, previous research indicates that using them correctly in buildings while maintaining their original nature can lead to reduced energy and carbon dioxide consumption and, consequently, a decreased reliance on mechanical cooling systems [23]. A windcatcher is set up on the building's roof and consists of two parts. The windcatcher's inlet has a partition and serves as the wind input shaft, and the windcatcher's body acts as the wind output shaft [24]. Its function is to catch the wind at high speeds on the building and direct it into the building. The temperature of the incoming air to the windcatcher decreases significantly due to the pressure difference, which is the change in air pressure as it enters the windcatcher, and collision with the inner wall of the windcatcher, where the air molecules hit the wall and lose some of their kinetic energy, as well as the evaporative cooling that occurs through the water basin at the end of the channel [25].

### 1.1. Research Novelty

The main innovations of this research include:

- **Simultaneous Integration of Windcatcher and Atrium:** For the first time, this study examines the simultaneous use of windcatcher and atrium systems as a combined wind-solar passive system to mitigate the disadvantages of each and optimize building energy consumption.
- **Simulation and Analysis of Windcatcher's Impact on the Atrium:** Using EnergyPlus software, the effect of adding a windcatcher to the atrium on cooling energy consumption was analyzed, revealing that cooling energy consumption can be reduced by up to 67%.
- **Utilization of Water Spray at the Windcatcher Inlet:** This study found that incorporating a water spray system at the windcatcher's inlet increases humidity and reduces cooling energy consumption by 7% to 17% compared to a windcatcher without water spray.
- **Sensitivity Analysis and Optimization of Windcatcher Height and Quantity:** The research examined the impact of windcatcher height, number, and geometry on optimizing their performance, demonstrating that taller windcatchers with larger inlets achieve better natural ventilation and greater energy savings.

### 1.2. Research background

In modern buildings, many elements, such as glass surfaces, are used for aesthetic purposes. An atrium is one of these elements, which forms a social meeting place [26], provides ample open interior space, exerts visual effects through natural light, and ultimately reduces the building's energy consumption [27]. The utilization of atriums to enhance lighting performance and natural daylight usage requires measures such as climate-responsive design and the implementation of shading tools or parameters like the window-to-wall ratio [28]. Additionally, the natural ventilation performance of atriums can be leveraged to

improve indoor air quality and safety and to design appropriate strategies for smoke management and ventilation [29]. A study on improving building energy efficiency and indoor environmental quality in university library atriums in regions with hot summers and cold winters utilized multi-objective machine learning algorithms. This research indicated significant improvements in energy consumption, thermal comfort, and daylighting performance [30].

Natural ventilation is one of the most effective ways to reduce energy consumption for cooling. Passive design strategies can also help improve a building's thermal comfort and reduce carbon emissions while saving energy [31]. The combination of active and passive systems aimed at improving thermal comfort in winter will result in reduced energy consumption [32]. Research findings indicate that utilizing atriums in conjunction with passive cooling systems, instead of using atriums as standalone systems, can achieve better performance in reducing building energy consumption [21-26]. Renowned as a key element of traditional architecture in Yazd, the windcatcher plays a unique role in providing cooling, natural ventilation, and thermal comfort. As a passive cooling system, it can be combined with other technologies, such as heating and dehumidification [33]. Modernization of wind catchers and their application as a traditional architectural element, in addition to revitalizing them and preserving cultural heritage, can, as an alternative to mechanical ventilation systems in contemporary architecture, reduce greenhouse gases and energy consumption [34]. In a study conducted on single-story and two-story buildings in Yazd, Iran, two passive solar and wind systems, namely solar chimneys and wind catchers, were combined to improve the performance of radiative cooling and natural ventilation in buildings. This research showed that this system can save up to 60% of cooling and 80% of ventilation energy in hot and dry regions. At the same time, the initial installation cost is estimated at around \$340 with a projected 4-year return on investment [35].

Table 1 examines several examples of research conducted in the fields of atriums, wind catchers, and the combination of these two elements with other active and passive systems.

**Table 1.** Previous research on atriums, wind towers, and their integration with other passive systems

Row	Researcher	Aim Novelty	Conclusion
1	Aram et al., 2019	Optimizing a building in the Mediterranean climate Utilizing atriums in different orientations	Energy consumption reduction in the cold season and avoidance of thermal comfort loss in warm seasons
2	Rastegari et al., 2021	Optimization of daylight through architectural modifications in atriums of office buildings, aiming to evaluate the effects of atrium geometry changes on lighting parameters. Investigating the impact of atrium dimensions and ratios, such as changing the height-to-width ratio.	Modifications in atrium design can significantly influence daylight levels and reduce glare.
3	Dai et al., 2022	Evaluating the impact of thermal stratification on HVAC energy consumption and analyzing thermal stratification characteristics in the atrium of a building in China. The effect of various variables, such as atrium height, roof glass type, and climatic conditions, on temperature distribution and energy consumption.	The best performance in maintaining temperature and reducing HVAC thermal load was achieved, while increasing atrium height led to greater thermal stratification and higher heating energy consumption in winter, but reduced cooling loads in summer.
4	Rastegari et al., 2022	Assessment and optimization of daylight in an office building in Tehran. Using the DLA index instead of the Daylight Factor (DF) and analyzing the impacts of atrium geometry and reflection surface management.	The optimal range of light intensity (lux) for visual comfort and employee productivity is between 100 and 2000 lux. The best daylight and energy consumption conditions are achieved with an atrium measuring 10 meters in width, 31.5 meters in length, and 20 meters in height.
5	Shaeri et al., 2023	Proposing strategies for optimal atrium roof design to enhance natural ventilation and reduce energy consumption in tropical regions. Examining various roof models in atriums and emphasizing the combined effects of sea breeze and solar radiation.	Aerodynamically shaped roofs generated greater negative pressure and improved airflow.
6	Xu et al., 2023	The thermal characteristics of atrium interiors in educational buildings in cold regions of China during winter and their effects on thermal comfort and energy consumption. Comparative analysis of radiant and air-flow-based heating/cooling systems to improve thermal performance.	Design modifications can significantly impact comfort and energy savings.
7	Shi et al., 2024	Feasibility of using solar chimneys in multi-story buildings with atriums. Analysis of airflow in solar chimneys with multiple air inlets and the capability of solar chimneys to meet ventilation requirements set by the World Health Organization.	Solar chimneys can provide adequate natural ventilation rates in atriums of multi-story buildings, but as the number of floors increases, stronger chimney designs are required.
8	Jin et al., 2024	Assessing the impact of various atrium designs and configurations on thermal comfort and their performance in public buildings' indoor environments. Using dynamic designs for atrium roofs, including transparent, shaded, and open modes, to control indoor thermal conditions.	Optimizing roof and HVAC system designs to prevent overheating and overcooling, resulting in up to 46% energy savings.
9	Chen et al., 2024	Optimizing energy consumption and providing visual and thermal comfort in atriums of educational buildings. Utilizing a combination of the NSGA-II algorithm and the LGBM machine learning model for multi-objective optimization of atrium performance.	Providing thermal and visual comfort, creating comfortable and sustainable indoor environments, and reducing energy consumption through optimization strategies such as adjusting the shading angle and optimizing the height-to-width ratio of atriums.
10	Su et al., 2025	Investigating the thermal environment of an atrium in a high-rise office building in China. Evaluating various thermal control strategies (e.g., shading and air conditioning) and their impacts on thermal conditions in summer and winter.	Combining shading and air conditioning in summer provides the most significant cooling effect, while air conditioning reduces thermal stratification in air-conditioned areas but increases it in non-air-conditioned upper zones of the atrium.
11	Cruz-Salas et al., 2018	Enhancing wind tower efficiency for energy conservation in buildings Analyzing the influence of wind tower geometry and size on ventilation efficiency	Increasing the surface area of a windcatcher can enhance its performance.

Table 1.

