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EFFAT UNIVERSITY
COLLEGE OF ENGINEERING
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING (ECE)



Design and Development of a Hybrid Active/Passive Cooling Smart System in Buildings Using a Windcatcher

A thesis submitted in partial fulfillment for the degree of Master's in Science in
Energy Engineering (MSEE) per the requirements of Effat University

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APPROVAL PAGE

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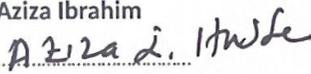
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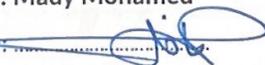
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DECLARATION

I hereby declare that this thesis titled " Design and Development of a Hybrid Active/Passive Cooling Smart System in Buildings Using a Windcatcher " is based on my original work except for quotations and citations been duly acknowledged. I also declare that the proposed dissertation has not been previously or concurrently submitted for the award of any degree at Effat University, any other university or institution.

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Date:

Globally, most building energy consumption is associated with heating, ventilation, and air conditioning systems (HVAC). Building energy consumption increased from 115 EJ in 2010 to nearly 135 EJ in 2021, accounting for 30% of global final energy consumption. In 2021, electricity will account for approximately 35% of building energy use, up from 30% in 2010. Space cooling, in particular, saw the greatest increase in demand across all building end uses in 2021, increasing by more than 6.5% over 2020. This study aims to set design guidelines to reduce energy consumption in building sector by proposing a hybrid active/passive cooling smart system. This can reduce energy consumed by the electricity grid by achieving natural ventilation through wind catchers. The later is a historical architectural element used in buildings to provide cross ventilation and passive cooling. The architectural modeling of the proposed system's design is conducted using Autodesk Revit. The smart controlling system is implemented with Fuzzy logic in MATLAB Simulink. Moreover, the accuracy of the system is improved by a PID tuning based on Backpropagation Neural Network. The results confirmed the effectiveness of the methodology used.

Keywords—Active/Passive, Smart System, Cooling, Wind catcher, Fuzzy Logic, Backpropagation.

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A. Overview

There is no doubt that the development of air conditioning (AC) systems for the built environment which operate on refrigeration units has been revolutionary in many ways, from assisting in curing patients in hospitals and increasing productivity in factories, to creating comfortable thermal conditions in buildings during the hot summer days of the year [1]. AC gives users control over their thermal environments and allows them to mechanically reproduce the best aspects of the outdoor weather indoors [2]. But to understand the value of passive cooling, it was important to become familiar with the share of energy and electricity consumed, as well as the environmental impacts imposed by the building sector in general and AC systems in specific (See Figure.1). This sector, along with human activities, are a major contributor to the current unprecedented rise in global surface temperatures where 16 of the 17 warmest years between 1880 and 2016 have occurred since 2001 [3]. Globally, Most building energy consumption is associated with heating, ventilation, and air conditioning (HVAC) systems. Building energy consumption increased from 115 EJ in 2010 to nearly 135 EJ in 2021, accounting for 30% of global final energy consumption. In 2021, electricity will account for approximately 35% of building energy use, up from 30% in 2010. Space cooling, in particular, saw the greatest increase in demand across all building end uses in 2021, increasing by more than 6.5% over 2020 [3].

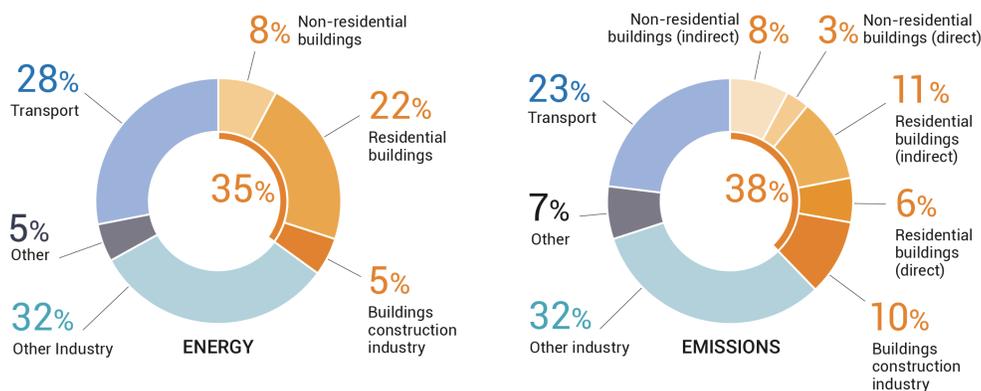


Figure .1 Global share of buildings and construction final energy and emissions, 2019 [4]

In the non-organization for Economic Cooperation and Development nations such as India and China, delivered energy consumption in buildings is expected to grow at nearly three times the growth rate of the OECD nations [5]. Additionally, building sector carbon dioxide emissions at the global level is predicted to rise 20 percent between now and 2035 [5].

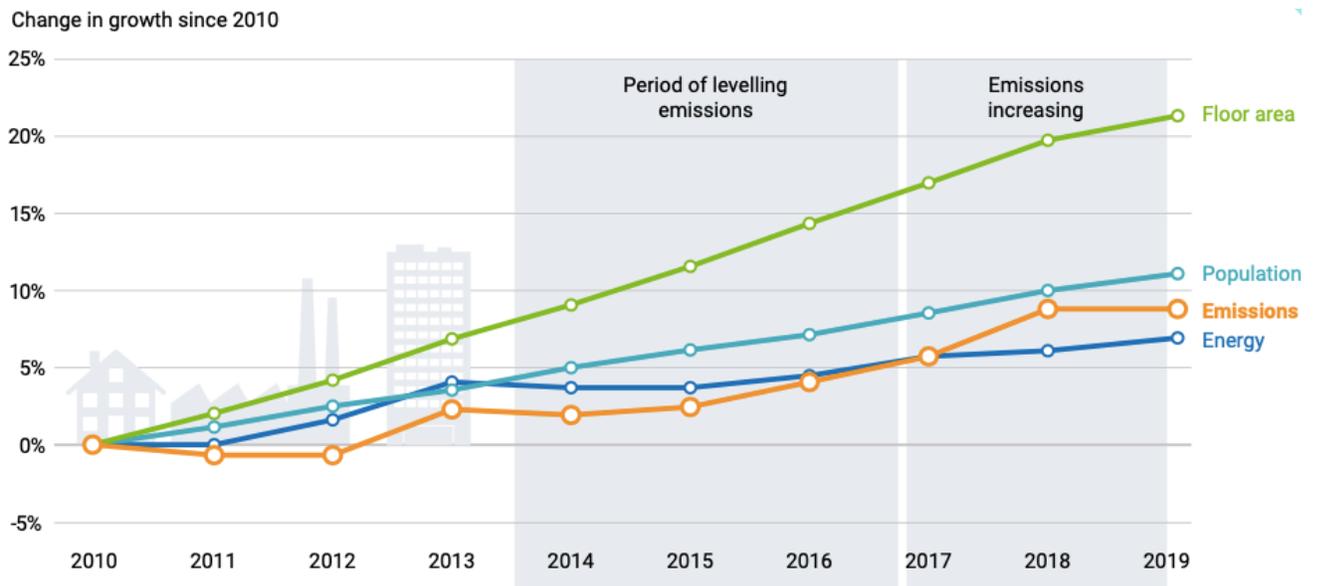


Figure .2 Change in global drivers of trends in buildings energy and emissions 2010-2019 [4]

AC is one of the main causes of environmental problems associated with ozone depletion and global warming, due to the environmental properties of refrigerants that are used as working medium in AC systems [6] AC in America is responsible for a quantity of carbon dioxide equivalent to what would be produced if every household in the U.S. bought an additional vehicle and drove it 7,000 miles per year on average [7]. Globally, cooling constituted 5 percent of the total space conditioning emissions in 2000 and is predicted to be responsible for 70 percent of the emissions from heating and cooling by 2100, mainly due to climate change [8]. There is a need for alternatives or complimentary to AC

systems and passive cooling techniques are one of the most energy efficient, environmentally friendly, and cost-effective solutions that can address the issues associated with AC. Passive cooling has received considerable attention recently and its development is reaching a phase of maturity on systems that utilize the different heat sinks, namely the ambient air, the water, the ground, and the sky [9].

The appearance of this cooling process integrated with building elements, specifically wind catchers, is dated back to 900 A.D. when wetted surfaces, such as pools and fountains, were placed at the tower outlet to further cool the air that has been partially cooled through sensible heat exchange with tower thick walls made of brick or stone [9].

Further, Saudi Arabia has a desert climate characterized by extreme heat during the day with summer temperatures frequently exceeding 45°C, making a high cooling demand in the building, Thus, high energy consumption. Buildings in Saudi Arabia consume 80% of the energy production of the country, 70% of the energy consumption is dedicated to ventilation means that air conditioning uses nearly 50% of the country's electricity [10]. As a result, this study aims to reduce energy consumption in buildings by utilizing wind and solar energy for cooling and ventilation in buildings in Saudi Arabia and any place that is characterized by hot climate to achieve natural ventilation and thermal comfort, through proposing a design of a hybrid active/passive smart system for cooling in buildings.

B. Research Aim and Objectives

1) Aim

Propose a hybrid active/passive smart system design to reduce energy consumed from the grid for cooling in buildings by achieving natural ventilation through a wind catchers.

2) Objectives

- Review different smart systems used in buildings to identify the different algorithms and techniques used (Active).
- Investigate previous wind catcher system designs to set a group of design decisions (Passive).
- Define a hybrid active/passive proposed system component to further simulate the system .
- Design an architectural model and the control system model of the proposed system.
- Discuss the findings and results.

C. Significant of the Study and Contribution

The Kingdom of Saudi Arabia set ambitious goals in its national transformation program and Vision 2030 to step away from oil reliance and shift resources expended on oil and gas exploration activities to other higher-value uses. This goal is accomplished by setting an energy roadmap to supply 10% of the country's energy consumption from renewable sources, with an initial target of 3.45 GW of renewable energy production by 2020 and 9.5 GW by 2023. Saudi Arabia is ideally located at the center of the sunbelt and has an excellent potential for sun irradiation across most of its regions. Also, it is ideally located in the Hadley cell and has an excellent potential for wind energy along the northeast, central regions and mountains in the western region.

Thus, this paper aim and objectives meet the 2030 vision of Saudi Arabia by utilizing the use of wind energy to decrease the energy consumption and achieve thermal comfort in building. Further, this study will fill the gap of the lack of in depth researches of a hybrid active/passive smart system with a wind catcher.

D. Outline of the Thesis

This thesis is divided into five chapters. Chapter 1 presented the thesis introduction. Chapter 2 presents the literature review, which investigates different smart system algorithms, PV system and wind catchers. Chapter 3 illustrates the thesis methodology. The following chapter presents the results and discussion. Finally, this thesis ends with a conclusion and a constraints of the study.

III.

LITERATURE REVIEW

1. Active Systems

Active cooling is a heat-reduction technology used in electronic devices and indoor buildings to ensure proper heat transfer and circulation from the inside. Active cooling, unlike passive cooling, is fully reliant on energy expenditure in order to function [10]. To dissipate heat, it employs a variety of mechanical systems that use energy. It's typically used in systems that can't keep their temperature under control through passive techniques. Active cooling systems are often powered by electricity or thermal energy, but certain systems can also be powered by solar energy or even hydroelectric energy. They must be well-maintained and long-lasting in order to execute their required functions; otherwise, harm to items may occur. Indoor air conditioners, computer fans, and heat pumps are all examples of commercial active cooling systems. The most used in the residential sector are three: fans, evaporative coolers and heat pumps (compression and absorption cooling machines) [11]. The need for air conditioning in buildings is a necessity that not only affects the health and comfort of people inside, but also their productivity [11].

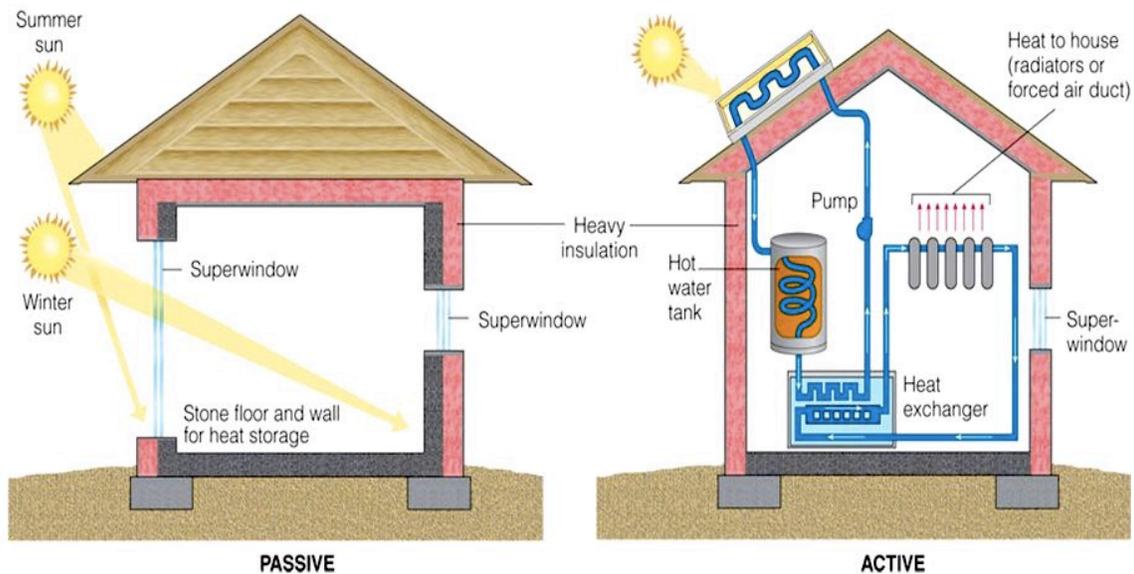


Figure .3 Active and passive system illustration [12].

2. Passive Systems

Passive cooling refers to technology or architectural features created to cool buildings with little or no energy use to increase their energy efficiency. When energy is consumed, it is insignificant compared to the energy consumed by active procedures. It is also frequently requested to be powered by renewable energy sources [11].

Using passive cooling techniques is an effective solution for addressing issues associated with AC systems. Many buildings worldwide utilize the passive cooling system in some form, but it remains limitedly optimized to just a few in comparison to the active system. While all surveyed energy-efficient and cost-effective structures were thermally comfortable with this method applied globally, there is still more that can be done for its advancement as an option among many other cooling techniques available today [10].

Table 1. Comparison between the maximum reviewed and simulated temperature drop of the cooling systems [11].

Technique	Reviewed temperature drop (°C)	Simulated temperature drop (°C)	Error (%)
Active methods			
Fans	~5	~6	17
Evaporative coolers	~15	~7	47
AC	> 20	> 28	28
Passive methods			
Shading systems	~3	~1	33
PCM	NA	~7	NA
Passive cooling shelter	> 20	~17	15
Heat sinks	~6	~4	33
Thermal capacity	NA	~16	NA
Radiant heat barriers	~13	~13	0
Eco-evaporation cooling	~6	~7	14
Natural ventilation	~15	~13	13
Solar-assisted AC	> 20	> 28	28
Intelligent facades	~10	~5	50

3. Smart System

Smart systems combine sensing, actuation, and control functions to describe and analyze a condition, and then make predictive or adaptive judgments based on the available data, resulting in smart actions. Most of the time, the system's "smartness" is due to autonomous operation based on closed loop control, energy efficiency, and networking capabilities. Different smart systems have been studied, with application of the traditional models and structures, in order to enhance warm generation, cooling, energy saving and reduction of costs [13].

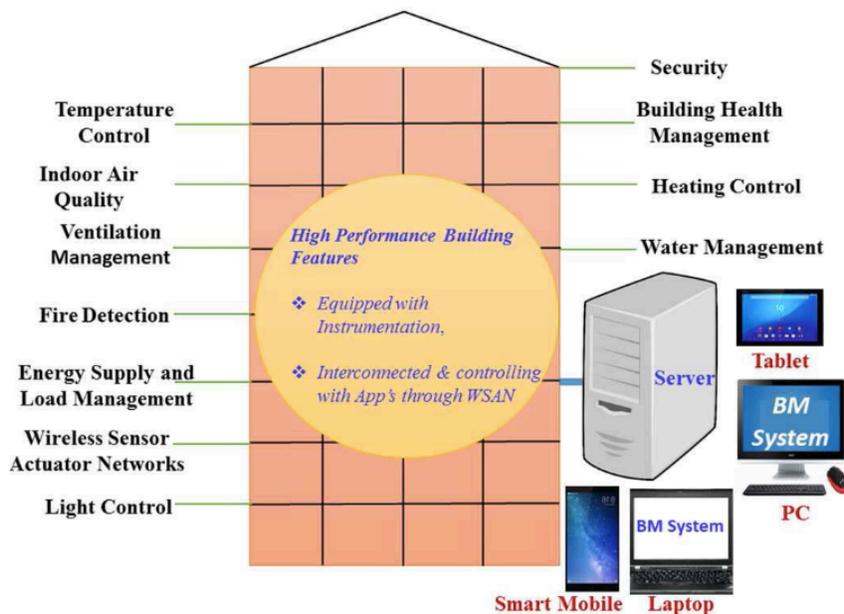


Figure .4 Schematic representation of an intelligent building [14].

The integration renewable energies and power storage in distribution facilities is one important feature that makes smart system so desirable, it not only helps users save money by using less fossil fuels for generating electricity; it also allows people to use non-renewable resources, such as coal or nuclear plants, without producing any harmful wastewater during industries which could poison the environment. However, scientists have focused on the use of smart systems in residential buildings in order to enhance the energy saving, using different technological systems and architectures [14]. Ma and Li (2020) published a paper regarding the hybridized intelligent home management systems, where the domestic energy control system

is the main component of the smart grid [15]. The proposed approach provides a sophisticated way to use renewable energy while minimizing costs. In this model, it is believed that all appliances utilize constant quantities of power at all times, rather than just occasionally, as may occur in real-world settings such as people's homes or workplaces, where there are fluctuations based on when you use particular equipment such as lights. Their strategy reduced energy consumption by 48% while maximizing renewable energy utilization by 65% [15].

