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Optimizing Windcatcher Designs for Effective Passive Cooling Strategies in Vienna's Urban Environment

Aida Shayegani *, Viera Joklova and Juraj Illes

Faculty of Architecture and Design, Slovak University of Technology in Bratislava, Námestie Slobody 19, 81245 Bratislava, Slovakia; viera.joklova@stuba.sk (V.J.); juraj.illes@stuba.sk (J.I.)
* Correspondence: aida.shayegani@stuba.sk; Tel.: +43-676-494-9211

Abstract: Urban overheating, intensified by climate change, poses a critical challenge in Central European cities, witnessing a rise in tropical days. Conventional mechanical cooling systems in buildings significantly contribute to carbon dioxide emissions, exacerbating global warming. In response, windcatchers—traditional Iranian natural cooling systems—emerge as a promising sustainable solution for contemporary architecture, even in non-arid climates. This research aims to evaluate windcatchers' efficacy in improving building thermal comfort in Central European climates, focusing on Vienna's urban environment. This study identifies optimal windcatcher designs by analyzing key variables: height variation, inlet dimensions, urban exposure, Building Management System (BMS) temperature thresholds, and integration with an earth tube system using Design Builder simulation software version 6. The findings reveal that a windcatcher standing at 2.5 m tall, with inlet dimensions of 0.9 m by 1.4 m, in an open, less densely populated urban setting, and with open valves when indoor temperatures surpass 22 °C, demonstrates the most effective reduction in cooling load. Moreover, both one-sided and two-sided windcatchers outperform conventional ventilation through openings. Additionally, combining a one-sided windcatcher with an earth tube system ensures efficient cooling even when exterior temperatures exceed 25 degrees Celsius. When augmented by a heat pump, this integrated system can provide heated ventilation.

Keywords: natural ventilation; windcatchers; passive cooling; Design Builder; Central European climate

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1. Introduction

Urban overheating, exacerbated by climate change, presents a critical challenge in Central European cities, evidenced by a rise in tropical days. Conventional mechanical cooling systems in buildings substantially contribute to carbon dioxide emissions, exacerbating global warming.

The building sector accounts for a significant portion of total energy consumption globally, emphasizing the need for energy-saving solutions [1]. Simultaneously, air pollution, particularly in urban centers, has escalated alarmingly, and despite the slight reduction between 2000 and 2017, it still exceeds the EU standards and WHO AQG for the protection of human health in Europe [2]. Natural ventilation emerges as a viable solution to mitigate these challenges, reducing reliance on fossil fuels and consequently decreasing air pollution [3]. Within sustainable development discourse, environmental sustainability emerges as a key objective, advocating for clean, recycled, or renewable energy sources. Sustainable architecture aims to minimize adverse environmental impacts and align with natural processes, recognizing the significance of natural ventilation and wind energy while eschewing polluting alternatives.

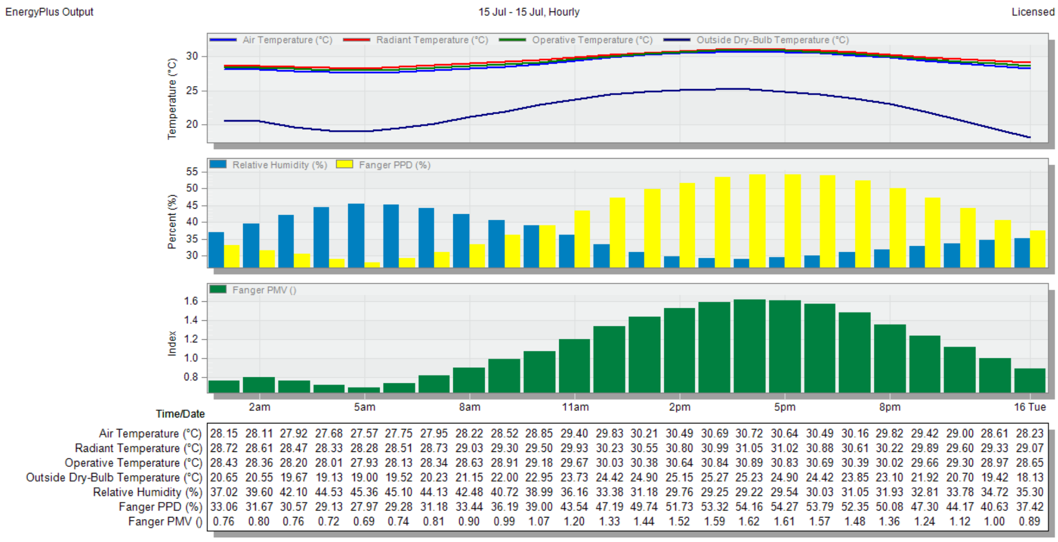
The pursuit of sustainable and energy-efficient building designs has become increasingly imperative in light of the global need to reduce energy consumption and mitigate the impacts of climate change. Among the array of available strategies, wind-driven ventilation emerges as a promising avenue for leveraging natural forces to improve indoor air quality and thermal comfort, thereby reducing dependence on mechanical cooling and heating systems. This introduction delves into the rationale behind investigating wind-driven ventilation systems, especially within the context of Central European climates, by examining their historical foundations, technological advancements, and potential applicability. The premise lies in the belief that natural ventilation offers a means to decrease the energy consumption and carbon emissions associated with conventional mechanical systems while also mitigating installation and maintenance costs. Furthermore, wind-driven ventilation systems hold the promise of enhancing thermal comfort and indoor air quality.

In response, it is both economical and beneficial within the framework of the built environment to utilize construction techniques that conform to the climate and make use of local materials. Past generations in arid climates found solutions compatible with nature [4–6]. Specifically, windcatchers—traditional Iranian natural cooling systems—emerge as promising sustainable solutions for contemporary architecture, even in non-arid climates. Windcatchers are passive cooling systems and among the most familiar traditional elements in Iranian architecture, widespread worldwide in many arid regions, significantly reducing cooling loads and supplying the necessary ventilation rate of buildings. Due to the lack of energy supply, windcatchers can be utilized as a sustainable attempt to achieve cooling and for ventilation purposes.

Drawing inspiration from traditional Iranian architecture, certain characteristics of Iranian design align with the principles of sustainable architecture, offering insights into modern architectural practices. In contrast, mechanical cooling systems in buildings, predominant producers of carbon dioxide emissions, pose significant environmental challenges, exacerbating global warming, particularly in warmer climates [7]. This research aims to evaluate windcatchers' efficacy in enhancing building thermal comfort in Central European climates, specifically focusing on Vienna's urban environment as a representative site. On the one hand, the number of hot days during the summer is increasing, and by analyzing weather data from past decades, it is anticipated that the trend of temperature increase will continue. On the other hand, considering the past climatic situation in Vienna, many buildings lack proper ventilation measures, except for some material selections or mechanical air conditioners. The figures below illustrate temperature differences on the so-called hottest day of the year, 15 July 2023, in Vienna, and a historical temperature record for the exact day in Kashan, one of Iran's central cities with an arid climate where the last Iranian windcatcher was constructed and applied. An overview of recent temperatures in Vienna suggests that similar natural ventilation approaches could be applied here as well. It is important to note that the weather conditions in Vienna are still more humid than the central cities of Iran, and while it may not be suitable to implement measures to increase evaporation or humidity in those arid Iranian cities, Vienna is windy enough to consider the mentioned measures (Figures 1 and 2).

1.1. Research Hypothesis and Scope

This study delves into the effectiveness of wind-driven ventilation systems within the Central European climate. Through a comprehensive review of the existing literature and theoretical models, knowledge gaps are identified, and global practices are adapted to suit Central European specifics. Methodologically, a blend of analytical evaluations and practical assessments is employed, including simulations of a base module conducted in Vienna as a representative city in the Central European climate, to validate theoretical propositions; hence, the results might have the capability to be generalized to real cases. Key areas of investigation include natural ventilation mechanisms, windcatcher functionality, design intricacies, and their integration with passive strategies such as earth tubes.



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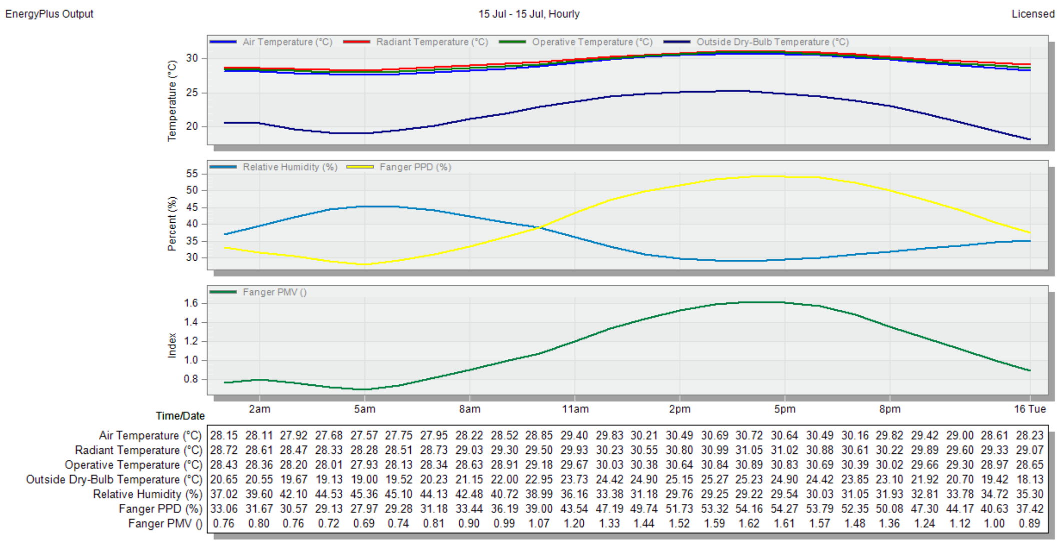
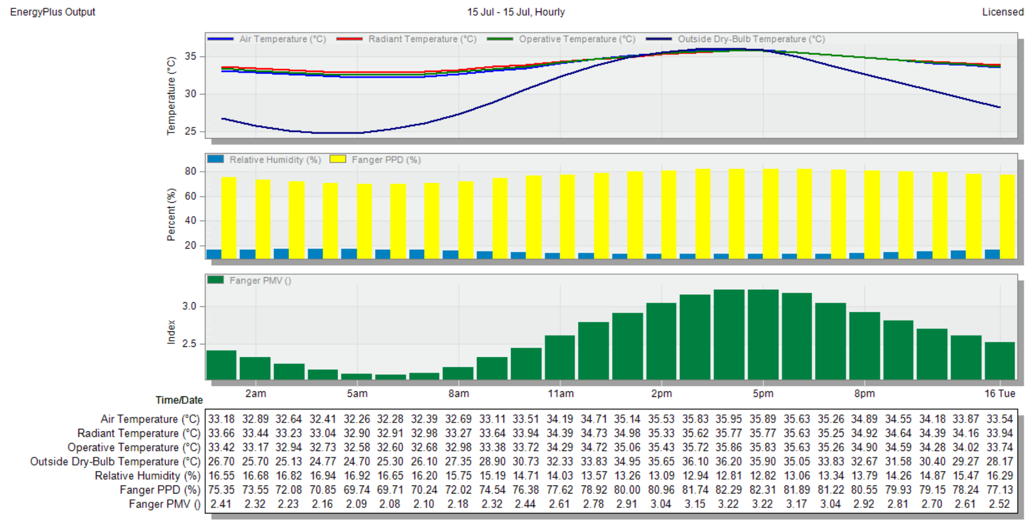


(**b**)

Figure 1. The average future temperature of Vienna (the period between the years 2020 and 2023) on 15 July: (**a**) a bar chart of temperature differences; (**b**) a graph of temperature differences [8].

This research hypothesizes that adapting this passive ventilation system (windcatcher) to Central Europe's unique climate and urban fabric can significantly improve indoor air quality, thermal comfort, and energy efficiency. Theoretical frameworks center on sustainable architecture, thermal comfort standards, and the synergy between wind-driven and other passive ventilation strategies, fostering the development of innovative, sustainable solutions for contemporary and future architectural endeavors. By applying this simulation process, the study aims to pave the way toward sustainable architectural practices that harness natural ventilation mechanisms, thereby contributing to both scientific advancement and societal wellbeing through the promotion of healthier, more sustainable living environments.