Row	Researcher	Aim	Conclusion
		<b>Novelty</b>	
12	Soltani et al., 2018	A novel wind tower design for enhanced energy efficiency and reduced carbon footprint Utilizing a small pump to spray and circulate water on a wet pad at the wind tower inlet	Enhancing evaporative cooling performance, natural ventilation, and thermal comfort in buildings
13	Kang et al., 2019	Improving wind tower performance through evaporative cooling Utilizing the PDEC system as a cooling system at the wind tower inlet	Significant space cooling savings and fresh air supply
14	Calautit et al., 2020	Providing thermal comfort and natural ventilation using a wind tower Employing a multi-directional wind tower	A multi-directional wind tower adapts to wind conditions to optimize cooling and thermal comfort
15	Morales et al., 2021	Utilizing a wind tower to provide thermal comfort Using a water spray system at the wind tower inlet	Improving wind tower performance
16	Zaki et al., 2021	Analyzing the impact of wind tower geometry on cooling efficiency Comparing the cooling performance of modern (short-height) wind towers with traditional wind towers	Both modern and traditional wind towers can achieve improved cooling performance with proper design.
17	Jafari et al., 2022	Ensuring natural airflow, thermal comfort, and improved wind tower performance Implementing a combined system of wind tower, water spray, and solar chimney for enhanced cooling	Achieving a 6-12°C temperature reduction, 80% relative humidity increase, and improved wind tower efficiency
18	Carreto-Hernandez et al., 2022	Improving wind tower performance and reducing energy consumption Utilizing wind towers as a passive system with an appropriate configuration	Optimizing wind tower design for energy conservation in hot and arid regions
19	Gorji Mahlabani et al., 2022	Modernizing wind towers for energy conservation Integrating wind towers with ground-source heat pump systems	Providing thermal comfort and reducing building energy consumption
20	Cao et al., 2023	Utilizing wind towers to reduce industrial pollutants Reviewing previous research and evaluating wind tower performance	Enhancing outdoor air quality through wind tower implementation
21	Hareesh Krishnan et al., 2023	Enhancing wind tower performance in winter Employing an HVAC heating system at the wind tower inlet	Improving wind tower performance by combining it with an HVAC heating system
22	Li et al., 2023	A wind catcher with wing-like louvers for providing multi-directional natural ventilation and integration with passive or low-energy technologies Providing a constant and controlled airflow regardless of wind direction and utilizing passive heating and cooling heat recovery technology	These findings confirm the potential of this design to reduce energy costs in buildings and improve indoor air quality
23	Liu et al., 2024	Evaluation of the impact of natural ventilation from wind catchers on reducing heat loss and managing thermal comfort in cold climates Evaluation of excessive ventilation in real-world conditions and analysis of the impact of wind speed on wind catcher performance.	Wind catchers alone cannot be suitable in cold climates, and their optimization to reduce heat loss is essential. For example, combining them with heat recovery systems or adaptive controls.
24	Heidari et al., 2024	Improving thermal comfort and natural ventilation in residential buildings A combination of a short horizontal wind catcher and evaporative cooling channels	This system reduced energy consumption by up to 50% compared to vertical wind catchers and had significant electricity savings compared to air conditioners and evaporative coolers.
25	Li et al., 2024	Improving ventilation rates, reducing limitations caused by changes in wind direction, and integrating passive or low-energy technologies in wind catcher design Parametric design and analysis of a novel two-channel wind catcher system with a rotational mechanism, capable of providing multi-directional natural ventilation for buildings	The optimized wind catcher model increased the ventilation rate by up to 28% and performed better than similar four-sided wind catchers

### 1.3. Research objectives

Previous studies investigated Windcatchers' effects on natural ventilation and on providing cool air through traditional and modern methods, such as evaporative coolers. The results of these studies show that windcatchers can reduce the temperature of a building during the need for cooling through natural ventilation and evaporative cooling. Additionally, considering the climate of Yazd and the presence of favorable and abundant winds, windcatchers can be very effective in achieving this goal. On the other hand, previous research climates has shown that atriums can reduce heating and lighting consumption[21]. Furthermore, solutions such as atrium window shading and shading devices can prevent excessive heating of the atrium during the summer. Therefore, the hypothesis of this study is based on the idea that adding windcatchers to the atrium space can reduce its temperature and, in other words, complement the atrium. This innovative study is the first to investigate the combination of a windcatcher with an atrium (a passive wind and solar system). The current study aims to look into how installing windcatchers in atriums affects how energy is used in buildings and how extreme summertime heating is eliminated. This study will answer the following question: "What is the effect of installing a windcatcher in an atrium on reducing cooling energy consumption?"

The following criteria will be looked into to provide an answer to this query:

1. The building's yearly energy consumption, which includes the consumption of heating, cooling;
2. The annual energy consumption of the building when the windcatcher is added to the atrium;
3. Parameters affecting energy consumption, such as windcatchers' height, number, and geometry, will be used to optimize windcatchers.

Also, as seen in Fig. 2, the research process is illustrated through a flowchart.

### Nomenclature

DB	Outdoor dry bulb temperature (°C)
H	Effective height of towers (m)
$\dot{m}_{out}$	Air mass flow rate from towers (kg/s)

$\dot{m}_{a,in}$	Outdoor air mass flow rate (kg/s)
$\dot{m}_{a,out}$	Initialized air mass flow rate (kg/s)
$\dot{m}_w$	Water mass flow rate (kg/s)
$Q_w$	Evaporation rate of water (m <sup>3</sup> /s)
$Q_{est}$	Estimated air volume flow rate (m <sup>3</sup> /s)
$Q_{act}$	Actual air volume flow rate (m <sup>3</sup> /s)
$Q_{out}$	Air volume flow rate, leaving towers (m <sup>3</sup> /s)
$T_{out}$	Exit air temperature leaving towers (°C)
$V_{out}$	Air velocity leaving towers (m/s)
WB	Outdoor wet bulb temperature (°C)
WF	Water flow rate (l/min)
$WF_{act}$	Actual water flow rate consumed (l/min)
$\omega_{out}$	Humidity ratio of the air leaving towers
$\omega_{in}$	Outdoor air humidity ratio
$\rho_{initial}$	Density of initialized air (kg/m <sup>3</sup> )
$\rho_a$	Density of air at the exit of the tower (kg/m <sup>3</sup> )
$\rho_{a,in}$	Density of outdoor air (kg/m <sup>3</sup> )
$\rho_w$	Density of water (kg/m <sup>3</sup> )
AWC	Area of windcatcher
IAWC	Inlet air of windcatcher
NWC	Number of windcatchers
HWC	Height of windcatcher

## 2. Methodology

In the previous research that was related to the present one, to provide heating and lighting, two passive solar systems (a central courtyard and an atrium) were combined climates [21]. The research results showed that the overheating of the atrium could be controlled in the summer by dynamic external shading on the atrium, with the ability to be opened and closed. The present study added a windcatcher to the atrium space to reduce cooling consumption. Dynamic shading is a system that can be adjusted to control the amount of sunlight and heat entering the space. Movable awnings are often used in outdoor spaces such as patios, decks, and gardens to provide shade and protection from the sun. They can also be used in commercial and residential buildings to reduce energy consumption by blocking direct sunlight and reducing heat gain. The atrium window shading used in this research is motorized and can be controlled remotely; it consists of a series of strips or horizontal plates that can be rotated or moved towards the block or allow sunlight to pass through.

Due to its location in the global arid belt, the weather in the city of Yazd is characterized by

cold and relatively humid winters and long and hot, dry summers (Fig. 1). The average annual relative humidity in Yazd is about 30%. The highest humidity is recorded in January, with 52%, followed by February, with 48%, and the lowest humidity is in August, with 16% (Fig. 1).

Adding windcatchers to the atrium space aims to achieve thermal comfort, reduce energy consumption, and utilize natural ventilation. This subject can lead to a decrease in atrium temperature and closure of their entry openings during the winter season. Besides, the defaults of the simulation software were set only during the use of the users and their school attendance. In fact, according to the climatic information of Yazd, the temperature is beyond thermal comfort in 6 months of the year (April, May, June, July, August, September, and October). In addition, given that schools are closed in the summer, the windcatchers are only active in 3 months, i.e., May, June, and October, being inactive during the rest of the year. Therefore, energy calculations and simulations have not been applied in the summer season. As a result, the rise in temperature during this season can be overlooked due to the school's closure. The thermal comfort range in Yazd during the

summer season is between 21.8 C°-28.6 C°. Additionally, given that the prevailing favorable winds of Yazd blow from the northwest and the west, the orientation of the windcatchers was north to south and westwards. It is noticeable that the finding analysis was done and that comparable conclusions were reached.

The building design is based on climatic considerations, and the simulation stages were performed using EnergyPlus software. A simulation program can model the thermal behaviors and physical phenomena in the building and its surrounding environment under realistic conditions by processing input information such as the climate file of the studied city, materials, ventilation, cooling load, heating load, and lighting. Given the consistency of this research's results with previous studies on atriums and wind catchers, which show that the combination of passive atrium and wind catcher systems with other passive systems will result in reduced energy consumption (Table 1), as well as the validation of the EnergyPlus engine in numerous reputable articles, the validity of the results of this research can also be confirmed. Table 2 lists some articles that have compared the results of EnergyPlus simulations with field data.