3.1 Definition and characteristics

When it comes to smart systems, there are different definitions depending on the infrastructure, scope of work, destination and desired outcome. However, all scientists agree that smart systems provide enhanced options for energy saving, reducing the usage of natural resources (such as gas, coal, wood and others), replacing these sources with renewable energy coming from the sun or the wind [16]. The smart home is a house in which interconnected devices and appliances are performing certain actions to monitor energy, optimize its usage for savings [16]. The smart home represents a future where people can control and manage their own green energy sources. This will make them more oriented towards an environmentally conscious lifestyle, which in turn satisfies the needs of this new era, by giving consumers what they want: intelligent homes that respond with flexibility to changing conditions without fail or delay [16].

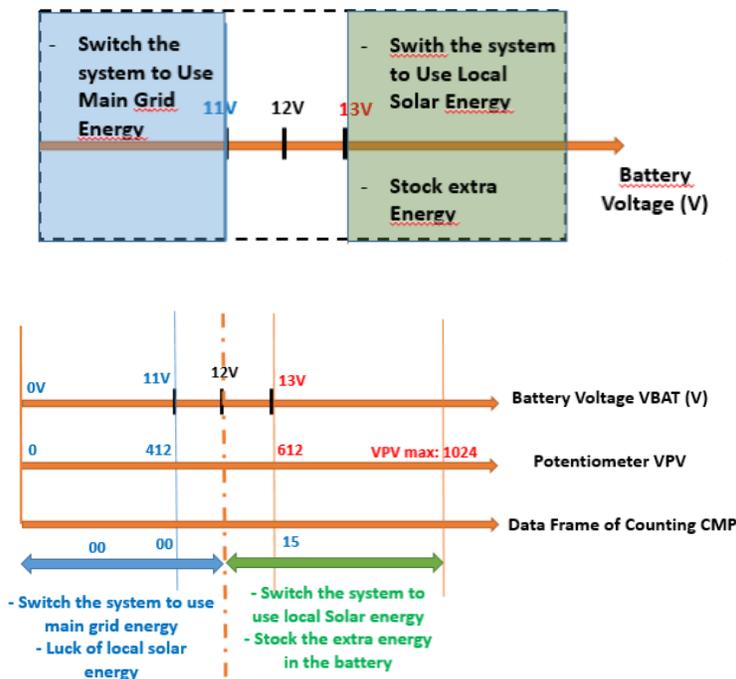


Figure .5 A proposed smart energy system [17]

Ullah and Hussain (2019) investigated smart homes and buildings using optimized algorithms to develop a more effective energy management system. The Moth-Flame Optimization (MFO) and Genetic Algorithm are two novel algorithms developed for an Energy Management System in smart homes. It's no surprise that in a world where we're constantly looking for ways to enhance our daily lives, there's a growing interest in discovering new technology that can accomplish just that. Algorithms, in fact, are a potential solution because they serve many different purposes, such as optimizing user experience or assisting with search engine results, and yet they all share one thing: their ability to simplify tasks by reducing the amount of human input required while still achieving desired outcomes efficiently enough to avoid end user frustration levels during use [18].

The smart homes have been the subject of study to more researchers in more recent years, since the implementation of a management system design can lead to improved efficiency and comfort [18].

3.2 Algorithms

In the following sections, we'll go through the most prevalent learning algorithms used in smart or intelligent-based models.

Machine Learning is a subfield of artificial intelligence that, according to Tom M. Mitchell, a computer scientist and pioneer in the field, is the study of computer algorithms that allow computer systems to automatically improve through experience [19]. One of the ways we intend to reach smartness is through machine learning.

Machine learning is the process of machines learning from algorithms that allow them to adapt to informations from their surroundings. Through mapping functions from a training dataset (supervised learning) or any form of the dataset (unsupervised learning), or even a sequence of decisions in an uncertain or complex system, ML allows non-linear relationships to be determined, such as the relationship between energy demand and other relevant factors [20]. Supervised learning is a sort of machine learning in which the algorithms have been pre-trained on a dataset's input–output values. When a different input (not from the training dataset) is fed into the model, the algorithm is supposed to return the proper output. Supervised learning is used to tackle classification and regression issues by predicting the proper output value given a new input. Unsupervised learning is a sort of machine learning in which the algorithm is not pre-trained on any dataset. The algorithm picks up on the input data as it comes in. Reinforcement learning is a sort of machine learning in which the algorithm learns by rewarding right outputs and punishing incorrect outputs. As a result, the algorithm gains significant time. The link between existing machine learning methods is depicted in Figure [20].

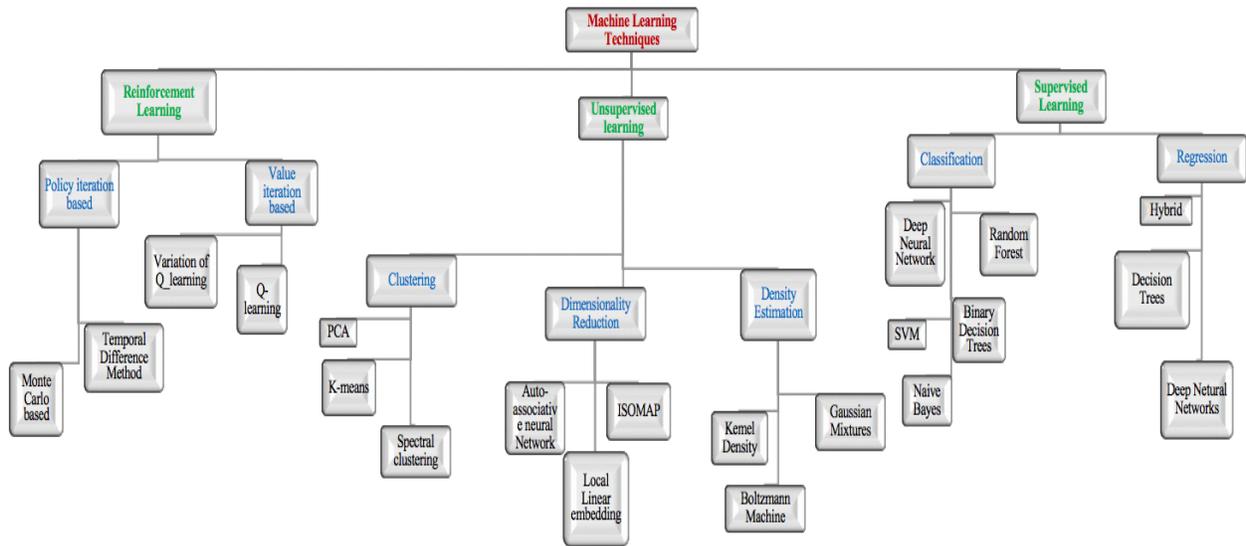


Figure .6 Machine learning approaches are categorized. [20]

Machine Learning methods

- Decision Trees:

A decision tree is a machine learning model in which classification decisions are separated into groups based on the characteristics of the input parameters, each of which is analyzed separately. This procedure begins with the basic feature and then proceeds in a tree branch-like way. A tree is made by separating the tree's root node (source set) into branch nodes (sub-sets) [20]. The division is based on a set of criteria derived from the collection's attributes and the classification's aim. Decision trees models have been applied in numerous areas in smart energy buildings, including predicting the danger of a blackout and energy storage planning and energy management in buildings.

- Random Forest

Random forest is an extension of machine learning that employs classification and regression tasks as well as numerous decision trees to increase prediction accuracy. A common approach for reducing the variance of a decision tree algorithm is bagging (bootstrap aggregation). Bootstrapping is the method of estimating a number from a sample of data. To implement the random forest approach, a fresh bootstrap sample of the training set is created and used to train a decision tree [21].

- Wavelet Neural Network

Another machine learning model that combines wavelet analysis and neural network design is the wavelet neural network. The wavelet notion is derived from the Fourier transform (FT) and the windowed Fourier transform (WFT) (WFT) [22]. The approach has been shown to be beneficial in predicting time series data for hybrid renewable residential micro-grids in order to optimize system cost and battery state of charge at the same time. [22]

- Naïve Bayes

On the Nave Bayes theorem, the Nave Bayes learning model is developed. When given previous knowledge, the theorem is used to calculate the likelihood of a guess. This learning methodology has been used to a variety of building energy issues. In their examination of building energy efficiency datasets, Prasetyo et al. employed a Nave Bayes classifier, while Bayindir et al. used it in the prediction of solar energy. Lin et al. used this technique to forecast HVAC energy using hourly data in another investigation [23].

- Artificial Neural Networks (ANNs)

In the modeling of non-linear processes, artificial neural networks are commonly employed. Natural language processing, decision making, classification, dimension reduction, regression issues, clustering, decision making, anomaly detection, and computer vision are just a few of the applications. ANNs have been widely used to anticipate power usage as well as building cooling and heating demands [24].

- Regression

Multiple linear regression (MLR) is a machine learning model based on statistical linear regression that has been widely used to estimate the monthly heating and cooling demands of residential buildings in a number of studies [25]. A support vector machine is most commonly

employed when the goal is to categorize data. The fundamental purpose of these approaches is to discover a function for all of the training data, including information on the weather, relative humidity, and solar radiation intensity, based on the achieved target. For usage with the highly non-linear energy demand function, both the MLR and SVR algorithms need to increase their forecast accuracy and resilience [26].

- Genetic Algorithm (GA)

Because of its capacity to cope with the non-linear properties of smart buildings, the GA is a heuristic search approach widely utilized in AI-based models. GA can solve both unconstrained and restricted optimization problems competently. This technique is widely used in the scheduling of residential loads in a dynamic pricing scheme with the goal of minimizing total energy costs, as well as in determining the optimal energy consumption to provide comfortable thermal conditions by selecting the optimal range of indoor temperature setpoints. Based on a mix of the GA and the teaching–learning-based optimization algorithm, Manzoor et al. created an intelligent energy management approach employing a DR program to plan home load with the goal of decreasing the cost of power [27].

- Fuzzy Logic (FL)

Fuzzy logic control models have been used more widely than other models that employ standard configuration control logic due to their simplicity (CCL) [28]. The adaptive network-based fuzzy inference system (ANFIS) is a machine learning model that blends fuzzy logic's forecasting method with a neural network's capabilities. Each learning model complements the deficiencies of the others in this hybrid arrangement, resulting in superior outcomes and performance. ANFIS is used in conjunction with a wireless sensor network to estimate demand load based on changes in indoor and exterior building temperature conditions [29].

- K-Nearest Neighbor

K-nearest neighbor (KNN) is a method of predicting the label of every new instance based on the labels of its closest neighbors in the training set after remembering the training set. KNN is commonly utilized in building energy management systems and demand studies of residential building energy usage [30].

Table 2. Different machine learning algorithms are compared and applied in smart buildings [31].

ML Models	Area of Application	Domain of Application in BMS	Advantages	Disadvantages
ANN	Modelling, forecasting, and curve-fitting of non-linear processes	HVAC energy consumption modelling	<ul style="list-style-type: none"> • High accuracy • Reasonable speed • Good for noisy data 	<ul style="list-style-type: none"> • Highly complex • Low user-friendliness
SVM	Data classification	Building energy consumption prediction	<ul style="list-style-type: none"> • High accuracy 	<ul style="list-style-type: none"> • Highly complex • Low user-friendliness • Low speed
Decision trees	Classification decision	<ul style="list-style-type: none"> • Energy storage planning • Building energy management 	<ul style="list-style-type: none"> • Reasonably accurate • Reasonable speed 	<ul style="list-style-type: none"> • Reasonably complex • Low user-friendliness
Random forest	Event forecasting and data classification	Energy consumption forecasting	<ul style="list-style-type: none"> • Reasonably accurate • Reduces over-fitting 	<ul style="list-style-type: none"> • Reasonably complex • Low user-friendliness • Low speed
Deep learning	Data prediction and pattern modelling	Energy efficient system design and modelling	<ul style="list-style-type: none"> • Reasonably user-friendly • High accuracy • Reasonable speed 	<ul style="list-style-type: none"> • Highly complex
WNN	Time series event prediction	<ul style="list-style-type: none"> • HRES operating cost optimization • Wind and solar power prediction 	<ul style="list-style-type: none"> • High accuracy 	<ul style="list-style-type: none"> • Low speed • Low user-friendliness • Reasonably complex

Fuzzy logic	Control applications	<ul style="list-style-type: none"> • Power point tracking • Control and monitoring 	<ul style="list-style-type: none"> • Reasonably user-friendly • Reasonably accurate • High speed 	<ul style="list-style-type: none"> • Reasonably complex
Hybrids	High-accuracy predictions	<ul style="list-style-type: none"> • Load forecasting • Energy generation forecasting 	<ul style="list-style-type: none"> • High speed • High accuracy • High speed 	<ul style="list-style-type: none"> • Reasonably complex
Regression	Prediction of the probability of occurrence	<ul style="list-style-type: none"> • HVAX energy consumption forecasting 	<ul style="list-style-type: none"> • Highly user-friendly • Simple structure • High speed 	<ul style="list-style-type: none"> • Low accuracy
Genetic algorithm	Problem optimization	<ul style="list-style-type: none"> • Optimal load scheduling 	<ul style="list-style-type: none"> • High accuracy • Used in hybrid mode 	<ul style="list-style-type: none"> • Low speed
PSO	Problem optimization	Operating cost optimization and energy scheduling	<ul style="list-style-type: none"> • High accuracy • Used in hybrid mode 	<ul style="list-style-type: none"> • Low speed • Low convergence rate • Fall in local optimum
KNN	Prediction	Building energy consumption analysis	<ul style="list-style-type: none"> • High speed • User-friendly 	<ul style="list-style-type: none"> • Low accuracy
Naïve Bayes	Calculating the probability of occurrence	<ul style="list-style-type: none"> • Building energy efficiency analysis • Energy generation prediction 	<ul style="list-style-type: none"> • High speed • User-friendly 	<ul style="list-style-type: none"> • Low accuracy

3.3 Applications in smarthomes

Countless researchers around the world are investigating different technologies in order to fulfill the needs of energy-efficient and smart homes. Many algorithms have been proposed for optimal use of existing energy resources. In this regard, below are summaries of various case studies that use machine learning in a building management system with different methods and algorithms. Several case studies will be explored further afterward. Case studies shown in the table will be used as a sample for the discussion in the next part of the paper (See Table below).

Table 3. Summaries of the applications

Author	Objectives	Domain	Outcomes	Algorithm\Method	Ref.
Ibrar Ullah and Sajjad Hussain, (2019)	- Reduction of energy cost - Minimization of the Peak to Average power Ratio (PAR) - Minimization of end-user discomfort.	✓ Energy ✓ Comfort ✓ Cost	The simulations through MATLAB show that our proposed algorithm has reduced the energy cost up to 32.25% for a single user and 49.96% for thirty users in a residential sector compared to unscheduled load.	Moth-Flame Optimization (MFO) algorithm and Genetic Algorithm (GA)	[32]
Yonghong Ma and Baixuan Li, (2020)	- A hybridized system that combines solar energy and energy storage services with the smart home is planned based on the demand response and time of consumption pricing is applied to programs that offer discounts to consumers that reduce their energy consumption during high demand periods	✓ Energy ✓ Cost	This showed that the proposed energy scheduling method minimizes the energy consumption by 48% and maximizes the renewable energy consumed at the rate 65% of the total energy generated.	Hybridized Intelligent Home Renewable Energy Management System (HIHREM)	[33]
Yasser AL Sultan, Ben Salma Sami and Bassam A. Zafar, (2021)	Implement an accurate home energy management system. The proposed approach aims to improve uninterrupted electricity production and provide comfortable services to families.	✓ Energy ✓ Comfort	The obtained results show that the proposed system meets the general objectives of RT-EMS.	Reel Time Energy Management System (RT-EMS) using the Multi-Agent System (MAS)	[34]
Yunlong Ma, Xiao Chen, Liming Wang and Jianlan Yang, (2021)	A model of home energy management is presented to optimize the home energy mix.	✓ Energy	an optimized simulation model for the scheduling of a new home energy management system is established. In addition, the application prospects of artificial intelligence in the HEMS are overviewed.	home energy management system (HEMS)	[35]
Alhasnaw. Jasim, Rahman, Z. (2021)	This paper devised a robust REM technique capable of monitoring and controlling residential loads within a smart home.	✓ Energy ✓ Cost	he results demonstrate and validate the effectiveness of the proposed technique, as well as the capability to track the changes of load with the interactions in real-time and the fast convergence rate.	grey wolf optimizer (GWO), artificial bee colony (ABC) optimization algorithm-based Time of Use (ToU)	[36]
Nadeem Javaid, Ihsan Ullah and Mariam Akbar (2017)	evolutionary algorithms-based (binary particle swarm optimization, genetic algorithm, and cuckoo search) DSM model for scheduling the appliances of residential users is presented.	✓ Energy	Simulation results show that the proposed model optimally schedules the appliances resulting in electricity bill and peaks reductions.	Demand side management (DSM)	[37]

Samia Shah, Rabiya Khalid, Ayesha Zafar (2017)	Present a HEMS using multi-agent system (MAS) for smart homes. The HEMS uses priority techniques with the integration of electrical supply system (ESS). Further, a bioinspired technique, binary particle swarm optimization (BPSO), is used for the optimal scheduling of appliances.	✓ Energy	Simulation results illustrate the effectiveness of the HEMS in terms of electricity cost, demand, user comfort and peak to average ratio (PAR).	HEMS using multi-agent system (MAS) for smart homes	[38]
Sadia Ismail, Hasan Mujtab, Mirza Beg, (2021)	satisfy electricity demands more efficiently. It implements strategies to reduce energy consumption during peak time or shift its usage to off-peak hours.	✓ Energy ✓ Cost ✓ Comfort	Results show that our model is computationally inexpensive, sustainable, and minimizes cost, consumption, and PAR with reduced discomfort of the user.	SPEMS (Sustainable Parasitic Energy Management System)	[39]
Saher Umer, Yasuo Tan, and Azman Osman Lim (2014)	achieving optimal system model for smart homes to reduce the risks of power blackout by applying two different criteria of power assignment for the HAs.	✓ Energy	The stability analysis verifies that the system stability is dependent on some time delay. Simulation results also help us to observe critical system behaviors such as stability and overshoot of energy waveform.	smart electric sensor (SES) and power provisioning controller (PPC).	[40]
Fatemeh Mohammadi, Ahad Kazemi, Amir H. Salemi (2021)	achieve cost reduction besides consumer risk minimization.	✓ Energy ✓ Cost	Results indicate presented risk-based GA increases the thermal and energy storage by 20.25% and 14.28% and reduces the consumer risk when a blackout occurs by increasing the spinning reserve.	Genetic algorithm (GA)	[41]

