APPLICATION OF WIND CATCHER IN COOLING PROCESS OF DATA CENTERS

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Abstract

The sustainability of IT facilities has become a top priority in the modern era due to the global energy crisis and ecosystem deterioration. Data centers, as complex infrastructures consisting of computers, networking equipment, and elaborate cooling systems, consume large amounts of electricity. Wind catchers, as a prominent vernacular architecture design, have been used as effective natural air-conditioning systems in desert climates. In this thesis we investigate the application of wind catcher as an effective and passive ventilation technology for controlling data centers' thermal conditions in appropriate climates. The study includes running a detailed "DesignBuilder" simulation for a hypothetical structure, consisting of a data center, a wind catcher with two openings, and an exhaust wind tower. The results of this study show that, over the course of a year, a data center located in Moscow, Idaho with 120.84MWh heat gain can be ventilated through external air with -136.12MWh heat removal.

Acknowledgements

I would like to express my deepest gratitude to my supervisor, Prof. Bruce Haglund, for the useful comments, remarks, and engagement through the learning and preparation processes of this master's thesis. I would like to especially thank Prof. Haglund for encouraging my research and for allowing me to grow as a researcher. His advice on both research as well as on my career have been priceless.

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A special thanks to my family. Words cannot express how grateful I am to my husband, Iraj, my sons, Arya and Armin, my mother, Soroor, and my brother, Behrooz, for all of the sacrifices that they made on my behalf. I thank all of my family and friends who supported me in writing, and incentivized me to strive towards my educational goal.

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Chapter 1: A Data Center

1-1. Data Centers

Over the recent three decades, computers have considerably changed the lives of human beings, and by the end of the twentieth century, computers had affected almost every aspect of human life. The Internet plays a significant role in communication and the exchange of information, and running businesses without data analysis and information management carried out by electronic systems is almost impossible. This dependency on the computational services has made the construction of new IT infrastructures a priority in today's society. Data centers as the main housing unit for the operation of the computing equipment and the associated cooling apparatus are considered as important infrastructures in developing countries. The data center market has been growing at 13-16% CAGR (compound annual growth rate) and future growth is expected to be around 5-10% per year [1].

1-2. What is a Data Center?

Generally, we use the term data center for a dedicated space for housing a large amount of electronic equipment, typically computers and communications equipment. IT infrastructure such as servers and storage equipment perform functions such as store, manage, process, and exchange digital data and information. Processed digital data and information is applied in two ways:

- Support the informational needs of corporations and educational centers.
- Provide various types of data processing services for applications such as web hosting, Internet access, and telecommunication [2].

As the name implies, a data center is a facility that is maintained by an organization for the purpose of processing the data necessary for its operations. For example, the data center for a bank is where all customers' account information is maintained and transactions involving these data are processed. Another example is Internet service, which is provided through data centers that are located in secure locations within or outside of large cities.

1-3. Different Types of Data Centers

Under the North American Industrial Classification System (NAICS), data centers are classified in two specific categories:

- Online Information Services – NAICS 514191– Internet access providers, Internet service providers, and similar establishments.
- Data Processing Services – NAICS 5142 –Establishments providing electronic data processing services [1].

The Uptime Institute, a professional service organization, developed a system which has been adopted as the industry standard: A four-level tier performance classification and standard describes the expected availability of data center operations within a facility. The individual tiers represent categories of site infrastructure topology.

Tier I of this classification is appropriate for small businesses using IT facilities for internal purposes or for companies whose web presence is primarily a passive marketing tool.

Tier II is appropriate for Internet-based companies that need multiple sites available but there are no significant financial penalties for their service quality.

A Tier III facility is appropriate for companies that support clients inside and outside the company 24/7, such as service centers and help desks, but can accept limited periods of service interruption.

Tier IV is appropriate for companies that have an international market presence and have highly critical, real time Internet commercial transactions that would be prohibitively costly to interrupt.

The computing equipment and infrastructure housed in data center require significant cooling apparatus. Therefore, the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) categorizes IT facilities into four classes. This categorization is based on the operational classes of the equipment [1].

- A1: Enterprise servers, storage products
- A2, A3, A4: Volume servers, storage products, personal computers, workstations [3]

Although several applications of data centers have very different functionalities with regards to their performances, there is a continuing process of technical convergence, which makes them more and more similar. The equipment arrangement and thermal codes within all types of IT centers follow a specific pattern dictating the same design process and thermal calculations, which are discussed in the following sections.

1-4. A Data Center layout

Data center equipment could occupy a varied amount of space ranging from one room of a building, to one or more floors, or even entire large-scale buildings (for a large group of networked computer servers.) A data center might house a simple cage or rack of equipment, or many cabinets, depending on the scale of their operation[4]. Major equipment in data centers include: (1) vertical data processing stations (racks), (2) UPS units (Uninterruptible Power Supply) that are free-standing batteries providing emergency power to run the servers when the input power source fails, and (3) CRAC (Computer Room Air Conditioning) units that keep the temperature of the data center at a specified low level. Cabinets are usually set in rows and corridors formed by their placement are called aisles. These aisles provide easy access to the front and rear of each cabinet [2], as demonstrated in Figure 1-1, in which solid gray blocks represent computing racks.

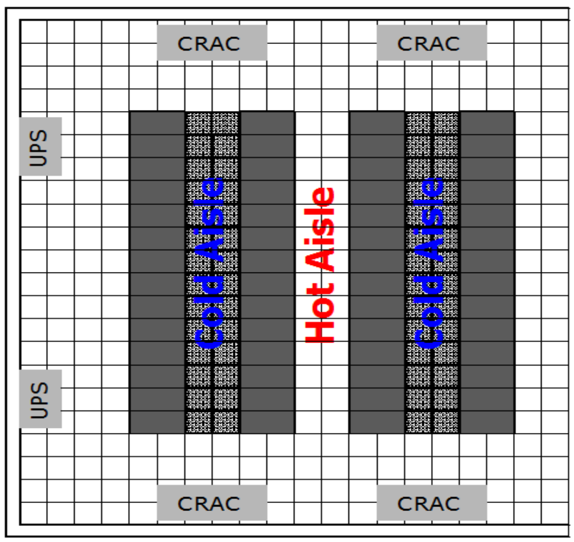


Figure 1-1: A Typical Data Center Layout

1-5. Hot and Cold Aisles

Rack equipment implemented in an arrangement of rows draw cold air from the front and exhaust hot air out the back. This intake of cold air and exhaustion of hot air divides the aisles into “cold aisles” and “hot aisles”. A cold aisle with perforated floor tiles allows air cooled by CRACs to come up from the plenum under the raised floor. In the cold aisle, the equipment racks are arranged face to face so the cold air discharged up through the perforated floor tiles is sucked into the front of the racks and after cooling the hardware of equipment racks it is exhausted out the back onto the adjacent hot aisles. Hot air will go back to the CRAC to be cooled through mechanical refrigeration [5]. Figure 1-2 and 1-3 show the air flow in conventional data center cooling systems. To increase the efficiency of cooling process, a containment system can be used to isolate hot aisles and cold aisles from one another and minimize the mixture of hot and cold air. Containment systems, show in Figure 1-4, start out as simple physical barriers that separate the hot and cold aisles [6].

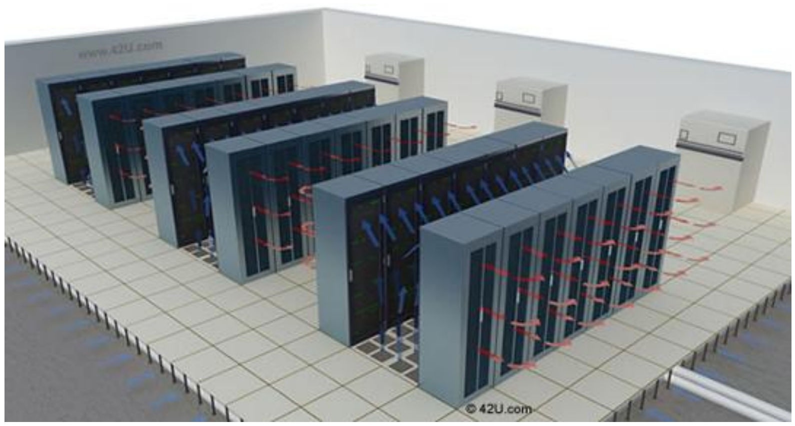


Figure 1-2: Hot Aisle/Cold Aisle Server Row Orientation [7]

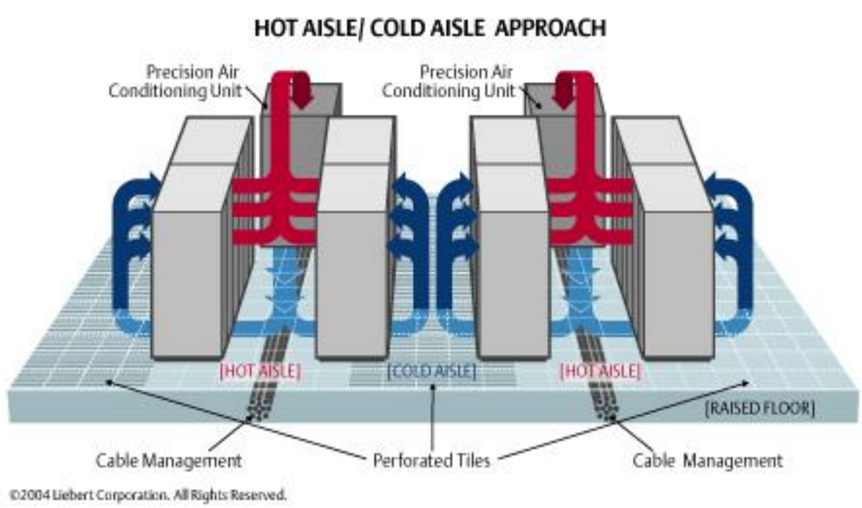


Figure 1-3: Airflow in Hot and Cold Aisle [8]

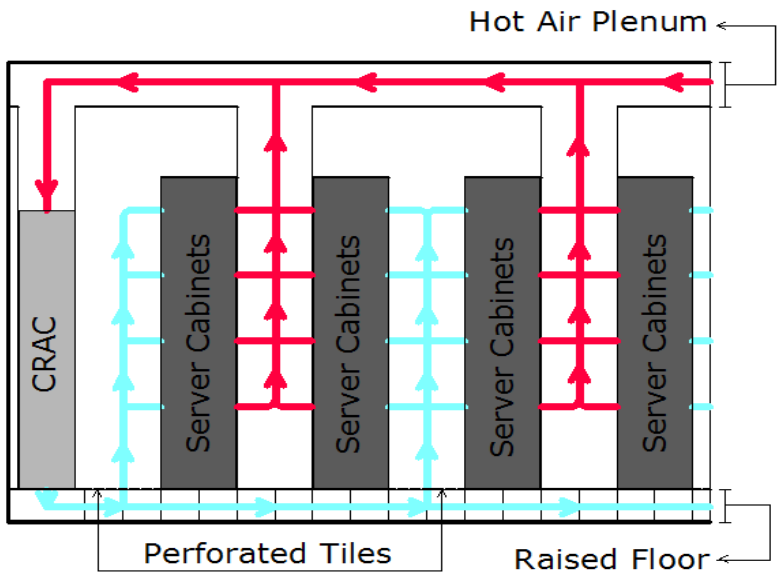


Figure 1-4: Isolated Hot Aisles and Cold Aisles

1-6. Data Centers Energy Consumption

Data centers are very energy demanding and their economic and environmental footprints cannot be denied. Data centers can consume 25 to 50 times more electricity compared to standard office spaces [9]. A report by the Environmental Protection Agency (EPA) indicates that the nation's servers and data centers alone, used about 1.5% of the total national energy consumed per year, for a cost of approximately $4.5 billion [1]. In 2006, worldwide data centers consumed 1% or 170.4 TWh of global electricity consumption at an estimated cost of $12.57 billion. These numbers are expected to grow exponentially given the increasing computational needs in the future. It is estimated that data centers electricity consumption is going to quadruple between 2010 and 2030, from an annual consumption of 125 TWh to over 500 TWh [10]. Generating electrical power is one of the most important sources of GHG (greenhouse gas emissions). While coal plants produce 37.4 percent of total electricity in the United States [11], 1 kWh of electricity produced from coal results in the emission 800 to 1050 grams of CO_2 [12]. In 2007 worldwide data centers' carbon emission was 2% of global emission [13]. Although data centers have helped humans conquer some of the most complicated challenges of modern life, they have many destructive impacts on the environment. Since data centers have high electricity and cooling requirements and operate continuously with nearly constant load, the energy demand in these facilities is of imperative concern. The economical impact of a high-energy consuming unit such as a data center is not the only issue, since the destructive environmental carbon footprints can be severe as well. High energy costs, depletion of fuel sources and negative environmental impacts have made sustainable computing facilities an important topic for research.

1-7. Energy Consumption Pattern in Data Centers

Compared to other business activities within commercial buildings, data centers are specified by their very high electricity consumption for a given floor area. The ratio of energy requirements as a function of building size are defined as the energy usage intensity (EUI) of the building and it is measured in Watts/ft^2 (W/m^2). The range of EUIs in data centers is typically from 20-90 Watts/ ft^2 (215-968 W/m^2) and it is much higher than the average office building that has an average EUI of only about 2 Watts/ft^2 (21.5 W/m^2) [1]. In table 1-1, there is a comparison of EUIs for different official areas and a server room.

Receptacle Loads	Nominal Values	
Computer intensive offices	22 W/m^2	2.04 W/ft^2
General office areas	16 W/m^2	1.48 W/ft^2
Large conference areas	11 W/m^2	1.02 W/ft^2
Server/Computer rooms	540 W/m^2	50.16 W/ft^2

Source: ASHRAE STD 90.1:1999

Table 1-1: EUIs for Different Official Areas [14]

The main types of electrical loads in data centers are:

- IT Load: servers, data storage, network communication
- Infrastructure Load: lighting, UPS (Uninterruptible Power Supply), air conditioning

A data center consumes large amounts of electricity when their computing equipment is operational or when elaborate cooling systems remove heat from the data center to keep the temperatures low. The temperature in a data center will naturally rise because the electrical power used in computing equipment heats the air. The heated air must be removed because the high temperature ambient results in the malfunction of the electronic systems. About one third (~30%) of total electrical load of data centers, indicated in energy usage pattern of data centers in Figure 1-5 are used to run HVAC systems and cooling process [15].

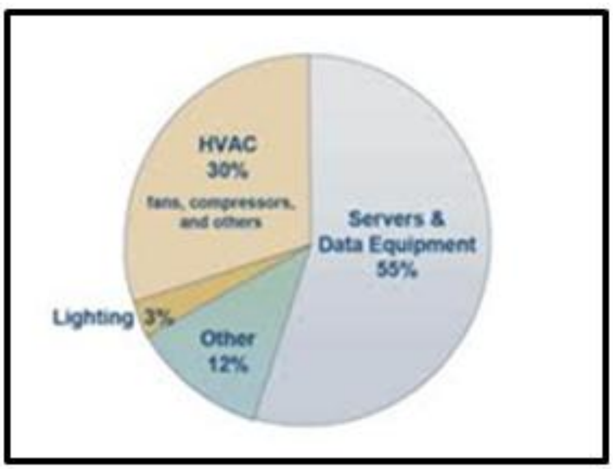


Figure 1-5: Energy Usage Pattern in Data Centers [15]

1-8. Conventional Cooling System of Data Centers

Air conditioning systems play a significant role in keeping the server components at the level within the specified temperature and humidity range. This is critical since server equipment generates a tremendous amount of heat, and higher temperatures tend to increase failure rates such as slow processing or shut down. The computer rooms are on a raised floor that serves as the conditioned air supply system. CRACs utilizing chilled water deliver cold air under the floor. Cold air passes through computing equipment via fans installed in computers' hardware and heated air goes back to the CRACs to be cooled again. CRAC units typically use refrigerants to exchange heat with water-cooled condensers that are tied into cooling towers for heat removal. Massive HVAC units, such as Google data center in Georgia, shown in Figure 1-6, placed in individual buildings are sometimes required to approach the cooling goals.

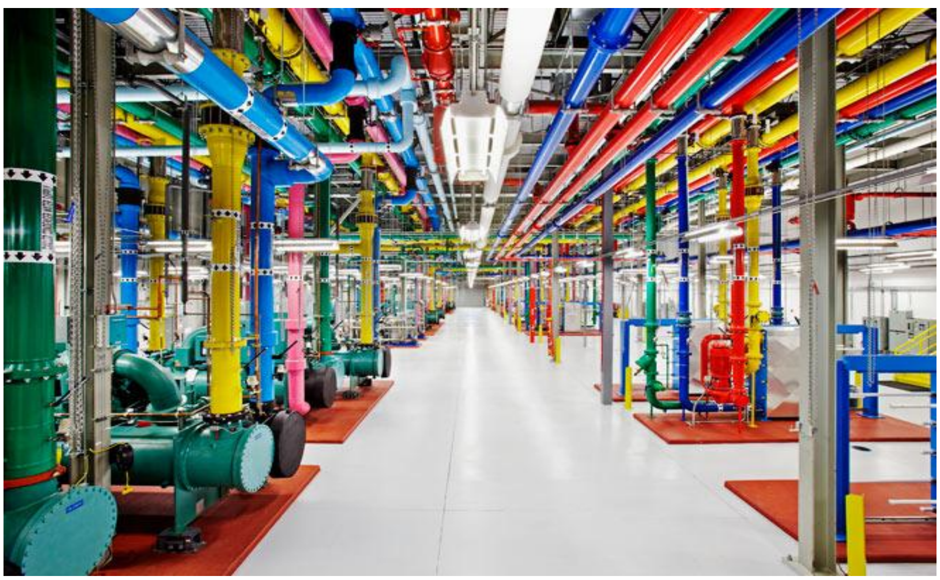


Figure 1-6: A Google's Data Center Cooling Plant, Georgia [16]

1-9. Air Distribution in Data Centers

There are three basic approaches to distribute (supply and return) air in a data center:

- Flooded: As it is illustrated in Figure 1-7, in this distribution system, walls, ceiling, and floor of the room are the only constraints to the supply and return airflow. This causes a heavy mixing of the cold and hot air. This is the least energy efficient of all air distribution systems.

- Targeted: Supply and return airflow are directed within 3 meters (10 feet) of the computing equipment intake and exhaust through ducts, perforated tiles, or other strategies. This is more energy efficient than flooded system. Schematic air circulation is demonstrated in Figure 1-8.
- Contained: Supply and return airflow are completely enclosed, shown in Figure 1-9, to eliminate air mixing. This is the most energy efficient of all air distribution systems [17].

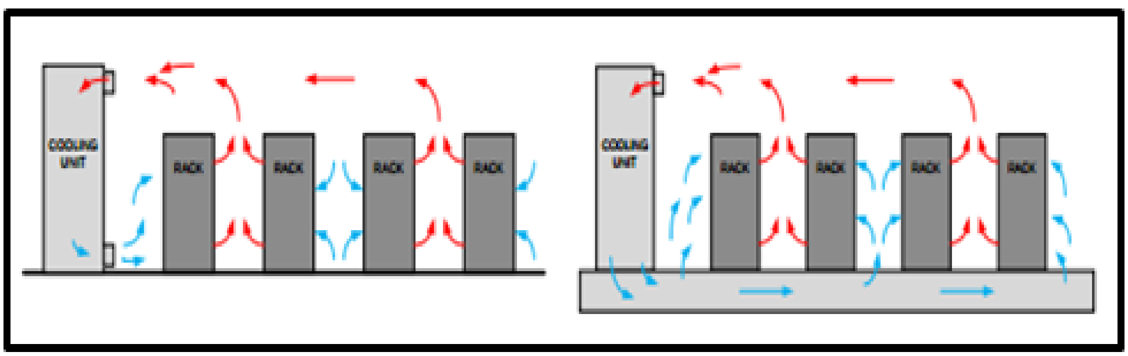


Figure 1-7: Flooded Air Distribution [18]

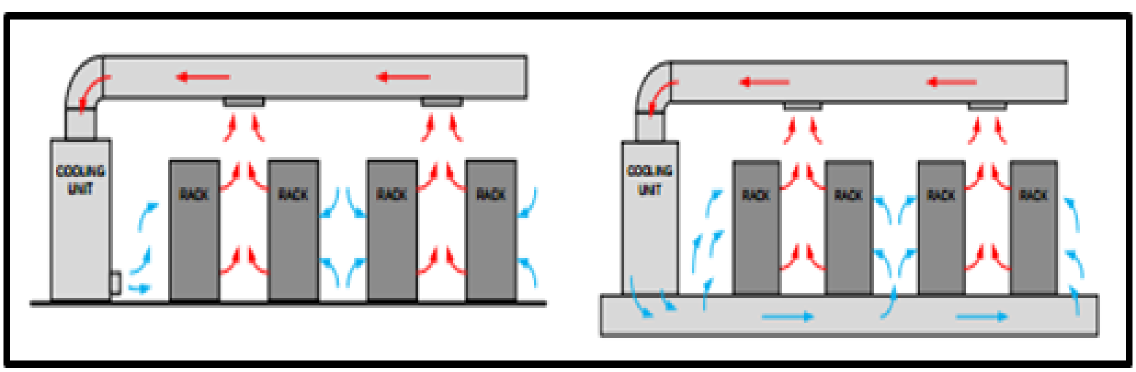


Figure 1-8: Targeted Air Distribution [17]

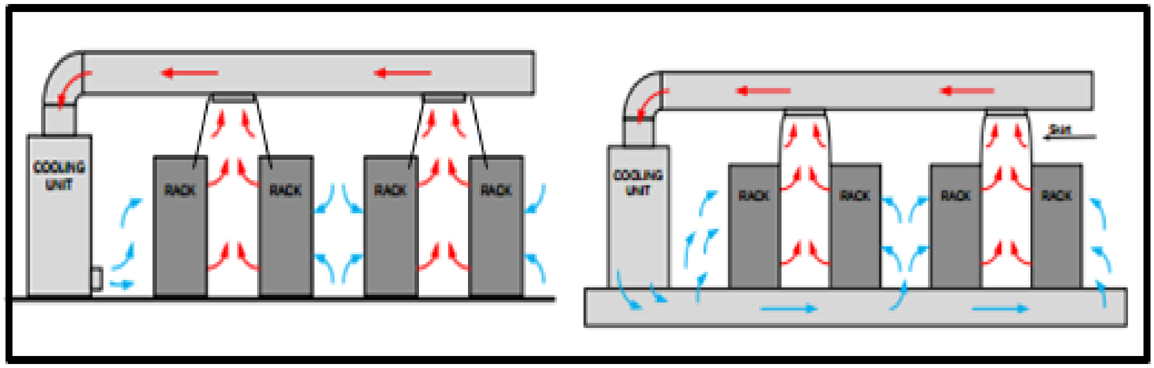


Figure 1-9: Contained Air Distribution [17]

Chapter2: Efficiency in Data Centers

2-1. Power Usage Effectiveness

The data center's effective use of power is determined by the standard metric of Power Usage Effectiveness (PUE). This parameter is defined as the ratio of two numbers: (data center input power) over (IT load Power) [19]:

$$\text{PUE} = \frac{\text{Total Facility Power}}{\text{IT Equipment Power}}$$

Total Facility Power is defined as the power to run everything that supports the IT equipment loads such as computers, UPSs, lighting, and cooling system components including CRACs, chillers, pumps, and cooling towers. IT Equipment Power is the load of all IT equipment such as computers, storage, and network equipment [20]. Smaller data center PUE values mean that the facility is operating more efficiently. A PUE of 2.0 means that for every watt of IT power, an additional watt is consumed for cooling and distributing power to the equipment. A PUE close to 1.0 means that nearly all of the energy is used just for computing [21]. Based on the information released by the Uptime Institute a few years ago, the average PUE of a data center was around 2.4 [22]. Recently, with an improvement in overall energy efficiency for the data center industry, it has dropped to1.8 [22]. Cooling system load, with 30 percent of total energy consumption of a data center, has a crucial effect on the total efficiency of the IT facility.

2-2. Free Cooling and Economizers

Aside from IT equipment, the biggest opportunity for energy savings comes from the cooling system. Free cooling is an approach to lower the temperature in a building or data center without any mechanical refrigeration. In this method outside environmental conditions, such as naturally cool air and water, are used to keep the inside temperature at a low level. It is possible to reduce or eliminate the use of high energy consuming systems such as compressors and chillers. Under the right conditions, there is a significant saving in electrical costs, which is often called “free cooling”. Free cooling technologies are recognized as economizers. When using outside air or a body of water, they are called air-side economizer or water-side economizer [23].

2-2-1. Air-Side Economizer

The prevailing air at many latitudes and elevations is cooler than the air that is warmed by equipment in a data center. This allows introducing cooler outside air into the data center directly through filters. In the low-humidity environments, it is possible to use the evaporative cooling system, which can significantly extend the hours of free cooling. One of the best examples of the implementation of this strategy is the Facebook Prineville data center in Oregon. Aside from many technical attempts for reducing equipment energy consumption, the chiller plant has been eliminated and free cooling is the only system applied to keep the temperature of the data center at low level. Locating the data center in the high desert of central Oregon enabled the designers to use a 100% outside air evaporative cooling and humidification system. When outside temperatures are high, an evaporation room, shown in Figure 2-1, uses the site’s dry air for evaporative cooling. Innovative IT architecture and mechanical refrigeration free cooling systems have made this facility to achieve a PUE of 1.07 at full load [24].

Figure 2-1: Evaporative Room in Facebook's Prineville Data Center [25]

2-2-2. Water-Side Economizer

In this case a source of cold water from local rivers, lakes or ocean is circulated into the data center to cool room air. Since most data centers use chilled water to cool their systems anyway, the implementation of this type of economizers is much easier for existing data centers. The Google data center in Hamina (Figure 2-2), Finland is established on the existing infrastructure of a paper plant. The cold water of the river adjacent to it is circulated into the plant's canals and cools the data center without any energy demanding refrigeration.

Figure 2-2: Google's Data Center, Hamina, Finland [26]

2-3. Data Center Environmental Requirements

The American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) has published guidelines for temperature and humidity operating ranges of IT facilities. Many data center administrators and infrastructure managers commonly accept these guidelines. The recommended range of data center condition in ASHRAE guidelines 2004 was very strict. With improvements in industry to manufacture more reliable components for hardware, ASHRAE expanded operating ranges in 2008 and 2011. These new ranges encourage the use of free-cooled, refrigerant-free facilities. In table 2-1, there is a comparison of recommended envelopes in 2004 and 2008. The 2011 operating ranges for all classes are indicated in table 2-2 and the psychometric chart in Figure 2-3 shows the expansion of data center environmental ranges. The wider operating conditions allow facility managers to design more efficient data centers and utilize free cooling methods in specific climates and locations. The refrigeration equipment can be eliminated or significantly reduced in size, as free cooling takes advantage of a data center's local climate by using outside air to cool IT equipment. Many implementations of free cooling systems are possible but in all of them the heat produced by the data center is directly transferred to the outside. The new guidelines allow the data center system administrators to operate in the most energy efficient mode.

Criteria	2004	2008
Low End Temp.	20°C	18°C
High End Temp.	25°C	27°C
Low End Moisture	40% RH	5.5°C DP
High End Moisture	55% RH	60% RH & 15°C DP

Table 2-1: Comparison of Operating Environment, ASHRAE 2004-2008 [27]

Class		Dry Bulb (°C)	Humidity Range	Max Dew Point (°C)	Max Elevation (m)	Max Rate of Change (°C / hr)
Previous	Current					
Recommended						
1 & 2	**A1 to A4**	**18 to 27**	**5.5°C DP to 60% RH & 15°C DP**	N/A		
Allowable						
1	A1	15 to 32	20% to 80% RH	17	3050	5* / 20
2	A2	10 to 35	20% to 80% RH	21	3050	5* / 20
N/A	A3	5 to 40	-12°C DP & 8% RH to 85% RH	24	3050	5* / 20
N/A	A4	5 to 45	-12°C DP & 8% RH to 90% RH	24	3050	5* / 20

Table 2-2: Operating Ranges for All Classes of Data Centers, ASHRAE 2011 [27]

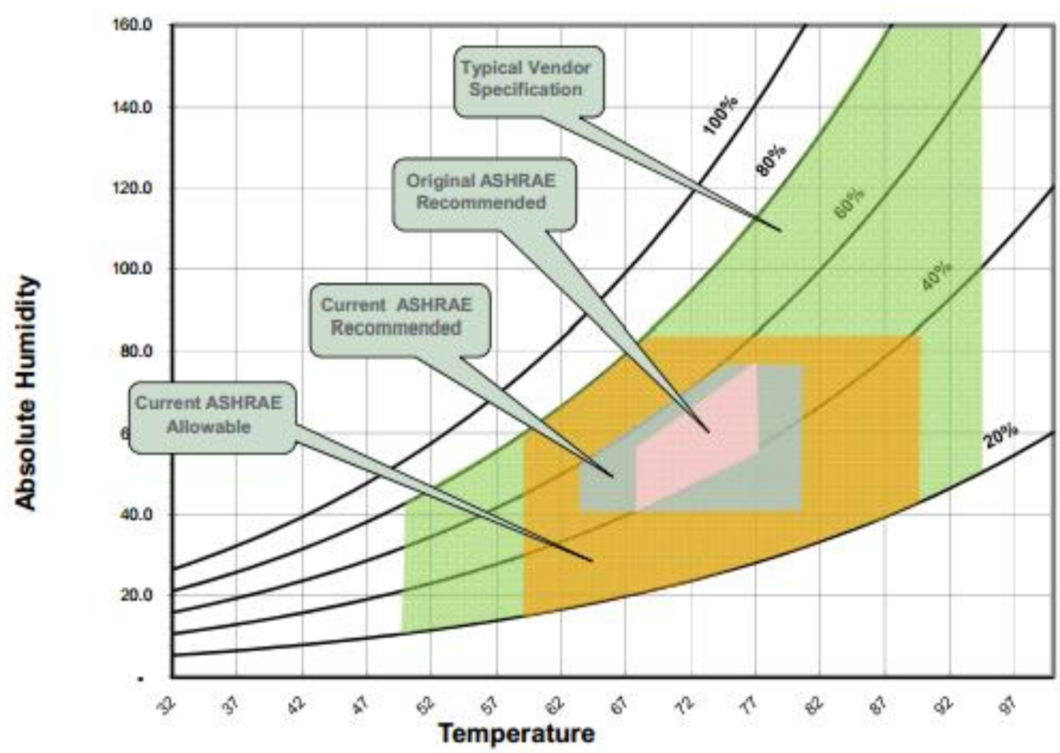


Figure 2-3: Psychometric Chart Showing Recommended and Allowable Limits in Data Centers, ASHRAE 2011 [28]

In a typical data center with mechanical cooling, a great deal of energy is consumed to maintain humidity through multiple CRAC units. When the humidity is lower than the rated amount, the CRAC unit generates heat to produce steam for humidification. This results in an overall raise of temperature in the data center. When dehumidification is necessary, the CRAC unit will cool the air to remove moisture and then reheat to keep the space temperature at specified condition. Each CRAC unit typically sets its temperature and humidity rates on what it measures in the return (heated) air. Given the proximity of these units' exhausts and intakes, it is possible for one CRAC to attempt to cool or humidify the air while another CRAC tries to dehumidify and/or reheat the air. Therefore, it is difficult to control humidity through active systems in data centers and expanding allowable humidity limits can save energy. Furthermore, most IT equipment is rated for the operation of up to 80% relative humidity. In August 2008, Intel conducted a 10-month proof-of concept test to see the results of using only outside air to cool a data center. The temperature range was 64°F to 92°F. Humidity varied from 4% to over 90% and changed rapidly at times. Under this circumstance no significant difference between failure rates using outside air and an HVAC system was observed [29]. In July 2012 the results of a study done by DLB Associates, Consultant Engineers, was released in the Green Grid Forum. The results show that IT hardware failure in Tokyo with a variable data center temperature is only 2.7% higher than the situation that data center was operating at a tightly controlled temperature of 20°C [27].