**Table 2.** A review of studies that have validated the EnergyPlus software

Row	Researcher	Aim	Conclusion
1	Andelković et al., 2016	Energy modeling of a multi-story building with a naturally ventilated double-skin facade	Good simulation accuracy with a 7-15% error rate
2	Im et al., 2020	Energy modeling for multi-zone buildings	Good agreement between the simulated models and the empirical model, with an error rate of around 1%
3	Kunwar et al., 2021	Validation and calibration of energy simulation models for buildings with dynamic shading systems	The simple model in EnergyPlus predicted building energy consumption more accurately than more complex models
4	Sarna et al., 2022	Simultaneous simulations between EnergyPlus and Contam software and experimental data to accurately reproduce instantaneous mass and energy flows in the building	The simulation model provided reliable results
5	Frank et al., 2023	Co-simulation of detailed electrical distribution models and overall building energy performance	The simulation results showed good agreement with experimental data

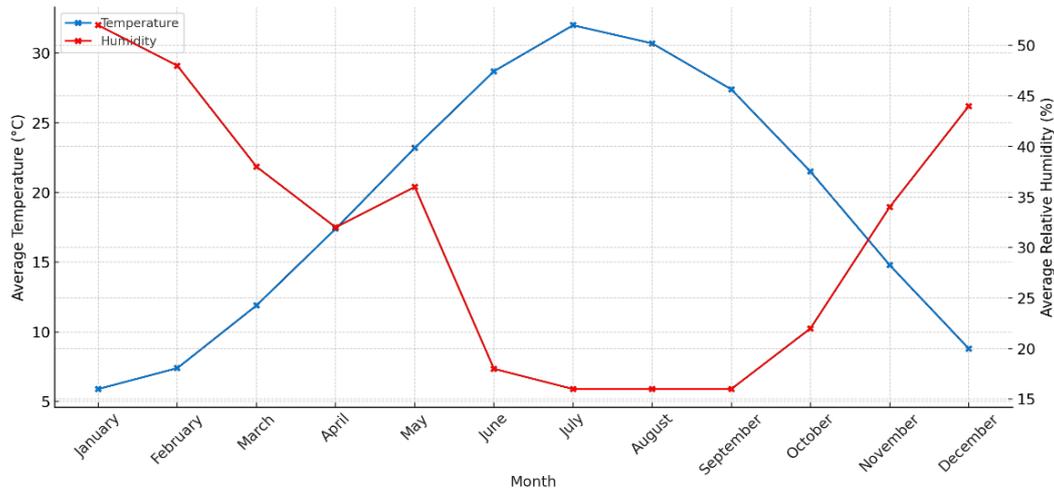


Fig. 1. Average temperature & humidity in Yazd city

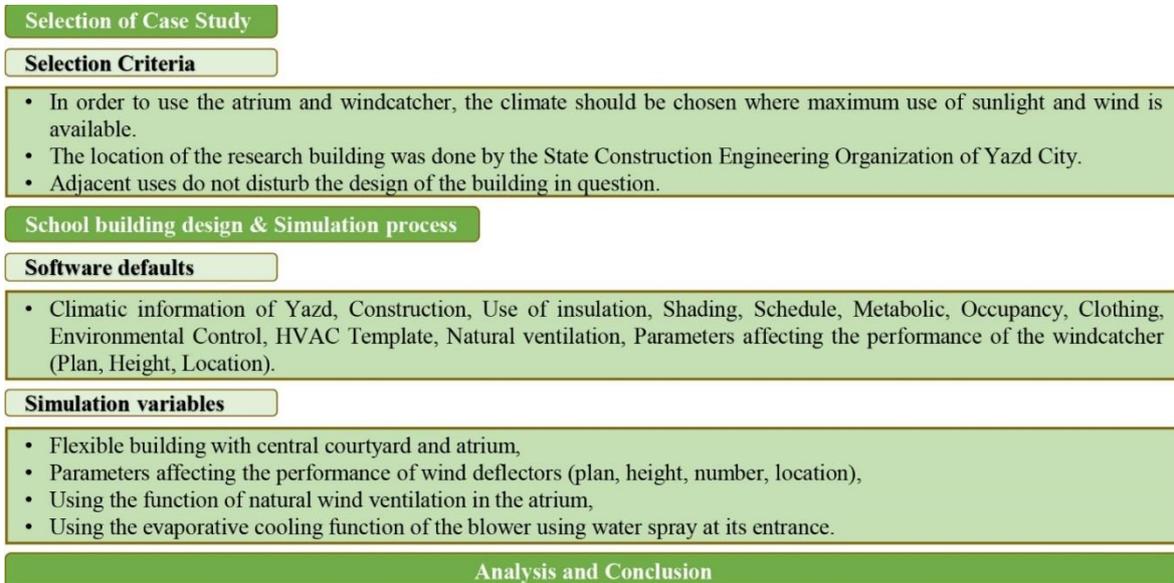


Fig. 2. The strategy used in this study's flowchart.

## 2.1. Case study

An elementary school in Yazd, Iran, with a hot and arid climate and a total built-up area of 2,500 m<sup>2</sup> and three floors, was examined. The building receives light from the north, east, and south. Because the building spot is located in the western part of the site and has an atrium attached to the western wall, half of the building space also receives light from the west. One of the most important parameters influencing the feasibility of natural ventilation in buildings is the geometry of the building itself, which must be considered at the early stages of design. Climate-adaptive strategies, such as the shape and orientation of the

building, the size and location of windows, and others, significantly impact the building's access to daylight [64]. The idea behind the building design is to create a design suitable for the climate and maximize the use of southern light.

One of the important parameters in the energy consumption of buildings is the U-value, which indicates the amount of heat transfer from inside to outside of the building (or vice versa). This parameter is determined based on the thermal insulation properties of building materials and affects the energy required to heat or cool the building. Studies have shown that using materials with lower U-values reduces energy consumption for heating and cooling the

building. In other words, materials with lower U-values have better thermal insulation properties and reduce the need for supplementary heating and cooling systems [65].

U-value is influenced by heat loss coefficient, thermal bridging, time lag, and heat transfer. It is directly related to these factors. For example, increasing the U-value will also improve heat transfer from one surface to another. Therefore, utilizing materials with lower U-values can have a greater impact on reducing building energy consumption [66].

The materials used in the walls of AAC block buildings and non-combustible brick facades can be suitable options for energy conservation and consumption reduction.

In this study, Model 1 was considered the base model. In this model, the building has an atrium without shading devices or wind catchers and only has openings in the roof and walls. Model 2, to which a wind catcher will be added, had window shading that allowed light to enter through the roof and walls. A 3-meter-thick shading was used around the atrium roof.

Additionally, the atrium's openings were located in 85% of the ceiling, the upper part of the southern wall, and in 100% of the eastern and northern walls.

The simulation process was initially used to investigate the effect of the windcatcher with

natural ventilation function on cooling consumption in the atrium space (without water spray). Next, cooling was simulated by the passive draught evaporative cooling (PDEC) system as a cooling tower. The windcatcher with the specifications of (Fig. 3) was only utilized in model 12 in the simulation model table (Table 7). The windcatchers in other simulated models (3 to 11) do not include passive draught evaporative cooling (PDEC).

## 2.2. Passive draught evaporative cooling

Precooling the air entering the cooling system is necessary in hot and dry climates to improve cooling performance [67]. This research investigates using a windcatcher as a cooling tower to provide cooling for the building.

A cooling tower is a structure designed to model a passive evaporative cooler, which is designed to absorb wind at the top of the tower and cool the air using a water spray or an evaporative pad, a shaft, and a water tank [68]. The PDEC system, as a suitable alternative to conventional mechanical cooling in buildings [69], can lead to energy savings without using mechanical cooling systems, resulting in thermal comfort [70]. Previous research findings indicate that integrating the PDEC system with

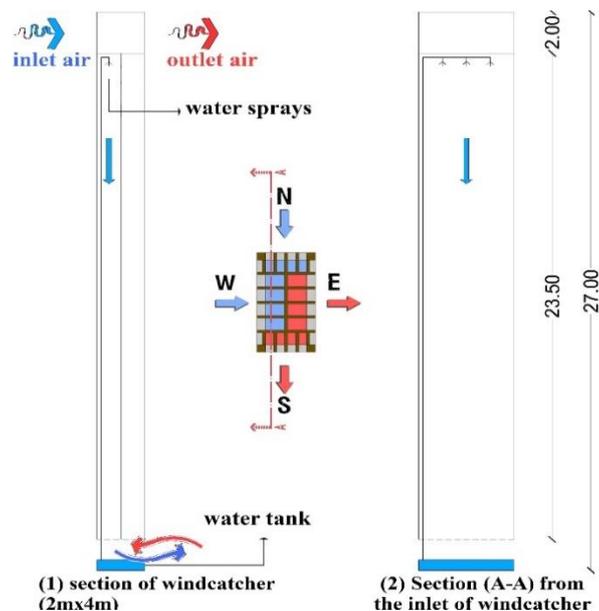


Fig. 3. Schematic of PDEC windcatcher with spray

other active and passive systems can enhance performance. For instance, climatic factors should be considered when designing and controlling sunlight with roof shades [71]. The PDEC system specifically pre-cools the air before it enters the windcatcher.

PDEC systems can be divided into some types, including cooling towers (using wet pads), misting towers (using a nebulizer), shower towers (using nozzles), porous media, and hybrid systems [72]. The air entering the tower is cooled after evaporation before it is delivered to the space. In these systems, airflow is expected because the evaporation process makes the air denser, allowing it to pass through the tower and into the surrounding area without the aid of a windcatcher. The only energy source used in this method is a water pump, which pumps water onto an evaporating device. This leads to the cooling and humidification of the incoming air. Next, cool and dense air flows naturally through the shaft and exits through large openings at the bottom of the cooling towers. The maximum water flow rate, volume flow rate, and minimum internal temperature can be scheduled and specified to regulate a water spray cooling tower. Weather data from style day specifications or weather conditions is needed for this model [73].

