YAŞAR UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MASTER THESIS

AN APPROACH FOR COMPARING THE ENERGY EFFECT OF WATERWALL SYSTEMS IN AN OFFICE SPACE; CASE STUDIES IN ISTANBUL, AND STOCKHOLM

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We certify that, as the jury, we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Natural Science.

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ABSTRACT

AN APPROACH FOR THE EFFECT OF WATERWALL SYSTEMS ON ENERGY EFFICIENCY IN BUILDINGS: ISTANBUL, AND STOCKHOLM REGION SAMPLES

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With the energy demand increasing worldwide, which is fueled by the increase in population, and the fact that fossil fuels are running out as well as the increase in CO^2 emissions made countries and facilities seeking to reduce energy consumption in the building sector. Passive architecture comes into play, as it’s sympathetic to climate conditions, as it reduces energy consumption levels while providing indoors thermal comfort levels in terms of heating and cooling in addition to the reduction of the building’s energy consumption which leads to cost reduction, as well as the reduction of HVAC systems usage.

This thesis is aimed to analyze and compare between different solar energy gain systems in a space using parametric modeling techniques supported by optimization methods and simulation techniques. The study is about simulating the behavior of a south-facing thermal storage wall which is Water Wall System in different building material configurations, as an indirect solar energy gain system, along with another type of thermal storage walls which is Trombe Wall and a direct solar gain system provided by the Single glazed wall. The objective considered in this study includes surface temperature, indoor temperature, and energy consumption. An application was presented using a base model assumed to be located Istanbul, and Stockholm to study the difference in behavior in two different climatic zones.

This thesis consists of 7 chapters namely introduction, passive solar energy gain systems in the building- literature review, passive solar energy gain systems in building-technical aspect, simulation tools used for assessing passive energy systems performance, generating models for passive solar energy systems, results and discussions, and conclusion.

Key Words: water wall system, Trombe wall, direct solar system, indirect solar system, passive solar systems, thermal performance, comfort zone, office building, energy simulation.

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I would like to express my enduring love to my mother and grandmother, who was always supportive, loving, and caring to me in every possible way in my life.

Pakinam El-Shinnawy
İzmir, 2018

TEXT OF OATH

I declare and honestly confirm that my study, titled "An Approach for the effect of water wall systems on energy efficiency in buildings: Istanbul, Stockholm, Ankara, and Moscow Region Samples" and presented as a Master's Thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions, that all sources from which I have benefited are listed in the bibliography, and that I have benefited from these sources by means of making references.

Pakinam El-Shinnawy

Izmir, 2017

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SYMBOLS AND ABBREVIATIONS

SYMBOLS

λ	Thermal Conductivity *($W.K^{-1}$), or (kA/L), or (W/ (m^2. K))*
ρ	Density *(kg/m^3)*
A	Area (m^2)
k	Thermal Conductivity (*kJ/m/s/ºC*)
$(\Delta Q/\Delta t)$	Heat Conduction rate in (*kJ/s*)
L	Thickness of the Layer (*m*)

ABBREVIATIONS

HVAC	Heating, Ventilation and Air-Conditioning
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CFD	Computer Fluid Dynamics
TES	Thermal Energy Storage
TSW	Thermal Storage Wall
PSH	Passive Solar House
PV	Photovoltaic
PCM	Phase Change Materials
VT	Visible Transmittance
SH	Specific Heat (*J/kg-K)*
SHGC	Solar Heat Gain Coefficient
WW	Water Wall
Trnsp	Transparent
Trnsl	Translucent

CHAPTER 1
INTRODUCTION

Energy has been dominating issues for the 21st century, as well as for climate change; hence it is prioritized to work on reducing the carbon dioxide footprint as it is the driving force behind climate change. In Europe, it's estimated that 40% of the total energy consumption is by public and commercial buildings. Energy efficient renovation of the existing buildings is needed to improve such state (Katafygiotou & Serghides, 2014). Nowadays, Residential and public buildings are responsible for the consumption of one-quarter of the total worldwide energy production, with an expected increase on annual bases from the year 2010 to the year 2040 by approximately 1.6%.

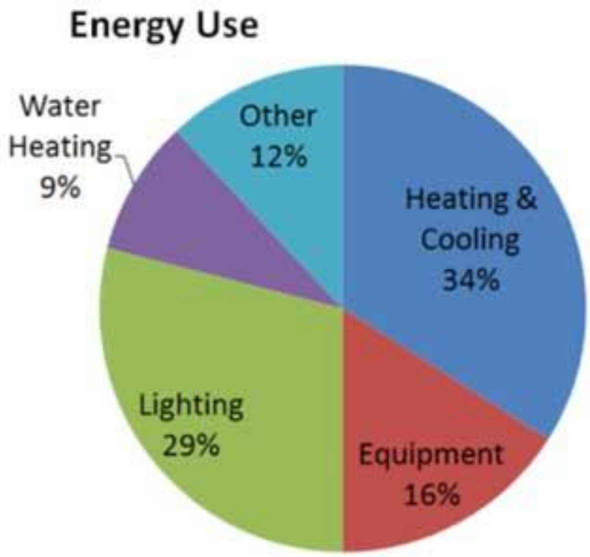

Figure 1.1 Office Building Electricity Chart **(Todd, 2011)**

Moreover, some countries lack the fossil fuels, which makes it a pressing matter for scientists to come up with alternative methods for energy production. Development in energy efficient building applications has rapidly increased and progressed in an attempt to reduce energy consumption in the building sector (Casamayor & Su, 2013). Heating, ventilation, and air-conditioning (HVAC) systems, accounts for half of the building's energy consumption levels (Pérez-Lombard, Ortiz, & Pout, 2008). Moreover HVAC systems require electricity, or fossil fuel, to provide the needed indoor environmental comfort level, subsequently, saving energy from HVAC systems in buildings becomes crucial for the combat against the ongoing energy crisis and climate change.

Renewable energy could have a great impact in cold climatic regions, in terms of passive and thermal solar energy. The passive solar energy system is a building subsystem that works on solar energy, through collecting and transferring that energy by natural means; convection, conduction, or radiation to distribute thermal energy throughout the structure, to establish the necessary level for indoor environmental comfort. This, in turn, makes passive solar energy system one of the most feasible methods in terms of accessibility, economic aspect, reducing carbon footprint. On the solar energy is only available in the daytime and savoring it for night time usage that's when thermal masses come into place. By definition, buildings in cold climates are designed to address the cold, through the material, insulation, orientation, and space design. According to (Balcomb J. D., 1992)), the thermal load of mechanical of HVAC systems in buildings is reduced significantly when passive solar building technology is used. Thermal storage wall is a passive solar technique that replaces standard walls, with a composed of a different material arrangement of glazing and materials of high thermal storage capacity. There have been studies conducted to address solar heating in cold climate, such as (Wang, Manzanares-Bennett, Tucker, Roaf, & Heath, 2012), where it was noted that the change of material used has an impact on TSW.

The office buildings energy consumption levels have been increasing as a result of technological development and usage of mechanical heating and cooling systems (HVAC) systems. This building sector has been on the course to design and advance in the performance-based building concept, assessing and providing tenants thermal comfort levels suited to increase productivity levels, as well as reducing the energy consumption of the building to reduce the usage of mechanical heating and cooling systems (HVAC) systems resulting in cost saving. To do so architects and developers started presenting a variety of passive architectural proposals. In (Skanska, Cushman & Wakefield, GO4 Energy, 2018) a behavioral study was conducted on tenants that are employed in both, an energy certified building and a non-certified building, the result was that employees working in an energy certified building consumed less electricity than those present in a non-certified building.

On the other hand, energy simulation tools come into play in building technology and its quest for achieving sustainable designs. They are implemented to simulate and analyze building energy performance and thermal behavior to reach the tenant's comfort zone as well as reduce future energy consumption cost. Using energy simulation tools provides architects, engineers, and researchers with the means to reduce the cost of on field experimentation, with much more reliable data, data management, user-friendly interfaces and ability to integrate other subdivisions in the process. Over the cross of the last 60 years, or so simulation tools and computer-aided software have come a long way, in terms of covering climatic analysis, building thermal behavior, daylight simulation, energy consumption, and building optimization.

1.1. The Subject of the Thesis

The subject of this thesis is assessing the thermal performance of different water wall configurations to compare them to other kinds of thermal storage wall as well as non-passive energy building element, by using parametric modeling technology in terms of user support tools, simulation techniques, and data analysis. Different water wall configurations have been determined to be compared, along with other wall configurations, the location has been determined based on climatic conditions.

This thesis also provided a research review concerning the use and performance of different thermal energy storage wall as well as different types of passive solar energy gain building systems, with an extensive study on water wall systems. The study emphasizes the performance of water wall systems in cold climatic regions and their thermal performance across time since it was first used.

1.2. Aims and Problem Definition

The aim of this thesis is to analyze the performance of different water wall configurations in different climatic regions while studying the predictor application in the literature review.

The problem is to find the water wall configuration that provides the best performance in cold climate both in winter and in summer, as well as studying its performance in a different climatic though to see the proper region for its application by using simulation technologies.

Wall configuration selection was based on the studies; the main aim of the thesis is to choose the water wall configuration that reached the highest thermal performance level by comparing between different configurations and other wall structures.

1.3. The context of the Thesis

This thesis focuses on different water wall configurations integrated into a building, to analysis their thermal performance for a case study which is schematic space designed. Starts with, review on the work studies conducted on water walls in building and the reasons for using them, with a brief historical insight as well as covering its presence across time based on application, climatic region, and performance.

An investigative study on different types of passive solar energy systems in buildings such as; Water Wall, Trombe wall, Double Façade and BIPV walls, as well as they, 're discussing the working principles.

Followed by, explanations of the simulation approach in terms of modeling, simulation tools, and physical properties of selected materials.

1.4. Method of the Thesis

This thesis is based on assessing the energy performance of different configurations of Water Wall system which are; Transparent Plexiglas Water Wall, Gazbeton Water Wall, Concrete Water wall, that in comparison to other passive and non-passive wall configurations such as; Trombe wall, and Single Glazing. This has been done through developing a computational design model for space and assessing the performance across a year. Two weather conditions have been chosen to evaluate the performance of those wall configurations which are Stockholm as a cold climatic region and Istanbul as a Hot and Dry Climatic region.

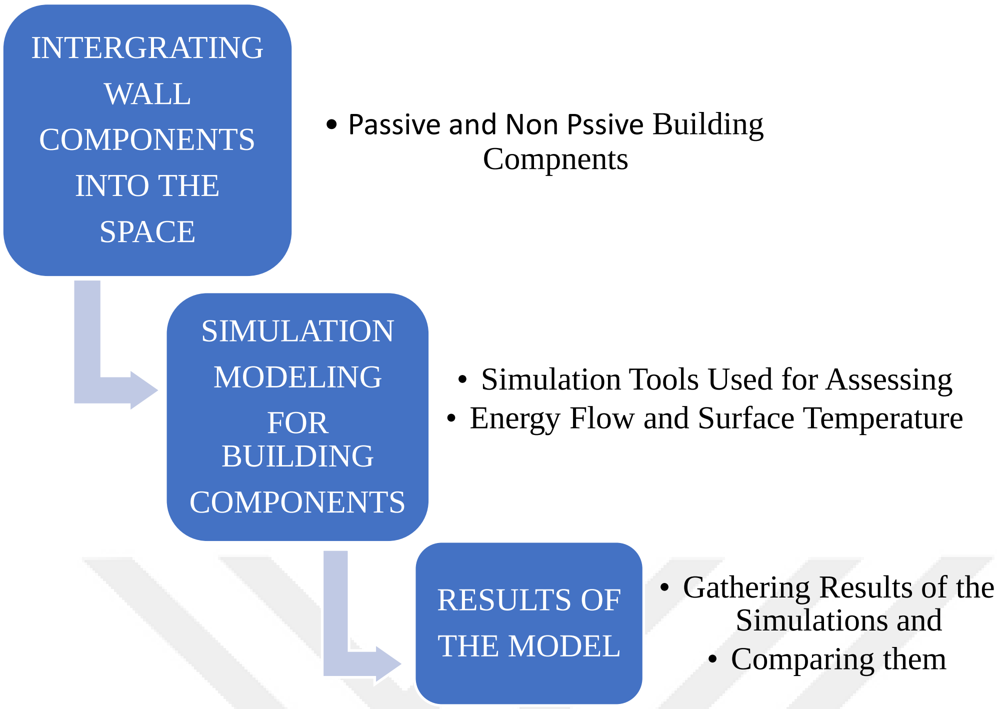

Figure 1.2 Schematic Illustration of Research Methodology

<u>Integrating Wall Components into space:</u> At this Stage different types of passive and non-passive energy wall configurations are integrated into the conceptual designed space. Those components have been researched and defined in terms of their physical priorities in order to evaluate the performance of each one based on their Thermal performance.

<u>Simulation Modelling for Building Components</u>: At this stage, simulation tools are used to assess thermal performance for building components.

<u>Results of the Model:</u> This is the final stage where simulation results for building components are gathered and then analyzed thorough comparative graphs.

CHAPTER 2
PASSIVE SOLAR ENERGY SYSTEMS - LITERATURE REVIEW

In this chapter different types of passive solar energy gain systems in buildings have been presented after dissecting relevant predecessors work. Passive solar energy systems utilize building components to gain control over solar heat generation that comes in contact with exterior walls, roofs and floors, by doing so designers can use them for heating and cooling purposes, and in some cases as a source of electrical generation, which result in reducing the use of mechanical HVAC in building along with the reduction of energy consumption.

The following tables have been used to dissect the source in terms of providing a sum-up for each source. The systems that have been presented in this review are as followed; Water Wall System, Trombe Wall, Building Integrated Photovoltaic (BIPV) System, Passive Cooling Wall, Solar Wall Heating (SWH), Solar Chimney, Solar Space heating system.

Table 2.1 Water Wall Systems

Year	Source Title	Author(s)	Location	Climatic Zone	Building Type	Simulation Type	Simulation Tool	System Description	Reason for application	Study Type
2017	A Case Study on the Use of Harvested Rainwater to Operate Passive Cooling Water Wall (PCWW) for SEGi University Tower	Vinod Kumar Venkiteswaran, Wong Dee Lern, Surenthira Stephen Ramachanderan	Kuala Lumpur, Malaysia	Tropical	Educational Building	Thermal Building Calculations	-ANSYS FLUENT -Steady State	Water Wall	Space Cooling	Simulation
2005	A water wall Solar Design Manual	David A. Bainbridge	Massachusetts	Humid Continental	Educational Building	-Thermal Building Calculations	No simulation Program is mentioned	Water Wall	Space Heating	-Numerical Simulation
1981	Thermal load leveling of heat flux through an insulated thermal storage water wall	M. S. Sodha, S. C. Bhardwaj, S. C. Kaushik	New Delhi, India	Humid subtropical, Semi-arid	Test Room	-Surface Temperature -Indoor Temperature	Heat Conduction Equation	Opaque Water Wall	Impact of insulation thickness on the surface temperature inside and outside	-Numerical Simulation
1989	Thermal comfort in buildings through a mixed water-mass thermal storage wall	S. C. Kaushik, S. Kaul	New Delhi, India	Humid subtropical, Semi-arid	Test Room	-Surface Temperature -Indoor Temperature	Heat Conduction Equation	compared between a concrete enclosed water wall mixed with thermal storage wall configuration, a pure concrete water wall configuration, and Trombe wall	-Impact of heat transfer through walls and roof -Comparison	-Numerical Simulation

Table 2.1 (Cont'd). Water Wall Systems

Year	Source Title	Author(s)	Location	Climatic Zone	Building Type	Simulation Type	Simulation Tool	System Description	Reason for application	Study Type
2013	Investigation on the influencing factors of energy consumption and thermal comfort for a passive solar house with water thermal storage wall	Weiliang Wang, Zhe Tian, Yan Ding	Tianjin, North China	Temperate	Passive Solar House	-Indoor Temperature -Energy Consumption	TRNSYS	Water Thermal Storage Wall	-Reduce energy consumption -Space Heating	Simulation
2012	Investigation of a Passive Solar House Equipped with Water Thermal Storage Wall	Wei Liang Wang, Zhe Tian, Xiao-Lei Niu, Xin Xu	Tianjin, North China	Temperate	Passive Solar House	-Indoor Temperature -Energy Consumption	Heat Conduction Equation	Water Thermal Storage Wall mixed with natural ventilation technology	-Reduce energy consumption -Space Heating -Space Cooling	-Numerical Simulation
2012	Integrating passive cooling and solar techniques into the existing building in South China	Lui, Wei Yi, Feng, Wei	Shenzhen, South China	Humid subtropical	Two Test Rooms in multi-purpose building	Indoor Temperature	- CFD -Ecotect -SolPass software	Transparent Water Wall Trombe Wall	Comparative Analysis	-Experimental -Simulation
1991	Relative Thermal Performance of South Walls in Winter	G. N. Tiwari, M. Upadhya, S. N. Rai	New Delhi, India	Humid subtropical, Semi-arid	Thermal Analysis	Indoor Temperature	Heat Conduction Equation	Water Wall Glass Wall Air Collector Wall Transwall	Comparative Analysis	-Numerical Simulation

Table 2.1 (Cont'd). Water Wall Systems

Year	Source Title	Author(s)	Location	Climatic Zone	Building Type	Simulation Type	Simulation Tool	System Description	Reason for application	Study Type
1983	Analysis of passive heating concepts	J.K. Nayak, N.K. Basal, M. S. Sodha	Colorado, USA	Cold winter and subtropical low desert	Test Room	-Average heat flux -Thermal load leveling	Heat Conduction Equation	Opaque Water Wall Trombe wall Solarium uncovered glazing Solarium covered glazing	performance analysis	Numerical Simulation
1986	Solar wall project: two demonstration houses with passive solar heating in Tasmania	R.G. Sutton, R.J. McGregor	Tasmania, Australia	Cool Temperate	Two Homes	-Thermal Comfort Level -Indoor Temperature	No simulation Program is mentioned	Opaque Water Walls	Space Heating	Experimental
2011	Solar chimney—A passive strategy for natural ventilation	Rakesh Khanal, Chengwang Lei	Not specified	Not specified	Any Building	Not specified	- Heat Conduction Equation -Computational Fluid Dynamics	Solar chimney integrated with Water Wall	Effects of geometry and inclination angle on the ventilation performance	-Numerical Simulation

Table 2.2 Trombe Wall System

Year	Source Title	Author(s)	Location	Climatic Zone	Building Type	Simulation Type	Simulation Tool	System Description	Reason for application	Study Type
2013	A numerical and experimental analysis of the air vent management and heat storage characteristics of a Trombe wall	Yanfeng Liu ⇑, Dengjia Wang, Chao Ma, Jiaping Liu	GangCha County, QingHai Province, China	Subpolar Climate	House	-Thermal Building Calculations -Design Optimisation -Air vent velocity - Air Vent Temperature -Indoor Air Temperature	Computational Fluid Dynamics	Trombe wall	Space Heating	Simulation
2015	An experimental investigation of a novel Trombe wall with Venetian blind structure	Zhongting Hu, Bingqing Luo, Wei He	Hefei, China	Sub-polar climate	Two Test Rooms	-Thermal Building Calculations	Equation	Trombe wall integrated with DC fan on the Venetian blind structure	Performance assessment	-Numerical Simulation
2016	An innovative Trombe wall as a passive heating system for a building in Athens – a comparison with the conventional Trombe wall and the insulated wall	Evangelos Bellos, Christos Tzivanidis, Eleni Zisopoulou, Georgios Mitsopoulos, Kimon A. Antonopoulos	Greece, Athens	Mediterranean	Isolated Room	-Thermal Building Calculations	-Solid works -Flow Simulation Module	-Trombe wall with a vent -Regular Trombe wall -Insulated wall	Space Heating	Experimental

Table 2.2 (Cont'd). Trombe Wall System

Year	Source Title	Author(s)	Location	Climatic Zone	Building Type	Simulation Type	Simulation Tool	System Description	Reason for application	Study Type
2007	Numerical study on the thermal behavior of classical or composite Trombe solar walls	Jibao Shen, Ste´phane Lassue, Laurent Zalewski, Dezhong Huang	Not specified	Not specified	Computer Model	-Thermal Building Calculations	-TRNSYS -FDM	-Trombe Wall -Composite Trombe Wall- Michel Wall	Thermal performance	Simulation
2011	Optimum design of Trombe wall system in Mediterranean region	Samar Jaber, Salman Ajib	Amman, Jordan	Mediterranean	Residential House (Dar)	-Thermal Building Calculations - Economical Equations	-TRNSYS -LCC Equation	Trombe Wall	Thermal, environment and economic impact	Simulation
2016	Analysis of Atrium Pattern, Trombe Wall and Solar Greenhouse on Energy Efficiency	Sama Modirrousta, Haleh Boostani	Not specified	Not specified	Any Building	Not specified	-No Simulation Program is mentioned	-Trombe wall -Greenhouse System -Atrium	Ventilation Heating Cooling Natural Lighting	-Descriptive -Theoretical
2016	Application of passive wall systems for improving the energy efficiency in buildings: A comprehensive review	Hossein Omrany a, Ali Ghaffarianhoseini, Amirhosein Ghaffarianhoseini, Kaamran Raahemifar d, John Tookey	Not specified	Not specified	Any Building	Not specified	-No Simulation Program is mentioned	-Trombe wall -Green Walls -Double Skin Walls -Autoclaved Aerated Concrete Walls	Space Heating	Theoretical

Table 2.3 Building Integrated Photovoltaic (BIPV) System

Year	Source Title	Author(s)	Location	Climatic Zone	Building Type	Simulation Type	Simulation Tool	System Description	Reason for application	Study Type
2003	Monitoring results of two examples of building integrated PV (BIPV) systems in the UK	S.A. Omer, R. Wilson, S.B. Riffat	Nottingham, UK	Temperate Maritime	-School of the Built Environment, University of Nottingham (Educational Building) - Residential House	Energy Analysis	- PVSYST Simulation -CAD modeling	Building integrated PV (BIPV)	Monitoring performance of PV roof slates and that of film PV façade	Experimental
2018	Assessing active and passive effects of façade building integrated photovoltaics/thermal systems: Dynamic modeling and simulation	Andreas K. Athienitisa, Giovanni Baroneb, Annamaria Buonomanoa, Adolfo Palombob	Prague Bolzano Freiburg Madrid Naples Athens Almeria	-Humid continental climate - warm and temperate - Mediterranean	Ten Floor Office building (High-rise building)	-Thermal Building Calculations Calculate Indoor Temperature - Thermo-economic results	DETECt 2.3	BIPV/T System	Passive heating Passive cooling Electrical production	Simulation
2013	An approach for energy modeling of a building integrated photovoltaic (BIPV) Trombe wall system	Basak Kundakci Koyunbaba, Zerrin Yilmaz, Koray Ulgen	Izmir, Turkey	Mediterranean	Test Room	Thermal Building Calculations	-Computational Fluid Dynamics (CFD) -Ansys CFX -Monte Carlo Model	Naturally Ventilated BIPV Trombe wall	Performance Analysis	-Experimental -Simulation

Table 2.3 (Cont'd). Building Integrated Photovoltaic (BIPV) System

Year	Source Title	Author(s)	Location	Climatic Zone	Building Type	Simulation Type	Simulation Tool	System Description	Reason for application	Study Type
2016	BIPV-temp: A demonstrative Building Integrated Photovoltaic installation	Anatoli Chatzipanagi, Francesco Frontini, Alessandro Virtuani	Lugano, Switzerland	Humid Subtropical	Mock-up Structure at SUPSI	- Normal Operating Cell Temperature -ECT	- Standard Test Condition (STC) - NOCT Model	BIPV installed in different inclinations 30° and 90°	Calculating the impact of the operating cell temperature on performance	-Experimental -Simulation
2016	Building integrated solar thermal design: assessment of performances of a low-cost solar wall in a typical Italian building	Marco Beccali, Giuliana Leone, Paola Caputo, Simone Ferrari	Milano, Italy	Humid Subtropical	House	Collector-wall system efficiency performance	-TRNSYS Model -FEM Model	building integration of solar thermal collector (BIST)	Heating generator	Simulation
2007	Modeling of a novel Trombe wall with PV cells	Ji Jie, Yi Hua, He Wei, Pei Gang, Lu Jianping, Jiang Bin	Hefei, China	Sub-polar climate	Test Room	-Thermal Building Calculations Calculate Indoor Temperature -Electrical Efficiency	FORTRAN	PV glass panel PV integrated Trombe wall	-Comparative analysis -Heat Distribution -Electrical Generation	Numerical Simulation

Table 2.4 Passive Cooling Wall System, Solar Space Heating System and Solar Wall Heating (SWH) System

Year	Source Title	Author(s)	Location	Climatic Zone	Building Type	Simulation Type	Simulation Tool	System Description	Reason for application	Study Type
2009	A 3D CAD-based simulation tool for prediction and evaluation of the thermal improvement effect of passive cooling walls in the developed urban locations	Jiang He, Akira Hoyano	Japan	Humid Subtropical	Experimental Space (Any Building Type)	-Thermal Building Calculations. - Mean Radiant Temperature.	3D CAD- Cased Simulation	Passive Cooling Wall (PCW)	Space Cooling	-Simulation -Theoretical
2012	A feasibility study on solar –wall systems for a domestic heating-An affordable solution for fuel poverty	Fan Wang, Alvaro Manzanares-Bennett, Jan Tucker, Susan Roaf, Nicholas Heath	Edinburgh, Scotland	Temperate Maritime	- Apartment in 4 story building - Single Storey Bungalow	-Thermal Building Calculations - Cost Analysis	-Unsteady state CFD model - PHOENICS (CHAM)	Solar Wall Heating (SWH)	-Space heating -Domestic hot water	Simulation
2014	Heating season performance improvements for a solar heat pipe system	Brian S. Robinson, M..Keith Sharp	Louisville, USA	Humid Subtropical	The two-room passive solar test facility	-Thermal Building Calculations -Building Heat Loss Coefficient	-Data Acquisition System -LabVIEW software	Heat pipe Solar Space Heating System Configuration	Testing Performance Levels	-Experimental -Simulation

2.1. Water Wall

According to (Bainbridge, 2005) the first water all was built at Massachusetts Institute of Technology in 1947 by Hoyt Hottel and his students. Their prototype was a full height water wall composed of one and five-gallon cans, painted black and set behind double pane glass, 38-48% of the heating demanded was provided by those walls. The problem that arose resulted from poor design, limited direct gain through the windows, inadequate curtains between water wall and the glass window, inadequate insulation, and the separation of the water mass from the room by curtains which reduced the performance level.

Water walls were brought back by Steve Baer in 1972 in a space-age design in New Mexico. In His design Corrales House, he used fifty-five gallons of water to provide thermal mass for an innovative passive solar design to 1.3- 1.5m in height in metal support frames. Single pane glass was used for the south walls, with reflective covers that are lowered on sunny winter days and closed at night. The system contributed by 85% of the total space heating required, although the insulation levels in the walls and ceilings were modest. Later on, Steve Baer applied water walls in both residential and commercial projects.

Based on (Steven Winter Associates, Inc., 1997), Tim Maloney worked on testing and developing a water wall module system back in 1974, which consisted of plastic bags supported between sheet metal panels. Later on, a group from the Kalwall Corporation started introducing fiberglass technology they developed translucent cylinders for water storage.

Water walls are considered an excellent short-term thermal energy storage system that works on maintaining the building's thermal comfort while reducing the heating and cooling loads. Water walls act as short-term thermal energy storage, its advantage is its availability, low cost, and the high heat capacity of water. Furthermore, water redistributes the stored heat through convection, thus providing a more rapid heat exchange than concrete or brick walls (Chan, Riffat, & Zhu, 2010).

Based on (Wu & Lei, 2016) literature review, water wall winter application is based on the wall absorbing solar radiation and storing it during the day to be released as heat at night by doing so it sets off the heating load of the building. As for the summer application, water wall works as a buffer zone preventing the living space from overheating during the day and thus makes the indoor environment more comfortable. Thermal comfort and energy consumption levels are maintained as a result of the water wall capability of moderating the temperature swing between the day and night.

In (Balcomb & McFarland, 1978) research a comparison was conducted based on the thermal performance of water walls with opaque building envelops against the performance of conventional walls; one with night-time insulation, against one without night-time insulation as well as one with reflectors against one without reflectors. The result was that the water wall had a higher monthly solar heating function in terms of the percentage of the space heating load provided by the passive solar system than that of the Trombe wall. While in (McFarland & Balcornb, 1979) study, an hourly computer simulation was conducted on the course of one year based on the solar radiation and temperature data to analyze for both Trombe walls and water walls in terms of the annual energy saving. Parameters used for the analyses were: number of glazing, wall absorbance, and emittance, night insulation R-value, thermal storage capacity, wall properties and vent area size. What was concluded is that the water wall performance levels improved by using night-insulation with a reduced R-value, in addition to the glassing number used, absorbance rate for the wall, and by increasing the wall's emissivity factor, and it's the thermal storage capacity.

While as in (Sodha, Bhardwaj, & Kaushik, 1981) research which was conducted to reach the optimum thickness distribution between inside and outside insulation layers of a water wall under the constraint of a given total thickness of the insulation layers. The results were that minimum temperature fluctuation was achieved through having an equal thickness between the inside and outside insulation layers, in addition, they realized the applying the entire insulation layer on the outside rather than the inside of the water wall reduced the temperature fluctuation.

(Kaul & Kaushik, 1989), compared between a concrete enclosed water wall mixed with thermal storage wall configuration and a pure concrete water wall configuration. They realized that using a water wall with insulated panels resulted in an informal low level of heat flux both during and after sun raise hours for winter days in New Delhi. Water walls integrated with insulation panels resulted in lower hourly heat flux than that of the concrete enclosed water wall mixed with thermal storage wall configuration. In the end, the favored combination was that a concrete enclosed water wall mixed with thermal storage wall configuration which resulted in a more stable and comfortable indoor temperature.

In (Nayak, Bansal, & Sodha, Analysis of passive heating concepts, 1983) comparison, they worked on investigating four different types of solar passive energy systems, which are: Trombe wall, water wall, a glazed uncovered solarium, and another solarium wall with a glazed covered by a movable insulation for non-lit hours of the day. The result showed that when night-time insulation was used, water walls had a more stable temperature and higher heating flux in compression to the Trombe wall.

In (Sutton & McGregor, 1986) Investigation, the application of water wall with an opaque building envelope in a comparison between two solar passive solar heating houses in Australia in terms of having a north facing the concrete wall to having a water wall system. The information gathered demonstrated that half of the annual heating energy consumption was saved in the house with the water –tube wall; unlike the conventional house with a concrete wall which. The house with the water consumed 70.8% of energy consumed by the concrete wall house. The application of water wall that is built out of 7.6cm diameter plastic tubes which is inserted into a conventional stud wall in a residential house was tested by (Turner, Liu, Harris, & Cengel, 1994). The system's thermal behavior was studied on the course of a 24hrs cycle that included 6 hrs. active charging with solar heated, and 18 hrs. of passive discharge. The conclusion was that the water wall maintained a temperature of 2.6°C higher than that of the indoor temperature 18 hrs. after discharging resulting in the reduction of the heating load for the house, correspondingly in summer time nocturnal water wall, thermal wall storage results in achieving daytime thermal comfort levels by discharging of the cool air ambient that has been charged through the night.

Several types of research have been conducted to demonstrate the advantages of water walls which exist in a semi-transparent building envelope. For instance, the work of (Fuchs & McClelland, 1979) on designing the most commonly used configuration of water wall with a semi-transparent envelop in a Transwall, in which a semi-transparent baffle was inside the water wall. They also held a comparison between the performance of the Transparent water wall against a Trombe wall and a direct gain system. The results were that the Transparent water wall system's solar performance surpasses the performance of the Trombe wall. In another study done by (Balcomb, 1977) on water wall thermal performance under five different configurations, which are; The water storage was placed inside the room with the same temperature as the room, the water storage was placed behind a glass panel, the water wall was placed behind an opaque wall and the water wall was placed behind a transparent insulation panel. The study indicated that the water wall placed behind a transparent insulated panel had the highest level of solar heat gain in winter when compared to the others.

In (Nayak, 1987) experiment, he worked on comparing between the thermal performance of a water wall with opaque building envelope and a Trans-wall based on the heat flux entering in a heated space. Transwells proved to be more effective than the concrete water wall in terms of meeting the daytime heating load, nonetheless concrete water wall has a better performance in reducing temperature variation, and in general the day and night performance. Using his work as a guideline, in (Nayak, 1987), a study he worked on comparing between different types of thermal storage walls; Trombe wall, Transwall, and water Trombe walls based on their thermal performance. Based on the end results Transwells have proven to be more efficient than Trombe walls in achieving the daylight heating load, on the other hand, the highest level of thermal performance was reached by the water Trombe wall in terms of fewer temperature fluctuations, and moderate phase shift hence proving to be the best option.

According to (Tiwari, Upadhya, & Rai, 1991) comparative study on the thermal performance of different types of south-facing walls, such as; glass wall, water wall, air collector wall and a Transwall. Different design parameters were taken into consideration such as the thickness of water wall and Transwall, the air flow rate in the air collector; those aspects were incorporated into the thermal analysis. Results were that the glass wall and the air collector had their highest performance levels during office hours, whereas the water wall and the Transwall were much more suitable for residential heating at night, depending on the thickness of the south-facing wall. Also, in (Tiwari, 1991) work, he performed a performance comparison between a water wall, a Transwall and an isothermal mass for heating in a non–air-conditioned passive solar house located in harsh climate cold conditions in Srinagar, India. The results were that the Transwall resulted in the much higher room temperature in the winter night, than the water wall and the isothermal mass.

One of the most recent works that have been carried out regarding passive heating strategies this is (Lui & Feng, 2012) comparison between a Trombe wall and a water-tube in terms of optimizing the indoor thermal performance and the energy consumption in buildings. The semi-transparent water tubes were built behind the east and west façade of the building to ensure that the room receives both light and heating from the water wall. Computer simulations using SolPass software to analyze the daily heat gain round the year during winter time. The data gathered stated that the water –tube wall obtained over 10 times the solar gain archived by the Trombe wall in winter. When comparing the data collected from their simulation, results were that passive solar systems have the ability to reduce the heating load of the building by approximately 25%, unlike its counterparty which didn't adopt those systems.

In (Tiwari, Yadav, & Lawrence, 1988) study, a number of different interactions between phase change component material and water wall to form a linked wall in a solarium to be sued in cold climate. The results were that the integration of PCM wall and water wall as a link wall had the highest thermal performance levels. Having equal water wall and PCM wall thickness caused low-temperature flux, as well as archiving thermal comfort in the living space.

PCMs in heating pipes were used as a passive solar heating system to absorb and transfer solar energy, according to (Rice, 1984)study, where he analyzed several types of passive heating and hybrid solar heating systems. The system proved to be a prosperous prospect for passive natural heating that is highly efficient as well as low in cost. (Susheela & Sharp, 2001) designed passive solar heating pipe system design for a south facing water wall façade. The end results stated showed that heat pipe and water wall integrated system provided 52% to 107% more solar thermal energy than that of a concrete wall. In (Albanese, Robinson, Brehob, & Sharp, 2012) investigation an experiment conducted to evaluate the use of pipes as passive solar space heating system, through transferring heat to a tank filled with water located inside the building. By using a computer-aided software to generate a model to test the pipe system, the gathered data indicated that:

- Solar heat loses on cloudy days and at night can be reduced by heat pipes.
- The capability of stabilizing the indoor temperature in comparison to conventional systems.
- Efficacy archived was as high as 85%.