2-4. Air-side Free Cooling (Maps and Tools)

Using the site air for cooling the data centers is the most efficient variety of economizers. The prevailing climate condition of the site plays the key role to determine the viability of air-side economizer application. The Green Grid is an industry consortium of 150 member organizations around the world, collaborating to improve the efficiency of data centers and business computing ecosystems [30]. The Green Grid survey (Portland, Ore. 2011) emphasizes that the use of economizers will result in saving an average of 20% on energy costs and 7% on maintenance costs [31] when compared to facilities designed without economizers. The expanded ranges, based on ASHRAE 2011 guidelines, allow greater savings in each data center, and increase the number of IT facilities that can take advantage of economization. The Green Grid published free cooling maps for different regions of the world to show graphically what the potential for free cooling might be at different locations. The free cooling map estimating the number of hours that air-side economizer could work effectively (Figure 2-4), shows that in all northern states of the United States, air-side economizers can operate the whole year [32].

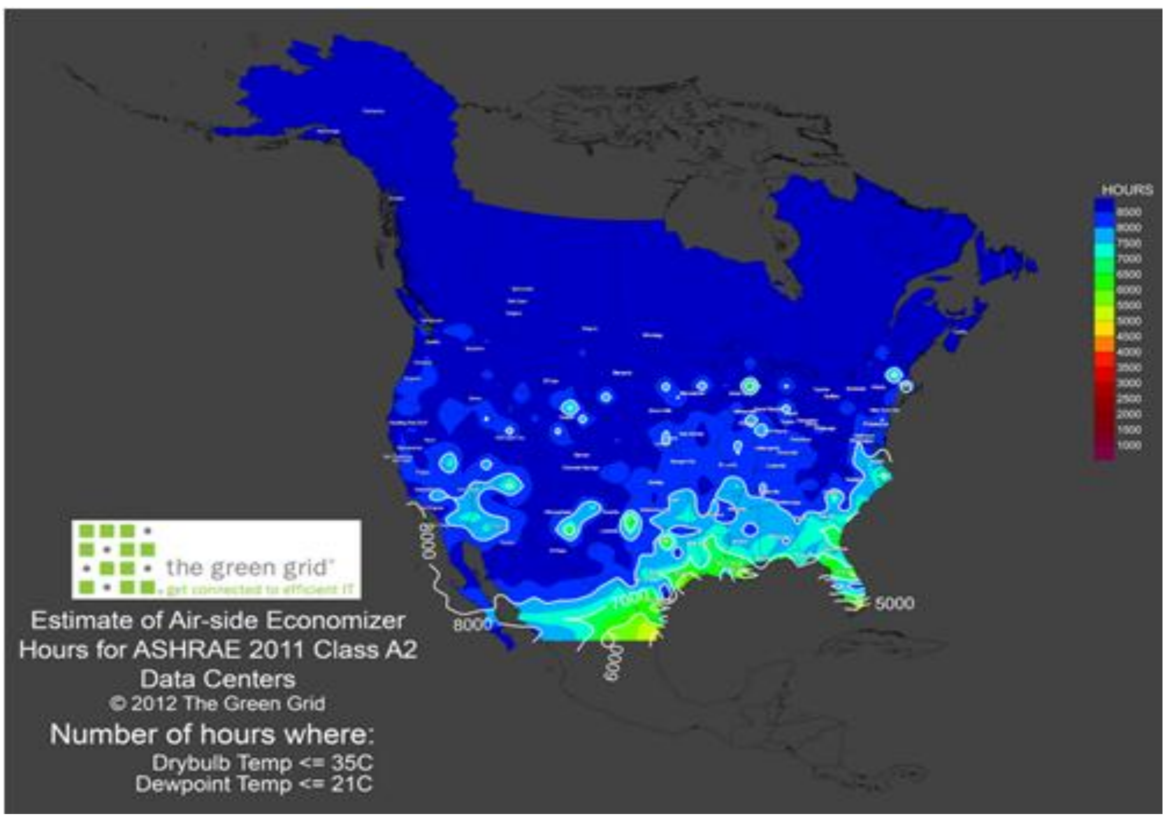


Figure 2-4: Air-side Free Cooling Hours Map, Green Grid [32]

There is also an online tool, provided by Green Grid, which shows an estimated savings plus the number of hours meeting criteria for free-air cooling in a specific data center. After inserting the location and other information such as climatic numbers, the tool calculates the exact hours for free-air cooling. As it is demonstrated in Figure 2-5, with the selected location for the current study being Moscow, ID and the inserting zip code being 83843, the calculator shows that a data center can directly use the outside air for cooling 8,345 hours out of 8,640 hours per year [33]. This overwhelming result gives us confidence for investigating the application of passive, green strategies for cooling data centers in Moscow, ID.

Figure 2-5: Free Cooling Hours Estimated for Moscow, ID (Green Grid Tool) [33]

The Schneider Electric, a multinational corporation specialized in electricity and energy management, has provided an online tool for the calculation of PUE, carbon emission and energy costs in a data center with 1000 KW IT capacity in different regions of the world. The closest city to Moscow, ID in the program is Spokane, WA. If we ignore the minimum climate differences between two cities, we can accept the results with proximity. In Figure 2-6, it is shown that the cooling only PUE for a data center with chiller and cooling tower is 1.64; this number for the data center with different types of free-air cooling is lowered to 1.09 and 1.05. Energy cost, based on the electricity price in the State of Washington, with mechanical cooling system, indicated in Figure 2-7, is $540.0K and with utilizing air-side economizer it is reduced to $334.3K, $323.1K and $320.6K, respectively. In Figure 2-8, it is demonstrated that the carbon generated for operating the data center with no economizer is 799t but with free cooling they are 530t, 512t and 508t, respectively [34].

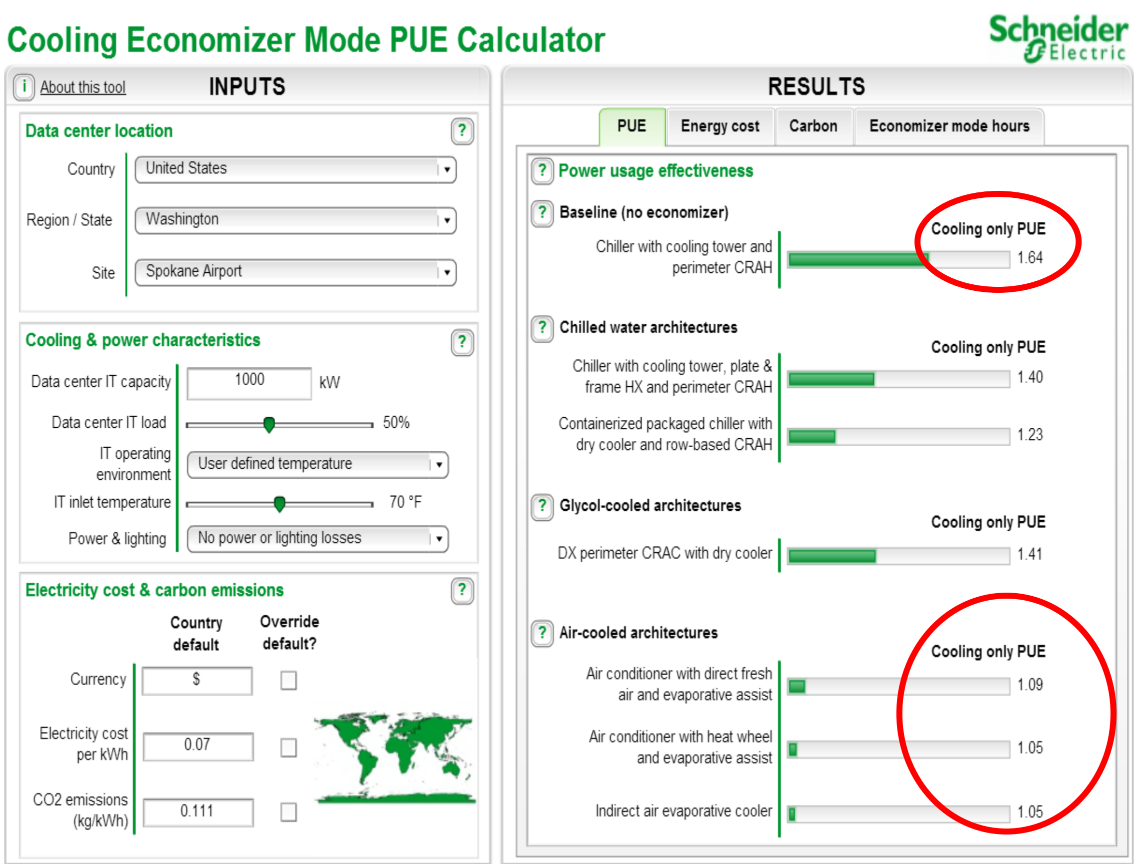


Figure 2-6: PUE Calculator, Schneider Electric [34]

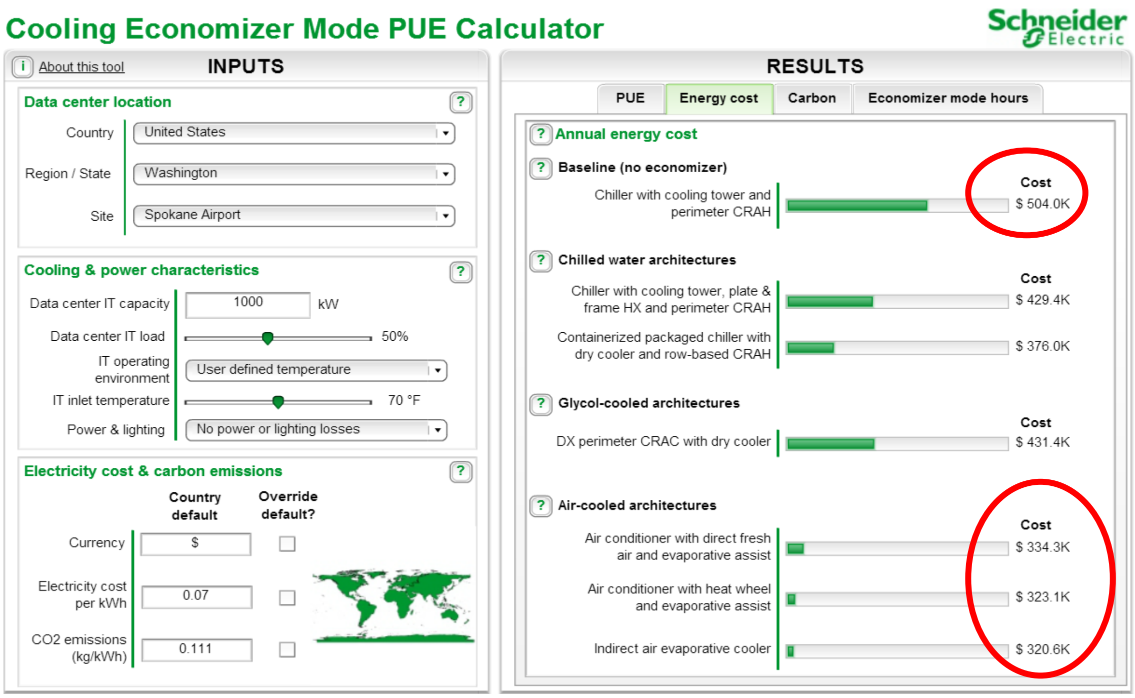


Figure 2-7: PUE Calculator (Energy Costs), Schneider Electric [34]

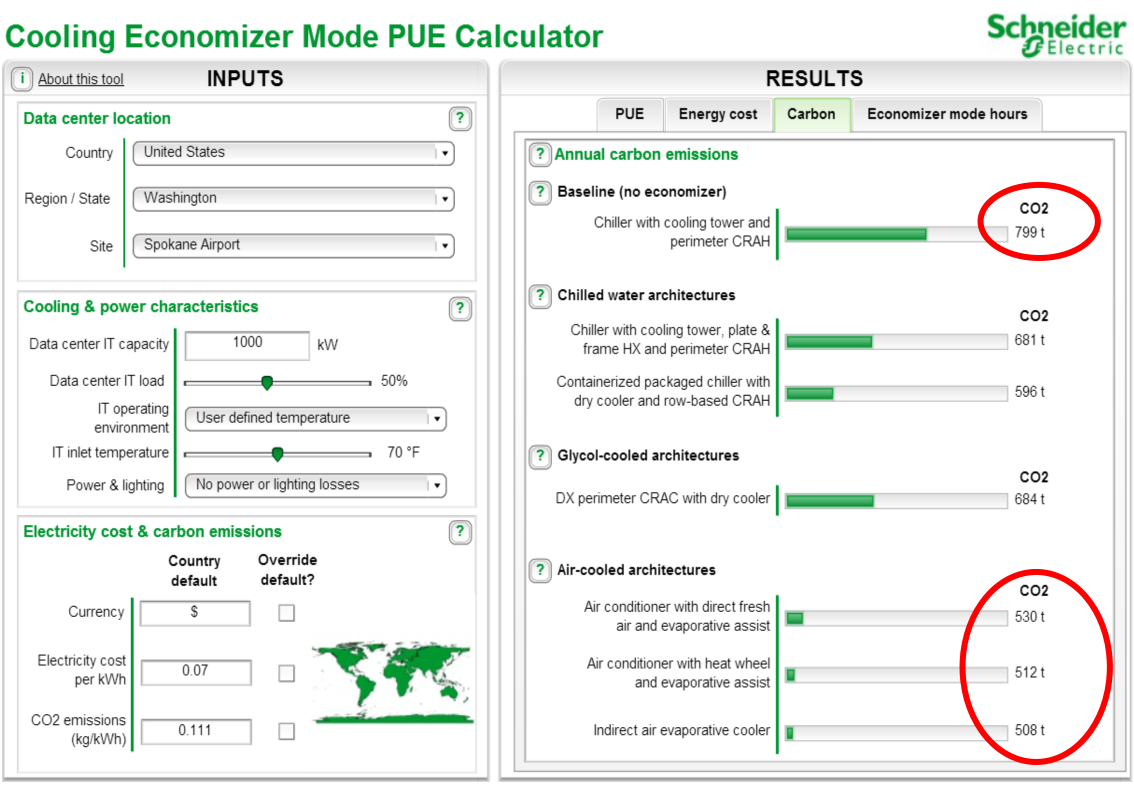


Figure 2-8: PUE Calculator (Carbon), Schneider Electric [34]

All facts and statistical evidence mentioned above show that the implementation of air-side economizers and the use of outside air directly for cooling data centers in Moscow, ID in the United States is a viable efficient approach that results in a significant reduction in energy consumption, energy costs, and carbon emission. As the computational needs show an exponential growth, the acquired savings will be drastic in the future as well.

2-5. Free Cooling is not Entirely Free

By the implementation of air-side or water-side economizers, there will be a significant reduction in mechanical cooling system use, which means a drastic reduction in data center power consumption. If the site's prevailing conditions allow constant use of economizers, industrial cooling systems could be eliminated entirely. Although this energy consumption reduction has notable positive environmental and economical consequences, it should be mentioned that these modes of free cooling are not entirely free. Fans, pumps and other air/water-handling equipment are needed to operate these efficient systems; such equipment also require periodic repairs and maintenance. In a study done by the University of California, Lawrence Berkeley National Laboratory and Rumsey Engineers, the energy savings of air-side and water-side economizer application in data centers in several climate zones of California are modeled. Disaggregated energy consumption in five cities with different economizer scenarios is shown in Figure 2-9. In all five chosen cities air-side economizer mode is the most efficient system, but a notable increase in energy consumption for fans operation can be observed [35].

A notable number of big fans, as are shown in Figure 2-10 and 2-11 in data centers like Facebook data centers in Lulea and Prineville, are needed to bring the outside air into the data center to provide ventilation for the IT facility.

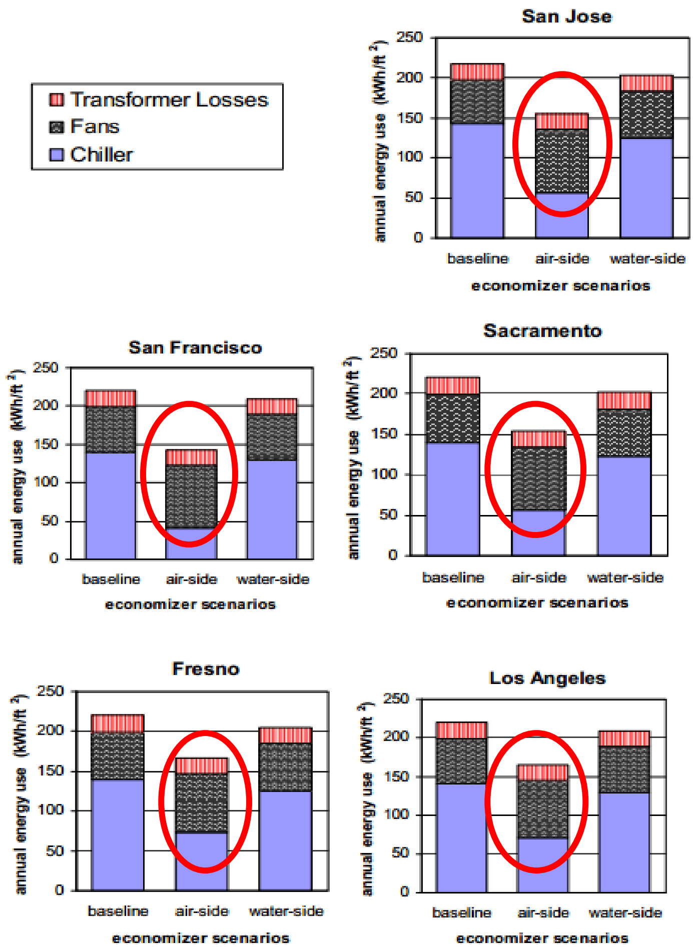


Figure 2-9: Disaggregated Energy Use for Data Centers in 5 Cities in California [35]

Figure 2-10: Lulea Facebook Data Center Cooling Fans [36]

Figure 2-11: Prineville Facebook Data Center Cooling Fans [37]

With proper specifications, installation, commission and maintenance, air-side economizers can provide significant energy savings. Unfortunately, the collection of economizer's equipment installation and management rarely allow it to achieve its savings potentials. Estimates show that due to logistical and maintenance issues, only about one in four economizer works efficiently and the remaining three perform partially or worse yet, waste notable amounts of energy [38]. Electricity consuming fans, equipment maintenance and the constant monitoring of the air-side economizer performances, have made these facilities a potential research area. Reconsideration for more sustainable cooling strategies may result in large amounts of energy savings and also more environmentally friendly solutions.

By focusing on utilizing natural ventilation as a green alternative system for the cooling process of data centers in the climate condition of Moscow, Idaho, this study will prove that it is possible to eliminate the energy consuming conventional air-side economizers. This idea is made possible by minimizing the reliance on energy consuming equipment and conventional cooling procedures. By incorporating wind-catchers in modern data center design, this work demonstrates that it is possible to allow the IT systems to operate in the most efficient way in suitable climates.

Chapter 3: Wind Catchers and Natural Ventilation

With an increase awareness of the costs and environmental impacts of fossil-based energy, natural ventilation has become an increasingly attractive alternative method to mechanical cooling systems. In this chapter we discuss how wind catchers, by utilizing natural forces, can be used for sustainable cooling. These iconic features with a zero carbon footprint have been efficiently used for thousands of years. Various types of wind catchers, from ancient to new versions, are introduced in this chapter.

3-1. Natural Ventilation in Vernacular Architecture

Over the course of history and before industrial class exploitation and refinement of energy resources, building designers came up with ingenious techniques for letting the forces of nature keep their buildings cool. Along with other passive strategies, such as utilizing ground shelter and thermal mass, natural ventilation was used to bring fresh air into the buildings. These thoughtful solutions helped providing thermal comfort inside the buildings during hot seasons in desert climate regions. Wind and temperature stratifications, that is a source of wind generation itself, force the air to come into the building from the windward side and be exhausted from the leeward side [39]. This airflow, through different zones of a construction, is an energy free mechanism that provides comfort by lowering the temperature and increasing the quality of the air. Vernacular architecture, with many years of use experience behind it, has achieved a sustainable solution for different climate conditions. Many cooling and heating devices and strategies have been used to make buildings appropriate built environments for the residency of people. One of the most distinguished among such devices is wind catcher, which is used to achieve proper ventilation and thermal comfort in built environments. These vertical shafts are built to both capture cool breezes for cooling purposes and also exhaust stale air from internal spaces. Wind catchers have been working so successfully that even now, at this advanced age of technology, significant numbers of them are still being utilized to provide essential ventilation in various constructions. Therefore, with zero environmental footprints, wind catchers should be reconsidered as an effective element in sustainable architectures.

3-2. Wind Catchers

Wind catchers are traditional architectural elements used to catch cooler breeze prevailing at a higher level above the ground and direct it into the interior of the buildings to provide thermal comfort for the occupants. Wind catchers worked as effective natural air-conditioning in desert regions where average summer temperatures exceed 100°F [40] (37.8°C). They have been utilized in the hot and arid zones, particularly in the Persian Gulf region in countries like Iran, Iraq, Dubai, and Qatar. Figure 3-1 shows an ornate wind catcher used in Iran. North Africa is another region that wind catchers have been vastly used to provide natural ventilation in countries like Algeria and Egypt. This architectural passive device, functioning to reduce the building heat load, has been the main cooling system for these regions for the past three thousand years [41]. One to multi-sided wind catchers sometimes use the principles of direct evaporative cooling to passively cool hot dry outside air and circulate it through the building [42]. Since abundant natural forces are the only necessary power behind wind catcher's functionality, they are a green, sustainable solution for building ventilation. Wind catchers can be categorized in two main groups: vernacular wind catchers and modern or commercial wind catchers, as described in the remainder of this chapter.

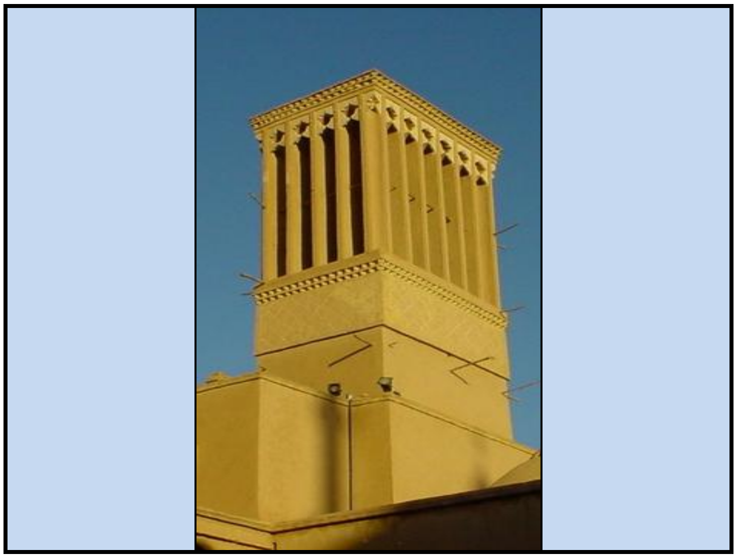


Figure 3-1: A Wind Catcher in Yazd, Iran [43]

3-3. Wind Catcher's Function

Generally, when a building is in the path of a wind, a zone of compression will be created on the windward side and a low-pressure zone at the leeward side [44]. The natural ventilation is based on the movement of air through the building to balance pressure differences between the two zones. As demonstrated in Figure 3-2, the wind causes a positive pressure on the windward side and a negative pressure on the leeward side of the wind catcher. Therefore, fresh air will enter from windward opening and stale air will go out from leeward opening.

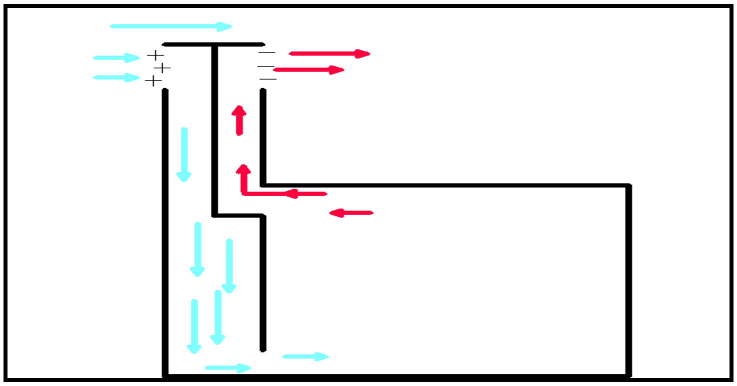


Figure 3-2: Ventilation through a Wind Catcher

Wind is not the only reason for pressure difference as it may also be generated as a result of buoyancy effect created by stratified warm air. Buoyancy or stack effect results from air density difference and it depends on temperature and humidity. The cool air is heavier than the warm air; therefore, dropping of the heavy cooler air from one side will cause airflow through the building to force the light warmer air exhaust from another channel [45].

Researchers at the University of Shiraz have studied the question of whether wind catchers function better and more efficiently in slower or faster winds. The researchers studied three naturally ventilated public buildings located in zones with different wind speeds in Yazd, Iran. This study shows that wind catchers work effectively in all of those places even in low wind speeds. By measuring temperature, relative humidity, and airflow velocity, the research team found out that even in calm weather, a wind catcher could provide thermal comfort by inducing certain volume of air circulation [41]. For example, measured air velocity inside a mosque in Yazd, Iran, ventilated by a wind catcher varies between 0 m/s and 2 m/s over a full day [46]. In Aynsley (2008) study, it is observed that an average air velocity at 0.5 m/s will provide 20% and at 2 m/s will provide 80% of the maximum possible cooling [46], which consequently would provide thermal comfort in wind catcher ventilated buildings in hot and arid climates.

3-4. Vernacular Wind Catchers

Vernacular wind catchers are architectural features mounted on the roof of buildings to bring in the fresh air from the outside. This feature, utilizing green technology, is called Baud-Geer in Iran and Persian Gulf area and Malqaf in Egypt. In the Persian Gulf vernacular architecture, the design and shape of the wind catcher depended on the socioeconomic status of the owner with fancy, ornate designs symbolizing the wealth and social stature of the homeowner. The height of the wind catchers in the Persian Gulf region ranges from 5 to 33 meters (16.5 to 108.5 feet). The tallest vernacular wind catcher with a height of 33m (108 feet 57 inches) is located in Dowlat-Abad garden in the city of Yazd, Iran [41]. In hot and arid regions, a shallow, small pool is placed under the wind catcher and the wind captured by the tower would pass over it before coming into the house as shown in Figure 3-3. This feature would lower the temperature and increase the humidity levels in the building.

Figure 3-3: Pond under Wind Catcher in Dowlat Abad Garden, Yazd, Iran (Photo [47])

3-4-1. Wind Catcher's Components

Wind catchers have three main components that are as follows: chimney, opening, and partitions. Chimney consists of a vertical shaft that directs the wind captured by the openings into the building and would also allow indoor stale air be exhausted through another shaft. Partitions divide the chimney to individual shafts based on their function: intake of the air or exhaust. The shape of the openings on the top of the wind catcher, their numbers, and their direction depends on the region's prevailing wind. Figure 3-4 shows an example chimney and opening while Figure 3-5 demonstrates the functionality of partitions.

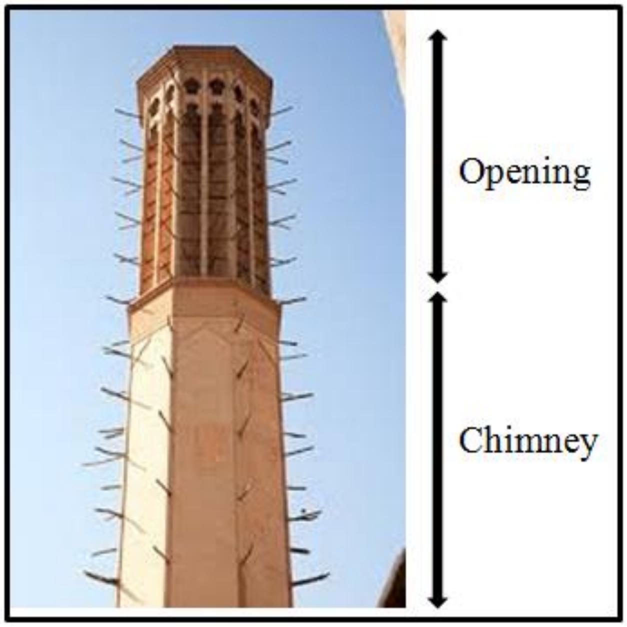


Figure 3-4: Opening and Chimney in a Wind Catcher (Photo [48])

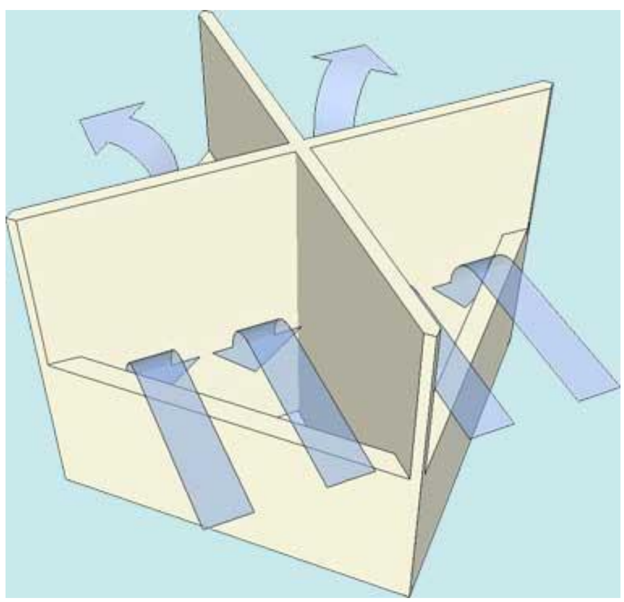


Figure 3-5: Partitions in a Wind Catcher [49]

3-4-2. Categorization of Wind Catchers Based on the Number of Openings

Depending on the direction of the prevailing wind(s), or number of openings, different wind catchers are implemented [50] as shown in Figure 3-6:

a) One-sided wind catchers: These types of towers are constructed in regions with a cool breeze from one direction. Sometimes there are hot and sandy winds in other directions and it is necessary for the wind catcher to be closed in those directions. Figure 3-7 shows an example of a one-sided wind catcher.

b) Two-sided wind catchers: These towers are on top of buildings in regions with prevailing winds in two directions as shown in Figure 3-7.

c) Four-sided wind catchers: In cities like Yazd, in which capturing the wind in all directions is viable, wind catchers have openings in all four directions with an example demonstrated in Figure 3-8.

d) Multi-sided wind catchers: these types of towers are often observed on top of structures such as water reservoirs, in which ventilation plays a vital role in keeping the water fresh. Figure 3-8 shows an example multi-sided wind catcher.

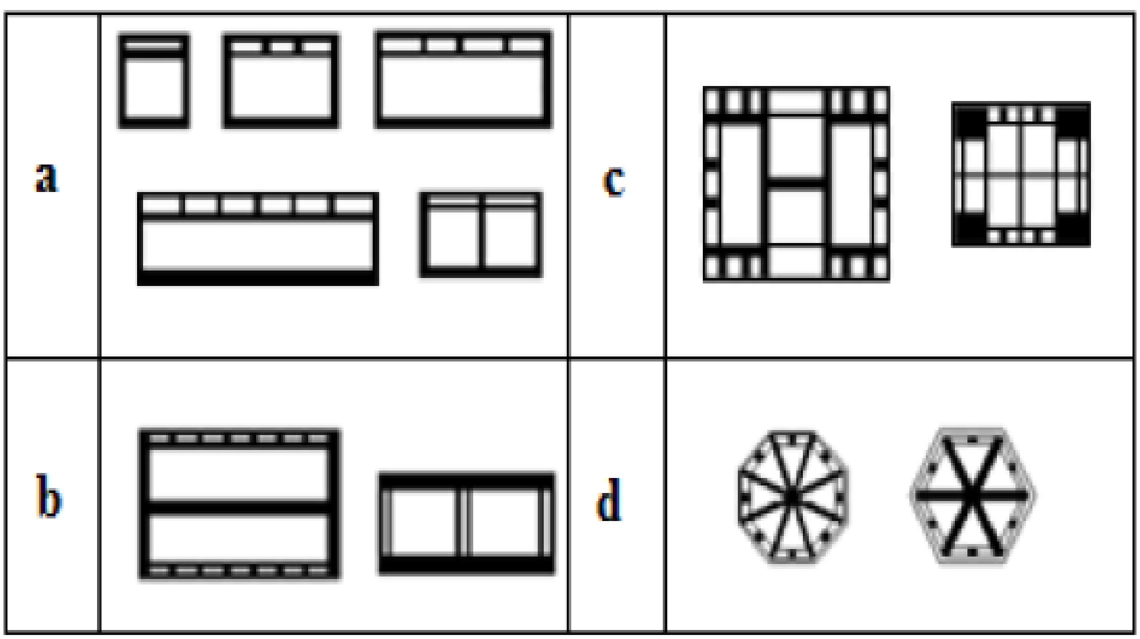


Figure 3-6: Types of Wind Catchers Based on the Number of Openings [50]

Figure 3-7: One-sided Wind Catcher [51] (Left), Two-sided Wind Catcher [52] (Right)

Figure 3-8: Four-sided Wind Catcher [53] (Left), Multi-sided Wind Catcher [54] (Right)

3-4-3. Categorization of Wind Catchers Based on the Cross Sectional Plan

Internal partitions divide chimneys into individual shafts that start from the inlet opening in the building and rise to the ceiling of the wind catcher. These partitions play a key role in directing the wind, modifying the air velocity, and providing thermal treatment. A study done by Mahmoudi [55] from Azad University, categorizes wind catchers in the city of

Yazd (known as the city of wind catchers) based on plan form and partitions [50]. As shown in Figure 3-9, wind catchers are classified in three main groups with circle, square, and rectangle form in plan. Different partitioning categorizes the wind catchers in groups such as wind catchers with X form, + form, H form, I form, and K form.