### 2.3. Modeling algorithm of the windcatcher in Energy Plus

The Givoni empirical model (1994) was utilized to determine the effect of water spray on windcatcher performance. This model can simulate weather conditions, temperature, humidity ratio, flow rate, water consumption, and pump power consumption. The equations of this empirical model are specified in Table 3 (Eqs. 1-12).

The model starts by calculating the exit air's temperature and volume flow rate. When the water flow rate is known, both parameters are directly determined to control the flow schedule. The water flow rate is obtained using the following Eq. (1).

The following equation also directly determines the volume flow rate of exiting air about the effective tower height and water flow rates (2).

The exit velocity is calculated by the model for wind-driven flow control simulations where the water flow rate is unknown (3).

The area of the bottom opening,  $A$ , is then multiplied by the estimated velocity to determine the air volume flow rate (4).

Equation (2)'s air flow rate can be replaced with the following Eq. (5).

After determining the water flow rate, the model checks the user input limit to avoid overestimating the exit air's actual volume flow rates. If the maximum water flow rate exceeds the calculated maximum, it will be applied. When the calculated air volume flow rate exceeds the maximum, the model swaps it out for the user input's maximum volume. The model then uses Eqs. (1) and (2) to determine the exit temperature and air volume flow rate.

Using the model, the user can specify the amount of water lost due to drift, blowdown, and airflow loss. The fractional values are applied to previously calculated values so that the model calculates both actual water flow rate and actual air volume flow rates as follows: If the user enters the fraction of water loss or flow schedule, some air is not supplied to the space (6-7).

Because the outlet density is unknown in this situation, it is impossible to accurately calculate the mass flow rates at the PDEC tower's inlet and outlet. Thus, ideal direct evaporative cooling assumptions are made, i.e., no enthalpy changes and no pressure drop between the inlet and outlet. Using EnergyPlus psychrometric units, the model calculates the outdoor air's enthalpy, exit air temperature, and outdoor barometric pressure to estimate the initial humidity ratio and densities at the inlet and outlet. Then, using the following methods, we can determine the initialized air's mass flow rates as well as that of the outside air (8-9).

The model then uses the relationship between the mass balances to calculate the exit humidity ratio, which is as follows (10).

Psychrometric functions can be used to determine the exit air density and the specific heat of exiting air once the humidity ratio has been established. Then, the exit mass flow rate is (11).

The model calculates the water's density by assuming it is the same temperature as an outdoor wet bulb. Thus, the rate of evaporation is (12).

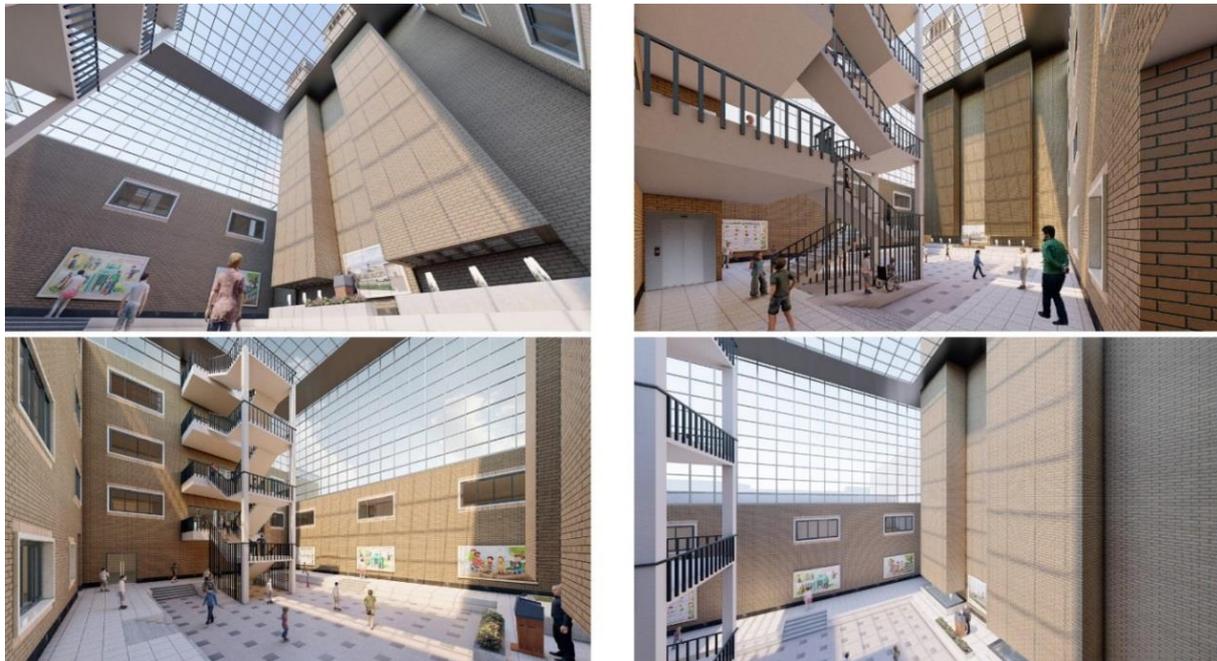
**Table 3.** The empirical Givoni model formula for determining the effect of water spray on wind catcher performance [73]

Equation Number	Equation
(1)	$T_{out} = DB - (DB - (WB) (1 - \exp(-0.8H)) (1 - \exp(-0.15WF)))$
(2)	$Q_{out} = 0.0125WF \cdot H^{0.5}$
(3)	$V_{out} = 0.7H^{0.5} + 0.47 (WS-1)$
(4)	$Q_{est} = A \cdot V_{out}$
(5)	$WF = \frac{Q_{est}}{0.0125 \cdot H^{0.5}}$
(6)	$WF_{act} = WF (1.0 + \text{Fraction})$
(7)	$Q_{act} = Q_{est} (1.0 - \text{Fraction})$
(8)	$\dot{m}_{a, in} = \rho_{a, in} \cdot Q_{act}$
(9)	$\dot{m}_{a, out} = \rho_{initial} \cdot Q_{act}$
(10)	$\omega_{out} = \frac{\dot{m}_{in} (\dot{m}_{a, in} + \dot{m}_w)}{\dot{m}_{a, out}}$
(11)	$\dot{m}_{out} = \rho_a \cdot Q_{act}$
(12)	$Q_w = \frac{\dot{m}_{out} (\omega_{out} - \omega_{in})}{\rho_w}$

Figure 4 also shows the final render of the atrium space and the placement of windcatchers in the school courtyard. These figures are modeled in 3D and are only presented as a proposed design.

In Fig. 5, the floor plan of the school building is shown, divided by usage. Also, in Fig. 6, the wind circulation is shown through section (A) of the proposed school building in

the atrium space. The favorable wind enters the windcatcher from the west and northwest, and the warm air that tends to rise exits through the outlet channel. This process balances the temperature inside the atrium for three months when the temperature is outside the comfort range. During the rest of the year, the entry and exit windows in the windcatcher will be closed entirely. The windcatchers have dimensions of (2x2) and (2x4).



**Fig. 4.** A 3D Render of the proposed school design and the atrium space and the placement of windcatchers within it.



Fig. 5. The floor plan from the Basement to the Second Floor.