In both (Wang, Tian, & Ding, 2013), and (Wang W. L., Tian, Niu, & Xu, 2012) studied the performance of natural ventilation by using solar chimney integrated with a water wall, built in a passive solar house in Northern China. The water wall was retrofitted into the house. Hourly indoor temperature and heating and cooling loads were simulated using TRNSYS software. The results showed that active cooling was not needed in summer, as the temperature indoors was 35°C while it was 47°C outdoors. While as for winter, the measured indoor temperature was 13.7°C, opposite to -0.4°C measured outside. Thereby, proving the efficiency in terms of heating and cooling of combining a water wall with the natural ventilation system.

In (Venkiteswaran, Lern, & Ramachanderan, 2017) investigative study in SEGi University Tower in terms of applying passive cooling water wall (PCWW) to the building's glass façade in an attempt to cool it. Two classrooms with the same area were chosen to conduct this study through a comparison in terms of energy saving upon using passive cooling water wall system and without using one. The water wall was applied in a way to maintain the glass façade which is the main building element as well as allowing the sunlight light the space by using 20mm thick glass panels as a compartment for the stored water that functions as a transparent water wall envelope. The water is supplied by a tank that harvests rainwater. The experiment was conducted at different indoor temperatures which are set by mechanical HVAC system. The results showed that in the presence of passive cooling water wall system the cooling load was equal to the heat gained, the experiment isn't valid as the conditions applied for the case study were fixed as a result of using steady-state simulation program which would result in inaccurate results proving that the water wall system isn't applicable in hot weather conditions.

2.2. Trombe Wall

(Liu, Wang, Ma, & Liu, 2013) Studied the performance of south facing Trombe wall with a window located in-house in GangCha Country in China, in terms of managing the vent's airflow through optimum opening and closing modes by using CFD simulation tool to analysis the heat investigation identified that the best possible time to open the air vents of the Trombe wall system is 2-3 hours after sunrise and to close it an hour before sunset. While when it comes to the most suitable circumstance for air vent management mode, along with surface and an average temperature of the Trombe wall, the results were that the highest value is reached at 16:00, while the lowest values were recorded at 7-8 am. Based on this study a reference was presented for design optimization, along with how it operates. an investigative and a comparative study was conducted by (Bellos, Tzivanidis, Zisopoulou, Mitsopoulos, & Antonopoulos, 2016) on three south facing walls which are; Trombe wall with an opening, conventional Trombe wall, and an insulated wall, accordingly finding which one has the highest performance levels through November until April. This experiment has taken place on computer models of buildings that were designed in Solidworks and simulated using Flow simulation module, to monitor the thermal performance of each of the three buildings. The study showed that the Trombe wall that has an opening, has a higher performance along the 6-month period in terms of increasing the indoor temperatures from noon until night by about 0.5k, that was followed by the conventional Trombe wall since solar energy has been employed to a greater extent, with the insulated wall giving a less than satisfactory performance. What has been deducted is that the Trombe wall with the opening configuration not only have the highest performance levels in terms of heating but also has the benefits of allowing sunlight to penetrate and lit the space as well as adding an element that provides natural ventilation.

In (Modirrousta & Boostani, 2016) analytical research, the focus was on presenting a different way to utilize solar energy in buildings mostly through Trombe wall, atriums, and greenhouse systems. In doing so an elaborate descriptive analysis was presented to give an intricate knowledge in terms of design and benefits that would be gained from each method. In the end, the studied methods presented their abilities to utilize and optimize solar energy, heating, cooling, ventilation and at times lighting in buildings, which system to be used is something that comes down to the designer's choice in the preliminary design stage of the project, based on different efficiency factors. In another comparative research, (Omrany, Ghaffarianhoseini, Ghaffarianhoseini, Raahemifar, & Tookey, 2016) worked on presenting different passive heating methods in as well as their ability to optimize energy in buildings, the methods that have been addressed are; Trombe Walls, Autoclaved Aerated Concrete Walls, Double Skin Walls, and Green Walls. By presenting the study results the designer can deduce which method would suit his needs, in terms of the Trombe wall it has been established that it plays an important role in reducing building energy consumption, as well as enhancing its performance by combining it with other methods. In terms of Autoclaved Aerated Concrete wall has the capability of not only providing satisfying energy performance but also improving acoustic properties, as for Double skin walls it presents a mean for energy consumption reduction with additional factors of integrating ventilations through a glazing system as well as adding PV systems. Last but not least, green wall system influences the building on the outside as well on the inside, in terms of functioning as an insulator by reducing the impact of solar radiation in return reducing building energy, while having a positive psychological impact on the building users, along with increasing property value and working as an acoustic buffer from the surrounding environment.

(Jaber & Ajib, 2011) Conducted an investigative analyzing that covers different aspects when it comes Trombe Wall performance, in terms of thermal, environmental impact and economic benefits, by focusing on residential building in Mediterranean region, in this case, a typical Jordanian home which is referred to as Dar that's located in Amman. TRNSYS program was used to generate an hourly energy computer simulation after that an LCC was used for calculating the economic aspect of this instigation. They concluded that a Trombe wall has the benefit of reducing the annual energy consumption of the building, with the assistance of using insulated curtains between glass and masonry as well as using roller shutters for an optimized performance to reduce solar radiation infiltration. In terms of the environmental annual impact, the Trombe wall reduced CO_2 levels by 445 kg.

2.3. Building Integrated Photovoltaic (BIPV) System

(Biyik, et al., 2017) Provided an investigative review of integrated photovoltaic (BIPV) and integrated photovoltaic thermal (BIPVT) systems which was based on their efficiency, type, performance, energy generation level, and nominal power. This stud resulted in a number of conclusions such as; the applicability of BIPV system with efficiency performance in both façade and rooftops, the important role shadowing, ambient temperature, building orientation as well as the PV cell slop play in acquiring a higher performance levels, computational analysis especially TRNSYS and EnergyPlus software, became a main pillar in recent studies as it is cost efficient as well as its capability of measuring performance level, power generation , shading factors, and electricity consumption. Grid integration has a significant effect when it comes to power output in terms of integrating building integrated photovoltaic system with other renewable energy sources; the key factor is to reduce the electricity lost on transformers, long lines, and electronic components by tweaking the distribution system configuration.

According to (Barkaszi & Dunlop, 2001) there are two categorizations in regards to buildings that have photovoltaic systems, in terms of it being building attached (BAPV) or building integrated (BIPV) system, those two differ in terms of application cost, labor and performance levels. The public view and their acceptance of photovoltaic technology aesthetic features play an important role in determining the PV array installations on a building, on the contrary to common belief that it would be affected by functionality, performance levels, and its lifetime value.

(Omer, Wilson, & Riffat, 2003) Worked on observing the performance of building integrated photovoltaic system in two different settings where a thin film PV façade was applied to the School of Built Environment in the University of Nottingham in the UK, and the other one is a crystalline photovoltaic roof slate which was fixated on the roof of a detached house. The experiment lasted for two years by integrating different methods which included energy analysis using PVSYST simulation and CAD modeling, in an effort to monitor and document the performance of photovoltaic systems in those two different applications; educational building and domestic house. Results showed that in both cases the shading even if it is only partial managed to diminish PV cells performance levels, in case of the educational building the reason for it was the surrounding buildings and trees, while in the case of the domestic house it resulted from the surrounding trees. That interfered along with other contributing factors; in the case of university building it was because of the poor PV system orientation array, inverter, and monitoring system outage, on the other hand, the domestic house PV roof slates had a manufacturing problem resulted in elevating the cell temperature. An experimental study has been conducted by (Koyunbaba, Yilmaz, & Ulgen, 2013) on a BIPV Trombe wall located on the south façade of a room that is located in Izmir, Turkey. Computational fluid dynamics (CFD) was used to generate and simulate a two-dimensional model, along with a test room model where the BIPV Trombe wall was applied to study the room's temperature and velocity distribution for February 4-7th, 2008. The resulted showed the ability of Computational fluid dynamics in calculating radiation, conduction, and natural convection for the BIPV Trombe wall system, the experiment showed that the wall worked on storing solar heat during daytime, to be released in later in the night time. In the case of (Athienitis, Barone, Buonomano, & Palombo, 2018), the aim was to use a dynamic simulation method which is DETECt 2.3 to analysis an air open-loop photovoltaic thermal system placed on the south façade of ten stories building and it's the effect electrical production and heating/ cooling demands. This investigation has been carried out in the form of a comparative and parametric analysis on high-rise office building located in different European cities in different climatic zones; Prague, Bolzano, Freiburg, Madrid, Naples, Athens, Almeria. Simulation results showed that the system provided passive and active effects contributing to building energy consumption reduction reaching a nearly or net positive zero energy building, as well as zero carbon emissions. In another aspect of this investigation, a calculative study has been conducted to find out the number of openings along the system in doing so heating and cooling demands got reduced as well as an increase in the photovoltaic electrical production by approximately 1%, and a reduction in the electrical supply needed by 2.5%.

In another case an experiment was conducted on Five Building with Integrated Photovoltaic modules implemented in different methods, as (Chatzipanagi, Frontini, & Virtuani, 2016) used a mock-up structure at the University of Applied Sciences and Arts of Southern Switzerland (SUPSI) by integrating as ventilated double glazed units with inclinations that vary between 30° and 90°, as well as a variation in their technology using double junction amorphous silicon and crystalline silicon. This investigation was conducted on south oriented Integrated Photovoltaic modules that were applied on two parts one is the form of a ventilated façade and roof which were fixated vertically and with 30° of inclination, while the other was the low energy house. The modules used in this experiment were customized to semi-transparent glass modules. The results showed that 90° inclined modules presented the lowest operating temperature, on the other hand, 30° inclined crystalline and amorphous silicon configuration modules presented the highest operating temperature. When comparing the data obtained for the average daily temperature calculated using Nominal Operating Temperature (NOCT) and Equivalent Cell Temperature (ECT), the difference was less than 5-6 °C.

In comparative performance analysis done by (Jie, et al., 2007) in testing Photovoltaic Trombe wall integration against a prototype for a two-dimensional PV glass panel in terms temperature distribution in the space and electrical generation and performance, in a test room in Hefei. FORTRAN numerical simulation which is written by Jie, Hua, Gang, Wei, Jianping, & Bin, was used to conduct this analysis, it calculates the thermal and electrical performance of the systems. This investigation proved that the PV glass panel works, Trombe wall integrated with PV panels proved that it has a higher thermal performance level that that of an average Trombe as well as adding an aesthetic aspect to the building design, another aspect when it comes to increasing the electrical efficiency of the photovoltaic panels adding an air duct behind it proved to increase it by 5%, and lastly the equation once integrated with the zone weather data and necessary factors has proven to credible in terms of calculating Trombe wall's temperature distribution which is necessary for improving the Trombe wall design and thermal performance levels.

2.4. Passive Cooling Wall

In (He & Hoyano, 2009) paper, presents their elaborated work on developing a 3D CAD-based simulation tool that would be implemented to predict and evaluate the thermal improvement that occurs when a passive cooling wall (PCW) system is constructed in a suggested urban location. PCW is developed by Jiang He and Akira Hoyano, where they constructed it out of moist void bricks with the ability to absorb water, which results in cooling its surface temperature as the air penetrate it, resulting in water evaporation. To validate the simulation tool, PCW was applied to the south façade of a space that was constructed in an urban location. The paper goal was to present a mean to simulate thermal performance of PCW, which was proven to be effective in such case as well as its capability in providing air temperature reduction effect as well as ventilation cooling effect.

2.5. Solar Wall Heating

Based on (Wang, Manzanares-Bennett, Tucker, Roaf, & Heath, 2012) experiment on a solar wall heating (SWH) system in two heavy thermal mass buildings (stone walls) in Edinburgh; one is an apartment in a four storey building and a one storey bungalow, in terms of performance levels, as the temperature was monitored for 24 hours cycle under different solar inputs, by using a model that has been created using unsteady state CFD. SWH works on storing solar heat that is absorbed during the daytime in the thermal mass walls and then releasing them with a time lag during the night time, a core component is this system is the heating panels that are attached to the wall which is composed of compressed row of thing pipes implanted in the interior walls which get supplied by water that is heated using solar collectors. PHOENICS (CHAM) was used to develop the CFD model of unsteady heat transfer that is used to simulate the performance of the heat exchange between the heating panel, the wall, and the adjacent rooms. The results showed that the interior walls of the apartment had an effective performance in storing heat and raising the temperature in the adjacent rooms, as well as validating the accuracy of the computer model in terms of measuring the fluctuation in the temperature transfer in the panel wall structure, presenting a base model for future studies in this field.

CHAPTER 3
PASSIVE SOLAR ENERGY SYSTEMS IN BUILDINGS – TECHNICAL ASPECT

(Sustainable Sources, 2018) defines passive solar systems as systems that use the solar energy for heating and cooling purposes. Passive solar design utilizes the building components, such as; walls, floors, roofs, windows and exterior building elements to control heat generation by direct solar gain, by putting natural characteristic of the materials in to play and their ability store heat, for example in the case of solar heating is designed to capture and collect thermal energy through large sun –facing windows and thermal mass, to be utilized for daylighting, as well as passive heating and cooling (Rahman, Rahman, & Jaman, 2010). Thermal masses are materials such as concrete, masonry, and water, that store solar energy, later on, emit them into space with a time lag which reduces temperature fluctuation proceed by the rapid change. Another advantage of passive systems is that it requires minim maintenance, cost reduction, no mechanical as well as the presence of a few moving parts. Although passive solar energy system for heating purposes is well developed and researched by still they are used for cooling purposes as well, which is the case when it comes to applying thermal chimneys which works based on the principle of thermodynamics; hot air rising and getting replaced by cooler air inducing air movement.

Working on façade improvement is crucial in terms of integration of solar energy in building optimization since there is a direct relation between façade design which is the building envelop that is widely exposed to the surrounding environment and is highly affected by the heat flux. When designing with thermal storage walls they are designed to be south-facing with glazing on the outside. The glazing is struck by the solar heat, which is absorbed into the wall which conducts the heat into the room over time. The thermal storage wall is at least 20cm in thickness, there is a direct relationship between increasing the wall thickness and reducing the indoor heat fluctuation (Sama, Prakash, & Naik, 2013). The working principle is that of a greenhouse in terms of allowing solar heat to infiltrate the building envelop through the glass which has them absorbed the thermal storage wall during sunlit hours to be emitted into the living space later on in the day with a time lag, which helps maintain a stage indoor temperature.

Guidelines for Passive Solar Energy Systems Application:

- When designing the building it should be elongated on the east-west axis.
- Applying passive solar energy systems on the south façade to have maximum sunlit hours' exposer.
- Locating the spaces that are frequently used that need better illumination and heating and cooling on the south facade to utilize the system efficiently, while locating the spaces that are less used on the north façade.
- Open floors maximize the utilization of the passive systems.
- Using shading in summer times prevents the interior from overheating

This study focuses on the application of passive solar energy systems for heating purposes, by presenting different systems and their working principles, examples of their application.

Passive Solar Heating System

There are there approaches when the purpose is to capture solar heat by building materials to be utilized for indoor heating by reaching the occupant's thermal comfort levels, those are; Direct Gain System, Indirect Gain System, and Isolated Gain System.

3.1. Direct Gain System

In this system, south facing glazing creates a direct gain system, that permits shortwave solar energy to penetrate the interior living space where it gets absorbed and stored via the thermal masses such as walls, and floors, to be released at night (Fig. 3.1, and 3.2). Solar energy that infiltrates the glass could reach up to 75% which is converted into thermal energy, while on the other hand glazing aka windows located in other orientation cause more heat loss than gain in the winter time. Glazing area should be moderated as impacts the building's thermal mass to reduce temperature fluctuation and overheating, moreover even distribution eliminates the localization of hot and cold spots. South facing glazing implicates having the walls and floor to be in a close proximity to store solar heat, typical glazing is 1.5m in height restricting a shallow heating effect, exceeding certain limits can result in overheating even in winter time hence shading elements would be needed or even resulting in cold effect in winter nights, and cloudy days. Another advantage of direct gain systems is the increase in daylight infiltration and visual continuity to building surroundings.

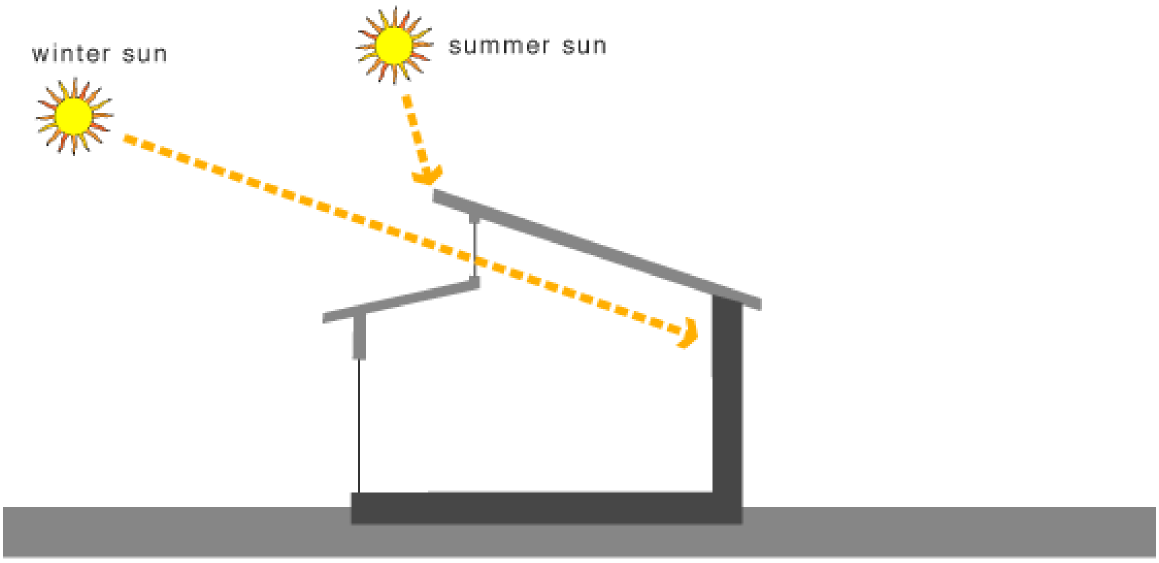

Figure 3.1 Direct Gain System in winter and summer period **(Greenspec, 2018)**

Figure 3.2 Direct Gain System in The Cross of One Day **(Greenspec, 2018)**

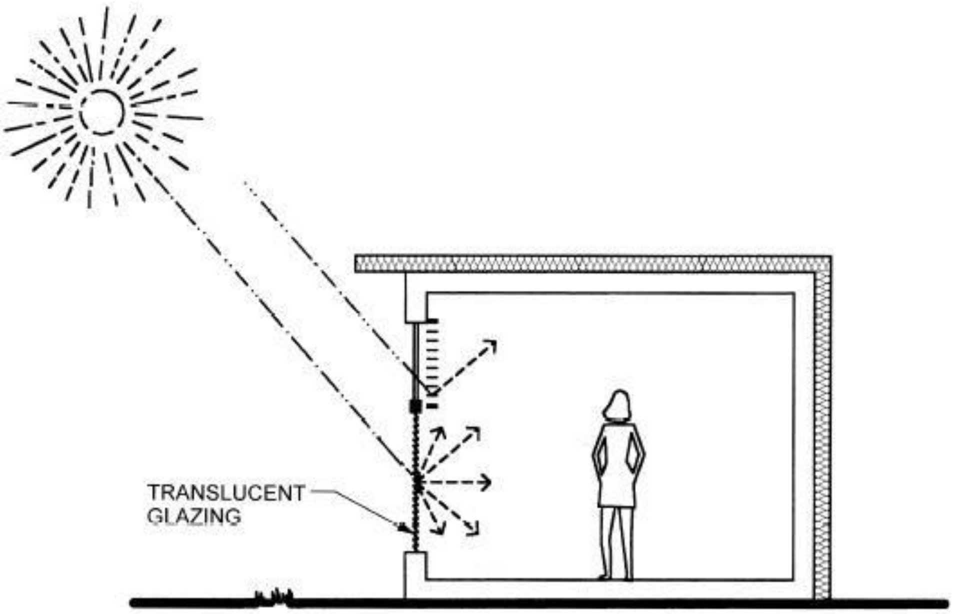

Figure 3.3 Diffused Radiation will Distribute the Heat more evenly in Open Space Interiors

Figure 3.4 Single-Family Residence in Lafayette **(energysage, 2018)**

3.2. Indirect Gain System

In this system, the thermal storage wall is located in the south façade located between a glass window and the living space. The solar energy penetrates the glass and strikes the thermal storage wall to be absorbed and later on conducted to the living space. Thermal storage walls can have an upper and lower vent to convict heat between the thermal wall and the glazing outside, at night those vents are closed allowing the heat to circulate into the living space. The distance between the glazing and the thermal wall should be at least 10cm, the wall ought to be in a dark color for maximum solar heat absorption. Thermal wall thickness varies according to the material, brick requires 25-35cm, concrete requires 30-45cm, while for water it requires 15cm. According to (ENERGY SAVER, 2018) in regards to the time it takes for the stored solar heat to travel through a masonry wall is 2.5cm per hour, which means that the heat that is stored in a 20cm thick concrete wall at mid-day, would be conducted to the living space at 8 in the afternoon. The most common form of this system is a Trombe Wall (Fig. 3.5).

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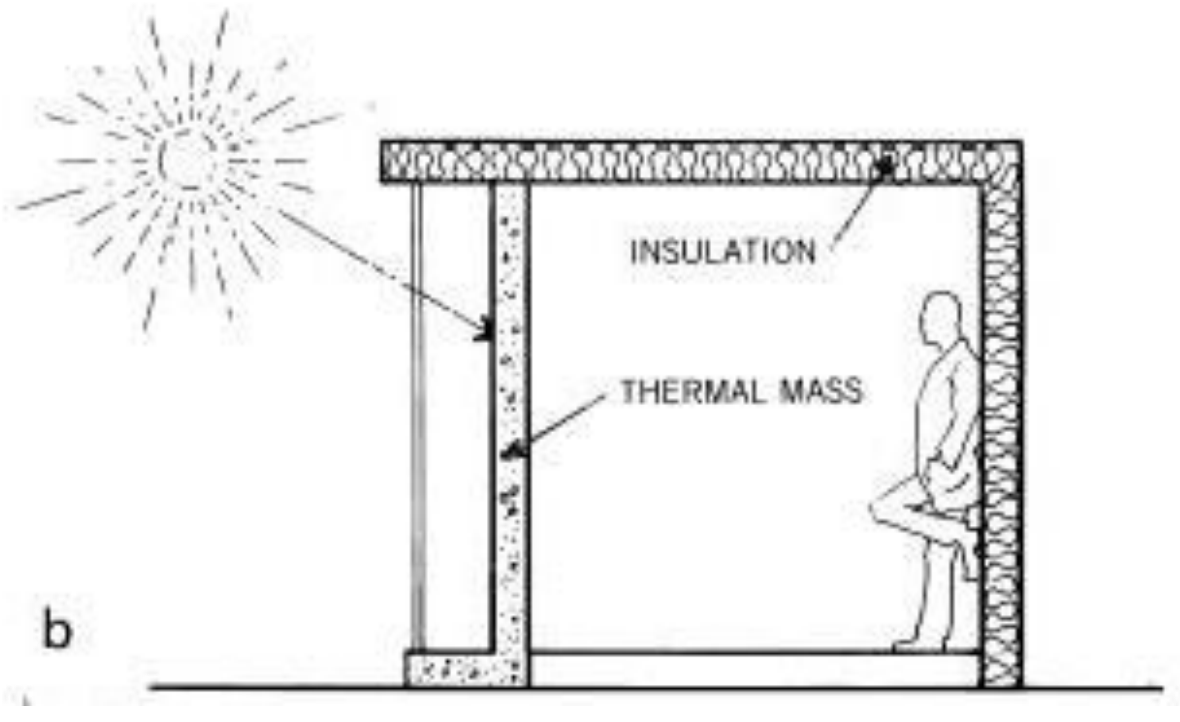


Figure 3.5 Indirect Gain System Section

3.2.1. Water Walls Systems

The water wall is a type of south-facing thermal storage walls, where water works as a medium that collects and stores solar heat through the sunlit hours, to be later on emitted into the interior living space. The working principle depends on the physical characteristics of water, on warming up space through conduction, and convection. In the case of The Bare Residency in Iceland, a reflective surface was placed outside of the south-facing glazed wall that is placed in front of the water wall to increase the performance of the wall (Fig. 3.6).

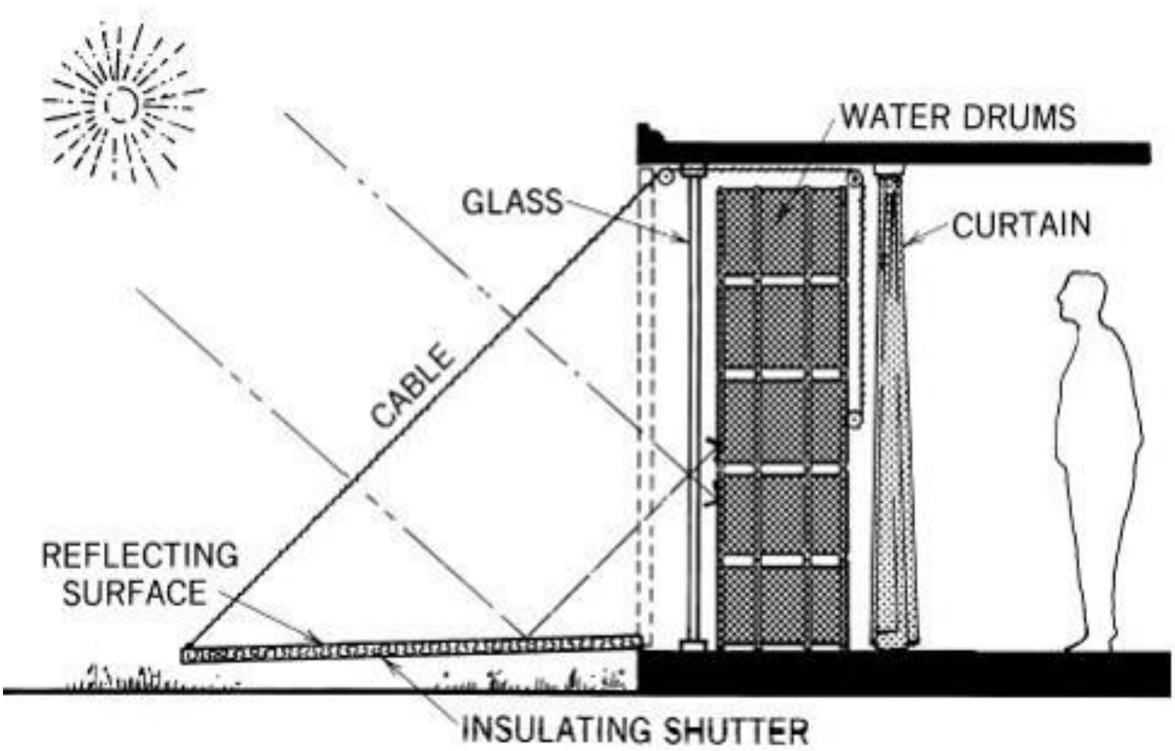


Figure 3.6 Section throw Water Wall System

Water Wall Variations

There are four types of water walls based on their configurations; opaque water wall system, transparent water wall system, translucent water wall system, water wall with phase change materials, and water wall combined with other passive technologies.

3.2.1.1. Opaque Water Wall System

This type is where the water wall is usually placed within an opaque building envelope; opaque PVC pipes, concrete, metallic plates, or insulation panels, that act as a separator between the ambient and the living spaces (see Figure 3.7).

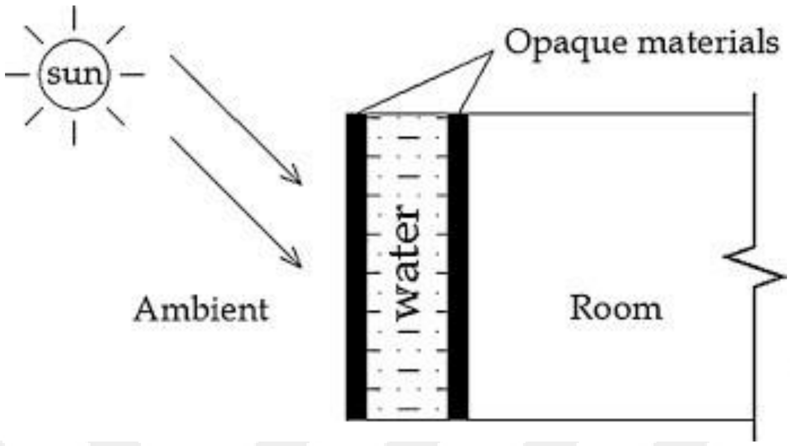


Figure 3.7 Opaque Water Wall system (Wu & Lei, 2016)

3.2.1.2.Transparent Water Wall System

Water wall system can also be fabricated in a structure that is transparent envelop, which permit's sunlight penetration inside the building, the envelope is usually made out of materials such as glass or plastic (Fig. 3.8)

Figure 3.8 Transparent/ Translucent Water Wall System

3.2.1.3. Translucent Water Wall System

Water wall system can also be fabricated in structure with a translucent outside façade that permit's sunlight penetration from outside to inside, using materials such as glass or plastic, as for the internal side of the water wall it can either be semi-transparent as well or opaque, and based on the choice of material sunlight can infiltrate the room (Fig. 3.9).

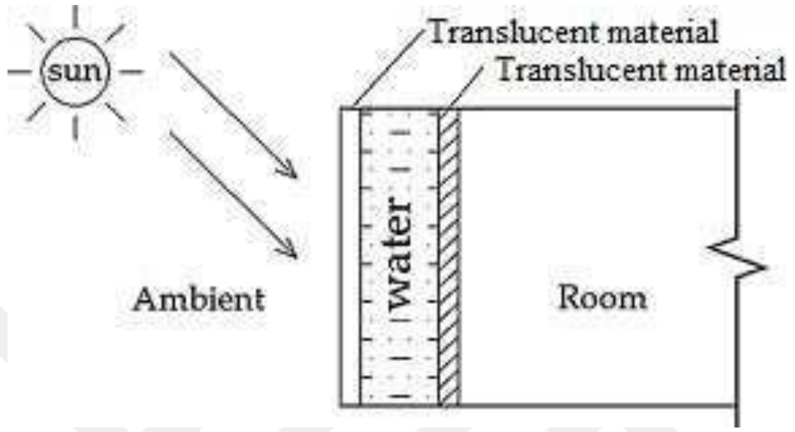


Figure 3.9 Translucent Water Wall System (Wu & Lei, 2016)

3.2.1.4. Water Wall with Phase Change Material

Water wall has the highest heat capacity among the other sensible heat storage systems, yet its heat capacity is relatively low in comparison to that of PCM heat storage system. On combining PCM and water wall greater results could be reached, by locating the PCM at the internal side, external side or even on both sides of the water wall (Fig. 3.10).

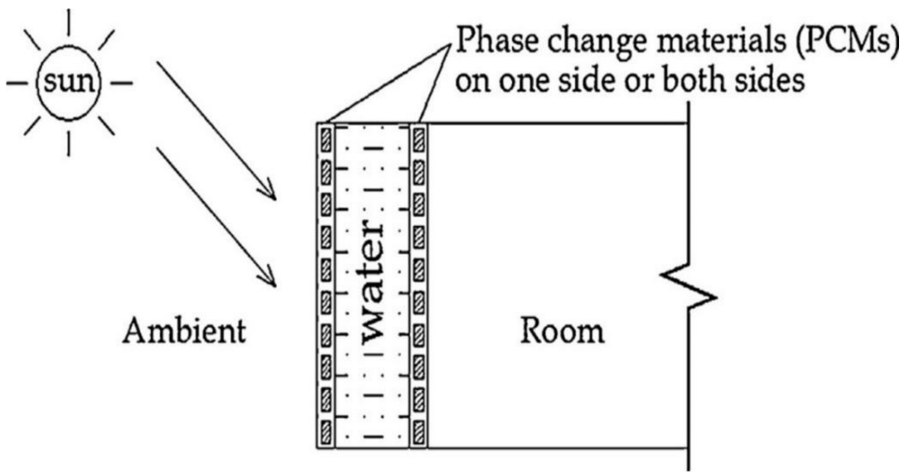


Figure 3.10 Water Wall System Integrated with Phase Changing Material **(Wu & Lei, 2016)**

3.2.1.4. Water Wall Incorporated with a Solar Chimney

According to (Lei & Khanal, 2011) review, the solar chimney was presented as a passive system for enhancing stack driven ventilation by buoyancy, to improve the night time ventilation water wall was incorporated into the solar chimney. Which makes it favored substitute to mechanical ventilation systems as a result of their operational cost, energy requirement, and carbon dioxide emission (Fig. 3.11).

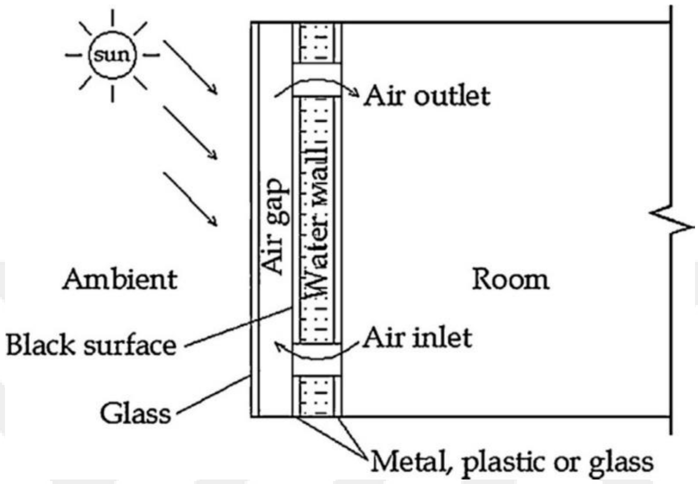


Figure 3.11 Water Wall incorporated with Solar Chimney **(Khanal & Lei, 2011)**

3.2.2. Trombe Wall System

In 1967, Felix Trombe and Jacques Michel constructed the first thermal storage wall in Odeillo, France, it was a 61cm concrete wall with vents (Hesson, 2017). That's when the first form of Trombe Walls was presented as a massive wall that is utilized in solar heat storage. It is a south-facing thermal storage wall that is glazed on the outside. The glazing is struck by UV light which is close to the electromagnetic spectrum penetrating it to be absorbed by the dark painted thermal mass wall (Fig. 3.12), which later on emits the heat into the indoor living space with a time lag (Fig. 3.13, and 3.14). The wall ought to be at least 20cm in thickness, there is a direct relation between wall thickness and the stabilization of the indoor temperature (Sama, Prakash, & Naik, 2013). The wall works on absorbing heat during sunlit hours then slowly releases the heat overnight, working based on a greenhouse principle, which can cause the interior living space to overheat in summer period hence a shading device applied to the glazing (Fig. 3.15).