This research aims to investigate the potential of wind-driven ventilation systems in the Central European climate to reduce energy consumption while enhancing indoor comfort. Specifically, the focus will be on introducing windcatchers as passive natural ventilation methods in hot and arid climatic zones within Central Europe and evaluating their effectiveness. By identifying optimal design configurations and integrating windcatchers with practical passive ventilation systems, this study seeks to maximize the energy efficiency of buildings in the region.



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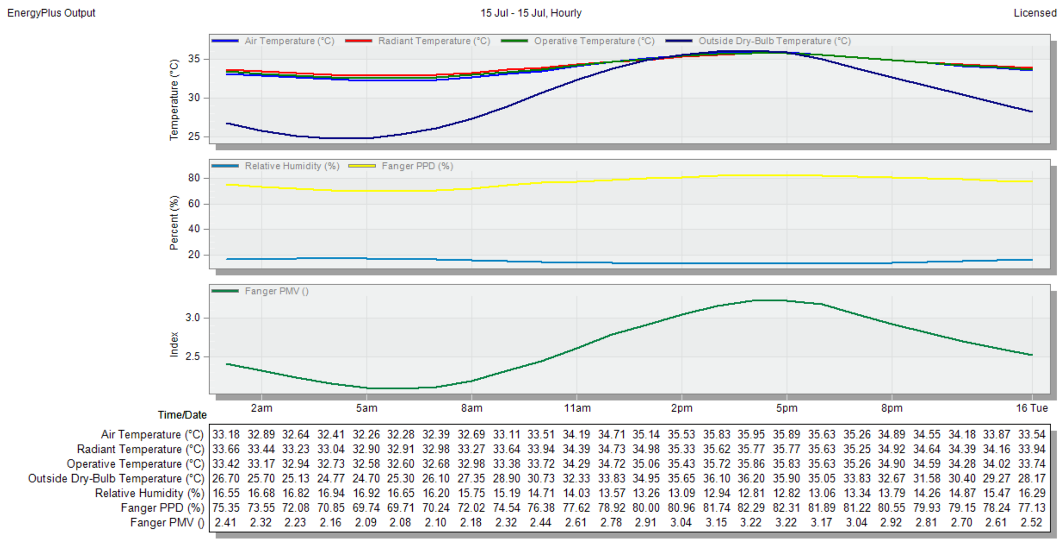

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Figure 2. The average historic temperature of Kashan (the period between the years 2020 and 2023) on 15 July: (**a**) a bar chart of temperature differences; (**b**) a graph of temperature differences [8].

The research objectives focus on the efficiency assessment of the traditional passive ventilation system (windcatcher) in Central European climate conditions; the specification of the system variables, specifically indicators; and finding the optimal module of a windcatcher by evaluating them. Additionally, experiments with different materials and the application of the Venturi and stack effect principles will be conducted to enhance the functionality of windcatchers. Through comprehensive analysis and simulations, this research aims to provide valuable insights into sustainable architectural practices that leverage wind-driven ventilation to promote energy efficiency and improve indoor comfort in Central European buildings.

By examining the latest advancements in computational modeling, material sciences, and architectural design, this study seeks to identify and analyze the most promising approaches for enhancing the efficiency and applicability of wind-driven ventilation systems. This includes investigating the potential of integrating windcatchers with other passive cooling and ventilation strategies, thereby creating synergies that amplify the overall environmental performance of buildings [9,10].

Assessing Solutions

The exploration of wind-driven ventilation systems in Central Europe is inherently multidisciplinary, necessitating a convergence of architectural design, urban planning, and environmental engineering insights. This research meticulously assesses the variables influencing the performance of wind-driven ventilation, from the micro-scale of building orientation to the macro-scale of urban morphology and regional climatic patterns. By dissecting the efficacy of wind-driven ventilation in various urban settings and building typologies, this study aims to illuminate the pathways toward scalable and adaptable design strategies that can significantly enhance building sustainability in Central European climates [11,12].

2. Historical Background and Key Thesis

Throughout history, the incorporation of natural ventilation strategies into architectural design has showcased human ingenuity in adapting to varying climatic conditions. Notably, traditional windcatchers in Iranian architecture serve as a prime example of this ingenuity, with ancient builders engineering sophisticated systems to capture and circulate cool breezes within buildings, thus ensuring comfortable indoor environments even in harsh desert climates [13–17]. The application of such historical knowledge to present-day architectural challenges lies at the heart of this research, prompting critical inquiries into the adaptability and efficacy of wind-driven technologies within the temperate and changeable climate of Central Europe [15].

This investigation is predicated on the hypothesis that the fundamental principles governing traditional wind-driven ventilation systems, despite originating in climatically disparate regions, can be reinterpreted and effectively applied in Central European contexts. It asserts that through meticulous analysis of design parameters, innovative material advancements, and seamless technological integration, wind-driven ventilation systems can be optimized to address the specific thermal comfort and air quality needs of Central European buildings. This research undertakes a critical examination of the convergence between historical architectural traditions and contemporary engineering solutions, with the aim of bridging the gap between age-old wisdom and modern sustainability imperatives [16].

2.1. Windcatchers in Traditional Architecture

The operation principles of the windcatcher natural ventilation system are mainly based on wind-driven ventilation and the stack (buoyancy) effect [11,13] (Figure 3).

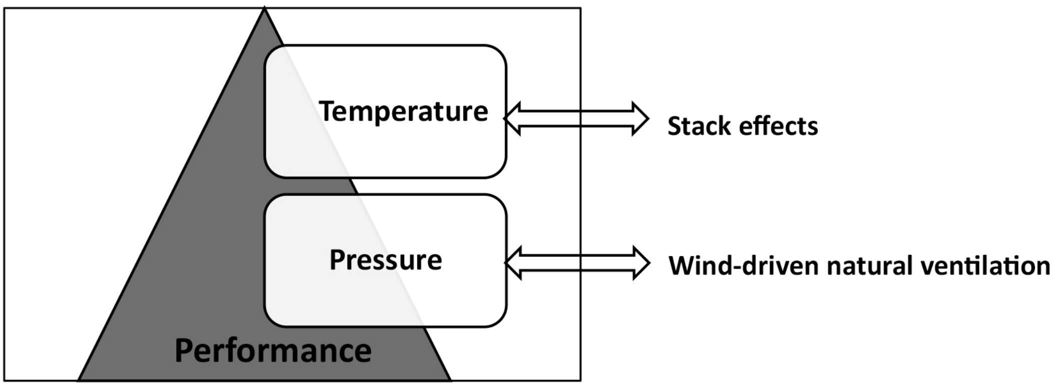


Figure 3. Windcatcher's function. Source: authors.

2.2. Operating Principles of Windcatchers

During the daytime, by the movement of external wind at roof level, both positive pressure on the windward side of the structure and, at the same time, negative pressure on the leeward side are produced. This pressure difference is sufficient to deliver fresh air to indoor spaces and extract stale and warm air from them [15,16]. During the night, in the absence of air movement or in low-wind conditions, the windcatcher device operates using the natural buoyancy of thermal forces like a chimney [18,19], which is yielded on account of the air temperature gradient between the inside and outside of a building (Figure 4). When the ambient air temperature is considerably lower than the indoor temperature, the subsequent pressure difference and air density gradient of the internal and external air masses lead to rising low, dense indoor air and expelling it through the windcatcher leeward side; simultaneously, denser cool air descends through the windward side of the system [20–22]. In this regard, the contribution of two driving forces of wind and buoyancy for a windcatcher's performance has been compared in other research. It has been concluded that the impact of wind-pressure-driven flow is more effective than buoyancy-driven force by 76%. Furthermore, the investigation confirmed that the stack effect is negligible in the windcatcher's device when there is inadequate external airflow movement [23–27].

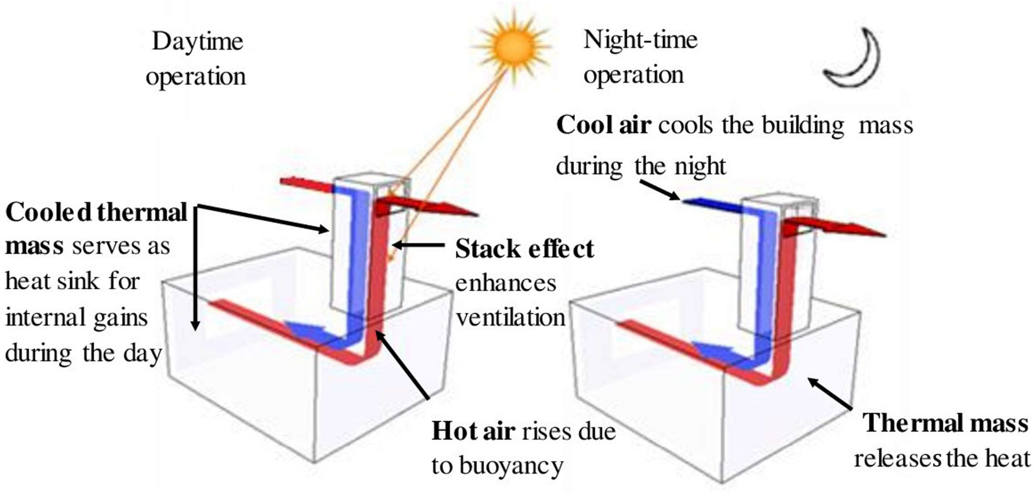


Figure 4. Windcatcher's operating principles during daytime and night-time [28].

As illustrated in Figure 5, in some cases, warm, dry air enters the underground water channel and passes a certain distance to reach the building. During this passage, the interaction between warm air and cool water causes water evaporation, leading to decreasing air temperature. On the other side, the wind blowing around the windcatcher causes negative pressure on the leeward side of the opening, which exhausts the warm indoor air and replaces it with fresh cooled air coming from Qanat. A Qanat is a system for transporting water from an aquifer or water well to the surface through an underground aqueduct; the system originated approximately 3000 years ago in what is now known as Iran [29].

Typically, conventional windcatchers consist of different components, including openings, roof, head, channel, and internal partitions, as depicted in Figure 6.

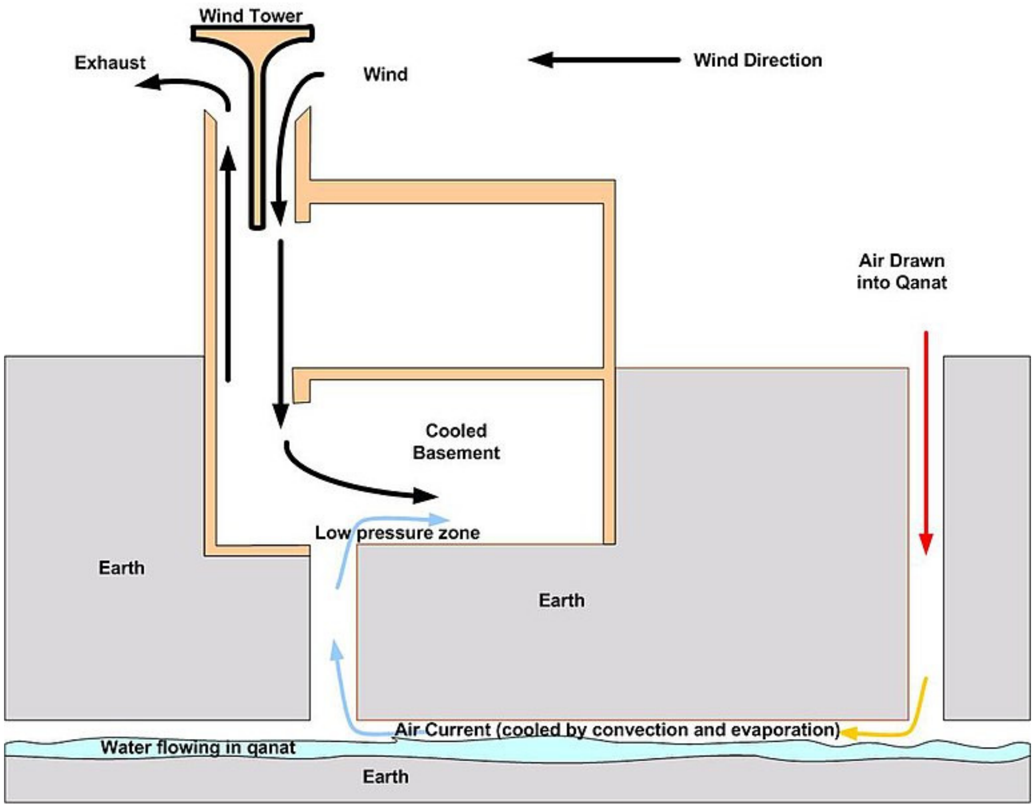


Figure 5. Illustration of the use of wind tower and Qanat for cooling [30].