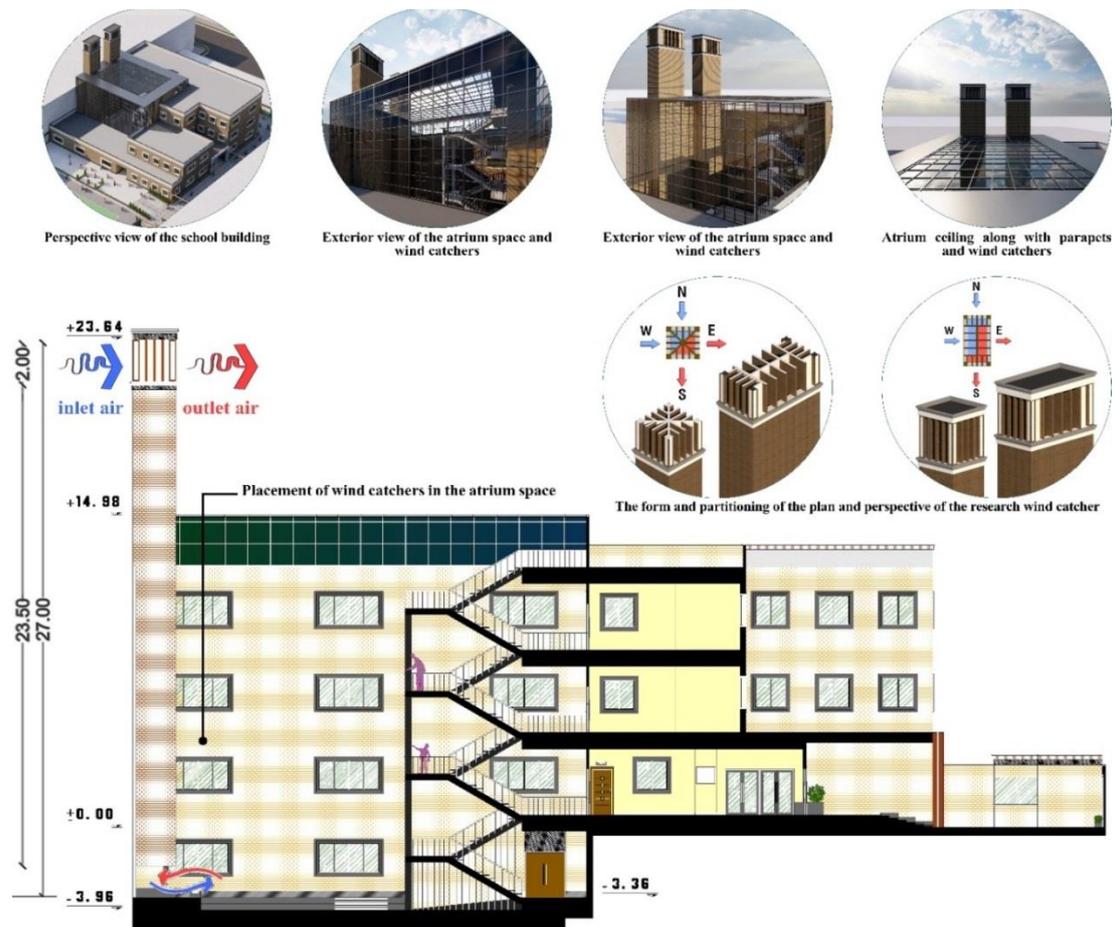


Fig. 6. Section A-A of the school building and the connection between the air duct and the atrium space within it.

Additionally, based on the climate of Yazd city, desirable winds come from the west and northwest, which are indicated by blue color. These winds are the cool air input into the windcatcher channel, and the red section shows the warm air outlet. Table 2 details the scheduling,

metabolic, lighting, and environmental control systems used in the simulation. Tables 3 and 4 provide atrium and windcatcher data. Table 5 lists the materials used for the school building's walls and ceiling. All simulation models are summarized in Table 6.

**Table 4.** Initial settings defined in the EnergyPlus software variables

Title	Description					
1	Schedule	7 AM- 1 PM				
2	Metabolic	Number of people	Activity	Winter (clo)	Summer (clo)	
		Office 2	Classroom 12	Standing/Walking	1.00	0.5
3	Lighting	Power density (W/m <sup>2</sup> )	Radiant Fraction (%)	Visible Fraction (%)	Working Plan Height (m)	
		7.5	0.42	0.18	0.8	
4	Environmental Control	Heating Setpoint Temperatures (°C)		Cooling Setpoint Temperatures (°C)		
		Heating 20.0	Heating Setback 12.0	Cooling 28.0	Cooling Setback 30.0	

**Table 5.** Initial settings defined in the EnergyPlus software as well as the atrium

Title	Description
1	Atrium Dimensions 17×21 (m)
2	Atrium Height 2.5 meters above the building's rooftop
3	Atrium window shading The atrium window shading has a smart scheduling program and is active from 7:00 to 13:00, as well as on Saturdays to Thursdays (Iranian schools are in session on these days), and from May to October. Tape Close weave light Thickness (m) 0.003 Conductivity (W/m-K) 0.1 Solar transmittance 0.05 Solar reflectance 0.55 Visible transmittance 0.05 Visible reflectance 0.55 Long-wave emissivity 0.9
4	Atrium Natural Ventilation During summer, the flexible atrium could be transformed into a central courtyard by opening its windows.

**Table 6.** Initial settings defined in the EnergyPlus software as well as Windcatcher

Title	Description							
1	Location of the Windcatcher Considering that the 3 sides of the atrium are the windows of the classrooms, office spaces, and the corridor, the only remaining front to place the Windcatcher is the west front (next to the neighbor).							
2	Windcatcher's Height Four heights are considered for the wind deflector. (21m-23m-25m-27m)							
3	Windcatcher's plan Windcatchers are simulated in two types: square and rectangular. The purpose of choosing a two-way c is favorable and dominant northwest and west winds. The dimensions of the square Windcatcher (2x2) and the rectangular wind deflector (2x4) have been selected.							
4	Windcatcher's number Windcatcher has been simulated in square type, in four single, double, triple, and quadruple types, and rectangular type in single and double types.							
5	Size of the air inlets and outlets of the Windcatcher's	Single (m) (2x2)	Double (m) (2x2)	Triple (m) (2x2)	Quadruple (m) (2x2)	Single (m) (2x4)	Double (m) (2x4)	
		Inlets	4m <sup>2</sup>	8m <sup>2</sup>	12m <sup>2</sup>	16m <sup>2</sup>	8m <sup>2</sup>	16m <sup>2</sup>
		Outlets	4m <sup>2</sup>	8m <sup>2</sup>	12m <sup>2</sup>	16m <sup>2</sup>	8m <sup>2</sup>	16m <sup>2</sup>
6	Wind tower defaults in Energy Plus	1	Flow Control Type	Wind Driven Flow				
		2	Maximum Water Flow Rate	0.03 m <sup>3</sup> /s				
		3	Effective Tower Height	27 m				
		4	Airflow Outlet Area	24 m <sup>2</sup>				
		5	Minimum Air Flow Rate	20 m <sup>3</sup> /s				
		6	Minimum Indoor Temperature	16 C				
		7	Fraction of Water Loss	0.1				
		8	Fraction of Flow Schedule	0.1				
		9	Rated Power Consumption	200 W				

**Table 7.** Atrium & Windcatcher Materials

Row	Title	Material	Thickness (m)	Total Thickness (m)	U-Value (W/m <sup>2</sup> -K)	R-Value (W/m <sup>2</sup> -K)
1	External Wall (Building and windcatchers)	Brick	0.02	0.25	0.484	2.065
		Cement	0.02			
		AAC Block	0.2			
		Gypsum Plastering	0.01			
2	Flat Roof (Building and windcatchers)	Terrazzo 1 in (TZ01)	0.02	0.80	0.398	2.512
		Cement	0.02			
		Vapor seal 2 layers	0.004			
		Cast Concrete (Lightweight)	0.08			
		XPS Extruded Polystyrene	0.05			
		Concrete, Reinforced (2% steel)	0.47			
		Air gap 300mm (downwards)	0.15			
		Gypsum Plastering	0.01			
3	Windcatcher and Atrium Windows (UPVC)	Generic Clear Glass	0.006	0.023	2.534	0.394
		Argon	0.013			
		Generic Clear Glass	0.004			

**Table 8.** Entry and classification of the tested designs

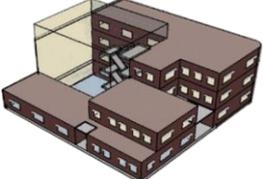
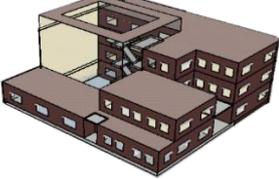
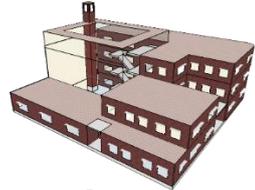
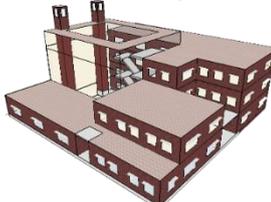
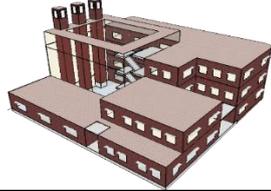
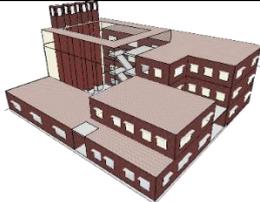
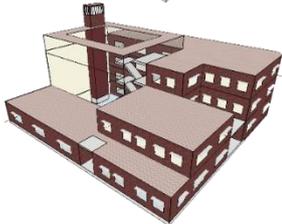
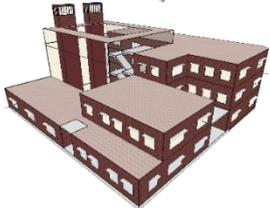
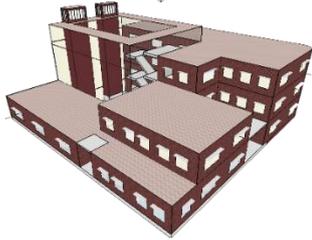
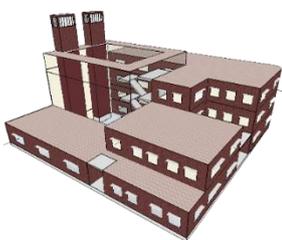
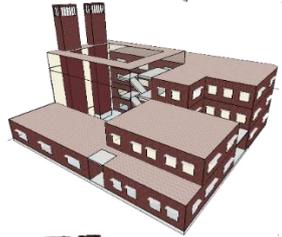
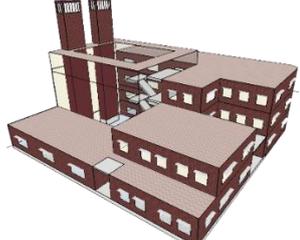
Model	Title	Description	Figure
1	The building with an atrium, without shading (Natural ventilation in the roof and all the windows)	This model has an atrium without any shading devices.	
2	The structure with an atrium, a roof that is 3 meters thick on all sides, and atrium window shading	In the mentioned model, the atrium had a window shading that allowed light to enter through the roof and walls. A 3-meter-thick shading was used around the atrium roof. Additionally, the atrium's openings were located in 85% of the ceiling and the upper part of the southern wall, and in 100% of the eastern and northern walls.	
3	A square windcatcher with the dimensions of 2x2 m and a height of 23 m	Model no. 2 was chosen as the base model. A square windcatcher with the dimensions of 2 x 2 m and a height of 23 m was added to it.	
4	Two square windcatchers with the dimensions of 2x2 m and a height of 23 m	Model no. 2 was chosen as the base model, and two square windcatchers with the dimensions of 2x2 m and a height of 23 m were added to it.	
5	Three square windcatchers with the dimensions of 2x2 m and height of 23 m	Model no. 2 was chosen as the base model, and three square windcatchers with the dimensions of 2x2 and a height of 23 m were added to it.	