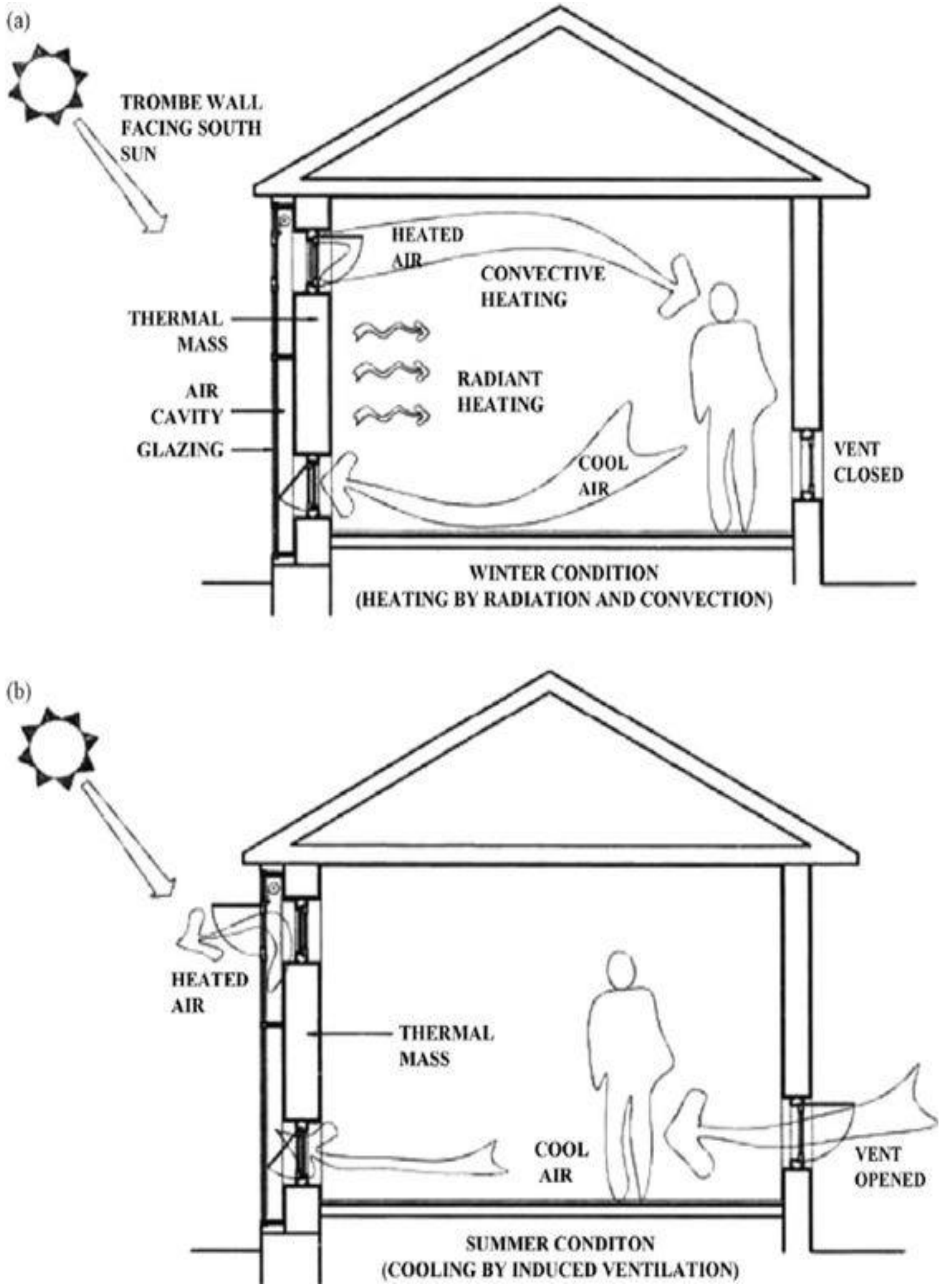


Figure 3.12 Trombe Wall with Vent (a) During Summer, (b) During Winter (Chel, Nayak, & Kaushik, 2008).

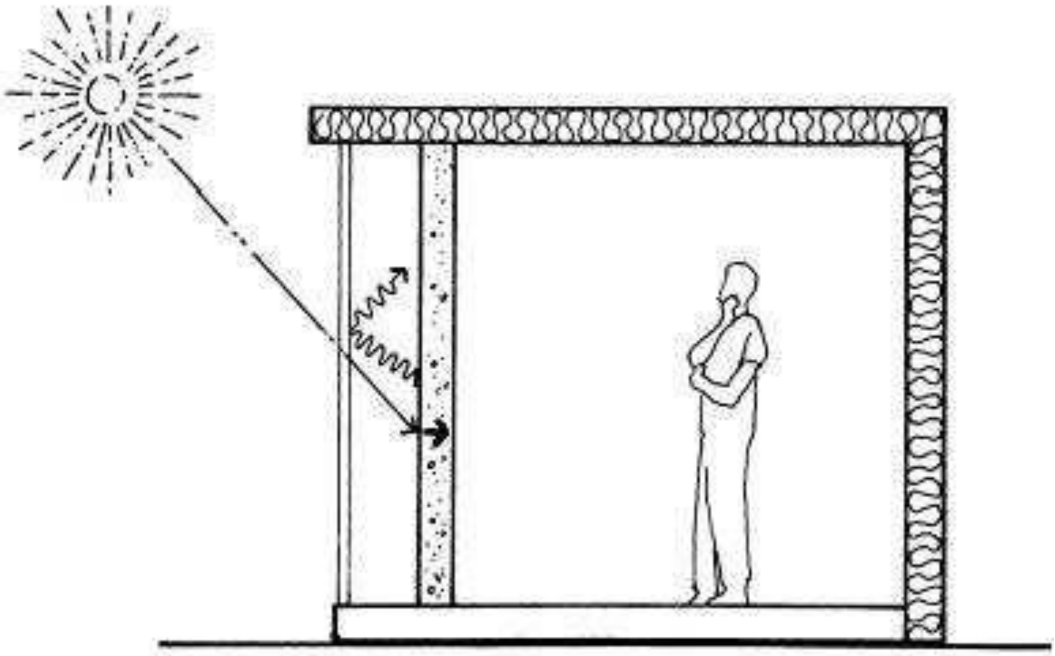


Figure 3.13 Trombe Wall Storing Solar Heat During Sun-lit Hours

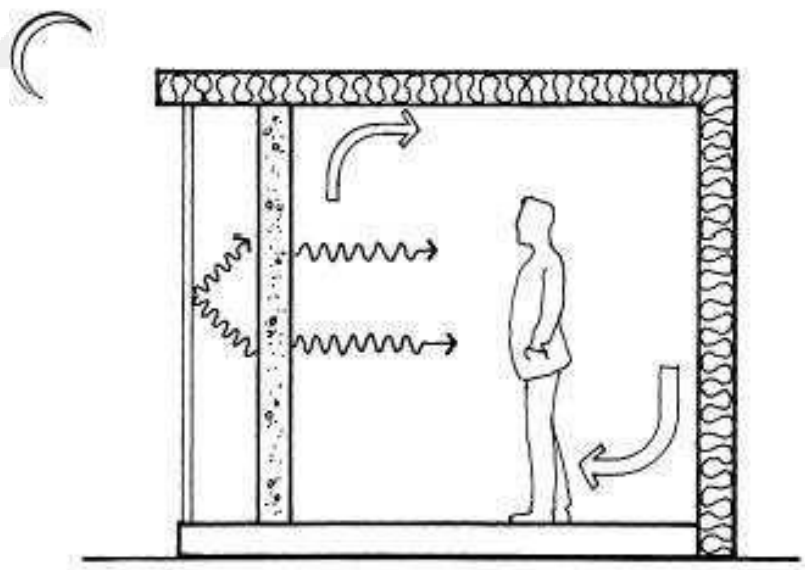


Figure 3.14 Trombe Wall Emitting Solar Heat during Night Time

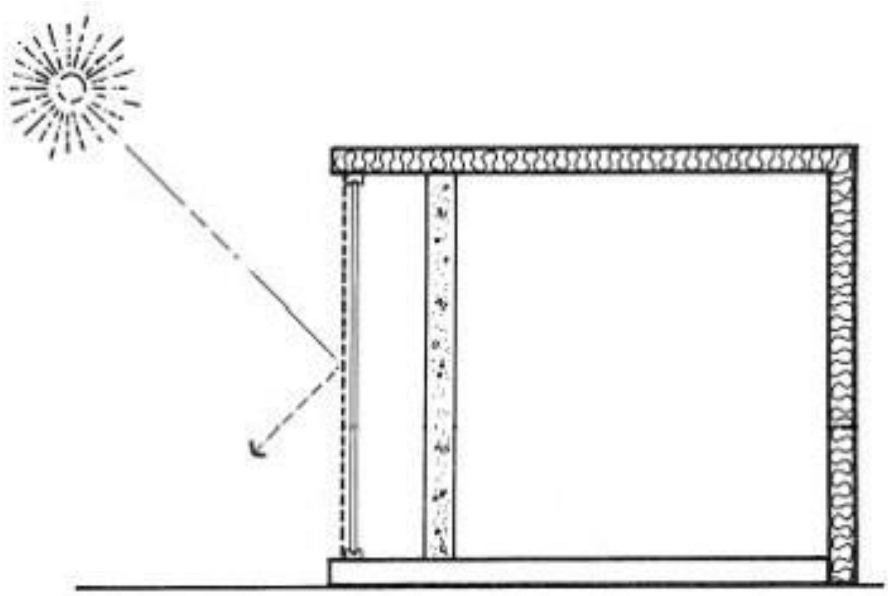


Figure 3.15 Shading Screen for Glazing Facade to prevent Trombe Wall from Over-Heating Living Space.

Trombe Wall system was constructed in The Druk White Lotus School dormitories in Ladakh, India which is designed by Arup Associates / Jonathan Rose, to warm them at night time (see Figure 3.16).

Figure 3.16 Trombe Wall Constructed at Druk White Lotus School in Ladakh, India **(solaripedia, 2010)**

Implicating mixture of Trombe walls and direct gain is the best course of action to get better results. Where half of the wall is controlled by direct heat gain by utilizing solar heat and natural illumination, as well as storing heat for heating for the night time (Fig.3.17)

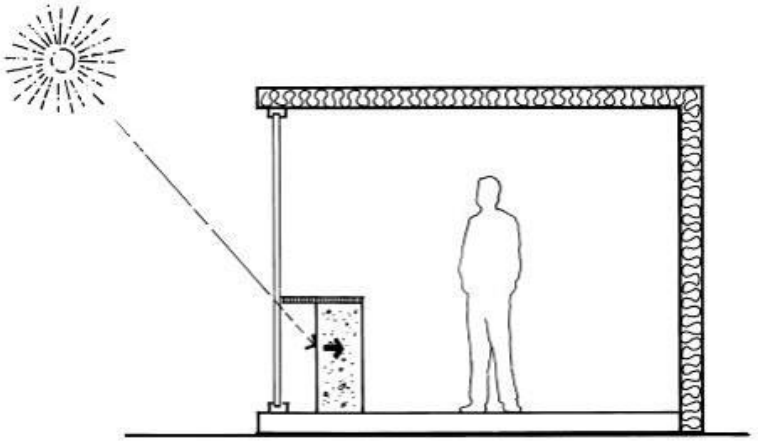


Figure 3.17 Mix Between Trombe Wall and Direct Gain System

In the case of The Shelley Ridge Girl Scout Centre built in 1982 in Philadelphia. The building has two passive gain systems; direct gain system and Trombe wall system. Where glass was used for direct gain purposes, and translucent Fiberglas panels were used for the Trombe wall, shading devices were fixated as well to shade the glass in the summertime (Fig. 3.18).

Figure 3.18 The Shelley Ridge Girl Scout Centre **(Kaiser, 2018)**

Zion's Visitor Center is a low energy, sustainable facility, designed by National Park Service-Denver Service Center, located in Zion National Park, Utah/ USA. In this facility building, a Trombe wall was built using heavy masonry, along with Clerestory windows. Zion's Visitor Center (Fig. 3.19, and 3.20)

Figure 3.19 Zion's Visitor Center **(Fosdick, 2016)**

3.2.3 Building Integrated Photovoltaic (BIPV) System

BIPV system building that is equipped with photovoltaic panels either on the pitched roofs and flat ones and on façade. It has the additional benefit of producing electricity resulting in the reduction of fossil fuels, carbon emissions, cost reduction, and mechanical HVAC reduction. Solar panels can be used as a replacement for façade glazing adding an architectural element see (Fig. 3.20, and 3.21).

Figure 3.20 Zion's Visitor Center Photovoltaics Roof System **(The American Institute of Architects, 2018)**

Figure 3.21 BIPV Roof fixation of Solar panels on a commercial building in Germany

CHAPTER 4
SIMULATION TOOLS USED FOR ASSESSING PASSIVE SOLAR ENERGY PERFORMANCE

Different methods have been used to evaluate passive solar energy gain systems and their impact on the building thermal comfort levels during its lifecycle, along with cost reduction and design optimization. The following methods have been used by engineers and architects in their investigative researches and experiments. Those simulation software programs and equations were used to analysis, measure indoor temperature, evaluate thermal comfort levels, calculate the energy conserved, assist in design optimization, calculate average heat flux, thermal load leveling, system performance levels, building heat loss coefficient, collector-wall system efficiency performance, electrical efficiency, PV systems performance levels, and Thermo-economic results. Simulation software and equations used to evaluate the systems, are either company productions or conducted as an experimental simulation to test a newly developed methodology by research engineers. The application and usage of those programs have been increased in recent time in compression with previous years, with the increasing approach towards optimizing existing buildings and designing new buildings that are energy efficient, along with the upcoming desire to reach a" net-zero energy building" or even a "plus energy building", a concept that surpassed architect's desires, to be adopted by governments in their growing energy supply agenda. In conclusion, this chapter provides detailed information for simulation software programs and equations that have been indicated in the studied literature as well as the tools used in this thesis. Each tool that is mentioned has its own characteristic and specific application, with different levels of responses to different inputted variables, which affect the user's decision process.

When choosing a simulation program different factors must be taken into consideration, such as its capability in analyzing complex geometries, building function and reading zones, building system, mechanical system input and material variation. Architects may demand the availability different design elements that permit the presence of passive solar devices either attached or integrated into the building. As the architectural design has the heaviest impact on the thermal performance of the building, through construction elements, such as walls, roofs, opening, and materials. Furthermore, finding working with a simulation tool that is capable of analyzing heat transfer through; convection, conduction, radiation, ventilation while taking into consideration the hierarchy of the room/ building model presented.

Energy simulation software is divided into three categories which are;

- Software with integrated simulation engine, for example (EnergyPlus).
- Software that dock to a specific engine, for example (DesignBuilder).
- Plugins added to a software to perform certain analysis, for example (Ladybug+ honeybee for Rhino).

4.1. EnergyPlus

EnergyPlus is a free, open-source and cross-platform console-based program, which means that it is designed to be used through computer text commands only; text-based interface. Its funded by the Department of Energy's (DOE) Building Technologies Office (BTO), and used by engineers, architects and researchers alike to model building energy consumption; heating loads, cooling loads, ventilation, lighting, water usage and process loads. Results are based on thermal zone conditions, having the capability of simulating loads resulting from HVAC system, as well as un-conditioned conditions. EnergyPlus has the capability for accounting for the air movement between different zones while calculating illumination levels in the sense of visual comfort and light control strategies in the form of different window glazing and shading devices. The downfall of EnergyPlus is that the graphical interface is user-friendly (Roth, 2018).

4.2. DesignBuilder

DesignBuilder is a user-friendly simulation program, it operates with EnergyPlus primarily in providing an environmental platform to calculate; annual energy consumption, Indoor building temperature, and HVAC load. DesignBuilder is capable of evaluating building façade to overcome overheating, thermal comfort, ventilation, Daylight calculations, solar shading, and heating/cooling loads. With it being easy to use its helpful in the preliminary design process for the whole design team, as well as providing the team with the building carbon emission outputs (DesignBuilder Software, 2009)

4.3. Radiance

Radiance is a free aid software system designed by U.S. Department of Energy, with later additions from the Swiss Federal Government, to provide designers and architects with the means to trace and predict lighting behavior through modeling, luminaire data, material properties, all of which are imputed to run the lighting simulation. The downfall of Radiance is its incapability to calculate light behavior on curved surfaces (Chadwell, 1997)

4.4. OpenStudio

OpenStudio is a free open source software by the National Renewable Energy Laboratory for Windows, and Mac is the combination of tools used for building energy modeling by using EnergyPlus and Radiance. It's a plugin for SketchUp, which provides architects with the possibility of visualizing and analyzing the energy performance of the building in the preliminary stage. OpenStudio is fully equipped with HVAC, loads, schedules, and envelope (NREL, ANL, LBNL, ORNL, and PNNL, 2017).

4.5. Rhino3D

Rhinoceros or as commonly known as Rhino3D is a CAD design software developed for Windows operating system used for Computer-aided manufacturing (CAM), drafting, analyzing, construction, 3D printing and reverse engineering, used by architects, industrial designers, automotive designers, graphic designer as well as multimedia. Scripting language got integrated into Rhino3D to support Grasshopper 3D (VisualARQ, 2017). Grasshopper 3D is a Rhino3D plugin that is an environment used to build generative algorithms used for parametric modeling. It has an advanced user interface, that requires no programming or scripting background (Davidson, 2018).

4.6. Ladybug + Honeybee for Rhino3D

Ladybug plug is a collection of free applications for Grasshopper3D that is designed by Mustapha Sadeghipour and Chris Mackey directed to architectural and educational usage. It supports environmental design in terms of daylight analysis and energy modeling by visualizing weather data (Roudsari, 2018). Ladybug and Honeybee are an interface for a number of industrial standards validated engines including Radiance, EnergyPlus, OpenStudio, Therm, and OpenFOAM.

4.7. ANSYS Fluent

ANSYS Fluent is a computational fluid dynamics tool that includes physical modeling in regards to calculating turbulence modeling, heat transfer, radiation, acoustics, air flow, and design optimization (ANSYS INC, 2018). The software conveys the means to identifies materials, functions, and loading. Its strength lays as an easy and accurate post-processing design assistant for complex models (PADT, 2018).

4.8. Heat Conduction Equation

Heat conduction equation is based on the first law of thermodynamics, following the principle of conservation of energy. The area of the material and rate of heat transfer by conduction impact the material conductivity, which is directly proportionate to the temperature difference (The Concord Consortium, 2013);

$$\Delta Q/\Delta t = -kA(\Delta T/L)$$

Where;

Δ delta represents a change

$(\Delta Q/\Delta t)$ is the heat conduction rate in kJ/s

ΔT represents the temperature difference along the material

L represents the thickness of the layer (m)

A represents the material area (m^2)

k represents the thermal conductivity of the material (kJ/m/s/ºC)

4.9. TRNSYS

TRNSYS is an acronym for Transient System commercial simulation program designed by Duffy Beckman at the University of Wisconsin, for solar simulation and thermal processing. Its capable of simulating solar thermal performance, traffic flow, biological processes, photovoltaics, and building energy performance. It’s a user-friendly program that works by establishing a network with solar collectors, Heat exchanges, pumps, and weather data with the possibility of creating customized settings. with a components library, its facilitates the zone definitions, adding solar panels, PV systems, and HVAC systems (TRNSYS, 2018).

4.10. Ecotect Analysis

Autodesk Ecotect Analysis is an environmental design analysis software which is user-friendly. It works on providing visual and analytical feedback models ranging from simple to complex. Intended to provide analysis for carbon emissions, total energy use, thermal performance, water usage, daylight, acoustics, cost, solar radiation, shadows, and reflection. In 2015 Ecotect Analysis ceased to exist as separate software as Autodesk is working on integrating it into Revit to maximize its usage possibilities as a part of the BIM technology (AUTODESK INC, 2018).

4.11. SolidWorks Flow Simulation

SolidWorks is a parametric modeling CAD software and a CAE program, its designed by Dassault Systèmes and is supported by Microsoft Windows. It's used for different fields; architectural, industrial, mechanical and electrical (SolidWorks Corporation , 2018).

4.12. CFD

CFD is an acronym for Computational Fluid Dynamics sponsored by Autodesk s, it's a software which models and simulates fluid flow and thermal behavior capable of practical tracing and high-quality visualization. CFD is used for architectural application, MEP, environmental analysis, thermal management, turbulent flows (AUTODESK INC, 2018)

4.13. ANSYS CFX

ANSYS CFX software is a high-performance CFD software. It is multi-disciplinary simulation software that works on fluid dynamics, heat transfer and structure, its designed for engineers and researchers as well as educational usage. It's capable of simulating complex designs, optimizes processors architecture, uses scripting for modeling. ANSYS is capable of calculating and analyzing heat transfer between liquids and solids (ANSYS INC, 2018).

4.14. PVsyst

PVsyst software is designed for architects, engineers and researchers to simulate the sizing, and studying the performance of photovoltaic systems. It has the capability of working with stand-alone, grid-connected, pumping and PV systems used for public transportation (DC-grid), as well as creating a database for the PV systems components. PVsyst can be implemented at any stage of the design process, giving approximated results according to the project stages. The database holds the whole system; PV components, PV modules, inverters, regulators, generators, and pumps for easy management (PVsyst SA, 2012).

CHAPTER 5
GENERATING MODELS FOR THE PASSIVE SOLAR ENERGY SYSTEMS

Simulation in the preliminary design stage became a necessity to have an established perception of the energy and thermal performance of the building, present software and tools facilitated the data gathering and analysis for the engineers or researchers through providing the essential data for the decision-making process. There are aspects that ought to be taken into consideration when attempting to simulate a building or a room, such as; heat loads, room conditions and geometry, materials applied, heat storage, climatic zone, thermal performance. The way each field approaches simulation tools differs, load profiles are the concern of an engineer as it fuels the system database, in the meanwhile architects are concerned with the flexibility it presents and illumination, and thermal comfort levels that assist in the architectural design process (Weiner, 1992).

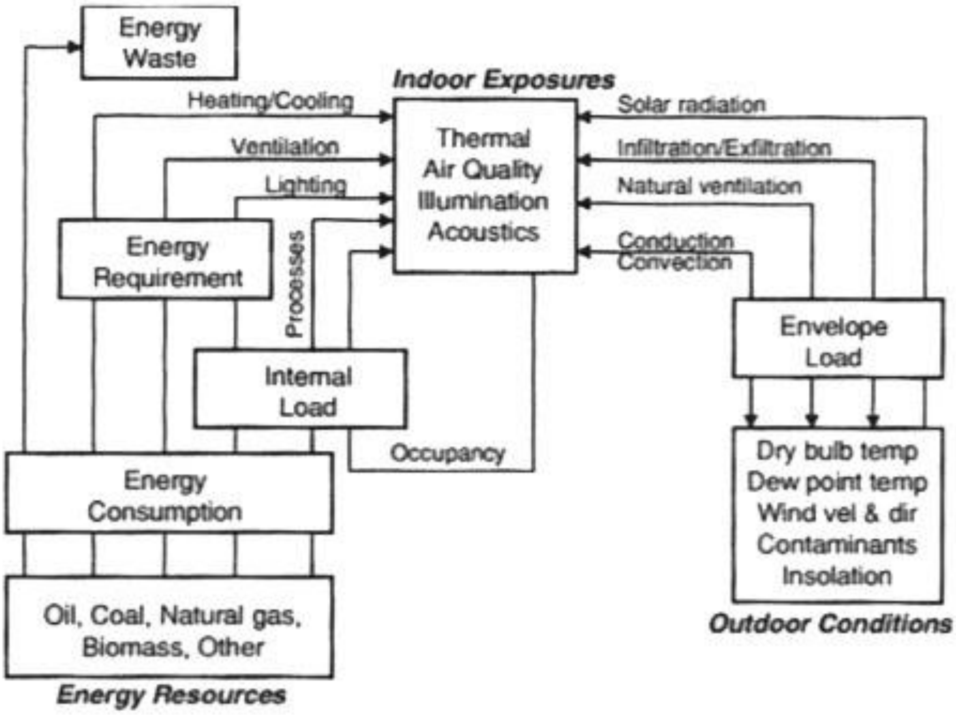


Figure 5.1 Building Energy Flow Diagram process **(Rallapalli, 2010)**

5.1 Location and Climate

This study has been conducted in the form of a comparative thermal performance analysis in two different climatic zones; hot and humid climatic region and semi-continental climatic region. City of choice for a hot and dry climatic region was Istanbul. It's population around 15 million people which makes it the most populated city in Turkey and it's an economic and historical hub, and the 6th largest in the world, it extends across Europe and Asia. The city has long, dry and hot summer period with up to 10 sunlight hours per day, while the winter period is cold and wet with some snowy days that happen usually in February and because of this rainy weather its mostly cloudy and dark, with months as December and January having 5 sunlight hours per day (Fig. 5.2). Istanbul's weather conditions as follows, July and August are the hottest most of the year with 28ºC, and the coldest one is February with 6 ºC (Fig. 5.3). in terms of the economy in Istanbul, it's growing by an average of 4.4% per year, with over 12 business districts that are supplied with all means of infrastructure and services (PROPIN, 2014). Turkey, in general, is mainly dependent imported fossil fuel, with the addition of 9% hydraulic energy production, the geographical location is a primary factor in the growing utilization of solar energy making Turkey one of the leading countries worldwide in photovoltaic technology manufacturing (Energypedia, 2016).

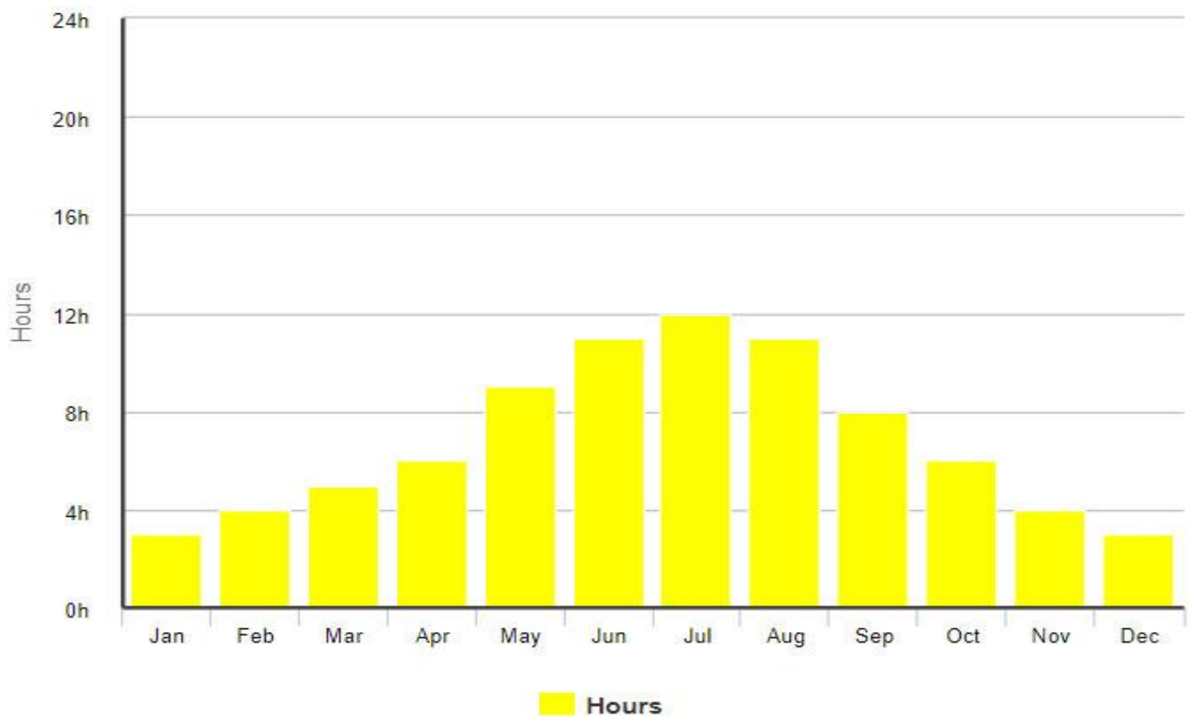


Figure 5.2 Average Sunlight Hours in Istanbul **(Holiday Weather, 2018)**

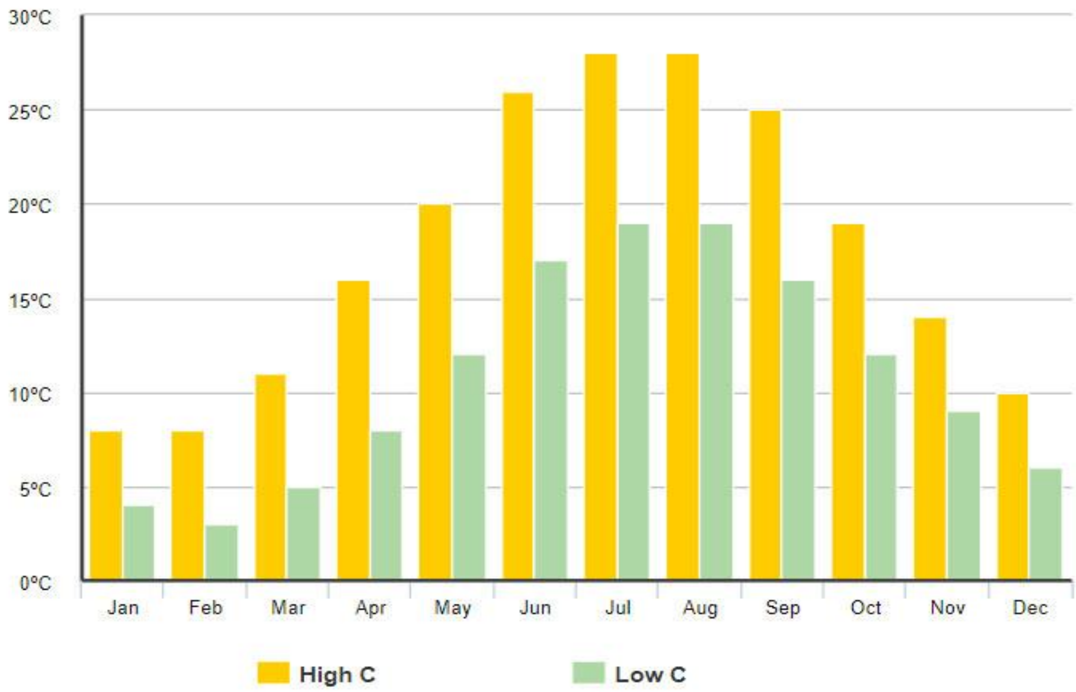


Figure 5.3 Average highs/ Lows Temperature in Istanbul in Celsius **(Holiday Weather, 2018)**

While for the semi-continental climatic, Stockholm was chosen. It is the capital of Sweden with the highest populated city in the Nomadic Countries, with a population of 9.5 million people living in it. The city is renowned for having long and dark winter days, with days that are as short as 6 hours, the darkest months are December and January with that have 2 hours of daylight, on the other hand, the dark hours in the summertime are a couple of hours long, with over than 12 hours of sunlight hours per day (Fig. 5.4). Stockholm's weather conditions are that July is the hottest month of the year with average temperature of 22ºC, and January is the coldest one with the temperature dropping to -3 ºC (Fig. 5.5). Stockholm is considered the center of the business hub of Europe that yet keeps growing, surpassed on by London, (Edwards, 2017) explains that the office rent in the city is considered the 2nd most expensive in Europe. With the growing efforts, Sweden is considered one of the leading countries in terms of using alternative energy resources such as nuclear power, wind and hydroelectric power plants, using only 20% of energy that is powered by fossil fuel, and as a result the CO_2 emissions are considered one of the lowest in comparison with the rest of the world (Fig. 5.6).

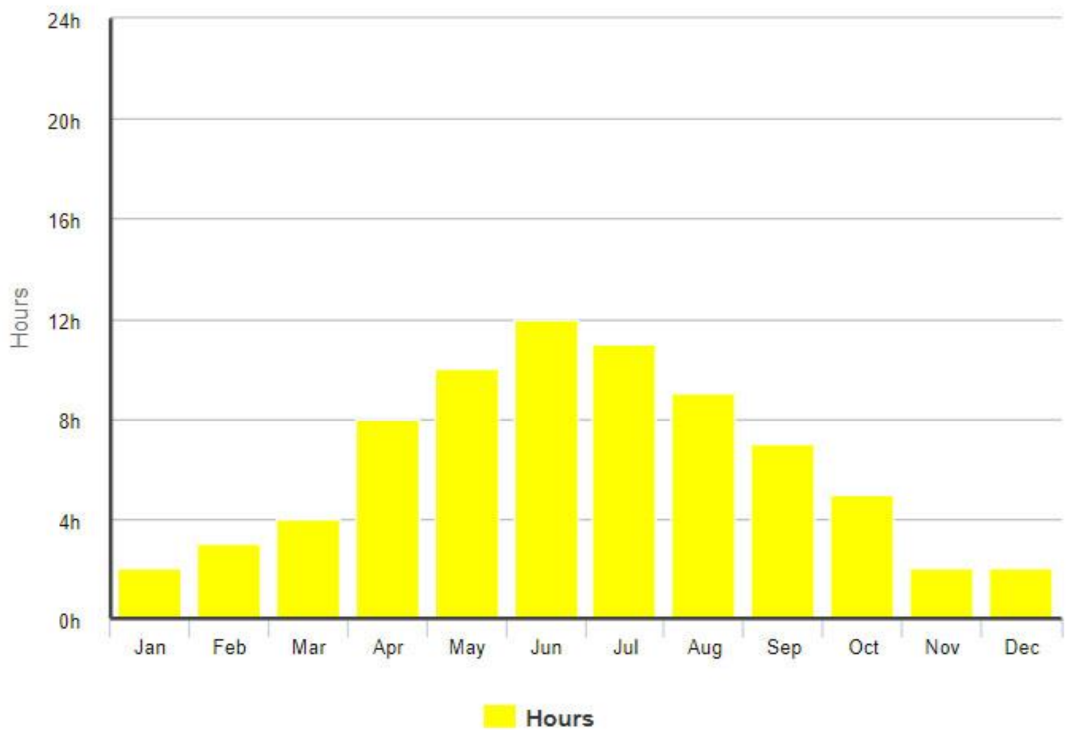


Figure 5.4 Average Sunlight Hours in Stockholm **(Holiday Weather, 2018)**

Figure 5.5 Average highs/ Lows Temperature in Stockholm in Celsius **(Holiday Weather, 2018)**

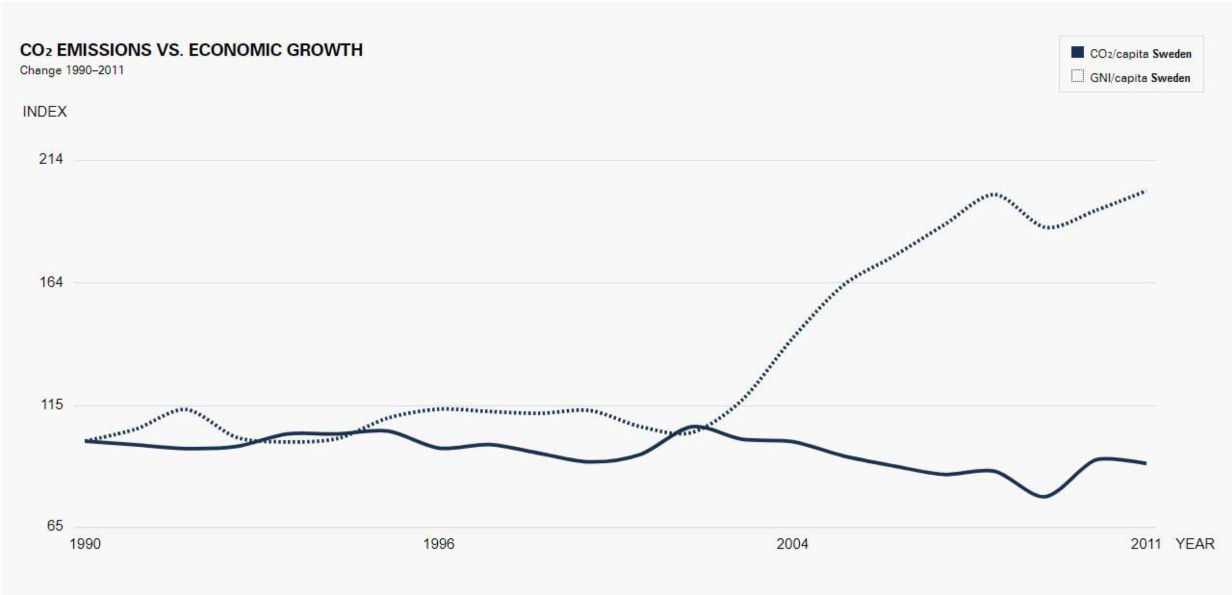


Figure 5.6 Co^2 Emissions Levels in Sweden in 10 years **(Sweden.se, 2016)**

5.2. Space Selection

An office space was used as a base for this study. With the upraise in the business sector and their reliance on mechanically managed environment using HVAC systems, that's besides the fact that humans spend most of their waking hours in offices. Active engagement and interaction with the designed space beyond passive presence stimulates a greater over all sense of satisfaction that increases the occupant's productivity levels.