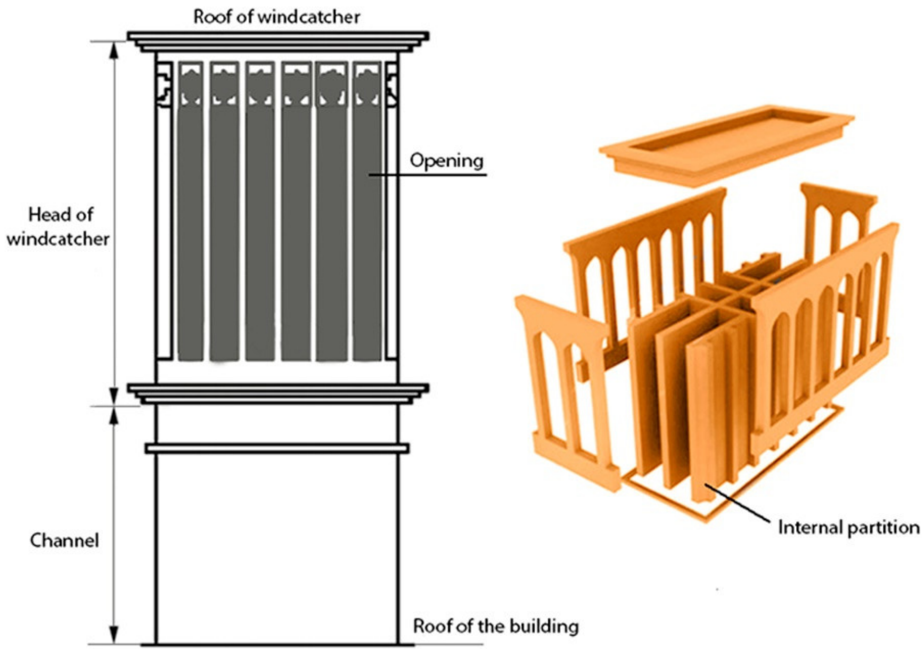


Figure 6. Different components of traditional windcatcher [31].

2.3. Windcatcher Typology

2.3.1. Classification by Number of Openings

Windcatchers, according to the number of openings, are classified into the following:

- One-sided windcatchers;
- Two-sided windcatchers;
- Four-sided windcatchers;

- Six-sided windcatchers;
- Eight-sided windcatchers [32,33].

2.3.2. Classification by Cross-Section

Windcatchers are classified into five main groups based on their cross-section:

- Cylindrical windcatchers;
- Square windcatchers;
- Rectangular windcatchers;
- Hexahedral windcatchers;
- Tetrahedral windcatchers [32,33].

2.3.3. Classification by Number of Stories

Windcatchers are most frequently one-story or two-story; they scarcely have more stories than this. The number of two-story windcatchers is remarkably lower than one-story windcatchers, and they are even considered a scarce type. Several outstanding samples of two-story windcatchers are in Amir Garden in Tabas city (eight-sided), in Aghazadeh House in Abarkooh (four-sided), and in Chehel Sotoon in Sarhanabad (cylindrical). In addition to one- and two-story types, there are some which have more stories. For example, a windcatcher in Sadra Garden in Taft is composed of three stories. However, windcatchers with more stories are scarce, and ignoring them is possible. One-story windcatchers are the most frequent ones [32,34].

2.3.4. Classification by Blade Configurations

Interior blades play an essential role in the efficiency of windcatchers. They divide the cross-section of windcatchers into smaller parts and consequently impact the velocity and turbulence of airflow. Therefore, windcatchers with different types of divisions have various features affecting windcatchers' performance (Table 1; Figures 7 and 8) [7,32,35].

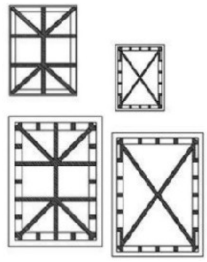
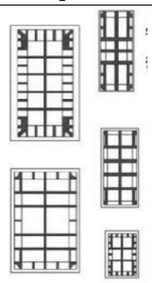
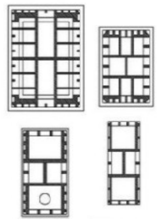
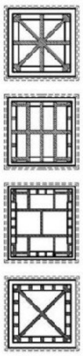
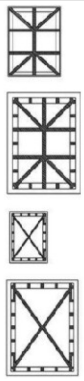
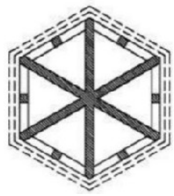
2.4. Factors Affecting Windcatcher's Efficiency

2.4.1. Internal Factors:

- Number of openings;
- Height;
- Wind angle;
- Velocity;
- Configuration (dimensions, cross-section, and blades).

Figure 7. Multi-story windcatcher, Aghazadeh mansion, Yazd, Iran (Photo by Salehzadeh, S.) [12].

Table 1. Different types of windcatchers in various aspects [35–37].

Different types of windcatchers in terms of the						
	Shape of the internal blades	**X shape blades**		**+ shape blades**	**H shape blades**	
						
	Cross section	**Cylindrical windcatchers**	**Square windcatchers**	**Rectangular windcatchers**	**Six-sided windcatcher**	**Eight-sided windcatchers**
						
	Number of stories	**One story**	**Two stories**		**Multi stories (Figure 5)**	
	Number of openings	**One opening**	**Two openings (Figure 6)**		**Four, six, or more openings**	

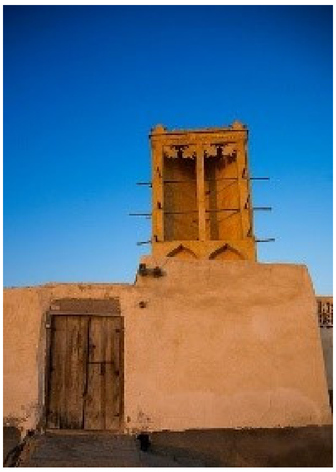


Figure 8. Windcatcher with two openings (Photo by Lafforgue, E.) [37].

2.4.2. Environmental Factors:

- Urban morphology;
- Building geometry and height;
- Urban obstacles;
- Orientation of the building;
- Street canyon [3,33].

3. Justification of the Research Territory

3.1. The Context of Climate Change in Europe

Climate change and environmental degradation are an existential threat to Europe and the world. To overcome these challenges, the European Green Deal will transform the EU into a modern, resource-efficient, and competitive economy, ensuring the following:

- No net emissions of greenhouse gases by 2050;
- Economic growth decoupled from resource use;
- No person and no place left behind [38–40].

In Europe alone, buildings consume 40% of the final energy consumption, with fossil fuels providing 80% of this energy [40].

The warmest decade recorded was 2011–2020, with global average temperature reaching 1.1 °C above pre-industrial levels in 2019. Human-induced global warming is presently increasing at a rate of 0.2 °C per decade. An increase of 2 °C compared to the temperature in pre-industrial times is associated with serious negative impacts on the natural environment and human health and wellbeing, including a much higher risk that dangerous and possibly catastrophic changes in the global environment will occur. For this reason, the international community has recognized the need to keep warming well below 2 °C and pursue efforts to limit it to 1.5 °C [38–40].

3.2. Countering Climate Change

As every tone of CO_2 emitted contributes to global warming; all reductions in emissions contribute to slowing it down. In order to stop global warming completely, CO_2 emissions have to reach net zero worldwide. In addition, reducing emissions of other greenhouse gases, such as methane, can also have a powerful effect on slowing global warming, especially in the short term. The consequences of climate change are extremely serious and affect many aspects of our lives [41]. Both countering climate change and adapting to a warming world are top priorities for the EU (Figure 9).

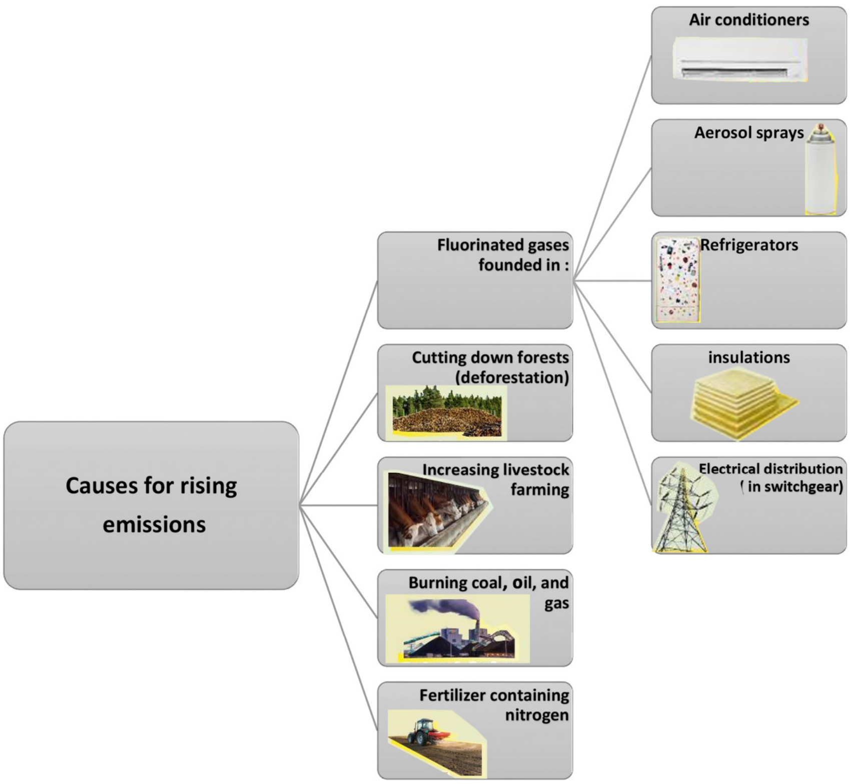


Figure 9. Causes of rising emissions [39].

The building sector represents a significant proportion of total energy consumption, and finding energy-saving solutions in this sector considerably impacts total energy consumption [1,42]. Fossil fuel use is an essential factor affecting air pollution [43]. Natural ventilation reduces the use of fossil fuels [44].

The European Climate Law writes into law the goal set out in the European Green Deal for Europe's economy and society to become climate-neutral by 2050. The law also sets the intermediate target of reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. Climate neutrality by 2050 means achieving net zero greenhouse gas emissions for EU countries as a whole, mainly by cutting emissions, investing in green technologies, and protecting the natural environment. The law aims to ensure that all EU policies contribute to this goal and that all sectors of the economy and society play their part [38–40].

The European Union stretches over many different climate zones, landscapes, and cultures. Considering all the issues of climate change and global warming, integrating a windcatcher could be introduced as an energy-efficient approach that can affect specific urban design conditions and reduce the use of fossil fuels [45–48]. As a representative of a Central European city and three different types of urban structures, the localities in Vienna city and the surrounding region have been selected for this research and simulation.