Following is a detailed exploration of selected case studies of a smart system:

3.3.1 Time-Constrained Nature-Inspired Optimization Algorithms for an Efficient Energy Management System in Smart Homes and Buildings

The key contributions of Ibrar Ullah and Sajjad Hussain work are summarized as follows: For an efficient Energy Management System (EMS) in smart homes, it has presented a novel hybrid end-user comfort-based TG-MFO algorithm. Additionally, it investigated and analyzed the performance of five bio-inspired algorithms for the residential energy optimization problem. Also, it has combined RESs and BSUs to reduce the total load and cost even more. The proposed algorithms were tested on a variety of consumer scenarios, including: (a) A single residence for a single day. (b) A 30-day in a single residence. (c) For one day, thirty various sizes of residences. (d) Thirty residences of various sizes for 30 days, compared to existing procedures. [42]

3.3.1.1 Architecture

For a dependable bi-directional power and information exchange between SG and SH, it consists of a smart meter and an EMC. A Home Area Network (HAN) connects all appliances, connected sensors, RESs, and BSUs to EMC, which is then connected to SG via a Wide Area Network (WAN). End-users regulate their energy usage activities based on utility incentives. The end-user enters numerous parameters for all appliances in EMC in each SH. The ON/OFF status of all appliances is then handled by EMC. [42]

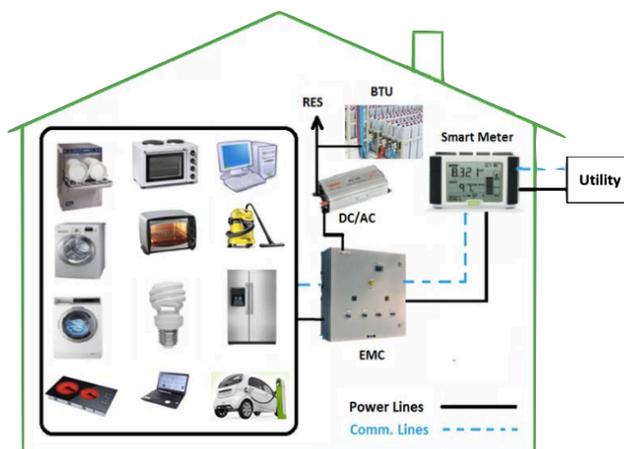


Figure .7 A typical overview of a house with smart appliances. EMC, Energy Management Controller. [42]

3.3.1.2 Appliances' Categorization and Their Energy Models

It have been divided the load according to the end-user's priorities, as:

The Fixed Load (FL): It is when consumer can start and stop these appliances any time. Ex, Refrigerator and interior lights. And elastic Load (EL): These include: dish washer, washing machine, spin dryer, electric car, laptop, desktop computer, vacuum cleaner, oven, cook top and microwave oven . [42]

3.3.1.3 RES Model

On consumer premises, photovoltaic (PV) cells and wind turbines can be employed as local power generators. These renewable energy sources can be used to generate local energy as well as charge the batteries in BSUs [42].

It is then sold back to the grid as agreed or utilized to charge batteries in BSUs for later usage, especially during peak hours [42].

3.3.1.4. BSU Model

When the energy generated by RESs exceeds the energy demand of the consumer, it is stored in batteries via BSUs, which can be used during peak hours or at night when RESs are not available [42]. The energy losses that occur throughout the charging and discharging processes in this model is ignored. [42]

The following goals are being pursued: (a) increasing consumer comfort by reducing appliance average waiting time, (b) lowering consumer electricity bills, (c) lowering PAR, and (d) integrating RES and BSU into the system to further reduce end-user waiting time. [42]

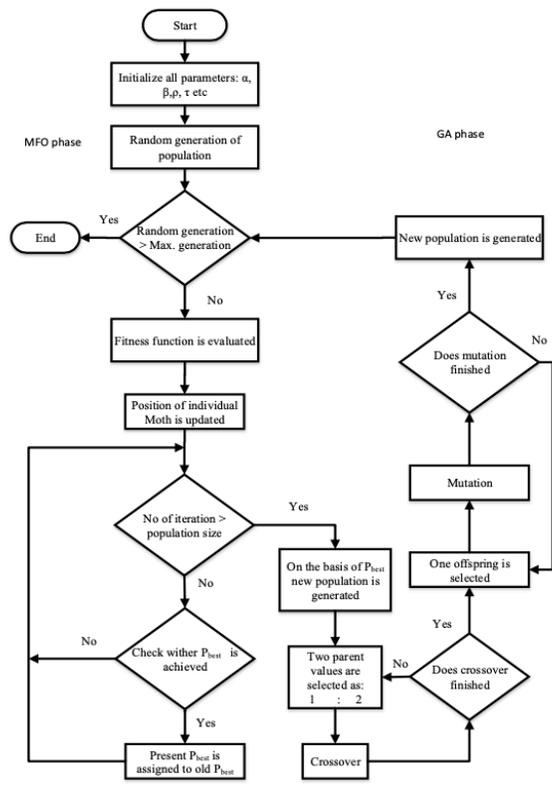


Figure .8 Flowchart for the proposed algorithm Time-constrained Genetic (TG)-MFO. [42]

In comparison to unplanned load, simulations using MATLAB demonstrate that the suggested approach has decreased energy costs by 32.25% percent for a single user and 49.96% percent for thirty users in the residential sector. [42]

It uses time constraints of a maximum average delay of 0.26–0.62 h to minimize the waiting time of home appliances. It not only lowers energy costs, but it also improves grid stability and reliability [42].

In the smart grid, waiting time is a critical component of appliance scheduling for efficient energy use. In order to save money on electricity, people frequently have to wait longer. A user wishes to start an appliance, but due to scheduling constraints, the user must wait for it to begin operating. The major goal of this project was to reduce the end-electricity user's bill while maintaining the highest level of comfort. Figure 6 shows how we used heuristic strategies for optimal scheduling to achieve our goal. In terms of achieving a near-zero waiting time for the end-user, TG-MFO outperformed ACO, CSA, GA, FA, and MFO, as shown in the graphs [42].

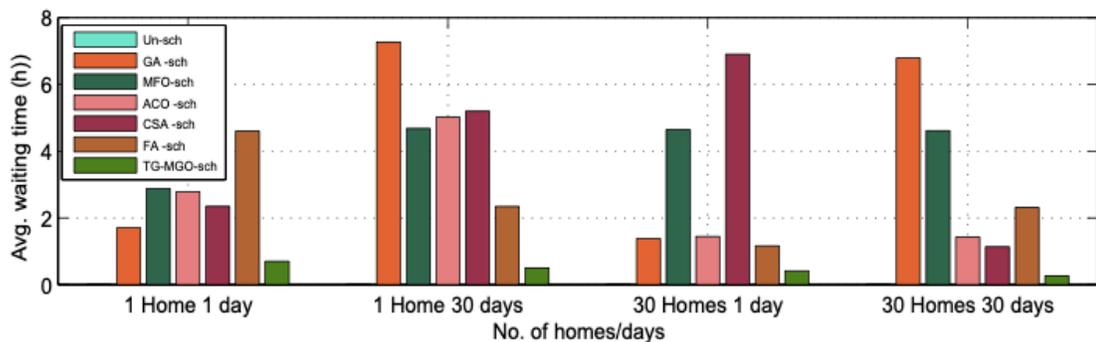
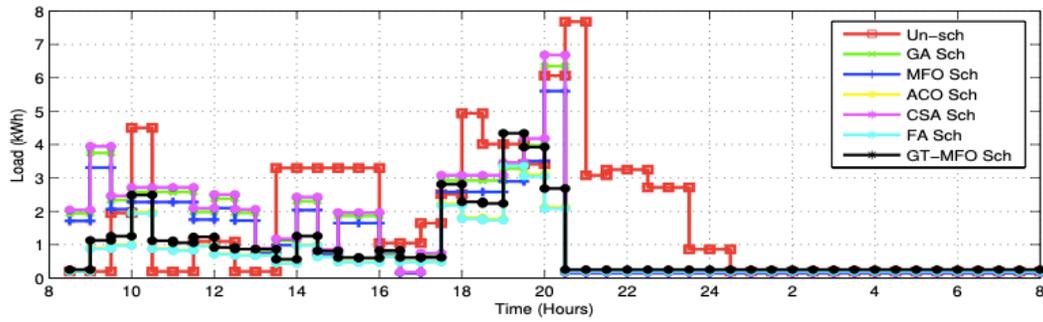
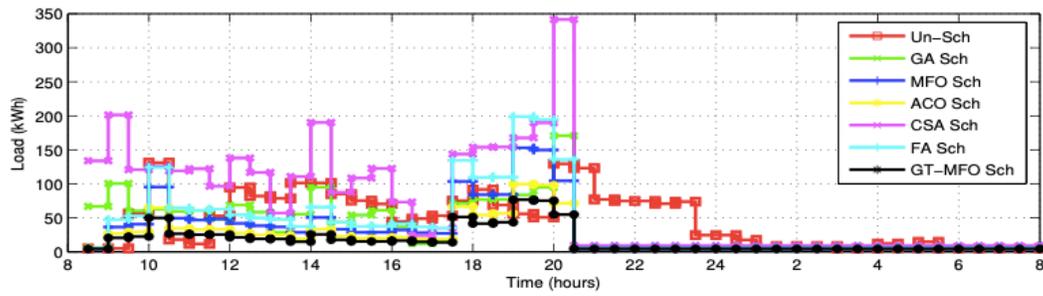


Figure .9 Average waiting time for a single home and 30 homes. [32]

The efficient scheduling of smart home equipment relies heavily on PAR. The utility confronts massive peak loads during peak hours because to high PAR, and most of the generating units are idle the remainder of the day. As a result, researchers are attempting to reduce PAR in order to achieve cost-effective load dispatch in smart grids. Figure 10 indicates that MFO outperformed FA in the case of a single home for a single day and thirty homes for a single day, but FA outperformed MFO in the case of a single home for thirty days and thirty homes for thirty days. We tried not only to schedule appliances optimally, economically, and with maximum end-user comfort in our proposed hybrid model, but also to give the lowest PAR, for the benefit of utility, and thus to further increase end-user comfort . [42]



(a)



(b)

Figure 10. The hourly load for un-scheduled and GA-, MFO-, ACO-, CSA-, FA- and TG-MFO-scheduled load. (a) The hourly load for a single home. (b) The hourly load for 30 homes. [42]

3.3.2 New Smart Home's Energy Management System Design and Implementation for Frugal Smart Cities

The architecture proposed by researchers for energy management systems in smart homes starts with the source of renewable energy, which is conducted to the controller (powered by batteries), then to a converter which develops the electrical loads. The inputs are taken into the calculation unit and the processing unit, which are both controlled by the graphic interface user apps. A proposed algorithm for smart systems combines a main smart grid and energy local mix, through an implemented Arduino card to process the algorithm [43]. The decision of using energy from main grid or local green sources such as solar power depends on if there is enough production within the building (local panel installed). Laraki concludes that a smart home energy system can help to reduce costs, using integrated consumption infrastructures, which are controlled using mobile apps [43].

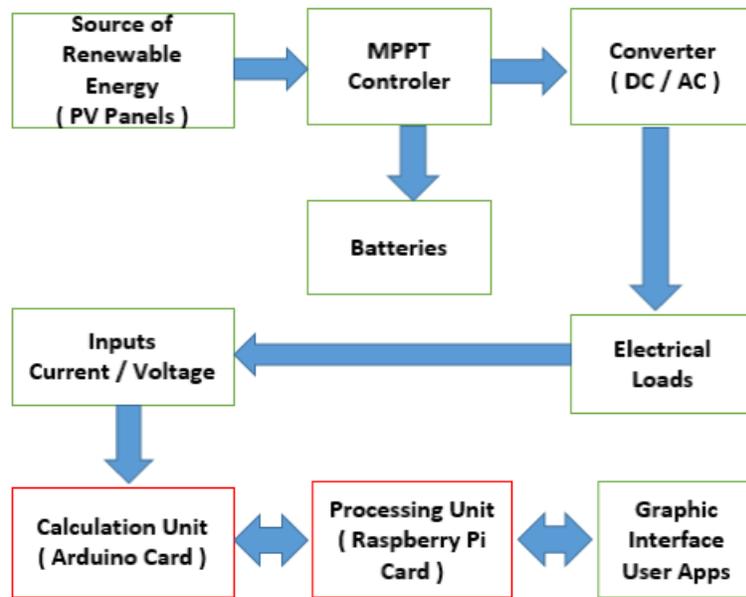


Figure .11 Laraki's proposed architecture for a smart home energy system [43]

3.3.3 Renewable Energy Management System for Smart Home

Another system architecture designed for smart home energy management systems was developed by Sinha and Khule [44]. Their paper proposes a system architecture for smart homes that simultaneously manages energy consumption and generation, leading to efficient use of resources while minimizing cost. A microcontroller based module with ZigBee is used in order control the household's lights from afar via WiFi enabled devices such as smartphones or tablets--allowing users ultimate convenience without sacrificing anything else about their lifestyles [44]. The design proposed associates the user interface with a controller interface and the system interface for renewable energy management. This system shows improved electricity generation provided by renewable resources, such as solar and wind, alternating within the first days between 5 V and 4.5 V for both solar and wind sources [44]. As a result, the electricity consumption dropped from 4.5 AH to 1.5 AH after applying the proposed architecture [44].

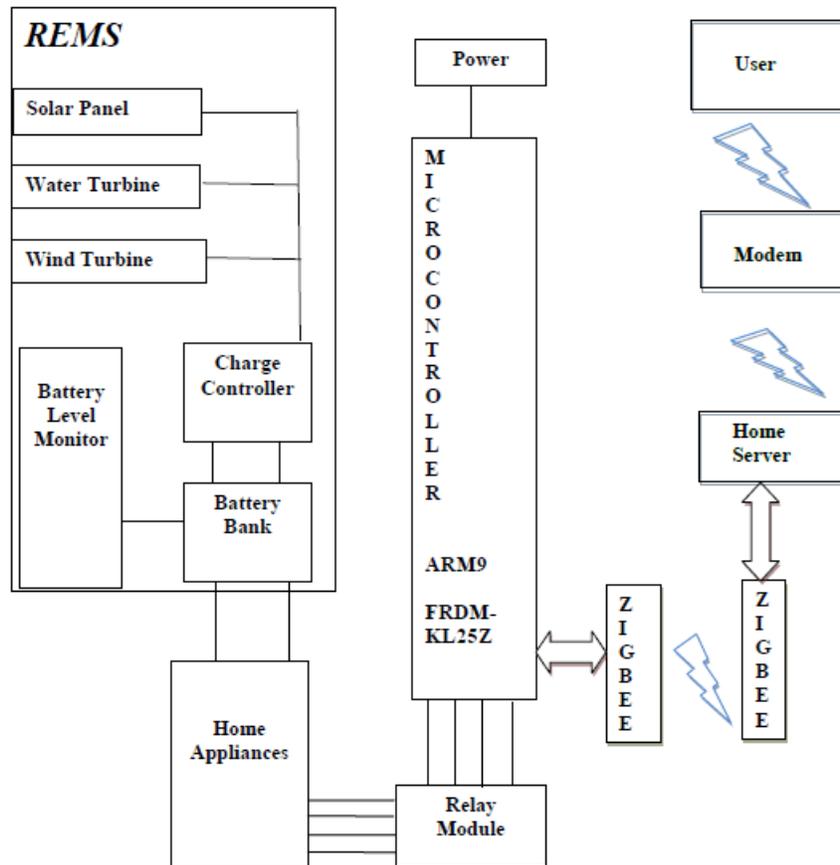


Figure .12 Proposed system architecture for smart home energy system [44]

3.3.4 Smart Home Energy Management System: A Multi-agent Approach for Scheduling and Controlling Household Appliances

Different other smart energy systems have been developed by other researchers, proposing several models and prototypes that can act in real-time [45], with different concepts and designs. The modelling systems are all aimed towards achieving progress through interconnections and interaction with sensors, algorithms and any other agents [45], in order to plan and automate the residential demands. For instance, the innovative home energy management design proposed by Sultan, Sami and Zafar represents an approach for controlling and scheduling the household appliances in different contexts , as shown in Figure .