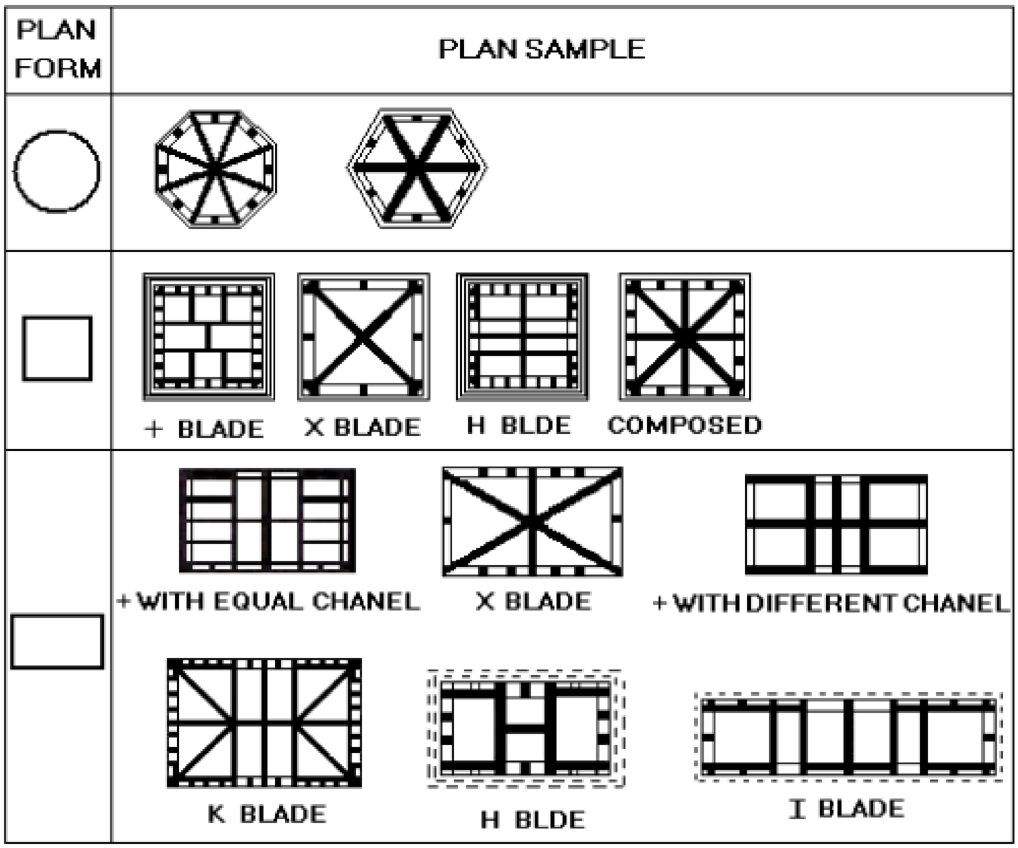


Figure 3-9: Typology of Wind Catchers in the City of Yazd [50]

The varied types of wind catchers in Yazd show the ingenuity of the architects in this ancient city. The different plan forms allow taking maximum advantage of cool breezes in a hot climate. Elongation in specific directions and different sizes of canals, shown in Figure 3-10, are effective strategies to create proper air volume and velocity for the ventilation of the buildings with wind catchers [55]. Mud brick partitions work as thermal mass that absorb the ambient heat during the day and help the exhaustion of the inside air during the night [56].

Subdivisions on the openings, shown in Figure 3-11, force the air to enter from a narrower area which results in an increase in the wind velocity and changes to the overall air flow rate [57].

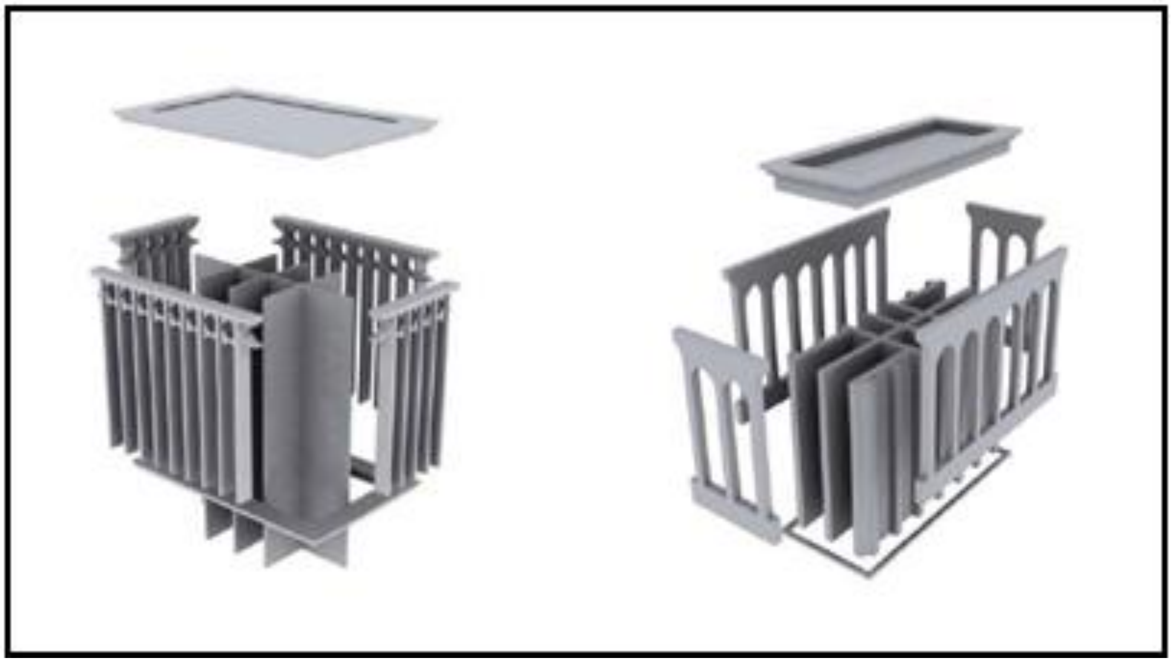


Figure 3-10: 3D Model of a Wind Catcher with Equal Canals [55] (Left), 3D Model of a Wind Catcher with Different Canals [55] (Right)

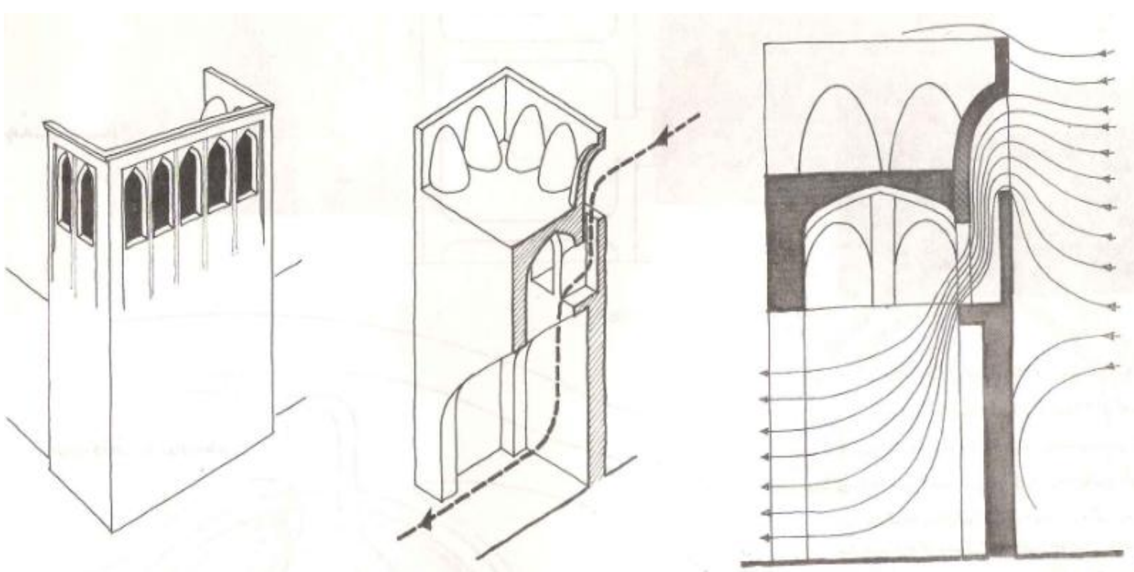


Figure 3-11: Subdivisions on the Opening of a Wind Catcher [57]

3-4-4. Wind Catcher's Efficiency

As previously mentioned in section 3-3, there are two main driving forces behind the performance of a wind catcher: the external wind and the buoyancy effect. The buoyancy effect is a physical phenomenon that occurs because of the differences in air density caused by differential temperature. The Catching Efficiency (CE) of a wind catcher is defined as the ratio of the air velocity and the cross sectional area of the tower. Higher CE values mean higher ventilation velocity with smaller tower cross sections [58]. The following factors are parameters that affect a wind catcher's CE rating:

An increase in the number of openings leads to a decrease in the efficiency of the wind catcher. However, in the lack of a prevailing wind, the best option is to use multi-opening wind catchers.

Cross sectional plan is another effective factor. It has been observed that the performance of an octagonal wind catcher with an octagonal cross section is weaker when compared to wind catchers with square and rectangular plans.

Inclination angle of a wind catcher in relationship to the prevailing wind is a crucial factor; and to get the highest ventilation rating, this angle should be 90° [41].

Since the air temperature and wind velocity notably change in higher elevation, the height of a wind catcher has a direct effect on its functionality. An investigation of the ventilation performance of four-sided rectangular wind catcher with different channel height, carried out by Ghadiri and her colleagues, shows that by increasing the wind catcher height, the air velocity increases on a windward side canal [50].

As the pressure differential between inlet and outlet increases, the ventilation rate increases as well [59]. Therefore, it is very important to locate the inlet at the highest pressure zone (windward side, or the point that has the highest air density) and the outlet at the lowest pressure zone (leeward side, or the point with the lowest air density).

3-4-5. Case Studies

Iran is bordered by the Persian Gulf in the south and Caspian Sea in the north. The eastern part of the Central plateau is covered with two deserts, the Dasht-e Kavir, with 30,000sq mi as the 24th largest desert in the world, and the Dasht-e Loot, with 20,000sq mi as the 25th largest desert in the world [60]. These deserts are uninhabited, but around their borders there are a few ancient cities representing many wonderful vernacular architectures. Over the centuries, local people have found sophisticated passive architectural solutions for survival in the hot and dry climate of the region. A wind catcher (Baud-Gir) is one of the most effective constructed elements that provide comfortable environmental conditions through natural ventilation. The skylines of all these cities are shaped by different types of wind catchers. Yazd, shown in the Figure 3-12, as one of the most important cities along the Silk Road, is sometimes called “The City of Wind Catchers”. A number of case studies, all located in these cities (indicated on the map of Figure 3-13), are discussed in this thesis, with an emphasis on three categories: dwellings, public places, and non-residential constructions. Some of the analysis and information for these cases are based on the author’s field observations and some are university architecture projects.

Figure 3-12: Yazd, the City of Wind Catchers [61]

Figure 3-13: Cities around Two Deserts in Central Plateau of Iran (Map [62])

3-4-5-1. Dowlat Abad Garden, Royal Residency, Yazd, Iran (1747 [63])

The Dowlat-Abad Garden Royal Residency is located in the Dowlat Abad Garden, one of the best representatives of Persian gardens, in the city of Yazd. There are a number of buildings in this garden but the wind catcher building, shown in Figure 3-14, is the most important construction in the complex. The multi-sided wind catcher on the top of this building with a height of 108 feet 57 inches (33 meters) is the tallest wind catcher in the world [64]. It catches cool winds at a higher level, in all directions, and channels them into the interior spaces. As demonstrated in Figure 3-15, there is an increase in air pressure at windward side and a decrease at leeward side of the wind catcher. Therefore, the air near the high pressure side runs into the building and the stale air is forced to come out from the low pressure side. The dry and warm wind passes over a pond right under the wind catcher and becomes cool and humid through the evaporation effect. Then the cool and humidified air flows in the room. The main hall in front of the wind catcher has a dome shape ceiling with openings on top of it which help complete the ventilation system in the building. In a complementary process, the fresh air, cooled by the garden vegetation, passes from big windows, enters the building, and goes out through openings in the dome. The dome has been constructed of mud-adobe material, which makes it a thermal mass. The dome absorbs the heat and works as a solar chimney while maintaining constant ventilation. A marbled pond right under the dome and three other pools in the middle of other rooms, shown in Figures 3-14 (right) and 3-15, add the humidity to the air, which is desired in such a dry climate. They also help lower the ambient temperature via evaporation cooling effects.

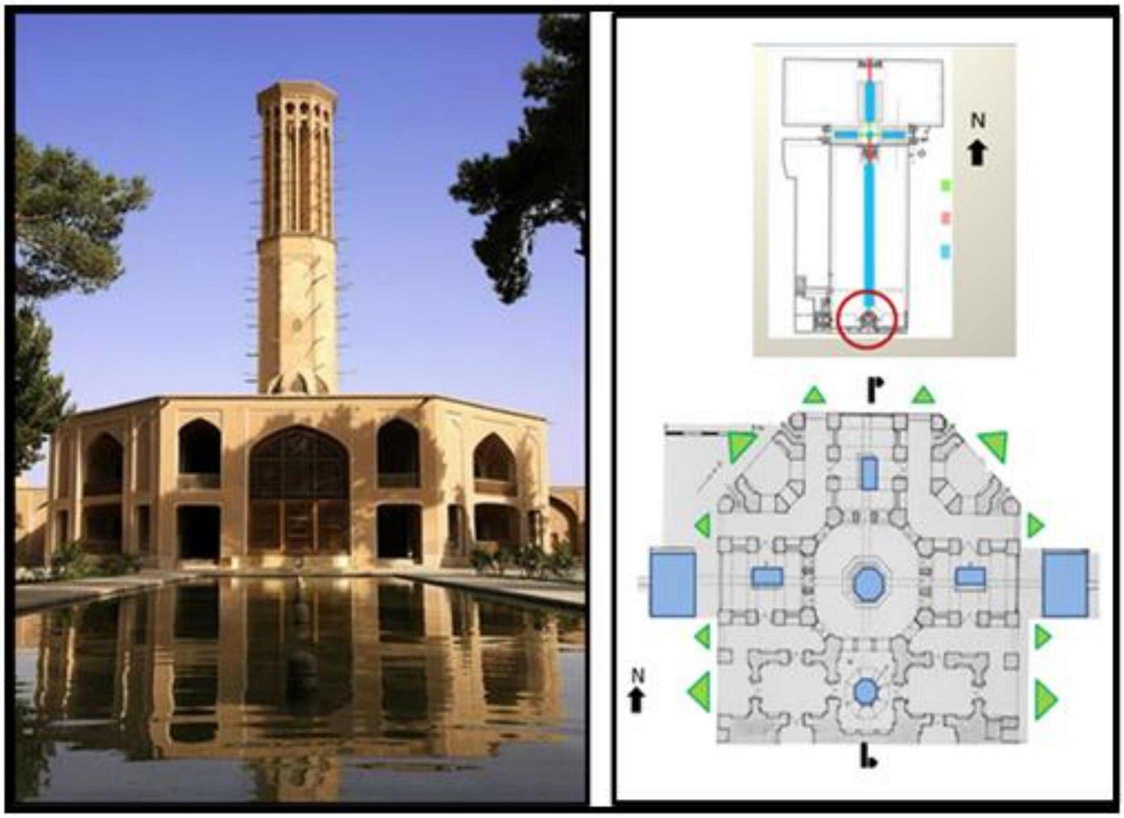


Figure 3-14: Wind Catcher Building, Yazd, Dowlat Abad Garden [65](Left), the Wind Catcher Building Location and Plan [64](Right)

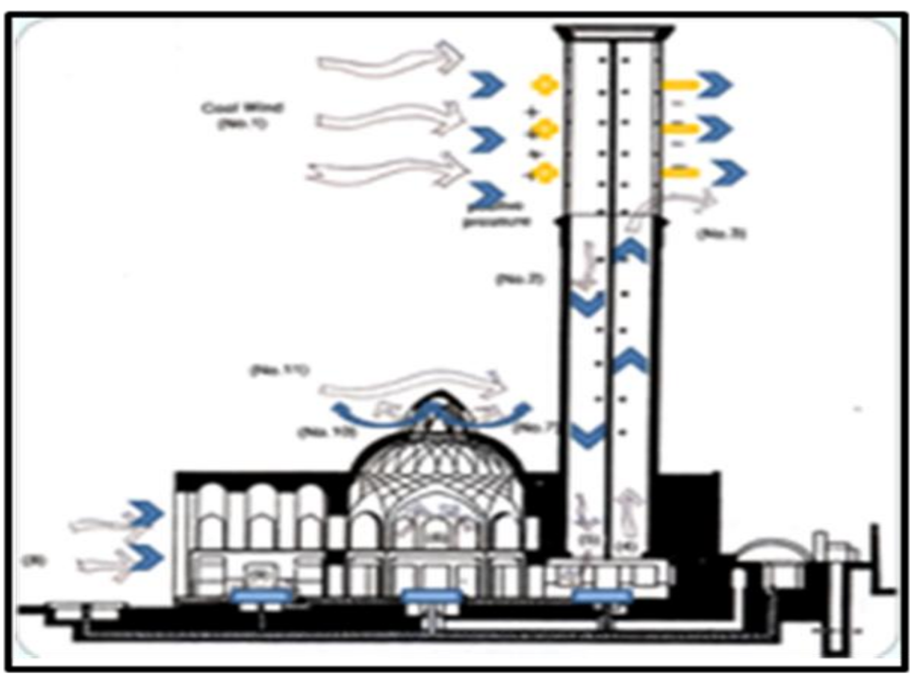


Figure 3-15: The Wind Catcher Building Section [64]

3-4-5-2. Typical House, Tabas, Iran

Residential buildings in the cities of this region follow almost the same architectural pattern. Dwellings are completely introverted and they have very little distinctive features on the outside and all are oriented to a north-south direction. Different parts of a typical house encompass a courtyard with small gardens and a pool. All spaces in a house face the courtyard, as demonstrated in Figure 3-16 (left), and they have windows that open to it. The vegetation, the small pool, and the mostly shaded courtyard, help create a micro climate with comfortable conditions in the heart of the hot and dry desert climate. The main design principle is based on seasonal migrations within the house. The northern sector, which has windows facing the south can absorb maximum amount of heat from the sun and is suitable for living during the winter time (shown in Figure 3-17). The southern part, which has windows facing the north, is completely shaded and is most suitable for the summer time (also see in Figure 3-17). As shown in Figures 3-16 (right) and 3-18, one or more wind catchers on the top of summer-living quarter provide natural ventilation during the hot summer days. At the basement level, there is a cellar that allows the occupants to keep foods cold and safe in the summer time. The temperature in these cellars is sometimes 20° C lower than outside temperature [66] and a canal that is connected to the wind catchers keeps them properly ventilated. Wind catchers play a crucial role in providing thermal control and fresh air through capturing cool breezes at higher levels and also pulling the air into the building. For these fully closed houses subjected to hot and sandy winds, wind catchers are the only feature that provide them with proper ventilation.

Figure 3-16: Courtyard in a Typical House, Tabas, Iran [67](Left), Wind Catchers on top of Summer Living Quarter [63] (Right)

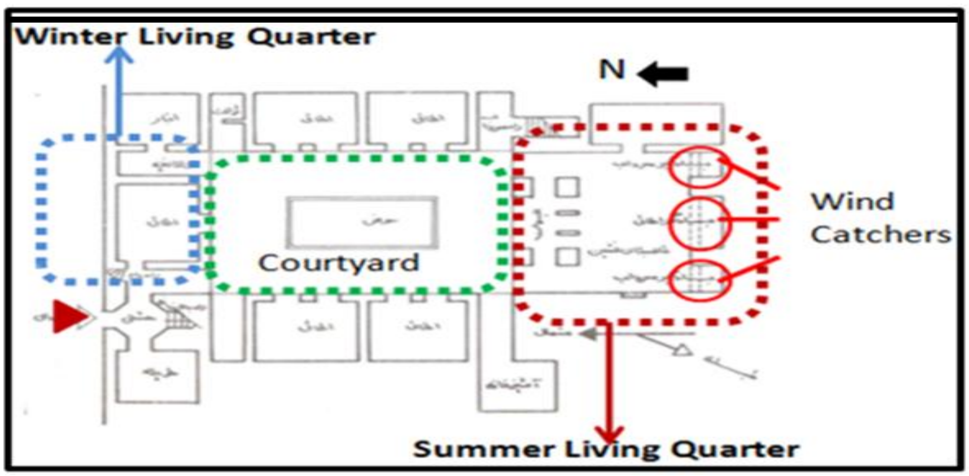


Figure 3-17: A Typical House Plan, Tabas, Iran (Map [57])

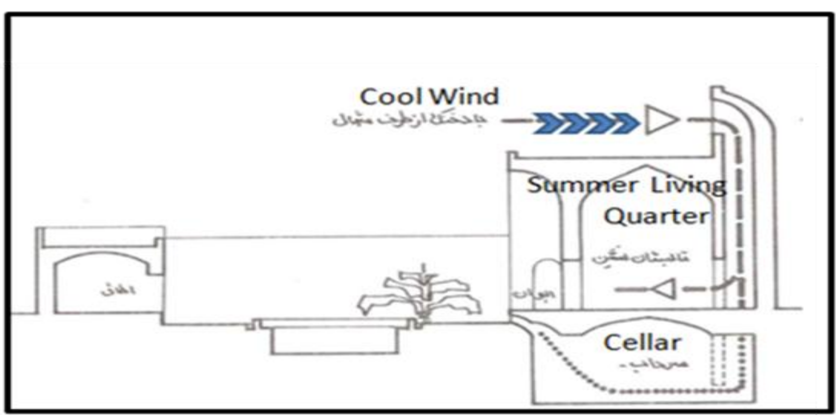


Figure 3-18: A Typical House Section, Tabas, Iran (Map [57])

3-4-5-3. Boroujerdiha House, Kashan, Iran (1875 [66])

Boroujerdiha House, illustrated in Figures 3-19, is a mansion built in 1875, which is located in the city of Kashan, Iran. This house has a 65 'x 98 ' courtyard, shown in Figure 3-19 (right), and has a total area of 32,000 sq ft [68], and is significantly larger than the typical house explained above. That being said, the basic architectural principles are very similar between the two. The main parts of the house consist of sectors for summer and winter living, an elaborate courtyard with gardens and a large pool, big cellars under the two sectors of the house, and three wind catchers for ventilation. In addition to these regular components, this house has a distinguishing element, illustrated in figure 3-20 (left), which makes it different from the other houses: As previously mentioned, the design of wind catchers was a way to demonstrate the owner's social class. Since this house belonged to a rich merchant, this element was built to represent the house occupants' social status. On the top of the dome shape ceiling of the summer living quarters, shown in Figure 3-20 (right), there is a unique complex of openings. This feature plays a significant complementary role in the natural ventilation by harvesting the cool winds in all directions and also exhausting the stale inside air through the stack effect. The summer-living quarter and the basement level under it, including the cellars and some living rooms, are ventilated using the wind catcher. The ventilation pattern is demonstrated in Figure 3-21. A network of horizontal and vertical canals allows winds captured by wind catchers to be conducted into the different underground spaces. The cellars under the winter-living quarter, shown in Figures 3-22 (right) and 3-23 (right), can be ventilated using the wind catcher on top of this sector. The ventilation circulation is demonstrated in Figures 3-22 (left) and 3-23 (left).

Figure 3-19: Boroujerdiha House [69] (Left), Boroujerdiha House's Courtyard [68] (Right)

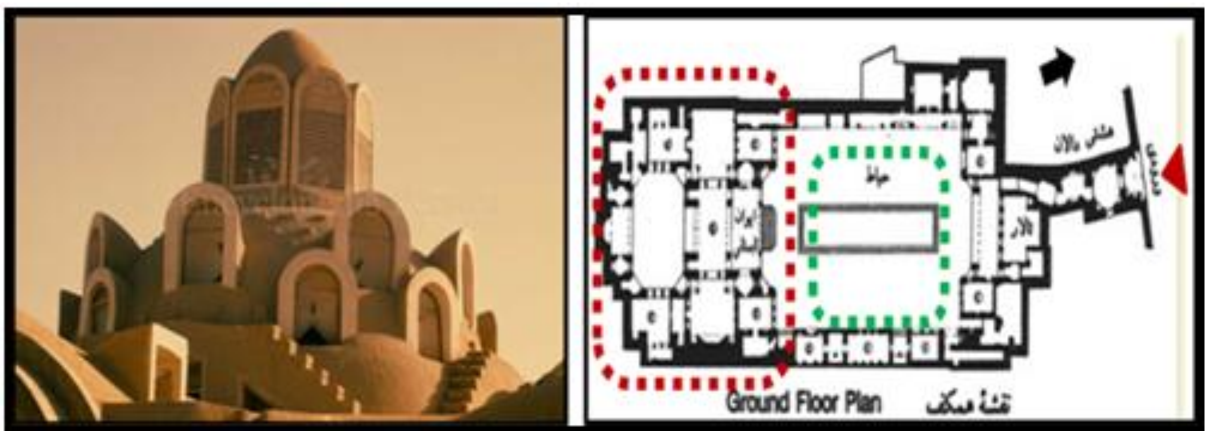


Figure 3-20: Ventilation Element on Top of the Summer-Living Quarter [70] (Left), Summer-Living Quarter (Map [71])(Right)

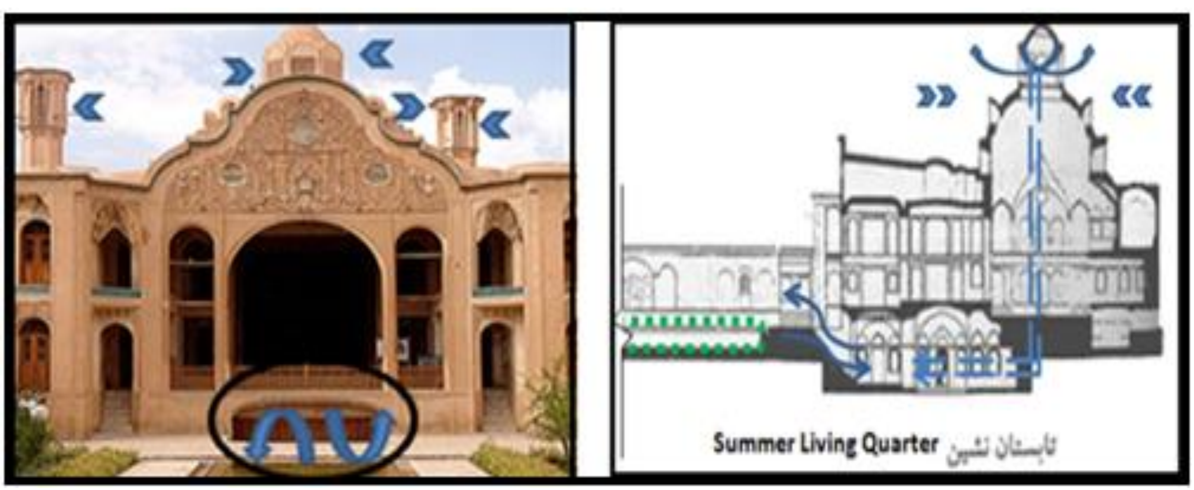


Figure 3-21: Basement Ventilation in the Summer-Living Quarter (Photo [69]) (Left), Ventilation through Element on Top of Summer-Living Quarter (Map [71]) (Right)

Figure 3-22: ventilation of Cellars under Winter- Living Quarter (Photo [70]) (Left), Winter-Living Quarter [70](Right)

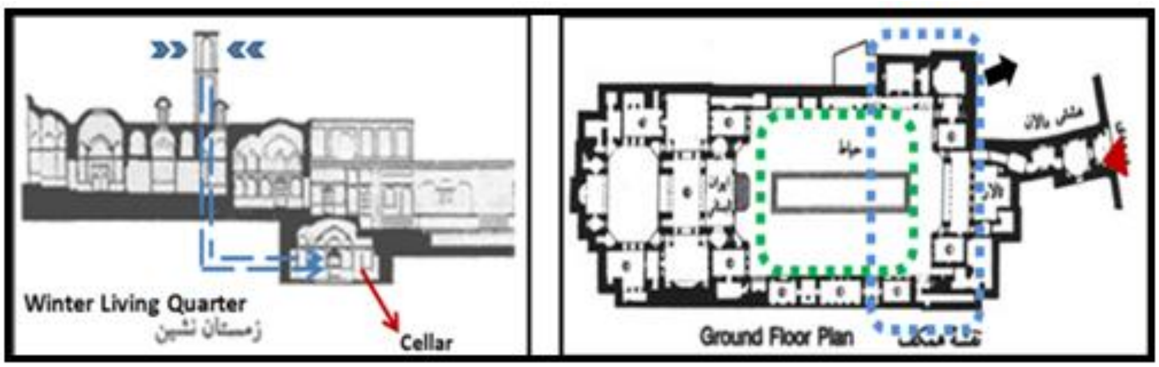


Figure 3-23: Ventilation of Cellars under the Winter-Living Quarter (Map [71]) (Left), Winter-Living Quarter (Map [71])(Right)

3-4-5-4. Agha Bozorg Mosque and Seminary, Kashan, Iran (1848 **[72])**

The Agha Bozorg Mosque in the city of Kashan, is a complex that consists of a mosque at the upper level and a seminary for religious studies at the basement level. As demonstrated in Figure 3-24 (left), the distinguishing feature of this building is a courtyard at the basement level, where all seminary chambers face it. The deep courtyard with the garden and the pool creates a comfortable micro climate for seminary chambers that are using the thermal effect of ground shelter. In the northern part of the building there are two big halls for prayers, shown in Figures 3-25, which are called Shabestan. The Shabestan at ground floor level is for winter time and the one at basement level is for summer time [73]. Two wind catchers, identified with circles in these Figures as well as in Figure 3-24 (right), capture the breezes at higher levels and conduct them into the summer-Shabestan at basement floor. At the top of southern wall of summer-Shabestan, there are openings, shown in Figure 3-26 (left), toward the courtyard. These openings act as an exhaust system for the stale air of the underground level Shabestan. The ventilation pattern is demonstrated in Figure 3-26.