4. Justification of the Selected Type of Windcatcher for This Research

The various categories of windcatchers mentioned thus far are chosen based on factors such as site location, weather conditions, temperature, wind direction, and structural stability. These factors primarily influence the windcatcher's suction capability, rather than its blowing characteristics. It is worth noting that internal divisions may reduce the blow rate, but in this research, the focus is on enhancing the suction quality to extract warmth from inside the building [49]. Considering Vienna's prevailing summer winds, which predominantly blow from one direction, this research emphasizes the use of a blowing windcatcher aligned with this prevailing direction during hot summer days. However, internal structural stability is not the primary focus of this study. Given Vienna's humidity levels, there is no requirement to humidify the incoming wind using a water reservoir at the windcatcher's base. Additionally, since the study location experiences severe winters, the windcatcher's inlet opening should be linked to the Building Management System (BMS) to automatically close when temperatures drop below the comfort zone threshold.

5. Materials and Methods

This study aims to reduce the cooling energy demand in buildings through optimized windcatcher systems, focusing on their economic viability. The methodology combines analytical approaches, cause-and-effect studies, and simulations.

To achieve the research goals, the following strategies have been employed:

Comprehensive Simulation System: We used the Design Builder software version 6 for detailed building energy performance simulations. This software streamlines the assessment of thermal properties, environmental impacts, and energy efficiency.

Standardized Module Selection: To ensure broad applicability, we chose the ASHRAE model as a standard reference point. This model, representing a typical building module, allowed us to generalize our findings to various buildings.

Location-Based Research: We selected a specific research location to utilize its climatic data. These data are crucial for accurate assessments, aligning our study with real-world conditions.

Variable Specification: We focused on four key variables and indicators, including windcatcher height, aperture dimensions, urban setting, and temperature adjustments in the Building Management System (BMS). These factors were critical in evaluating windcatcher performance based on specific criteria.

These strategies, discussed in detail in subsequent sections, provided a comprehensive framework for assessing passive ventilation systems' effectiveness in Central European conditions. The research's culmination involved comparing heating, ventilation, and air conditioning (HVAC) energy costs to measure the impact of passive cooling methods.

5.1. Building Simulation Tool

In this research, the Design Builder software plays a pivotal role in simulating building energy performance. This sophisticated software is instrumental in evaluating a range of critical aspects related to thermal parameters and environmental impacts concerning energy efficiency. Furthermore, in Design Builder simulation software, the natural ventilation system just starts automatically working when the average temperature inside the examination zone is above the temperature outside [50].

Design Builder software is known for its high-quality, user-friendly features, making it a valuable tool for swift assessments of both new and existing buildings. Its advanced simulation tools significantly reduce modeling time and enhance productivity. The software accommodates a variety of modeling approaches, enabling the importation of Building Information Models (BIMs) [51] or the rapid creation of custom models within the platform.

Design Builder provides a fully integrated analysis encompassing energy consumption, thermal comfort, heating, ventilation, air conditioning, daylighting, cost estimation, design optimization, and the generation of reports that adhere to numerous national building regulations and certification standards.

This powerful software is globally distributed and supported by an extensive network of international partners. It excels in the analysis of a building's cooling and heating loads and can accurately predict the impact of passive strategies on energy consumption. Furthermore, it estimates the quantity of solar radiation affecting openings and various surfaces within the building. Design Builder's capabilities extend to computing energy consumption levels on hourly, daily, monthly, and yearly bases, all of which are derived from climate data and the incorporation of passive and active design elements [52].

The aforementioned attributes of Design Builder make it an indispensable tool for architects and designers in shaping energy-efficient building solutions. It proves particularly invaluable in modeling the effects of windcatcher variations in our base module (BM).

The efficacy of Design Builder software has been corroborated in various studies, including those by [53–55]. Notably, Design Builder enjoys the trust of many prestigious companies and academic institutions worldwide. It has garnered formal recognition and validation from decision-making bodies in England and numerous other countries, as evidenced by its website [50].

5.2. Base Module (BM)

The module considered in this study to be the base module (BM) is an ASHRAE Module (American Society of Heating, Refrigerating, and Air Conditioning Engineers) standard focusing on building energy modeling sets' minimum requirements for providing energy design assistance using building energy simulation and analysis of the building model with an area of 48 square meters and a height of 2.9 m [56]. The localization of the simulation is in the Vienna region The simulated BM consisted of a heating, ventilation, and air conditioning (HVAC) system using gas and electricity to provide thermal comfort in the interior space. In this research, a proposed windcatcher has been added in the middle of the BM's roof geometry with two large windows located on the south façade to observe the energy efficiency of such an organized ventilation system. As mentioned above, all the dimensions of the BM are based on ASHRAE standards in all simulation steps. The orientation of buildings is determined based on the wind analysis described in Section 5.3.2. The results show that 15 degrees southwest is the optimum orientation for the BM's openings to utilize the cool air stream in hot seasons. To be more precise, according to the wind analysis that will be outlined later, the BM's best orientation is when the BM's wall with windows is turned 15 degrees toward the geographical southwest (Figure 10).

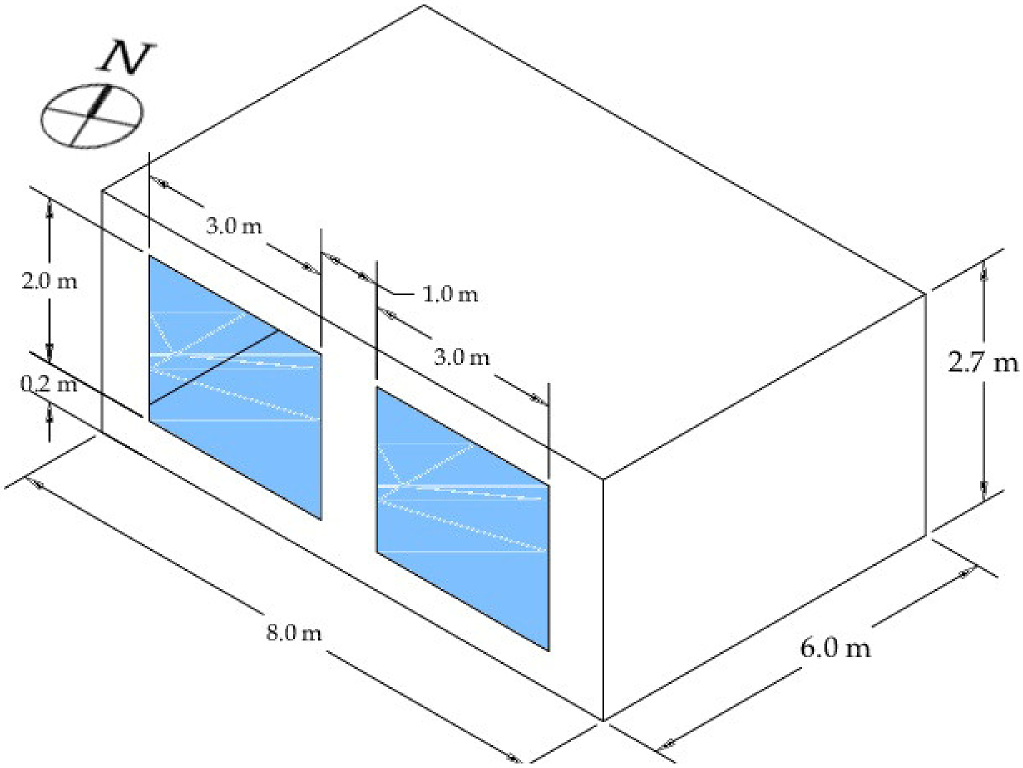


Figure 10. ASHRAE model standard [56].

In Figures 11 and 12, the diagram illustrates the airflow from the entry point within the windcatcher to its exit at the southern window, specifically when the wind direction originates from the southeast. Positioned at an elevated height, the windcatcher induces a rise in positive air pressure within its upper segment (depicted in dark blue), consequently prompting airflow towards the regions characterized by lower pressure levels.

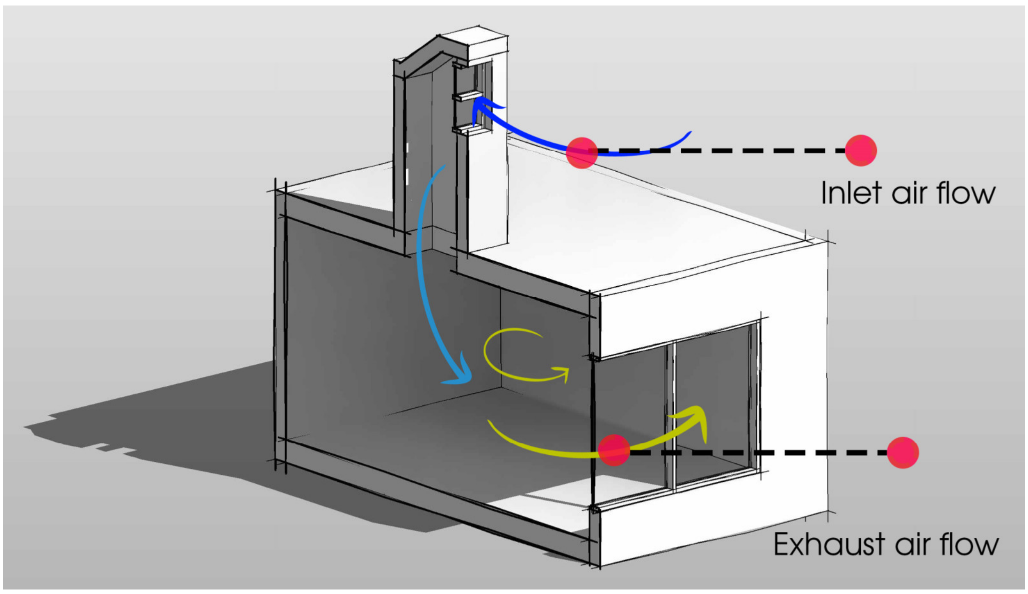


Figure 11. Base module (BM) with windcatcher in Design Builder. Elaboration on DB data [50].

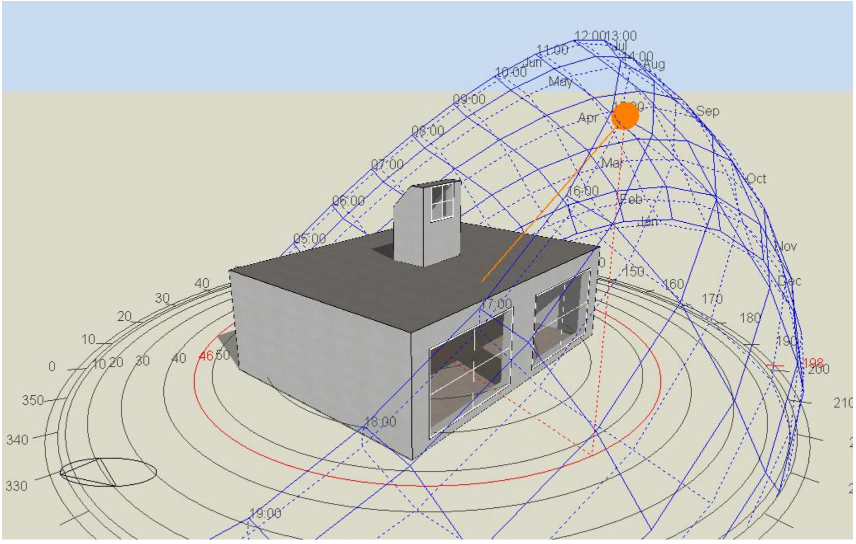


Figure 12. Base module (BM) in Design Builder, with the simulation of the position of the sun. Elaboration on DB data [50].

5.3. Study Location

As mentioned, the city of Vienna, the capital of Austria, has been selected as the representative of Central European cities to examine the efficiency of the proposed natural ventilation system in specific Central European climatic conditions. Furthermore, to thoroughly determine the windcatcher's efficiency and effectiveness and evaluate the impact of surrounding urban configurations and external obstacles affecting wind flow characteristics in different urban contexts, the three geographical regions are considered as the basis for simulation in this study. These three urban structures have been selected as the three types of residential density in Vienna, as shown in Figure 13:

1. Dense urban area at the center of the city, Innere Stadt region (called Sheltered Urban Configuration in Design Builder) (Figure 14).
2. Semi-dense urban area, Hohe Warte district (called Normal Urban Configuration in Design Builder) (Figure 15).
3. An individual isolated building on the city's outskirts, Schwechat region (called Exposed Urban Configuration in Design Builder) (Figure 16).