5.3. Problem Definition

The comparative analysis of different types of indirect solar gain systems and a direct solar gain system, in terms of minimizing total energy consumption for HVAC system and thermal comfort level in an office space. According to this problem the systems were tested in different climatic zones to observe which one is more suited for each weather conditions.

5.4. Variables

The variables in this study are the solar energy systems, with a common factor which is that they are located on the south façade. The climatic zones presented are different as well.

5.5. Limitation

The common façade element for an office space is a glass surface, usually in the form of floor to ceiling window which increases natural lighting but results in an increase of solar heat gain resulting from solar infiltration to the space. As a result, glass façade was chosen as a base system in the comparative analysis with the other indirect solar gain energy systems.

5.6. Objective

The objective of this study is a reduction of total energy consumption, stable indoor temperature, and reaching thermal comfort level needed for office space tenants. According to ASHRAE Standards 55-1992, thermal comfort is archived in average temperature of 23-26 ºC, with 26 ºC being the comfort temperature for an office space.

5.7. Energy Objective

The base model of this study total energy consumption which includes heating and cooling was calculated using Grasshoppers' Ladybug + Honeybee plugin which is a calculative interface for total energy consumption. This plugin uses EnergyPlus format and infrastructure.

5.8. Base Model

The base model is for a conceptual office space, with 5m width, 10m length, and 5m height. The longest side facing the south direction where the direct and indirect solar energy gain systems are located. The chosen systems are; Single Glazed Wall, Transparent Water Wall, Concrete Water Wall, Trombe Wall, Gazbeton Water Wall (Fig. 5.7).

5.9. Generating Model

The model generation in Rhino, the Ladybug + Honeybee Tools plugin was added to Grasshopper Environment. Honeybee components were used to define the geometries, this process is divided into two parts, one which is identifying building structural and nonstructural elements (walls, flooring, ceiling, window, and thermal storage wall), this is followed by assigning the building materials along with their physical characteristics. Then weather data files (EPW files) which is in an EnergyPlus weather format, for Stockholm and Istanbul are then identified in separate Rhino files into the Honeybee component (EnergyPlus, 2018).

5.8 Performance Evaluation

Energy simulation model was created using Ladybug + Honeybee, Information regarding the plugin was provided in the previous chapter.

5.9 Parametric Definitions of the Solar Gain Energy Systems

First of all, the model is constructed in Rhino (Fig. 5.7) with that is followed by assigning materials to each construction element in the model to specify its function and composition such as; walls, floor, ceiling. The main façade with the variable wall compositions is the South facing façade as shown in (Tables 5.1 - 5.2 – 5.3 - 5.4, and 5.5), as for three other sides they are assigned the same materials as shown in (Tables 5.7 – 5.8 and 5.9) represent the materials assigned to the ceiling and flooring consequently. The physical characteristic that was needed to assign water as a material in the Honeybee material component is in (Table 5.6). In (Fig. 5.8) shows the overall Honeybee material assignment the detailed parametric material assignment of each building component for the model was created in the Grasshopper environment.

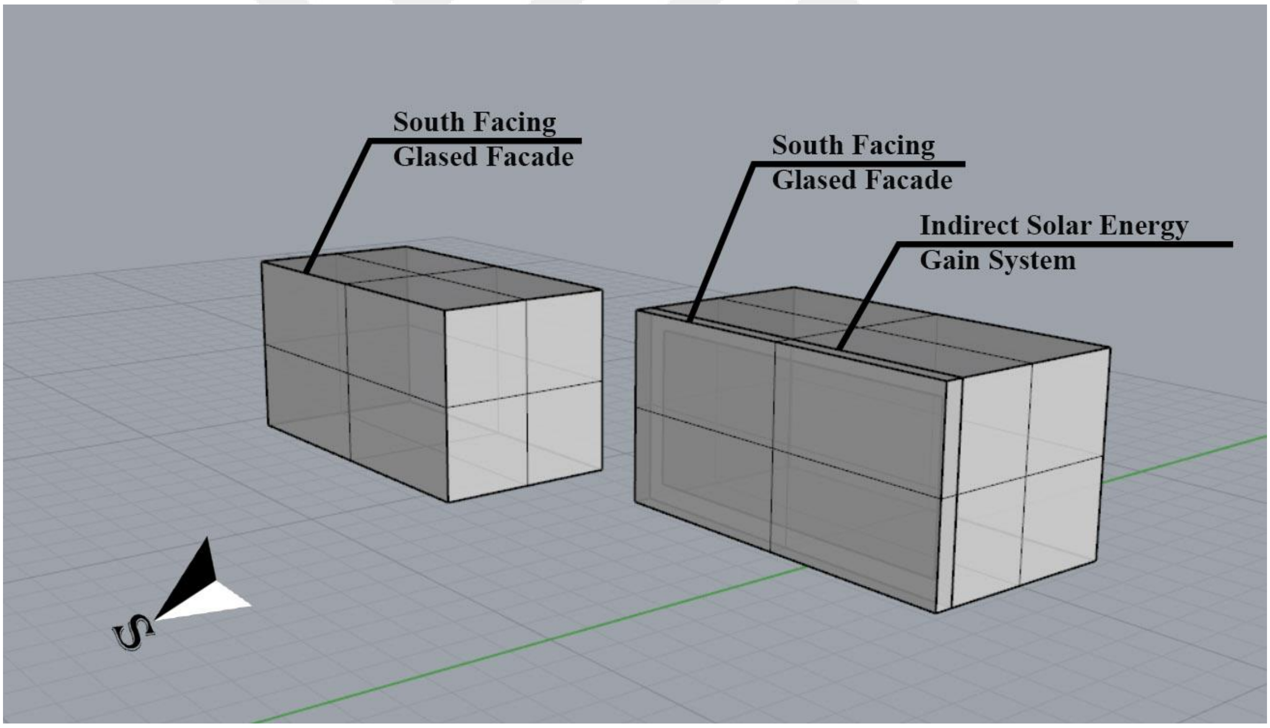


Figure 5.7 Rhino Base Models for Direct and Indirect Solar Gain Systems

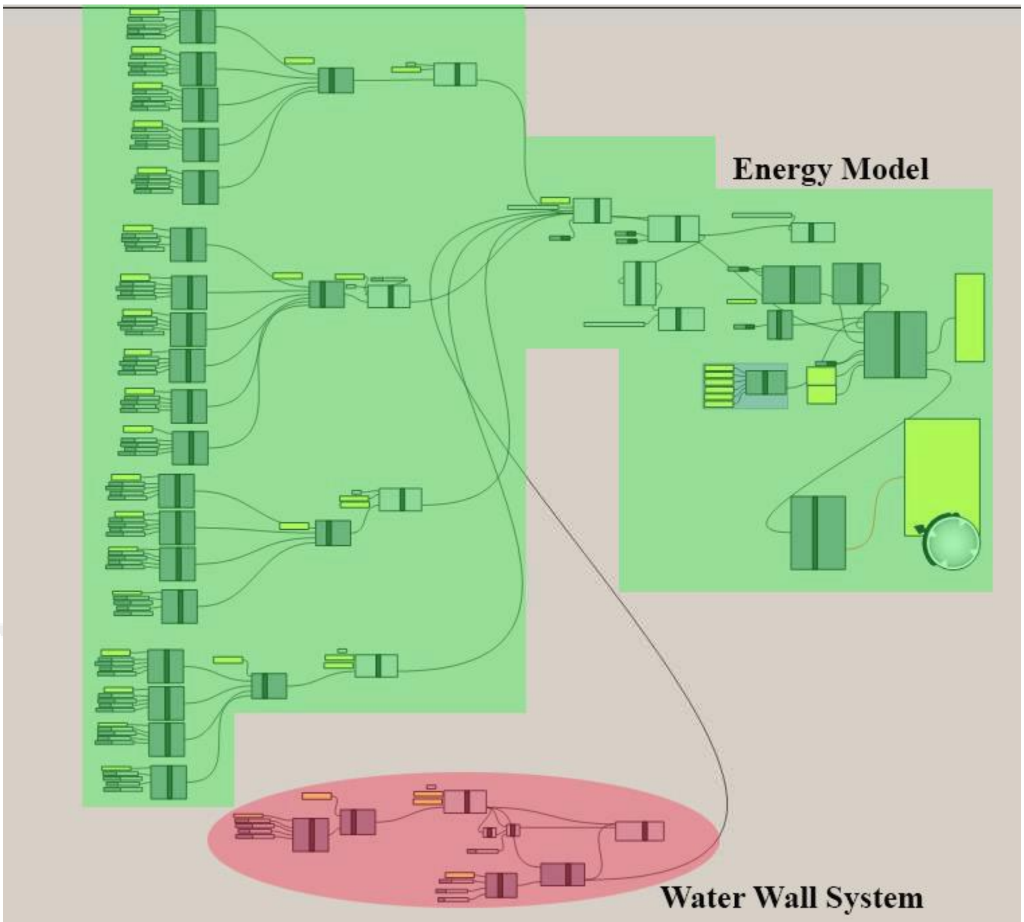


Figure 5.8 Overall Grasshopper Model for the Material Assignment for the WaterWall System

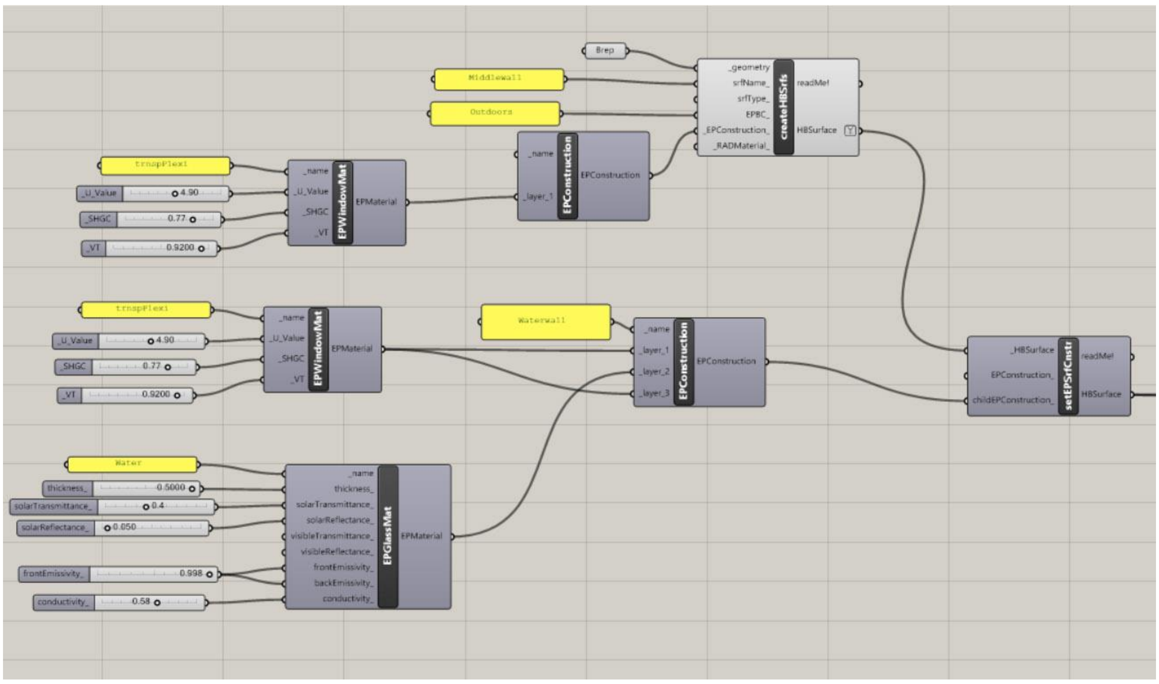


Figure 5.9 Grasshopper Model for The Transparent WaterWall System

5.12. Water as a Material

As there is no previous reference that could be used in this situation, and with the few available studies that have been conducted concerning Water Wall System, it presented a problem. The problem was faced during a material assignment in terms of identifying water as a construction element in Honeybee component to be simulated and analyzed. This has been solved in two different ways, one is to identify and treated water as if it’s glass material which happened in the case Transparent Water Wall System, using Honeybee_PlusEnergy Glass Material (Fig. 5.10), meanwhile in the case of having an opaque envelope (Concrete, Gazbeton) for the Water Wall System, its identified as an opaque material using Honeybee_PlusEnergy Opaque Material (Fig.5.11) as its reflective and visual transmittance aren’t hindered by the opaque envelop.

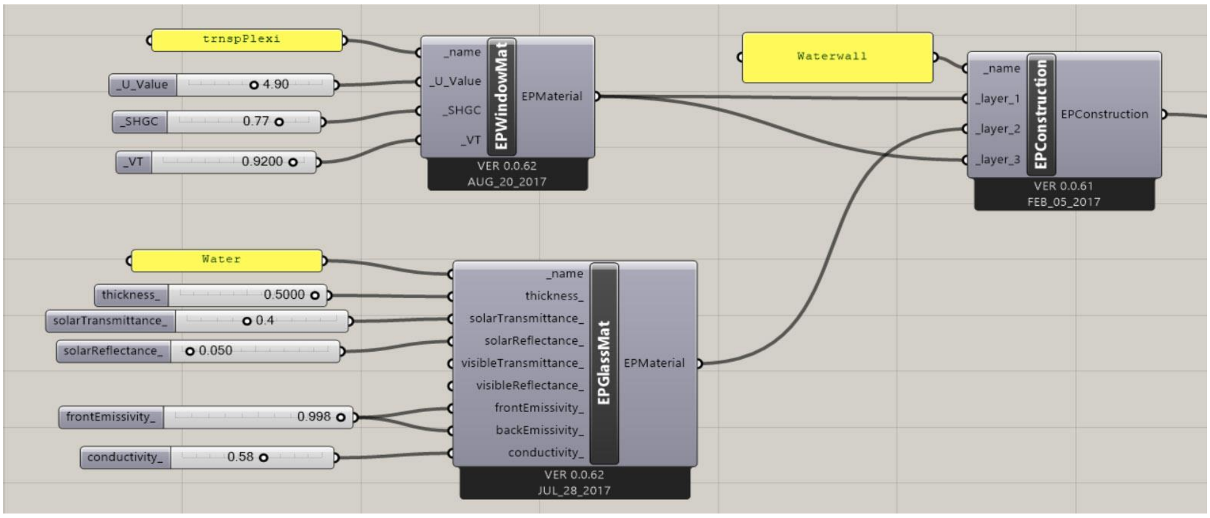


Figure 5.10 Detailed indication of Water in Transparent WaterWall System

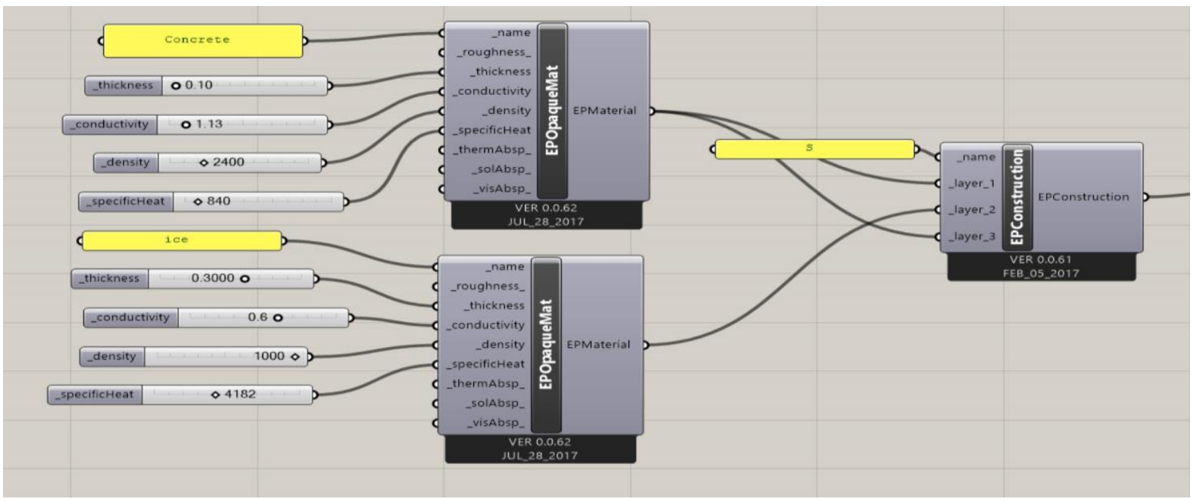


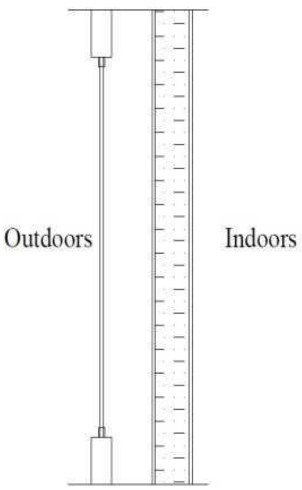
Figure 5.11 Detailed indication of Water in Opaque Water Wall System

5.11. Solar Gain Energy Systems Section Compositions

The following tables provide sections and physical characteristic that were used to identify direct and indirect solar gain systems in the energy models.

Table 5.1; Display Transparent Water Wall material configurations, in terms of each material used and its physical properties as identified in the Grasshopper simulation components.

Table 5.1 Transparent Plexiglass Water Wall Configuration

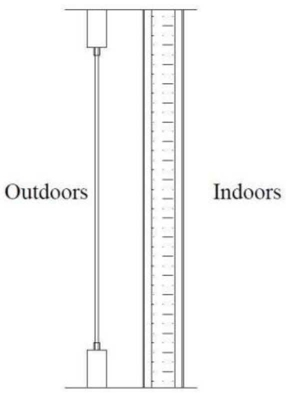
Transparent Water Wall Section	**N**	**Material**	**D** *(m)*	**U-Value** *(W/m2)*	**SHGC**	**VT %**
	1	Single Glazing	0.04	5.2	0.88	0.9
	2	Air Gap	0.5	-	-	-
	3	Transparent Plexiglass	0.04	4.9	0.77	0.92
	4	Water	0.42	-	-	-
	5	Transparent Plexiglass	0.04	4.9	0.77	0.92

D (Distance), U-value (Thermal Transmittance), SHGC (Solar Heat Gain Coefficient)

VT (Visible Transmittance), SH (Specific Heat)

Table 5.2; Display Concrete Water Wall material configurations, in terms of each material used and its physical properties as identified in the Grasshopper simulation components.

Table 5.2 Concrete Water Wall Configuration

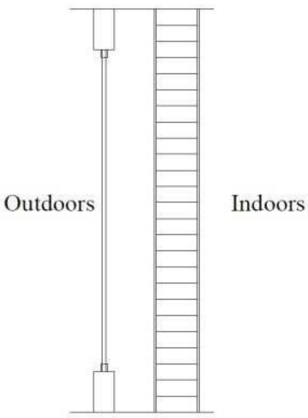
Concrete Water Wall Section	**N**	**Material**	**D** *(m)*	**U-Value** *(W/m2)*	***SHGC***	**VT %**	**ʎ** *(kA/L)*	**ρ** *(kg/m^3)*	**SH***(J/kg-K)*
	1	Single Glazing	0.04	5.2	0.88	0.9	-	-	-
	2	Air Gap	0.5	-	-	-	0.025	-	-
	3	Concrete Block	0.1	1.13	-	-	2.5	2400	840
	4	Water	0.3	-	-	-	993	-	-
	5	Concrete	0.1	1.13	-	-	2.5	2400	840

U-value (Thermal Transmittance), SHGC (Solar Heat Gain Coefficient), VT (Visible Transmittance)

ʎ (Thermal Conductivity), ρ (Density), SH (Specific Heat)

Table 5.3; Display Trombe Wall material configurations, in terms of each material used and its physical properties as identified in the Grasshopper simulation components.

Table 5.3 Trombe Wall Configuration

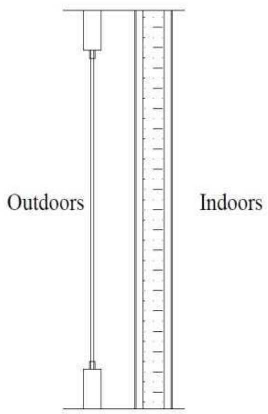
Trombe Wall Section Section	**N**	**Material**	**D** *(m)*	**U-Value** *(W/m2)*	***SHGC***	**VT** *%*	**ƙ** *(kA/L)*	**ρ** *(kg/m³)*	**SH***(J/kg-K)*
	1	Single Glazing	0.04	5.2	0.88	0.9	-	-	-
	2	Air Gap	0.5	-	-	-	0.025	-	-
	3	Sandstone	0.5	2.33	-	-	-	2650	920

U-value (Thermal Transmittance), SHGC (Solar Heat Gain Coefficient),

VT (Visible Transmittance), ƙ (Thermal Conductivity), ρ (Density), SH (Specific Heat)

Table 5.4; Display Gazbeton Water Wall material configurations, in terms of each material used and its physical properties as identified in the Grasshopper simulation components.

Table 5.4 Gazbeton Water Wall Configuration

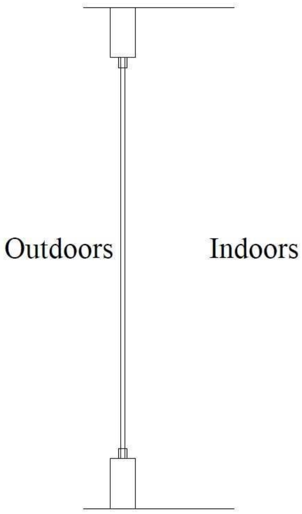
Gazbeton Water Wall Section	N	Material	D *(m)*	U-Value *(W/m2)*	*SHGC*	VT %	ƛ *(kA/L)*	ρ *(kg/m^3)*	SH*(J/kg-K)*
	1	Single Glazing	0.04	5.2	0.88	0.9	-	-	-
	2	Air Gap	0.5	-	-	-	0.025	-	-
	3	Gazbeton	0.1	0.16	-	-	-	500	1000
	4	Water	0.3	-	-	-	-	993	-
	5	Gazbeton	0.1	0.16	-	-	-	500	1000

U-value (Thermal Transmittance), SHGC (Solar Heat Gain Coefficient),

VT (Visible Transmittance), ƛ (Thermal Conductivity), ρ (Density), SH (Specific Heat)

Table 5.5; Display Single Glazed wall material configuration, in terms of each material, used and its physical properties as identified in the Grasshopper simulation components.

Table 5.5 Single Glazed Wall Configuration

Single Glazing Section	**N.**	**Material**	**D** *(m)*	**U-Value** *(W/m2)*	***SHGC***	**VT** *%*	**ρ** *(kg/m³)*	**SH***(J/kg-K)*
	1	Single Glazing	0.04	5.2	0.88	0.9	-	-

U-value (Thermal Transmittance), SHGC (Solar Heat Gain Coefficient),

VT (Visible Transmittance), ƙ (Thermal Conductivity), ρ (Density), SH (Specific Heat)

Table 5.7 - 5.8, and 5.9; Display the material configuration of the model components; 3 Exterior walls, Ceiling, and Flooring, in terms of their position and their physical properties as identified in the Grasshopper simulation components.

Table 5.6 Water Physical Characteristic

Material	**Solar Transmittance**	**Solar Reflectance**	**Emissivity**	**Conductivity**
Water	0.4	0.05	0.998	0.58

Table 5.7 Wall Material Configuration

	Layer	Material	D (m)	ϰ (kA/L)	ρ(kg/m³)	SH (J/kg-K)
Wall Layers	Layer 1	gypsum plaster	0,01	0.35	1680	1085
	Layer 3	XPS	0,03	0,04	28	1200
	Layer 2	Brick	0,19	0,30	1922	840
	Layer 4	lime plaster	0,01	0.35	1680	1085

Table 5.8 Ceiling Material Configuration

	Layer	Material	D (m)	ϰ (kA/L)	ρ(kg/m³)	SH (J/kg-K)
Ceiling Layers	Layer 1	Leveling concrete	0,05	1,4	2300	750
	Layer 2	XPS	0,12	0,034	28	1200
	Layer 3	Leveling concrete	0,03	1,4	2300	750
	Layer 4	RC Slab	0,12	2,5	2400	840
	Layer 5	lime plaster	0,01	0.35	1680	1085

U-value (Thermal Transmittance), SHGC (Solar Heat Gain Coefficient), VT (Visible Transmittance), ϰ (Thermal Conductivity), ρ (Density), SH (Specific Heat)

Table 5.9 Flooring Material Configuration

	Layer	Material	D *(m)*	ʎ *(kA/L)*	ρ*(kg/m³)*	SH *(J/kg-K)*
Flooring Layers	Layer 1	Blockade	0,15	1.74	1500	960
	Layer 2	Lean Concrete	0,10	1,10	1100	750
	Layer 3	leveling concrete	0,02	1,40	2300	750
	Layer 4	XPS	0,08	0,04	28	1200
	Layer 5	leveling concrete	0,03	1,40	2300	750
	Layer 6	Laminate	0,02	0,19	545	2385

U-value (Thermal Transmittance), SHGC (Solar Heat Gain Coefficient),

VT (Visible Transmittance), ʎ (Thermal Conductivity), ρ (Density), SH (Specific Heat)

CHAPTER 6
RESULTS AND DISCUSSION

In this study, a passive design solution which is water wall system has been applied to 2 different cities which are Istanbul and Stockholm that are located in different climatic regions. The energy performance of transparent water wall system, concrete water wall system, gas concrete water wall system; single glazing direct gain system and Trombe wall system has been done for 2 different cities in 2 different climatic regions which are hot and humid climatic region and semi-continental climatic region respectively.

Istanbul has a hot and humid climate with hot and humid summers and warm winters.

Stockholm has a semi-continental climate with cold winters and warm and sunny summers (https://www.climatestotravel.com/climate/sweden).

(Fig. 6.1, and 6.2) display the hourly indoor air temperature variations for 1 month and for 1 day in January for Istanbul. During night time when heating is needed, the indoor air temperature variations from highest to lowest are concrete water wall system, gas concrete water wall system, transparent water wall system, Trombe wall system and single glazing direct gain system respectively.

During daytime when the sun is high in the air and there is solar radiation, the indoor air temperature variations from highest to lowest are single glazing direct gain system, concrete water wall system, gas concrete water wall system, transparent water wall system and Trombe wall system respectively. The indoor air temperatures in the single glazed direct gain system are higher in the daytime when there is solar radiation due to the higher heat transfer coefficient it has. The concrete water wall system, gas concrete water wall system, transparent water wall system, and Trombe wall system are indirect gain systems which transmit heat with a time lag. Thus, in these systems, the indoor air temperature neither rises nor drops that rapidly compared to the single glazed direct gain system. The minimum and maximum indoor air temperatures are 3.16C and 36.48C throughout January.

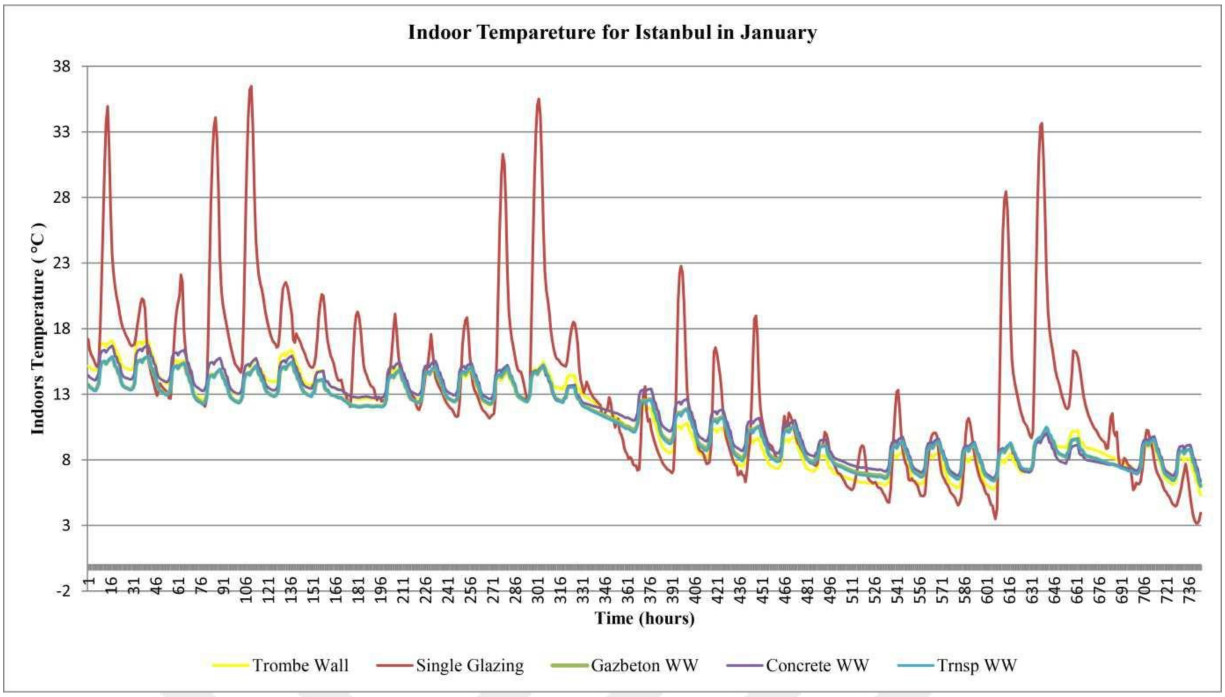


Figure 6.1 Hourly indoor air temperature variations for Istanbul on January

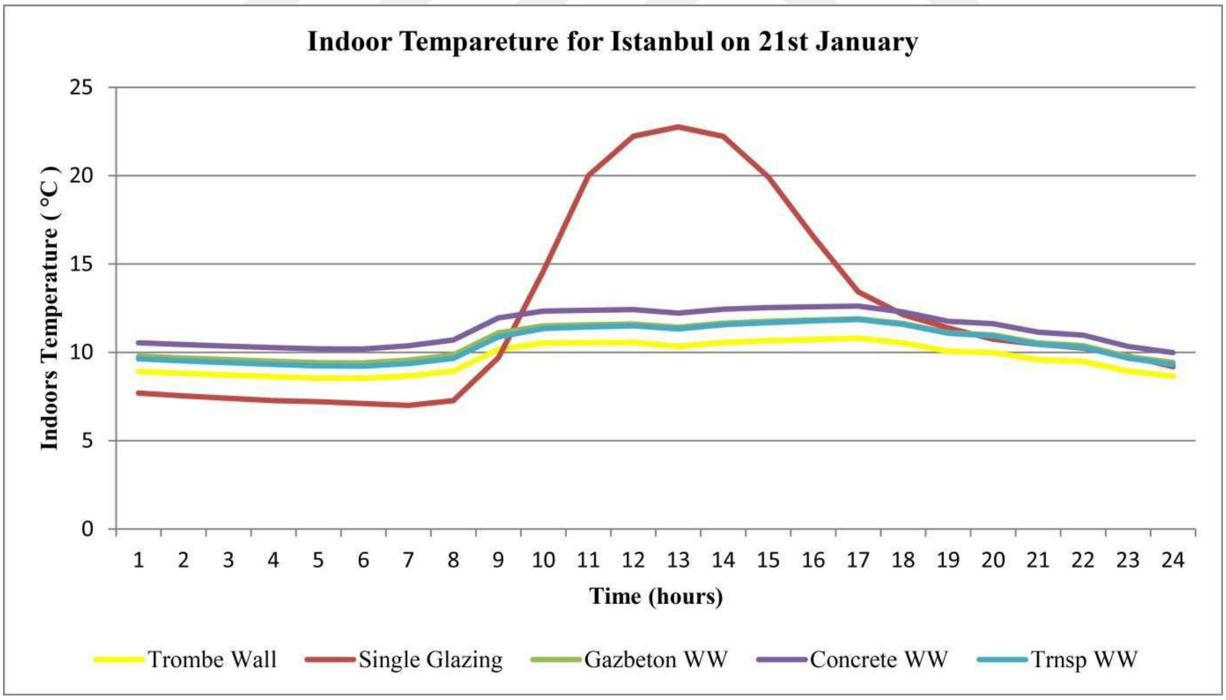


Figure 6.2 Hourly indoor air temperature variations for Istanbul on January, 21^{st}

In (Fig. 6.2), it is seen that the indoor air temperatures at 01.00 are 7.69ºC, 10.54 ºC, 9.79 ºC, 9.63 ºC, 8.92 ºC for single glazing direct gain system, concrete water wall system, gas concrete water wall system, transparent water wall system and Trombe wall system respectively. The

indoor air temperatures drop down to 7.10 ºC, 10.19 ºC, 9.41 ºC, 9.22 ºC, and 8.53 ºC at 06.00 respectively. Then, they start increasing up to 16.56 ºC, 12.58 ºC, 11.83 ºC, 11.78 ºC, and 10.73 ºC at 16.00 respectively. Then, they start decreasing up to 9.19 ºC, 9.98 ºC, 9.43 ºC, 9.31 ºC, and 8.65 ºC at 00.00. As seen from the graphs, the indoor air temperature fluctuation is so high in the alternative with single glazing direct gain system. This affects the thermal comfort of a room for the occupants in a negative way.