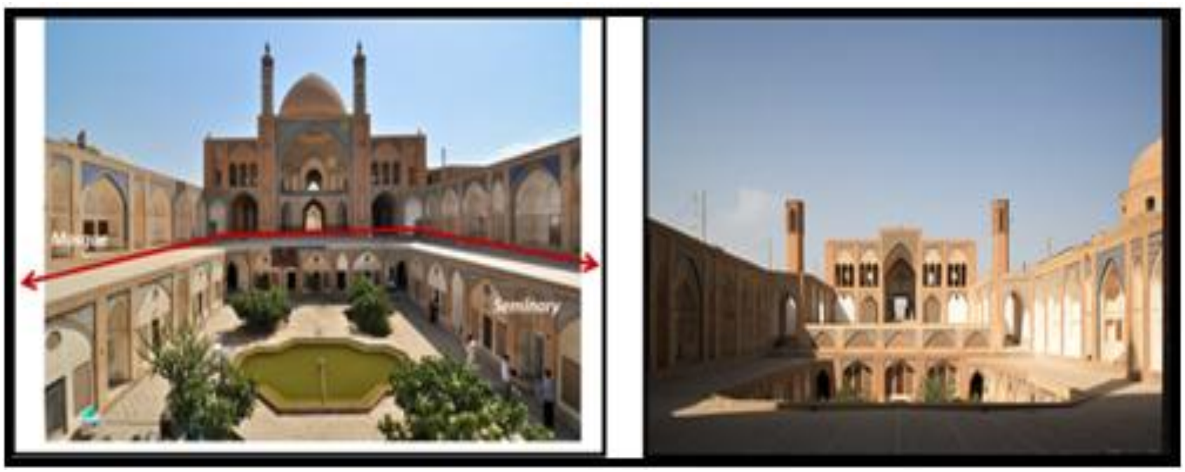


Figure 3-24: Seminary, Mosque, and Courtyard of Agha Bozorg Mosque Complex (Photo [74]) (Left), Wind Catchers at Northern Sector [72] (Right)

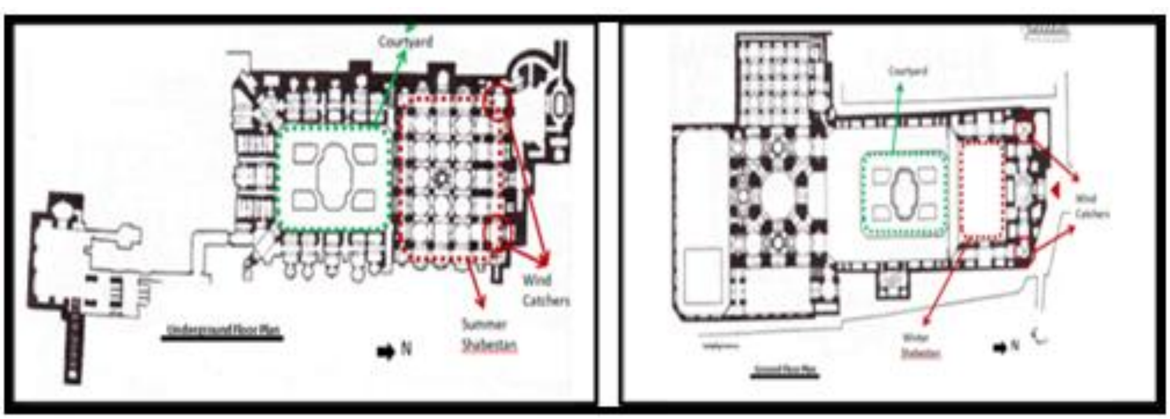


Figure 3-25: Underground Floor Plan (Map [71]) (Left), Ground Floor Plan (Map [71]) (Right)

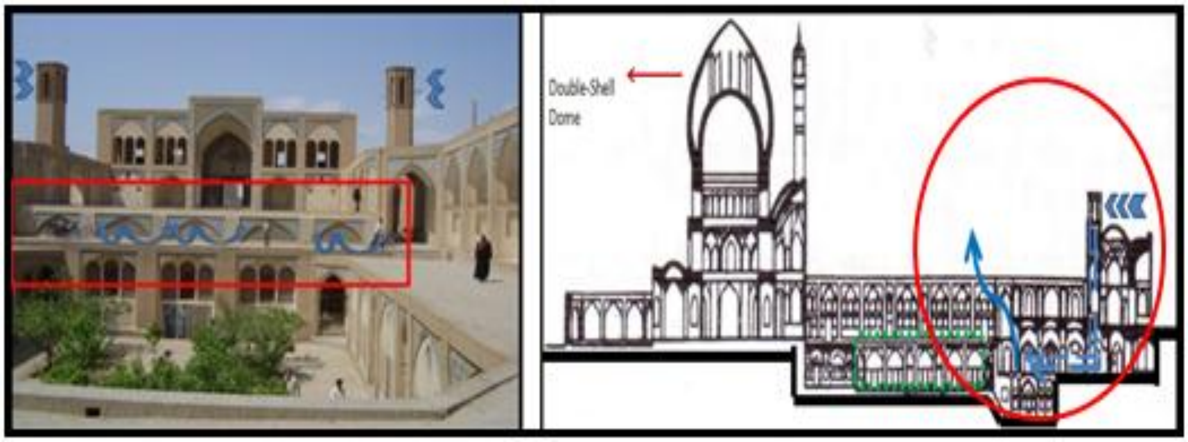


Figure 3-26: Openings toward Courtyard (Photo [72]) (Left), Ventilation at Northern Sector (Map [71]) (Right)

3-4-5-5. Water Reservoir with six Wind Catchers, Yazd, Iran (1838 [75])

A water reservoir, in Persian called Ab-anbar, is one of the structures developed in Iran as part of a water management system. Water was stored in private and public cisterns during the rainy season to be used in the hot and dry seasons. This structure consists of a big waterproof cistern, underground access corridors, sometimes one or two cool rooms for resting, and a number of wind catchers for ventilation. Proper ventilation is essential when massive amounts of water are being stored in one place for a prolonged period of time. Therefore, the number of wind catchers on top of these structures is more than the other buildings of the region. In some of these structures, the architects placed a few rooms for the resting of tired travelers in hot seasons. The temperature in these rooms is significantly lower than the outside. The Ab-anbar with six wind catchers in Yazd, illustrated in Figure 3-27 (left), is the most famous one. As shown in Figure 3-27 (right), six multi-sided wind catchers provide high rates of ventilation above the huge cistern. This was a public water reservoir and two long stairways provide access to the cistern from the sides.

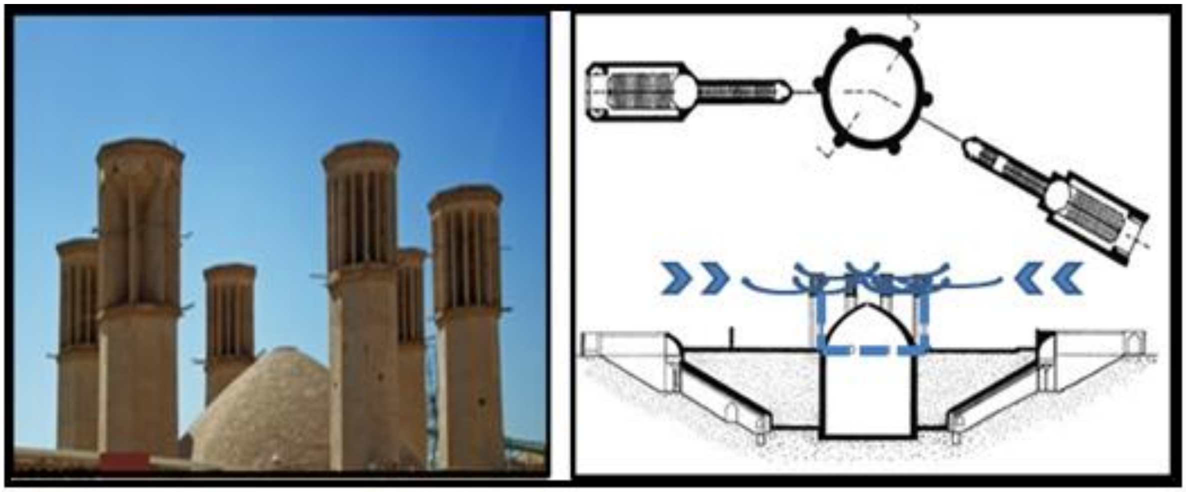


Figure 3-27: Water Reservoir with Six Wind Catchers, Yazd, Iran [76] (Left, Ventilation through Wind Catchers (Map [77])

3-4-5-6. Bagh-e Mosala Water Reservoir, Nain, Iran (18th Century [78])

Nain is one of the Iran's desert region cities and is known as the city of water reservoirs. In one side of a traditional garden in this city there is a public water reservoir called Ab-Anbare Mosala, shown in Figure 3-28, with its construction dating back to the eighteenth century[77]. Two four sided wind catchers draw fresh air into the cistern and one octagonal shape wind catcher exhaust the humid air to the outside. The location of wind catchers and ventilation patterns are shown in Figure 3-29.

Figure 3-28: Bagh-e Mosala Water Reservoir [79]

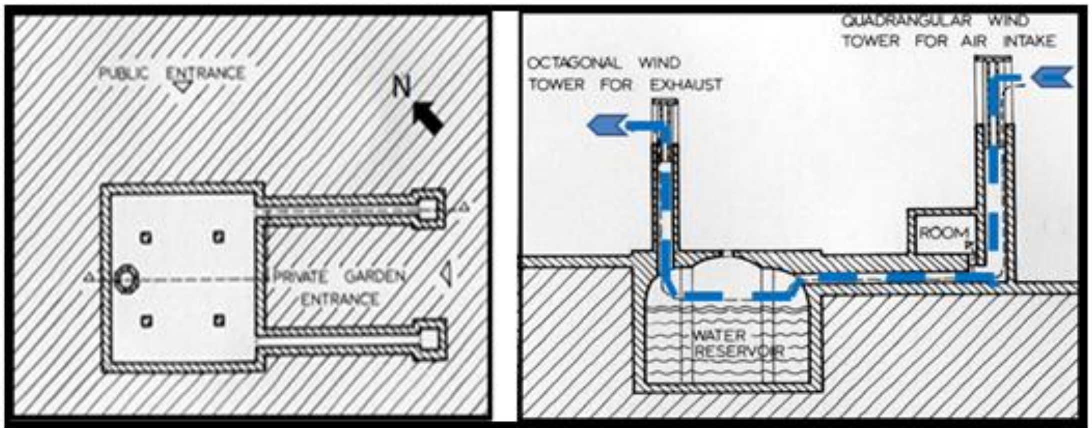


Figure 3-29: Bagh-e Mosala Water Reservoir, Plan [80] (Left), Bagh-e Mosala Water Reservoir, Section (Map [80]) (Right)

3-4-5-7. Discussion

The cases presented above are varied in categorization from small dwellings to public places and even non-residential constructions. They have different ventilation requirements, with wind catchers playing a key role in providing essential air conditioning in hot and dry climates. This vertical element has shown to be a reliable device to ventilate buildings with different applications. This distinguishing structure of vernacular architecture needs to be reconsidered as a strong strategy to help solve some big challenges in the ventilation industry. The purpose of this thesis is to prove that one of the most energy demanding facilities in the field of ventilation, i.e., IT rooms, can utilize this system to minimize or eliminate the energy they use for cooling. It is possible that this green solution inherited from the past can solve our modern problems with virtually no destructive environmental footprints.

3-5. Modern Wind Catchers

One important approach to improve the sustainability of buildings in the recent decades is the use of natural ventilation. As traditional wind catchers have proven their efficiency, modern designs of wind catchers have integrated the principles of old ones with modern technology to provide effective natural ventilation in new buildings. The new devices vary from modified traditional forms of wind catchers to pre-fabricated ventilation units (sometimes called commercial wind towers [81]), such as Monodraught company products.

3-5-1. Modern Structural Wind Catchers

The modern wind catchers utilize the principles of their ancestors and as architectural elements are integrated with building structures to provide natural ventilation. In recent decades due to concerns such as global warming, environment pollution, fuel resource depletion, and energy costs, air conditioning of buildings has become a major issue from sustainability point of view. As Durwood Zaelke, president of the nonprofit Institute for Governance and Sustainable Development (IGSD) in Washington, DC mentions, part of the answer is returning to a design mindset that was prevalent before the advent of air conditioning [82]. Mick Pearce, the Zimbabwean architect of the Eastgate Shopping Centre in Harare, Zimbabwe, asserts that mechanical air conditioning has allowed architects to design buildings based on formal concepts without any response to the natural environment; and that they should design buildings whose forms are shaped by a scientific understanding of the natural environment surrounding the building and not by purely sculptural shapes [82]. Following these concepts has resulted in the construction of buildings that successfully show the implementation of the old strategies in modern buildings. The Torrent Research Centre of Ahmadabad, India, illustrated in Figure 3-30, is one of these buildings. The wind-catching intake towers pull in air and cool it by diverting it through a fine mist. The cooled air descends through an open central corridor and is then drawn into different spaces on each level. The hot air is exhausted through towers around the perimeter of the complex [82].

Figure 3-30: The Torrent Research Centre of Ahmedabad, India [82]

Qatar University, in Doha, illustrated in Figure 3-31, is one of the other modern buildings that utilizes the old ventilation devices. The octagonal modules topped with rotated square, four-sided wind catchers have formed the buildings of the university. All rooms, shown in Figure 3-32, are arranged in a compact organization around a series of internal courtyards. As it is demonstrated in Figure 3-33, vertical panels direct wind down into the building so the stale air can exit through smaller adjacent rooms and porches on the opposing side [58].

Figure 3-31: Qatar University, Doha [83]

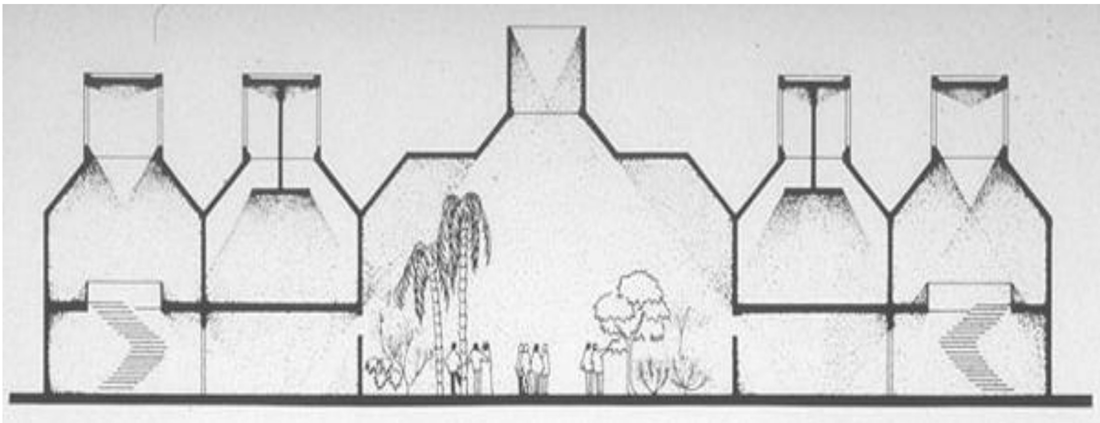


Figure 3-32: Rooms around Internal Courtyards in Qatar University [83]

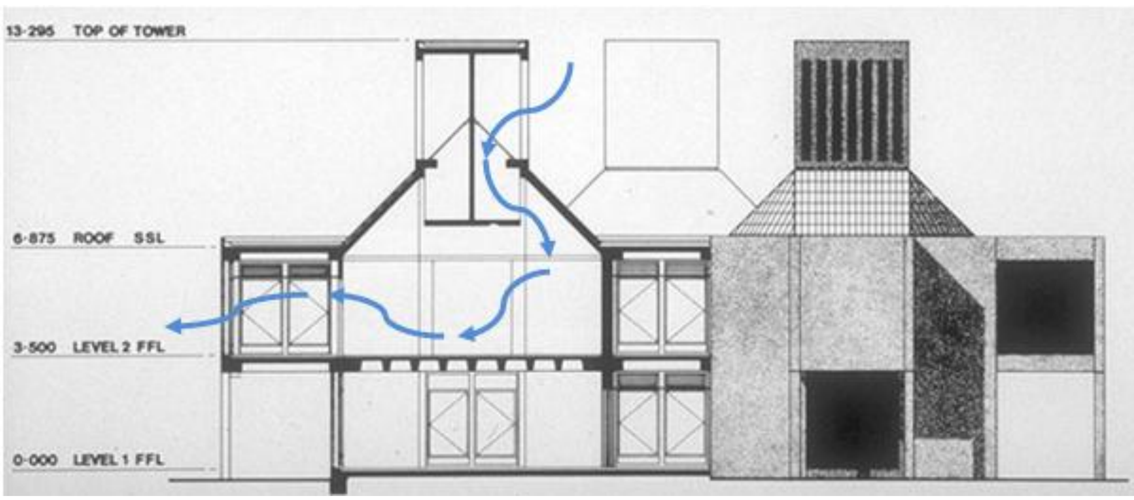


Figure 3-33: Air Circulation in the Building, Qatar University (Map [83])

3-5-2. Commercial Wind Towers

Combining the ancient green strategies and modern technologies has resulted in a new generation of wind catchers mainly known as Monodraught products; some models of which are illustrated in Figure 3-34. Monodraught wind catchers typically have automatic controls and the mechanism allows for the control of temperature, humidity, airflow, noise level, and CO_2 depending on the requirements [41]. Compared to the traditional wind catchers, modern wind towers are usually more compact and smaller in size. As it is shown in Figure 3-35, the device is installed on top of a structure to catch the wind at roof level and channels fresh air through a series of horizontal louvers into the building. This happens under the action and re-action of positive air pressure and negative air pressure at the opposite side, which extracts the stale air out of the room [81]. Volume control dampers at the base of the system at ceiling level control the amount of air flow passing through the device [84]. In the construction of the St Annes School in Haute Valley, Jersey, all aspects such as heating and ventilation are designed to have a more natural approach to maximize fresh air with the least environmental footprints. A series of Monodraught wind catchers on the roof, illustrated in Figure 3-36 provide ventilation for the school. This building received a plaque for LEED silver certification in 2013 [85].

Figure 3-34: A Number of Monodraught Wind Catchers [84]

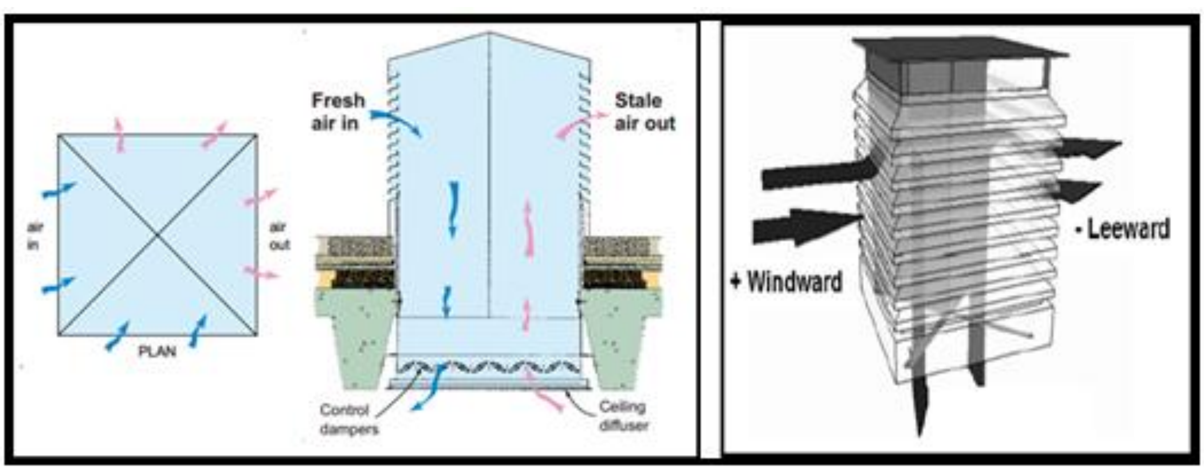


Figure 3-35: The Modern Wind Catcher Function [84] (Left), Air Flow Diagram in Modern Wind Catcher [86](Right)

Figure 3-36: St Annes School in Haute Valley, Jersey [84]

Another type of pre-fabricated wind catchers is called wind cowls. Wind cowls on the roof of the BedZED (Beddington Zero Energy Development) project in Hackbridge, London, UK, illustrated in Figure 3-37, are distinctive examples of this type of wind tower. These devices which won the Air Movement Product Award of the year in 2002 [87], with a weather vane have the ability to rotate so that the inlet duct faces the incoming wind at all times and the outlet duct, separated from inlet duct, discharges stale air at low pressure area [88] . The schematic of wind cowl functionality is demonstrated in Figure 3-38.

Figure 3-37: BedZED Project Wind Cowls [89]

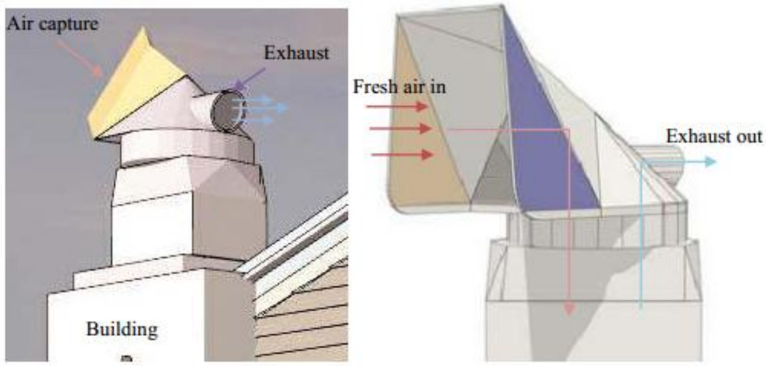


Figure 3-38: A Wind Cowl Function [90]

On the roofs of the Jubilee Campus buildings at the University of Nottingham, UK, there are rotating wind cowls as illustrated in Figure 3-39. These 5m tall aluminum-clad cones sit on the top of the air-handling units (AHUs) and are always rotating around to face the opposite of the prevailing wind. Therefore, they assist the mechanical air conditioning system by lowering the energy for fan rotations. The air rises up in the stair tower and is exhausted through the directional wind cowls. The complex won the Building Award of the British Construction Industry Awards in 2000 [91]. Air extraction in this complex is shown in Figure 3-40.

Figure 3-39: Cowls on the School of Management and Finance[87]

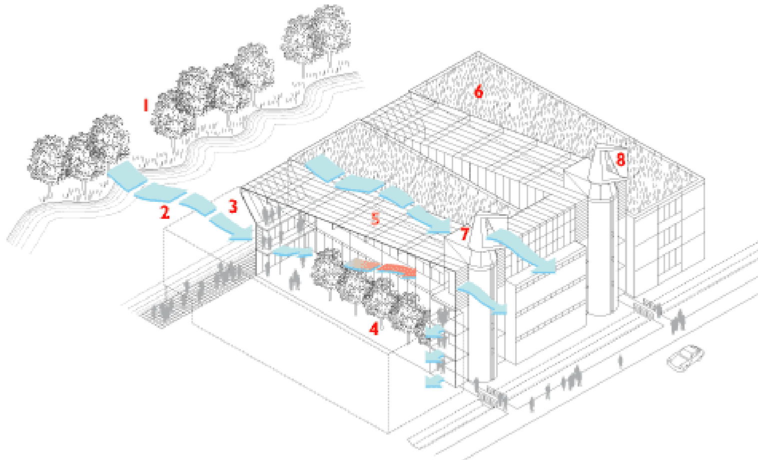


Figure 3-40: Air Extraction from Wind Cowls, Jubilee Campus, University of Nottingham [92]

Figure 3-41 shows the Bluewater shopping center designed by Battle McCarthy Consulting Engineers, in Kent, UK. This center is the Europe's largest retail and leisure complex [93]. 39 rotating wind cowls, featured in Figure 3-42 (left), provide natural ventilation for the building. The cowls are designed to rotate into the wind. In the event of a fire, they are rotated away from the wind and act as chimney to extract smoke out of the building. The natural ventilation system is integrated with mechanical monitoring to control the temperature and humidity as well as the CO_2 levels [94]. Figure 3-42 (right) shows the inside of the building and openings under the wind cowls.

Figure 3-41: Bluewater Shopping Center, Kent, UK [95]

Figure 3-42: Wind Cowl [96] (Left), Inside the Mall [97] (Right)

3-6. Conclusion

Although the concept of wind catcher has been commercially applied in the UK for the past 30 years, wind catchers are for the most part ignored in designing new modern buildings[39]. Despite this neglect, wind catchers are still considered as one of the most important passive airflow management techniques. The exclusive attribute of a wind catcher is that it can provide appropriate ventilation for semi-closed and even closed spaces within the building. This capability makes the wind catcher a potential solution for providing fresh air supply in compact urban fabrics. It can also play a significant role in providing proper ventilation for buildings such as data centers that according to strict technical codes should be closed spaces. The idea of utilizing the wind catcher for different spaces in different climate conditions should be more practiced by researchers. Looking at the past and considering valuable old experiences may open gates that can help us solve some of the challenging issues of modern life. This thesis focuses on studying the application of wind catchers in the design of data centers, with a constantly high heat load, in the climate conditions of Moscow, Idaho, U.S.A.

Chapter 4: Moscow, Idaho, U.S.A. Climate

4-1. Geography of Moscow

Idaho, shown in Figure 4-1(left), is a mountainous state in the northwestern region of the United States. It is surrounded by the states of Washington, Oregon, Nevada, Utah, Wyoming, Montana, and the Canadian province of British Columbia [98]. As shown in Figure 4-1 (right), Moscow is a city in the northern part of Idaho situated along the Washington and Idaho border. The city of Moscow is located on the eastern edge of the Palouse region of north central Idaho in the Columbia River Plateau. East of the city is a valley within the mountains of the Palouse Range to the northeast and Paradise Ridge and Tomer Butte are at the southeast of the city. Paradise Creek, with headwaters on Moscow Mountain to the northeast, passes through Moscow and eventually drains into the Snake River and Columbia River on its way to the Pacific Ocean [99]. In accordance with the United States Census Bureau, the city has a total area of 6.85 square miles [100].

Geographic coordinates of Moscow are:

- Latitude: 46°43′56″ N
- Longitude: 117°00′00″
- Elevation above sea level: 778 m = 2,552 ft [101]

4-2. Temperature

The temperature maps of the United States published by PRISM Climate Group for the maximum average temperature in January (winter) and July (summer), illustrated in

Figure 4-2, shows that Moscow has a deviation maximum temperature of 34-38ºF in winter and 80-84ºF in summer [104]. The climate data reported from Pullman-Moscow Regional Airport shows that this region has a continental climate with dry warm summers. As it is demonstrated in Figure 4-3, over the course of a year, the temperature varies from 25 ºF to 85 ºF and is rarely below 10 ºF or above 94 ºF. June 26 to September 9 is the warm season with an average daily high temperature above 75 ºF. July 30 is the hottest day of the year with an average high of 85 ºF and low of 54 ºF. November 13 to February 27 is the cold season with an average daily high temperature of 44 ºF. December 28 is the coldest day of the year with an average low of 25 ºF and high of 34 ºF. Figure 4-4 shows the fraction of time in the year spent in various temperature bands [105]. The charts depicted in Figures 4-3 and 4-4 as well as the air-side free cooling hour map provided by the Green Grid (Chapter 2, Figure 2-4) indicate that round year utilization of outside air for the cooling of a data center is an efficient option in the Moscow, Idaho region.

Figure 4-1: Idaho State Location in the US [102] (Left), Moscow Location in Idaho State[103] (Right)

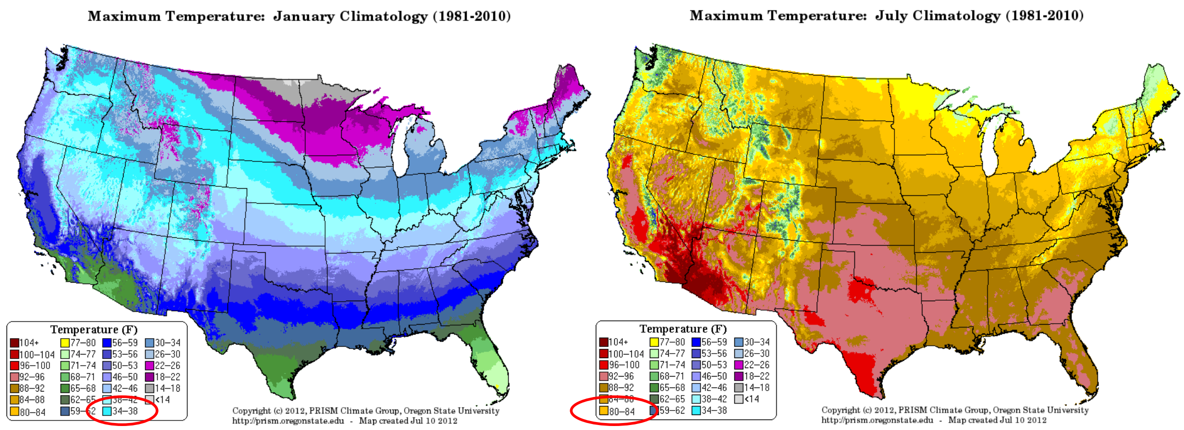


Figure 4-2: Maximum Average Temperature in January (left) and July (right) [104]

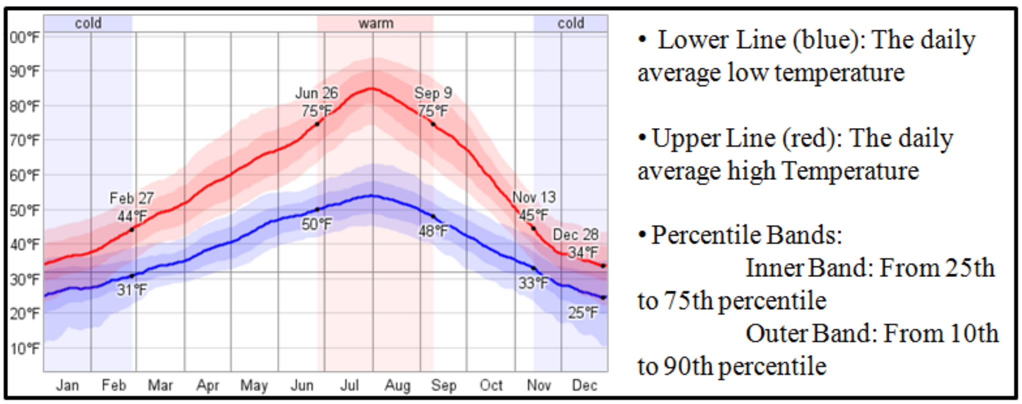


Figure 4-3: Daily High and Low Temperature [105]

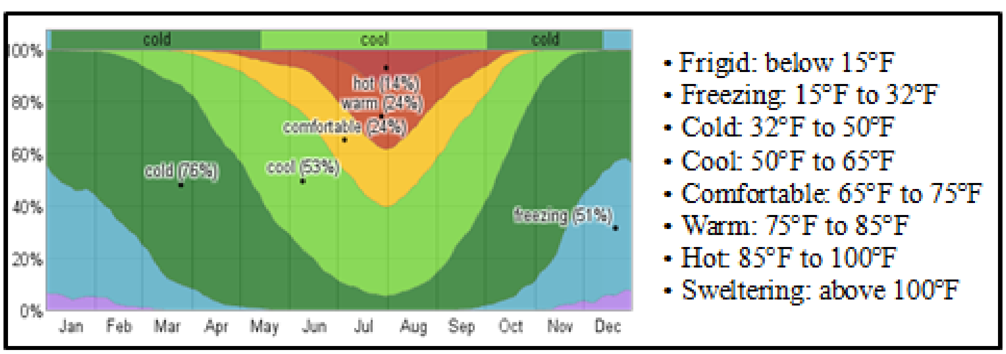


Figure 4-4: Fraction of Time Spent in Various Temperature Bands [105]

4-3. Humidity

The map of the climate zones of the United States, shown in Figure 4-5, indicates that Moscow is located in semiarid steppe climate zone. The mean relative humidity map, illustrated in Figure 4-6, shows that this city is located in the zone with 56-65 percent mean humidity. As shown in Figure 4-7, over the course of the year, the relative humidity ranges from 29% to 97% and rarely drops below 16% and reaches as high as 100%. In August 4, the air is the driest with the relative humidity that drops below 35% and it is the most humid around November 28 exceeding 97%. The graph, illustrated in Figure 4-8, shows that over the course of a year, the dew point varies from 22 ºF to 56 ºF and is rarely below 8 ºF or above 64 ºF [105]. Based on the notes mentioned in chapter 2, humidity in data centers is not a key factor; small deviations in humidity still fall within the allowable ASHRAE ranges shown in Chapter 2, Table 2-2.