Figure 13. Three different urban configurations were selected in the study location, Vienna [57].

Figure 14. Dense urban area at the center of the city, Innere Stadt region, Vienna [57].

Figure 15. Semi-dense urban area, Hohe Warte district, Vienna [57].

5.3.1. Climatic Data Survey

Climatic data of the study location are essential information that need to be obtained adequately. Therefore, to acquire the energy performance results of the BM, comprehensive climatic data of the three types of urban structures in Vienna are needed. In this research, various climatic data, including solar radiation, wind direction, temperature, humidity, etc., are derived from Vienna's synoptic station from 2002 to 2022 during the months of May to September (which represent hot months in Vienna that need to run the ventilation system). The concluded data are demonstrated in Figure 17 below. These data are used as a simulation climatic data basis in Design Builder software. Furthermore, designing the windcatcher for the BM in different scenarios, such as windcatcher's height variation, inlet dimension ratio, and urban exposure (that will be vastly defined in the next section), is conducted based on this climatic information.

Figure 16. An individual isolated building on the city's outskirts, Schwechat region, Vienna [57].

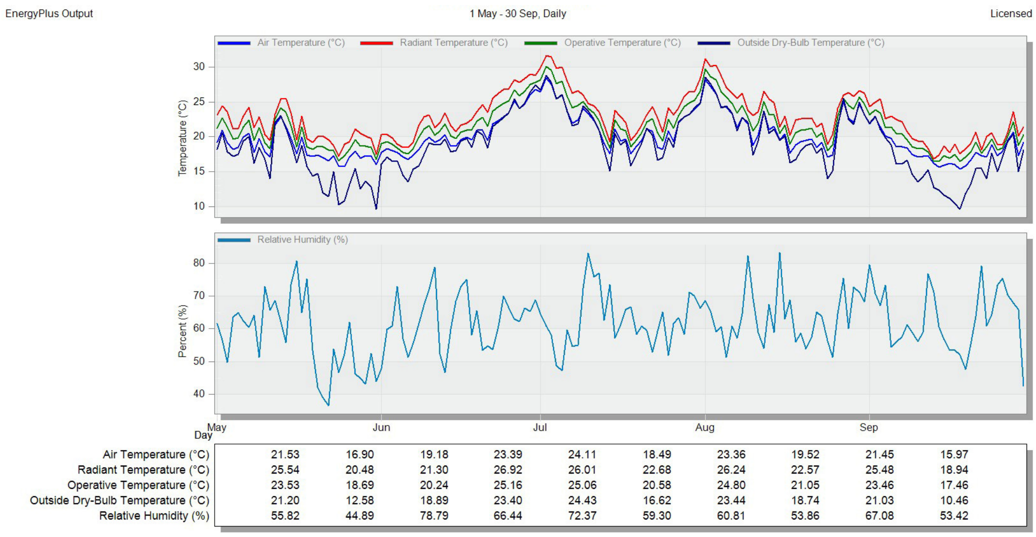


Figure 17. Statistical ten-year average (May to September 2002–2022) climatic data: Vienna synoptic station [8].

5.3.2. Wind Analysis

To optimize the efficiency of the proposed windcatcher, some information about wind speed and direction at different times of the year in Vienna should be analyzed. Thus, to reach the research objectives, the orientation of the windcatcher's openings is defined based on prevailing wind direction, maximum wind speed, mean wind speed, and distribution of wind direction in the months of May to September to promote natural ventilation in the summer. As it is impossible to include all analytical tables in this section, only summarized data are expressed. According to the obtained data, from energy plus weather base data (https://climate.onebuilding.org/, accessed on 20 May 2023), the prevailing wind direction is 15 degrees southwest (from Vienna's geographical north direction) in the summer, and the mean wind speed is 3.9 m/s. These results are helpful to orientate the base module's windcatcher and its openings to conduct airflow into the building by using natural ventilation on hot days and protecting the building against cold and high-speed winds in cold seasons.

5.4. Specified Variables and Indicators

In this research, the level of building energy demand is evaluated by utilizing various windcatcher specifications to determine its efficient form. The passive cooling methods in this paper are considered by four independent variables, including the following:

1. Windcatcher's height variation (HV): Changing the height of the windcatcher to achieve the optimal height to capture the most prevailing wind yield from the perspective of thermal behavior.
2. Inlet dimension ratio (IDR): To evaluate different inlet dimensions, the assumed opening between the windcatcher vent and interior of the base module, including 90 cm × 90 cm, 90 cm × 140 cm, and 90 cm × 190 cm, has been implemented and examined.
3. Urban exposure: Investigating windcatcher's performance in the three different urban areas, including dense, semi-dense, and isolated urban environments.
4. Adopting four various temperature degrees for the Building Management System (BMS) to set the best temperature adjustment to control the windcatcher's vent opening time and achieve less energy consumption.

5.5. Research Problems

We encountered several limitations during this research process. Firstly, there was a lack of sufficient weather stations to provide the necessary EPW (EnergyPlus weather) data. To address this, an interpolated station was utilized to establish the required basic data for the simulation system. Secondly, the urban configuration and airflow influenced by Vienna's city morphology were not the primary focus of this research. Although evaluating windcatcher functionality in different urban configurations would have been valuable, the adjustment of the simulation software to accommodate various urban layouts was deemed sufficient for the research's purposes. Despite potential variations in wind speed due to urban arrays, windcatchers' interior structures, enabling both blow and suction capabilities, are adaptable to different urban configurations, including variations in height, materials, and directional designs [50]. However, the research suggests that windcatchers may be more effective in exposed or isolated urban areas, such as the outskirts of the city and individual buildings. Thirdly, the historical urban configuration of Iranian cities where primitive windcatchers were utilized primarily featured single-story buildings. Consequently, this research focused on single-story buildings to ensure the generalizability of results from the base module. However, there remains a gap in understanding whether windcatcher applications are compatible with multi-story buildings, which warrants further investigation in future research endeavors.

6. Results and Discussion

The impact of each independent variable indicator, as is detailed in Section 5.4, is assessed concerning the energy demand of the base module's heating, ventilation, and air conditioning (HVAC) system during the summer months, spanning from May to September. It is imperative to note that the degree to which gas and electricity are conserved to ensure the internal thermal comfort of the base module reflects the effectiveness of the windcatcher in association with the specific variable.

The most promising windcatcher design, incorporating the specified variable from each section, is further investigated in the subsequent phase to explore other variables and identify the most efficacious configuration. Our graphical representation adopts the vertical axis to convey the quantification of energy consumption, while the horizontal axis delineates the temporal dimension under scrutiny. This comprehensive scrutiny of the building's energy demands encompasses a one-year duration.

The meticulous temporal scope is deliberately designed to facilitate an exhaustive exploration into the impact of natural ventilation on the annual energy requirements of the building. Our objective is to elucidate the extent to which natural ventilation strategies contribute to a reduction in annual energy consumption, guided by the parameters expounded in this accompanying article.

Furthermore, it is worth noting that future research endeavors are poised to encompass additional variables, introducing innovative approaches aimed at optimizing air movement and ventilation rates.

6.1. Effect of Windcatcher Height Variation (HV)

The energy consumption of the BM is primarily evaluated based on the height of the designed windcatcher above the roof plane of the model by using the four height variants (1.5 m; 2.0 m; 2.5 m; 3.0 m).

The graphics of the height simulations (Figure 18) confirm that the height of 2.5 m has the lowest energy consumption among all the simulated heights.

6.2. Impact of Inlet Dimension Ratio (IDR)

Subsequently, the various windcatcher's inlet dimension ratios applied to the optimum height (2.5 m) are examined and evaluated on the base of the module's energy consumption from May to September. Assessed are different inlet dimensions, including 90 cm × 90 cm, 90 cm × 140 cm, and 90 cm × 190 cm.

Following the simulation results (Figure 19), the inlet dimension of 90 cm × 140 cm is the optimal ratio for reducing energy consumption.

6.3. Influence of Urban Exposure

Further research deals with the impact of the location of an architectural object with applied passive ventilation in an urbanized environment. Specified were three different variants of the built-up area, that were already mentioned in Section 5.3, which are in accordance with the simulation databases of Design Builder (Figures 13–16).

The simulations conducted on the ASHRAE model using the optimized windcatcher design across three distinct urban structures reveal that the lowest energy consumption occurs in the scenario of an exposed (or isolated) urban area, which considers the outskirts of the city and individual buildings (Figure 20). This analysis underscores the influence of external obstacles and urban layout on the flow of the wind.

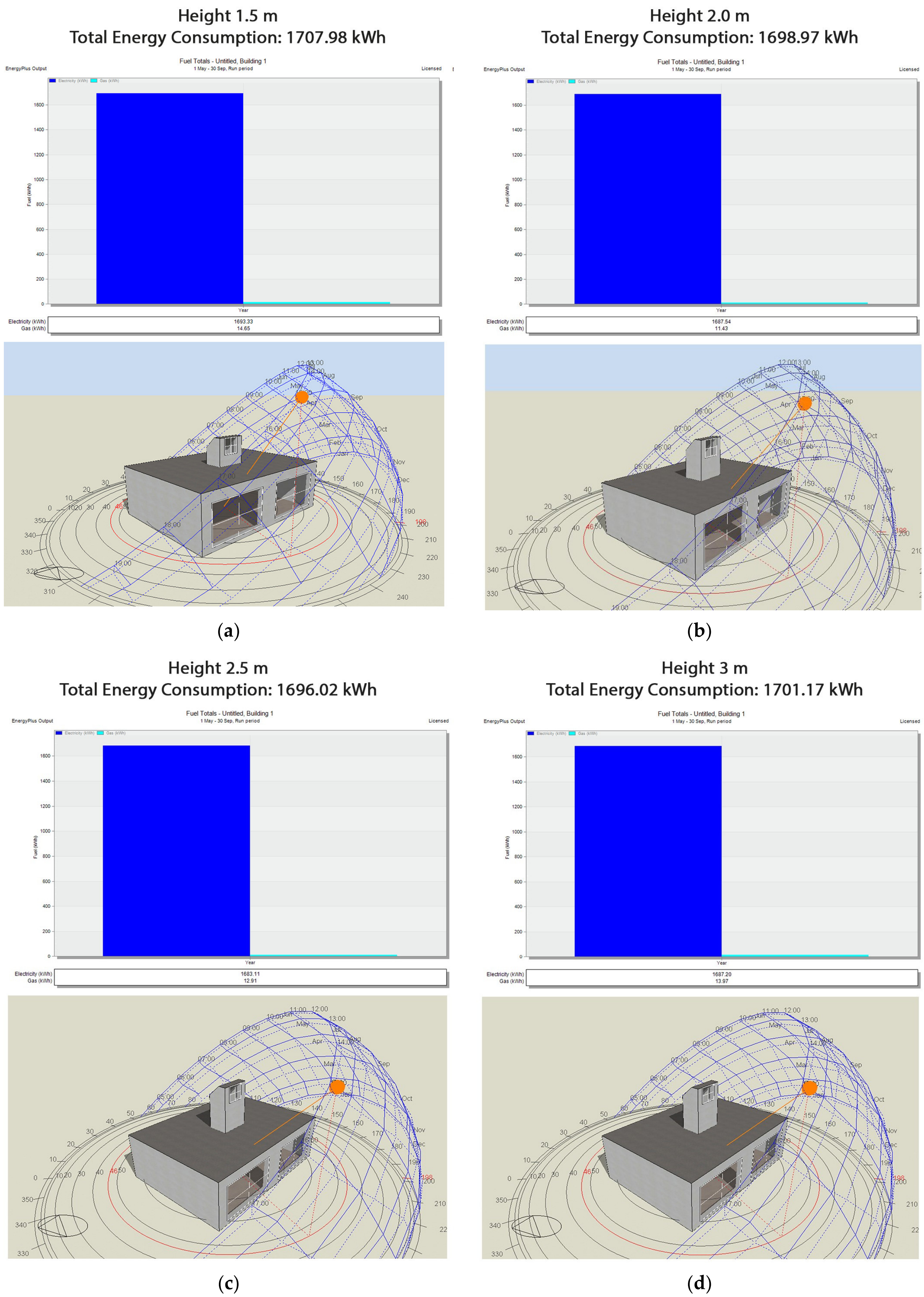


Figure 18. The level of annual energy demand in BM with the proposed windcatcher with four various heights. Elaboration and simulation on DB data: (**a**) windcatcher with 1.5 m height; (**b**) windcatcher with 2 m height; (**c**) windcatcher with 2.5 m height; (**d**) windcatcher with 2.5 m height [50].