Table 8.

Model	Title	Description	Figure
6	Four square windcatchers with the dimensions of 2x2 m and a height of 23 m	Model no. 2 was chosen as the base model, and four square windcatchers with the dimensions of 2x2 m and a height of 23 m were added to it.	
7	A rectangular windcatcher with the dimensions of 2x4 m and a height of 23 m	Model no. 2 was chosen as the base model, and a rectangular windcatcher with dimensions of 2x4 m and a height of 23 m was added to it.	
8	Two rectangular windcatchers with the dimensions of 2x4 m and a height of 23 m	Model no. 2 was chosen as the base model, and two rectangular windcatchers with the dimensions of 2x4 m and a height of 23 m were added to it.	
9	Two rectangular windcatchers with the dimensions of 2x4 m and a height of 21 m	Model no. 8, with two windcatchers, showed better performance than the square type. In addition, as against the single windcatcher, it is considered the basic model and would be simulated on the height parameter. In this model, two rectangular windcatchers were added to the dimensions of 2x4 m and a height of 21 m.	
10	Two rectangular windcatchers with the dimensions of 2x4 m and a height of 25 m	In this model, a double windcatcher with the dimensions of 2x4 m and a height of 25 m was simulated.	
11	Two rectangular windcatchers with the dimensions of 2x4 m and a height of 27 m	In this model, a double windcatcher with the dimensions of 2x4 m and a height of 27 m was simulated.	
12	Two rectangular windcatchers with the dimensions of 2x4 m and a height of 27 m, with water spray	Model no. 11 had the best performance among the previous models. Therefore, it was employed in the Energy Plus software for simulation using water spray.	

### 3. Results and Discussion

The results obtained from the simulation confirm the research hypothesis. The combined system of an atrium and windcatchers reduced the building's energy consumption. As mentioned in previous research, turning the central courtyard into an atrium reduced the building's heating and lighting consumption. However, it increased cooling consumption in the summer. This waste of energy was compensated for after using dynamic shading installed in the atrium and shading devices placed on the atrium ceiling.

However, given that the cost of cooling in Iran is much higher than that of heating, this research was conducted based on the fact that reducing cooling consumption would be possible using a passive system. Therefore, a windcatcher was added to the atrium space to reduce the temperature increase caused by heating in the summer, during the three months of the year when the temperature of Yazd was uncontrollable, and schools were not closed.

The mechanism of the atrium and windcatchers is that the windows are opened for natural ventilation, turning the space into a central courtyard. In addition, the windows placed in the entrance opening of the windcatcher channel are closed in the cold season to prevent cold air from entering the building.

In this section, two parameters are analyzed. The first parameter is the school building's annual cooling and heating energy consumption, while the second parameter examines the 'Time Setpoint Not Met During Occupied Hours.' This term refers to the duration (in minutes or hours) during which

the indoor temperature of the building deviates from the setpoint temperature during occupied hours. A high value of this indicator signifies a reduction in thermal comfort for occupants and potential issues in the HVAC system's performance, including increased energy consumption and operational costs, as well as potential inefficiencies in the HVAC system.

This metric is typically divided into two categories:

1) "Time Setpoint Not Met During Occupied Cooling" refers to when the indoor temperature exceeds the cooling setpoint during occupied hours.

2) "Time Setpoint Not Met During Occupied Heating" refers to the duration when the indoor temperature falls below the heating setpoint during occupied hours.

An increase in this indicator (prolonged temperature mismatches) can lead to several problems, including reduced thermal comfort for occupants, increased energy consumption and operational costs, and potential inefficiencies in the HVAC system, such as uneven temperature distribution, frequent system breakdowns, and increased wear and tear on system components.

The results of the simulation process, which illustrate the building's energy consumption, are presented in tabular and graphical formats in Table 9 and Figure 7, respectively. These results provide a comprehensive overview of the building's energy usage patterns, which can be used to identify areas for potential energy savings. As previously mentioned, the results of the second parameter are shown in Table 10 and Figure 9, providing further insights into the HVAC system's performance.

**Table 9.** Energy consumption levels of the building

Model	Model Name	Heating (kWh/m <sup>2</sup> )	Cooling (kWh/m <sup>2</sup> )	Total (kWh/m <sup>2</sup> )
1	The building with an atrium, without shading	2.76	40.47	43.23
2	The structure with an atrium, a roof that is 3 meters thick on all sides, and window shading	2.73	29.44	32.17
3	A square windcatcher with dimensions of 2x2 and a height of 23 meters	2.75	27.4	30.15
4	Two square windcatchers with dimensions of 2x2 and a height of 23 meters	2.76	27.28	30.04
5	Three square windcatchers with dimensions of 2x2 and a height of 23 meters	2.77	27.16	29.93
6	Four square windcatchers with dimensions of 2x2 and a height of 23 meters	2.77	27.07	29.84
7	A rectangular windcatcher with dimensions of 2x4 and a height of 23 meters	2.75	27.32	30.07
8	Two rectangular windcatchers with dimensions of 2x4 and a height of 23 meters	2.76	27.15	29.91
9	Two rectangular windcatchers with dimensions of 2x4 and a height of 21 meters	2.74	27.41	30.15
10	Two rectangular windcatchers with dimensions of 2x4 and a height of 25 meters	2.77	26.95	29.72
11	Two rectangular windcatchers with dimensions of 2x4 and a height of 27 meters	2.79	26.79	29.58
12	Two rectangular windcatchers with dimensions of 2x4 and height of 27 meters with water spray	3.28	24.15	27.43

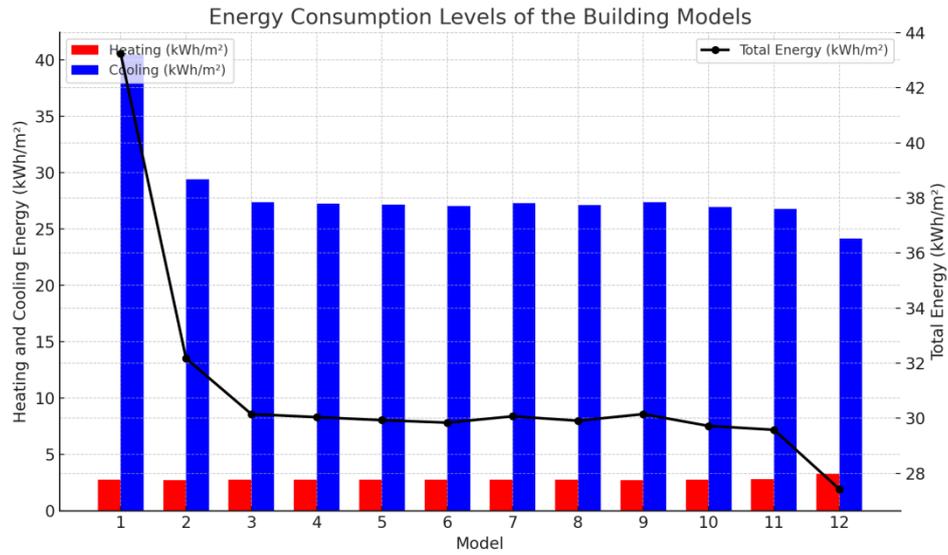


Fig. 7. Energy consumption levels of the building.