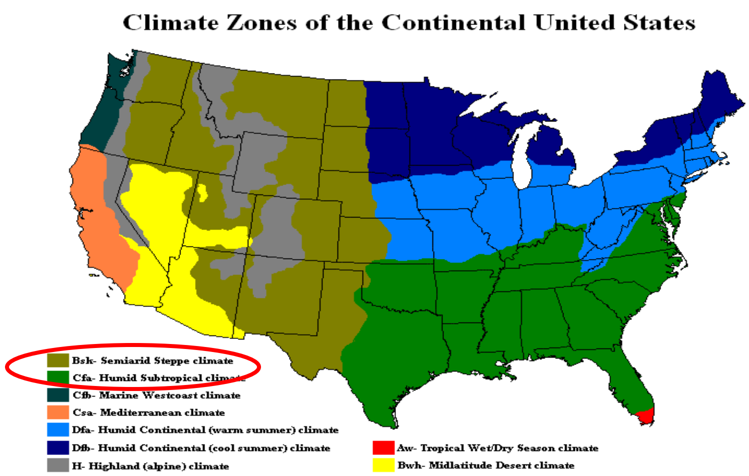


Figure 4-5: The Climate Zones of the United States Map [106]

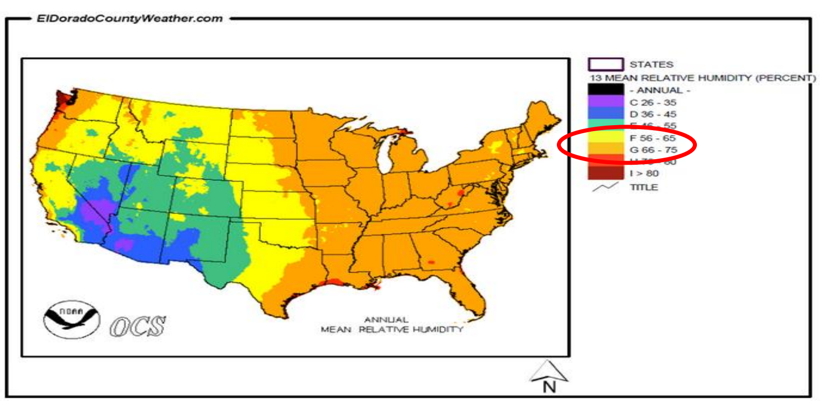


Figure 4-6: The Mean Relative Humidity of the United States Map [107]

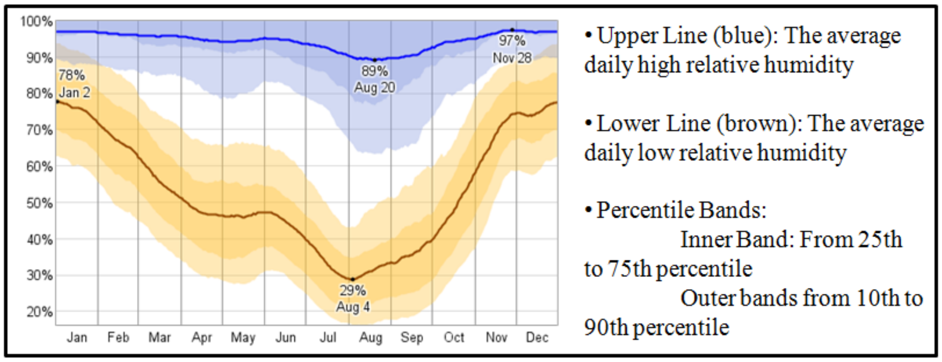


Figure 4-7: Relative Humidity [105]

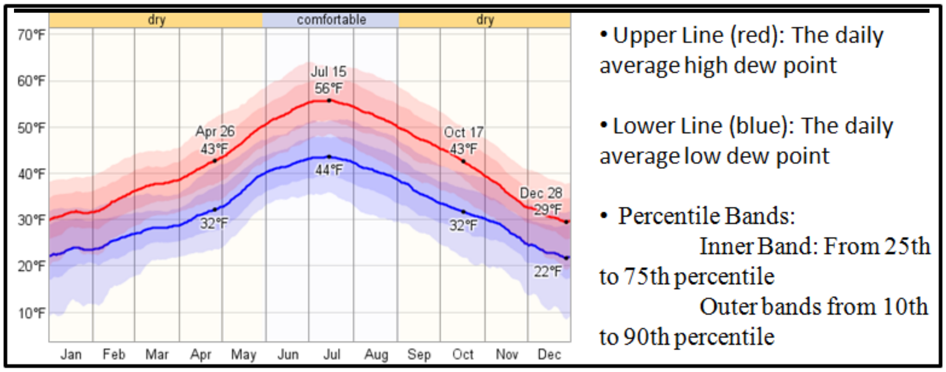


Figure 4-8: Dew Point [105]

4-4. Wind

The Figure 4-9 illustrates the annual average wind speed at a height of 30m for different parts of the United States. Moscow is located in the zone with an average wind speed of 4.0m/s or 8.9mph. In Moscow, as shown in Figure 4-10, over the course of a year, typical wind speeds vary from 0 mph to 15 mph and rarely exceed 24 mph. Around December 5, the highest average wind speed occurs, at which time the average daily maximum wind speed is 15 mph. Around July 16 the lowest average wind speed of 4 mph occurs, at which time the average daily maximum wind speed is 11 mph. In Figure 4-11, the fraction of time that winds blow from the various directions over the entire year is illustrated. The wind direction is mostly from east, west, and south west [105]. The chart of prevailing wind direction (Figure

4-12) based on the hourly data from 1992-2002, provided by Western Regional Climate Center, affirms this point [109]. In Figure 4-13, the fraction of time that winds blow from the various directions on a daily basis is demonstrated [105].

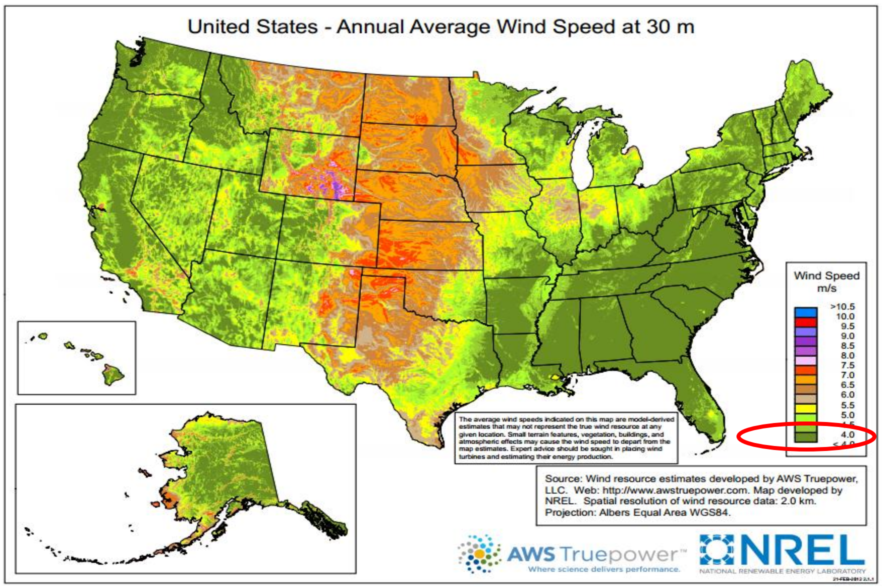


Figure 4-9: Annual Average Wind Speed at 30 m [108]

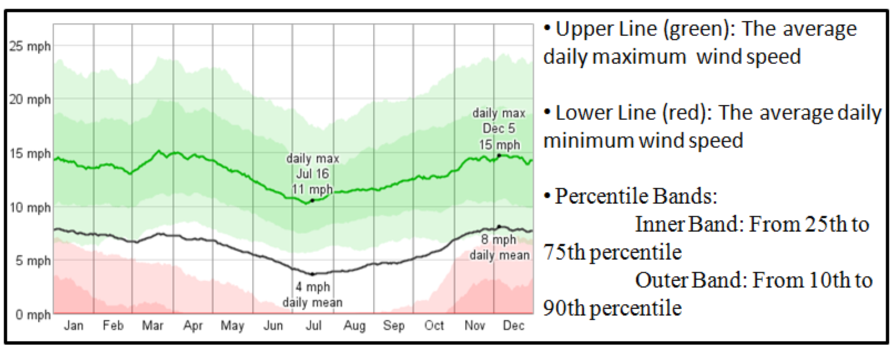


Figure 4-10: Wind Speed [105]

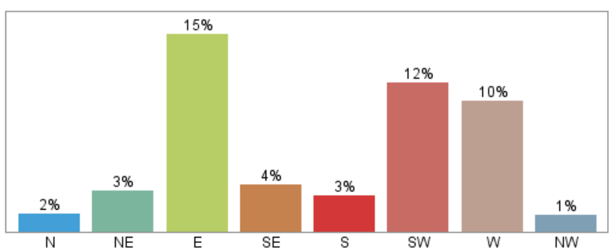


Figure 4-11: Wind Directions over the Entire Year [105]

STATION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
PULLMAN-MOSCOW AP, WA (KPUW)	E	E	E	SW	WSW	WSW	WSW	WSW	WSW	E	E	E	E

Figure 4-12: Prevailing Wind Direction [109]

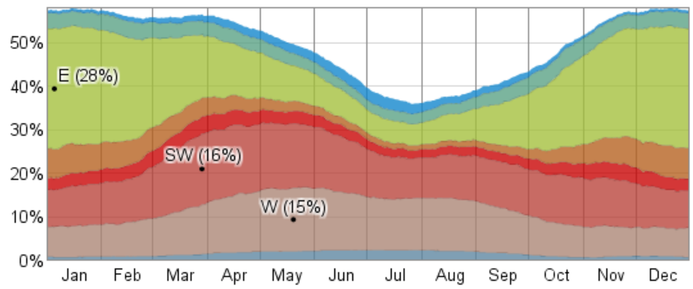


Figure 4-13: Fraction of Time Spent with Various Wind Directions [105]

The wind rose chart of Figure 4-14, provided by Idaho National Library, shows that most powerful winds, from 2003 to 2004, most of the time blow from east with an approximate 15 degree toward the north and also from west with an approximate 15 degree toward the south [110]. The wind persistency chart of Figure 4-15 shows that, from 1995 to 2004, surface winds are mostly from east and southwest [111].

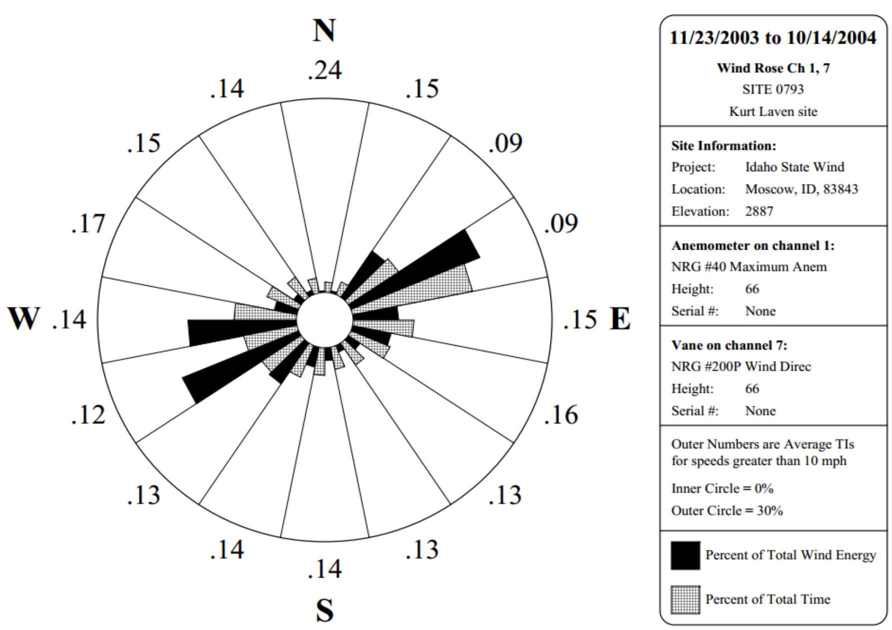


Figure 4-14: Wind Rose Chart [110]

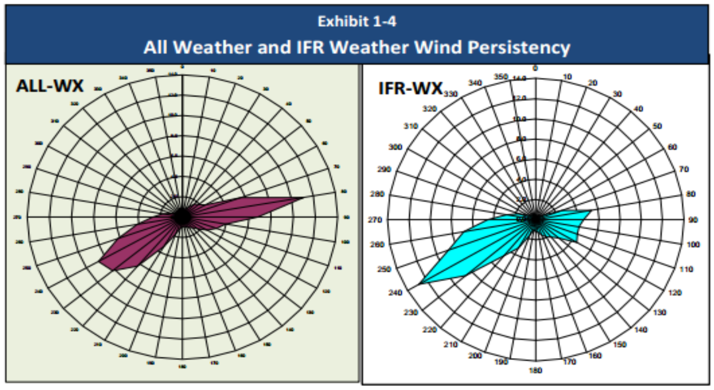


Figure 4-15: Wind Persistency Chart [111]

4-5. Are Wind Catchers Suitable for Moscow, Idaho?

As discussed in Section 3-4-5, the city of Yazd is called “The City of Wind Catchers” and these vernacular devices provide natural ventilation for the city. In this section, we study a comparison between Yazd and Moscow in terms of wind patterns in an effort to justify the application of wind catchers in improving the energy efficiency of data centers in Moscow.

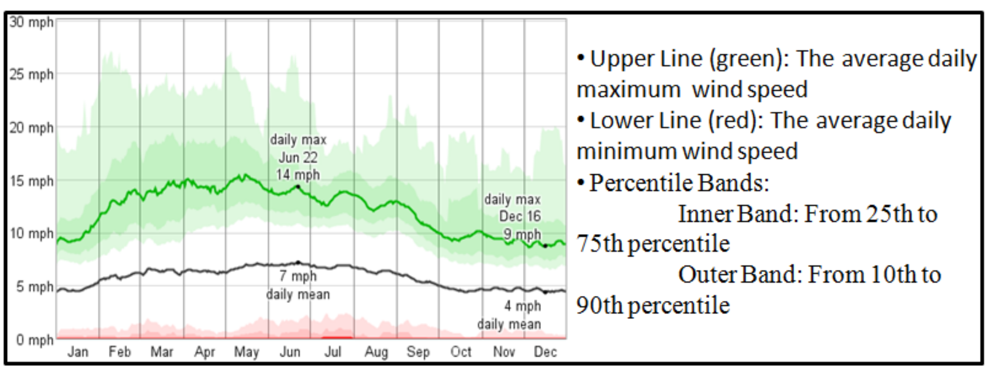


Figure 4-16: Wind Speed [112]

In Yazd, as shown in Figure 4-16, over the course of the year typical wind speeds vary from 0 mph to 15 mph and rarely exceeds 27 mph. Around June 22 the highest average wind speed occurs, at which time the average daily maximum wind speed is 14 mph. Around December 16 the lowest average wind speed of 4 mph occurs, and the average daily maximum wind speed is 9 mph [112]. In Figures 4-17 and 4-18, the fraction of time that winds blow from the various directions over the entire year and on a daily basis are illustrated, respectively.

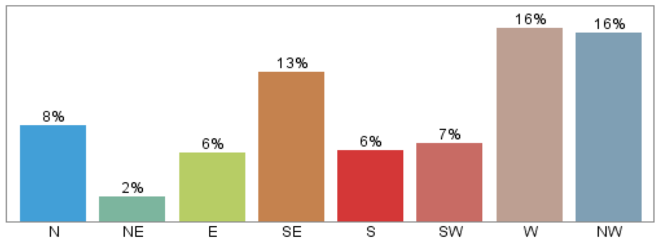


Figure 4-17: Wind Directions over the Entire Year [112]

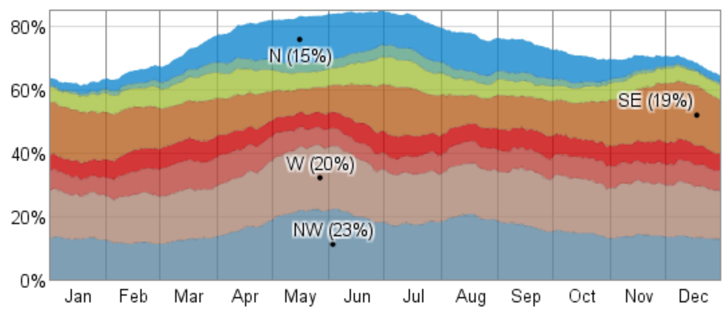


Figure 4-18: Fraction of Time Spent with Various Wind Directions [112]

Based on these graphs, although wind patterns in Yazd are different from those in Moscow in terms of directions and durations, the average wind speed in Moscow is slightly higher than that of Yazd. As mentioned in Section 3-3, wind is not the only natural force that impacts the operations of a wind catcher. The buoyancy/stack effect plays a major role as well. These points lead us to the conclusion that wind catchers can be utilized in Moscow for natural ventilation as effectively as it has been used in Yazd. Except for northeast, the wind blows effectively from all directions in Yazd, which shows why four-sided and multi-sided wind catchers work very well in this city. In Moscow, prevailing winds that affect wind catcher operations blow from east, west, and southwest. Therefore, a wind catcher facing the east with an approximate 15 degree orientation to the north and one facing the west with an approximate 15 degree orientation to the south (directions mentioned above) will be the best options. As it was discussed in the Section 3-4-4, with this arrangement, the openings are located at the highest pressure point, which are necessary for optimizing the performance of the wind catcher. For the optimal operation of an exhaust tower, its opening should be located at the lowest pressure point, which means an opening facing the north with a 15 degree orientation to the west. For the 2% of the time (Figure 4-11) that winds blow from the north, there are two approaches for the ventilation system. If the flooded system (Section 1-9) is used for air distribution, the solution is to allow a reverse ventilation cycle. That is, the incoming wind is captured by the wind catcher facing the north and is exhausted through the wind catcher with openings toward east and west. However, if a targeted or contained system (Section 1-9) is employed for air distribution, the reverse ventilation cycle will not work. The reason is that the air will be supplied directly into the hot aisles without fist passing through the computing equipment. Therefore, a monitoring and control system is required to close the north opening and a fan must be used to exhaust the intake air through a second opening on the north tower.

Chapter 5: A Simulation Study: Application of Wind Catchers as a Sustainable Solution for Data Center Thermal Management

As previously mentioned, the goal of this thesis is to investigate the application of wind catchers for the cooling of data centers in the Moscow, ID climate conditions. To carry out this study, we chose the "DesignBuilder" program as a tool to quantitatively measure the effects of using wind catchers to manage thermal conditions of a data center. DesignBuilder is software package for measuring and evaluating the energy consumption, carbon emissions, and lighting effects of a building. In this tool it is possible to model the building and receive environmental performance data based on Energy Plus dynamic thermal simulations. Lists of data for different templates such as activity, construction, or HVAC systems are included by default in this program [113]. To define external conditions during simulation, the Energy Plus formatted hourly weather data is used for a vast number of locations. For the United States, typical weather data includes WYEC2 and TMY3 [114] that are weather data sets used for simulating building energy performance released by ASHRAE and NREL (National Renewable Energy Laboratory) respectively [115].

The book "Sun, Wind & Light" [58] was used as the handbook for the wind catcher construction design. Principles and dimensions listed in the book formed the size and shape of the wind catchers we used in our simulation study. The climate data shown in chapter 4 and the data center heat load information mentioned in chapter 2 were used to complete the calculations of wind catcher sizes as suggested in "Sun, Wind & Light". There are also some general guidelines that must be followed when designing a wind catcher as the ventilation system for a given building. As explained in the next section, we also extended a graph in "Sun, Wind & Light" to show a more complete picture of the heat gain and wind speed data.

5-1. A Hypothetical Data Center Design

A building with a width of 4 meters, length of 6 meters, and a height of 3 meters, was presumed to be a data center in our simulation study. As mentioned in section 4-4, a wind catcher with two openings and a wind tower functioning as chimney are attached to the building. Below are requirements for the design of wind catchers listed in "Sun, Wind & Light" [58]:

- To rise above the layer of turbulence and drag, the inlets should be at least 8ft (2.4 m) above the height of surrounding buildings and obstructions.
- For wind catcher designs with openings in multiple directions, the openings in each direction should be sized to meet the building's heat load.
- The inlet from a single direction should be no larger than the cross-sectional area of the tower.
- The outlets should be about twice as large as the inlets.
- Steps to find the size of a wind catcher: The size of the wind catcher opening may be determined from the sizing graph illustrated in Figure 5-1. The size of opening required to remove building heat gain is a percentage of floor area, assuming a temperature difference of 3°F (1.7°C) between the inside and the outside. On the vertical axis there are different wind speeds that should be chosen based on the wind speeds of the building location. Then by moving horizontally, the curve for the building's rate of heat gain is intersected. A vertical drop from that point will indicate the size of the inlet as a percentage of the floor area.

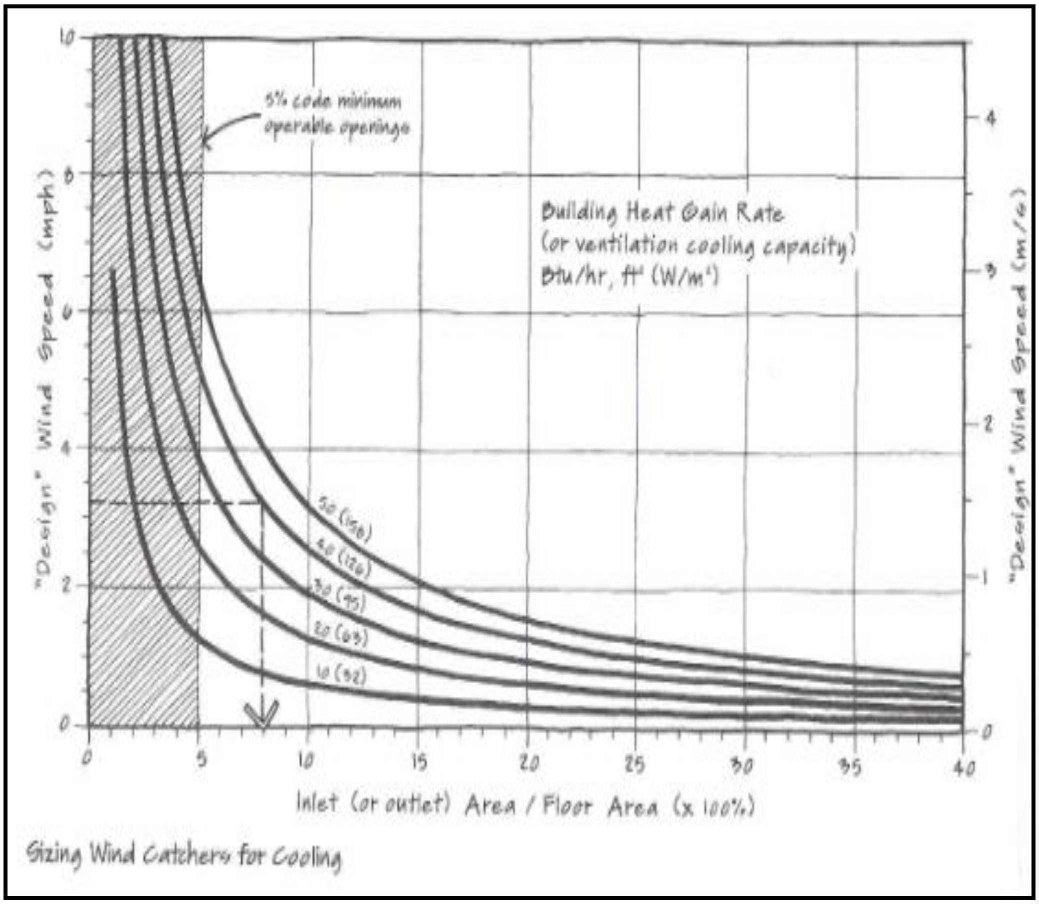


Figure 5-1: Sizing Wind Catcher Graph for Cooling [58]

As mentioned in chapter 2, the heat gain in a data center is 540W/m^2 while the maximum heat gain represented in the graph of Figure 5-1 is at 158W/m^2. Also, the highest rate of wind speed presented in Figure 5-1 is 10 mph while the highest average wind speed in Moscow, ID (Section 4-4) is 15 mph. In order to expand the heat gain and wind speeds to the ranges required for our simulation study, we have extended the curvature functions of Figure 5-1 by manual extrapolation. This extended function is shown in Figure 5-2.

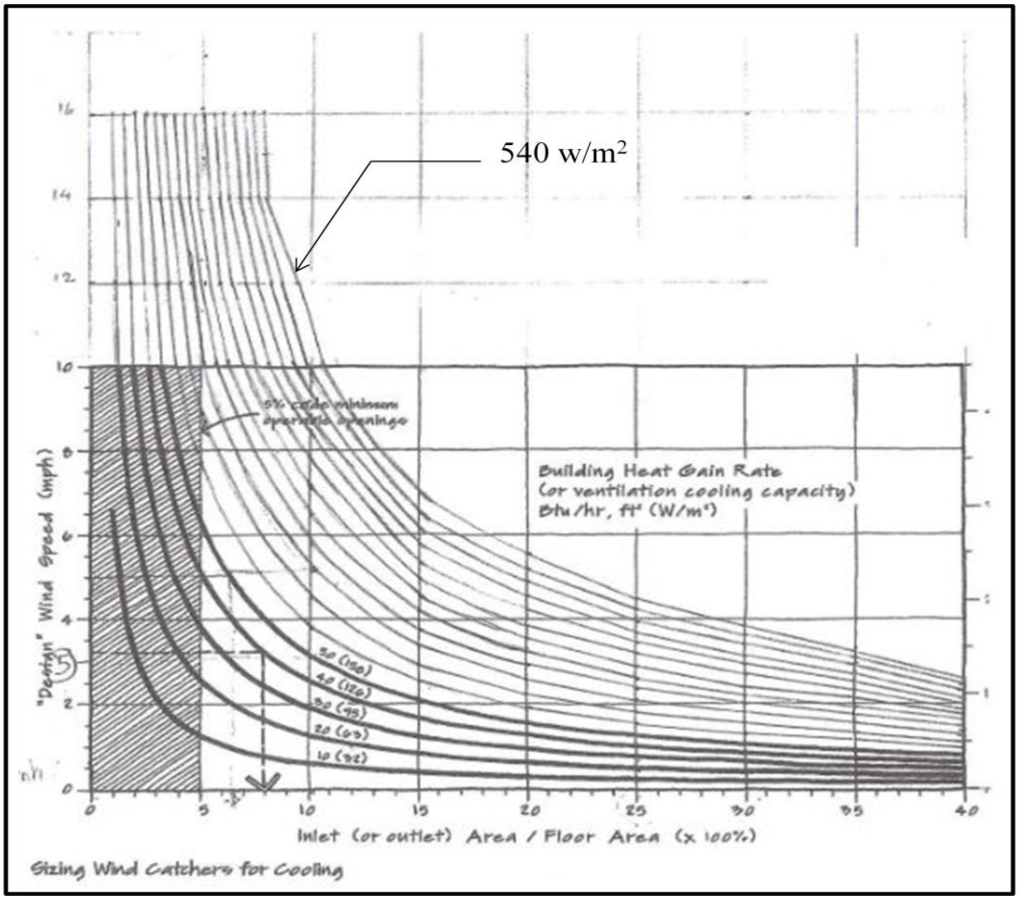


Figure 5-2: Completed Sizing Wind Catcher Graph

In section 4-4 it was shown that in Moscow, ID the average daily maximum wind speed varies from 11 mph to 15 mph and average daily minimum wind speed varies from 4 mph to 8 mph. By following the steps for finding the opening size of a wind catcher from Figure 5-2, we conclude that for wind speeds of 4, 8, 11, and 15 mph, the wind catcher opening sizes, as a percentage of the floor area, are 28%, 13%, 10%, and 8%, respectively. Therefore, the opening sizes of the wind catcher in different wind speeds for our hypothetical building with a floor area of 24 m^2 are listed below:

- At 4 mph: 28% floor area = 6.72 m^2
- At 8 mph: 13% floor area = 3.12 m^2

- At 11 mph: 10% floor area = 2.4 m^2
- At 15 mph: 8% floor area = 1.92 m^2

Since the equipment in a data center typically operate 24/7, an uninterrupted ventilation system is required as well. Therefore, the wind catcher should be able to remove the heated air in the facility at the critical condition, which is a minimal wind speed of 4 mph. As mentioned above, the calculations on the graph are based on the 3°F temperature difference (ΔT) between the inside and the outside. If ΔT is greater than 3°F, the openings may be smaller by multiplying the size from the graph of Figure 5-2 by the ratio of 3°F over the actual ΔT°F [58]. The reasoning behind this is shown in the formula below [116]:

$$\text{CFM}=\frac{\text{BTUs}}{\Delta T \times 1.08}$$

Since the standard ΔT for data centers is 10°F [116], the actual opening size of the wind catcher will be determined through the calculation below:

$3 \div 10 = 0.3$

$0.3 \times 6.72 = 2.016\ m^2$

The size of the outlet is consequently:

$2 \times 2.016 = 4.032\ m^2$

The height for the data center, the wind catcher, and the wind tower, functioning as a chimney, are presumed to be at 3m, 9m, and 6m, respectively. These structures are illustrated in Figure 5-3 and 5-4. The whole building is oriented at 345 degrees (mentioned in section 4-4) to allow the wind catcher openings capture the prevailing winds.