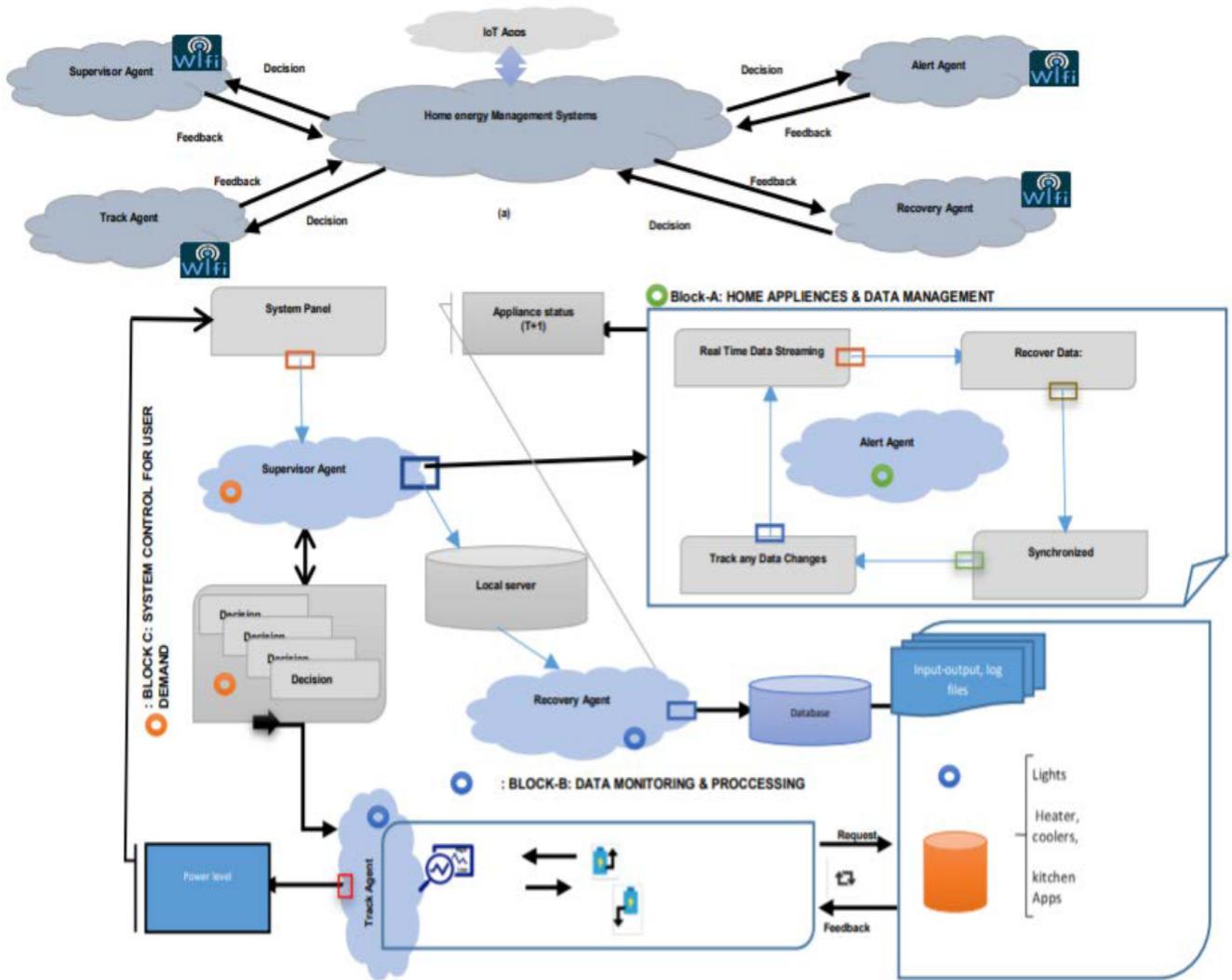


Figure .13 Sultan, Sami and Zafar's proposed smart home energy system (2021) [45]

4. Solar Photovoltaic System

4.1 Definition

Sunlight-based energy is a clean, modest, limitless energy source that can be harnessed anywhere in the world - any point where sunlight hits the outside of the earth is a prospective location to manufacture sunlight-based energy. Furthermore, because sunlight-based energy is derived from the sun, it refers to an infinite wellspring of intensity [46]. Sustainable power source advances generate energy from enormous resources. Consider the difference between producing energy using sustainable investments and doing so

with petroleum goods. Because oil, gas, and coal require a long time to form, every time one of those resources is burned to generate electricity, that finite resource is brought insignificantly closer to consumption. Using the unlimited resource, such as wind, solar, and hydropower, to generate energy is sustainable. There will consistently be steady daylight sparkling on the earth's surface. In the wake of transforming sunlight into power, there is, as yet, a limitless measure of light to convert into energy later on. That is the thing that makes sun-based force a naturally sustainable power source. [46]

4.2 Technology

Sunlight based energy is caught in an assortment of ways, the most well-known of which is with photovoltaic sun oriented boards that convert the sun's light into usable power. Besides utilizing photovoltaics to create power, sunlight based vitality is generally utilized in warm applications to warm indoor spaces or liquids. Private and business landowners can introduce sunlight based boiling water frameworks and plan their structures in light of latent sun based warming to completely exploit the sun's vitality with sun-powered innovation. [46]

Furthermore, photovoltaics, sun-based heating and cooling, and conceptualizing sun-oriented force are important techniques to enhance sunlight-based life. Photovoltaics generate power directly from sunlight via an electronic process and can be used to drive anything from little devices, for example, minicomputers and street connects, to residences and large business enterprises. Sunlight-based heating and cooling (SHC) and concentrating solar power (CSP) applications both use the heat produced by the sun to provide space or water heating as SHC frameworks, or to run conventional power producing turbines as CSP power plants. [47]

4.3 Parameters that influence the solar energy production

As referenced already, ingestion and reflection influence the sunlight based radiation in the air. Different elements impact the sunlight based vitality creation, for example,

Insolation

The higher the insolation of the sun at the area of the arranged sunlight based force plant, the higher can be the vitality yield. Contingent upon the sort of the sun based force plant, distinctive radiation parameters ought to be estimated, e.g., DNI is significant for an arranged CSP power plant [46].

Wind speed and wind heading

To structure and construct strong module bearers, the nearby wind conditions ought to be estimated. Also, the cooling impact of the breeze on the modules can be evaluated [46].

Air temperature

The air temperature impacts the effectiveness of sun-powered modules. The exhibition of sunlight based modules is temperature-subordinate. Higher cell temperatures lead to bring down execution and henceforth to a lower coefficient of productivity. The coefficient of proficiency demonstrates the amount of daylight can be changed over into usable electrical vitality [46].

Precipitation and dirtying (dust storms)

Information about the sum and recurrence of precipitation just as dirtying can assist with clarifying low vitality yields at high sun radiation [46].

5. Windcatchers

5.1 Structure and function

A windcatcher is a historic architectural element used in buildings to provide cross ventilation and passive cooling. There are three types of windcatchers: unidirectional, bidirectional, and multidirectional. Windcatchers have been utilized for three thousand years in Iran, North Africa, and the West Asian regions surrounding the Persian Gulf. Modern architects ignored them in the second half of the twentieth century, but they were utilized again in the early twenty-first century to promote ventilation and reduce air-conditioning power demand. A windcatcher ventilated building typically costs less to build than a comparable building with traditional heating, ventilation, and air conditioning (HVAC) systems. The costs of maintenance are also reduced [48].



Figure .14 (a) Windcatcher in the City of Yazd, Iran (b) Windcatcher in Bastikia, Dubai [48]

Windcatchers have been an integral part of Asian architecture for centuries and they continue to be a popular choice among architects today. A wind catcher is essentially just as it sounds: it catches the breeze that blows through its open spaces, but this simple design also plays an important role in cooling buildings by pulling air from outside into inside which helps regulate temperature levels naturally without using electricity or other fuels sources [48]. The ventilation rates within these structures can often approach 50%. A research paper published by Sangdeh and Nasrollahi (2022) aims at providing an in-depth review of the recent developments and applications for windcatchers, with particular attention paid to their efficiency. The article also discusses these devices' configuration according to relevant parameters such as height or cross section. The research reveals that factors such as the type and size have significant impacts on windcatcher performance [48]. It is shown, for example, how one-sided designs are better suited to regions with privileged winds but can withstand more variable conditions elsewhere in certain types than others.

Windcatchers are a fascinating example of physical design that can be used to change the flow and circulation around an area. Wind catcher designs have been implemented in contemporary architecture, as well as urban planning with its potential for applying these principles shown on various buildings throughout this passage; new designs utilizing windcatching abilities include those seen within sections about "new technologies" or just plain old technique implementation where they serve their purpose by catching breezes [48] so people don't need negative externalities such as tornadoes or heavy storms. The use of wind catchers is an ancient technology with different names and shapes, having been in practice for more than one thousand years. The Middle-Eastern country Iran has played a significant role in its development as well as many others around Asia where this form originated from [48].

5.2 Types and technologies

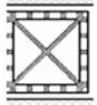
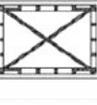
The construction of windcatchers is a centuries-old practice that has been used for generations in hot and arid regions. The distinctive shape makes them an excellent way to naturally ventilate buildings, without the need for expensive equipment or fuel sources [49].

Rezaeian conducted a literature review on the subject of windcatchers. He found that research began in 1984 with an increase coming about two decades later, 1990s which had saturation levels at 1997 and 2000 respectively but still today there is growth due to increased articles written using CFD (Computational Fluid Dynamic) methods lately launched by academics within this field [49].

As it can be seen in the chart above, the number of published papers regarding wind catchers has increased in the past 40 years. Even though in the 1980s only three studies were conducted, the 1990s showed a small increase of up to 8 published papers discussing this topic. However, together with the improvement of technology and research methodology, the 2000s brought 35 research studies about wind catchers. A large boost of studies was then developed during the 2010s, with more than 135 papers being published, discussing not only the history and structure of wind catchers, but also the smart technology that can benefit from them.

As stated above, the research published earlier this year by Sangdeh and Nasrollahi takes into consideration different types of wind catchers, in the aspects of the internal dividing, the cross-section, the number of stores and the number of openings, as it can be observed in Table 1 below.

Table 4. Different types of windcatchers in various aspects [48]

In the aspect of the internal dividing			In the aspect of the cross-section			In the aspect of the number of stores		In the aspect of the number of openings	
Fig.	No.	Des.	Fig.	Des.	No.	Des.	No.	Des.	No.
	1	Square		Square	1	One store	1	One-sided	1
	2			Rectangular	2			Two-sided	2
	4			Six-sided	3	Two stores	2	Four-sided	3
	5			Six-sided	3			Six-sided	
	1	Six-sided Eight-sided		Six-sided	3	Two stores	2	Eight-sided	4
	2			Eight-sided	4			Cylindrical	
	H	Rectangular							
	+								
	X								

In some parts of the world, people use windcatchers as a way to collect and store energy. The tallest type are found in areas with harsh deserts. These tend to be fairly large since taller structures take advantage all available space below them [48].

According to the number of openings, the wind catchers can be classified into: one-sided (a), two-sided (b), four-sided (c), six-sided and eight-sided (d).

- a. **The one-sided** windcatcher has an inlet incoming the north direction and no opening for east, west or south. This brings cold northern winds into indoor spaces, while this type of wind catchers is more resistant to storms than the other types [48];
- b. **Two-sided** windcatchers, also called twin collectors are smaller than one sided versions. To divide them into two separate parts brick blades are used with the exception that they do not have an edge

on either side (to ensure no obstruction in front when trying to capture air flow through this type of design [48];

- c. **The four-sided** work by catching breezes that blow across their faces on four different sides so they can turn those waves into usable power for things like lighting or heating homes during cold months when there isn't much sun shining down from above [48].
- d. **The eight-sided** windcatchers are mostly used for water storage and very few of them exist [48].

The construction of cylindrical windcatchers is more complicated than square, rectangular or tetrahedral. For this reason they were not too common compared to the others; however designing them relies on knowing how airflow moves within a given environment which has led researchers developing high efficiency models for these types of structures over time [49]. Cylinder-shaped devices can be used as either passive ventilation systems where breezes flow through open spaces into rooms below (a cooling effect), The most common type of windcatcher is square because it has more surface area to catch the air flowing around its shape, but other shapes such as circle and hexahedral have their own benefits. The drawback with this design choice may be that they are not able hold water like rectangular shaped ones do; however these limitations can easily be overcome by making sure there's enough space inside for storing rainwater during dry times [49].

5.3 Principles of Air Movement

In this chapter, the principles of air movement are discussed. Environmental temperature is one of the most critical factors governing human comfort and survival; air movement plays a big role in cooling down the body temperature in hot or humid conditions. Natural air movement can be applied through two principles: Pressure Differential or Convection [50].

5.3.1 Air movement by Pressure Differential

When wind velocity varies it produces a pressure differential, which causes air movement from a higher air pressure zone to a lower pressure zone. This is based on the Bernoulli theory and it's called "Venturi action," which explains that when the velocity of a moving fluid increases the pressure decreases. When air is directed into the larger end of the funnel-shaped tube, which opens to a side tube in the figure below, it accelerates as it passes through, owing to the reduced open area through which the same volume of air must pass in the same period. This increased airspeed lowers the pressure in the airstream at A, with respect to the atmospheric pressure at B in the lower part of the side tube. Thus air is drawn up the side tube by the pressure difference, which is proportional to the square of the velocity. This concept can be used in a variety of ways to provide steady streams of air through buildings [48].

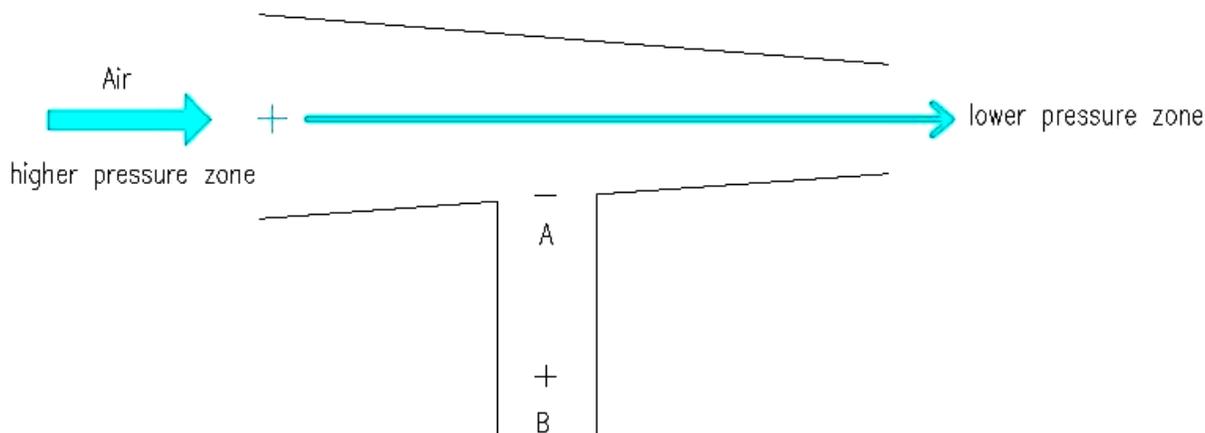


Figure .15 Funnel-Shaped Tube Diagram [48]

Based on the same principle, when the air flows over a building it produces a zone of low pressure on the leeward side and a higher pressure zone on the windward side. This produces a steady airflow due to the suction through the leeward side opening. Figure

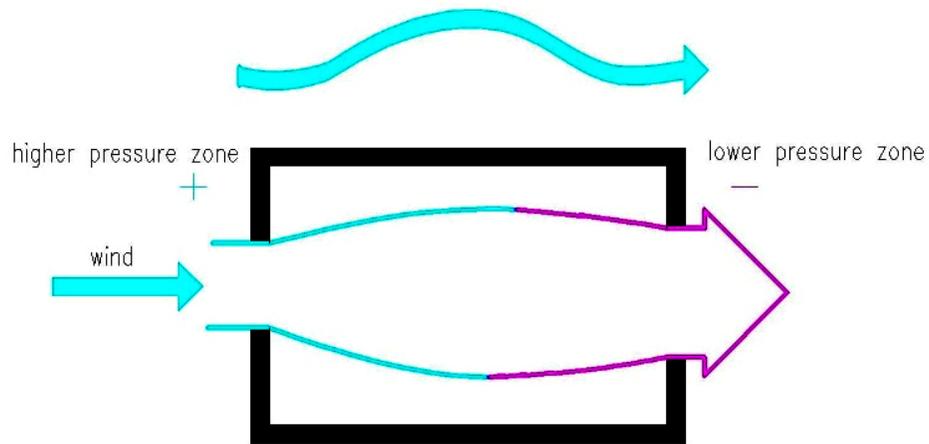


Figure .16 A section Showing Air Movement In the Building Caused by Pressure Differential [48]

The good example of a system that runs with pressure differential is a wind-catcher. A wind-catcher is a duct mounting above the building and has an aperture toward the prevailing wind. Figure below; this device catches the cooler air above the building and brings it inside. Therefore, a window or a door that acts as a wind-escape is needed to ensure that ventilation occurs [49].



Figure .17 An Image of a Wind-Catcher

The basic wind-catchers design follows the same principle of using air that is drawn in by the pressure differential, which can create a constant flow.

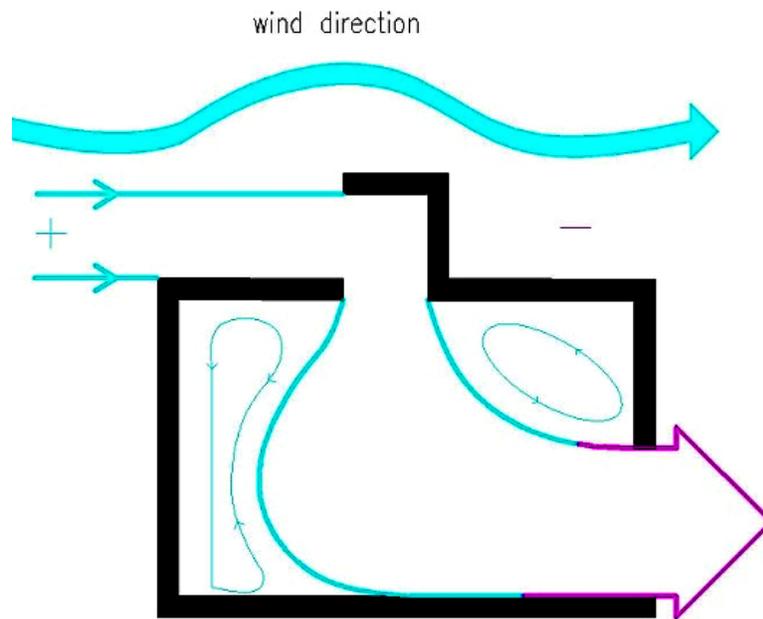


Figure .18 A Cross Section of a Space Showing The Performance of a Basic Wind-Catcher [48]

Figure shows that when the air flows over a building it creates a higher air pressure on the windward side of the wind-catcher. Due to the lower air pressure on the other side, air moves from the higher pressure to the lower pressure region and generates an air movement [49].

5.3.2 Air movement by Convection:

The tendency of a liquid or gas to cause less dense object to float or rise to the surface is called buoyancy. Because of the difference in density between cool air and warmer air, warm air tends to move upward and escape due to its lower density. This air movement, called convection, can lead to a stack effect driven by buoyancy. As long as there is a continuous source of heat and a considerable amount of cool air available, a constant stream of air is produced. The higher the temperature difference and the height of the building, the greater the buoyancy force and stack effect will be. This leads to greater air movement. The constant natural

cooling system used in the courtyard homes in hot-arid regions in Middle-East is a good example of producing air movement by convection [50].

In these hot and dry areas, most residential homes have a courtyard that is located in the center of the house and is usually surrounded by several rooms. Inhabitants of these regions have learned to close their doors to the outside and open them toward their courtyards. In the evening, since the air temperature drops due to re-radiation of heat to the sky, warm air in the courtyard rises and is replaced by cooled night air from above, which starts cooling the courtyard and surrounding rooms. Figure 2.2.1; This cool air gathers in the courtyard in layers and eventually moves into the surrounding rooms [50].