Table 10. Energy consumption levels and Comfort and Setpoint Not Met Summary of the building

Model	Time Setpoint Not Met During Occupied Cooling (Hours)	Time Setpoint Not Met During Occupied Heating (Hours)	Heating (kWh/m <sup>2</sup> )	Cooling (kWh/m <sup>2</sup> )
1	150	3.5	2.76	40.47
2	226	3.5	2.73	29.44
3	135	4.5	2.75	27.4
4	132	4.5	2.76	27.28
5	130.5	4.5	2.77	27.16
6	128.5	4.5	2.77	27.07
7	141.5	4.5	2.75	27.32
8	137	4.5	2.76	27.15
9	136.5	4.5	2.74	27.41
10	139.5	6	2.77	26.95
11	140	6.5	2.79	26.79
12	140.5	7	3.28	24.15

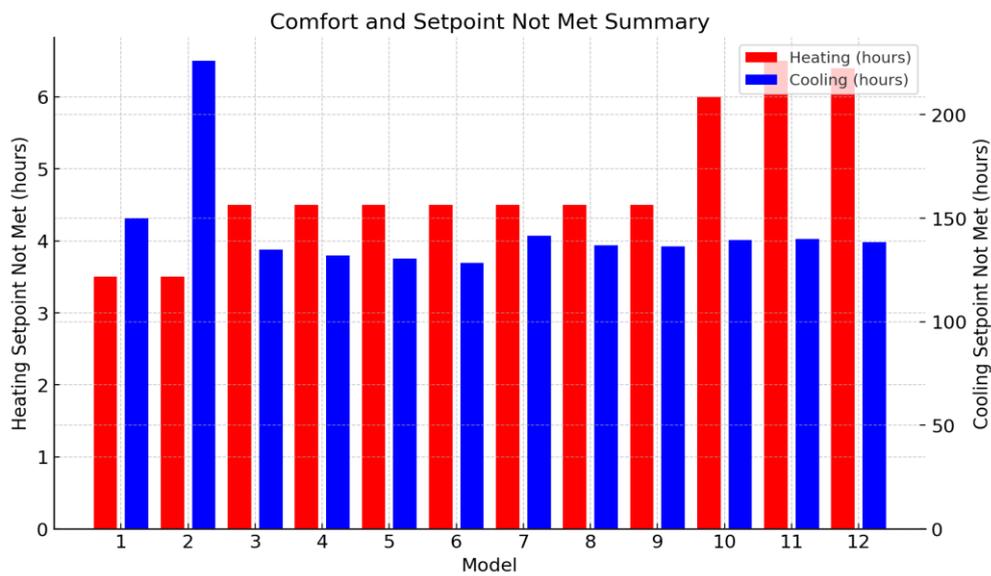


Fig. 8. Setpoint Not Met Summary of the building

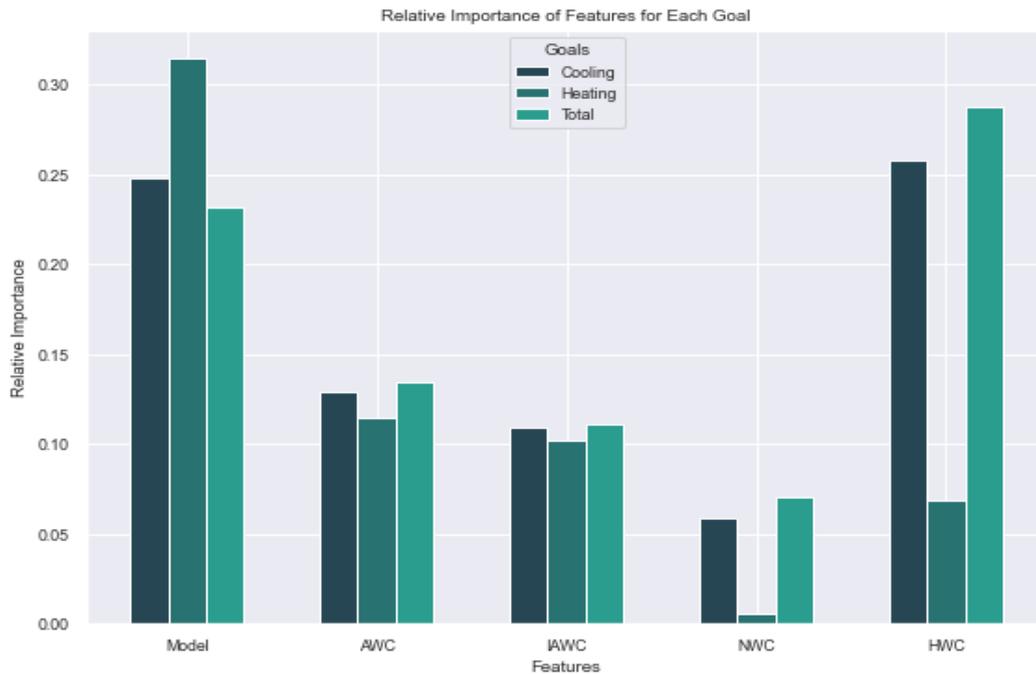


Fig. 9. Sensitivity analysis

The results of previous studies, as presented in Table 1, and the results obtained from the building simulation process indicate that atriums require elements such as canopies and shades to perform optimally. Model 1, which features an atrium without a canopy or shade, consumes more energy than Model 2, which has added canopies and shades. While there is not much difference in energy consumption between the two models regarding heating load, Model 2 exhibits a 27% decrease in cooling load compared to Model 1. This reduction in cooling consumption is the presence of canopies and shades when the sun directly hits the atrium's ceiling and walls. Therefore, the canopy prevents direct heat from entering the atrium, leading to decreased cooling consumption.

Adding a windcatcher to the atrium results in a slight increase in heating consumption (approximately 0.7%) and a decrease in cooling consumption (approximately 7% to 9%). This subject is where only the natural ventilation function of the windcatcher is used (Models 3 to 11). When the building is tested in EnergyPlus software for a wind tower with water spray (Model 12), the cooling rate decreases even more (9% to 12%) than before. Although this affected the heating consumption, the overall energy consumption of the building

was lower than that of the simulated models. The research results are as follows:

Increasing the number of windcatchers, i.e., increasing the air supply volume, results in better performance of the windcatcher. Conversely, the heating load increases slightly (between 0.7% and 1.45%). On the other hand, when a 2x2 square windcatcher is added to the atrium (Model 3), and this number is increased to 4 windcatchers in each subsequent stage (Models 4-6), cooling consumption decreases by 7.4% to 8.7% compared to an atrium without a windcatcher.

The more air enters the windcatcher, the better its performance. In Model 3, which has a square windcatcher, cooling consumption decreases by 7.4% compared to the base model (Model 2), and in Model 7, which has a rectangular windcatcher, cooling consumption decreases by 7.7%. The percentage change in cooling load between a square windcatcher and a rectangular windcatcher is 0.2%. Similarly, in comparing Models 4 and 8, which have two square windcatchers and two rectangular windcatchers, respectively, cooling loads decrease by 7.9% and 8.4%, respectively, compared to the base model (Model 2). The percentage change in cooling load between Models 4 and 8 is also 0.4%. In general, two

rectangular windcatchers showed better performance than two square windcatchers. In addition, due to architectural limitations, as the atrium space was considered a secondary courtyard of the school and as it was the space where the efforts and games of the students occurred, the use of two rectangular windcatchers was preferred to four square windcatchers.

Given the presence of dust in the city of Yazd, which limits the performance of wind catchers, increasing the height of the wind catcher is one way to address this issue. Furthermore, when the length of the wind catcher's body is increased, the air entering the wind catcher's channels has more time to cool down. Wind catchers were simulated at 21, 23, 25, and 27 meters. The best performance was observed with a wind catcher height of 27 meters.

An increase in the height of wind catchers from 21 meters to 27 meters leads to a decrease in cooling consumption (Models 8-11)

In Model 11, which uses two rectangular wind catchers with a height of 27 meters, the cooling load decreases by 2% compared to Model 9, which uses two rectangular wind catchers with a height of 21 meters. This difference indicates the superior performance of the 27-meter wind catcher compared to those with lower heights. Moreover, the cooling load in Model 11 is 9% lower than the base model (Model 2). It is worth noting that this decrease in cooling load leads to a 2% increase in heating load.

Placing a water basin at the end of the wind catcher channel is one way to reduce the temperature of the incoming wind and prevent dust from entering the building. In general, using water in combination with wind catchers can accelerate the cooling process. The innovation used in this research is the application of water spray at the wind catcher inlet, which can accelerate the evaporative cooling process and ultimately improve the performance of the wind catcher.

In Model 12, water spray was used to reduce the temperature of the incoming air, which could lead to a more significant reduction in cooling consumption compared to previous models without water spray. Comparing Model 12 to Model 11, an 11% decrease in cooling

load and a 17% increase in heating load were observed. The results indicate that the presence of water can accelerate the cooling process and improve the performance of the wind catcher and building in terms of cooling consumption.