(Fig. 6.3) displays the hourly indoor air temperature variations for 1 month in July for Istanbul. During night time, the indoor air temperature variations from highest to lowest are single glazing direct gain system, transparent water wall system, gas concrete water wall system, concrete water wall system and Trombe wall system respectively. There is not much difference between transparent water wall system, gas concrete water wall system, and concrete water wall system results.

During daytime when the sun is high in the sky and there is solar radiation, the indoor air temperature variations from highest to lowest are single glazing direct gain system, transparent water wall system, gas concrete water wall system, concrete water wall system and Trombe wall system respectively. The indoor air temperatures in the single glazed direct gain system are higher in the daytime when there is solar radiation due to the higher heat transfer coefficient it has. In a similar way, the single glazed direct gain system loses heat more rapidly compared to Trombe wall and water wall systems. Thus, the temperature fluctuation in the single glazed direct gain system is the highest during 1 day in the cooling period as it is in the heating period. The minimum and maximum indoor air temperatures are 27.57 ºC and 45.74 ºC throughout July in Istanbul.

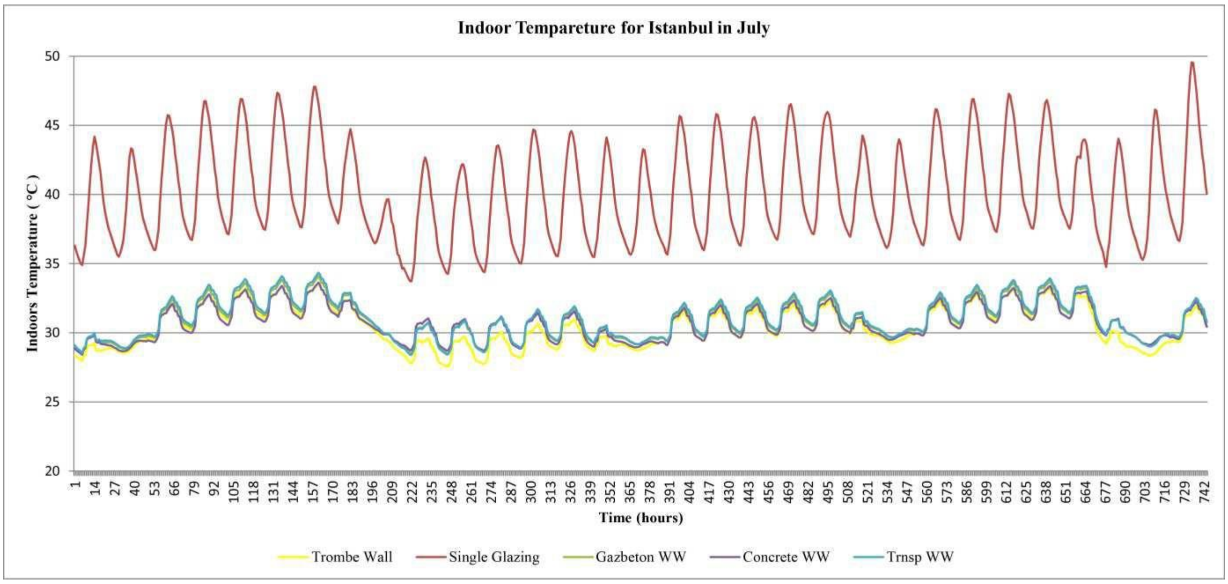


Figure 6.3 Hourly Indoor Air Temperature Variations for Istanbul on July

In (Fig. 6.4) it is seen that the indoor air temperatures at 01.00 are 35.40 ºC, 28.97 ºC, 28.90 ºC, 28.90 ºC and 27.96 ºC for single glazing direct gain system, concrete water wall system, gas concrete water wall system, transparent water wall system, and Trombe wall system respectively. The indoor air temperatures drop down to 34.39 ºC, 28.72 ºC, 28.64 ºC, 28.59 ºC, and 27.76 ºC at 06.00 respectively. Then, they start increasing up to 43.18 ºC, 31.06 ºC, 31.02 ºC, 30.98 ºC and 29.95 ºC at 16.00 respectively. Then, they start decreasing up to 36.47 ºC, 29.37 ºC, 29.31 ºC, 29.22 ºC, and 28.46 ºC at 00.00 respectively. As seen from the graphs, the indoor air temperature fluctuation is so high in the alternative with single glazing direct gain system. This affects the thermal comfort of a room for the occupants in a negative way in cooling period.

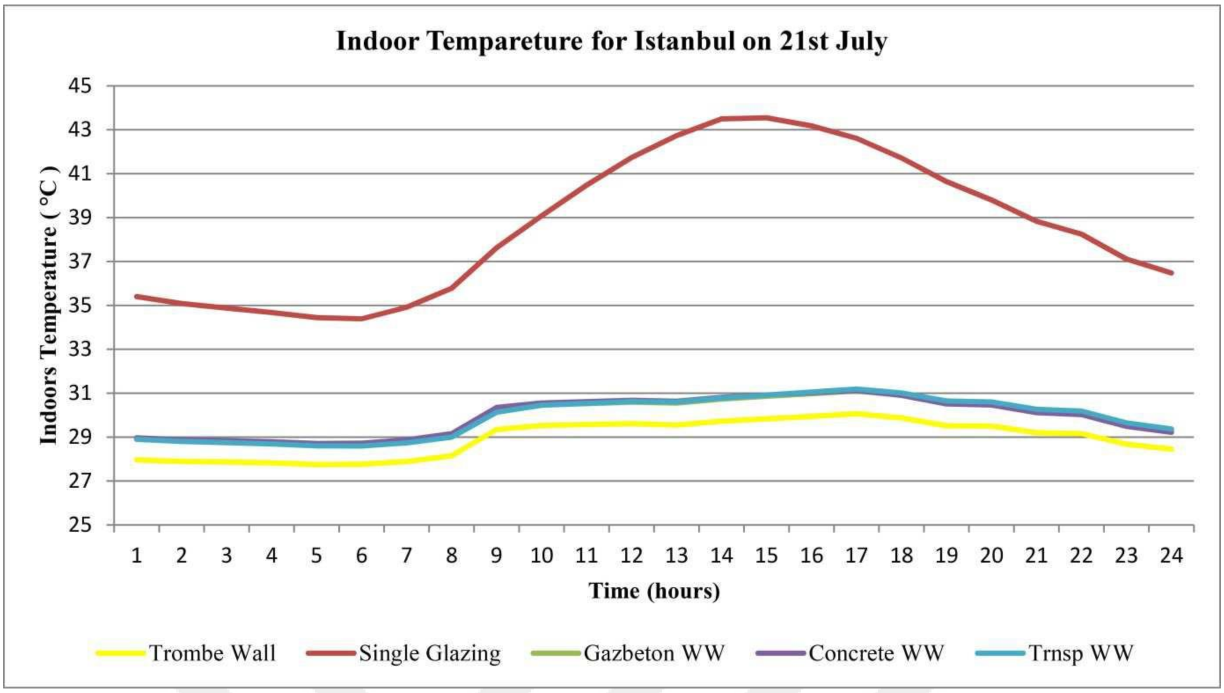


Figure 6.4 Hourly Indoor Air Temperature Variations for Istanbul on July, 21st

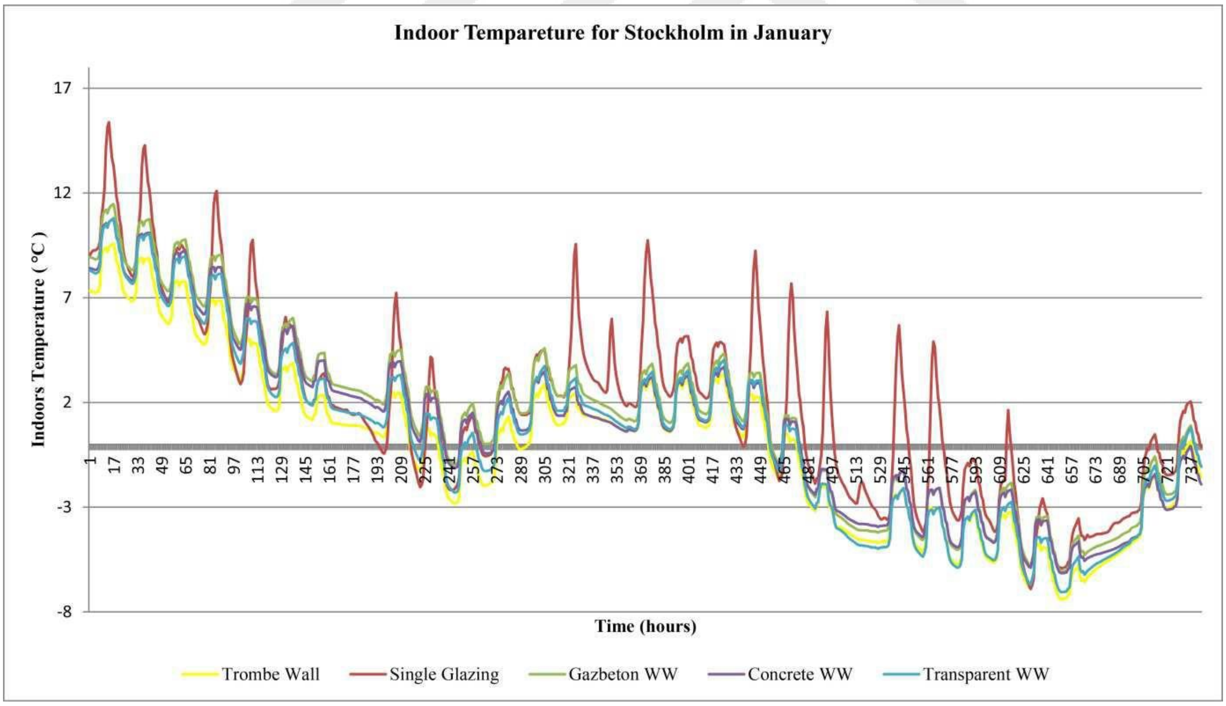


Figure 6.5 Hourly Indoor Air Temperature Variations for Stockholm on January

(Fig.6.5) displays the hourly indoor air temperature variations for 1 month in January for Stockholm. During night time when heating is needed, the indoor air temperature variations from highest to lowest are gas concrete water wall system, transparent water wall system, concrete water wall system, Trombe wall system and single glazing direct gain system respectively. The minimum and maximum indoor air temperatures are -6.90 ºC and 15.38 ºC throughout January in Stockholm.

(Fig. 6.6) displays the indoor air temperature variation in Stockholm on January 21st. In Figure 6.2, it is seen that the indoor air temperatures at 01.00 are 1.52 ºC, 1.30 ºC, 1.12 ºC, 0.82 ºC, and 0.78 ºC for gas concrete water wall system, transparent water wall system, concrete water wall system, single glazing direct gain system, and Trombe wall system respectively. The indoor air temperatures drop down to 1.1C, 0.80 ºC, 0.72 ºC, -0.11 ºC and 0.34 ºC at 06.00 respectively. Then, they start increasing up to 3.41 ºC, 3.05 ºC, 2.92 ºC, 6.63 ºC, and 2.25 ºC at 16.00 respectively. Then, they start decreasing up to 0.10 ºC, -0.20 ºC, -0.19 ºC, 0.20 ºC and -0.71 ºC at 00.00. As seen from the graphs, the indoor air temperature fluctuation is so high in the alternative with single glazing direct gain system that is applied to a south façade in Stockholm like in Istanbul. This affects the thermal comfort of a room for the occupants in a negative way.

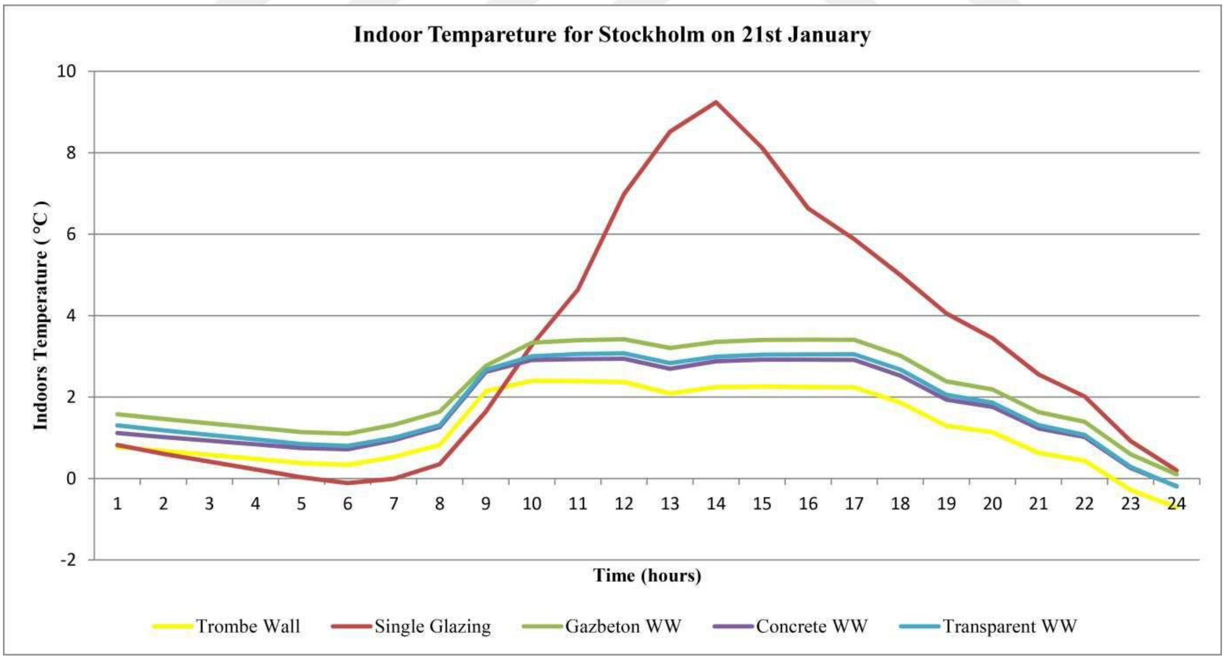


Figure 6.6 Hourly Indoor Air Temperature Variations for Stockholm on January, 21st

(Fig. 6.7) displays the hourly indoor air temperature variations for 1 month in July for Stockholm. During night time, the indoor air temperature variations from highest to lowest are single glazing direct gain system, concrete water wall system, gas concrete water wall system, transparent water wall system and Trombe wall system respectively.

During daytime when the sun is high in the sky and there is solar radiation, the indoor air temperature variations from highest to lowest are single glazing direct gain system, concrete water wall system, gas concrete water wall system, transparent water wall system and Trombe wall system respectively.

The indoor air temperatures in the single glazed direct gain system are higher in the daytime when there is solar radiation due to the higher heat transfer coefficient it has. In a similar way, the single glazed direct gain system loses heat more rapidly compared to Trombe wall and water wall systems. Thus, the temperature fluctuation in the single glazed direct gain system is the highest during 1 day. The minimum and maximum indoor air temperatures are 19.95 ºC and 48.21 ºC throughout July.

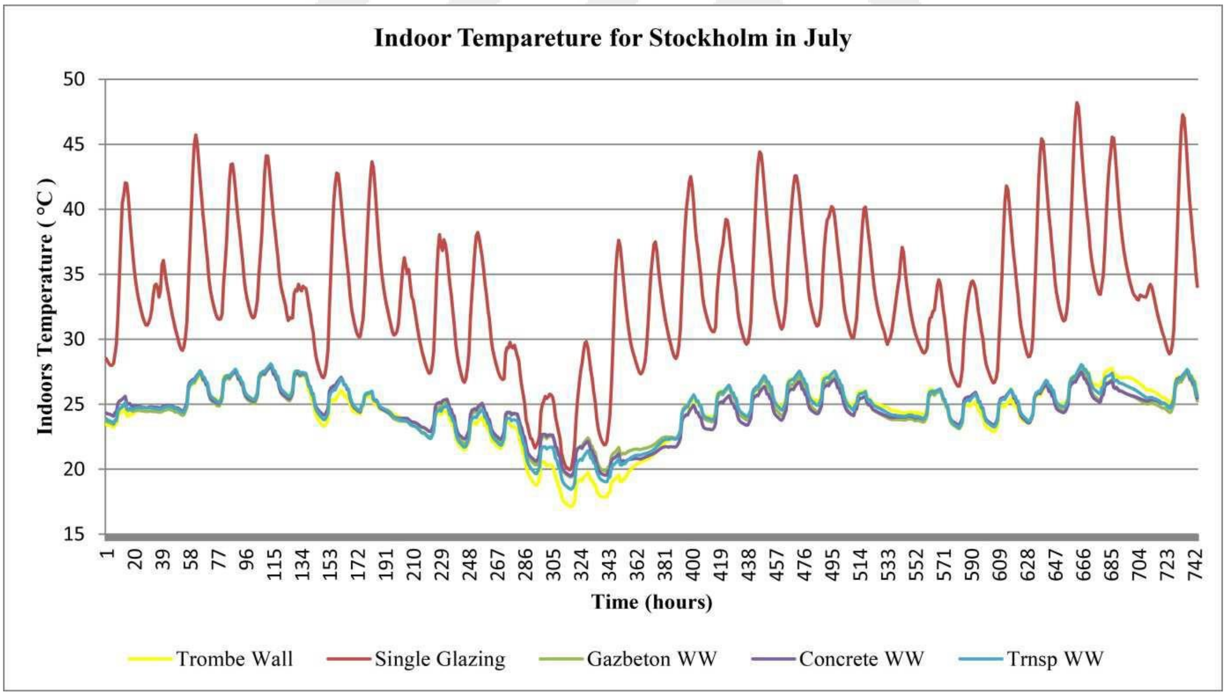


Figure 6.7 Hourly Indoor Air Temperature Variations for Stockholm on July

(Fig.6.8) displays the indoor air temperature variations for 5 different south façade alternatives applied in Stockholm on July 21st. It is seen that the indoor air temperatures from highest to lowest are seen in single glazing direct gain system, concrete water wall system, gas concrete water wall system, transparent water wall system and Trombe wall system respectively.

Transparent water wall alternative provides the best thermal conditions for a cooling period even if the indoor air temperature variations in Trombe wall alternative are lower than the transparent water wall alternative.

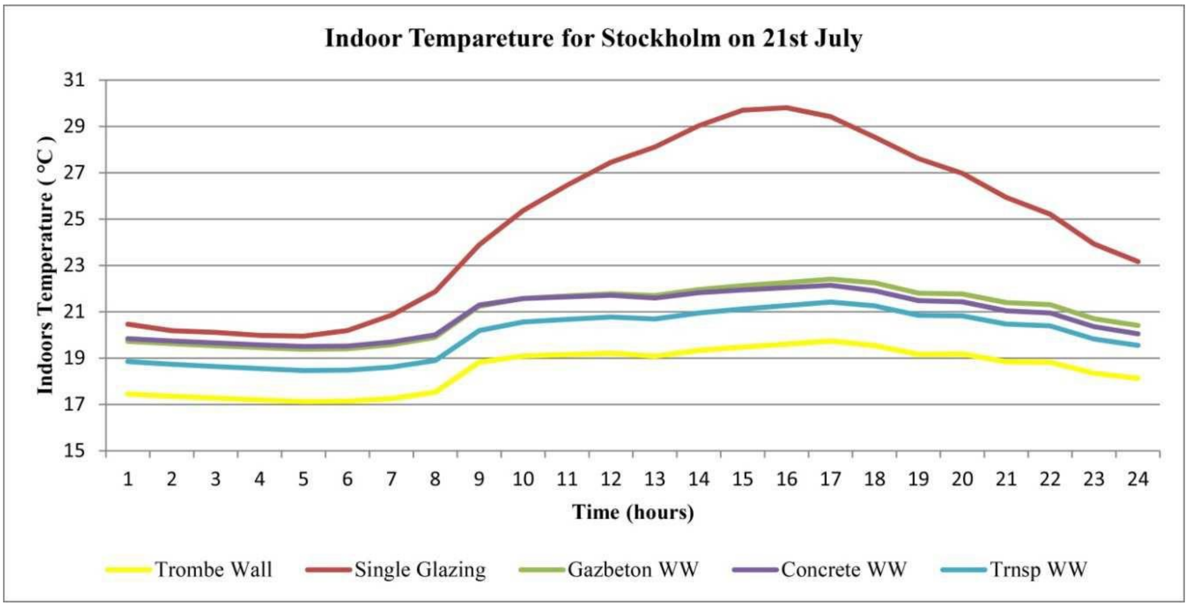


Figure 6.8 Hourly Indoor Air Temperature Variations for Stockholm on July, 21st

(Fig. 6.9, and 6.10) display the hourly surface energy flow through the inner envelope of the south facade for indirect gain system alternatives and the envelope itself for the single glazing direct gain system. The maximum and minimum hourly heat gains for 5 different wall alternatives that are applied to south façade throughout January are 23.06kWh and -2.72kWh respectively.

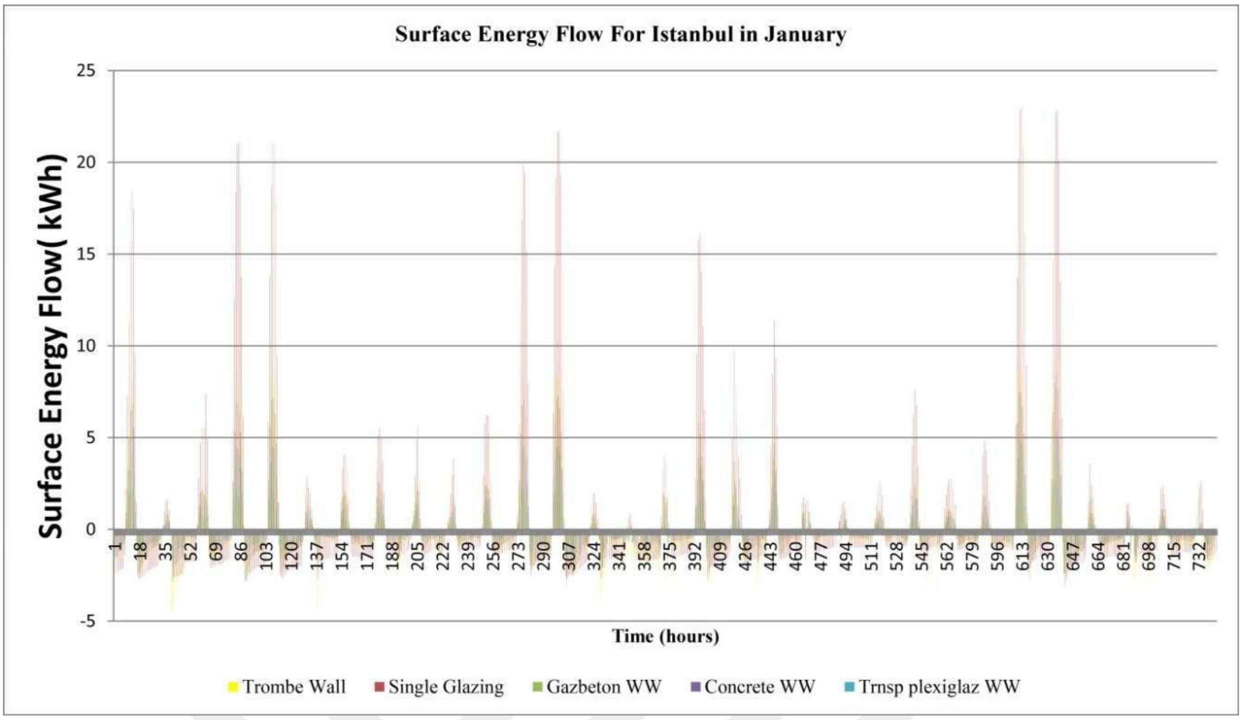


Figure 6.9 The Hourly Surface Energy Flow Through the Envelope for Istanbul on January

In (Fig.6.10, 6.13) all the envelope alternatives lose heat to outside during night time on January in Istanbul and in Stockholm; while they gain heat during the daytime when there is solar radiation heating up the volume. As seen from the graphs, the maximum heat loss to outside and maximum heat gain to the inner volume occur in single glazing direct gain system both in Istanbul and Stockholm but as the temperature fluctuation inside the volume during the whole day is too much, it is not preferable for the thermal comfort of occupants. Similar comments can be made for the heat gains and losses in Istanbul and in Stockholm in July.

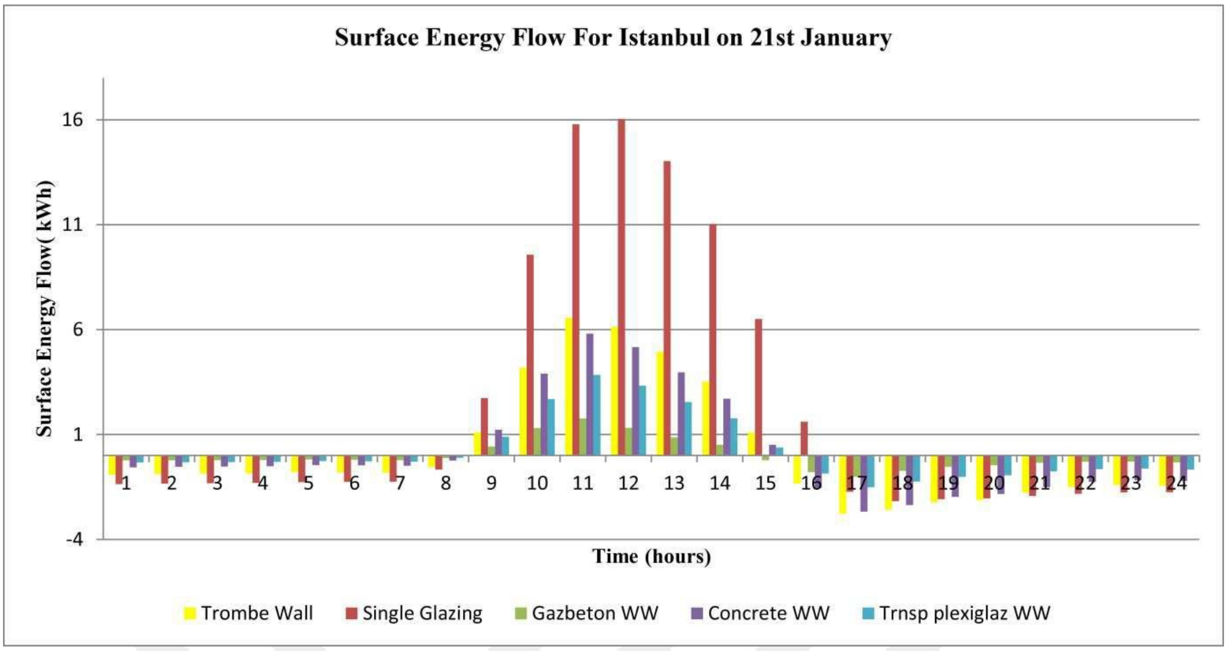


Figure 6.10 The Hourly Surface Energy Flow Through the Envelope for Istanbul on January, 21st

(Fig. 6.11, and 6.15) display the hourly surface energy flow through the envelope for Istanbul and Stockholm in July. The volume loses heat to outside as the indoor air temperature is higher than the outdoor temperature during night time. The exact opposite occurs in daytime where the volume gains heat during the day as the outdoor temperature is higher than the indoor air temperature.

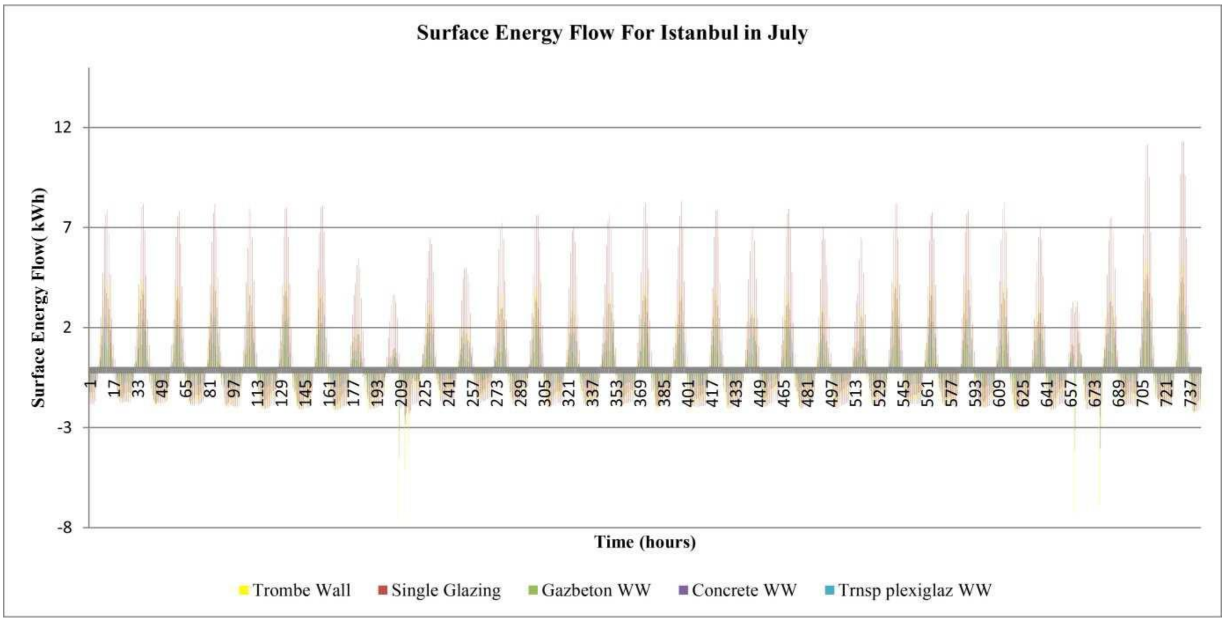


Figure 6.11 The Hourly Surface Energy Flow Through the Envelope for Istanbul on July

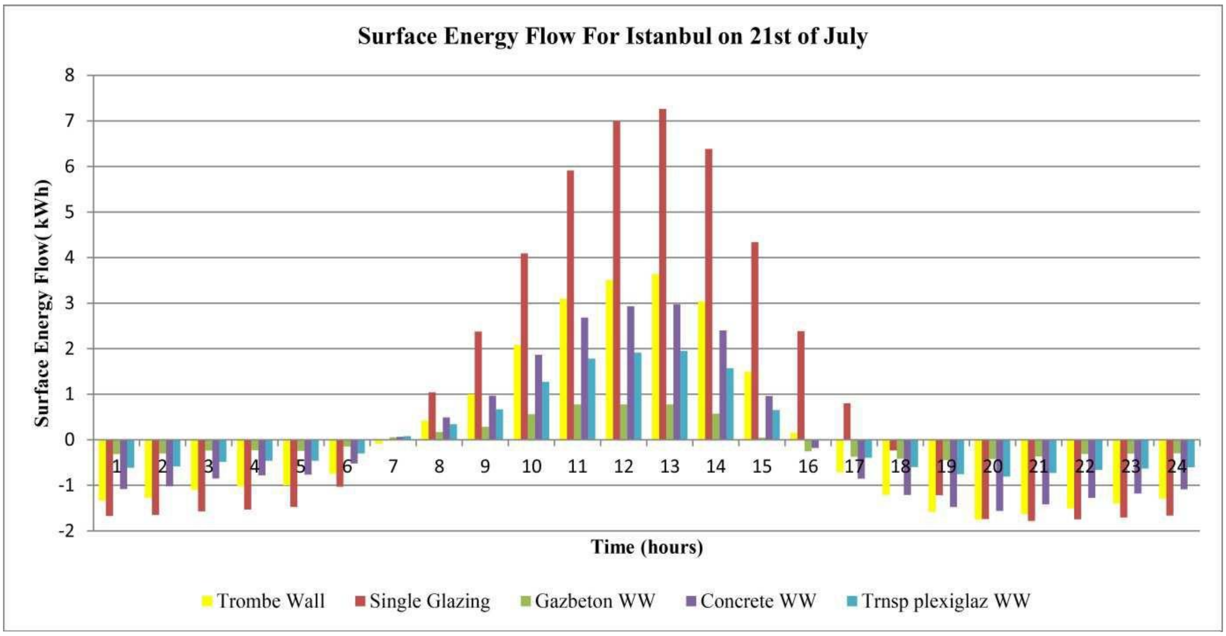


Figure 6.12 The Hourly Surface Energy Flow Through the Envelope for Istanbul on July, 21st

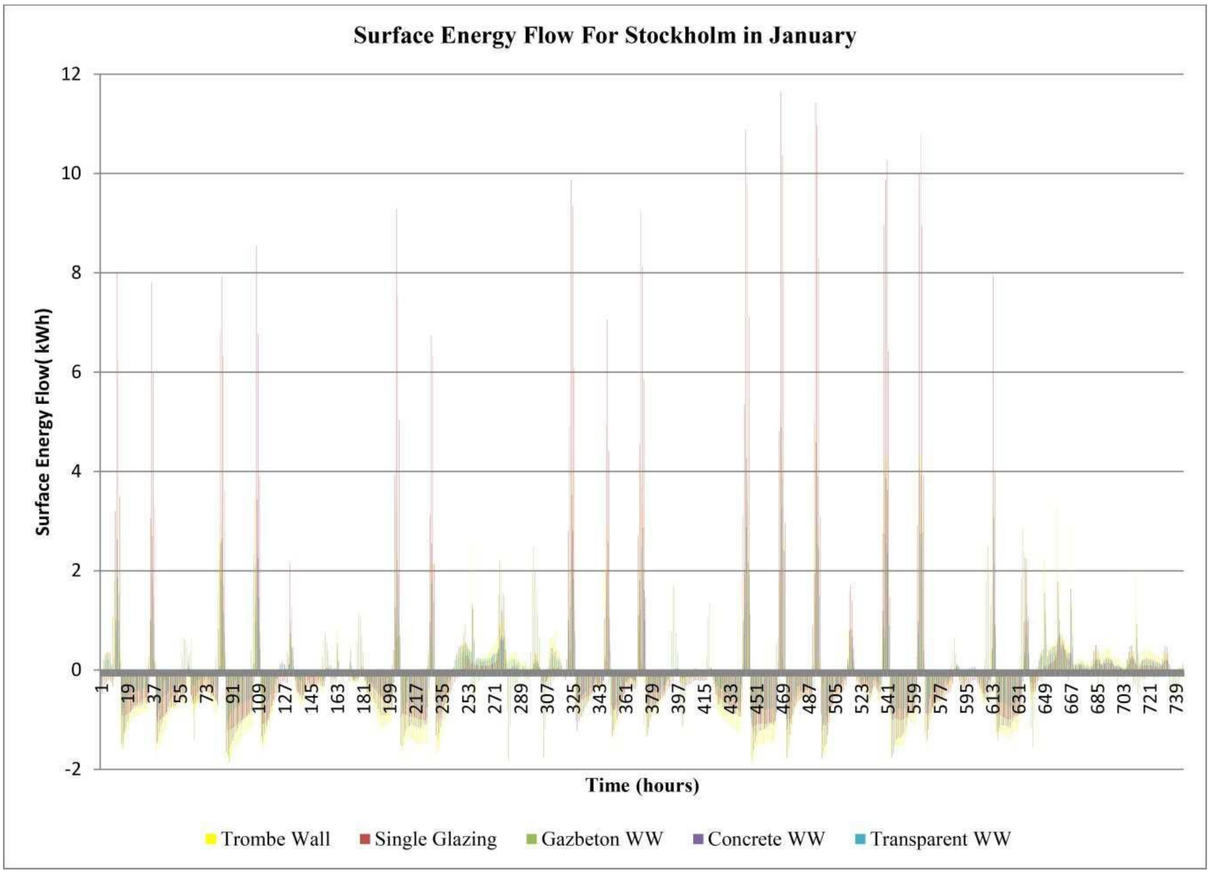


Figure 6.13 The Hourly Surface Energy Flow Through the Envelope for Stockholm on January