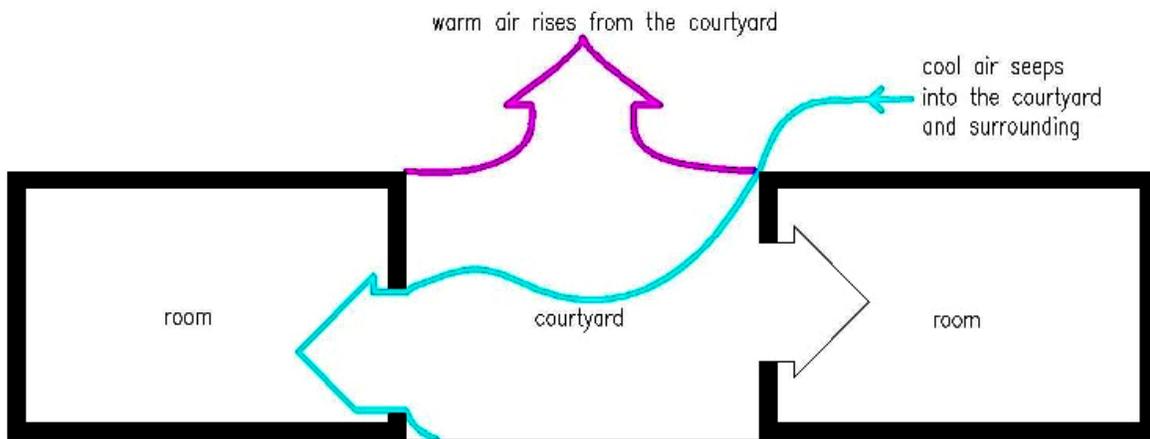


Figure .19 A Schematic Graph Section of Air Change By Convection in Homes with Central Courtyard [48]

Another example of air movement by convection is shown in figure 2.2.3 This cross section of a house in Zavareh (located at the northeast of Isfahan Province, next to the central desert area in Iran) shows how the summer living area in this house could stay cool by convection [50].

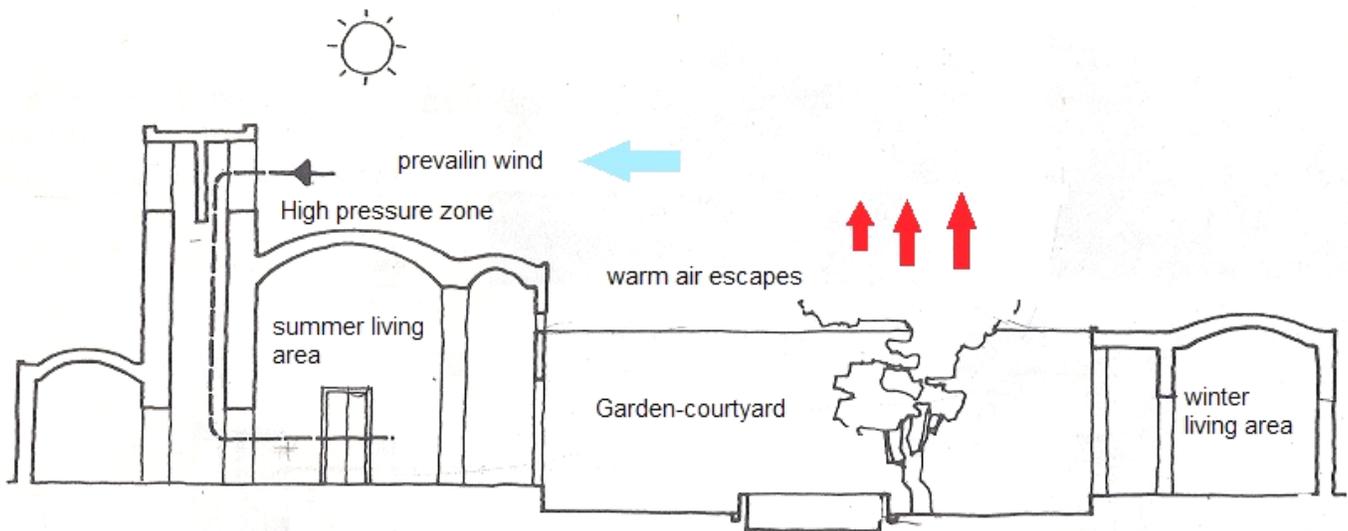


Figure .20 A Cross Section of a House in Zavareh, Iran [48]

5.4 Smart Windcatchers

Various research was developed during the past decade in regards to wind catchers, their previous structure and how modern technology can improve these systems. With the increasing access capacity for wind catchers, it's clear that these systems will have an impact on the electrical grid system, as they become more popularized in coming years - which means there needs to be research into how we can best predict their output. Science foresight was also sustained by Rezaeian et al. (2017), with theories that will be further debated in the following.

In the contemporary times and in an urban context, the efficiency of windows shows poor results, as researched by Sangdeh and Nasrollahi (2022) [51]. This leads to the main advantage that windcatchers are an efficient solution for the right ventilation rate, as it can be shown in the table below.

Table 5. Pressure coefficient for windcatcher and other openings in different wind angles and areas. WC: windcatcher, O.O: other openings

Areas	The angle between wind and inlet											
	0°		45°		90°		120°		150°		180°	
	W.C.	O.O	W.C.	O.O	W.C.	O.O	W.C.	O.O	W.C.	O.O	W.C.	O.O
Rural area	0.53	0.04	0.43	0.12	0.66	0.35	0.50	0.35	0.54	0.25	0.61	0.25
Open area	0.54	0.12	0.43	0.18	0.71	0.33	0.53	0.32	0.55	0.38	0.61	0.32

The results of the Table 2 proves that the pressure coefficient for wind catcher systems is higher than other openings [51].

The economic aspects of wind catchers is also part of the smart systems, due to the fact that their efficiency should be directly related to costs and sustainability. Thus, the reduction in cost can be achieved by combining architectural techniques with climatic strategies and renewable energy systems, which will lead us towards economic efficiency [51]. As discussed by Sangdeh and Nasrollahi, the scenario with wind catchers is more practical and economical when the ground floor level has cooling by an absorption chiller, the second level consists of a basement level, while the third level is built as a basement level with cooling by the wind catcher [52].

Even though wind catchers have become the primary focus of research in the past decade, it seems that modern technology is still poorly developed in published literature, in order to obtain clear and precise information regarding the smart systems to be used in wind catchers [52]. However, from the data obtained during the literature review of this study, several aspects have been identified, which will be detailed in the following subchapter. The literature review shows different valuable information regarding traditional wind catchers, but very few papers have been published considering modern technology, especially regarding

smart systems. Today, there are several types of modern windcatchers, among which: the chimney cowl, combination of wind towers with other regenerative sources of energy, rotary windcatchers or the two-sided windcatchers with a wing wall integrated. The modern windcatchers have been of interest in different countries as shown in the figure below [52].

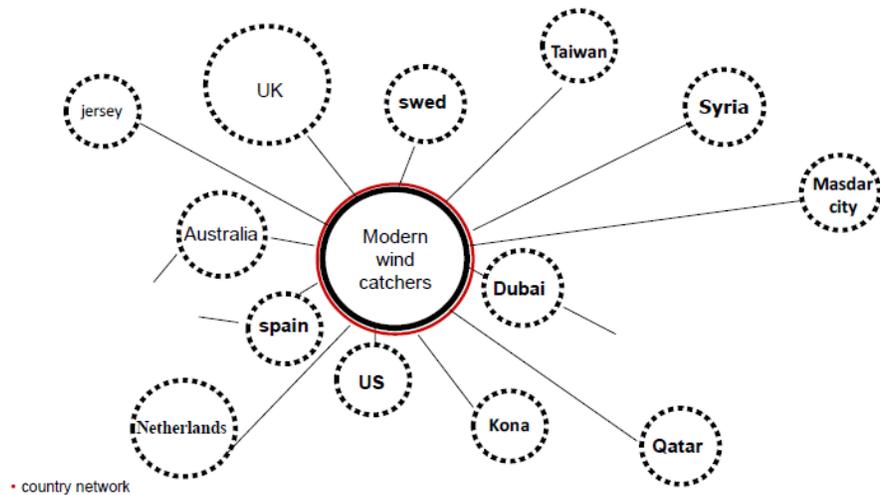


Figure .21 Modern windcatchers country network [51]

In this subchapter, an exploration of different smart wind catcher will be discussed. The wind power forecasting are very debated in the 21st century, due to the large availability of wind power. However, there is one major difficulty in the integration of wind power into electrical grids. The intermittent nature makes it difficult for engineers to predict when and how much energy will be produced by these sources so that they may integrating them into existing framework without any problems or disruptions caused by fluctuations [52].

The approach taken up by Agarwal et al. (2018) has been using models which can estimate future values based on past performance but this doesn't account for all eventualities, since not every situation follows similar trends, without knowing the potential outcome. A series of models for prediction of wind power have been developed globally: WPPT, WPMS, WPFS Ver. 1.0, Prediktor or ARMINES [53], models that have

been reviewed to better understand the diversity of wind power forecasting models, depending on different scales of time. Different other prediction methods have been discussed by various scientists. For instance, Blaylock and Horel (2020) consider that forecasters should take advantage of HRRR lightning forecasts to get an idea for the occurrence, region and timing in a broad area, in order to provide more information on where storms may happen locally without sacrificing accuracy across larger regions [54]. Also, Carrillo and Del Ser discussed the forecasting using ant colony optimization through learning machine, concluding that in order to optimize how much wind energy is actually inserted into the electricity grid, it's important that we know what factors contribute most towards its variability [55]. In other published papers, the aspect of decomposition and AI methods were recommended for short-term wind power forecast, as proposed by Cevik, Conkas and Polat (2019). Their study concluded that the proposed multistage forecast model is an efficient solution to forecasting the wind power, which produced very close values to the actual recorded data [56]. Last but not least, forecasting the wind power using methods of deep learning was surveyed by Chinese researchers, leading to the same conclusions. Wind farm owners and operators can significantly reduce the risk of blackouts when connecting to a power grid [57]. Their research paper provided researchers with reference strategies for relevant studies as well practical applications of deep learning, enforcement learning and transfer-based approaches in wind speed forecasting models. The deep neural networks are a promising method for high-dimensional feature extraction. The input data can be accurately transformed using the network's structural designs, such as adding noise to outputs or evolutionary learning used to optimize hidden layer weights, so that they optimize both objective function accuracy while filter out irrelevant information [58]. Different other methods and models of wind power forecasting can be observed in the book edited by Georges, Kariniotakis, where mathematical approaches, short-term and characteristics are discussed together with direct application to the power system [59].

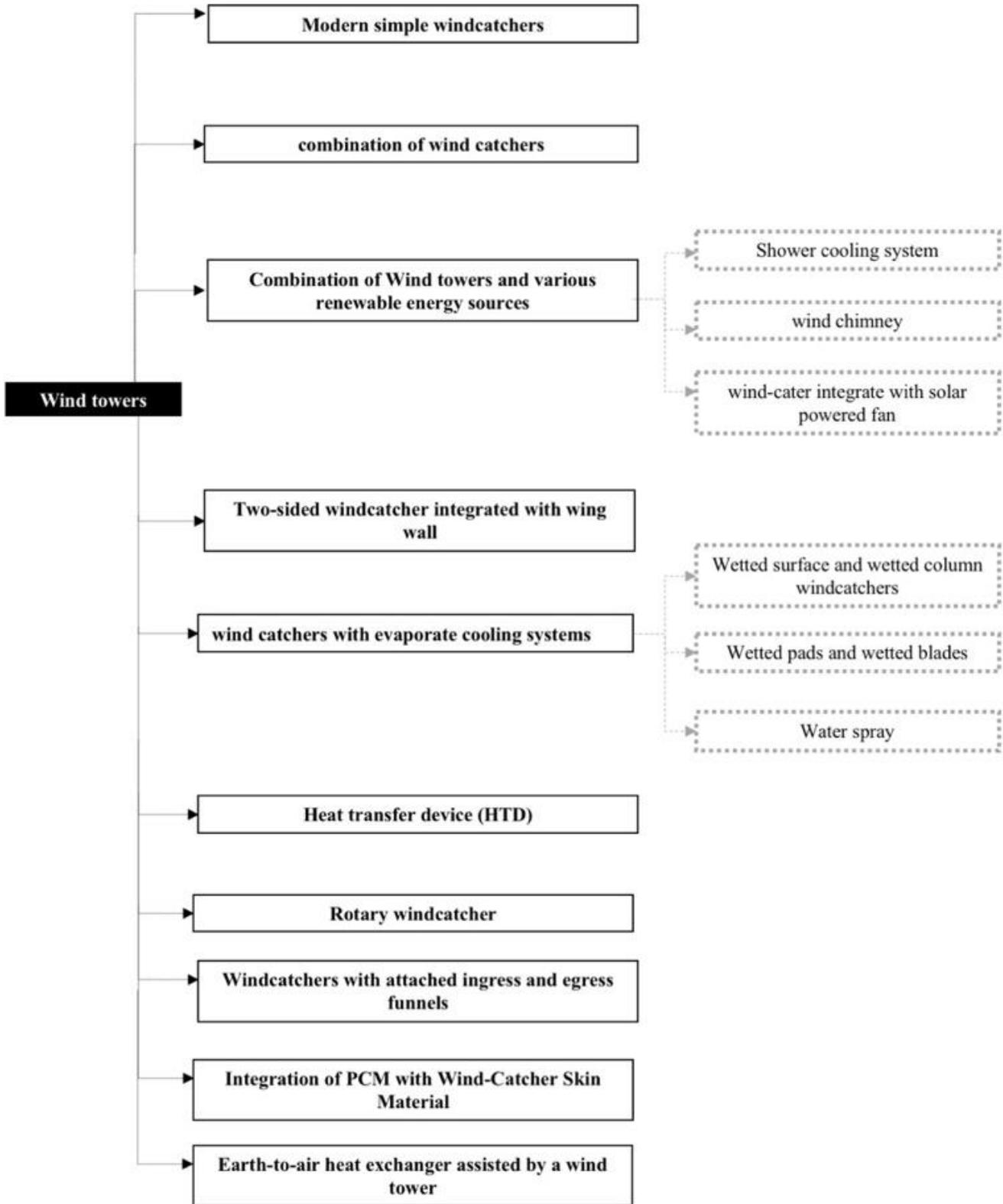


Figure .22 Previous studies with focus on various modern windcatcher techniques [59]

Previous researchers proposed that passive cooling systems be utilized to improve thermal and wind comfort while decreasing energy consumption. These measures would not only benefit the environment, but also the costs and economical aspects, as suggested by Zafarmandi and Mahdavinejad (2021). In principle, the idea behind a windcatcher is not new. It has been used for centuries to harvest natural ventilation in buildings through an architectural element called “badgir”, which combines proper devices such as fans and chimneys with modern technology [60]. A major difference between traditional methods and those that utilize renewable energy sources (like winds turbines or solar panels) lies within their ability provide constant airflow indoors without relying on outside forces. This means they can be particularly beneficial in warm places, where air conditioners often don't work properly [61]. Modern windcatchers have been using new technologies to improve their effectiveness like damper, fan and louver. The most common structure of modern wind catchers are wind towers, which are also divided into the following subsections [61]:

A. Modern simple windcatchers (using the traditional idea of original windcatchers) from which the most common is the Mono Draught Windcatcher.

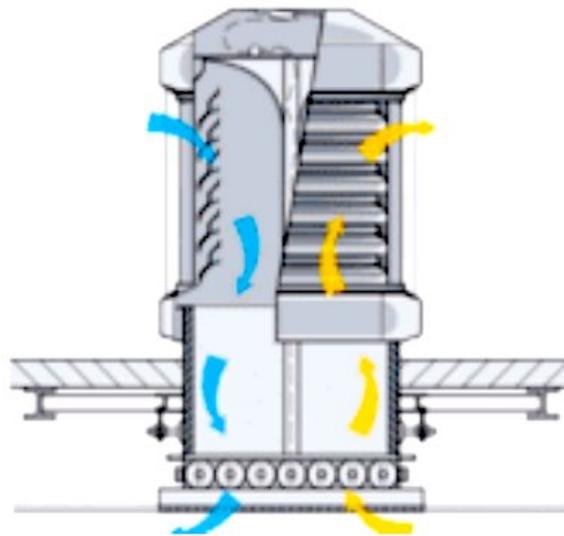


Figure .23 The circulation of air in a Mono Draught Wind Tower [62]

B. Combination of windcatchers (also known as the Chimney Cows).

Wind or chimney cowls are a generic term for a rooftop ventilation structure used to connect windcatchers. This style of windcatcher can rotate independently in response to changing wind directions, ensuring that the air entrance is always facing the windward side and the air outlet is always facing the leeward side. As a result, the airflow heads inside the pipes change in accordance with the rate twist course. Pressure cowls and suction cowls are the two types of cowls [63].

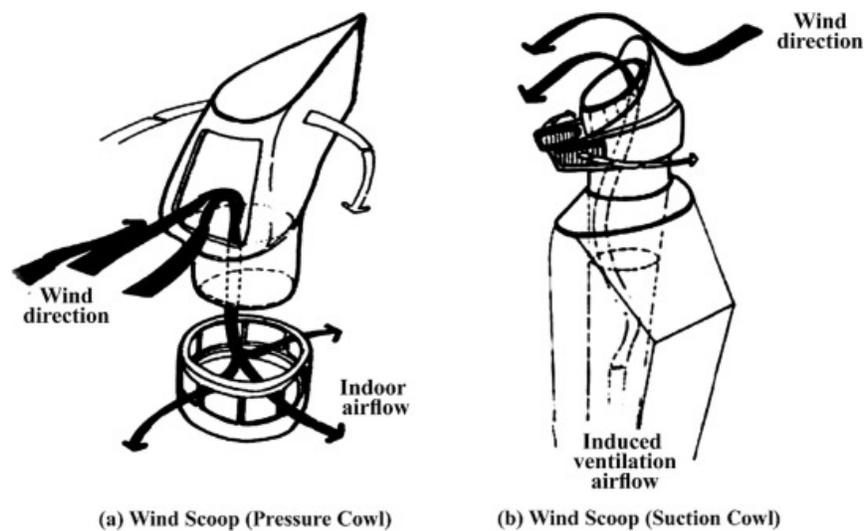


Figure .24 The Chimney Cowl (a) Pressure Cowl (b) Suction Cowl

C. Combination of wind towers and other renewable energy sources.

The combination of windcatchers with other renewable energy sources are one of the most sustainable modern methods used today. To begin with, the windcatchers using passive cooling (such as the shower cooling system, see Figure)

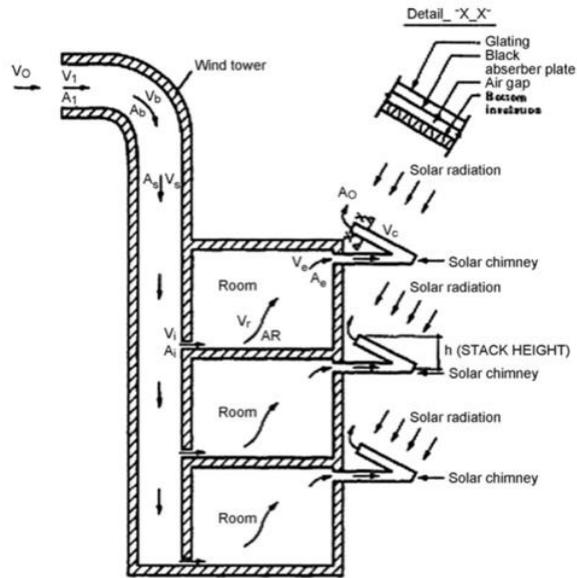


Figure .25 Schematic of two-story wind catcher with shower cooling system [64]

Further, the windcatcher with suncatchers integrated (Figure 9), together with the solar-powered-fan-integrated wind catcher are the most common combinations included in modern technology. Their schematics can be found in the Figures 7, 8 and 9.