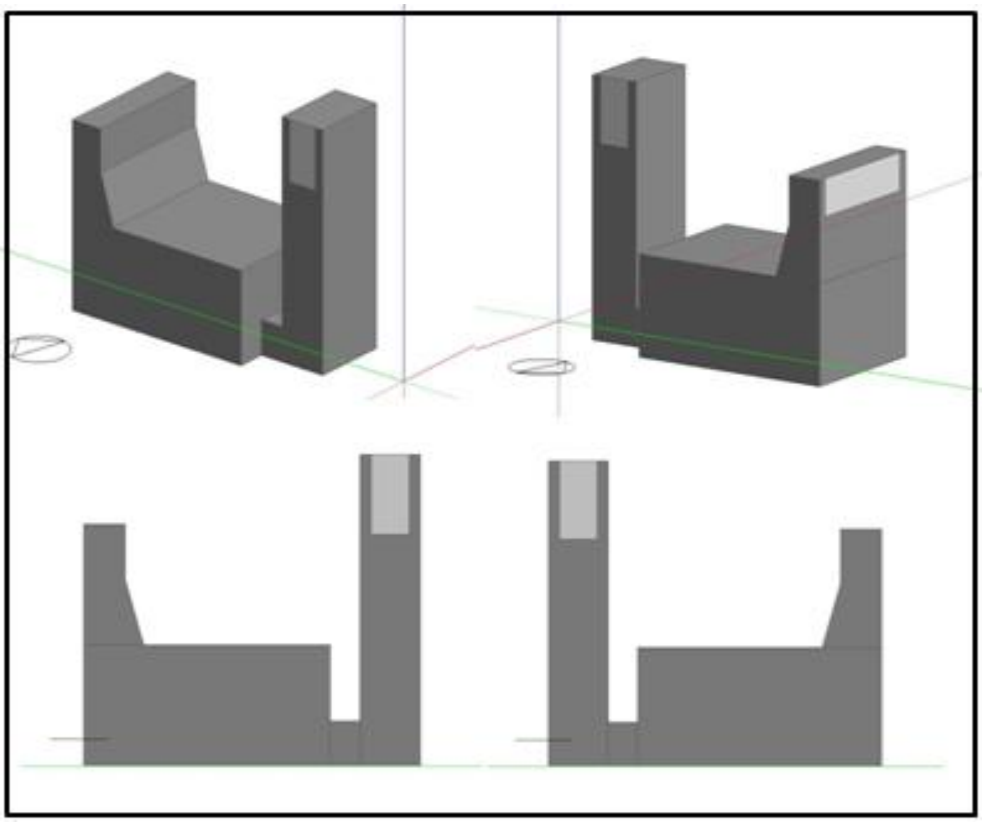


Figure 5-3: The Structure of Data Center, Wind Catcher, and Wind Tower

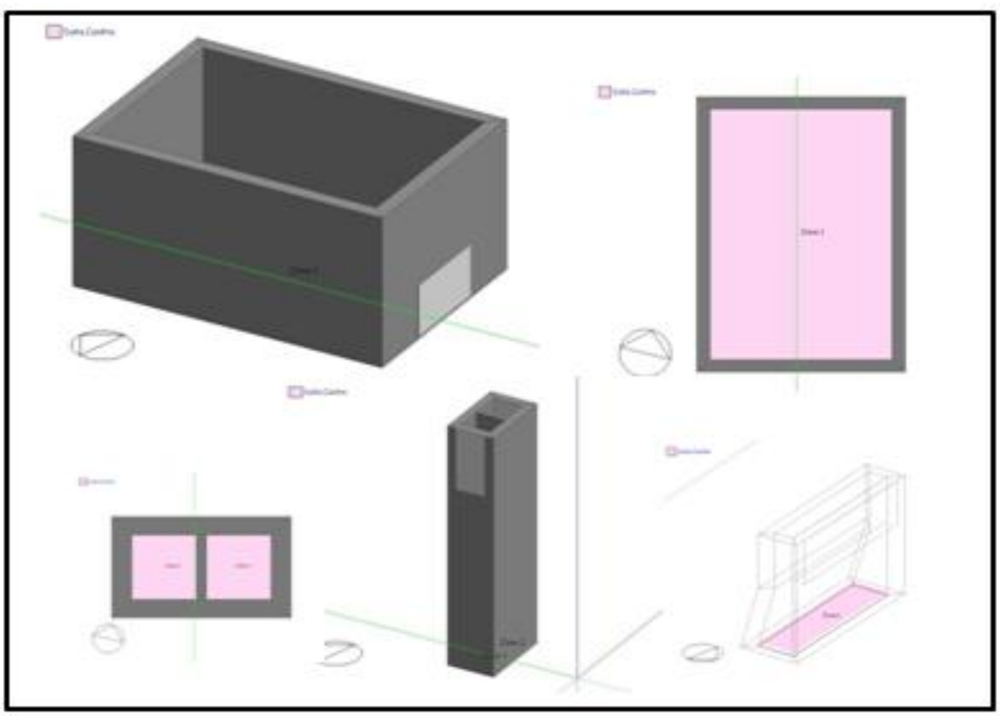


Figure 5-4: The Data Center, Wind Catcher, and Wind Tower

5-2. The Simulation Study

There are a series of weather and operation data parameters that are provided by DesignBuilder (in a pull down menu) for running any specific simulation study. The site data used to run the simulations for this study, shown in Figure 5-5, are listed below:

- Location template: WA – Pullman/Moscow regional airport.
- Hourly weather data: U.S.A_WA_Pullman-Moscow regional airport_TMY3
- Full treatment of wind effects: Exposed to wind, and Wind factor: 1.00.
- Model of ventilation: Natural ventilation: In this option, the natural ventilation and infiltration are calculated for all the zones of the building.
- Model of natural ventilation: Calculated: Although using the "Calculated" option increases the complexity of the model, results are more accurate because it takes into account wind driven and buoyancy effect pressures. By defining the openings and control strategies, the program calculates the natural ventilation flow rates, including consideration of wind and buoyancy pressure effects, as well as the flow rates between various zones of the building [117]. The calculated airflows through openings such as windows, doors, and holes are all lumped into "External air" data on the simulation results screen [118]. The calculations in this model option are based on the following principles: The ventilation rate q, through each opening in the model is calculated based on the pressure difference using wind and stack pressure effects:

$$q = C.(DP)^n$$

Where:

- q is the volumetric flow through the opening,
- *DP* is the pressure difference across the opening,
- n is the flow exponent varying between 0.5 for fully turbulent flow and 1.0 for fully laminar flow, and
- C is the flow coefficient, related to the size of the opening.

The pressure on any point on the surface of a building façade can be represented by:

$$P_w = 0.5\ .rho.\ C_p\ .\ v_z^2$$

Where:

- P_w is the surface pressure due to wind,
- *Rho* is the density of air,
- C_p is the wind pressure coefficient at a given position on the surface, and
- v_z is the mean wind velocity at height z [118].

Various templates for individual zones of the building are demonstrated in the Figure 5-6:

- After selecting the “Data Center” for the main building on the activity template tab, the following data was uploaded into the program:

  - Office equipment heat gain: 500.00 W/m^2 which is compatible with the heat load mentioned in chapter 2.

- Schedule: the equipment is on a 24 hour operation schedule with high internal gains from equipment.

- On the HVAC template tab, “Natural ventilation – no heating/cooling” was selected.
- For the wind catcher structure on the activity template tab, the “None” option was selected and the zone type is “Semi exterior unconditioned”.
- On the HVAC template tab, “No heating or Cooling” was selected.

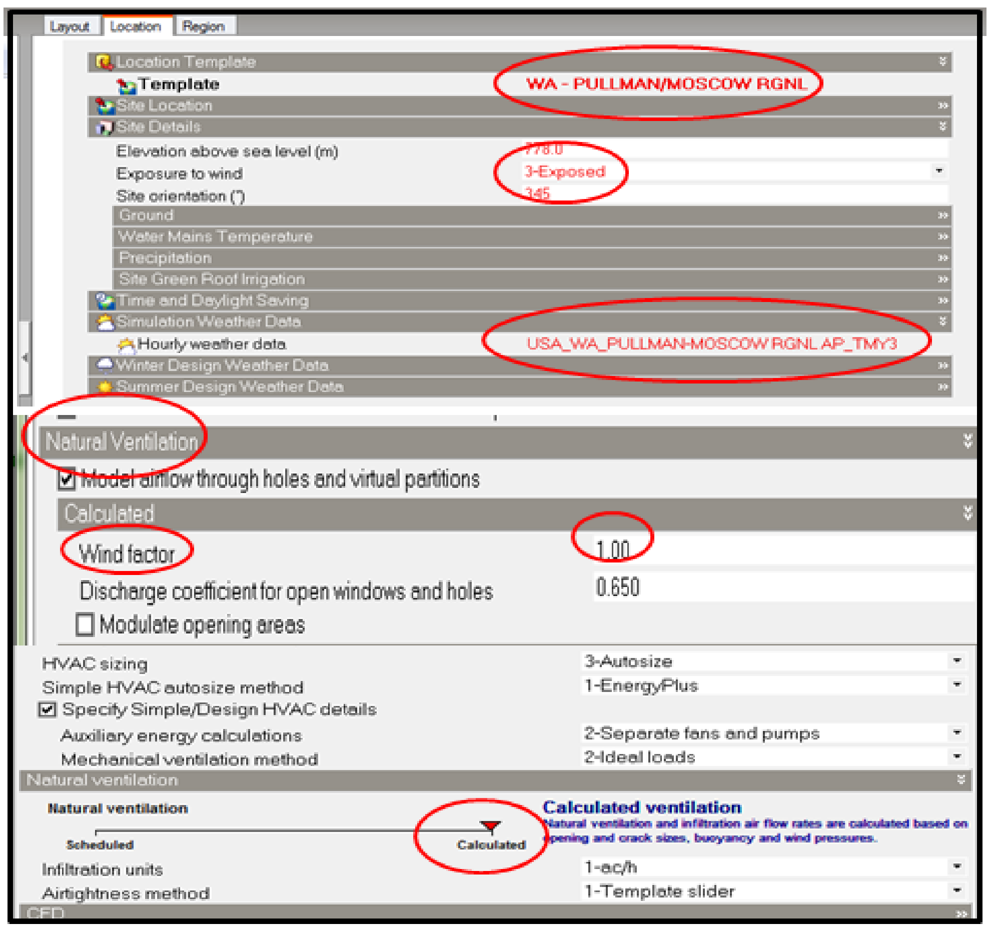


Figure 5-5: Site Data for the Simulation

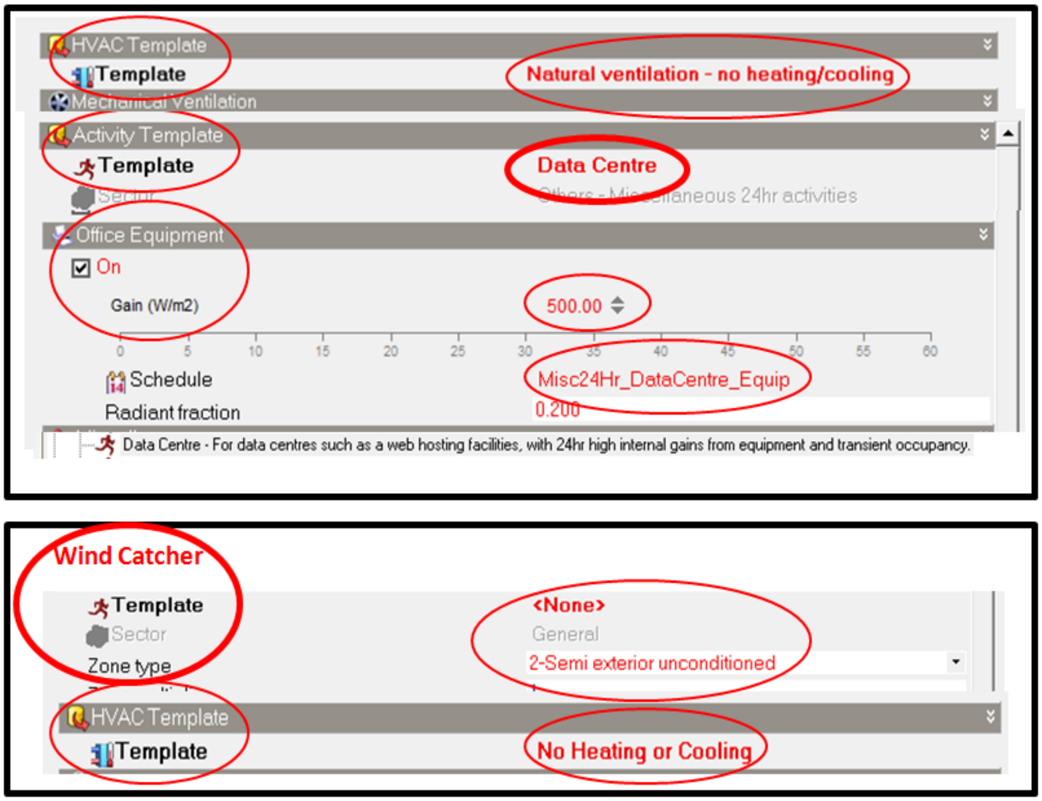


Figure 5-6: Activity and HVAC Templates

5-3. The Simulation Results

By configuring the DesignBuilder simulation program based on the parameters mentioned above, a series of results showing the energy efficiency levels of the building are derived. These results show the performance of strategies selected in building design on the annual, daily, and hourly basis. The environmental behavior of the conceptual data center building in Moscow, Idaho is demonstrated in terms of the required electricity, generated CO2, heat gain, heat removal, temperature distribution, and relative humidity. The annual graphs of the climate conditions, such as wind directions and wind speeds, help with doing a more accurate analysis. The CFD (Computational Fluid Dynamics) graphs show the temperature distribution and air velocity in the building at specific times of the year. The information captured from these graphs are discussed in the following sections. Please note that from this point on we use “the building” to refer to the conceptual data center infrastructure demonstrated in Figures 5-3 and 5-4.

5-3-1. Heat Balance

In the Figure 5-7 a number of graphs and a table showing the environmental performance of the building over the course of one year are illustrated. Different parameters, which will be discussed individually, indicate the efficiency level of the building. Among all the graphs, the heat balance graph, shown in the Figure 5-8, is the most important one since it demonstrates that the building with an annual heat gain of 126.84MWh from the equipment is ventilated through external air with -136.12MWh of energy. External air is defined in the program as: “heat gain due to the entry of outside air through external windows, vents, doors, holes, and cracks when using the calculated natural ventilation option” [119]. Lighting, windows, and occupancy generate very low amounts of energy (6.34MWh, 6.31MWh, and 1.59MWh, respectively.) Since there were no windows in the structure design of the building, and since the amount of energy generated by lighting and occupancy are very small quantities, these numbers are ignored in the final analysis. Because equipment in a data center operates 24/7, a daily based graph is required to show the success of the ventilation system. Daily heat balance graph, illustrated in the Figure 5-9, shows that heat gain, due to the uninterrupted operation of the equipment, is a straight line at the level of 347.51kWh. The “external air” curve in the graph, shows the heat removal rates, with fluctuations due to the different ventilation rates varies from -353.63kWh to -401.60kWh. Although there is a fluctuation of around 50kWh, no critical point can be observed on the graph and the minimum rate is still sufficient to remove the heat gain.

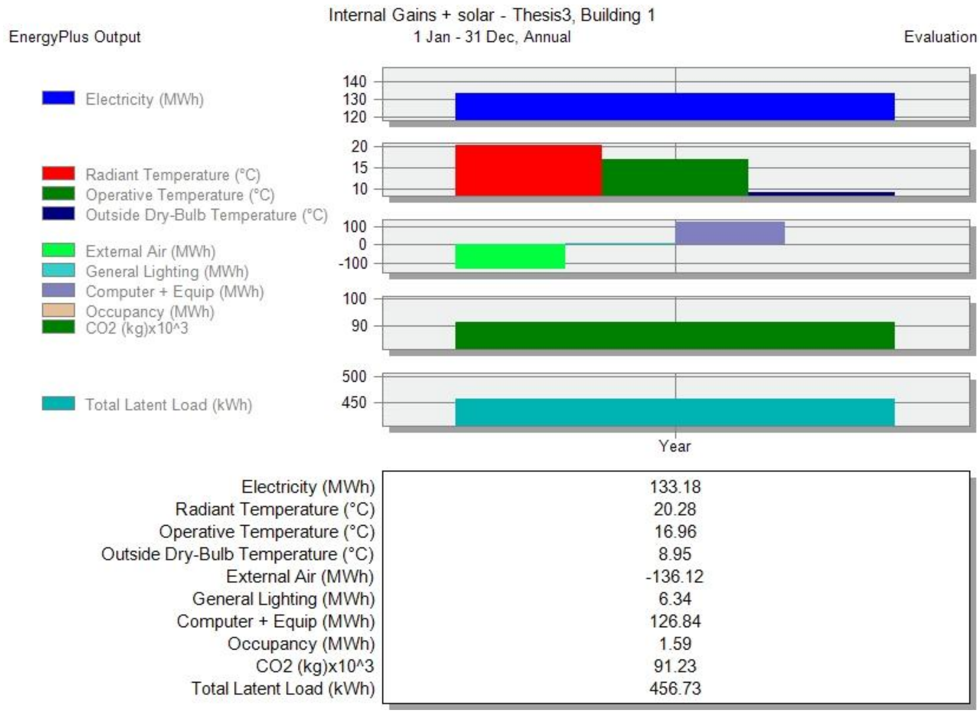


Figure 5-7: A Number of Annual Results of the Simulation

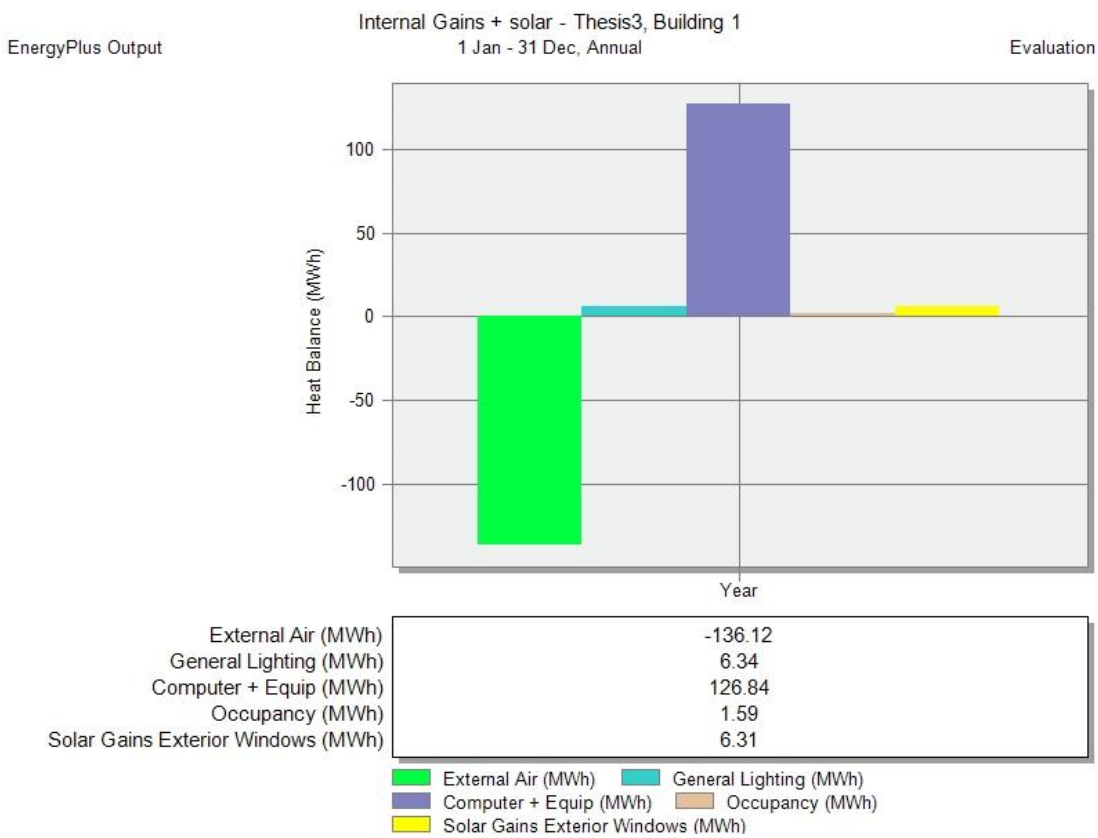
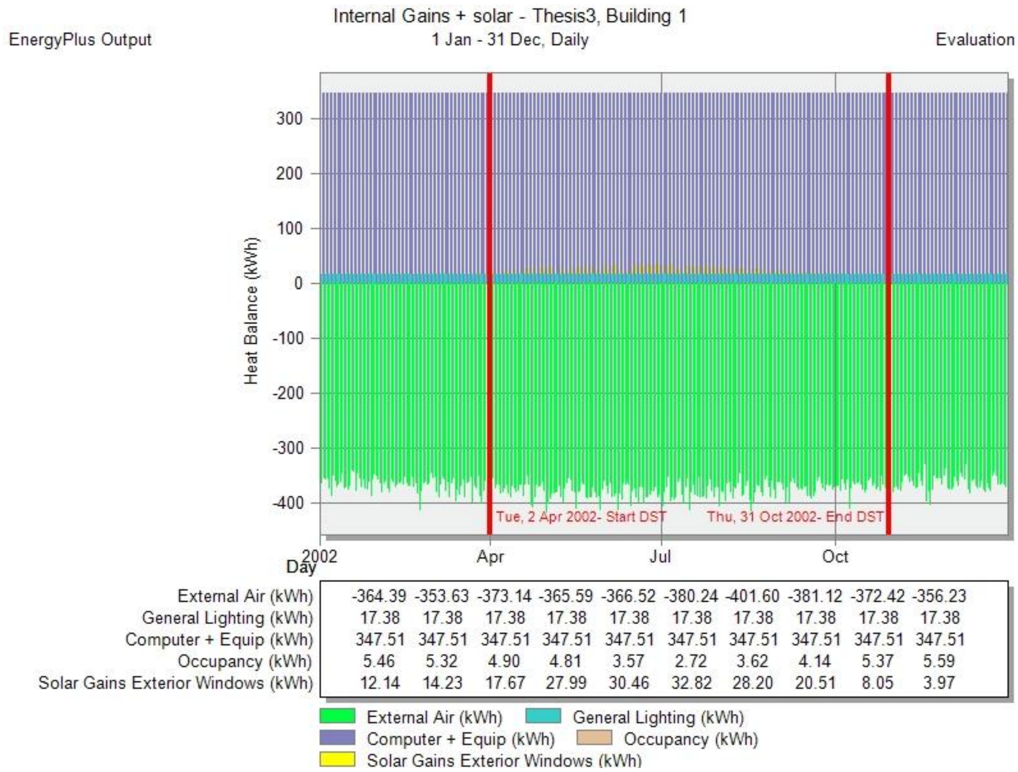


Figure 5-8: Annual Heat Balance Graph



External Air (kWh)	-364.39	-353.63	-373.14	-365.59	-366.52	-380.24	-401.60	-381.12	-372.42	-356.23
General Lighting (kWh)	17.38	17.38	17.38	17.38	17.38	17.38	17.38	17.38	17.38	17.38
Computer + Equip (kWh)	347.51	347.51	347.51	347.51	347.51	347.51	347.51	347.51	347.51	347.51
Occupancy (kWh)	5.46	5.32	4.90	4.81	3.57	2.72	3.62	4.14	5.37	5.59
Solar Gains Exterior Windows (kWh)	12.14	14.23	17.67	27.99	30.46	32.82	28.20	20.51	8.05	3.97

Figure 5-9: Daily Heat Balance Graph

5-3-2. Temperature and Humidity

Annual graph of Temperature, illustrated at the top of Figure 5-10, shows that over a year, the mean air temperature inside the building is 16.96°C while the outside mean temperature is 8.95°C. The bottom portion of Figure 5-10 shows that the mean relative humidity over a year in the data center is 49.35%.

There is no heating or cooling system, and as we can see in Figure 5-11, the upper daily graph illustrates how the inside temperature follows the same pattern as the outside temperature, although it is shifted by an average of 5°C to 9°C. The three upper lines represent radiant temperature, operative temperature, and air temperature, respectively, and the lowest line shows the outside dry-bulb temperature. The table indicates that the air temperature inside the data center varies from 6.43°C to 27.52°C. These numbers indicate that no extra cooling is required and the temperature ranges are within the allowable operating ranges specified by ASHRAE (Chapter 2). In cold days of the year, mixing the returned air with the supply air results in quick, desirable thermal conditions in the building.

The lower daily graph in Figure 5-11 shows the levels of relative humidity inside the building over the course of a year. The table indicates that relative humidity varies from 34.33% to 66.71%, and these ranges are compatible with the allowable ASHRAE ranges (Chapter 2).

In the Figure 5-12, the three charts of temperature distribution show the number of hours over a year that temperature in the building is “at or below” (upper chart), “at” (middle chart), and “at or above” (lower chart) a specific temperature. It is shown that by moving from 11°C to 32°C, the number of hours “at or below” increases while the number of “at or above” decreases. This demonstrates that over the year, the temperature inside the data center does not increase drastically.

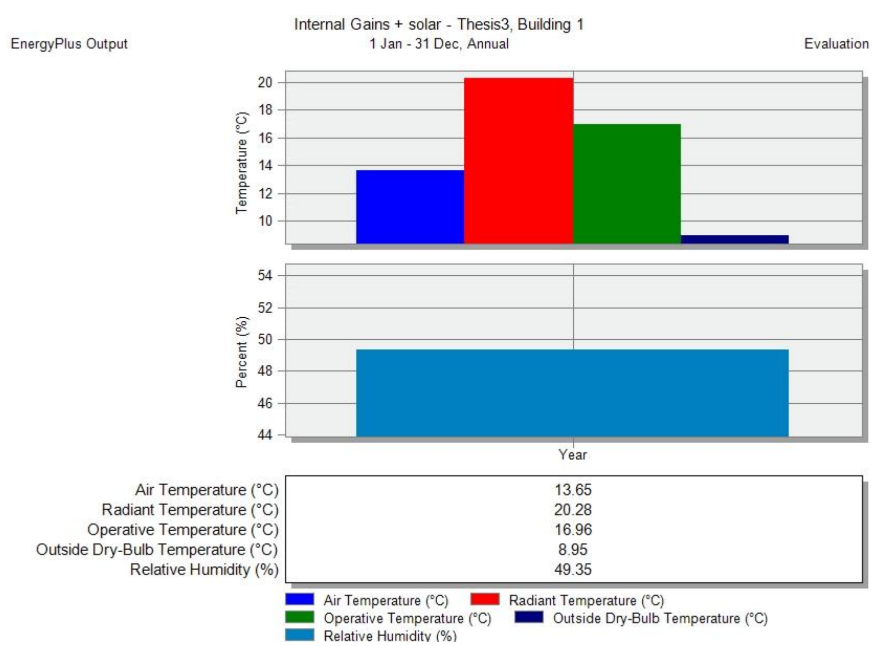
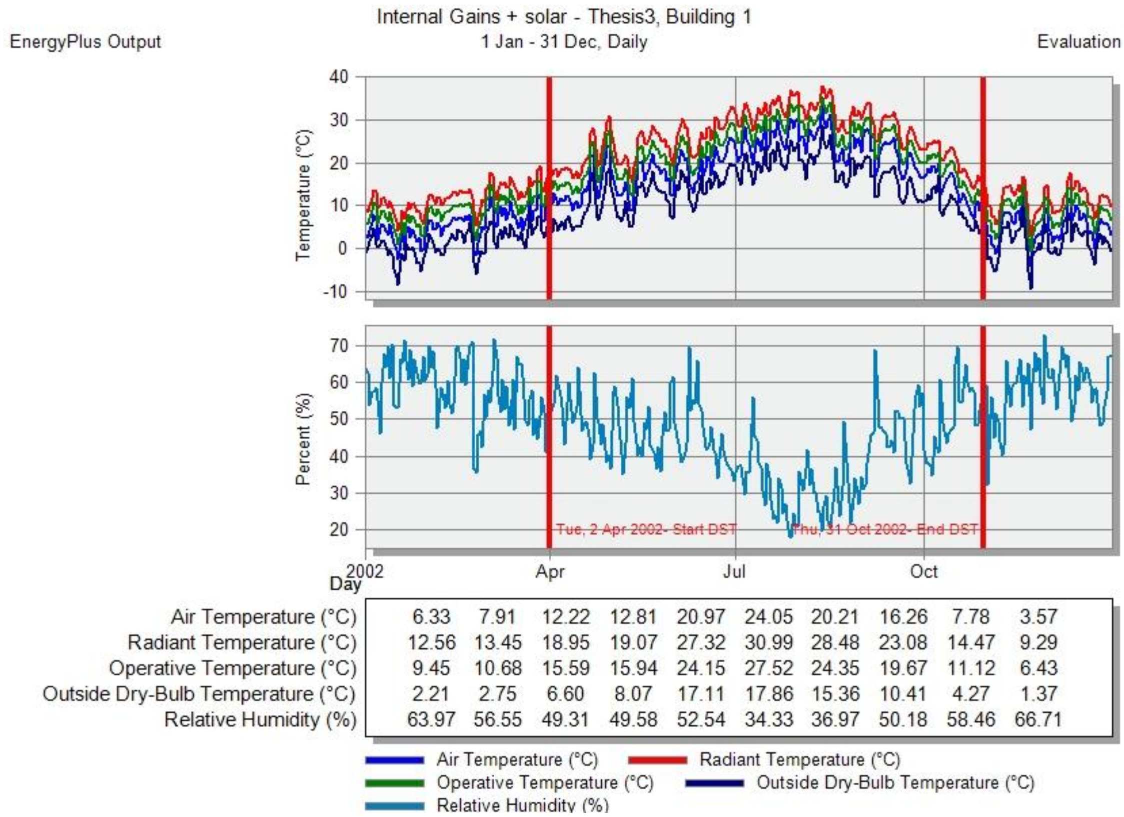
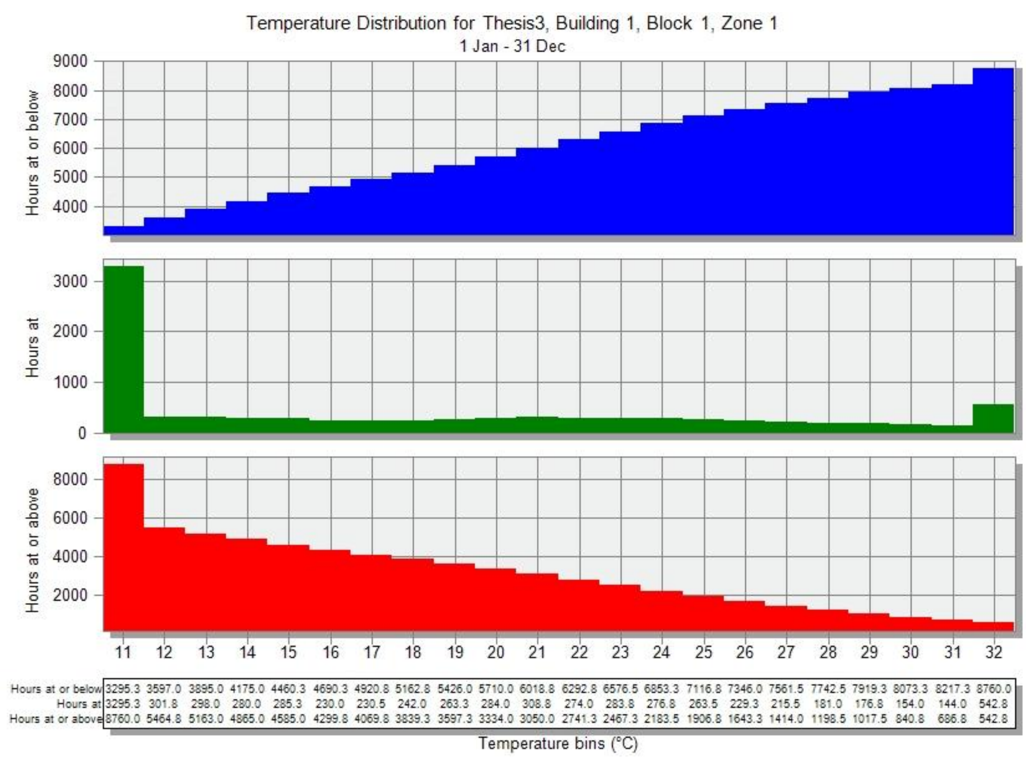


Figure 5-10: Annual Temperature and Relative Humidity



Air Temperature (°C)	6.33	7.91	12.22	12.81	20.97	24.05	20.21	16.26	7.78	3.57
Radiant Temperature (°C)	12.56	13.45	18.95	19.07	27.32	30.99	28.48	23.08	14.47	9.29
Operative Temperature (°C)	9.45	10.68	15.59	15.94	24.15	27.52	24.35	19.67	11.12	6.43
Outside Dry-Bulb Temperature (°C)	2.21	2.75	6.60	8.07	17.11	17.86	15.36	10.41	4.27	1.37
Relative Humidity (%)	63.97	56.55	49.31	49.58	52.54	34.33	36.97	50.18	58.46	66.71

Figure 5-11: Daily Temperature and Relative Humidity Graphs



	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Hours at or below	3295.3	3597.0	3895.0	4175.0	4460.3	4690.3	4920.8	5162.8	5426.0	5710.0	6018.8	6292.8	6576.5	6853.3	7116.8	7346.0	7561.5	7742.5	7919.3	8073.3	8217.3	8760.0
Hours at	3295.3	301.8	298.0	280.0	285.3	230.0	230.5	242.0	263.3	284.0	308.8	274.0	283.8	276.8	263.5	229.3	215.5	181.0	176.8	154.0	144.0	542.8
Hours at or above	8760.0	5464.8	5163.0	4865.0	4585.0	4299.8	4069.8	3839.3	3597.3	3334.0	3050.0	2741.3	2467.3	2183.5	1906.8	1643.3	1414.0	1198.5	1017.5	840.8	686.8	542.8

Figure 5-12: Annual Temperature Distribution Chart

5-3-3. Airflow and Ventilation Results

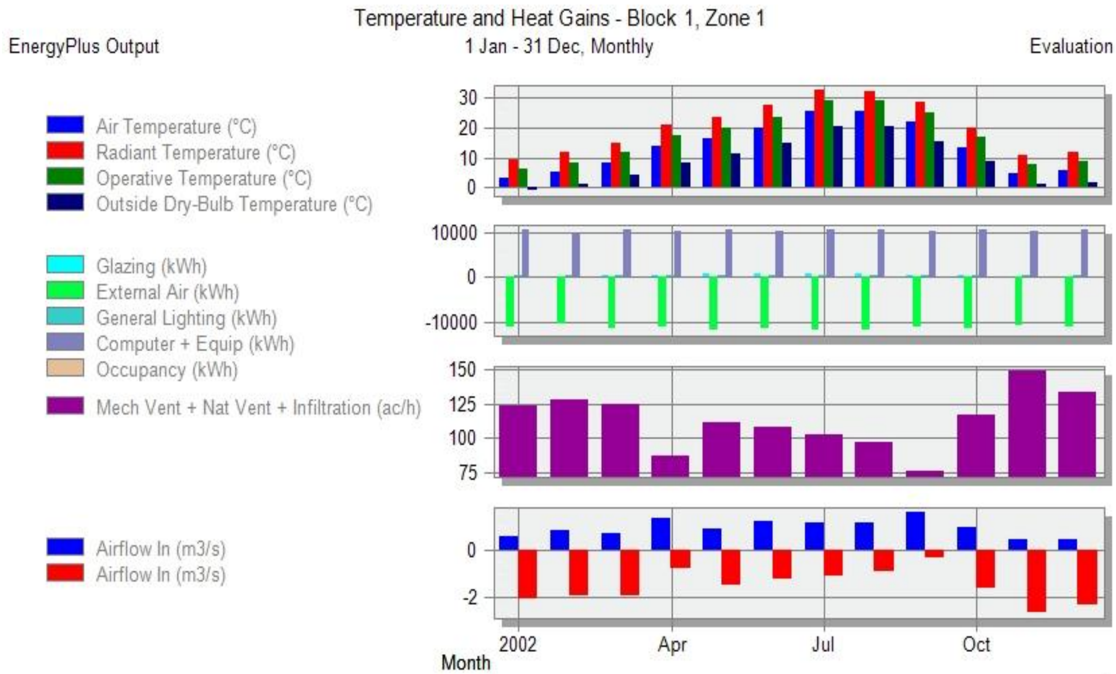
Figure 5-13 illustrates the monthly graphs of volumetric airflow rates (lower graph) and ventilation rates (above that) in the building. In the airflow chart, the upper bars (above zero) show the volumetric “airflow in” rates and the lower bars (below zero) show the volumetric “airflow out” rates. Adding the two bars (m^3/s) shows the total fresh air rates in ac/h (air change per hour) for each month of the year [120]:

$$\mathrm{m^3/s} = \frac{\mathrm{ac/h} \times \mathrm{ZoneVolum}}{3600}$$

The second graph from the top in Figure 5-13 shows the monthly rates of heat balance in the building. The upper bars (above zero) show the heat gain rates through equipment and the lower bars (below zero) show the heat loss rates through external air. The graph on the top shows the outdoor/indoor temperatures deviations in a monthly database. The heat loss is derived from the equation below [121]:

Heat loss/gain due to external air = mass flow rate × specific heat of air × (outdoor DB – indoor DB)

Although there are various rates of ventilation, due to other variables interfering, the heat balance chart shows almost an even rate of heat loss through external air over the course of a year. The heat gain rates vary from 9730.19 kWh to 10772.71 kWh and heat loss rates vary from -10318.35 kWh to -111894.88 kWh.