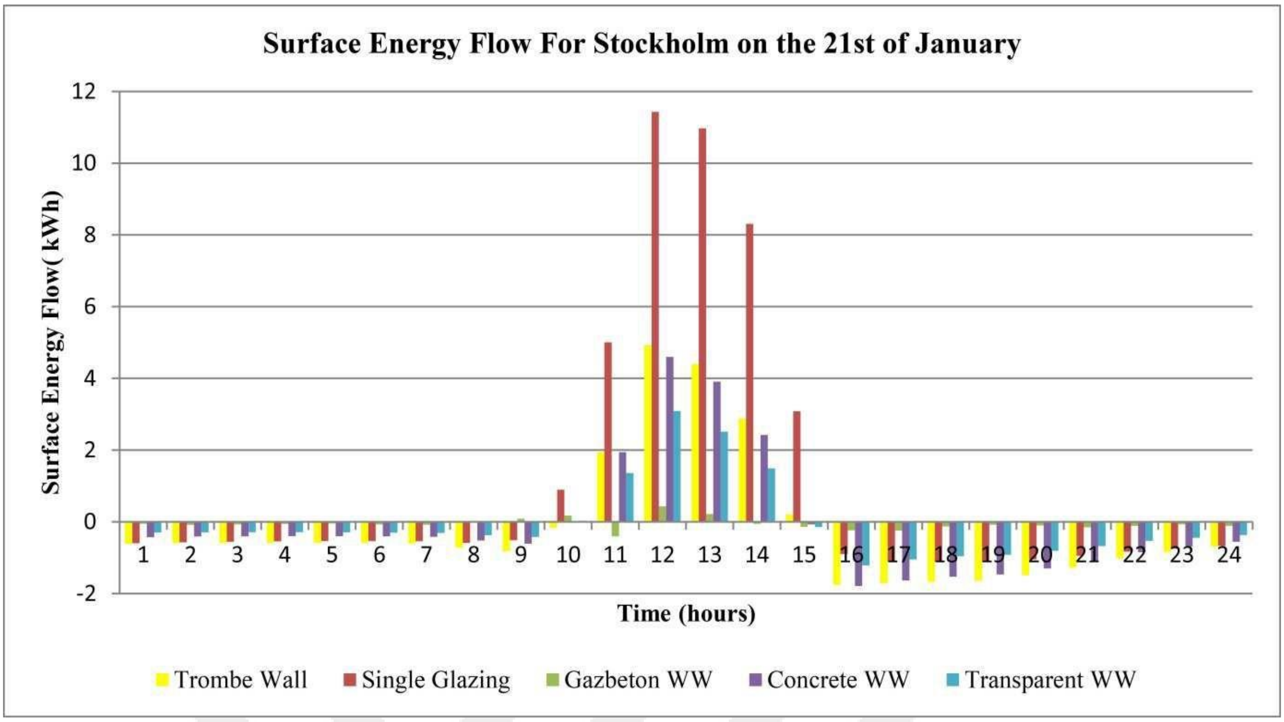


Figure 6.14 The Hourly Surface Energy Flow Through the Envelope for Stockholm on January, 21st

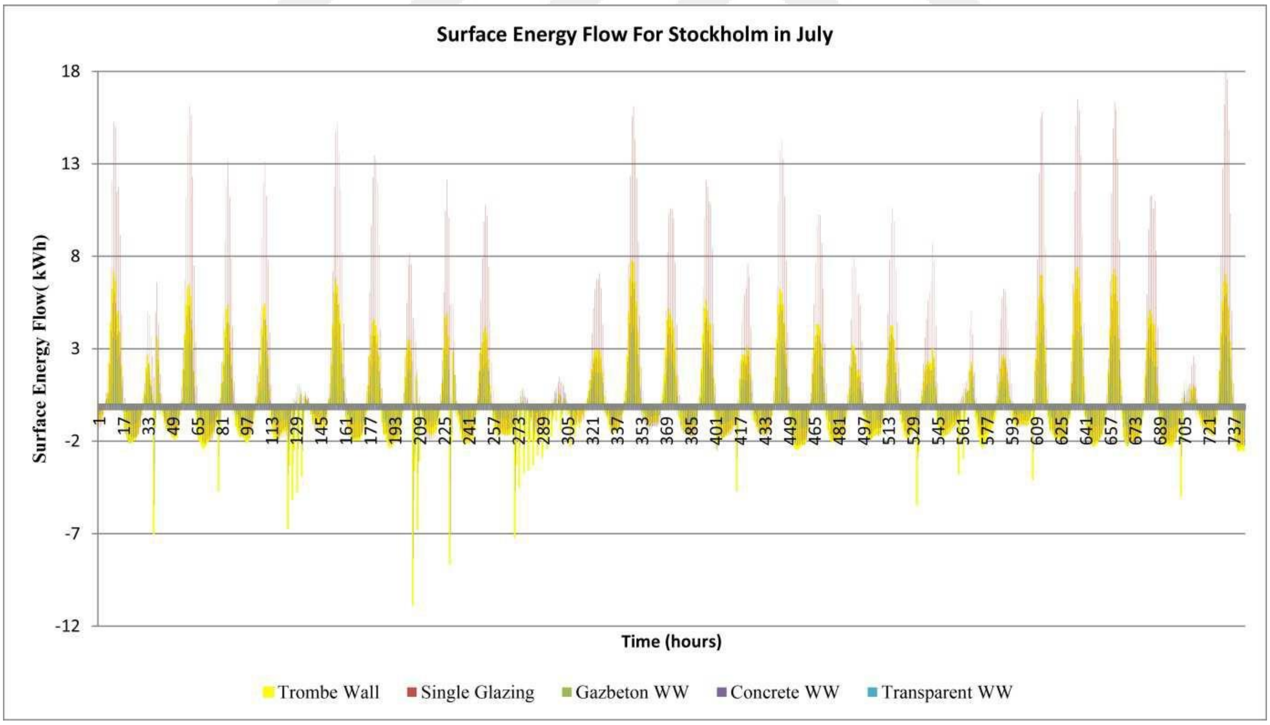


Figure 6.15 The Hourly Surface Energy Flow Through the Envelope for Stockholm on July

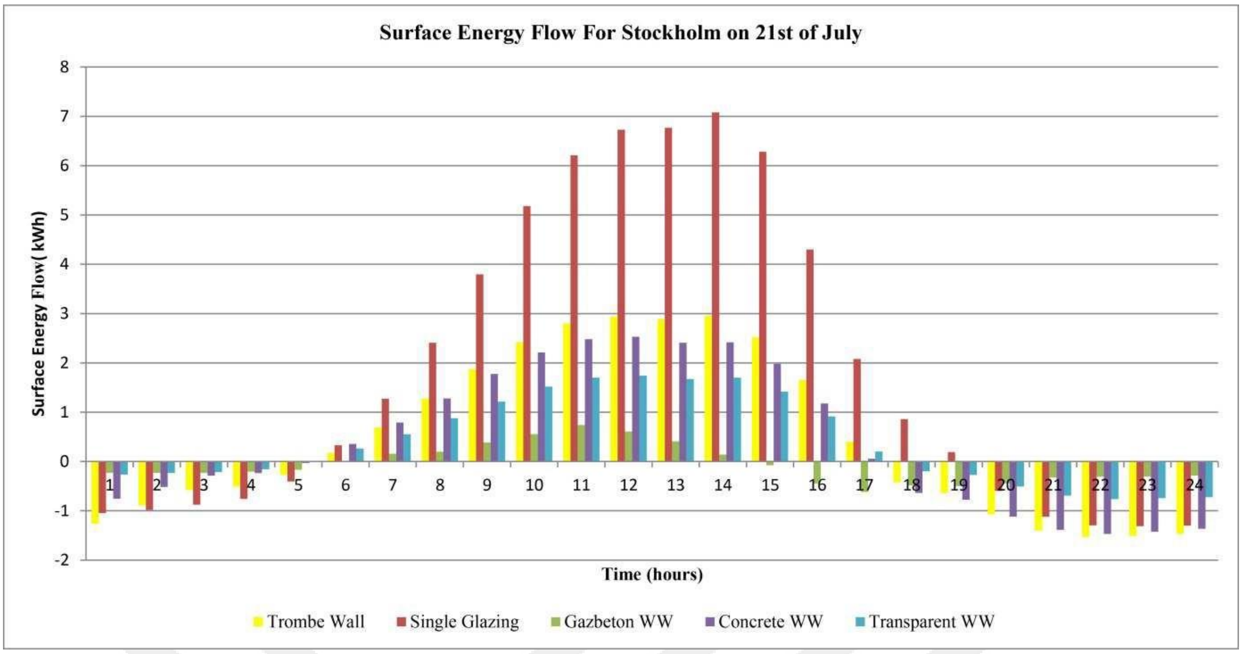


Figure 6.16 The Hourly Surface Energy Flow Through the Envelope for Stockholm on July, 21st

(Table 6.1) shows the number of heat gains and losses for 5 envelope alternatives of the south façade for the whole year in Istanbul and in Stockholm. The results show that the water wall alternatives perform better than the Trombe wall and single glazing direct gain alternatives for the heating period when applied to south façade of a room that is located in Istanbul. Transparent water wall alternative performs the best in Istanbul in the heating period.

Single glazing direct gain alternative performs the worst both in Istanbul and in Stockholm.

Trombe wall performs slightly better than concrete water wall alternative in Stockholm in the heating period. Thus, the occupant should decide which one to apply according to cost or manufacturing benefits.

Table 6.1 The Energy Performance (*kWh*) for 5 South Facade Envelope Alternatives in Istanbul and Stockholm for The Whole Year.

	Istanbul	Stockholm
Single glazing	-6106,4	-4071,44
Trombe wall	-494,8	117,24
Gazbeton WaterWall	-170,46	-23,51
Concrete WaterWall	-179,31	114,33
Transparent WaterWall	-87,17	12,2

Measuring Unite (kWh)

CHAPTER 7
CONCLUSION AND FUTURE RESEARCH

Energy became the increasing trend in the world as it is hard to find and expensive. It shapes the strategic development and the policies of countries. The improvement level is defined by the use of energy amount for each country in both for industry and for residential uses. This necessity for energy leads countries to use fossil fuels. Unfortunately, fossil fuels have a great negative impact on the environment, the living creatures and the world. It causes pollution, which leads to diseases, geographical change, climate change, erosions, a decrease in the efficiency of the land, a decrease in water sources, lack of energy, a decrease in biological variety and lack of food. Precautions should be taken not to face these.

It is possible to decrease the amount of energy consumed in a building from the early design stage. Architects may design the buildings in a passive way. These passive strategies have been used across the globe for centuries.

In this study, a passive design solution which is water wall system has been applied to 2 different cities which are Istanbul and Stockholm that are located in different climatic regions. The comparison of transparent and opaque water wall systems; Trombe wall system and the direct gain system has been done for 2 different cities in 2 different climatic regions.

The results show that the energy performance of the water wall alternatives in Istanbul performs better than Trombe wall alternative in the heating period. Among the water wall alternatives, transparent water wall alternative performs the best in Istanbul.

In Stockholm, the Trombe wall alternative performs the best throughout the whole year. Then, the concrete water wall, transparent water wall, and gas concrete water wall come in sequence. The single glazing performs the worst both in Istanbul and in Stockholm in the heating period.

As a result, water wall system performs better in the hot-humid climatic region but the system should be retrofitted by using vents or/and shading devices in a cooling period. In continental climate, Trombe wall and concrete water wall have close results and better than the other alternatives.

The proposals have been made above according to the simulation results but it should be left to the occupant to pick the alternative as the inner comfort conditions differ according to each person.

In this study, the invented version of water wall system has been analyzed and compared with different system alternatives. The vented water wall system for heating and cooling periods will be analyzed as a future study.

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YAŞAR UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MASTER THESIS

AN APPROACH FOR COMPARING THE ENERGY EFFECT OF WATERWALL SYSTEMS IN AN OFFICE SPACE; CASE STUDIES IN ISTANBUL, AND STOCKHOLM

Pakinam El-Shinnawy

THESIS ADVISOR: ASSOC. PROF. DR. BAŞAK KUNDAKCI KOYUNBABA

COMPUTATIONAL DESIGN PROGRAM

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We certify that, as the jury, we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Natural Science.

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ABSTRACT

AN APPROACH FOR THE EFFECT OF WATERWALL SYSTEMS ON ENERGY EFFICIENCY IN BUILDINGS: ISTANBUL, AND STOCKHOLM REGION SAMPLES

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MSc, Computational Design
Advisor: Assoc. Prof. Dr. Başak Kundakçı Koyunbaba
April 2018

With the energy demand increasing worldwide, which is fueled by the increase in population, and the fact that fossil fuels are running out as well as the increase in CO^2 emissions made countries and facilities seeking to reduce energy consumption in the building sector. Passive architecture comes into play, as it's sympathetic to climate conditions, as it reduces energy consumption levels while providing indoors thermal comfort levels in terms of heating and cooling in addition to the reduction of the building's energy consumption which leads to cost reduction, as well as the reduction of HVAC systems usage.

This thesis is aimed to analyze and compare between different solar energy gain systems in a space using parametric modeling techniques supported by optimization methods and simulation techniques. The study is about simulating the behavior of a south-facing thermal storage wall which is Water Wall System in different building material configurations, as an indirect solar energy gain system, along with another type of thermal storage walls which is Trombe Wall and a direct solar gain system provided by the Single glazed wall. The objective considered in this study includes surface temperature, indoor temperature, and energy consumption. An application was presented using a base model assumed to be located Istanbul, and Stockholm to study the difference in behavior in two different climatic zones.

This thesis consists of 7 chapters namely introduction, passive solar energy gain systems in the building- literature review, passive solar energy gain systems in building-technical aspect, simulation tools used for assessing passive energy systems performance, generating models for passive solar energy systems, results and discussions, and conclusion.

Key Words: water wall system, Trombe wall, direct solar system, indirect solar system, passive solar systems, thermal performance, comfort zone, office building, energy simulation.

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Pakinam El-Shinnawy
İzmir, 2018

TEXT OF OATH

I declare and honestly confirm that my study, titled “An Approach for the effect of water wall systems on energy efficiency in buildings: Istanbul, Stockholm, Ankara, and Moscow Region Samples” and presented as a Master’s Thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions, that all sources from which I have benefited are listed in the bibliography, and that I have benefited from these sources by means of making references.

Pakinam El-Shinnawy

Izmir, 2017

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SYMBOLS AND ABBREVIATIONS

SYMBOLS

ʎ	Thermal Conductivity *($W.K^{-1}$), or (kA/L), or ($W/(m^2.K)$)*
ρ	Density *(kg/m^3)*
A	Area (m^2)
k	Thermal Conductivity (*kJ/m/s/ºC*)
$(\Delta Q/\Delta t)$	Heat Conduction rate in (*kJ/s*)
L	Thickness of the Layer (*m*)

ABBREVIATIONS

HVAC	Heating, Ventilation and Air-Conditioning
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CFD	Computer Fluid Dynamics
TES	Thermal Energy Storage
TSW	Thermal Storage Wall
PSH	Passive Solar House
PV	Photovoltaic
PCM	Phase Change Materials
VT	Visible Transmittance
SH	Specific Heat (*J/kg-K)*
SHGC	Solar Heat Gain Coefficient
WW	Water Wall
Trnsp	Transparent
Trnsl	Translucent

CHAPTER 1
INTRODUCTION

Energy has been dominating issues for the 21st century, as well as for climate change; hence it is prioritized to work on reducing the carbon dioxide footprint as it is the driving force behind climate change. In Europe, it's estimated that 40% of the total energy consumption is by public and commercial buildings. Energy efficient renovation of the existing buildings is needed to improve such state (Katafygiotou & Serghides, 2014). Nowadays, Residential and public buildings are responsible for the consumption of one-quarter of the total worldwide energy production, with an expected increase on annual bases from the year 2010 to the year 2040 by approximately 1.6%.

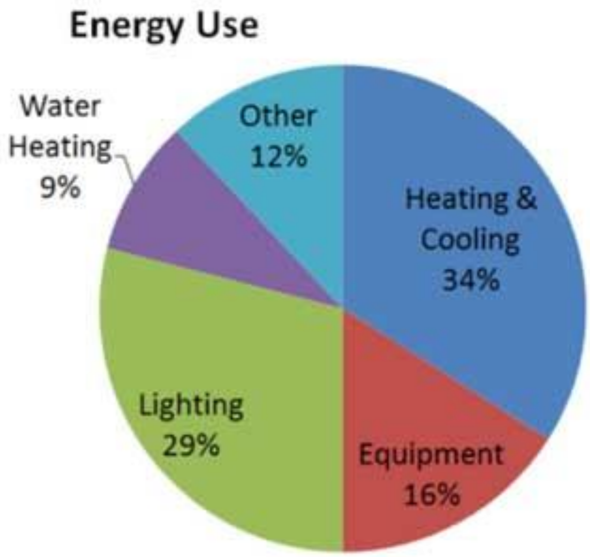

Figure 1.1 Office Building Electricity Chart **(Todd, 2011)**

Moreover, some countries lack the fossil fuels, which makes it a pressing matter for scientists to come up with alternative methods for energy production. Development in energy efficient building applications has rapidly increased and progressed in an attempt to reduce energy consumption in the building sector (Casamayor & Su, 2013). Heating, ventilation, and air-conditioning (HVAC) systems, accounts for half of the building's energy consumption levels (Pérez-Lombard, Ortiz, & Pout, 2008). Moreover HVAC systems require electricity, or fossil fuel, to provide the needed indoor environmental comfort level, subsequently, saving energy from HVAC systems in buildings becomes crucial for the combat against the ongoing energy crisis and climate change.

Renewable energy could have a great impact in cold climatic regions, in terms of passive and thermal solar energy. The passive solar energy system is a building subsystem that works on solar energy, through collecting and transferring that energy by natural means; convection, conduction, or radiation to distribute thermal energy throughout the structure, to establish the necessary level for indoor environmental comfort. This, in turn, makes passive solar energy system one of the most feasible methods in terms of accessibility, economic aspect, reducing carbon footprint. On the solar energy is only available in the daytime and savoring it for night time usage that’s when thermal masses come into place. By definition, buildings in cold climates are designed to address the cold, through the material, insulation, orientation, and space design. According to (Balcomb J. D., 1992)), the thermal load of mechanical of HVAC systems in buildings is reduced significantly when passive solar building technology is used. Thermal storage wall is a passive solar technique that replaces standard walls, with a composed of a different material arrangement of glazing and materials of high thermal storage capacity. There have been studies conducted to address solar heating in cold climate, such as (Wang, Manzanares-Bennett, Tucker, Roaf, & Heath, 2012), where it was noted that the change of material used has an impact on TSW.

The office buildings energy consumption levels have been increasing as a result of technological development and usage of mechanical heating and cooling systems (HVAC) systems. This building sector has been on the course to design and advance in the performance-based building concept, assessing and providing tenants thermal comfort levels suited to increase productivity levels, as well as reducing the energy consumption of the building to reduce the usage of mechanical heating and cooling systems (HVAC) systems resulting in cost saving. To do so architects and developers started presenting a variety of passive architectural proposals. In (Skanska, Cushman & Wakefield, GO4 Energy, 2018) a behavioral study was conducted on tenants that are employed in both, an energy certified building and a non-certified building, the result was that employees working in an energy certified building consumed less electricity than those present in a non-certified building.

On the other hand, energy simulation tools come into play in building technology and its quest for achieving sustainable designs. They are implemented to simulate and analyze building energy performance and thermal behavior to reach the tenant’s comfort zone as well as reduce future energy consumption cost. Using energy simulation tools provides architects, engineers, and researchers with the means to reduce the cost of on field experimentation, with much more reliable data, data management, user-friendly interfaces and ability to integrate other subdivisions in the process. Over the cross of the last 60 years, or so simulation tools and computer-aided software have come a long way, in terms of covering climatic analysis, building thermal behavior, daylight simulation, energy consumption, and building optimization.

1.1. The Subject of the Thesis

The subject of this thesis is assessing the thermal performance of different water wall configurations to compare them to other kinds of thermal storage wall as well as non-passive energy building element, by using parametric modeling technology in terms of user support tools, simulation techniques, and data analysis. Different water wall configurations have been determined to be compared, along with other wall configurations, the location has been determined based on climatic conditions.

This thesis also provided a research review concerning the use and performance of different thermal energy storage wall as well as different types of passive solar energy gain building systems, with an extensive study on water wall systems. The study emphasizes the performance of water wall systems in cold climatic regions and their thermal performance across time since it was first used.

1.2. Aims and Problem Definition

The aim of this thesis is to analyze the performance of different water wall configurations in different climatic regions while studying the predictor application in the literature review.

The problem is to find the water wall configuration that provides the best performance in cold climate both in winter and in summer, as well as studying its performance in a different climatic though to see the proper region for its application by using simulation technologies.

Wall configuration selection was based on the studies; the main aim of the thesis is to choose the water wall configuration that reached the highest thermal performance level by comparing between different configurations and other wall structures.

1.3. The context of the Thesis

This thesis focuses on different water wall configurations integrated into a building, to analysis their thermal performance for a case study which is schematic space designed. Starts with, review on the work studies conducted on water walls in building and the reasons for using them, with a brief historical insight as well as covering its presence across time based on application, climatic region, and performance.

An investigative study on different types of passive solar energy systems in buildings such as; Water Wall, Trombe wall, Double Façade and BIPV walls, as well as they, 're discussing the working principles.

Followed by, explanations of the simulation approach in terms of modeling, simulation tools, and physical properties of selected materials.

1.4. Method of the Thesis

This thesis is based on assessing the energy performance of different configurations of Water Wall system which are; Transparent Plexiglas Water Wall, Gazbeton Water Wall, Concrete Water wall, that in comparison to other passive and non-passive wall configurations such as; Trombe wall, and Single Glazing. This has been done through developing a computational design model for space and assessing the performance across a year. Two weather conditions have been chosen to evaluate the performance of those wall configurations which are Stockholm as a cold climatic region and Istanbul as a Hot and Dry Climatic region.

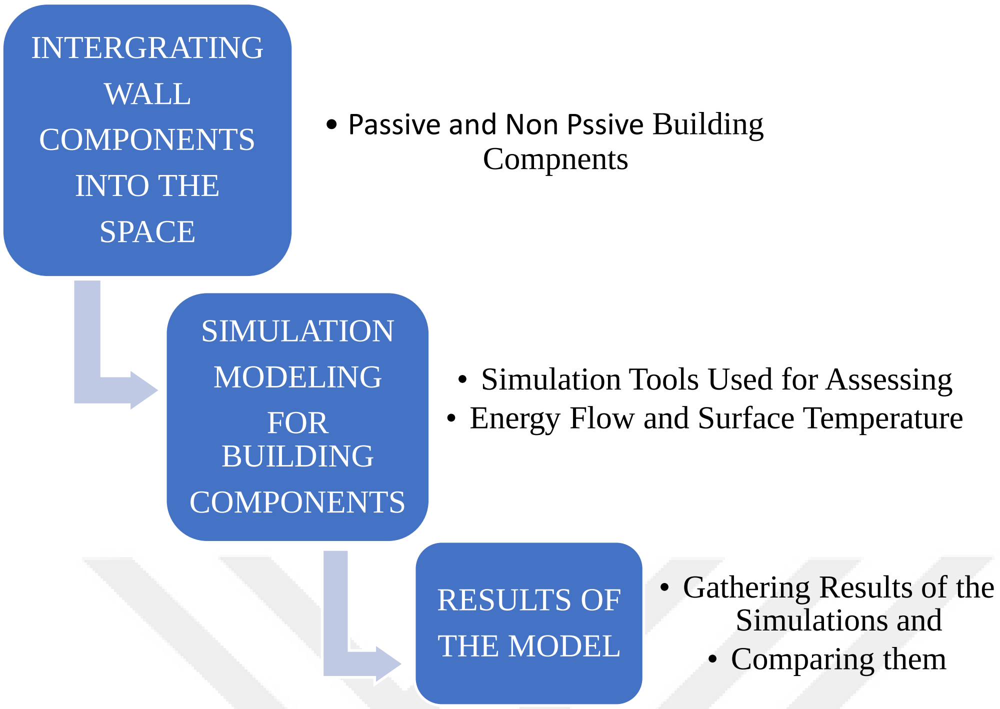

Figure 1.2 Schematic Illustration of Research Methodology

<u>Integrating Wall Components into space:</u> At this Stage different types of passive and non-passive energy wall configurations are integrated into the conceptual designed space. Those components have been researched and defined in terms of their physical priorities in order to evaluate the performance of each one based on their Thermal performance.

<u>Simulation Modelling for Building Components</u>: At this stage, simulation tools are used to assess thermal performance for building components.

<u>Results of the Model:</u> This is the final stage where simulation results for building components are gathered and then analyzed thorough comparative graphs.

CHAPTER 2

PASSIVE SOLAR ENERGY SYSTEMS - LITERATURE REVIEW

In this chapter different types of passive solar energy gain systems in buildings have been presented after dissecting relevant predecessors work. Passive solar energy systems utilize building components to gain control over solar heat generation that comes in contact with exterior walls, roofs and floors, by doing so designers can use them for heating and cooling purposes, and in some cases as a source of electrical generation, which result in reducing the use of mechanical HVAC in building along with the reduction of energy consumption.

The following tables have been used to dissect the source in terms of providing a sum-up for each source. The systems that have been presented in this review are as followed; Water Wall System, Trombe Wall, Building Integrated Photovoltaic (BIPV) System, Passive Cooling Wall, Solar Wall Heating (SWH), Solar Chimney, Solar Space heating system.

Table 2.1 Water Wall Systems

Year	Source Title	Author(s)	Location	Climatic Zone	Building Type	Simulation Type	Simulation Tool	System Description	Reason for application	Study Type
2017	A Case Study on the Use of Harvested Rainwater to Operate Passive Cooling Water Wall (PCWW) for SEGi University Tower	Vinod Kumar Venkiteswaran, Wong Dee Lern, Surenthira Stephen Ramachanderan	Kuala Lumpur, Malaysia	Tropical	Educational Building	Thermal Building Calculations	-ANSYS FLUENT -Steady State	Water Wall	Space Cooling	Simulation
2005	A water wall Solar Design Manual	David A. Bainbridge	Massachusetts	Humid Continental	Educational Building	-Thermal Building Calculations	No simulation Program is mentioned	Water Wall	Space Heating	-Numerical Simulation
1981	Thermal load leveling of heat flux through an insulated thermal storage water wall	M. S. Sodha, S. C. Bhardwaj, S. C. Kaushik	New Delhi, India	Humid subtropical, Semi-arid	Test Room	-Surface Temperature -Indoor Temperature	Heat Conduction Equation	Opaque Water Wall	Impact of insulation thickness on the surface temperature inside and outside	-Numerical Simulation
1989	Thermal comfort in buildings through a mixed water-mass thermal storage wall	S. C. Kaushik, S. Kaul	New Delhi, India	Humid subtropical, Semi-arid	Test Room	-Surface Temperature -Indoor Temperature	Heat Conduction Equation	compared between a concrete enclosed water wall mixed with thermal storage wall configuration, a pure concrete water wall configuration, and Trombe wall	-Impact of heat transfer through walls and roof -Comparison	-Numerical Simulation

Table 2.1 (Cont'd). Water Wall Systems

Year	Source Title	Author(s)	Location	Climatic Zone	Building Type	Simulation Type	Simulation Tool	System Description	Reason for application	Study Type
2013	Investigation on the influencing factors of energy consumption and thermal comfort for a passive solar house with water thermal storage wall	Weiliang Wang, Zhe Tian, Yan Ding	Tianjin, North China	Temperate	Passive Solar House	-Indoor Temperature -Energy Consumption	TRNSYS	Water Thermal Storage Wall	-Reduce energy consumption -Space Heating	Simulation
2012	Investigation of a Passive Solar House Equipped with Water Thermal Storage Wall	Wei Liang Wang, Zhe Tian, Xiao-Lei Niu, Xin Xu	Tianjin, North China	Temperate	Passive Solar House	-Indoor Temperature -Energy Consumption	Heat Conduction Equation	Water Thermal Storage Wall mixed with natural ventilation technology	-Reduce energy consumption -Space Heating -Space Cooling	-Numerical Simulation
2012	Integrating passive cooling and solar techniques into the existing building in South China	Lui, Wei Yi, Feng, Wei	Shenzhen, South China	Humid subtropical	Two Test Rooms in multi-purpose building	Indoor Temperature	- CFD -Ecotect -SolPass software	Transparent Water Wall Trombe Wall	Comparative Analysis	-Experimental -Simulation
1991	Relative Thermal Performance of South Walls in Winter	G. N. Tiwari, M. Upadhya, S. N. Rai	New Delhi, India	Humid subtropical, Semi-arid	Thermal Analysis	Indoor Temperature	Heat Conduction Equation	Water Wall Glass Wall Air Collector Wall Transwall	Comparative Analysis	-Numerical Simulation

Table 2.1 (Cont'd). Water Wall Systems

Year	Source Title	Author(s)	Location	Climatic Zone	Building Type	Simulation Type	Simulation Tool	System Description	Reason for application	Study Type
1983	Analysis of passive heating concepts	J.K. Nayak, N.K. Basal, M. S. Sodha	Colorado, USA	Cold winter and subtropical low desert	Test Room	-Average heat flux -Thermal load leveling	Heat Conduction Equation	Opaque Water Wall Trombe wall Solarium uncovered glazing Solarium covered glazing	performance analysis	Numerical Simulation
1986	Solar wall project: two demonstration houses with passive solar heating in Tasmania	R.G. Sutton, R.J. McGregor	Tasmania, Australia	Cool Temperate	Two Homes	-Thermal Comfort Level -Indoor Temperature	No simulation Program is mentioned	Opaque Water Walls	Space Heating	Experimental
2011	Solar chimney—A passive strategy for natural ventilation	Rakesh Khanal, Chengwang Lei	Not specified	Not specified	Any Building	Not specified	- Heat Conduction Equation -Computational Fluid Dynamics	Solar chimney integrated with Water Wall	Effects of geometry and inclination angle on the ventilation performance	-Numerical Simulation

Table 2.2 Trombe Wall System

Year	Source Title	Author(s)	Location	Climatic Zone	Building Type	Simulation Type	Simulation Tool	System Description	Reason for application	Study Type
2013	A numerical and experimental analysis of the air vent management and heat storage characteristics of a Trombe wall	Yanfeng Liu ⇑, Dengjia Wang, Chao Ma, Jiaping Liu	GangCha County, QingHai Province, China	Subpolar Climate	House	-Thermal Building Calculations -Design Optimisation -Air vent velocity - Air Vent Temperature -Indoor Air Temperature	Computational Fluid Dynamics	Trombe wall	Space Heating	Simulation
2015	An experimental investigation of a novel Trombe wall with Venetian blind structure	Zhongting Hu, Bingqing Luo, Wei He	Hefei, China	Sub-polar climate	Two Test Rooms	-Thermal Building Calculations	Equation	Trombe wall integrated with DC fan on the Venetian blind structure	Performance assessment	-Numerical Simulation
2016	An innovative Trombe wall as a passive heating system for a building in Athens – a comparison with the conventional Trombe wall and the insulated wall	Evangelos Bellos, Christos Tzivanidis, Eleni Zisopoulou, Georgios Mitsopoulos, Kimon A. Antonopoulos	Greece, Athens	Mediterranean	Isolated Room	-Thermal Building Calculations	-Solid works -Flow Simulation Module	-Trombe wall with a vent -Regular Trombe wall -Insulated wall	Space Heating	Experimental

Table 2.2 (Cont'd). Trombe Wall System

Year	Source Title	Author(s)	Location	Climatic Zone	Building Type	Simulation Type	Simulation Tool	System Description	Reason for application	Study Type
2007	Numerical study on the thermal behavior of classical or composite Trombe solar walls	Jibao Shen, Ste´phane Lassue, Laurent Zalewski, Dezhong Huang	Not specified	Not specified	Computer Model	-Thermal Building Calculations	-TRNSYS -FDM	-Trombe Wall -Composite Trombe Wall- Michel Wall	Thermal performance	Simulation
2011	Optimum design of Trombe wall system in Mediterranean region	Samar Jaber, Salman Ajib	Amman, Jordan	Mediterranean	Residential House (Dar)	-Thermal Building Calculations - Economical Equations	-TRNSYS -LCC Equation	Trombe Wall	Thermal, environment and economic impact	Simulation
2016	Analysis of Atrium Pattern, Trombe Wall and Solar Greenhouse on Energy Efficiency	Sama Modirrousta, Haleh Boostani	Not specified	Not specified	Any Building	Not specified	-No Simulation Program is mentioned	-Trombe wall -Greenhouse System -Atrium	Ventilation Heating Cooling Natural Lighting	-Descriptive -Theoretical
2016	Application of passive wall systems for improving the energy efficiency in buildings: A comprehensive review	Hossein Omrany a, Ali Ghaffarianhoseini, Amirhosein Ghaffarianhoseini, Kaamran Raahemifar d, John Tookey	Not specified	Not specified	Any Building	Not specified	-No Simulation Program is mentioned	-Trombe wall -Green Walls -Double Skin Walls -Autoclaved Aerated Concrete Walls	Space Heating	Theoretical

Table 2.3 Building Integrated Photovoltaic (BIPV) System

Year	Source Title	Author(s)	Location	Climatic Zone	Building Type	Simulation Type	Simulation Tool	System Description	Reason for application	Study Type
2003	Monitoring results of two examples of building integrated PV (BIPV) systems in the UK	S.A. Omer, R. Wilson, S.B. Riffat	Nottingham, UK	Temperate Maritime	-School of the Built Environment, University of Nottingham (Educational Building) - Residential House	Energy Analysis	- PVSYST Simulation -CAD modeling	Building integrated PV (BIPV)	Monitoring performance of PV roof slates and that of film PV façade	Experimental
2018	Assessing active and passive effects of façade building integrated photovoltaics/thermal systems: Dynamic modeling and simulation	Andreas K. Athienitisa, Giovanni Baroneb, Annamaria Buonomanoa, Adolfo Palombob	Prague Bolzano Freiburg Madrid Naples Athens Almeria	-Humid continental climate - warm and temperate - Mediterranean	Ten Floor Office building (High-rise building)	-Thermal Building Calculations Calculate Indoor Temperature - Thermo-economic results	DETECt 2.3	BIPV/T System	Passive heating Passive cooling Electrical production	Simulation
2013	An approach for energy modeling of a building integrated photovoltaic (BIPV) Trombe wall system	Basak Kundakci Koyunbaba, Zerrin Yilmaz, Koray Ulgen	Izmir, Turkey	Mediterranean	Test Room	Thermal Building Calculations	-Computational Fluid Dynamics (CFD) -Ansys CFX -Monte Carlo Model	Naturally Ventilated BIPV Trombe wall	Performance Analysis	-Experimental -Simulation

Table 2.3 (Cont'd). Building Integrated Photovoltaic (BIPV) System

Year	Source Title	Author(s)	Location	Climatic Zone	Building Type	Simulation Type	Simulation Tool	System Description	Reason for application	Study Type
2016	BIPV-temp: A demonstrative Building Integrated Photovoltaic installation	Anatoli Chatzipanagi, Francesco Frontini, Alessandro Virtuani	Lugano, Switzerland	Humid Subtropical	Mock-up Structure at SUPSI	- Normal Operating Cell Temperature -ECT	- Standard Test Condition (STC) - NOCT Model	BIPV installed in different inclinations 30° and 90°	Calculating the impact of the operating cell temperature on performance	-Experimental -Simulation
2016	Building integrated solar thermal design: assessment of performances of a low-cost solar wall in a typical Italian building	Marco Beccali, Giuliana Leone, Paola Caputo, Simone Ferrari	Milano, Italy	Humid Subtropical	House	Collector-wall system efficiency performance	-TRNSYS Model -FEM Model	building integration of solar thermal collector (BIST)	Heating generator	Simulation
2007	Modeling of a novel Trombe wall with PV cells	Ji Jie, Yi Hua, He Wei, Pei Gang, Lu Jianping, Jiang Bin	Hefei, China	Sub-polar climate	Test Room	-Thermal Building Calculations Calculate Indoor Temperature -Electrical Efficiency	FORTRAN	PV glass panel PV integrated Trombe wall	-Comparative analysis -Heat Distribution -Electrical Generation	Numerical Simulation

Table 2.4 Passive Cooling Wall System, Solar Space Heating System and Solar Wall Heating (SWH) System

Year	Source Title	Author(s)	Location	Climatic Zone	Building Type	Simulation Type	Simulation Tool	System Description	Reason for application	Study Type
2009	A 3D CAD-based simulation tool for prediction and evaluation of the thermal improvement effect of passive cooling walls in the developed urban locations	Jiang He, Akira Hoyano	Japan	Humid Subtropical	Experimental Space (Any Building Type)	-Thermal Building Calculations. - Mean Radiant Temperature.	3D CAD- Cased Simulation	Passive Cooling Wall (PCW)	Space Cooling	-Simulation -Theoretical
2012	A feasibility study on solar –wall systems for a domestic heating-An affordable solution for fuel poverty	Fan Wang, Alvaro Manzanares-Bennett, Jan Tucker, Susan Roaf, Nicholas Heath	Edinburgh, Scotland	Temperate Maritime	- Apartment in 4 story building - Single Storey Bungalow	-Thermal Building Calculations - Cost Analysis	-Unsteady state CFD model - PHOENICS (CHAM)	Solar Wall Heating (SWH)	-Space heating -Domestic hot water	Simulation
2014	Heating season performance improvements for a solar heat pipe system	Brian S. Robinson, M..Keith Sharp	Louisville, USA	Humid Subtropical	The two-room passive solar test facility	-Thermal Building Calculations -Building Heat Loss Coefficient	-Data Acquisition System -LabVIEW software	Heat pipe Solar Space Heating System Configuration	Testing Performance Levels	-Experimental -Simulation

2.1. Water Wall

According to (Bainbridge, 2005) the first water all was built at Massachusetts Institute of Technology in 1947 by Hoyt Hottel and his students. Their prototype was a full height water wall composed of one and five-gallon cans, painted black and set behind double pane glass, 38-48% of the heating demanded was provided by those walls. The problem that arose resulted from poor design, limited direct gain through the windows, inadequate curtains between water wall and the glass window, inadequate insulation, and the separation of the water mass from the room by curtains which reduced the performance level.