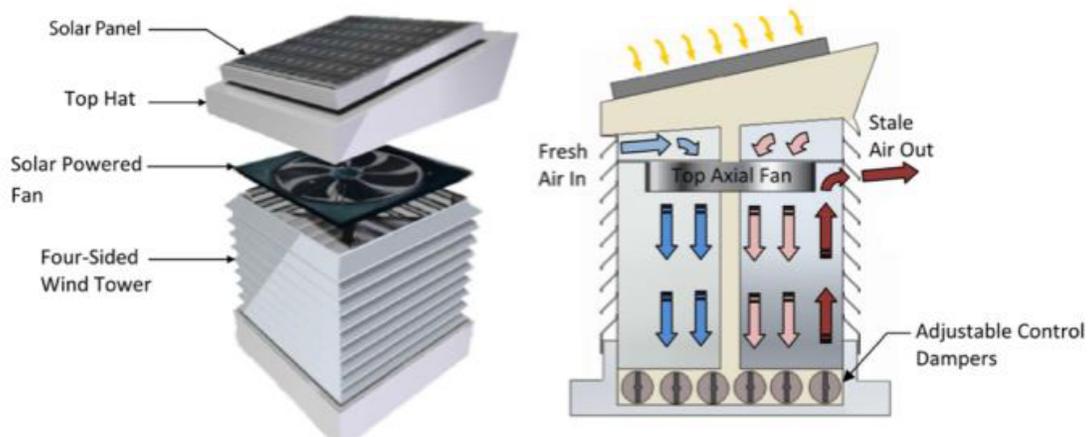


Figure .26 Wind Tower integrated with a solar-powered fan [65]

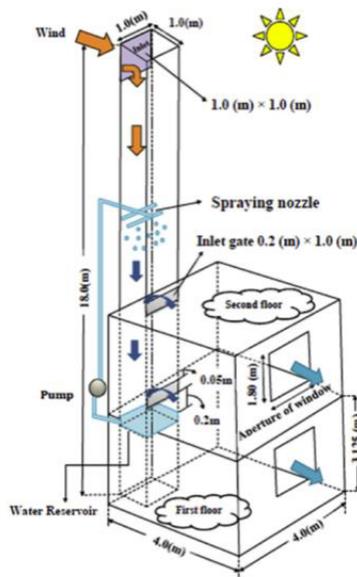


Figure .27 Schematic view of a windcatcher with suncatcher integrated [66]

Another type of modern windcatcher is the structure using wetted surface and wetted column, very useful in cases of low and high winds together. When put in comparison with the traditional structures, the modern design shows higher efficiency, due to the fact that the interior temperature shows reductions, while the level of humidity is increasing.

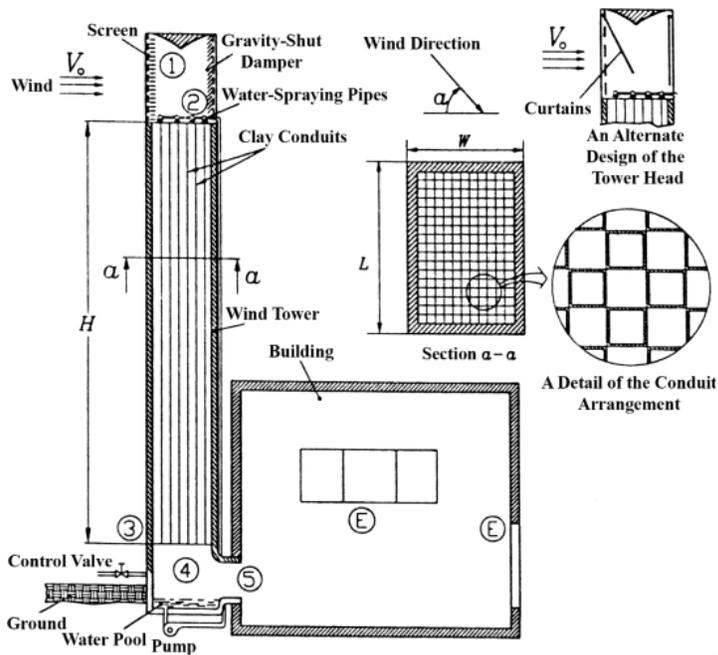


Figure .28 Windcatchers using wetted surface and wetted column [67]

Last but not least, the wetted pads and wetted blades structure of windcatchers is another important system to consider, as researched by Noroozi and Veneris (2018) [68]. This system combines the evaporating cooling system with the moist pad and blades unit. Its efficiency is shown in the windy conditions, since velocity of the interior air is higher during the periods when pads are open, while closed pads during no wind speed can increase the interior airflow to twice the value [69].

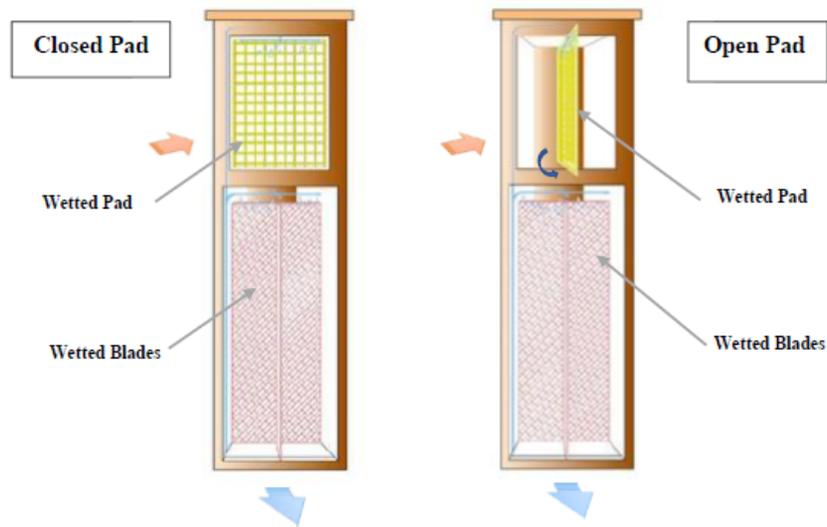


Figure .29 Windcatchers with wetted pads and wetted blades [69]

More other methods, structures and technologies are currently in use, among which the following: water spray, HTD integrated with windcatcher, attached ingress and egress funnels, windcatchers with PCM integration of wind-catcher skin material, which are illustrated in the figures below.

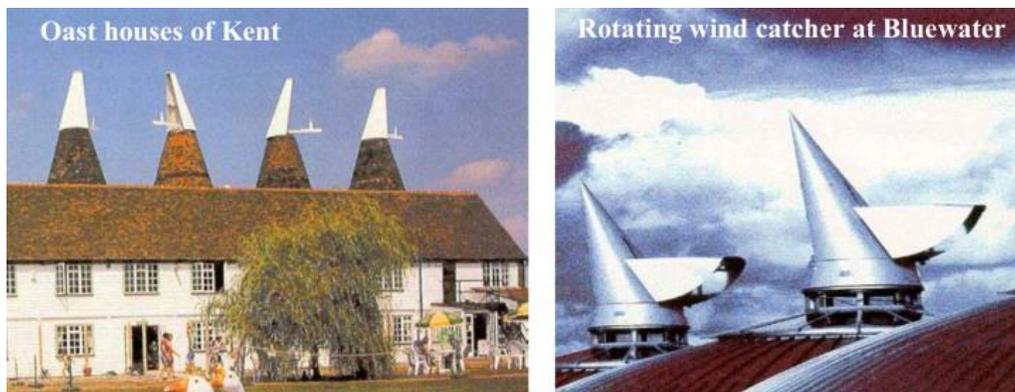


Figure .30 Examples of rotary wind catchers [70]

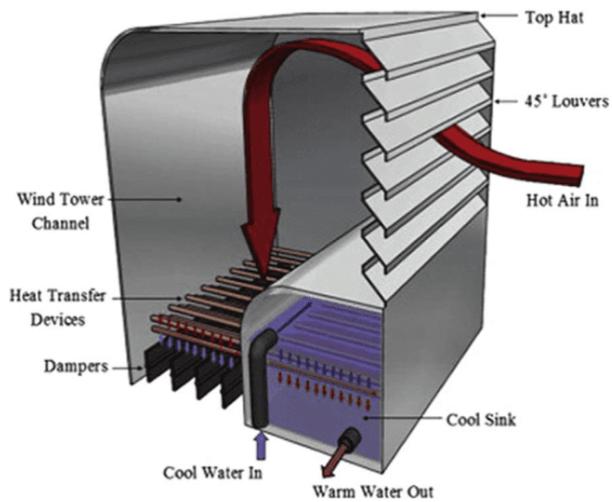


Figure .31 One-sided wind catcher with devices for heat transfer [71]

Shown in the figure above, the results of the CFD analysis showed that depending on the outdoor air speed, the proposed one-sided wind catcher might reduce the supply temperature by up to 12 K within the microclimate. However, the installation of the cylindrical HTD resulted in a 20–35% reduction in air supply rates [71].

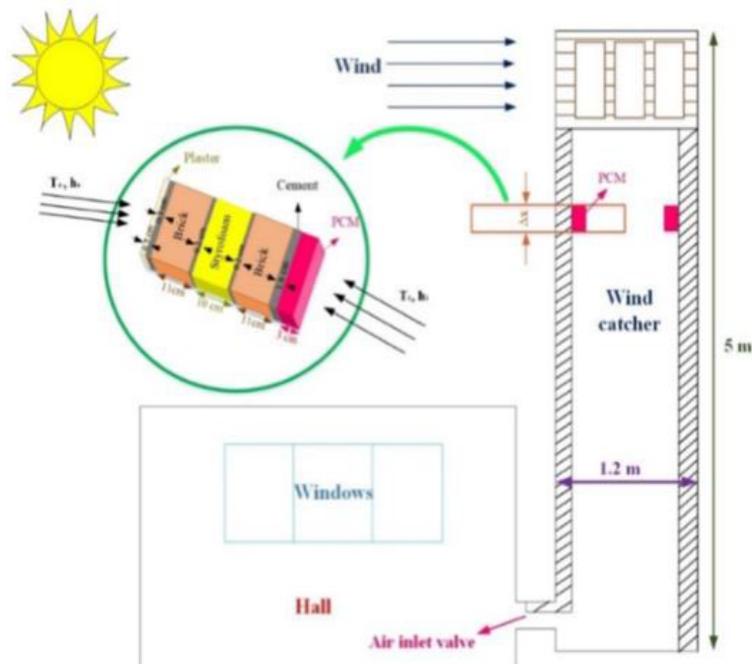


Figure .32 Windcatcher with PCM Integration [72]

An overview and brief description of each method are provided in the following table (Table).

Table 6. Classification of modern windcatchers [73]

section	Wind cater techniques	Type of building	Method of system	Employed methods to foster the windcatchers performance	Climate features	Results
A	Modern simple windcatchers	Hospital, School, Houses	Dry system	Using damper, sensors and adjustable mechanism	Various kinds of hot region (wind speed,...)	Providing ventilation similar to traditional wind catchers with adjustable methods according to regions need
B	chimney cowls	Small scale buildings	Dry system	combination of windcatchers	Regions with variable wind directions	Its features often working with other concepts such as atria or hybrid ventilation systems to perform optimally
C.1	Shower cooling system	Small scale buildings	Wet system	Evaporating cooling system	Hot	Reducing temperature and brings thermal comfort inside the building
C.2	wind chimney		Dry system	sun catcher , diffuser	Low radiation areas	Bring fresh air and natural light together
C.3	wind-cater integrate with solar-powered fan		Dry system	Using solar panel, louvers, fan and dampers	Low wind power (no wind)and polluted regions	providing a continuous supply of fresh air even when there is no wind and can extracting stale air out of the building
D	Two-sided windcatcher integrated with TWIW	Experimental scaled wind tunnel testing and CFD simulation (room-scale analysis)	Wet system	Using wing wall	In low wind speed and variable wind directions	Enhancing ventilation performance
E.1	Wetted surface and wetted column windcatchers	Simulation stage		Evaporating cooling system	Hot and dry	Reducing inner temperature, increasing relative humidity
E.2	Wetted pads and wetted blades					
E.3	Water spray					
F	HTD integrated with windcatcher	Public buildings		Heat transfer device, conserved slender tube and a small amount of fluid	Hot	covering shortcomings of Windcatchers with evaporative cooling
G	Rotary windcatcher		Dry system	Adjustable openings	low wind speed regions	Facing max wind, bring natural light inside
H	Windcatchers with attached ingress and egress funnels	wind tunnel and CFD model (testing scale)		Using funnels	low-pressure regions	Enhancing the ventilation
I	Integration of PCM with Wind-Catcher Skin Material	Public buildings such as shopping malls		Using PCM	Hot	Decrease the interior temperature about 25°C for 7 hours
J	EAHE assisted by a wind tower	Public buildings		Using Earth-to-air heat exchanger	Arid and hot	Decreasing temperature, reducing fossil fuel

In order to achieve the main aim of this research, which is to reduce energy consumed from the grid in buildings by achieving natural ventilation through wind catchers. A hybrid active/passive system has been proposed and validated through the following tasks:

1. Brief context analysis of the location of the proposed system.
2. Description of the proposed system's components required to establish the research's aim.
3. Architectural 3D modeling design of the proposed system using Autodesk Revit.
4. Control system development based on fuzzy logic algorithms using Matlab and Simulink - in part of the proposed system, which is the wind catcher controller -.
5. Discuss findings and results.

1. Context analysis

Following is the site information of the proposed system.

1.1 Site Information

The proposed system is suggested to be located in Jeddah city, situated in Makkah province in northeastern Saudi Arabia. Jeddah was chosen because of its hot, humid climate, which suits the system's primary goal of cooling the space. Weather Tool software is used to visualize and analyze the data. Jeddah features an arid climate under Koppen's climate classification. Unlike other Saudi Arabian cities, Jeddah retains its warm temperature in winter, which can range from 15 °C at midnight to 25 °C in the afternoon. Summer temperatures are very hot, often breaking the 40 °C mark in the afternoon and dropping to 30 °C in the evening. Rainfall in Jeddah is generally sparse, and usually occurs in small amounts in December. There

have also been several notable incidents of hail. Heavy thunderstorms are common in winter. It is clear that Jeddah climate is classified as a tropical moist climate where precipitation occurs all year long. Monthly temperature variation is less than 3 °C. Intense heating and humidity cause afternoon clouds almost every day. Daily highs about 32°C while night time temperature average 22°C. Using Weather Tool and Mahoney tables the recommended passive strategies and measures have been set out. The climatic analysis using Weather Tool, and Olgay Chart confirmed that natural ventilation can enhance significantly the thermal performance of the building during the summer season in Jeddah.

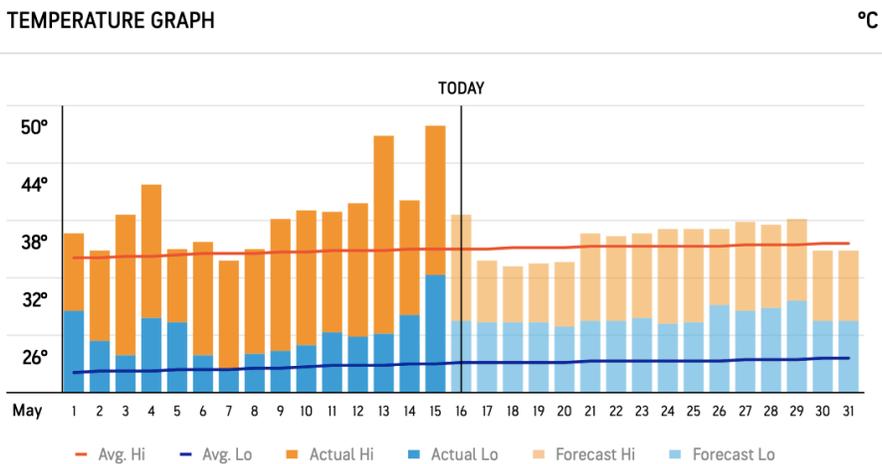


Figure .33 Jeddah- Saudi Arabia Temperature [74]

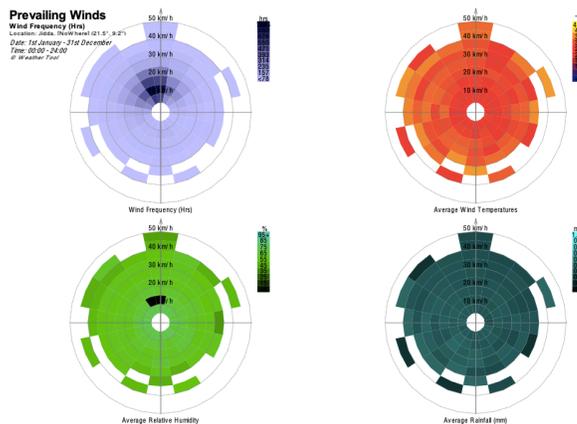


Figure .34 Wind frequency, average wind temperature, average relative humidity and average rainfall, after Weather Tool [74]

2. Proposed System Modeling

Figure.35 below illustrates the system components. In this research, only part of the proposed system will be demonstrated further which is the wind catcher's part.