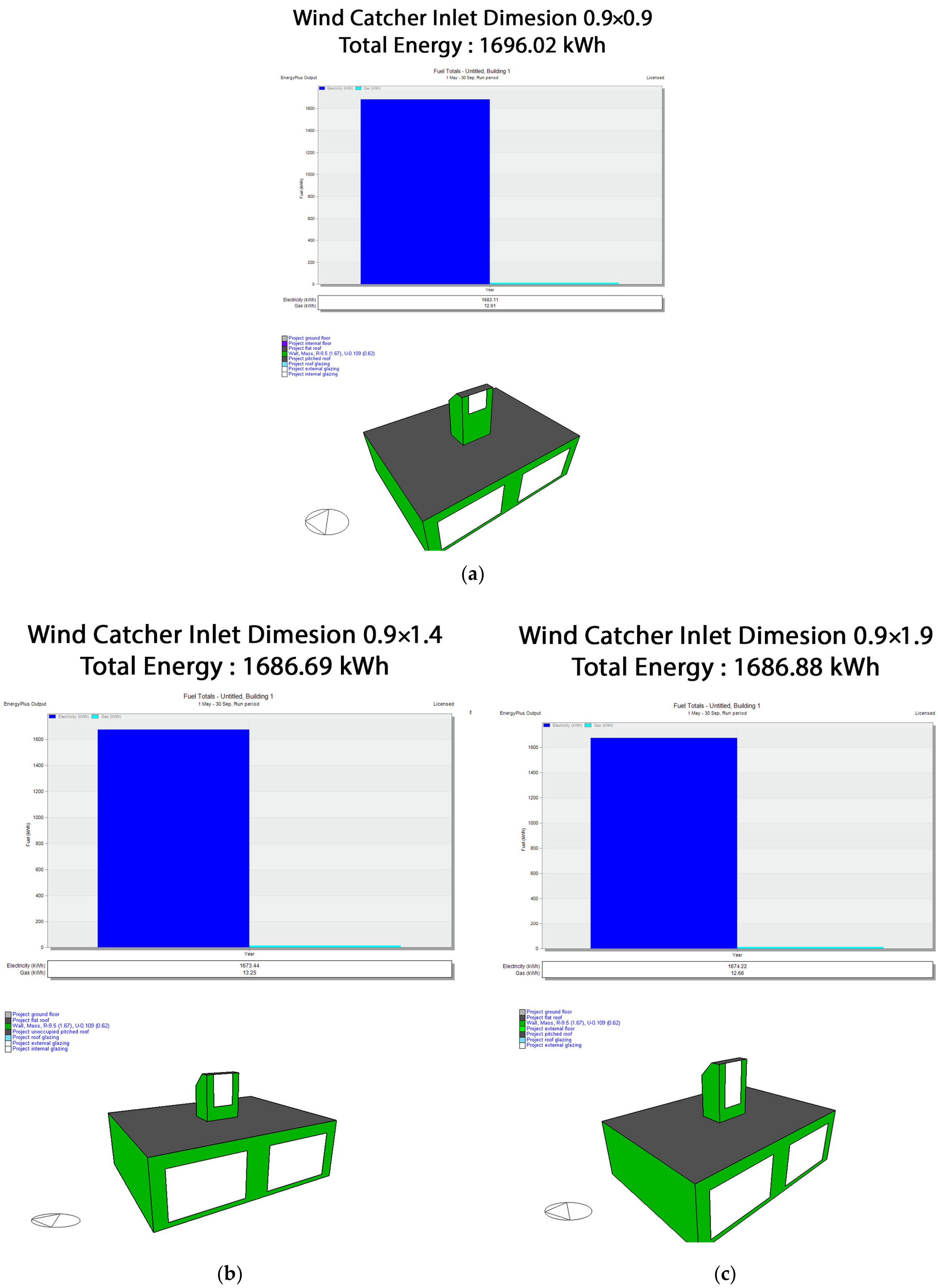


Figure 19. The level of energy demand by using various windcatcher's inlet dimension ratios from May to September. Elaboration and simulation on DB data: (**a**) windcatcher with 1.5 m height; (**b**) windcatcher with 2 m height; (**c**) windcatcher with 2.5 m height [50].

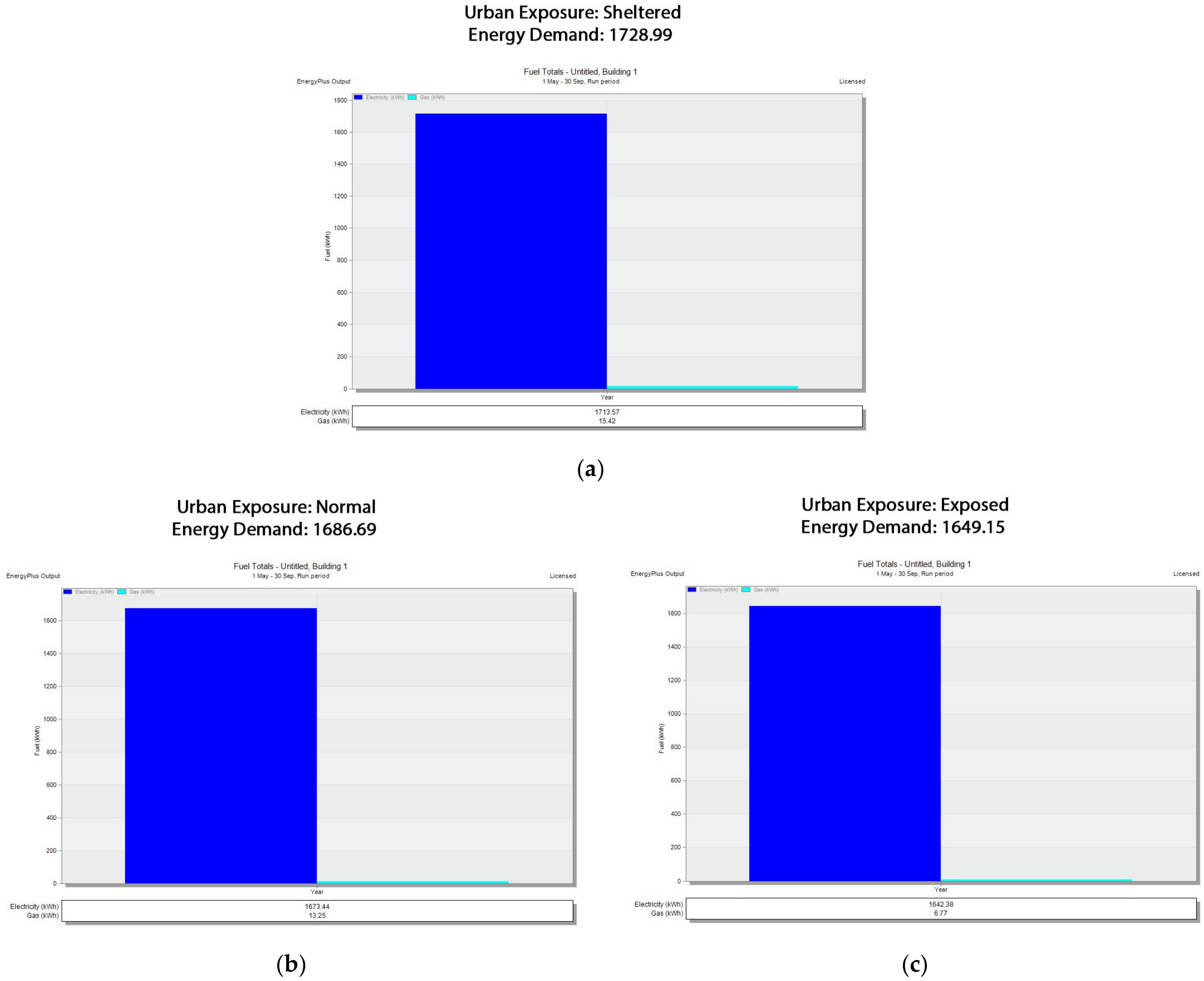


Figure 20. The level of the base module's energy demand in 3 different urban exposures: (**a**) dense urban configuration; (**b**) semi-dense urban configuration; (**c**) isolated urban configuration [50].

6.4. Building Management System (BMS) for Temperature Variation

The subsequent simulation focuses on evaluating the Building Management System (BMS) as the fourth designated variable. The BMS is designed to optimize the opening time of the windcatcher vents based on variations in the inner air temperature of the building (BM). This involves implementing an intelligent management system utilizing temperature sensors. Consequently, four distinct air temperatures are applied within the inner comfort zone. Whenever the internal air temperature of the BM rises by any of the Defined Temperatures (DTs)—set at 21, 22, 23, and 24 degrees Celsius—the windcatcher vents are opened, enabling airflow into the BM. The simulation outcomes for each temperature are depicted in Figure 21.

Simulation results show that the 22 Celsius degrees' temperature for the temperature sensor is the most efficient option for energy savings. To clarify more, when the inner temperature gets to 22 Celsius, it is best for the BMS to open the inlets.

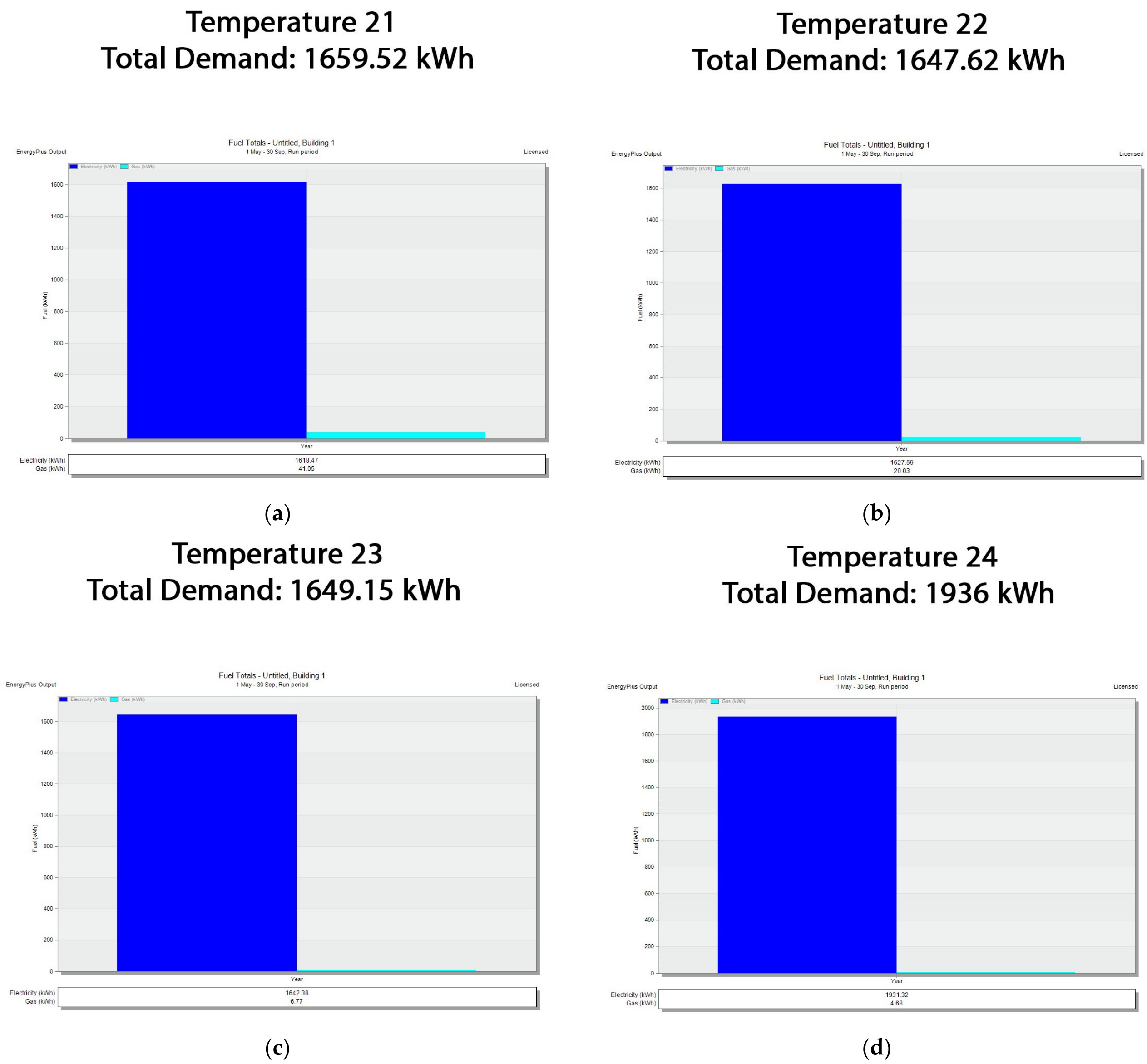


Figure 21. The base module's energy demand levels in the different opening times of inlet in four different temperatures. Elaboration and simulation on DB data: (**a**) in 21 degrees; (**b**) in 22 degrees; (**c**) in 23 degrees; (**d**) in 24 degrees [50].