Water walls were brought back by Steve Baer in 1972 in a space-age design in New Mexico. In His design Corrales House, he used fifty-five gallons of water to provide thermal mass for an innovative passive solar design to 1.3- 1.5m in height in metal support frames. Single pane glass was used for the south walls, with reflective covers that are lowered on sunny winter days and closed at night. The system contributed by 85% of the total space heating required, although the insulation levels in the walls and ceilings were modest. Later on, Steve Baer applied water walls in both residential and commercial projects.

Based on (Steven Winter Associates, Inc., 1997), Tim Maloney worked on testing and developing a water wall module system back in 1974, which consisted of plastic bags supported between sheet metal panels. Later on, a group from the Kalwall Corporation started introducing fiberglass technology they developed translucent cylinders for water storage.

Water walls are considered an excellent short-term thermal energy storage system that works on maintaining the building's thermal comfort while reducing the heating and cooling loads. Water walls act as short-term thermal energy storage, its advantage is its availability, low cost, and the high heat capacity of water. Furthermore, water redistributes the stored heat through convection, thus providing a more rapid heat exchange than concrete or brick walls (Chan, Riffat, & Zhu, 2010).

Based on (Wu & Lei, 2016) literature review, water wall winter application is based on the wall absorbing solar radiation and storing it during the day to be released as heat at night by doing so it sets off the heating load of the building. As for the summer application, water wall works as a buffer zone preventing the living space from overheating during the day and thus makes the indoor environment more comfortable. Thermal comfort and energy consumption levels are maintained as a result of the water wall capability of moderating the temperature swing between the day and night.

In (Balcomb & McFarland, 1978) research a comparison was conducted based on the thermal performance of water walls with opaque building envelops against the performance of conventional walls; one with night-time insulation, against one without night-time insulation as well as one with reflectors against one without reflectors. The result was that the water wall had a higher monthly solar heating function in terms of the percentage of the space heating load provided by the passive solar system than that of the Trombe wall. While in (McFarland & Balcornb, 1979) study, an hourly computer simulation was conducted on the course of one year based on the solar radiation and temperature data to analyze for both Trombe walls and water walls in terms of the annual energy saving. Parameters used for the analyses were: number of glazing, wall absorbance, and emittance, night insulation R-value, thermal storage capacity, wall properties and vent area size. What was concluded is that the water wall performance levels improved by using night-insulation with a reduced R-value, in addition to the glassing number used, absorbance rate for the wall, and by increasing the wall's emissivity factor, and it's the thermal storage capacity.

While as in (Sodha, Bhardwaj, & Kaushik, 1981) research which was conducted to reach the optimum thickness distribution between inside and outside insulation layers of a water wall under the constraint of a given total thickness of the insulation layers. The results were that minimum temperature fluctuation was achieved through having an equal thickness between the inside and outside insulation layers, in addition, they realized the applying the entire insulation layer on the outside rather than the inside of the water wall reduced the temperature fluctuation.

(Kaul & Kaushik, 1989), compared between a concrete enclosed water wall mixed with thermal storage wall configuration and a pure concrete water wall configuration. They realized that using a water wall with insulated panels resulted in an informal low level of heat flux both during and after sun raise hours for winter days in New Delhi. Water walls integrated with insulation panels resulted in lower hourly heat flux than that of the concrete enclosed water wall mixed with thermal storage wall configuration. In the end, the favored combination was that a concrete enclosed water wall mixed with thermal storage wall configuration which resulted in a more stable and comfortable indoor temperature.

In (Nayak, Bansal, & Sodha, Analysis of passive heating concepts, 1983) comparison, they worked on investigating four different types of solar passive energy systems, which are: Trombe wall, water wall, a glazed uncovered solarium, and another solarium wall with a glazed covered by a movable insulation for non-lit hours of the day. The result showed that when night-time insulation was used, water walls had a more stable temperature and higher heating flux in compression to the Trombe wall.

In (Sutton & McGregor, 1986) Investigation, the application of water wall with an opaque building envelope in a comparison between two solar passive solar heating houses in Australia in terms of having a north facing the concrete wall to having a water wall system. The information gathered demonstrated that half of the annual heating energy consumption was saved in the house with the water –tube wall; unlike the conventional house with a concrete wall which. The house with the water consumed 70.8% of energy consumed by the concrete wall house. The application of water wall that is built out of 7.6cm diameter plastic tubes which is inserted into a conventional stud wall in a residential house was tested by (Turner, Liu, Harris, & Cengel, 1994). The system's thermal behavior was studied on the course of a 24hrs cycle that included 6 hrs. active charging with solar heated, and 18 hrs. of passive discharge. The conclusion was that the water wall maintained a temperature of 2.6°C higher than that of the indoor temperature 18 hrs. after discharging resulting in the reduction of the heating load for the house, correspondingly in summer time nocturnal water wall, thermal wall storage results in achieving daytime thermal comfort levels by discharging of the cool air ambient that has been charged through the night.

Several types of research have been conducted to demonstrate the advantages of water walls which exist in a semi-transparent building envelope. For instance, the work of (Fuchs & McClelland, 1979) on designing the most commonly used configuration of water wall with a semi-transparent envelop in a Transwall, in which a semi-transparent baffle was inside the water wall. They also held a comparison between the performance of the Transparent water wall against a Trombe wall and a direct gain system. The results were that the Transparent water wall system's solar performance surpasses the performance of the Trombe wall. In another study done by (Balcomb, 1977) on water wall thermal performance under five different configurations, which are; The water storage was placed inside the room with the same temperature as the room, the water storage was placed behind a glass panel, the water wall was placed behind an opaque wall and the water wall was placed behind a transparent insulation panel. The study indicated that the water wall placed behind a transparent insulated panel had the highest level of solar heat gain in winter when compared to the others.

In (Nayak, 1987) experiment, he worked on comparing between the thermal performance of a water wall with opaque building envelope and a Trans-wall based on the heat flux entering in a heated space. Transwells proved to be more effective than the concrete water wall in terms of meeting the daytime heating load, nonetheless concrete water wall has a better performance in reducing temperature variation, and in general the day and night performance. Using his work as a guideline, in (Nayak, 1987), a study he worked on comparing between different types of thermal storage walls; Trombe wall, Transwall, and water Trombe walls based on their thermal performance. Based on the end results Transwells have proven to be more efficient than Trombe walls in achieving the daylight heating load, on the other hand, the highest level of thermal performance was reached by the water Trombe wall in terms of fewer temperature fluctuations, and moderate phase shift hence proving to be the best option.

According to (Tiwari, Upadhya, & Rai, 1991) comparative study on the thermal performance of different types of south-facing walls, such as; glass wall, water wall, air collector wall and a Transwall. Different design parameters were taken into consideration such as the thickness of water wall and Transwall, the air flow rate in the air collector; those aspects were incorporated into the thermal analysis. Results were that the glass wall and the air collector had their highest performance levels during office hours, whereas the water wall and the Transwall were much more suitable for residential heating at night, depending on the thickness of the south-facing wall. Also, in (Tiwari, 1991) work, he performed a performance comparison between a water wall, a Transwall and an isothermal mass for heating in a non–air-conditioned passive solar house located in harsh climate cold conditions in Srinagar, India. The results were that the Transwall resulted in the much higher room temperature in the winter night, than the water wall and the isothermal mass.

One of the most recent works that have been carried out regarding passive heating strategies this is (Lui & Feng, 2012) comparison between a Trombe wall and a water-tube in terms of optimizing the indoor thermal performance and the energy consumption in buildings. The semi-transparent water tubes were built behind the east and west façade of the building to ensure that the room receives both light and heating from the water wall. Computer simulations using SolPass software to analyze the daily heat gain round the year during winter time. The data gathered stated that the water –tube wall obtained over 10 times the solar gain archived by the Trombe wall in winter. When comparing the data collected from their simulation, results were that passive solar systems have the ability to reduce the heating load of the building by approximately 25%, unlike its counterparty which didn't adopt those systems.

In (Tiwari, Yadav, & Lawrence, 1988) study, a number of different interactions between phase change component material and water wall to form a linked wall in a solarium to be sued in cold climate. The results were that the integration of PCM wall and water wall as a link wall had the highest thermal performance levels. Having equal water wall and PCM wall thickness caused low-temperature flux, as well as archiving thermal comfort in the living space.

PCMs in heating pipes were used as a passive solar heating system to absorb and transfer solar energy, according to (Rice, 1984)study, where he analyzed several types of passive heating and hybrid solar heating systems. The system proved to be a prosperous prospect for passive natural heating that is highly efficient as well as low in cost. (Susheela & Sharp, 2001) designed passive solar heating pipe system design for a south facing water wall façade. The end results stated showed that heat pipe and water wall integrated system provided 52% to 107% more solar thermal energy than that of a concrete wall. In (Albanese, Robinson, Brehob, & Sharp, 2012) investigation an experiment conducted to evaluate the use of pipes as passive solar space heating system, through transferring heat to a tank filled with water located inside the building. By using a computer-aided software to generate a model to test the pipe system, the gathered data indicated that:

- Solar heat loses on cloudy days and at night can be reduced by heat pipes.
- The capability of stabilizing the indoor temperature in comparison to conventional systems.
- Efficacy archived was as high as 85%.

In both (Wang, Tian, & Ding, 2013), and (Wang W. L., Tian, Niu, & Xu, 2012) studied the performance of natural ventilation by using solar chimney integrated with a water wall, built in a passive solar house in Northern China. The water wall was retrofitted into the house. Hourly indoor temperature and heating and cooling loads were simulated using TRNSYS software. The results showed that active cooling was not needed in summer, as the temperature indoors was 35°C while it was 47°C outdoors. While as for winter, the measured indoor temperature was 13.7°C, opposite to -0.4°C measured outside. Thereby, proving the efficiency in terms of heating and cooling of combining a water wall with the natural ventilation system.

In (Venkiteswaran, Lern, & Ramachanderan, 2017) investigative study in SEGi University Tower in terms of applying passive cooling water wall (PCWW) to the building's glass façade in an attempt to cool it. Two classrooms with the same area were chosen to conduct this study through a comparison in terms of energy saving upon using passive cooling water wall system and without using one. The water wall was applied in a way to maintain the glass façade which is the main building element as well as allowing the sunlight light the space by using 20mm thick glass panels as a compartment for the stored water that functions as a transparent water wall envelope. The water is supplied by a tank that harvests rainwater. The experiment was conducted at different indoor temperatures which are set by mechanical HVAC system. The results showed that in the presence of passive cooling water wall system the cooling load was equal to the heat gained, the experiment isn't valid as the conditions applied for the case study were fixed as a result of using steady-state simulation program which would result in inaccurate results proving that the water wall system isn't applicable in hot weather conditions.

2.2. Trombe Wall

(Liu, Wang, Ma, & Liu, 2013) Studied the performance of south facing Trombe wall with a window located in-house in GangCha Country in China, in terms of managing the vent's airflow through optimum opening and closing modes by using CFD simulation tool to analysis the heat investigation identified that the best possible time to open the air vents of the Trombe wall system is 2-3 hours after sunrise and to close it an hour before sunset. While when it comes to the most suitable circumstance for air vent management mode, along with surface and an average temperature of the Trombe wall, the results were that the highest value is reached at 16:00, while the lowest values were recorded at 7-8 am. Based on this study a reference was presented for design optimization, along with how it operates. an investigative and a comparative study was conducted by (Bellos, Tzivanidis, Zisopoulou, Mitsopoulos, & Antonopoulos, 2016) on three south facing walls which are; Trombe wall with an opening, conventional Trombe wall, and an insulated wall, accordingly finding which one has the highest performance levels through November until April. This experiment has taken place on computer models of buildings that were designed in Solidworks and simulated using Flow simulation module, to monitor the thermal performance of each of the three buildings. The study showed that the Trombe wall that has an opening, has a higher performance along the 6-month period in terms of increasing the indoor temperatures from noon until night by about 0.5k, that was followed by the conventional Trombe wall since solar energy has been employed to a greater extent, with the insulated wall giving a less than satisfactory performance. What has been deducted is that the Trombe wall with the opening configuration not only have the highest performance levels in terms of heating but also has the benefits of allowing sunlight to penetrate and lit the space as well as adding an element that provides natural ventilation.

In (Modirrousta & Boostani, 2016) analytical research, the focus was on presenting a different way to utilize solar energy in buildings mostly through Trombe wall, atriums, and greenhouse systems. In doing so an elaborate descriptive analysis was presented to give an intricate knowledge in terms of design and benefits that would be gained from each method. In the end, the studied methods presented their abilities to utilize and optimize solar energy, heating, cooling, ventilation and at times lighting in buildings, which system to be used is something that comes down to the designer's choice in the preliminary design stage of the project, based on different efficiency factors. In another comparative research, (Omrany, Ghaffarianhoseini, Ghaffarianhoseini, Raahemifar, & Tookey, 2016) worked on presenting different passive heating methods in as well as their ability to optimize energy in buildings, the methods that have been addressed are; Trombe Walls, Autoclaved Aerated Concrete Walls, Double Skin Walls, and Green Walls. By presenting the study results the designer can deduce which method would suit his needs, in terms of the Trombe wall it has been established that it plays an important role in reducing building energy consumption, as well as enhancing its performance by combining it with other methods. In terms of Autoclaved Aerated Concrete wall has the capability of not only providing satisfying energy performance but also improving acoustic properties, as for Double skin walls it presents a mean for energy consumption reduction with additional factors of integrating ventilations through a glazing system as well as adding PV systems. Last but not least, green wall system influences the building on the outside as well on the inside, in terms of functioning as an insulator by reducing the impact of solar radiation in return reducing building energy, while having a positive psychological impact on the building users, along with increasing property value and working as an acoustic buffer from the surrounding environment.

(Jaber & Ajib, 2011) Conducted an investigative analyzing that covers different aspects when it comes Trombe Wall performance, in terms of thermal, environmental impact and economic benefits, by focusing on residential building in Mediterranean region, in this case, a typical Jordanian home which is referred to as Dar that's located in Amman. TRNSYS program was used to generate an hourly energy computer simulation after that an LCC was used for calculating the economic aspect of this instigation. They concluded that a Trombe wall has the benefit of reducing the annual energy consumption of the building, with the assistance of using insulated curtains between glass and masonry as well as using roller shutters for an optimized performance to reduce solar radiation infiltration. In terms of the environmental annual impact, the Trombe wall reduced CO_2 levels by 445 kg.

2.3. Building Integrated Photovoltaic (BIPV) System

(Biyik, et al., 2017) Provided an investigative review of integrated photovoltaic (BIPV) and integrated photovoltaic thermal (BIPVT) systems which was based on their efficiency, type, performance, energy generation level, and nominal power. This stud resulted in a number of conclusions such as; the applicability of BIPV system with efficiency performance in both façade and rooftops, the important role shadowing, ambient temperature, building orientation as well as the PV cell slop play in acquiring a higher performance levels, computational analysis especially TRNSYS and EnergyPlus software, became a main pillar in recent studies as it is cost efficient as well as its capability of measuring performance level, power generation , shading factors, and electricity consumption. Grid integration has a significant effect when it comes to power output in terms of integrating building integrated photovoltaic system with other renewable energy sources; the key factor is to reduce the electricity lost on transformers, long lines, and electronic components by tweaking the distribution system configuration.

According to (Barkaszi & Dunlop, 2001) there are two categorizations in regards to buildings that have photovoltaic systems, in terms of it being building attached (BAPV) or building integrated (BIPV) system, those two differ in terms of application cost, labor and performance levels. The public view and their acceptance of photovoltaic technology aesthetic features play an important role in determining the PV array installations on a building, on the contrary to common belief that it would be affected by functionality, performance levels, and its lifetime value.

(Omer, Wilson, & Riffat, 2003) Worked on observing the performance of building integrated photovoltaic system in two different settings where a thin film PV façade was applied to the School of Built Environment in the University of Nottingham in the UK, and the other one is a crystalline photovoltaic roof slate which was fixated on the roof of a detached house. The experiment lasted for two years by integrating different methods which included energy analysis using PVSYST simulation and CAD modeling, in an effort to monitor and document the performance of photovoltaic systems in those two different applications; educational building and domestic house. Results showed that in both cases the shading even if it is only partial managed to diminish PV cells performance levels, in case of the educational building the reason for it was the surrounding buildings and trees, while in the case of the domestic house it resulted from the surrounding trees. That interfered along with other contributing factors; in the case of university building it was because of the poor PV system orientation array, inverter, and monitoring system outage, on the other hand, the domestic house PV roof slates had a manufacturing problem resulted in elevating the cell temperature. An experimental study has been conducted by (Koyunbaba, Yilmaz, & Ulgen, 2013) on a BIPV Trombe wall located on the south façade of a room that is located in Izmir, Turkey. Computational fluid dynamics (CFD) was used to generate and simulate a two-dimensional model, along with a test room model where the BIPV Trombe wall was applied to study the room's temperature and velocity distribution for February 4-7th, 2008. The resulted showed the ability of Computational fluid dynamics in calculating radiation, conduction, and natural convection for the BIPV Trombe wall system, the experiment showed that the wall worked on storing solar heat during daytime, to be released in later in the night time. In the case of (Athienitis, Barone, Buonomano, & Palombo, 2018), the aim was to use a dynamic simulation method which is DETECt 2.3 to analysis an air open-loop photovoltaic thermal system placed on the south façade of ten stories building and it's the effect electrical production and heating/ cooling demands. This investigation has been carried out in the form of a comparative and parametric analysis on high-rise office building located in different European cities in different climatic zones; Prague, Bolzano, Freiburg, Madrid, Naples, Athens, Almeria. Simulation results showed that the system provided passive and active effects contributing to building energy consumption reduction reaching a nearly or net positive zero energy building, as well as zero carbon emissions. In another aspect of this investigation, a calculative study has been conducted to find out the number of openings along the system in doing so heating and cooling demands got reduced as well as an increase in the photovoltaic electrical production by approximately 1%, and a reduction in the electrical supply needed by 2.5%.

In another case an experiment was conducted on Five Building with Integrated Photovoltaic modules implemented in different methods, as (Chatzipanagi, Frontini, & Virtuani, 2016) used a mock-up structure at the University of Applied Sciences and Arts of Southern Switzerland (SUPSI) by integrating as ventilated double glazed units with inclinations that vary between 30° and 90°, as well as a variation in their technology using double junction amorphous silicon and crystalline silicon. This investigation was conducted on south oriented Integrated Photovoltaic modules that were applied on two parts one is the form of a ventilated façade and roof which were fixated vertically and with 30° of inclination, while the other was the low energy house. The modules used in this experiment were customized to semi-transparent glass modules. The results showed that 90° inclined modules presented the lowest operating temperature, on the other hand, 30° inclined crystalline and amorphous silicon configuration modules presented the highest operating temperature. When comparing the data obtained for the average daily temperature calculated using Nominal Operating Temperature (NOCT) and Equivalent Cell Temperature (ECT), the difference was less than 5-6 °C.

In comparative performance analysis done by (Jie, et al., 2007) in testing Photovoltaic Trombe wall integration against a prototype for a two-dimensional PV glass panel in terms temperature distribution in the space and electrical generation and performance, in a test room in Hefei. FORTRAN numerical simulation which is written by Jie, Hua, Gang, Wei, Jianping, & Bin, was used to conduct this analysis, it calculates the thermal and electrical performance of the systems. This investigation proved that the PV glass panel works, Trombe wall integrated with PV panels proved that it has a higher thermal performance level that that of an average Trombe as well as adding an aesthetic aspect to the building design, another aspect when it comes to increasing the electrical efficiency of the photovoltaic panels adding an air duct behind it proved to increase it by 5%, and lastly the equation once integrated with the zone weather data and necessary factors has proven to credible in terms of calculating Trombe wall's temperature distribution which is necessary for improving the Trombe wall design and thermal performance levels.

2.4. Passive Cooling Wall

In (He & Hoyano, 2009) paper, presents their elaborated work on developing a 3D CAD-based simulation tool that would be implemented to predict and evaluate the thermal improvement that occurs when a passive cooling wall (PCW) system is constructed in a suggested urban location. PCW is developed by Jiang He and Akira Hoyano, where they constructed it out of moist void bricks with the ability to absorb water, which results in cooling its surface temperature as the air penetrate it, resulting in water evaporation. To validate the simulation tool, PCW was applied to the south façade of a space that was constructed in an urban location. The paper goal was to present a mean to simulate thermal performance of PCW, which was proven to be effective in such case as well as its capability in providing air temperature reduction effect as well as ventilation cooling effect.

2.5. Solar Wall Heating

Based on (Wang, Manzanares-Bennett, Tucker, Roaf, & Heath, 2012) experiment on a solar wall heating (SWH) system in two heavy thermal mass buildings (stone walls) in Edinburgh; one is an apartment in a four storey building and a one storey bungalow, in terms of performance levels, as the temperature was monitored for 24 hours cycle under different solar inputs, by using a model that has been created using unsteady state CFD. SWH works on storing solar heat that is absorbed during the daytime in the thermal mass walls and then releasing them with a time lag during the night time, a core component is this system is the heating panels that are attached to the wall which is composed of compressed row of thing pipes implanted in the interior walls which get supplied by water that is heated using solar collectors. PHOENICS (CHAM) was used to develop the CFD model of unsteady heat transfer that is used to simulate the performance of the heat exchange between the heating panel, the wall, and the adjacent rooms. The results showed that the interior walls of the apartment had an effective performance in storing heat and raising the temperature in the adjacent rooms, as well as validating the accuracy of the computer model in terms of measuring the fluctuation in the temperature transfer in the panel wall structure, presenting a base model for future studies in this field.

CHAPTER 3
PASSIVE SOLAR ENERGY SYSTEMS IN BUILDINGS – TECHNICAL ASPECT

(Sustainable Sources, 2018) defines passive solar systems as systems that use the solar energy for heating and cooling purposes. Passive solar design utilizes the building components, such as; walls, floors, roofs, windows and exterior building elements to control heat generation by direct solar gain, by putting natural characteristic of the materials in to play and their ability store heat, for example in the case of solar heating is designed to capture and collect thermal energy through large sun –facing windows and thermal mass, to be utilized for daylighting, as well as passive heating and cooling (Rahman, Rahman, & Jaman, 2010). Thermal masses are materials such as concrete, masonry, and water, that store solar energy, later on, emit them into space with a time lag which reduces temperature fluctuation proceed by the rapid change. Another advantage of passive systems is that it requires minim maintenance, cost reduction, no mechanical as well as the presence of a few moving parts. Although passive solar energy system for heating purposes is well developed and researched by still they are used for cooling purposes as well, which is the case when it comes to applying thermal chimneys which works based on the principle of thermodynamics; hot air rising and getting replaced by cooler air inducing air movement.

Working on façade improvement is crucial in terms of integration of solar energy in building optimization since there is a direct relation between façade design which is the building envelop that is widely exposed to the surrounding environment and is highly affected by the heat flux. When designing with thermal storage walls they are designed to be south-facing with glazing on the outside. The glazing is struck by the solar heat, which is absorbed into the wall which conducts the heat into the room over time. The thermal storage wall is at least 20cm in thickness, there is a direct relationship between increasing the wall thickness and reducing the indoor heat fluctuation (Sama, Prakash, & Naik, 2013). The working principle is that of a greenhouse in terms of allowing solar heat to infiltrate the building envelop through the glass which has them absorbed the thermal storage wall during sunlit hours to be emitted into the living space later on in the day with a time lag, which helps maintain a stage indoor temperature.

Guidelines for Passive Solar Energy Systems Application:

- When designing the building it should be elongated on the east-west axis.
- Applying passive solar energy systems on the south façade to have maximum sunlit hours' exposer.
- Locating the spaces that are frequently used that need better illumination and heating and cooling on the south facade to utilize the system efficiently, while locating the spaces that are less used on the north façade.
- Open floors maximize the utilization of the passive systems.
- Using shading in summer times prevents the interior from overheating

This study focuses on the application of passive solar energy systems for heating purposes, by presenting different systems and their working principles, examples of their application.

Passive Solar Heating System

There are there approaches when the purpose is to capture solar heat by building materials to be utilized for indoor heating by reaching the occupant's thermal comfort levels, those are; Direct Gain System, Indirect Gain System, and Isolated Gain System.

3.1. Direct Gain System

In this system, south facing glazing creates a direct gain system, that permits shortwave solar energy to penetrate the interior living space where it gets absorbed and stored via the thermal masses such as walls, and floors, to be released at night (Fig. 3.1, and 3.2). Solar energy that infiltrates the glass could reach up to 75% which is converted into thermal energy, while on the other hand glazing aka windows located in other orientation cause more heat loss than gain in the winter time. Glazing area should be moderated as impacts the building's thermal mass to reduce temperature fluctuation and overheating, moreover even distribution eliminates the localization of hot and cold spots. South facing glazing implicates having the walls and floor to be in a close proximity to store solar heat, typical glazing is 1.5m in height restricting a shallow heating effect, exceeding certain limits can result in overheating even in winter time hence shading elements would be needed or even resulting in cold effect in winter nights, and cloudy days. Another advantage of direct gain systems is the increase in daylight infiltration and visual continuity to building surroundings.

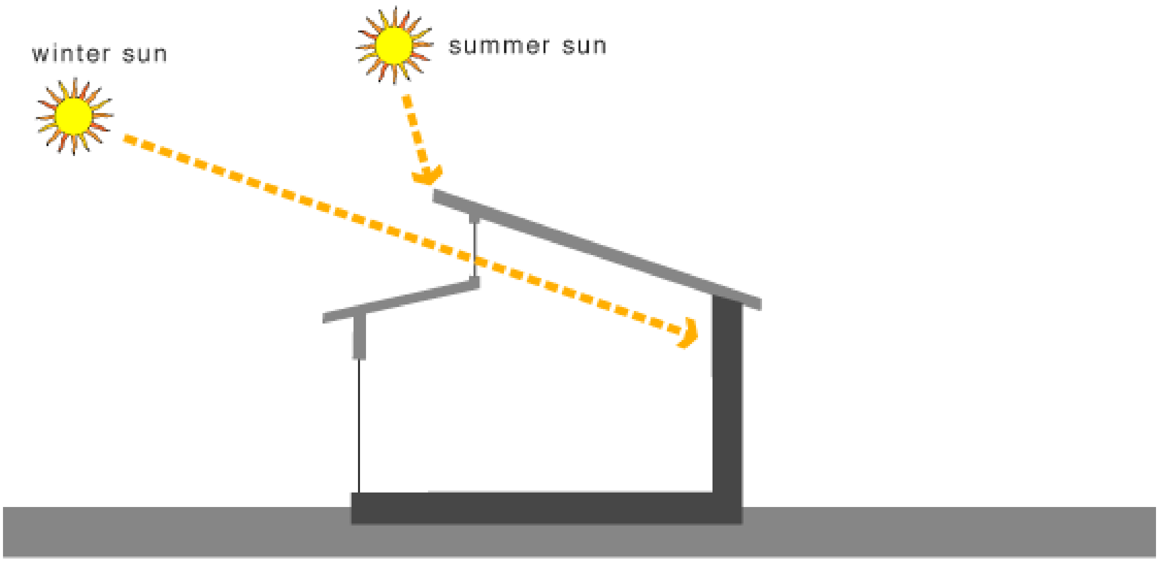

Figure 3.1 Direct Gain System in winter and summer period **(Greenspec, 2018)**

Figure 3.2 Direct Gain System in The Cross of One Day **(Greenspec, 2018)**

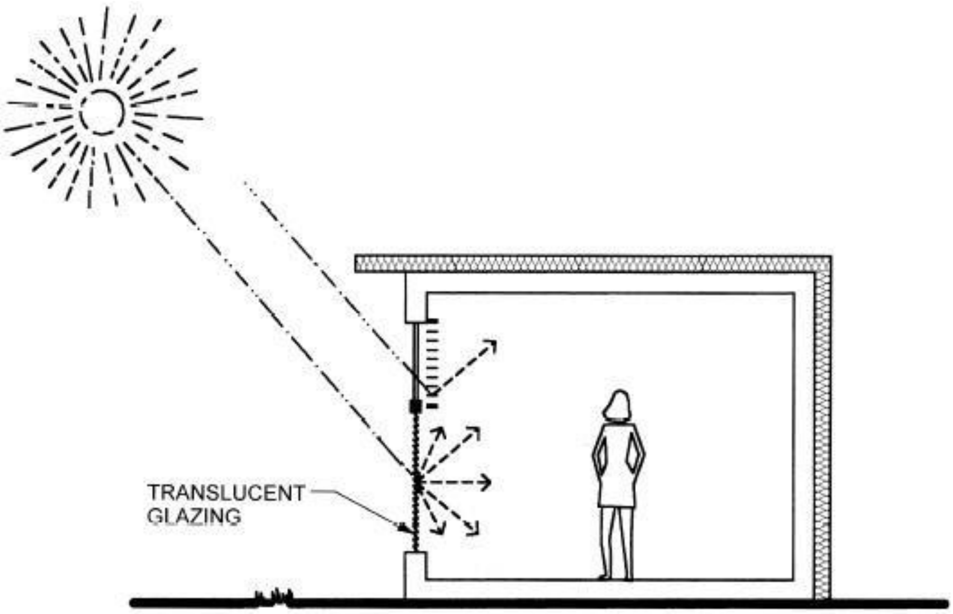

Figure 3.3 Diffused Radiation will Distribute the Heat more evenly in Open Space Interiors

Figure 3.4 Single-Family Residence in Lafayette **(energysage, 2018)**

3.2. Indirect Gain System

In this system, the thermal storage wall is located in the south façade located between a glass window and the living space. The solar energy penetrates the glass and strikes the thermal storage wall to be absorbed and later on conducted to the living space. Thermal storage walls can have an upper and lower vent to convict heat between the thermal wall and the glazing outside, at night those vents are closed allowing the heat to circulate into the living space. The distance between the glazing and the thermal wall should be at least 10cm, the wall ought to be in a dark color for maximum solar heat absorption. Thermal wall thickness varies according to the material, brick requires 25-35cm, concrete requires 30-45cm, while for water it requires 15cm. According to (ENERGY SAVER, 2018) in regards to the time it takes for the stored solar heat to travel through a masonry wall is 2.5cm per hour, which means that the heat that is stored in a 20cm thick concrete wall at mid-day, would be conducted to the living space at 8 in the afternoon. The most common form of this system is a Trombe Wall (Fig. 3.5).