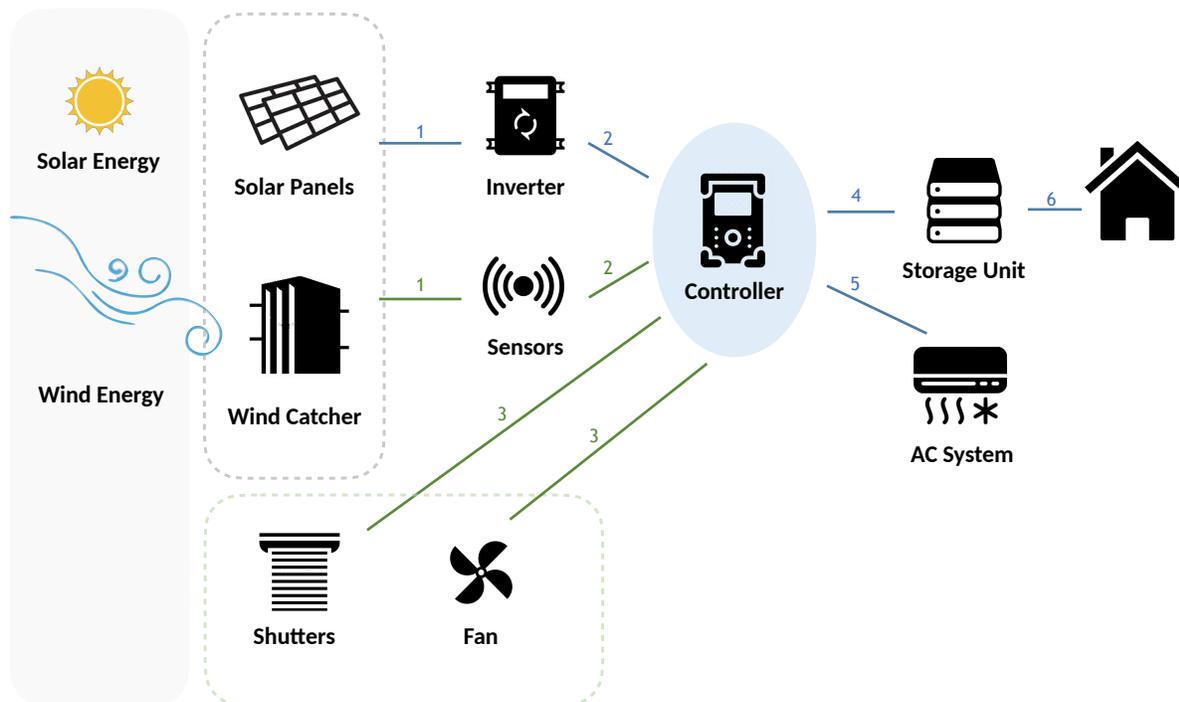


Figure .35 Proposed System Components

2.1 Proposed system components

1. Solar PV panel:

The sun's light, made up of tiny units of energy called "photons," is converted into electricity by solar panels so that electrical loads can be powered.

2. Windcatcher:

As defined in the previous chapter is a traditional architectural element used to create natural ventilation and passive cooling in buildings. [75]

3. Windcatcher's shutter:

Wind-catcher shutters are designed to optimize capturing air flowing outside a building in order to increase its natural ventilation or preventing the flow depending on pre-defined conditions. [76]

4. Inverter:

A PV inverter is a sort of electrical converter that transforms a photovoltaic solar panel's variable direct current output into a utility frequency alternating current that can be used by a local, off-grid electrical network or fed into a commercial electrical grid. [77]

5. Anemometer:

A tool used to measure wind direction and speed is an anemometer. It is also a typical tool seen in weather stations.[78] It is used to sense the airflow of the wind and send it to the controller.

6. Controller:

6.1 Charge-controller

A charge controller in this system determines the flow of energy conducted by the PV to run the system.

6.2 Windcatcher-controller

A windcatcher-controller controls the mode of the system dependent on pre-defined conditions. The wind catcher controller only will be explored further in the upcoming chapter.

7. Storage unit:

Battery storage, also known as battery energy storage systems, are technologies that allow renewable energy sources such as wind and solar to be stored and released when users need it most. [79]

8. AC System:

Air conditioning is a cooling and heating system that removes heat and moisture from a room. [80]

9. Fan

A fan is a machine that uses electricity to move air [81]. It is located above the opening of the wind catcher to encourage the flow of air.

10. Evaporative cooling pipes

In humid climates, it is preferable to use indirect water. The method used is evaporative cooling. Evaporative cooling works by cooling the air through evaporation. Hot, dry outside air is pulled through water-soaked cooling pipes using evaporation principles. As the air moves by these pads, the heat in the air is absorbed and the water evaporates, resulting in a decrease in air temperature. [82]

2.2 Proposed system requirements

The functional requirements of the system are described. To design an optimize system architectures, the following requirements must be satisfied:

- The sensors must accurately get the wind speed and temperature throughout the day of the macro-climate surrounding the building.
- The inverter must convert the direct current (DC) energy they produce into the alternating current (AC) energy that the smart system requires.
- The charge controller needs to determine the energy required to open or close the shutters according to the data collected by the sensors.
- The windcatcher-controller must make appropriate decisions depending on pre-defined conditions based on the data collected by the sensors and control the shutters accordingly to create a comfortable and healthy environment utilizing supplying fresh air from outside.
- The systems must be running 24/7 to parse the readings received by the sensors modem and control the windcatcher accordingly.
- The charge controller must send excess energy to the storage unit.
- An extra layer of service can be added to control the energy stored at the house using BMS.

2.3 Proposed system 3D modeling

The structure dimensions of the proposed wind catcher is designed following guidelines of a research conducted by group of researchers, which devise some important design guidelines to assure the successful use of the wind catcher in Jeddah - Saudi Arabia. The model has been simulated using Autodesk Revit. See figure below for the proposed system architecture.

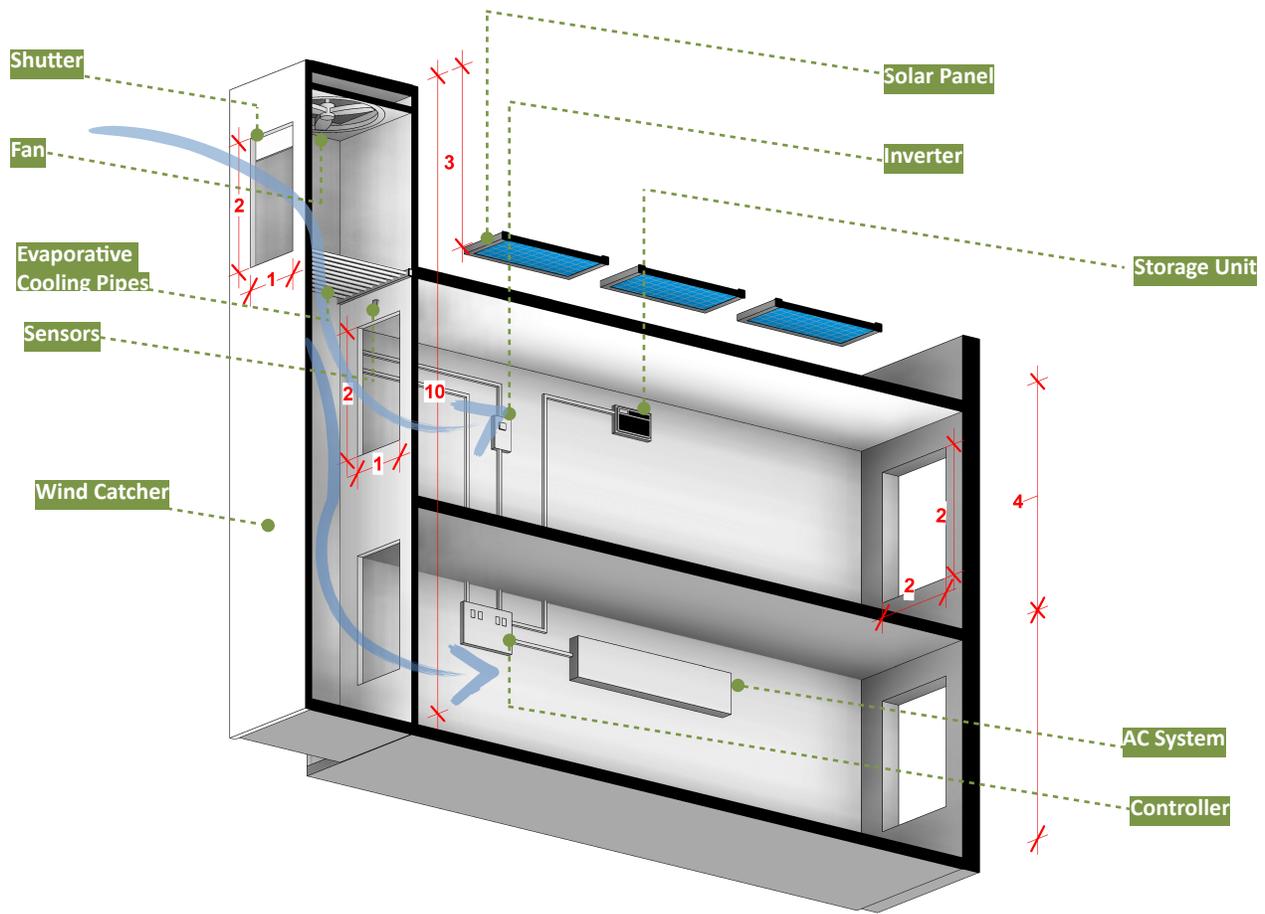


Figure .36 Proposed system architecture

The main design decisions to utilize the wind catcher techniques following Mohammad and Mohammad [83], 2019 guidelines are:

- 1) The wind catcher is 10m in height, which is the preferable height to capture the cool breeze without dust particles.
- 2) A rectangular section of the wind catcher, which is more efficient than a circular section.
- 3) Openings along the wind catcher (Inward) are 50% in area of the exhaust side openings (Outward) of the floors, which accelerate the airflow. See table below.

Table 7. Dimensions of the openings

	Dimensions	Area
Inward Openings	2mX1m	2 m ²
Outward Openings	2mX2m	4 m ²

- 4) Two floors are employed following the recommendation of the guidelines.
- 5) Windcatcher is 3m above the roof of the second floor.
- 6) The dimensions of the wind catcher is 2mX2m to optimize the stack effect in the wind catcher.
- 7) The fan is located above the opening of the wind catcher to encourage the flow of air.
- 8) The shutter is chosen to be a wholesale shutter, in order to not to obstruct the airflow.

3. Control System Modelling

In this thesis, the Fuzzy Logic Algorithm has been selected for implementation of the proposed system on the wind catcher controller part, due to time limitation. A fuzzy logic system can be definite as the nonlinear mapping of an input response of data set to a scalar output data [84]. The modeling simulation design consists of three main parts, as shown in figure below. The first part is the inputs, the second is the controller, and the third is the outputs. The main parts of each will be discussed and described further in this section.

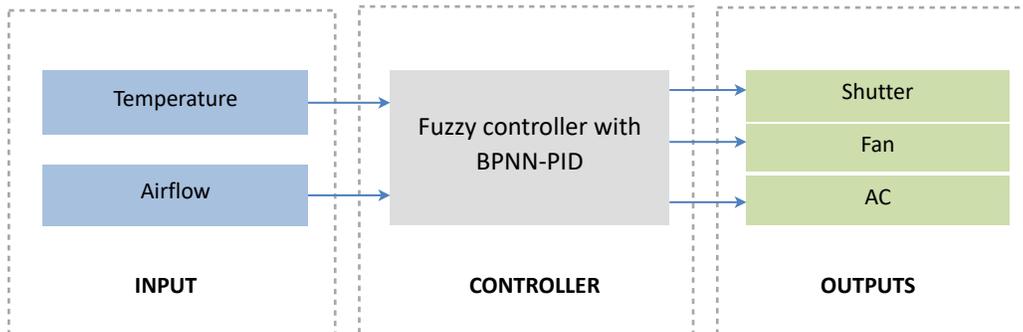


Figure .37 Block diagram of the control system modeling

The first section describes the system's inputs. As previously discussed, the system's inputs come from the wind catcher's sensors. In the simulation model, the system will generate inputs depending on the generator's design to generate sensor input. The generator was driven by the shower simulation design's generator temperature and airflow, which was addressed in [85]. Figure 38 depicts the basic suggested system design in Simulink, while figures 39 and 40 depict the inputs generator of the system's supposed inputs.

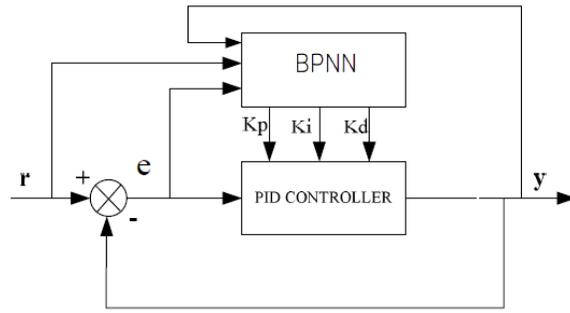


Figure .41 Block diagram PID-BPNN

In the PID controller, the three general equations that can be written as: [86]

$$u(t) = k_p \left[e(t) + \frac{1}{T_I} \int_0^t e(t)dt + T_D \frac{de(t)}{dt} \right] \quad (1)$$

$$u(k) = u(k - 1) + k_p(e(k) - e(k - 1)) + k_i e(k) + k_d(e(k) - 2e(k - 1) + e(k - 2)) \quad (2)$$

$$e_y(k) = y(k) - r(k) \quad (3)$$

Where u is the output, K_p is the proportional control constant, K_i is an integral control constant, e_y is the error of the system, r is the reference and y is the output which will be as input for fuzzy controller. The using of PID based on BPNN is for tuning the controller values. BPNN has generated the optimal values of PID to obtain the values of air generator to be suitable for the design.

The basic concept of extracting the values of PID is based on BPNN structure. It consists of three layers of input layer, hidden layer, and output layer. In the input layer, there are three neurons. Also, in the hidden layer, there are three neurons. At the output layer, there are four neurons and each of them are P-neuron, I-neuron, and D-neuron show figure 42. The training process equations of this design is based on the same equation which is discussed in [86]. Figure 43, show the PID design with BPNN tuning.

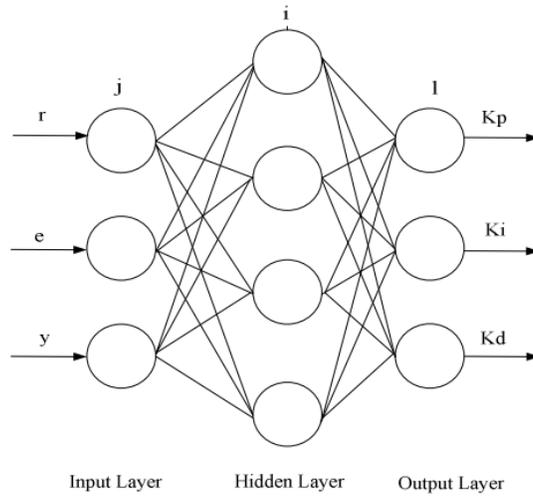


Figure .42 BPNN structure [86]

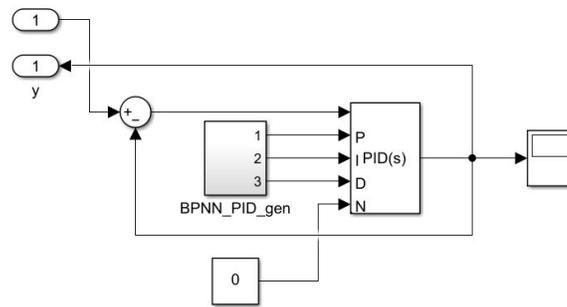


Figure .43 PID tuning based on the BPNN

After the input values have been tuned, a fuzzy logic system will control the system. A fuzzy logic system can be defined as the nonlinear mapping of a data set's input response to scalar output data [86]. As is well known, fuzzy logic comprises four main parameters, which are represented in Figure 13. This paper's system simulation employed fuzzy logic control with two inputs. The first input is from the temperature sensor, and the second is from the air after the BPNN PID has been tuned. The fuzzy engine periodically compares the reading from a temperature sensor or generation values to the target temperature and the readings from the airflow, which comes from PID. The fuzzy generates the required command based on the matrix representation of the fuzzy rules, as shown in table 3.

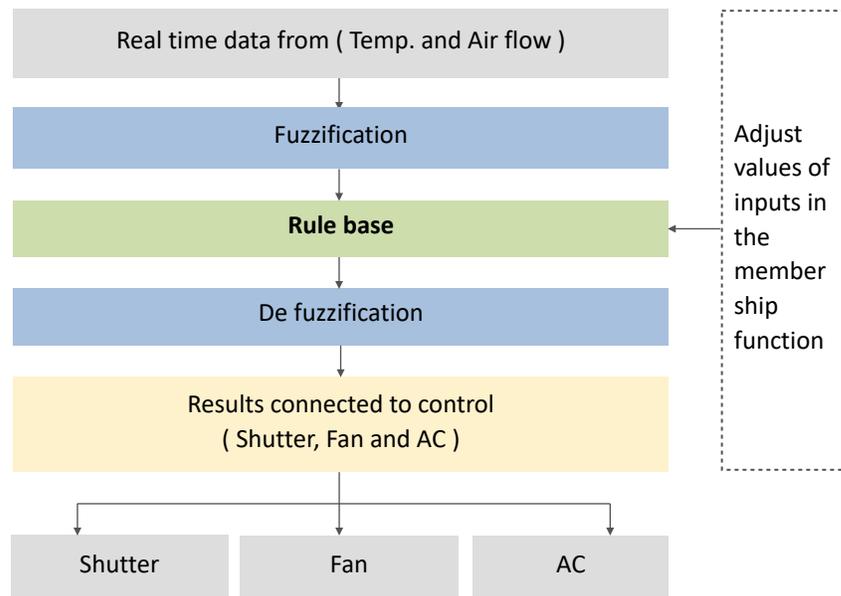


Figure .44 Fuzzy logic components based on wind catcher design

Fuzzy variables consist of two inputs and three outputs. The values taken into consideration during the membership function are the values approximated from the data provided by the proposed system design, as discussed before [86]. Figure 14 shows the membership function of the temperature and airflow input.