Air Temperature (°C)	3.18	5.15	8.33	13.98	16.10	20.02	25.56	25.37	21.72	13.48	4.72	5.57
Radiant Temperature (°C)	9.30	11.57	14.88	20.74	23.45	27.21	32.59	32.15	28.21	19.91	10.90	11.76
Operative Temperature (°C)	6.24	8.36	11.60	17.36	19.78	23.61	29.07	28.76	24.97	16.70	7.81	8.66
Outside Dry-Bulb Temperature (°C)	-0.91	1.02	4.03	8.45	11.31	15.01	20.27	20.20	15.56	8.86	1.10	1.83
Glazing (kWh)	133.28	238.70	412.96	579.59	727.52	847.97	854.00	700.29	468.29	309.89	161.34	128.27
External Air (kWh)	11261.76	10318.35	11496.39	11257.23	11894.88	11457.19	11805.54	11724.84	11196.06	11473.19	10938.19	11298.29
General Lighting (kWh)	538.64	486.51	538.64	521.26	538.64	521.26	538.64	538.64	521.26	538.64	521.26	538.64
Computer + Equip (kWh)	10772.71	9730.19	10772.71	10425.20	10772.71	10425.20	10772.71	10772.71	10425.20	10772.71	10425.20	10772.71
Occupancy (kWh)	172.29	153.52	163.30	137.03	135.53	109.44	75.87	74.86	95.66	144.04	163.50	169.24
Mech Vent + Nat Vent + Infiltration (ac/h)	123.87	127.68	124.93	86.86	111.06	107.67	102.20	96.98	75.68	116.96	149.03	133.04
Airflow In (m3/s)	0.58	0.80	0.71	1.35	0.88	1.21	1.18	1.13	1.61	0.97	0.47	0.46
Airflow In (m3/s)	-2.06	-1.89	-1.89	-0.74	-1.49	-1.23	-1.09	-0.92	-0.35	-1.59	-2.63	-2.30

Figure 5-13: Monthly Graphs of Temperature, Heat Balance, Ventilation, and Airflow

Figure 5-14 illustrates the daily graphs of wind speed, wind direction, and volumetric airflow in the data center over the course of a year. The airflow graph shows that in September “airflow out” (lower line) is at its minimum rate. In this time of the year the wind speed is at the lowest rate and wind direction is mostly from the south-east which results in high rates of “airflow in.” The table indicates that the “airflow in” rates (upper line), vary from 0.00 m^3/s to 2.32 m^3/s and the “airflow out” rates (lower line) vary from -0.05 m^3/s to -4.09 m^3/s. An overall review of the airflow graph shows that rates of “airflow in” and “airflow out” are practically equal, which demonstrates that over a year, the data center is efficiently ventilated through airflow captured and exhausted by wind towers attached to the building.

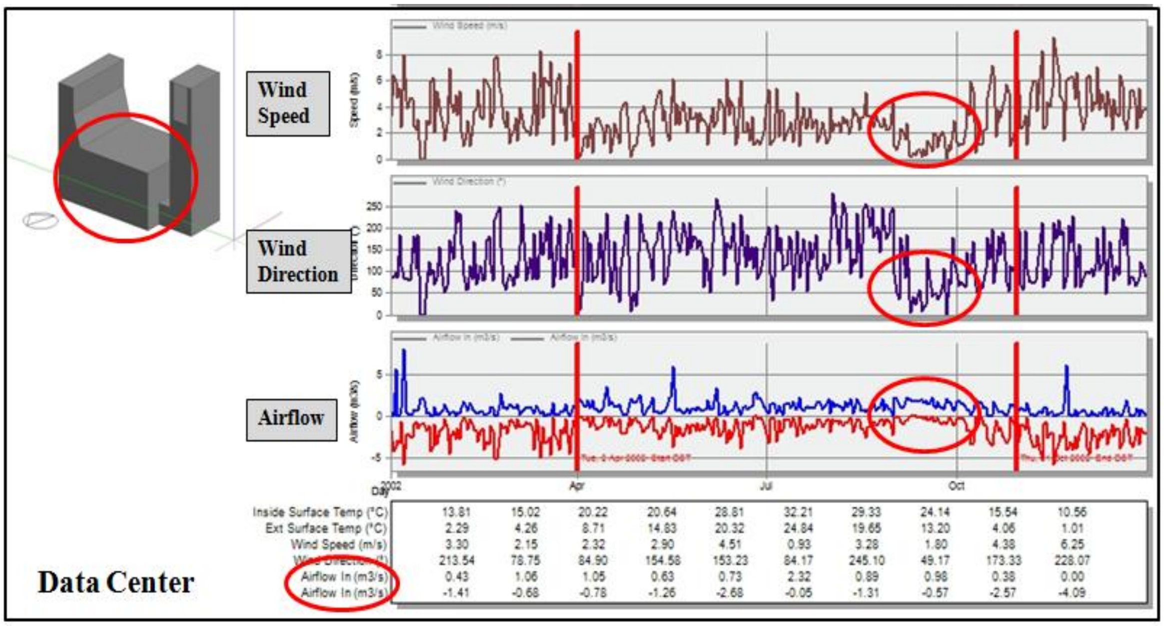


Figure 5-14: Daily Graphs of Wind Speed, Wind Direction, and Airflow in the Data Center

Figure 5-15 shows the daily graphs of wind speed, wind direction, and airflow for the wind catcher's opening facing the west over the course of a year. The airflow graph shows that in September "airflow in" (upper line) is at its minimum rate. The reason is that not only at this time of the year the wind speed is at the lowest, but wind direction is also mostly from the south-east. The table indicates that the "airflow in" rates (upper line), vary from 0 to 6.09 m^3/s and the "airflow out" rates (lower line) vary from 0 to -1.49 m^3/s. An overall review of the airflow graph shows that the rates of "airflow in" are much higher than the "airflow out," which demonstrates that over the year, except for the month of September, the wind catcher's opening facing west is working efficiently to provide fresh air for the data center.

Figure 5-16 illustrates the daily graphs of wind speed, wind direction, and airflow for the wind catcher's opening facing the east over the course of a year. The airflow graph shows that in May the "airflow in" (upper line) is at low levels. The reason is that at this time of the year the wind is mostly blowing from the west. In September, the wind directions are dominantly from southeast and due to minimal wind speeds, the “airflow in” rates are at minimum levels. The table indicates that the “airflow in” rates (upper line), vary from 0 to 1.48 m^3/s and the “airflow out” rates (lower line) vary from -0.38 m^3/s to -1.99 m^3/s. An overall review of the airflow graph shows that in winter, the rates of “airflow in” are much higher than summer. The reason is that not only at this time of the year the wind speed is at high rates, but winds are mostly coming from the east and south-east. The total rates of “airflow in” are higher than “airflow out,” which demonstrates that this opening is working efficiently to supply air for the data center ventilation.

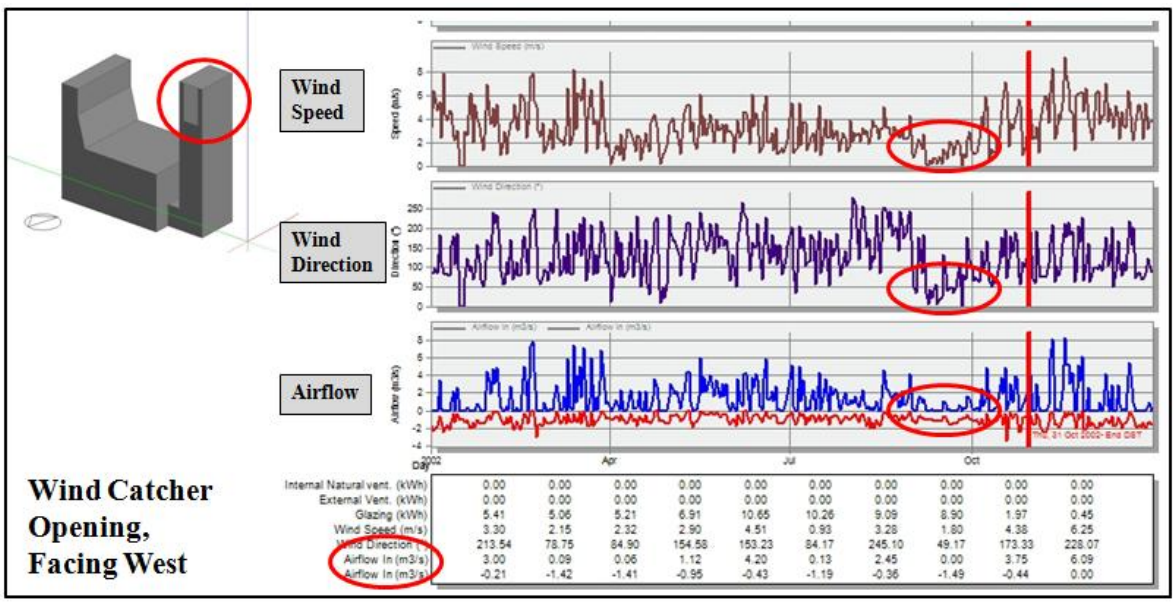


Figure 5-15: Daily Graphs of Wind Speed, Wind Direction, and Airflow for the Wind Catcher’s Opening Facing West

Figure 5-17 demonstrates the daily graphs of wind speed, wind direction, and airflow for the wind tower, functioning as a chimney, over the course of a year. The airflow graph shows that except for the months of April and September, the “airflow out” rates are much higher than “airflow in” rates. Wind directions, except for two very short periods of time, never pass 250 degree, which means over a year there is no wind blowing from the north. This is the main reason why the chimney works so efficiently. The table indicates that the “airflow in” rates (upper line) vary from 0 to 2.32 m^3/s and the “airflow out” rates (lower line) vary from -0.05 m^3/s to -4.09 m^3/s.

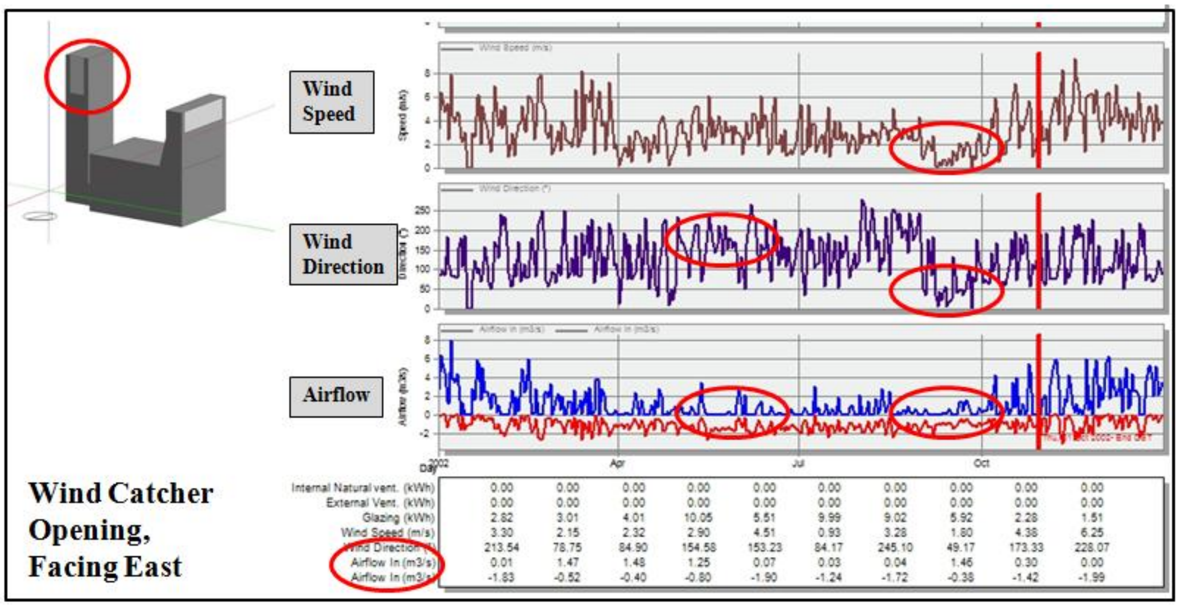


Figure 5-16: Daily Graphs of Wind Speed, Wind Direction, and Airflow for the Wind Catcher’s Opening Facing East

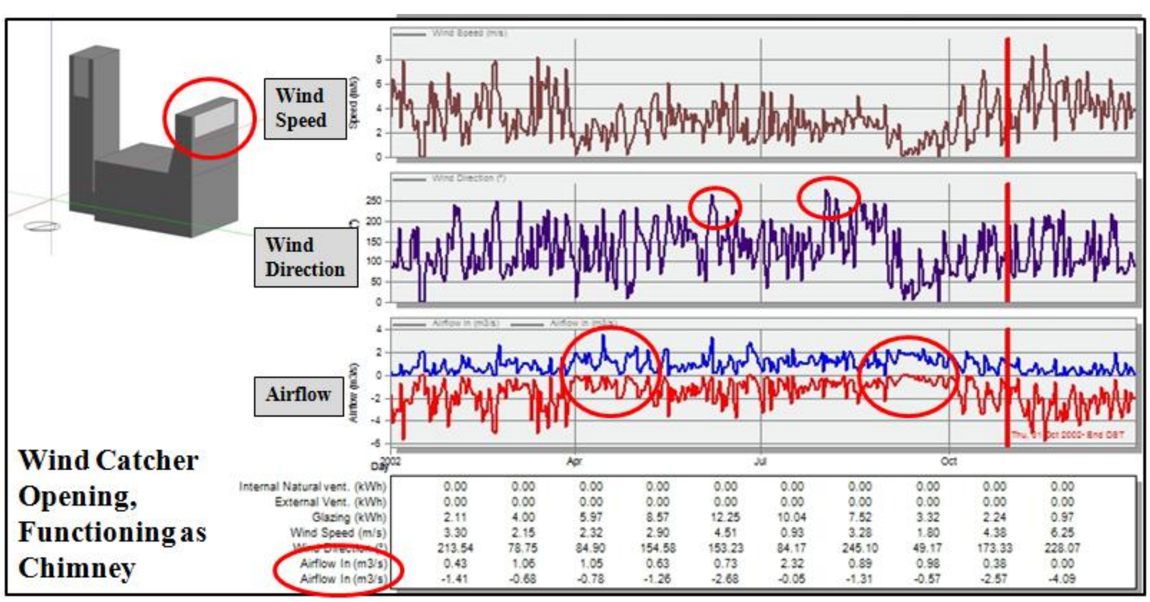


Figure 5-17: Daily Graphs of Wind Speed, Wind Direction, and Airflow for the Wind Tower Functioning as Chimney

5-3-4. The CFD Results

CFD (Computational Fluid Dynamics) graphs, resulted from the simulation, provide a better perception of the environmental performance inside the building. To investigate the airflow in the building through CFD graphs we choose two specific dates and times with different characteristics: A cold, evening date/time in the fall (November 11, 8 pm) and a warm, summer date/time (August 13, 12 noon).

In Figures 5-18 and 5-19, 3D CFD graphs of air velocity in the building on November 11, at 8 pm, are illustrated. The graphs show that the opening of the wind catcher that is facing west is functioning much more efficiently than the one facing east. The air velocity in this shaft reaches to 4.76 m/s and at the opposite end of the room it reaches to 2.6 m/s, which is still enough for efficient ventilation. At the top of the tower, the velocity is 1.3 m/s and inside the shaft, due to the venture effect [44], it increases up to 4.76 m/s.

In Figure 5-20 demonstrates a 3D graph of temperature distribution on November 11, at 8 pm in the building. Cold outside air with a temperature of 5.33°C is captured by the wind catcher and after warming by the equipment it is exhausted at 17.82°C. The room temperature is about 10°C near the floor and 13.14°C near the ceiling.

Figure 5-21 shows the pressure differentials in the wind tower shafts and the building. In the section 3-4-4, it was mentioned that an increase in pressure differential increases the ventilation rates. Figure 5-19 shows that the opening at the top of the wind catcher is located at the point with the highest positive pressure and the outlet is at the point with the highest negative pressure. This high difference in pressure levels results in efficient ventilation inside the building.

Figures 5-22 and 5-23 illustrate 3D CFD graphs of air velocity in the building on August 13, at 12 noon. The graphs show that the opening of the wind catcher that is facing east is functioning much more efficiently than the one facing west. The air velocity in this shaft reaches 6.02 m/s and at the opposing end of the room it reaches to 2.26 m/s, which is still more than enough for efficient ventilation. At the top of the tower, the velocity is 3.01m/s and inside the shaft, due to the venture effect [44], it increases up to 6.02 m/s.

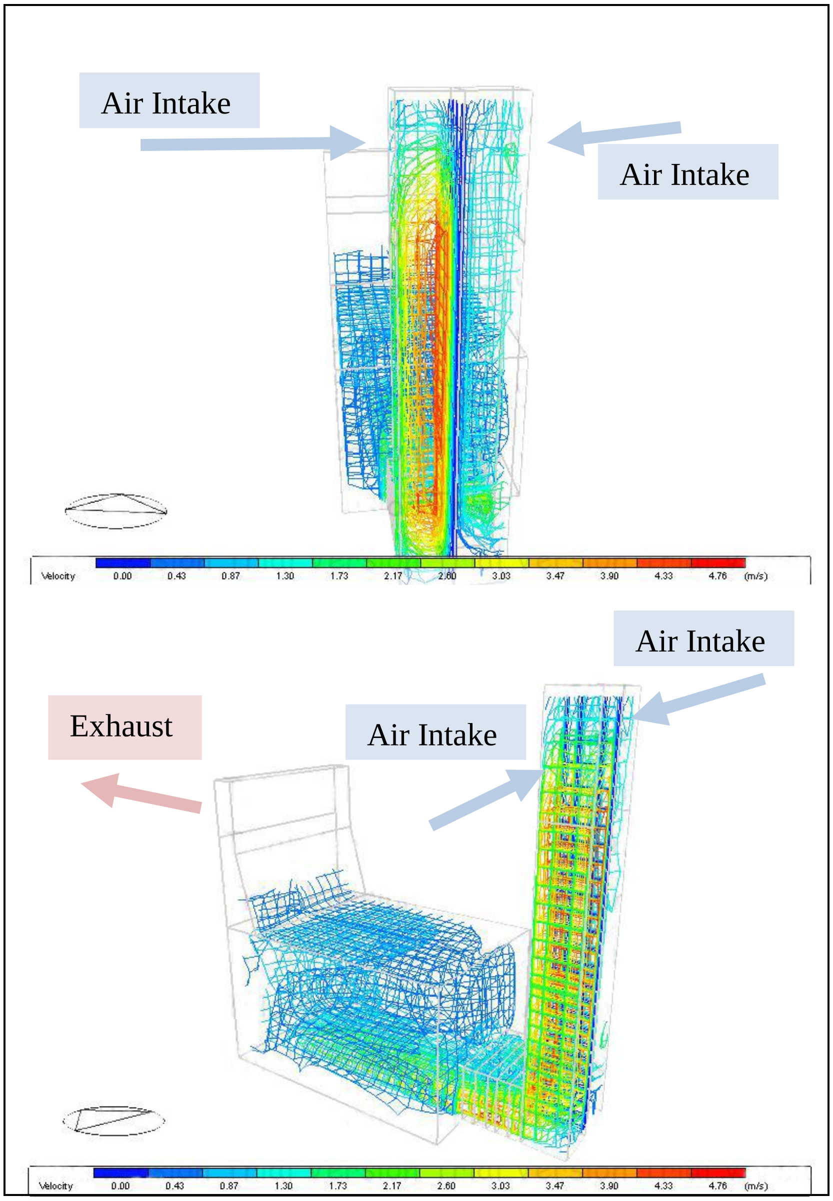


Figure 5-18: Air Velocity in the Building, Nov 11, 8 pm

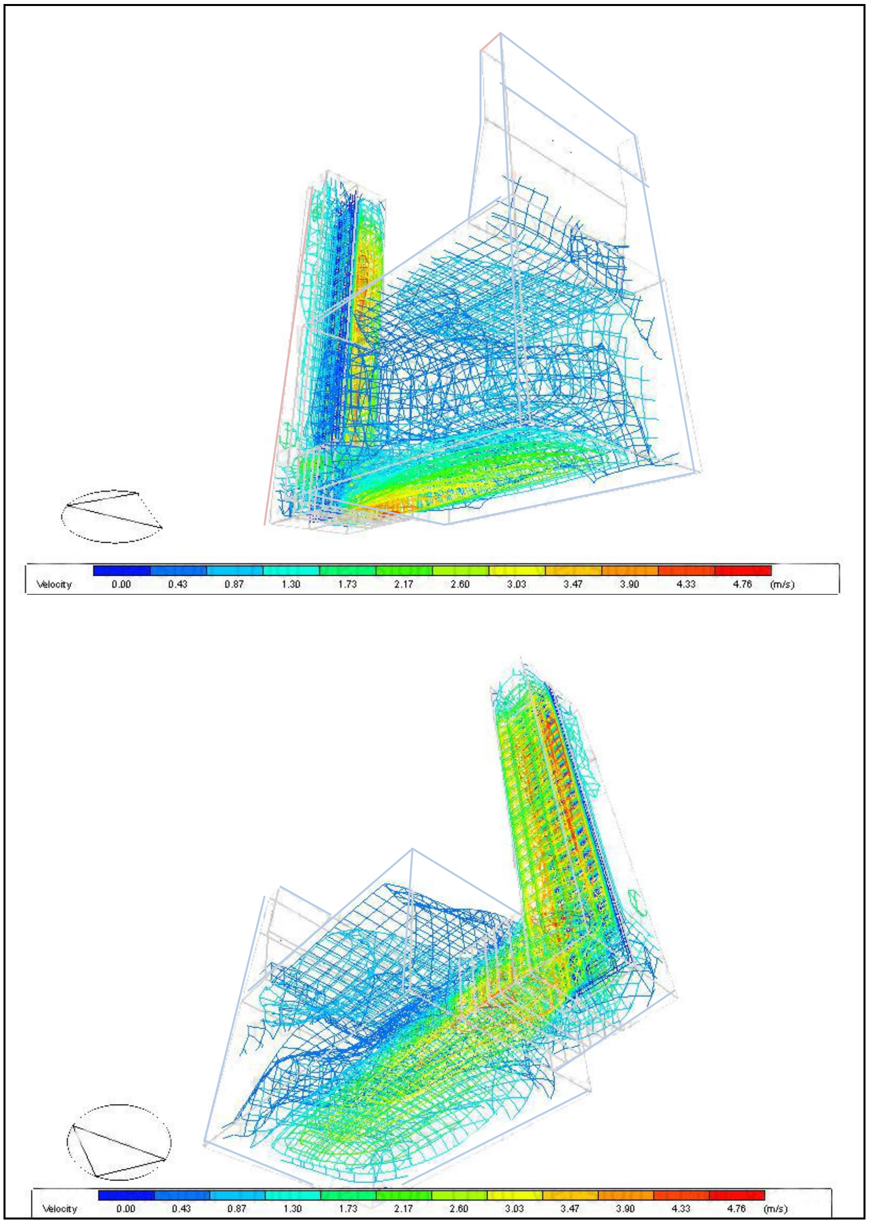


Figure 5-19: Air Velocity in the Building, Nov 11, 8 pm

Figure 5-24 demonstrates a 3D CFD graph of temperature distribution on August 13, at 12 noon in the building is demonstrated. The outside air with a temperature of 28.72°C is captured by the wind catcher and after warming by the equipment it is exhausted at 34.85°C. The room temperature is about 31.79°C near the floor and 33.32°C near the ceiling.

Figure 5-25 shows the pressure differentials in the wind tower shafts and the building. This Figure shows that the inlet opening is located at the point with the highest positive pressure and the outlet is at the point with the highest negative pressure. This high difference in pressure levels results in efficient ventilation inside the building.