7. Comparative Analysis of One-Sided and Two-Sided Windcatchers (Assessing Performance Disparities)

In this section, we delve into an examination of the distinctive performance attributes of one-sided and two-sided windcatchers (Figure 22). The aim is to ascertain whether discernible disparities exist that could influence the selection of windcatcher designs. Through a comprehensive assessment of their respective performance metrics, this research reaches a significant finding, namely the disparities between the two windcatcher types are minimal, thereby substantiating a preference for one-sided windcatchers as the prospective choice. These findings provide invaluable insights into windcatcher technology, thereby contributing to the advancement of architectural design and environmental engineering [58–60].

A series of comprehensive simulations were conducted to scrutinize the performance distinctions between one-sided and two-sided windcatchers. These simulations involved subjecting both windcatcher types to controlled airflow conditions while measuring crucial performance metrics, including indoor air temperature, as demonstrated in Figure 23. The simulations were conducted with the optimized windcatcher parameters, which were assessed beforehand. To ascertain the significance of observed differences in the performance of the two windcatcher designs, statistical analysis was employed.

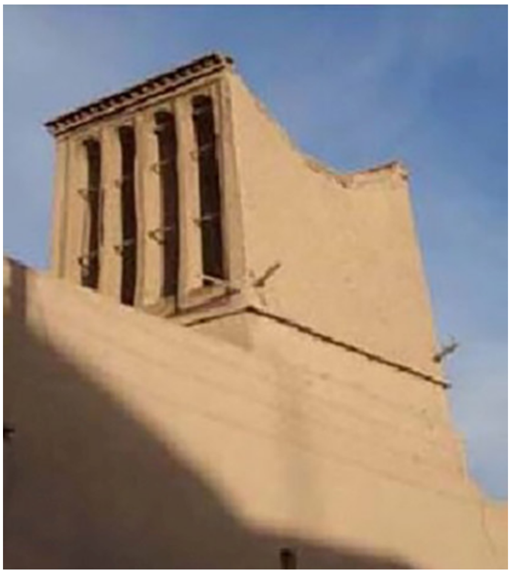


Figure 22. Ancient two-sided windcatcher of Kharmani's school in Iran [58].

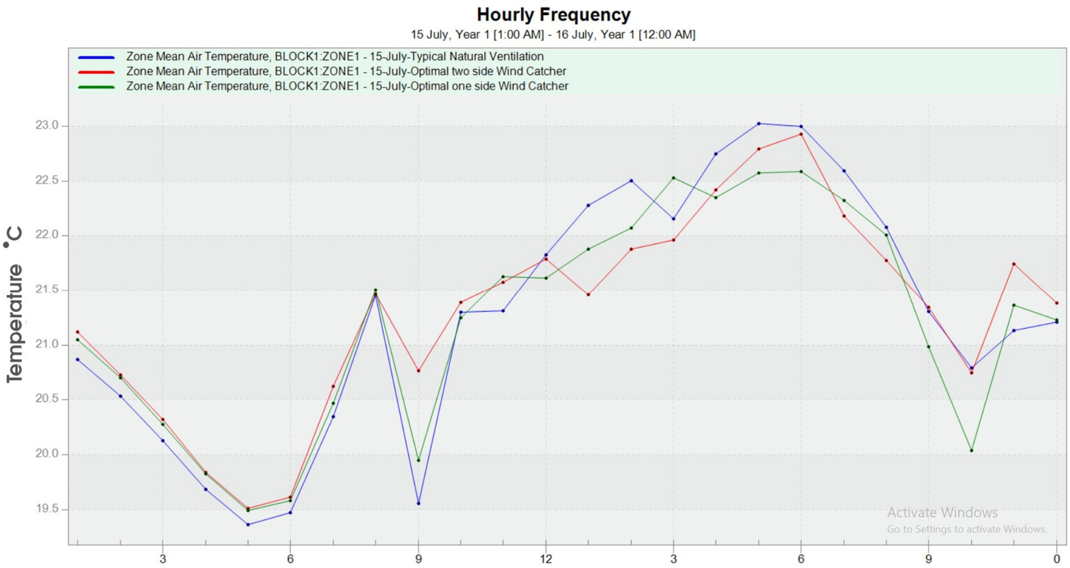


Figure 23. The comparison between one-sided and two-sided windcatcher and natural window ventilation in July and August. Elaboration and simulation on DB data [50].

Upon comparing the performance metrics between one-sided and two-sided windcatchers, the results revealed a slight variance that lacked statistical significance. Both windcatcher designs exhibited analogous air exchange rates, reductions in indoor air temperatures, and improvements in air quality. The marginal variations observed in the simulation results data indicated that the choice between one-sided and two-sided windcatchers does not substantially affect their overall performance.

8. Integration of Windcatcher with Earth Tube System

The historical use of windcatchers as passive cooling mechanisms in buildings is well documented, capitalizing on natural air movement to augment indoor ventilation. Integrating earth tubes into this system further amplifies its cooling potential by tapping into stable subterranean temperatures. These earth tubes serve as pre-coolers, harnessing consistent ground temperature to lower the incoming air's temperature before it circulates within indoor spaces. This technology can also be harnessed for controlled heating and ventilation in winter conditions through the use of heat pumps [61–64].

A notable advantage of coupling windcatchers with earth tubes is the capacity to achieve significant indoor cooling, particularly on scorching summer days. This synergy ushers cooler air into the building, effectively reducing indoor temperatures and alleviating discomfort caused by soaring heat. This holds particular relevance in regions with hot, arid climates where conventional cooling systems may prove inefficient or costly to operate.

By leaning on natural ventilation and the constant subterranean temperature, this integrated system curtails the reliance on energy-intensive mechanical cooling. Consequently, this approach significantly reduces energy consumption and associated greenhouse gas emissions, bolstering environmental sustainability and easing the strain on electricity grids during peak demand periods.

However, it is vital to acknowledge that the effectiveness of merging windcatchers with earth tubes is subject to multiple variables. Local climate conditions, soil composition, architectural design, tube characteristics, and operational practices all exert substantial influence over the performance of this integrated system. Thoughtful design considerations, encompassing the proper sizing, placement, and alignment of windcatchers, in conjunction with well-conceived earth tubes, are pivotal in optimizing performance and maximizing cooling potential.

This study, as exemplified in Figure 24, demonstrates promising outcomes regarding the integration of windcatchers with earth tubes, notably in the context of substantial indoor cooling during sweltering summer periods. This integrated approach holds the potential to enhance indoor comfort, heightening energy efficiency, and reinforcing environmental sustainability. Nevertheless, further research, experimentation, and system refinement are essential to comprehensively grasp its capabilities and constraints. With continued exploration and innovation, the integration of windcatchers with earth tubes can pave the way for sustainable and efficient cooling solutions in the constructed environment.

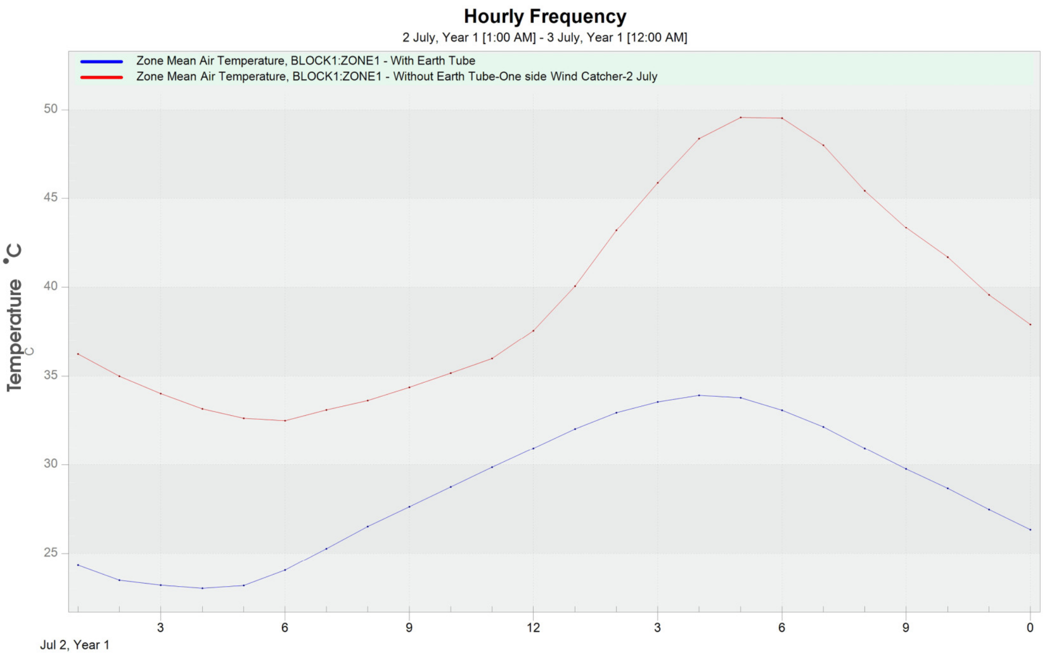
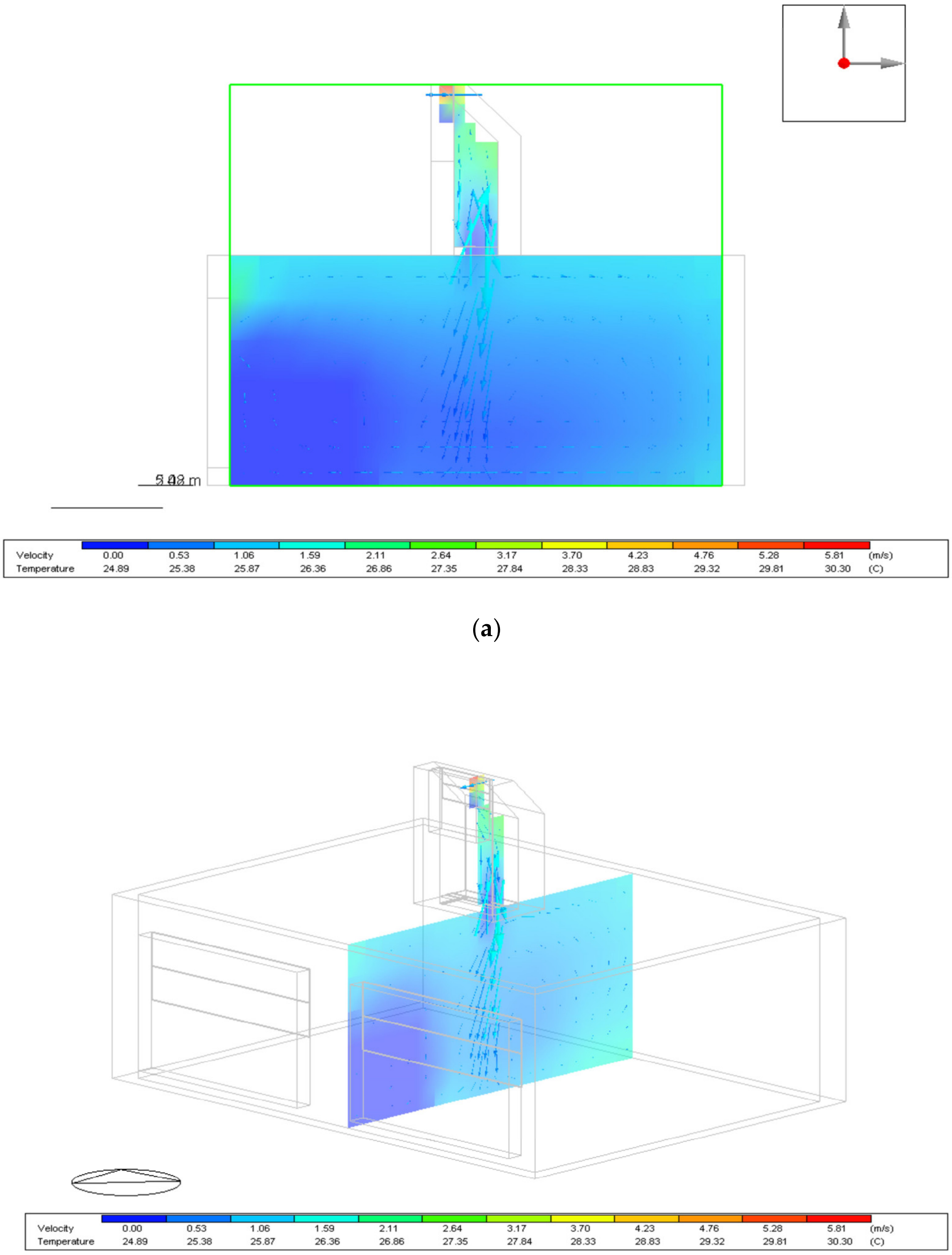