Model 12, which has a 27-meter wind catcher with water spray, results in an 18% decrease in cooling load, a 16% increase in heating load, and a 17% reduction in annual energy consumption compared to the base model (Model 2) without a wind catcher in the atrium.

It is worth noting that Model 2 has an atrium with optimal performance. When the cooling and heating consumption of the optimized atrium with a wind catcher (Model 12) is compared to the atrium without any equipment (Model 1), a significant reduction in energy consumption is observed. Simulation results showed a 67% decrease in cooling load in Model 12 compared to Model 1. Additionally, the heating load increased by 15%, while the total annual energy consumption decreased by 57%. Obviously, when the air temperature decreases more, the heating load will also increase.

Based on the table and chart above, the results regarding cooling and heating energy consumption will first be briefly reviewed, followed by an analysis of thermal comfort.

In the cooling consumption section, the value of this parameter decreased from 40.47 kWh/m<sup>2</sup> in Model 1 to 24.15 kWh/m<sup>2</sup> in Model 12, indicating an improvement in the cooling system's performance or an increase in the building's energy efficiency in Model 12. Models 3 to 11 have a cooling consumption of approximately 27 kWh/m<sup>2</sup>, showing a downward trend. In heating consumption, the values remained relatively constant between 2.73 and 2.79 kWh/m<sup>2</sup> for Models 1 to 11. However, in Model 12, this value increased to 3.28 kWh/m<sup>2</sup> due to the building's increased heating demand due to reduced cooling consumption. This increase in heating demand presents an opportunity for future enhancements in the heating system.

Regarding thermal comfort in the cooling section, the "Time Setpoint Not Met During Occupied Cooling" parameter varied between 128.5 to 150 hours per year across different models. In Model 2, this value reached 226

hours, indicating a cooling system malfunction in that model. Model 12's value was 140.5 hours, showing that its cooling performance is within the range of previous models and has not significantly changed.

It's crucial to address the issue of thermal comfort during heating, as the 'Time Setpoint Not Met During Occupied Heating' parameter ranged between 3.5 to 4.5 minutes in the initial models. However, in Models 10 and 11, this value increased to 6 to 6.5 minutes. Model 12 increased to 7 minutes, indicating a higher heating demand and reduced thermal comfort during the cold season. This underscores the urgency of maintaining thermal comfort in all models.

- Optimal Model Selection Based on Two Key Criteria:

- 1) Efficiency in Energy Consumption (Least Energy Consumption)
- 2) Thermal Comfort Performance (Least Temperature Deviations from Setpoints)

Models 12, 11, 10, 9, and 5 have the lowest energy consumption. If the designer's primary goal is to minimize energy use, Model 12 is the optimal choice. Regarding thermal comfort, the best models are those with the fewest temperature deviations from the setpoint. Models 6, 5, 4, 3, and 10 are the most optimal based on this criterion. If the primary objective is to maximize occupant comfort, then Model 6 is the best choice.

- Sensitivity analysis

Key Driver Analysis (KDA) is a powerful statistical technique in marketing research used to identify and quantify the impact of various factors, or "drivers," on an outcome variable, such as customer satisfaction. This method helps you understand which factors significantly impact a specific outcome, such as customer satisfaction, sales, and loyalty. KDA utilizes various statistical models, such as linear or logistic regression, to examine the relationships between multiple independent variables (drivers) and one dependent variable (outcome variable). In KDA, instead of solely focusing on regression coefficients, various methods are employed to analyze and visualize the contribution of each driver in predicting the outcome variable. These methods help better

- Prioritization for Educational Buildings (Schools)

In educational buildings such as schools, thermal comfort for students and teachers is of high importance because:

- ✓ A comfortable environment enhances focus and learning.
- ✓ Inappropriate temperatures can lead to reduced student performance and early fatigue.
- ✓ Frequent temperature fluctuations can affect children's health.

Given these factors, thermal comfort should be prioritized, while energy consumption remains important but should not compromise the quality of indoor conditions.

- Additional Considerations: Aesthetics and Atrium/Wind Catcher Design

Along with the above factors, architectural aesthetics, atrium design, and wind catchers should also be considered.

- ✓ Model 6, the best model in terms of thermal comfort, features four square wind catchers, each 23 meters high. However, selecting this model might negatively impact the building's exterior appearance.
- ✓ The most visually appealing models are among Models 7 to 12.
- ✓ Models 9 and 10 offer a balanced trade-off between energy consumption and thermal comfort, making them strong alternative choices.

understand which drivers have the most and least influence in the process [74-75-76].

The relative importance chart illustrates the significance of various features for different objectives. Specifically, this chart is applied to heating and cooling and their combined effect (total) to analyze sensitivity assessment and evaluate the impact of key parameters on the performance of the combined wind catcher and atrium system. This method is crucial in identifying determinant factors for reducing energy consumption and optimizing system efficiency. Variables such as the number and height of wind catchers, the dimensions of air inlets and outlets, and the use of water spray systems have been analyzed. Since different climatic conditions directly affect the performance of natural ventilation systems, a

deep understanding of these variables can contribute to improving future design models. This type of visualization is commonly used in data science to represent feature importance in predictive models, which aids in understanding how different variables impact the model's predictions. The relative library is used to compute and visualize the relative importance of features. To further explain the chart, the x-axis labels represent different models: "AWC," "IAWC," "NWC," and "HWC." These parameters represent models, windcatcher area, inlet air volume to the windcatcher, the number of windcatchers, and their height. The y-axis measures the relative importance of these features, ranging from 0 to 1.

Additionally, the bars are color-coded to indicate the targets. The "Model" and "HWC" features have the highest overall importance for heating and cooling. "NWC" and "IAWC" have moderate importance, while "NWC" has a minimal contribution to heating. The "AVC" feature exhibits low to moderate importance across the goals (Fig. 8).

Based on this chart, the following conclusions can be summarized:

- 1) HWC (Height of Wind Catchers): This variable significantly reduces cooling energy consumption. Increasing wind catcher height results in more effective natural cooling, as it enhances the incoming airflow rate and reduces the impact of high outdoor temperatures on indoor spaces.
- 2) NWC (Number of Wind Catchers): Increasing the number of wind catchers improves natural ventilation performance and reduces cooling energy consumption. However, excessive wind catchers may not significantly reduce energy consumption and may become economically and architecturally impractical due to construction costs and spatial limitations.
- 3) IAWC (Inlet Air Width Capacity): This parameter plays a crucial role in enhancing cooling performance and increasing the volume of incoming air.
- 4) AWC (Area of Wind Catchers): This variable has the least effect, indicating that simply increasing the wind catcher

area is not optimal unless combined with other design variables.

Based on the sensitivity analysis results, an optimal combination of wind catcher number, height, cross-section, and integration of water spray systems can significantly enhance energy efficiency in buildings. Furthermore, using taller and rectangular wind catchers yields better performance in specific climatic conditions, such as hot and arid regions. However, the impact of the water spray system should be evaluated in terms of heating costs during colder seasons. These findings suggest that achieving optimal performance requires assessing and optimizing a combination of multiple factors rather than focusing on a single parameter. Future research can explore experimental and field studies to validate these results further.

#### 4. Conclusion

This research focused on meeting a portion of the cooling needs of the building using the passive wind energy system. This research hypothesized that the simultaneous use of an atrium and the windcatcher would reduce the cooling energy consumption of the building. The results obtained from this research confirmed the hypothesis. When a windcatcher was added to the atrium, the heating consumption increased from 0.7 to 20%. On the other hand, the cooling consumption decreased from 7 to 22%. Since cooling is more expensive than heating in Iran, it would significantly reduce the costs of building cooling facilities. This is while the windcatchers have been added to an atrium with a canopy and shade. In other words, an atrium with a canopy has a 27% difference in cooling consumption compared to an atrium without a canopy. According to the results obtained, to save energy consumption, it would be necessary for an atrium to be flexible and turn into a central courtyard when cooling was needed due to dynamic window shading and openings. In addition, when heating is needed, all its openings should be closed, with its window shading opened to receive better sunlight. In addition, the air supply valves of the wind deflectors, having double-glazed windows, can be closed when heating is needed. They should also be opened again when cooling

is needed. Parameters affecting the performance of windcatchers were the number, height, and plan shape. The results showed that with an increase in the height and number of windcatchers, i.e., with an increase in the volume of the air entering the windcatcher at a higher height, the performance of the windcatcher would improve. In addition, using water spray in the windcatcher led to a decrease in the air temperature and an increase in relative humidity, resulting in a decrease in cooling consumption. On the other hand, lower energy consumption does not necessarily indicate better building performance, as it may come at the expense of thermal comfort. The natural ventilation system may fail to meet thermal requirements during certain hours, even though energy consumption is reduced. Therefore, maintaining a balance between energy efficiency and thermal comfort is essential and should be carefully considered.

#### Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. Due to the nature of this research being a private study conducted without financial support; the data are not publicly available. However, they can be provided for legitimate scientific purposes upon request.

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