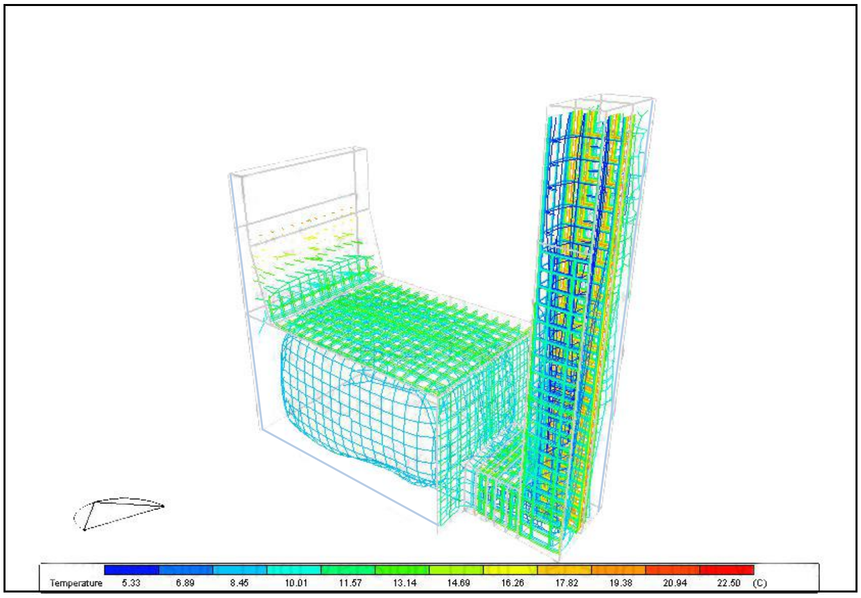


Figure 5-20: Temperature Distribution in the Building, Nov 11, 8 pm

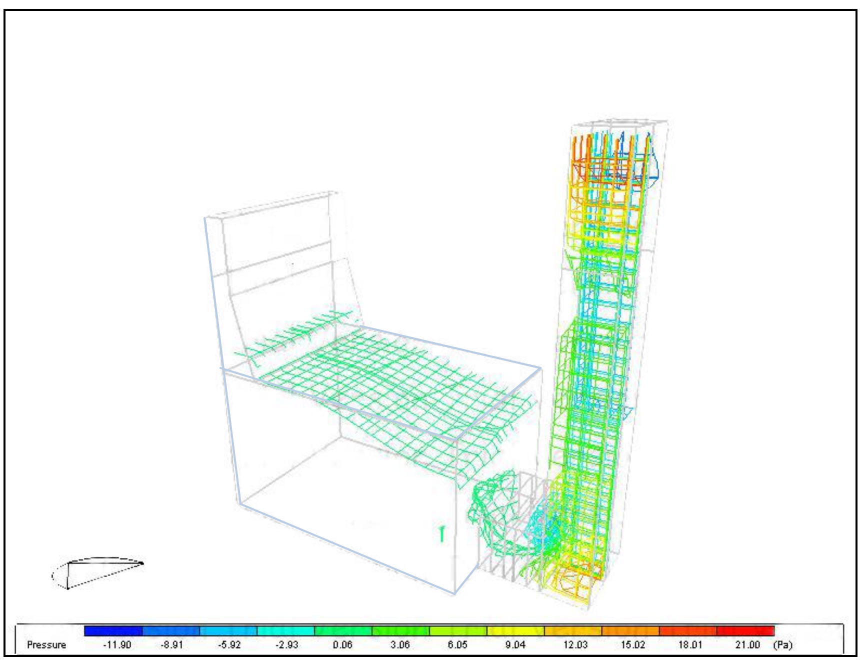


Figure 5-21: Pressure Differential in the Building, Nov 11, 8 pm

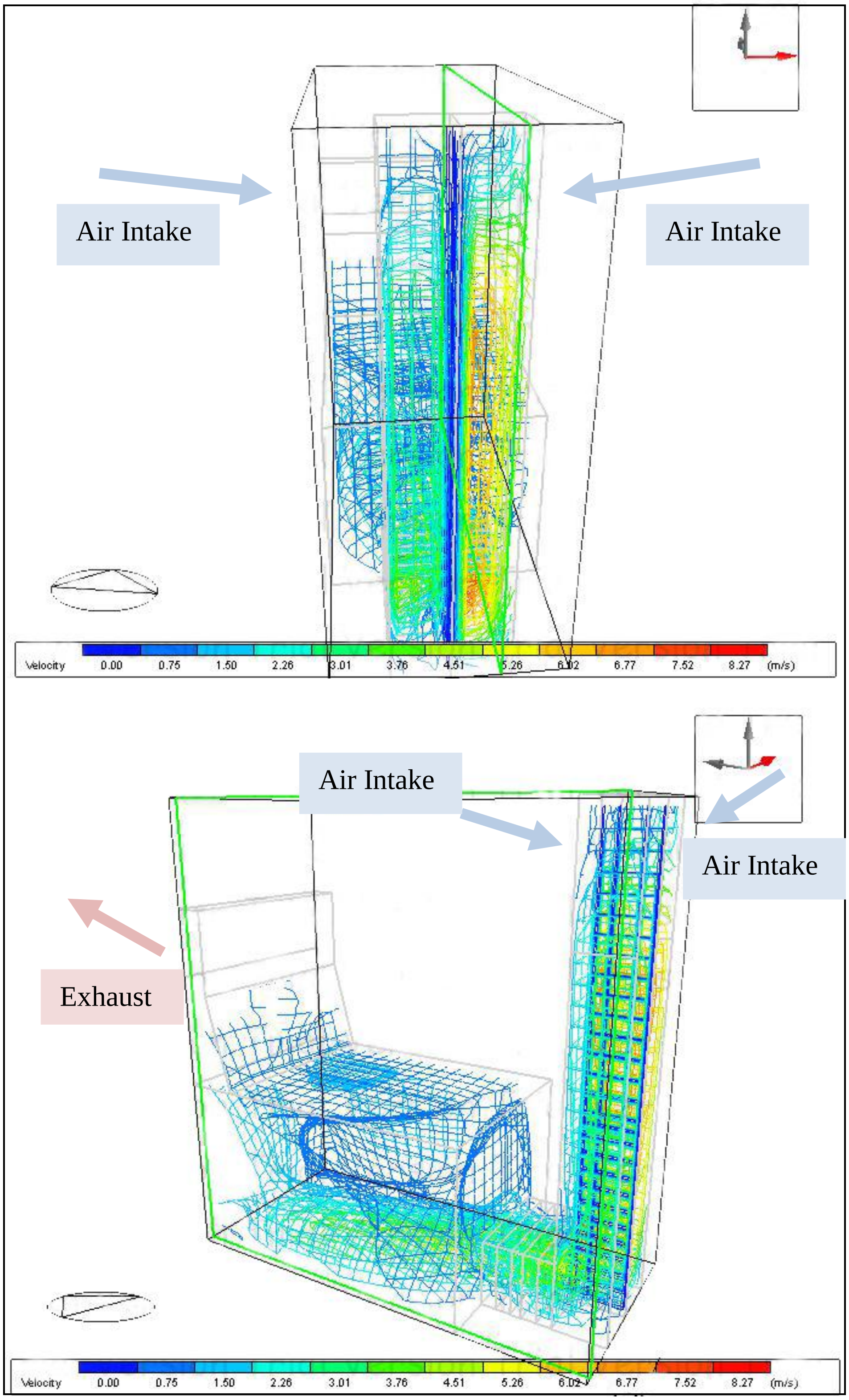


Figure 5-22: Air Velocity in the Building, Aug 13, 12 Noon

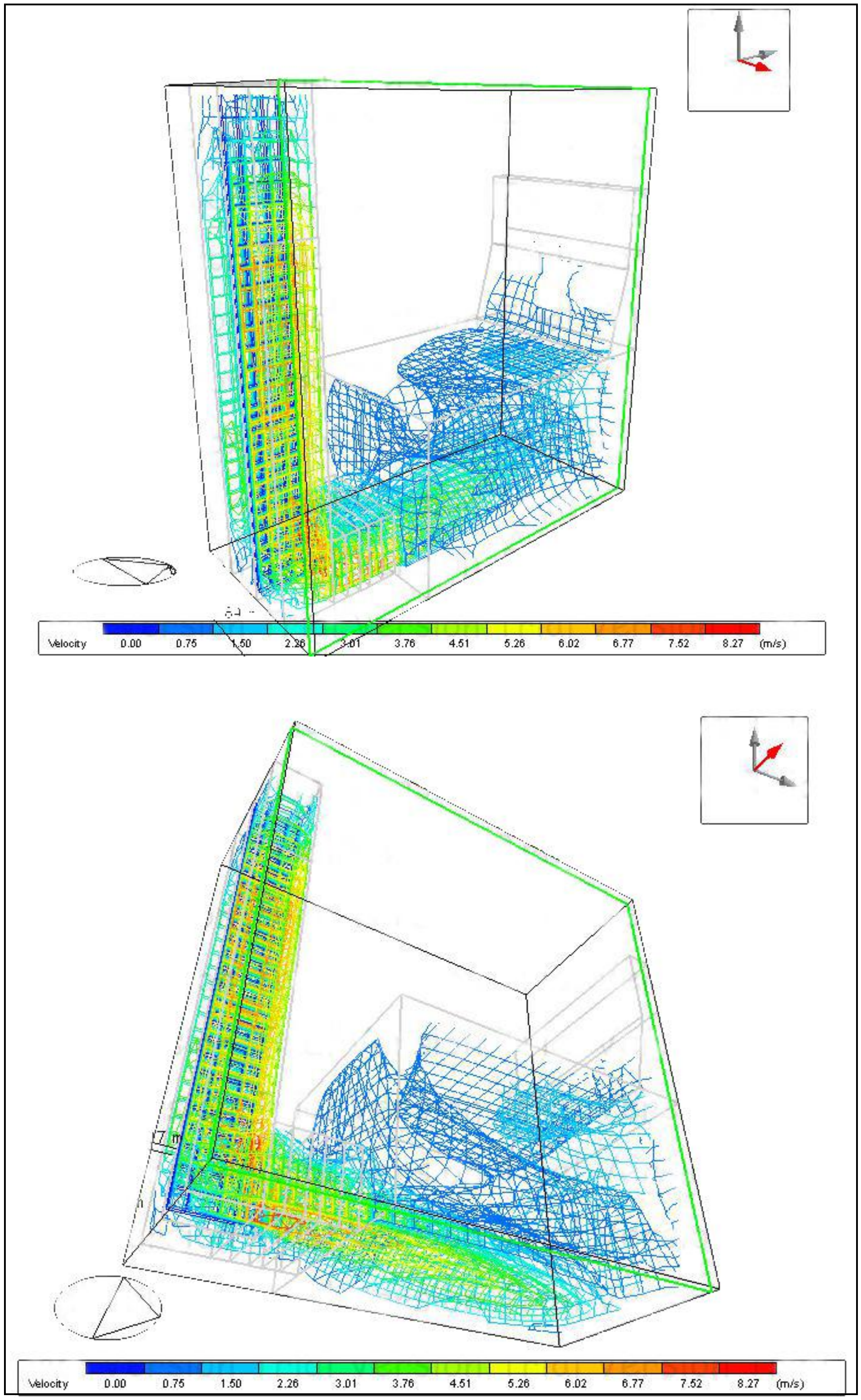


Figure 5-23: Air Velocity in the Building, Aug 13, 12 Noon

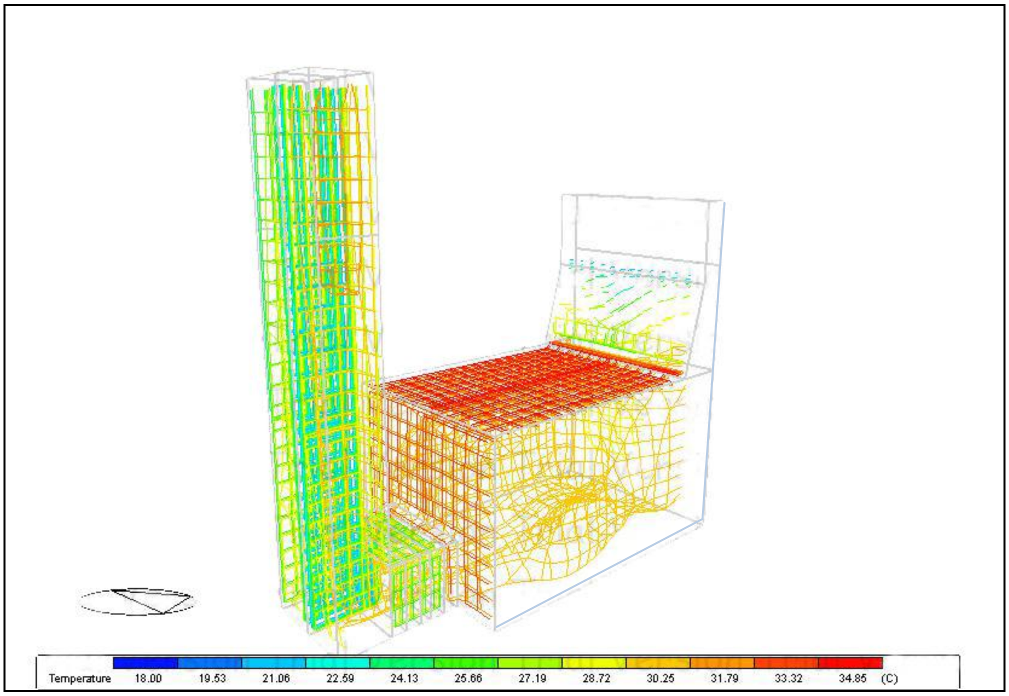


Figure 5-24: Temperature Distribution in the Building, Aug 13, 12 Noon

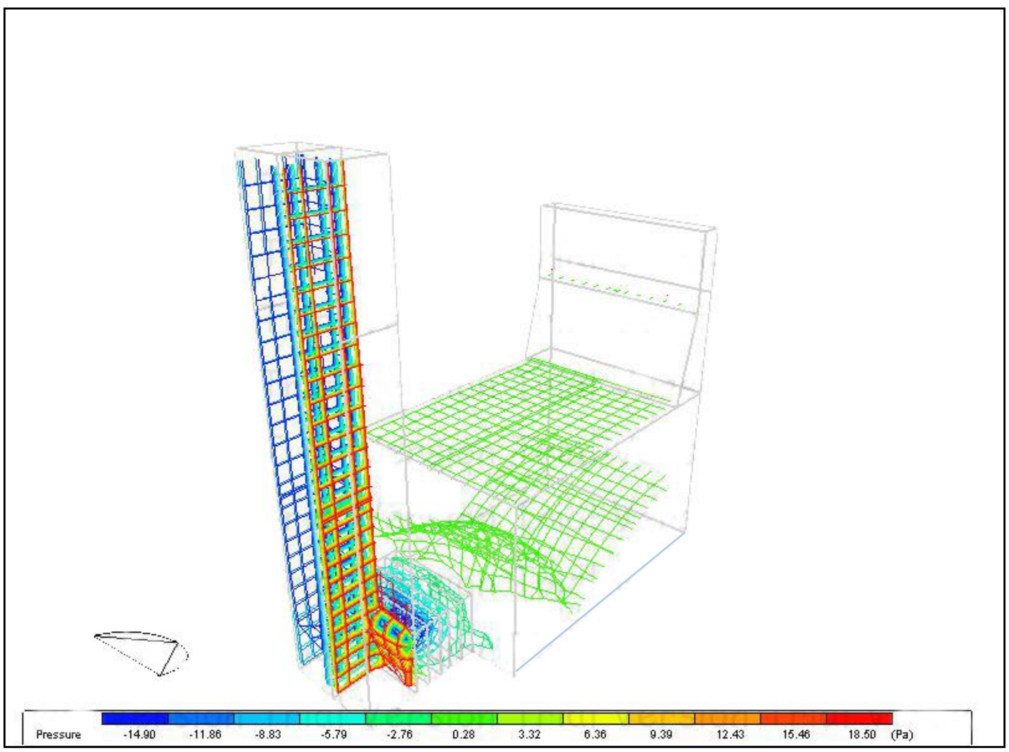


Figure 5-25: Pressure Differential in the Building, Aug 13, 12 Noon

5-3-5. Summary

The results outlined below are obtained through the simulation of a hypothetical data center in Moscow, Idaho.

- A data center with a width of 4 meters, length of 6 meters, height of 3 meters, and a heat load of 500W/m2 was efficiently ventilated through a wind catcher with openings facing the region's prevailing winds.
- Daily graphs of total fresh air and the CFD results show that both openings work effectively in different times of the year to capture the outside winds.
- The "airflow out" rates in the daily graphs show that the wind tower facing north functions as an exhaust for taking out the stale inside air.
- The sizes of inlet and outlet openings were designed for the minimum average wind speeds of the region. Therefore, the data center with the annual heat gain of 126.84MWh produced by the equipment was ventilated through external air with -136.12MWh of power.
- Temperature and humidity remain at allowed ASHRAE ranges over the year.

5-3-6. Data Center with Mechanical Cooling

For the last part of the study and with the purpose of estimating the efficiency performance of the hypothetical design, another simulation with a mechanical air-conditioning system was carried out in the DesignBuilder program using the same building specifications. In Figure 5-26, the temperature graph shows how despite the outside temperature deviations, the inside temperature is maintained at a constant level. Although the heat gain graph shows a straight line, which means a constant level of equipment operation, the cooling graph follows a fluctuating pattern. There is a reverse relationship between the cooling graph and the CO2 and electricity graphs. When cooling grows larger in negative quantities, the rates of CO2 emissions and electricity consumption grow larger in positive quantities.

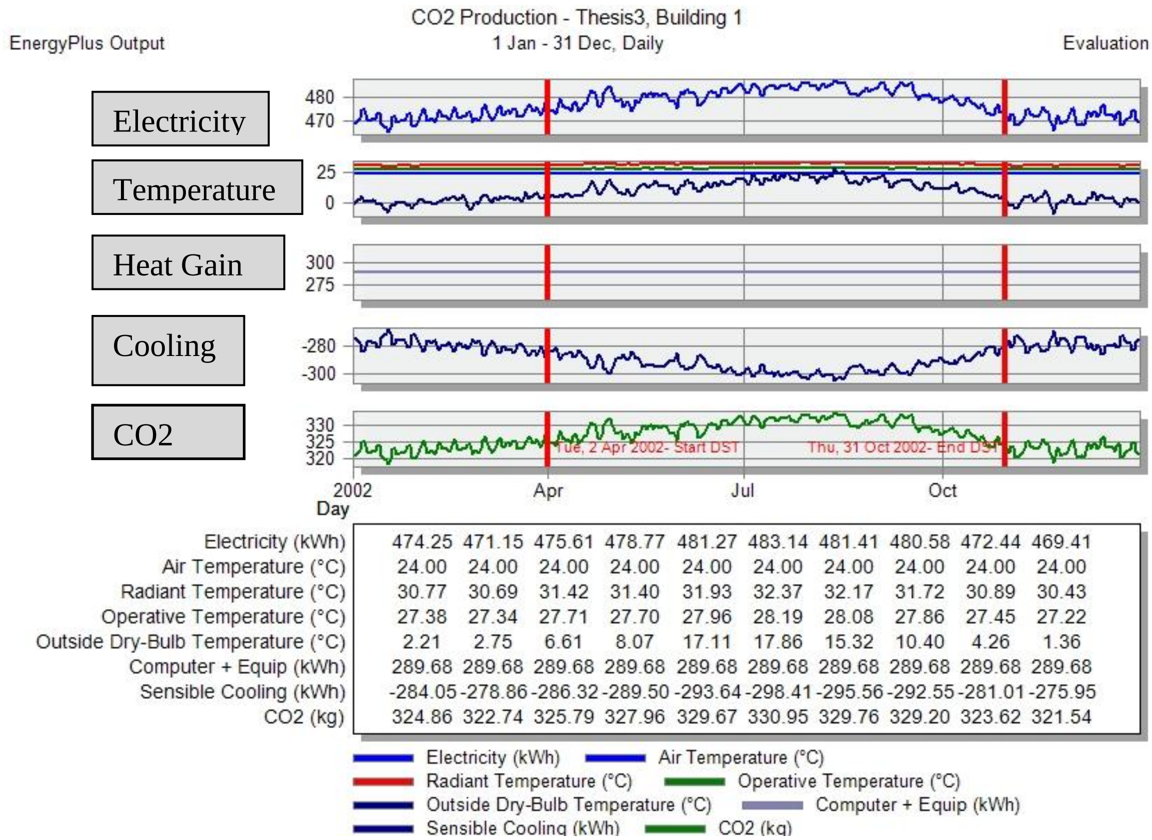


Figure 5-26: Daily Graphs of Electricity, Temperature, Heat Gain, Cooling, and CO2

Annual results, demonstrated in Figure 5-27, show the amounts of total electricity consumption and generated CO2. Figure 5-28 illustrates the same annual results for the main simulation with natural ventilation. A comparison between the two cases shows:

- Total annual electricity consumption of the data center including consumption by the computers using natural ventilation is 133.18 MWh and using mechanical air-conditioning is 174.10 MWh.

- Total annual CO_2 emission in natural ventilation is 91.28 kg×10^3 and in mechanical air-conditioning is 119.26 kg×10^3.

Both rates confirm the Chapter 1 assertion that the percentage of energy consumption for cooling process in data centers is about 30% of the total consumed energy.

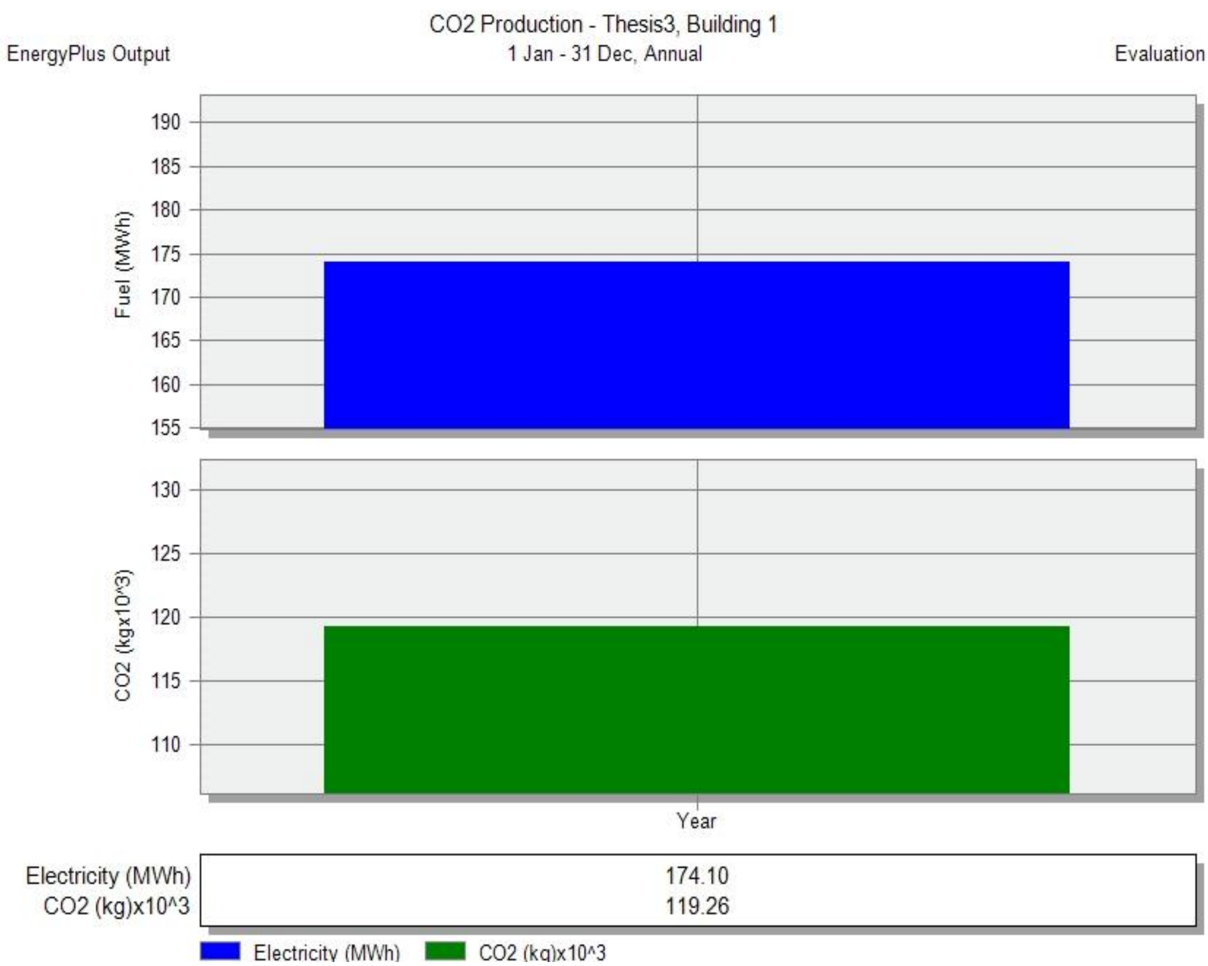


Figure 5-27: Annual Electricity and CO2 Graphs with Mechanical Air-conditioning

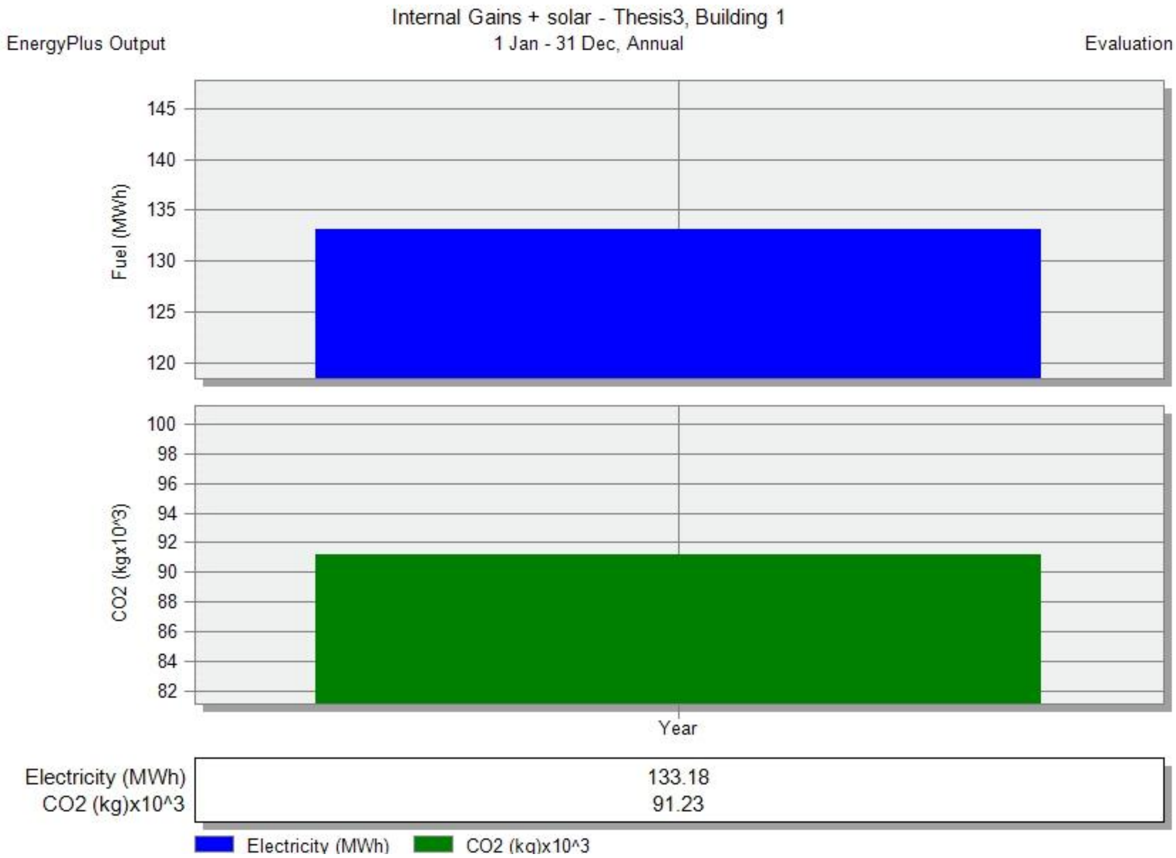


Figure 5-28: Annual Electricity and CO2 Graphs with Natural Ventilation

5-3-7. Other Considerations

The simulation results demonstrate that the wind catcher is a viable, sustainable solution for the cooling of data centers. There are some issues, beyond the scope of this thesis, that need to be addressed in more depth, which will result in a more successful cooling system. Some of these issues are listed below:

- As mentioned in chapter 1, the contained air distribution is the most efficient pattern of airflow in data centers. Therefore, the application of this system using a hot air return plenum would prevent the mixing of hot and cold air in the room. This will help keep the equipment in a safer condition and also increases the overall efficiency of the ventilation system.

- Wind catchers are able to capture winds at higher levels. At those levels, the air is cleaner and winds carry less dust. On the other hand, based on the ASHRAE standards, data centers should be kept clean to Class 8 of ISO clean rooms [122]. These rooms are rated by the amount of particles allowed per cubic foot and distinguished by a class system. Particle concentration goes up as clean room classification goes up in number. The higher number means the environment is less strictly regulated [123]. Although ASHRAE recommends using MERV 11 (Minimum Efficiency Reporting Value) filters to filter the outside air, for data centers with airside economizers, the choice of filters to achieve ISO class 8 cleanliness depends on the specific conditions present at that data center [124]. For example, in the proof-of-concept study that Intel set up in New Mexico (mentioned in Section 2-3), minimal filtering for particles was used; i.e., a standard household air filter that removed only large particles from the incoming air. The failure rate was only 0.63% higher than Intel's main data center with conventional HVAC system [125]. Therefore, a minimal filtering should be considered to keep the internal conditions at allowable ranges.

- One type of commercial wind catchers uses a fan running by the electricity generated through a small solar panel installed on top of the wind catcher (Sola-Boost system) [84]. This green strategy can be applied to wind catchers for cooling data centers to counteract the rare reductions in ventilation rates caused by decreases in wind velocities or in the case of using air filters.

Chapter 6: Conclusion

Among other principles, the Universe is established based on the fundamentals of "balance". All creatures consider this rule and instinctively live in constant interaction and balance with the other occupants of the world. But humans, as the most intelligent creatures, deliberately give themselves the right to interfere in major aspects of life on the earth. As a result, the hands of humanity have vastly transformed the environment. This transformation has had its biggest impact in the most recent two or three centuries. Pollution, ecosystem destruction, and natural resource depletion are some of the problems that this transformation has caused.

The acceleration of modern life has not only affected individuals' lives, but it has also made footprints on the natural environment. Unfortunately, most often, technological developments intended for improving the human life have had negative impact on earth's closed cycle ecosystem. Mechanical technological devices, as double-edged swords, play a key role in the design and implementation of the built environments.

Energy demanding facilities, such as IT infrastructures, have had an exponential growth due to the ever-growing computing requirements of modern life. Data centers are among the most energy consuming facilities that are growing rapidly worldwide due to the dependency of today's life on Internet and computational services. For example, the ICT (Information Communications Technology) industry produces the same amount of annual CO2 emissions (2% of the global amount) as the aviation industry [126]. In 2011, the electricity sector, with 33% of the U.S. total, was the largest source of U.S. GHG (Greenhouse Gas) emissions [127]. The computing and data center sectors are among the major consumers of electricity with the mechanical refrigeration cooling systems accounting for a third of the electricity consumed by these sectors. The current global warming, ecosystem depletion, and energy crisis have presented a need to reconsider the issue of sustainability related to this sector.

Moving forward at high speeds has kept us from looking at the past while at the same time one of the most effective ways to respond to the future needs is to learn from and be inspired by the past. Over thousands of years, built environments have been constructed to provide comfort by only using natural forces. Architecture, as the most important tool involved in shaping the built environment, plays a major role in this process. Over the centuries, vernacular architecture has reached a climax of balance between preserving the environment and changing it to better suit mankind's needs. The expansion and the growth of architecture in general benefits from enriched vernacular architecture. Harmony and balance integrated in the vernacular architecture presents wonderful, sustainable solutions for achieving natural air conditioning in suitable climates. Reconsideration of the sophisticated solutions such as wind catchers for natural ventilation can open new doors in the field of sustainable architecture for one of the most modern facilities such as data centers.

A wind catcher is one of the vernacular architecture elements that can provide efficient ventilation through natural forces: wind and buoyancy effect. This feature on the rooftops of public or private buildings such as mosques and family homes, and even none-residential structures like water reservoirs, has been providing efficient ventilation for those spaces for many centuries. In the rigid desert climates, they operate to ensure that thermal comfort inside the building is provided. These architectural elements with zero footprints are able to capture breezes at higher levels with less dust and other pollutants and bring it into the structures.

In this thesis we studied the use of wind catchers to improve the cooling process of data centers in Moscow, Idaho. We proved the viability of this approach through a detailed simulation study, using the “Designbuilder” simulator, on a hypothetical data center in the Moscow, ID region. The results demonstrated that we could efficiently ventilate a reasonable size data center using a wind catcher and a wind tower functioning as chimney. More specifically, the studied data center with 120.84MWh heat gain could be ventilated through external air with -136.12MWh heat loss using only wind catchers and with no additional electricity consumption for cooling.

Although this research focuses on a specific case study, it proves that wind catchers, as a vernacular feature, could potentially significantly lower energy demands. Through this study, it was shown that the use of vernacular architecture should not be limited to a superficial mimicking of its forms, symbols, and signs. Understanding the underlying conceptual foundation behind vernacular architectural components would allow modern architecture to find best solutions for the most complicated issues of today’s communities. These are often solutions that, by utilizing natural resources, balance the relationship between the buildings and the surrounding environments. In this way, architecture becomes a tool in the hands of humanity to make compatible and harmonic changes to the nature surrounding him.

In summary, earth is a planet that we inherited from our ancestors and are responsible to give to the future generations in a habitable condition. Any attempt aimed at reducing the negative effects of energy generation (such as CO_2 emissions in many cases), is a step in the right direction. This project has been attempting to make a small contribution towards this end goal by offering green, sustainable solutions for the design of data centers. The IT and data center sectors are among the most energy consuming industries globally. This thesis proposes the use of wind catchers to assist with the thermal management of the data centers using wind as a natural, free, and green resource. Our simulation study demonstrates the viability of the proposed solution especially in climate regions similar to that of the Moscow, Idaho area. We conclude that this study points to a new research direction for the construction of more sustainable IT and data center facilities.

Chapter 7: Future Directions

Currently, due to strict construction codes, the data centers are categorized as semi-industrial buildings. One of the main reasons for this categorization is due to the notion of isolating the data centers within other buildings or preferably constructing them in standalone, remote areas. Because of the interest in and growth of sustainable designs, architectural specifications of these buildings are being reconsidered with an eye towards energy efficient, green solutions.

Consultant companies, like ARUP Associates, focus on the design of more environmentally friendly data centers while giving high priority to aesthetic features of the buildings. The Citie data center, in Frankfurt, Germany, designed by ARUP Associates is shown in Figure 7-1. The tall green wall provides a tranquil sight for the main façade. The Meeza data center in Qatar, also designed by ARUP, shown in Figure 7-2, is another example of a thoughtful design. However, here the main building used for housing the servers, Figure 7-3, still looks like an industrial structure. Adding architectural features like wind catchers can change the design process and give specific aesthetic characters to these rigid looking buildings.

Figure 7-1: Citi Data Center, Frankfurt, Germany [128]

Figure 7-2: Meeza Data Center, Qatar [129]

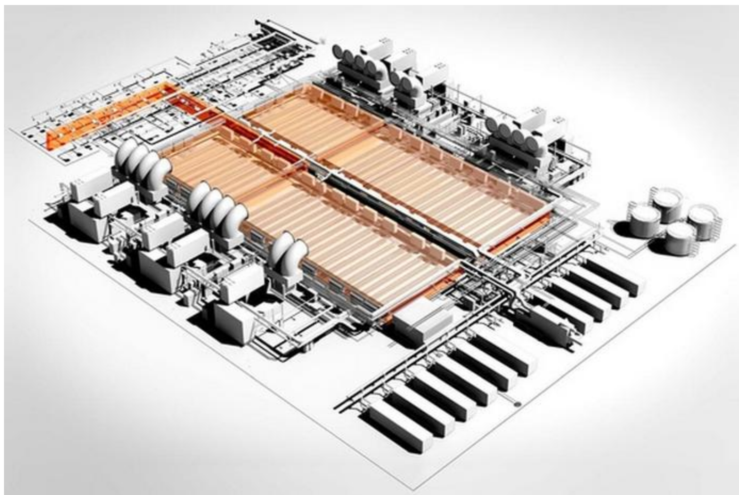


Figure 7-3: Meeza Data Center, Servers Room Building [129]

Based on ASHRAE ranges, in regions with hot-arid climates, energy-free cooling is not a practical option. Adding evaporative cooling system to the wind catchers will make them a viable natural solution for the cooling of data centers in these regions. Evaporative cooling not only lowers the air temperature to the desirable levels, but with an increase in pressure differentials [130], it results in higher ventilation rates. This strategy in wind catchers has been successfully used for centuries in the Middle Eastern countries. This solution may also lower the air particles density to the acceptable standard levels (discussed in Section 5-4.)

Further studies for the application of wind catchers in hot and humid climates may show the possibility of using this passive device in such climates as well. Many scholars do not propose employing wind catcher in the extreme hot and humid climates. The reason is that they believe the buoyancy effect in these climates is not significant enough for the optimal operations of wind catchers [41]. On the other hand, wind catchers, shown in figure 7-4, have been working effectively for centuries in coastal cities, such as Bandar Lengeh, Iran, with high mean temperature and humidity levels. Therefore, further studies for the application of wind catchers for cooling data centers in hot and humid climates may result in the expansion of the utilization of this passive device in new vast regions.

Figure 7-4: Wind Catchers in Bandar Lengeh, Iran [131]

In summary, due to the direct relationship between a wind catcher's functionality and the climate in which it is located, any new study for the application of wind catchers for cooling data centers in various climates may open new doors for the construction of more energy-efficient and green IT facilities.

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