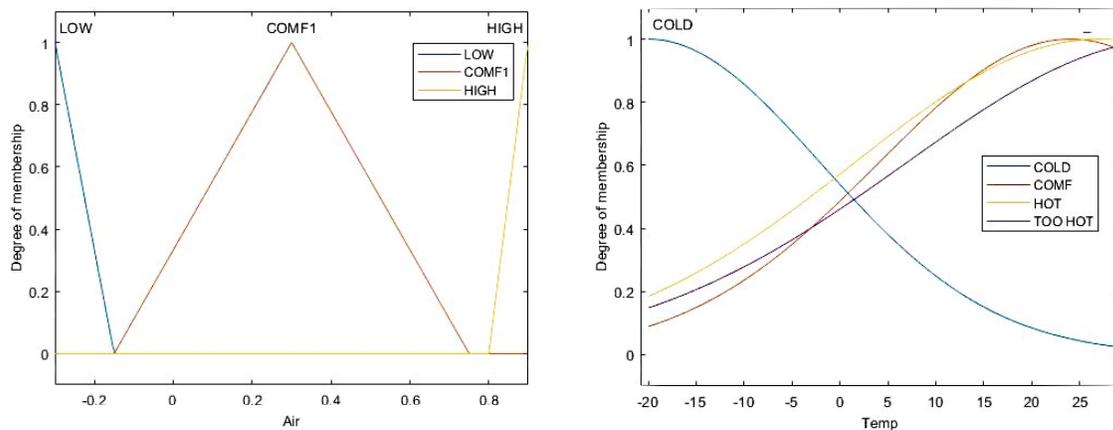


Figure .45 Membership function of temperature and airflow sensor

In figure 45, the Gaussian fuzzy presents the membership function of the temperature sensor. Gaussian fuzzy membership functions are quite popular in the fuzzy logic literature, as they are the basis for connecting fuzzy systems and radial basis function neural networks [85-86]. On the other hand, the trapezoidal rule has been applied for the membership function of the second input. In tables 8 and 9, the sorting of the inputs can be observed. And the fuzzy rules set of the components are shown in table 10, and

it will be discussed further in the next section. The general blocks of a fuzzy system for inputs and outputs are shown in figure 46.

Table 8. Sorting of temperature for inputs in the fuzzy controller

Temp.	State
< 20	Cold
(20 - 24)	Comfortable
(24 - 27)	Hot
> 27	Too hot

Table 9. Sorting of airflow for inputs in the fuzzy controller

Airflow	State
< 0.2	Low
(0.2 - 0.8)	Comfortable
> 0.8	High

Table 10. Fuzzy rules set for wind catcher components

FUZZY RULES	TEMP.	AIRFLOW	SHUTTER	FAN	AC
1	(20 - 24)	(0.2 - 0.8)	ON	OFF	OFF
2	(20 - 24)	< 0.2	ON	ON	OFF
3	(20 - 24)	> 0.8	0.5 OPEN	OFF	OFF
4	(24 - 27)	(0.2 - 0.8)	ON	ON	OFF
5	(24 - 27)	< 0.2	ON	ON	OFF
6	(24 - 27)	> 0.8	0.5 OPEN	ON	OFF
7	< 20	-	OFF	OFF	OFF
8	> 27	-	OFF	OFF	ON

Table 11. Matrix of fuzzy rules set

No.	Rule
1	<i>IF</i> temp is comf. and airflow is comf. <i>THEN</i> Shutter is ON , Fan is OFF and AC is OFF
2	<i>IF</i> temp is comf. and airflow is low. <i>THEN</i> Shutter is ON , Fan is ON and AC is OFF
3	<i>IF</i> temp is comf. and airflow is high. <i>THEN</i> Shutter is 0.5 Open , Fan is OFF and AC is OFF
4	<i>IF</i> temp is hot and airflow is comf. <i>THEN</i> Shutter is ON , Fan is ON and AC is OFF
5	<i>IF</i> temp is hot and airflow is low. <i>THEN</i> Shutter is ON , Fan is ON and AC is OFF
6	<i>IF</i> temp is hot and airflow is high. <i>THEN</i> Shutter is 0.5 Open , Fan is ON and AC is OFF
7	<i>IF</i> temp is cold. <i>THEN</i> Shutter is OFF , Fan is OFF and AC is OFF
8	<i>IF</i> temp is too hot. <i>THEN</i> Shutter is OFF , Fan is OFF and AC is ON

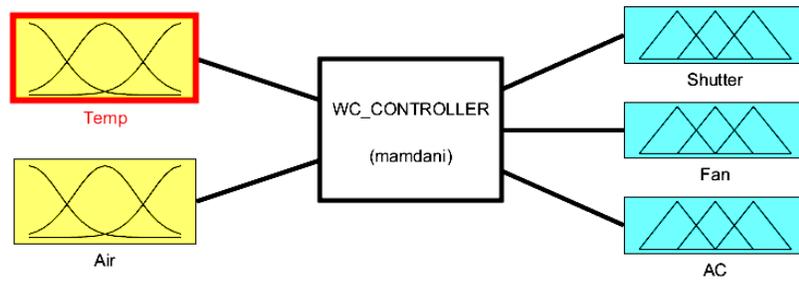


Figure .46 Wind catcher controller based on fuzzy Mamdani system

In figure 46, the fuzzy rules set of table 11 is showcased per each input in The Rule Viewer. This part of the design is involved in the Simulink model of the fuzzy controller.

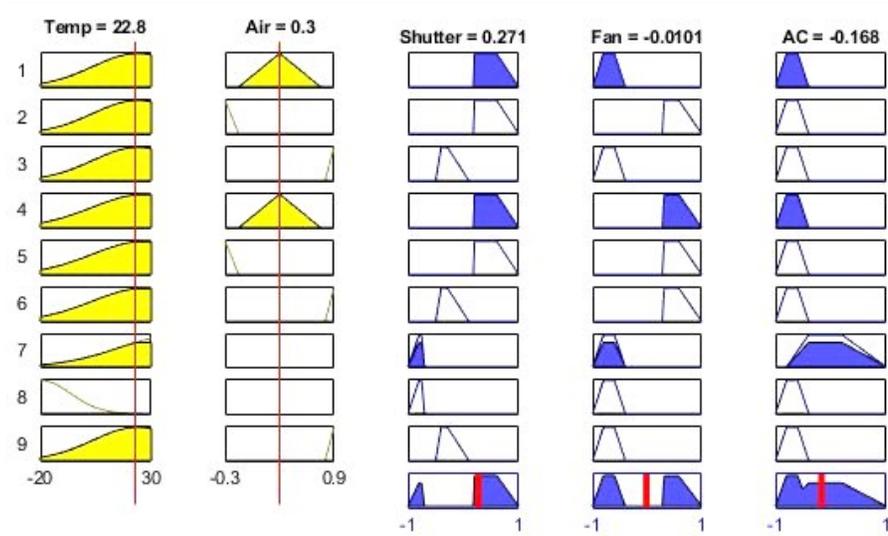
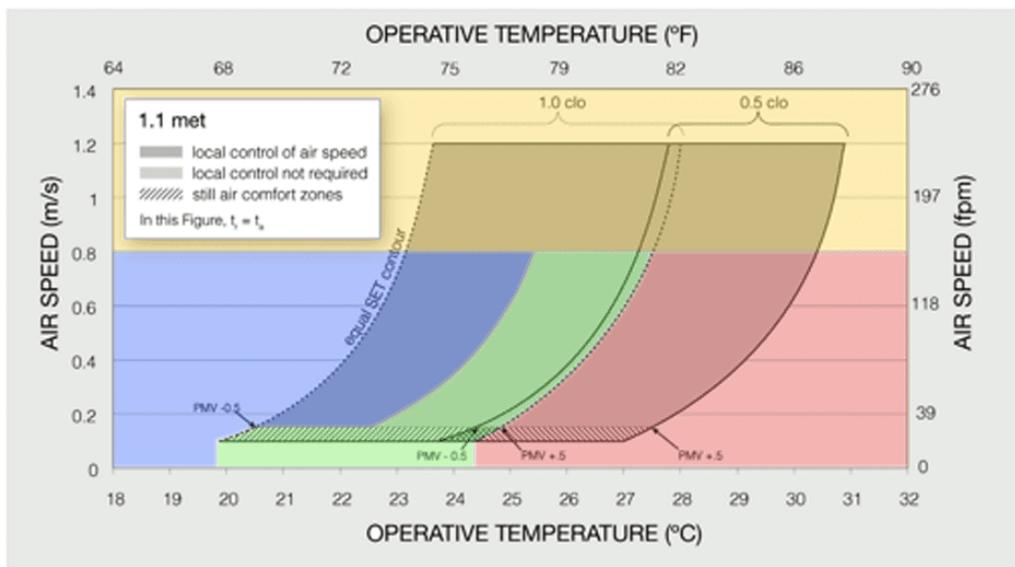


Figure .47 Fuzzy rules of wind catcher controller

This thesis presents a smart system that combines active and passive components. The passive component responsible for naturally ventilating the building is called the wind catcher. The wind catcher controller has been designed and developed as part of the proposed system using a fuzzy logic controller to control three outputs (Shutter - Fan - AC). The distributed output depends on two environmental values, which are temperature-related conditions and airflow-related conditions. Fuzzy rules set for wind catcher components have been conducted relating to the Thermal comfort chart using ASHRAE 55 parameters shown in figure 48.



Comfortable | **Too Hot** | **Too Cold** | **Too Drafty**

Figure .48 Thermal comfort chart using ASHRAE 55 parameters [87]

A range of temperature considered comfortable, as following the ASHRAE chart, is between 20° C and 24° C, as shown in figure 48. Less than 20° C is considered cold, and more than 24° C to 27° C is considered hot, then temperature above 27° C is considered too hot that an AC only is needed for achieving thermal

comfort. A range of airflow regarded as comfortable is between 0.2 m/s and 0.8 m/s. Less than 0.2 m/s was considered low, so a fan needed to be turned on to increase the flow. Moreover, if the airflow is more than 0.8 m/s, the shutter will be half-opened to decrease the airflow.

The system has been simulated in MATLAB Simulink toolbox using Mamdani fuzzy system. Fuzzy logic is a suitable algorithm for the proposed system as it is concerned with decision-making conducted after considering all the input data. Further, the Mamdani model is one of the most popular fuzzy logic algorithms. It is made to include expert knowledge in IF-THEN rules articulated in linguistic language; Mamdani systems might appear particularly inviting for applying the proposed system.

In this thesis, the wind catcher controller part of the proposed system was simulated in MATLAB, and the fuzzy rule set was demonstrated in a table in the previous chapter. The membership function of the two inputs is shown, and the sorting of the temperature and airflow is discussed. As discussed, the inputs were generated based on the model generator introduced in [85-86]. The primary simulation result demonstrates an inaccuracy in the output air generator values, resulting in a fuzzy mistake. Thus, the self-tuning PID technique is used to have more accurate and responsive desired outputs in the shutter, fan, and AC with the least amount of error. Therefore, one solution and a strong candidate for this problem is using BPNN.

As previously indicated, the initial step is to construct PID parameters using BPNN. Figure 49 shows the K_p , K_i , and K_d BPNN training values after generation. The simulation was then ran, and the outcomes of the fuzzy outputs based on fuzzy rules were displayed.

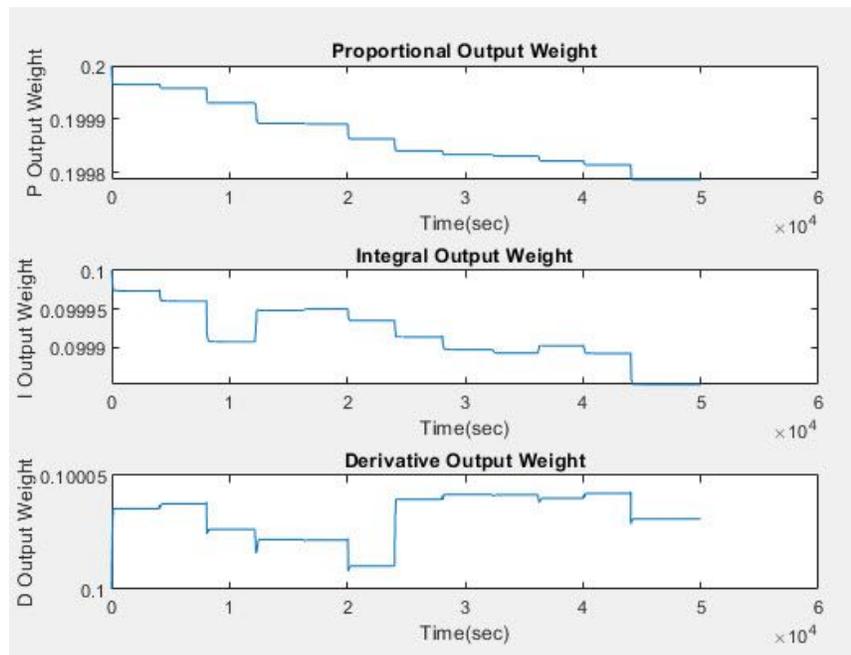


Figure .49 PID Tuning values after BPNN generation

The results have been showcased on displays connected to three output valves (shutter, fan, and AC). Then, the display shows the values [0, 1, 0.5], which correspond to OFF, ON, or half opened to decrease the airflow. The values are then compared to the fuzzy rules set in the table conducted in the previous section. The windcatcher controller effectively functions the rules. Which means the system is accurately working as designed.

Further validation of the proposed system could be achieved by building a hardware experiment with actual data and a wind catcher model. The following table 12 shows samples of results for the modeling before PID and after the PID tuning with BPNN. Note that the values of the shutter, fan, and AC are based on the modeling of the fuzzy rule output system.

Table 12. Fuzzy rules set for wind catcher components

System Model	Temperature	Air flow	Shutter	FAN	AC
System without PID-BPNN	21.5	$0.7 * e^{-5}$	0.2 (ON)	-0.01 (—)	-0.8 (OFF)
System with PID-BPNN	21.5	0.7	0.2 (ON)	-0.33 (OFF)	-0.8 (OFF)
System without PID-BPNN	29	0.008	-0.07 (—)	-0.3 (OFF)	-0.4 (ON)
System with PID-BPNN	29	0.8	-0.8 (OFF)	-0.89 (OFF)	-0.45 (ON)
System without PID-BPNN	22.8	$0.3 * e^{-7}$	-0.01 (—)	-0.11 (OFF)	-0.169 (OFF)
System with PID-BPNN	22.8	0.3	0.27 (ON)	-0.11 (OFF)	-0.169 (OFF)

The output decisions have improved with PID-BPNN tuning in the system, as shown in the table. Because of the narrow number of airflows, the system couldn't decide which output to use before tuning. As a necessary consequence, tuning was required to improve the airflow values and stabilize the controller's decision.

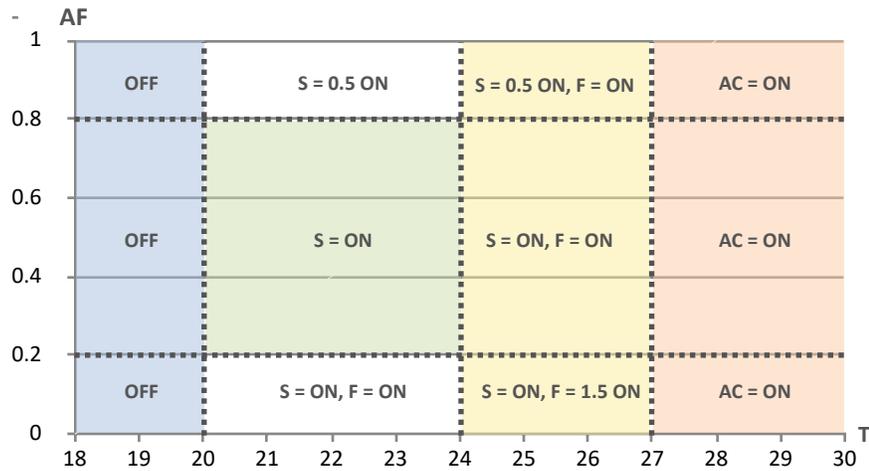


Figure .50 Thermal comfort chart using ASHRAE 55 parameters in the proposed system.

The study's findings must be viewed in light of significant limitations. Due to time constraints and the author's limited experience, the study's findings are limited to only one component of the proposed system. Furthermore, the proposed system design is not numerically validated in the study. The suggested system's validity can be studied and expanded in future work through hardware experiments demonstrating the effect of this system on indoor thermal comfort using real-time temperature and airflow data.

A. Conclusion

This thesis discusses the design and development of a hybrid active/passive smart system integrated into buildings. The first chapter of the thesis introduces the subject and gives an overview of the main aim and objectives of the work. This study aims to reduce energy consumption in buildings by utilizing wind and solar energy for cooling and ventilation to achieve natural ventilation and thermal comfort by proposing a hybrid active/passive smart system for cooling in buildings.

The second chapter explores the background knowledge of active and passive systems. Smart buildings research and building energy and comfort management has been presented along with different algorithms and techniques required for an intelligent system (Active). Further, an investigation of previous wind catcher system designs to set a group of design decisions in the proposed method (Passive).

The third chapter presents the proposed hybrid active/passive smart system design. The components of the system are identified, and a 3D modeling of the system is conducted via Autodesk Revit, showcasing the proposed design. Further, the control system modeling is developed using the fuzzy logic controller via Matlab Simulink packages.

The fourth chapter analyzes the results of the control system simulation in Matlab. The development of a fuzzy controller for the wind catcher controller is described. The realization of the need to fine-tune the fuzzy logic system to operate at its optimal point is processed. A Backpropagation Neural Network is used to enhance the results.

The fifth chapter discusses the overall results and suggests how to improve the proposed system further and validate it via hardware experiments.

Finally, the thesis demonstrated a hybrid active\passive smart system design, highlighted the effective solution of using passive cooling techniques, implemented a fuzzy logic control, and fine-tuned the system to operate at its optimal point. The result of the simulation demonstrated the effectiveness of the applied methodology. Although this design controls only the wind catcher controller part of the proposed system, the design process can be extended to other control parts.

B. Future work

The design concept may be developed to output other necessary variables of the proposed system, such as solar PV and storage systems. Moreover, for the wind catcher's controller, the design concept can be planned to expand further for the shutters to be opened at a particular angle responding to the airflow. Also, the fan could operate at different powers, not limited to three conditions. Further, a CO2 sensor could also be integrated to achieve a healthy indoor environment.

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