Figure 24. The comparison between indoor air temperature with and without the combination of windcatcher and earth tube. Elaboration and simulation on DB data [50].

9. Computational Fluid Dynamics (CFDs) Analysis

In order to scrutinize the airflow dynamics within the building model (BM), a comprehensive Computational Fluid Dynamics (CFDs) analysis was carried out to elucidate the intricate patterns of airflow within the BM, as illustrated in Figures 25–27. The examination of fluid dynamics within the building's confines, as rendered by Computational Fluid Dynamics (CFDs) analysis [65,66], unveils a distinct pattern. These patterns distinctly manifest when the prevailing wind direction originates from the southwest, a prominent meteorological feature during the hot season. Under such conditions, the airflow transition extends from regions of positive pressure located at the upper sections of the structure to areas characterized by negative pressure in the lower segments of the building. This particular airflow pattern is intricately guided by a modular mechanism. Notably, this modulated airflow adeptly channels cooler air through the upper wind deflector, facilitating a refreshing inflow, and subsequently orchestrates the outflow through pre-existing windows situated in the lower portion of the structure.



(**a**)

(**b**)

Figure 25. (**a**,**b**) CFDs airflow analyses inside the base model. Simulation on DB data (1) [50].

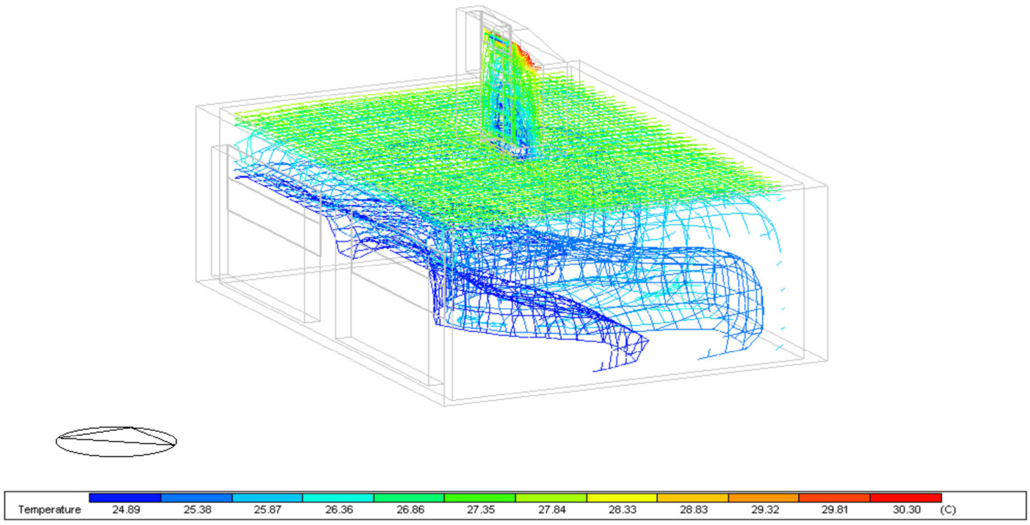


Figure 26. CFDs airflow analysis inside the base model. Elaboration and simulation on DB data (2) [50].

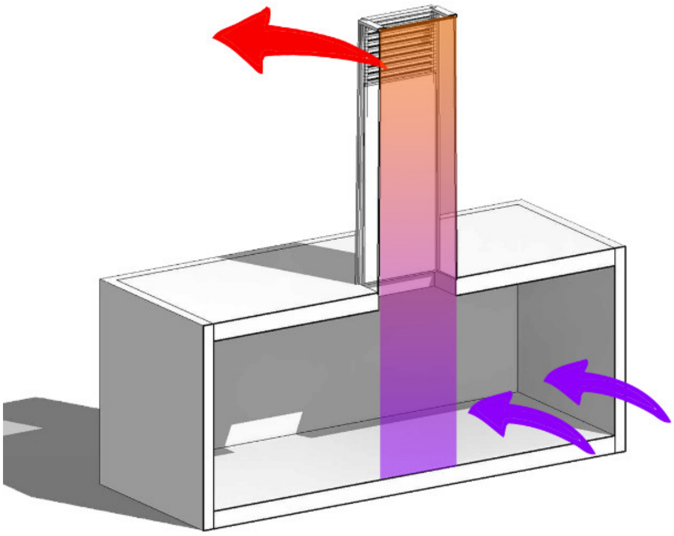


Figure 27. CFDs airflow analysis inside the base model. Elaboration and simulation on DB data (3) [50].

The analysis derived from the CFDs calculations demonstrates that the wind velocity in the upper sections, proximate to the windcatcher's inlet, is higher than its velocity in the lower regions, precipitating the flow of air from the positively pressured upper parts to the negatively pressured lower segments.

These figures elucidate the airflow patterns when the windcatcher faces the windward direction, leading to upward airflow due to the temperature increase in the upper part and the corresponding decrease in air density, underscoring the efficacy of the airflow modulation.

10. Conclusions and Future Work

This study aimed to identify the most effective windcatcher design for the Vienna region, taking into account four key independent variables: height variation, inlet dimension ratio, urban exposure, and the Building Management System (BMS) for temperature control, involving the operation of windcatcher inlets and windows. The research employed a base module, conforming to ASHRAE standards, to evaluate these variables and their implications on thermal load calculations during the warm seasons, spanning from May to

September. The initial simulation phase disclosed that windcatchers with a height of up to 2.5 m improved cooling and reduced energy consumption. However, beyond a height of 3 m, energy usage escalated. Consequently, based on the specific simulation results, the optimal windcatcher's height for Vienna's climate was determined to be 2.5 m.

In the ensuing phase, the optimized height module underwent simulations with three inlet dimensions: 90 cm × 90 cm, 90 cm × 140 cm, and 90 cm × 190 cm. The simulations discerned that the 90 cm × 140 cm inlet exhibited superior performance among the three alternatives.

Subsequently, urban exposure, as the next independent variable, was scrutinized, encompassing three exposure categories: dense urban (sheltered area), semi-dense (normal area), and an individual building on the city outskirts (exposed area). The findings underscored that the windcatcher's performance was most pronounced in the Exposed area, yielding a significant reduction in cooling load relative to the sheltered and normal urban areas.

In the final stage, the Building Management System (BMS) was integrated to ascertain the optimal timing for operating the windcatcher's openings and windows. The results of this simulation established that opening all the inlets when the indoor temperature surpassed 22 degrees Celsius guaranteed optimal energy savings and an efficient cooling process.

Furthermore, the comparative analysis between one-sided and two-sided windcatchers demonstrated that the choice between them had a negligible impact on overall performance. Additionally, the integration of windcatchers with earth tubes exhibited substantial energy efficiency benefits.

In conclusion, the most efficient windcatcher design for Vienna comprises a one-sided windcatcher with a height of 2.5 m and an opening dimension of 90 cm × 140 cm, sited in an exposed urban area, with the openings set to activate when the indoor temperature exceeds 22 degrees. Augmenting this configuration with earth tubes significantly enhances its performance, offering an optimal cooling and energy-saving solution for the Vienna region. The temperature curves depicted in Figure 28 clearly delineate the substantial influence of this optimal windcatcher's configuration on the internal temperature of the base module, guaranteeing indoor comfort.

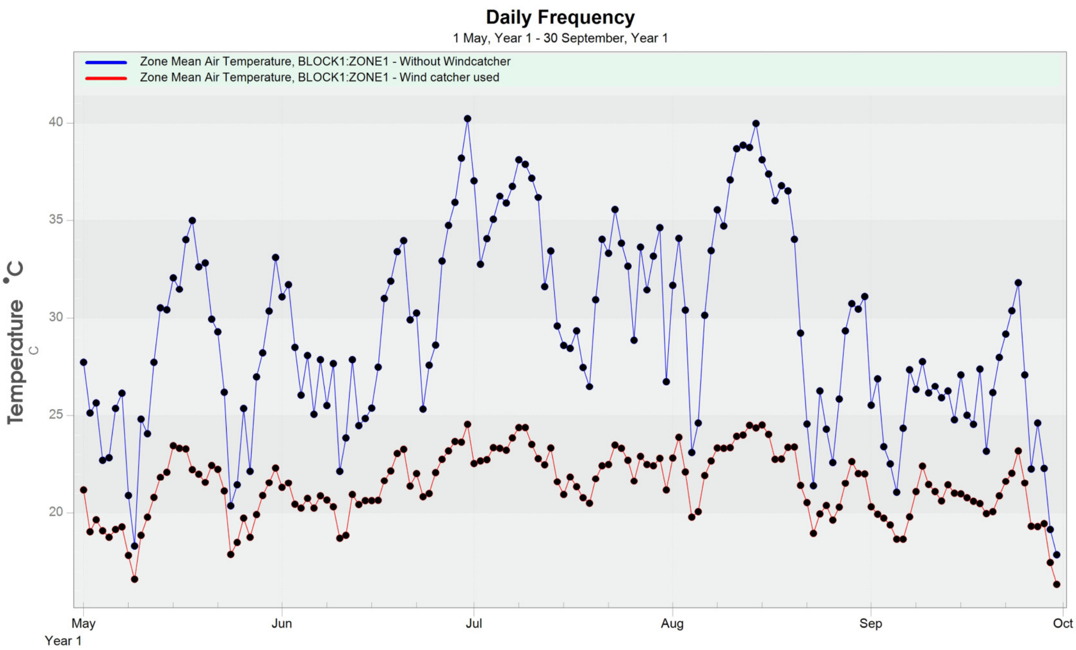


Figure 28. The internal BM's temperature difference before and after using windcatcher. Elaboration and simulation on DB data [50].

For future research, subsequent phases may encompass real-scale model testing and the exploration of chimney vents as a vertical ventilation system in multi-story buildings. Research may delve into optimizing the stack effect through the Venturi effect, buoyancy conditions, and precise temperature control. Additionally, the potential of windcatchers featuring double-glazed sealed glass and sub-absorbing bodies constructed from black materials will be explored. Moreover, the application of research findings in the revitalization of chimney vents in multi-story buildings in Vienna will be investigated as a potential vertical ventilation solution.

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