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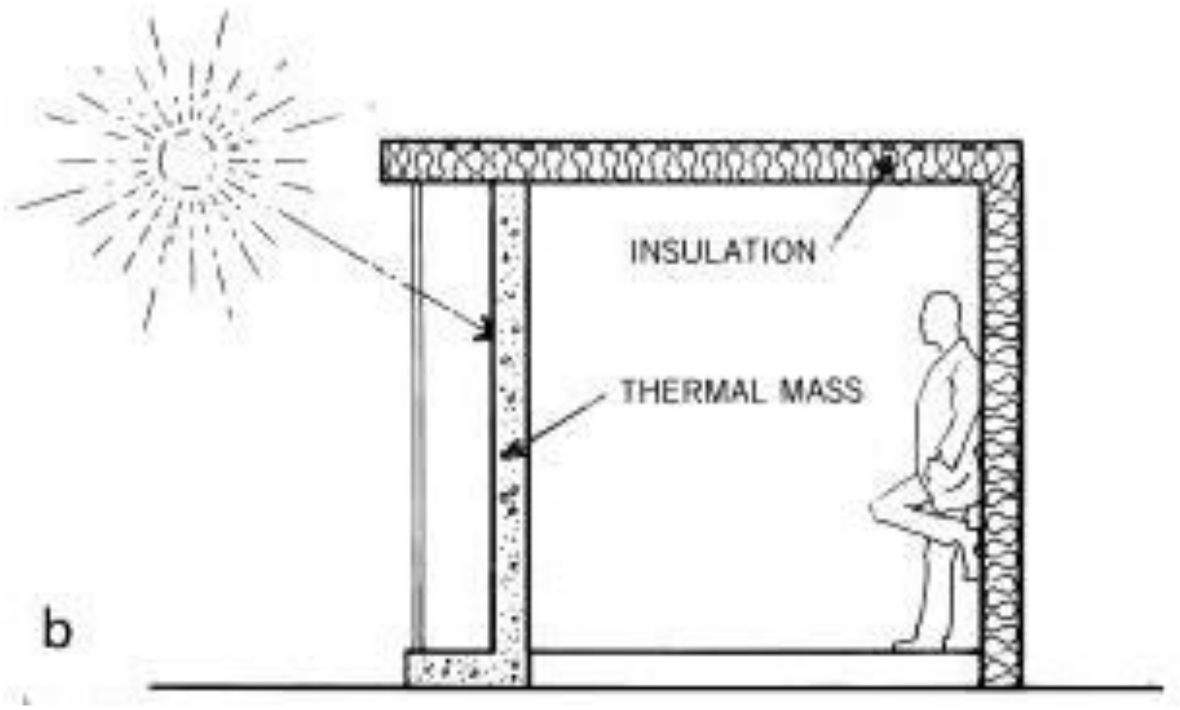


Figure 3.5 Indirect Gain System Section

3.2.1. Water Walls Systems

The water wall is a type of south-facing thermal storage walls, where water works as a medium that collects and stores solar heat through the sunlit hours, to be later on emitted into the interior living space. The working principle depends on the physical characteristics of water, on warming up space through conduction, and convection. In the case of The Bare Residency in Iceland, a reflective surface was placed outside of the south-facing glazed wall that is placed in front of the water wall to increase the performance of the wall (Fig. 3.6).

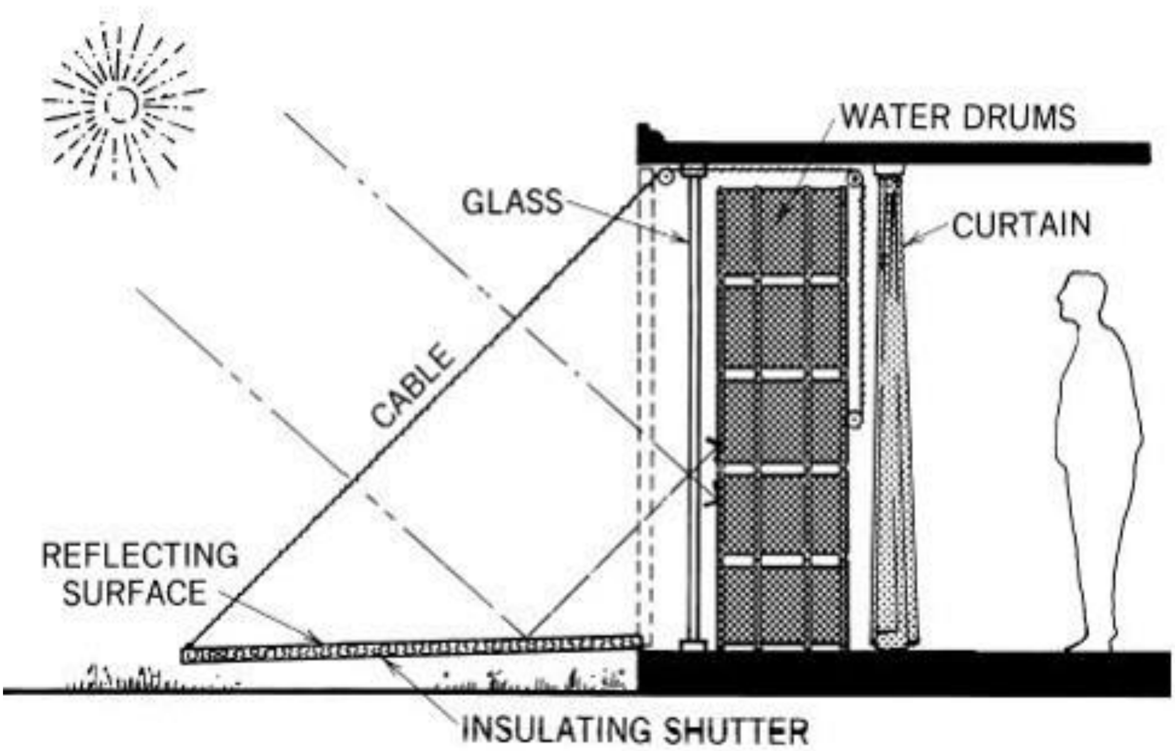


Figure 3.6 Section throw Water Wall System

Water Wall Variations

There are four types of water walls based on their configurations; opaque water wall system, transparent water wall system, translucent water wall system, water wall with phase change materials, and water wall combined with other passive technologies.

3.2.1.1. Opaque Water Wall System

This type is where the water wall is usually placed within an opaque building envelope; opaque PVC pipes, concrete, metallic plates, or insulation panels, that act as a separator between the ambient and the living spaces (see Figure 3.7).

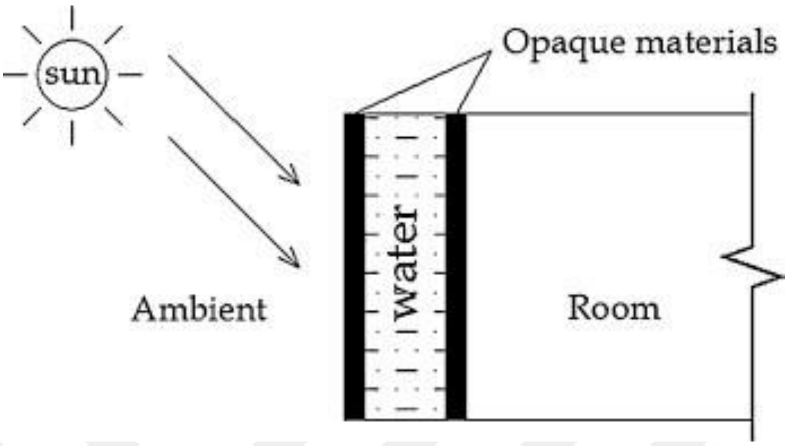


Figure 3.7 Opaque Water Wall system (Wu & Lei, 2016)

3.2.1.2.Transparent Water Wall System

Water wall system can also be fabricated in a structure that is transparent envelop, which permit's sunlight penetration inside the building, the envelope is usually made out of materials such as glass or plastic (Fig. 3.8)

Figure 3.8 Transparent/ Translucent Water Wall System

3.2.1.3. Translucent Water Wall System

Water wall system can also be fabricated in structure with a translucent outside façade that permit's sunlight penetration from outside to inside, using materials such as glass or plastic, as for the internal side of the water wall it can either be semi-transparent as well or opaque, and based on the choice of material sunlight can infiltrate the room (Fig. 3.9).

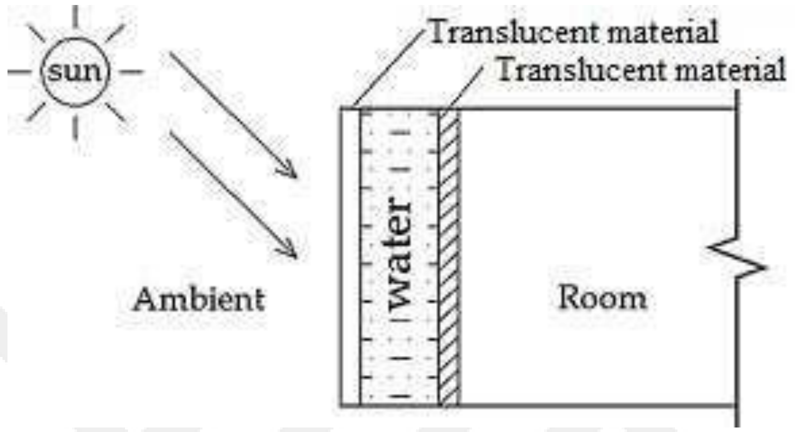


Figure 3.9 Translucent Water Wall System (Wu & Lei, 2016)

3.2.1.4. Water Wall with Phase Change Material

Water wall has the highest heat capacity among the other sensible heat storage systems, yet its heat capacity is relatively low in comparison to that of PCM heat storage system. On combining PCM and water wall greater results could be reached, by locating the PCM at the internal side, external side or even on both sides of the water wall (Fig. 3.10).

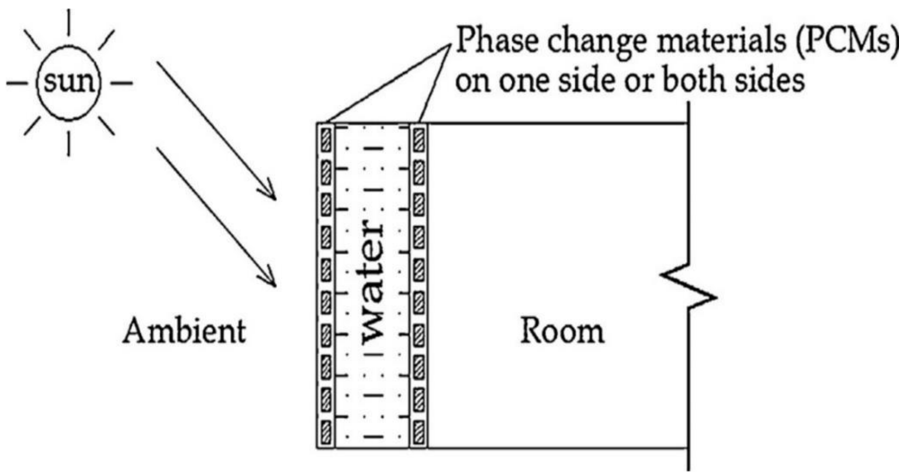


Figure 3.10 Water Wall System Integrated with Phase Changing Material **(Wu & Lei, 2016)**

3.2.1.4. Water Wall Incorporated with a Solar Chimney

According to (Lei & Khanal, 2011) review, the solar chimney was presented as a passive system for enhancing stack driven ventilation by buoyancy, to improve the night time ventilation water wall was incorporated into the solar chimney. Which makes it favored substitute to mechanical ventilation systems as a result of their operational cost, energy requirement, and carbon dioxide emission (Fig. 3.11).

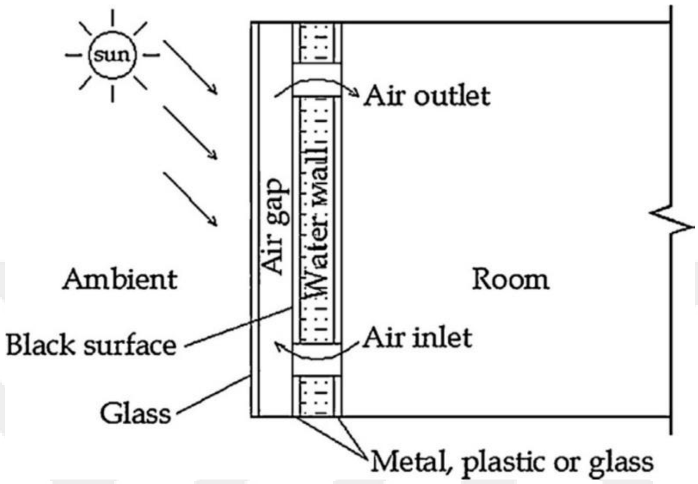


Figure 3.11 Water Wall incorporated with Solar Chimney **(Khanal & Lei, 2011)**

3.2.2. Trombe Wall System

In 1967, Felix Trombe and Jacques Michel constructed the first thermal storage wall in Odeillo, France, it was a 61cm concrete wall with vents (Hesson, 2017). That's when the first form of Trombe Walls was presented as a massive wall that is utilized in solar heat storage. It is a south-facing thermal storage wall that is glazed on the outside. The glazing is struck by UV light which is close to the electromagnetic spectrum penetrating it to be absorbed by the dark painted thermal mass wall (Fig. 3.12), which later on emits the heat into the indoor living space with a time lag (Fig. 3.13, and 3.14). The wall ought to be at least 20cm in thickness, there is a direct relation between wall thickness and the stabilization of the indoor temperature (Sama, Prakash, & Naik, 2013). The wall works on absorbing heat during sunlit hours then slowly releases the heat overnight, working based on a greenhouse principle, which can cause the interior living space to overheat in summer period hence a shading device applied to the glazing (Fig. 3.15).

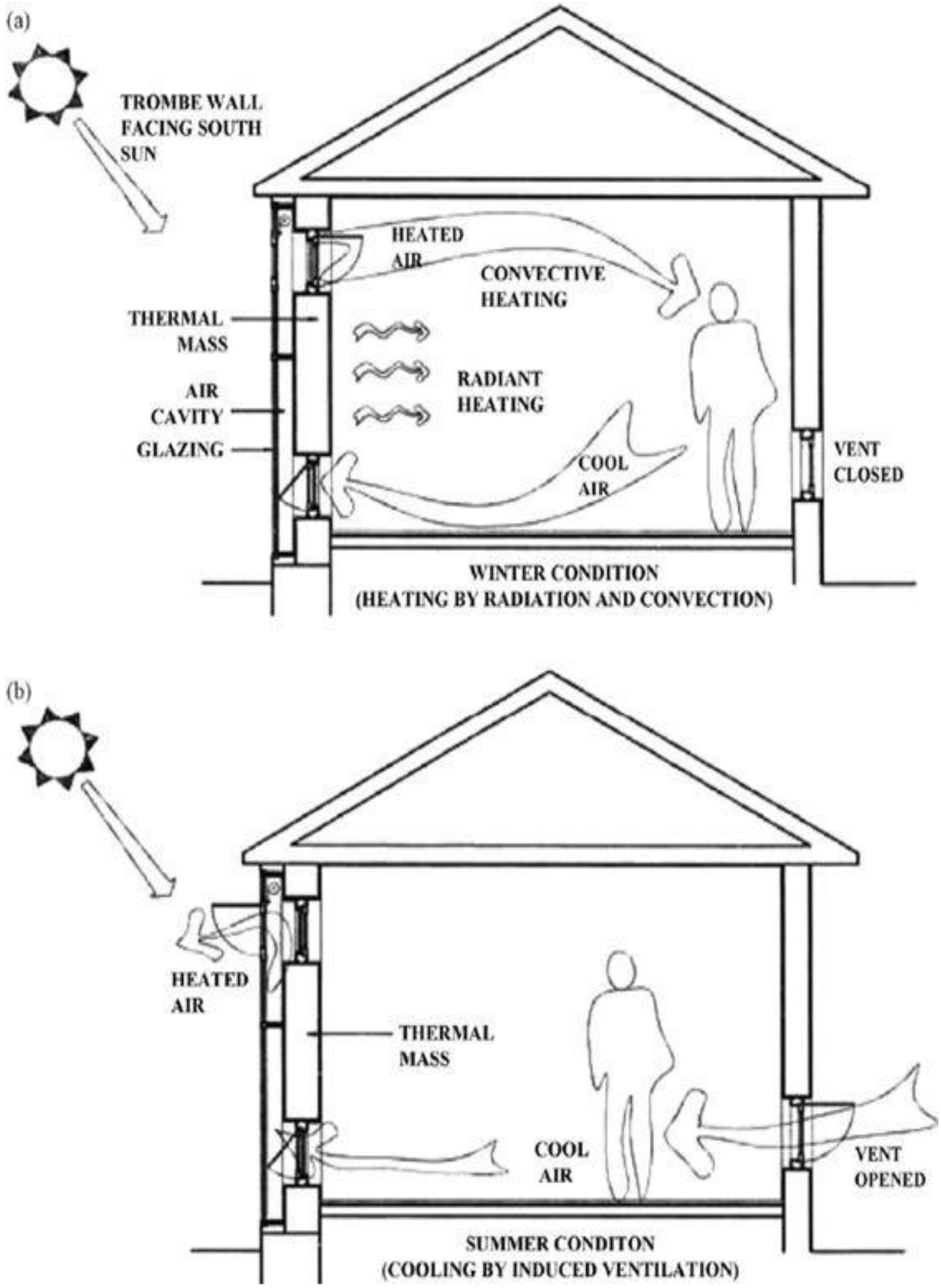


Figure 3.12 Trombe Wall with Vent (a) During Summer, (b) During Winter (Chel, Nayak, & Kaushik, 2008).

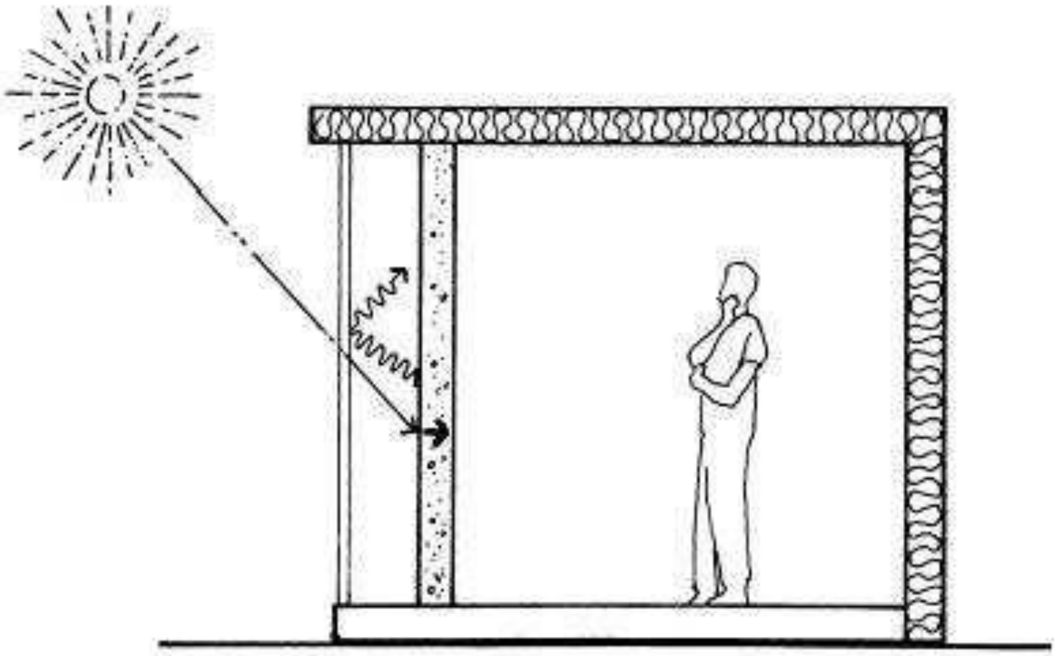


Figure 3.13 Trombe Wall Storing Solar Heat During Sun-lit Hours

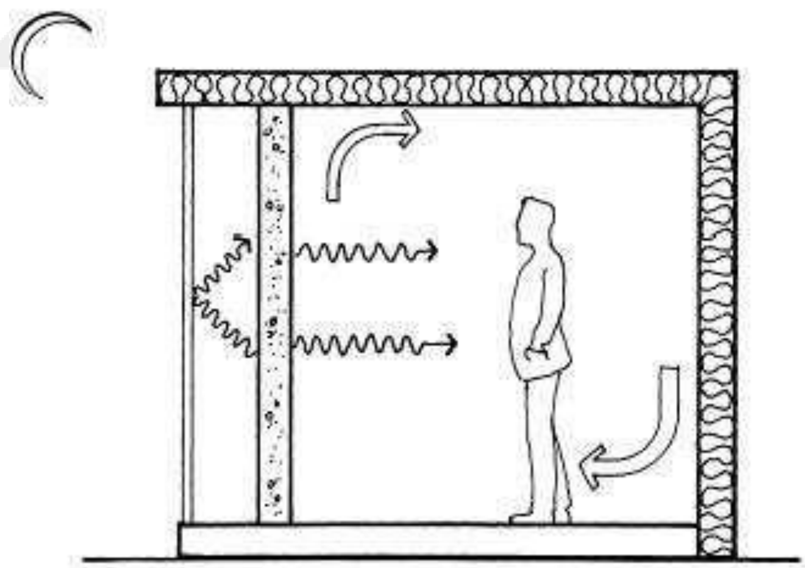


Figure 3.14 Trombe Wall Emitting Solar Heat during Night Time

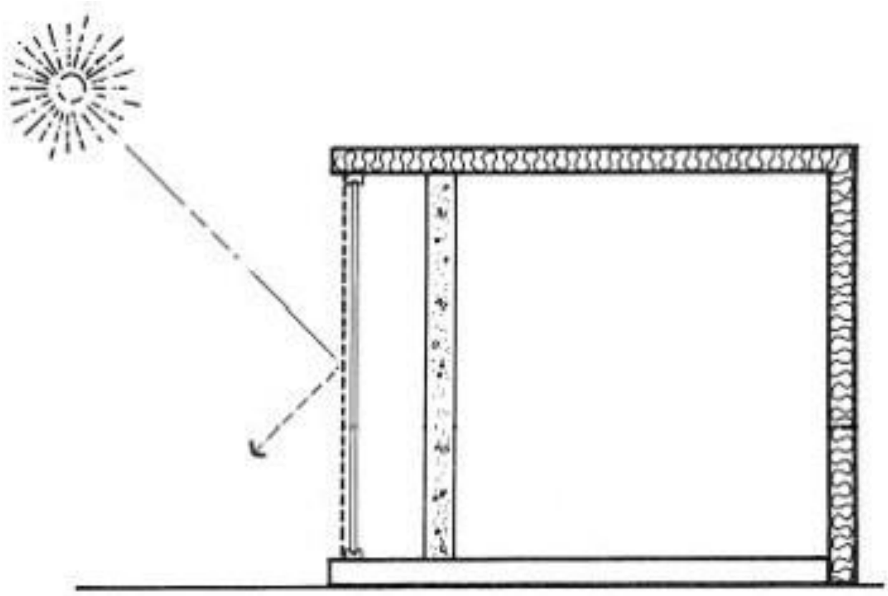


Figure 3.15 Shading Screen for Glazing Facade to prevent Trombe Wall from Over-Heating Living Space.

Trombe Wall system was constructed in The Druk White Lotus School dormitories in Ladakh, India which is designed by Arup Associates / Jonathan Rose, to warm them at night time (see Figure 3.16).

Figure 3.16 Trombe Wall Constructed at Druk White Lotus School in Ladakh, India **(solaripedia, 2010)**

Implicating mixture of Trombe walls and direct gain is the best course of action to get better results. Where half of the wall is controlled by direct heat gain by utilizing solar heat and natural illumination, as well as storing heat for heating for the night time (Fig.3.17)

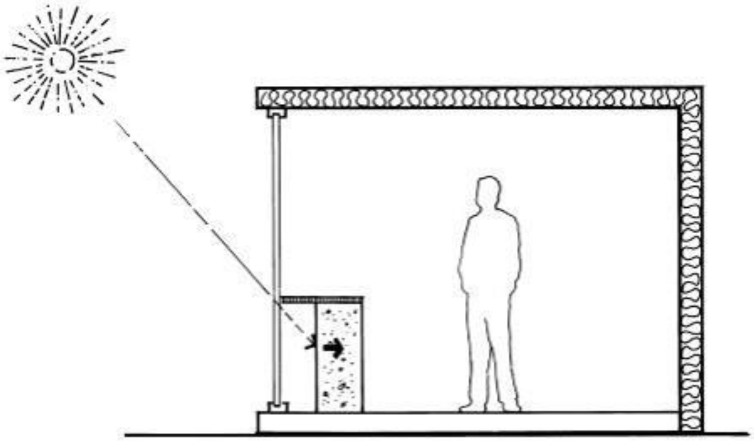


Figure 3.17 Mix Between Trombe Wall and Direct Gain System

In the case of The Shelley Ridge Girl Scout Centre built in 1982 in Philadelphia. The building has two passive gain systems; direct gain system and Trombe wall system. Where glass was used for direct gain purposes, and translucent Fiberglas panels were used for the Trombe wall, shading devices were fixated as well to shade the glass in the summertime (Fig. 3.18).

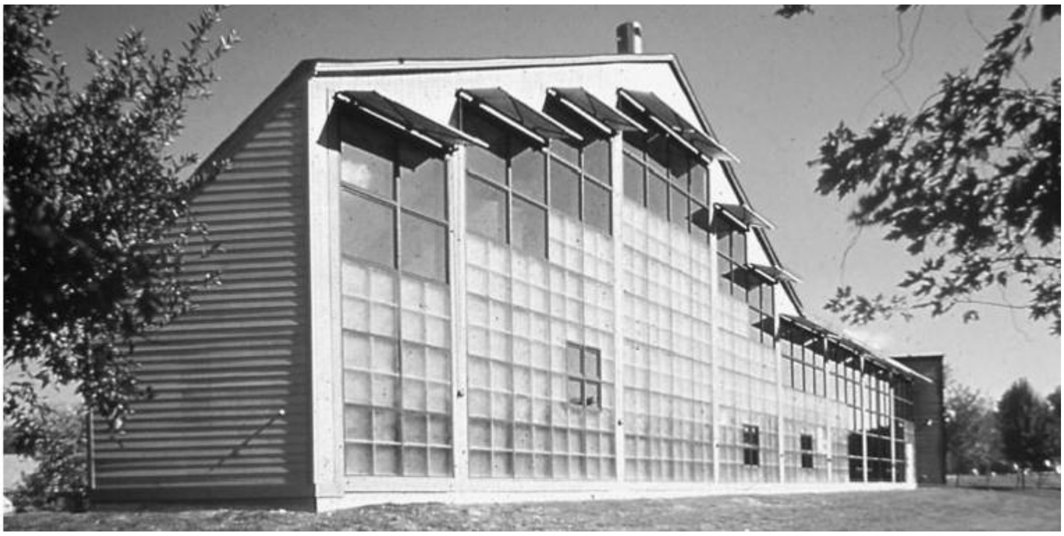


Figure 3.18 The Shelley Ridge Girl Scout Centre **(Kaiser, 2018)**

Zion's Visitor Center is a low energy, sustainable facility, designed by National Park Service-Denver Service Center, located in Zion National Park, Utah/ USA. In this facility building, a Trombe wall was built using heavy masonry, along with Clerestory windows. Zion's Visitor Center (Fig. 3.19, and 3.20)

Figure 3.19 Zion's Visitor Center **(Fosdick, 2016)**

3.2.3 Building Integrated Photovoltaic (BIPV) System

BIPV system building that is equipped with photovoltaic panels either on the pitched roofs and flat ones and on façade. It has the additional benefit of producing electricity resulting in the reduction of fossil fuels, carbon emissions, cost reduction, and mechanical HVAC reduction. Solar panels can be used as a replacement for façade glazing adding an architectural element see (Fig. 3.20, and 3.21).

Figure 3.20 Zion's Visitor Center Photovoltaics Roof System **(The American Institute of Architects, 2018)**

Figure 3.21 BIPV Roof fixation of Solar panels on a commercial building in Germany

CHAPTER 4
SIMULATION TOOLS USED FOR ASSESSING PASSIVE SOLAR ENERGY PERFORMANCE

Different methods have been used to evaluate passive solar energy gain systems and their impact on the building thermal comfort levels during its lifecycle, along with cost reduction and design optimization. The following methods have been used by engineers and architects in their investigative researches and experiments. Those simulation software programs and equations were used to analysis, measure indoor temperature, evaluate thermal comfort levels, calculate the energy conserved, assist in design optimization, calculate average heat flux, thermal load leveling, system performance levels, building heat loss coefficient, collector-wall system efficiency performance, electrical efficiency, PV systems performance levels, and Thermo-economic results. Simulation software and equations used to evaluate the systems, are either company productions or conducted as an experimental simulation to test a newly developed methodology by research engineers. The application and usage of those programs have been increased in recent time in compression with previous years, with the increasing approach towards optimizing existing buildings and designing new buildings that are energy efficient, along with the upcoming desire to reach a" net-zero energy building" or even a "plus energy building", a concept that surpassed architect's desires, to be adopted by governments in their growing energy supply agenda. In conclusion, this chapter provides detailed information for simulation software programs and equations that have been indicated in the studied literature as well as the tools used in this thesis. Each tool that is mentioned has its own characteristic and specific application, with different levels of responses to different inputted variables, which affect the user's decision process.

When choosing a simulation program different factors must be taken into consideration, such as its capability in analyzing complex geometries, building function and reading zones, building system, mechanical system input and material variation. Architects may demand the availability different design elements that permit the presence of passive solar devices either attached or integrated into the building. As the architectural design has the heaviest impact on the thermal performance of the building, through construction elements, such as walls, roofs, opening, and materials. Furthermore, finding working with a simulation tool that is capable of analyzing heat transfer through; convection, conduction, radiation, ventilation while taking into consideration the hierarchy of the room/ building model presented.

Energy simulation software is divided into three categories which are;

- Software with integrated simulation engine, for example (EnergyPlus).
- Software that dock to a specific engine, for example (DesignBuilder).
- Plugins added to a software to perform certain analysis, for example (Ladybug+ honeybee for Rhino).

4.1. EnergyPlus

EnergyPlus is a free, open-source and cross-platform console-based program, which means that it is designed to be used through computer text commands only; text-based interface. Its funded by the Department of Energy’s (DOE) Building Technologies Office (BTO), and used by engineers, architects and researchers alike to model building energy consumption; heating loads, cooling loads, ventilation, lighting, water usage and process loads. Results are based on thermal zone conditions, having the capability of simulating loads resulting from HVAC system, as well as un-conditioned conditions. EnergyPlus has the capability for accounting for the air movement between different zones while calculating illumination levels in the sense of visual comfort and light control strategies in the form of different window glazing and shading devices. The downfall of EnergyPlus is that the graphical interface is user-friendly (Roth, 2018).

4.2. DesignBuilder

DesignBuilder is a user-friendly simulation program, it operates with EnergyPlus primarily in providing an environmental platform to calculate; annual energy consumption, Indoor building temperature, and HVAC load. DesignBuilder is capable of evaluating building façade to overcome overheating, thermal comfort, ventilation, Daylight calculations, solar shading, and heating/cooling loads. With it being easy to use its helpful in the preliminary design process for the whole design team, as well as providing the team with the building carbon emission outputs (DesignBuilder Software, 2009)

4.3. Radiance

Radiance is a free aid software system designed by U.S. Department of Energy, with later additions from the Swiss Federal Government, to provide designers and architects with the means to trace and predict lighting behavior through modeling, luminaire data, material properties, all of which are imputed to run the lighting simulation. The downfall of Radiance is its incapability to calculate light behavior on curved surfaces (Chadwell, 1997)

4.4. OpenStudio

OpenStudio is a free open source software by the National Renewable Energy Laboratory for Windows, and Mac is the combination of tools used for building energy modeling by using EnergyPlus and Radiance. It's a plugin for SketchUp, which provides architects with the possibility of visualizing and analyzing the energy performance of the building in the preliminary stage. OpenStudio is fully equipped with HVAC, loads, schedules, and envelope (NREL, ANL, LBNL, ORNL, and PNNL, 2017).

4.5. Rhino3D

Rhinoceros or as commonly known as Rhino3D is a CAD design software developed for Windows operating system used for Computer-aided manufacturing (CAM), drafting, analyzing, construction, 3D printing and reverse engineering, used by architects, industrial designers, automotive designers, graphic designer as well as multimedia. Scripting language got integrated into Rhino3D to support Grasshopper 3D (VisualARQ, 2017). Grasshopper 3D is a Rhino3D plugin that is an environment used to build generative algorithms used for parametric modeling. It has an advanced user interface, that requires no programming or scripting background (Davidson, 2018).

4.6. Ladybug + Honeybee for Rhino3D

Ladybug plug is a collection of free applications for Grasshopper3D that is designed by Mustapha Sadeghipour and Chris Mackey directed to architectural and educational usage. It supports environmental design in terms of daylight analysis and energy modeling by visualizing weather data (Roudsari, 2018). Ladybug and Honeybee are an interface for a number of industrial standards validated engines including Radiance, EnergyPlus, OpenStudio, Therm, and OpenFOAM.

4.7. ANSYS Fluent

ANSYS Fluent is a computational fluid dynamics tool that includes physical modeling in regards to calculating turbulence modeling, heat transfer, radiation, acoustics, air flow, and design optimization (ANSYS INC, 2018). The software conveys the means to identifies materials, functions, and loading. Its strength lays as an easy and accurate post-processing design assistant for complex models (PADT, 2018).

4.8. Heat Conduction Equation

Heat conduction equation is based on the first law of thermodynamics, following the principle of conservation of energy. The area of the material and rate of heat transfer by conduction impact the material conductivity, which is directly proportionate to the temperature difference (The Concord Consortium, 2013);

$$\Delta Q/\Delta t = -kA(\Delta T/L)$$

Where;

Δ delta represents a change

$(\Delta Q/\Delta t)$ is the heat conduction rate in kJ/s

ΔT represents the temperature difference along the material

L represents the thickness of the layer (m)

A represents the material area (m^2)

k represents the thermal conductivity of the material (kJ/m/s/ºC)

4.9. TRNSYS

TRNSYS is an acronym for Transient System commercial simulation program designed by Duffy Beckman at the University of Wisconsin, for solar simulation and thermal processing. Its capable of simulating solar thermal performance, traffic flow, biological processes, photovoltaics, and building energy performance. It’s a user-friendly program that works by establishing a network with solar collectors, Heat exchanges, pumps, and weather data with the possibility of creating customized settings. with a components library, its facilitates the zone definitions, adding solar panels, PV systems, and HVAC systems (TRNSYS, 2018).

4.10. Ecotect Analysis

Autodesk Ecotect Analysis is an environmental design analysis software which is user-friendly. It works on providing visual and analytical feedback models ranging from simple to complex. Intended to provide analysis for carbon emissions, total energy use, thermal performance, water usage, daylight, acoustics, cost, solar radiation, shadows, and reflection. In 2015 Ecotect Analysis ceased to exist as separate software as Autodesk is working on integrating it into Revit to maximize its usage possibilities as a part of the BIM technology (AUTODESK INC, 2018).

4.11. SolidWorks Flow Simulation

SolidWorks is a parametric modeling CAD software and a CAE program, its designed by Dassault Systèmes and is supported by Microsoft Windows. It’s used for different fields; architectural, industrial, mechanical and electrical (SolidWorks Corporation , 2018).

4.12. CFD

CFD is an acronym for Computational Fluid Dynamics sponsored by Autodesk s, it’s a software which models and simulates fluid flow and thermal behavior capable of practical tracing and high-quality visualization. CFD is used for architectural application, MEP, environmental analysis, thermal management, turbulent flows (AUTODESK INC, 2018)

4.13. ANSYS CFX

ANSYS CFX software is a high-performance CFD software. It is multi-disciplinary simulation software that works on fluid dynamics, heat transfer and structure, its designed for engineers and researchers as well as educational usage. It’s capable of simulating complex designs, optimizes processors architecture, uses scripting for modeling. ANSYS is capable of calculating and analyzing heat transfer between liquids and solids (ANSYS INC, 2018).

4.14. PVsyst

PVsyst software is designed for architects, engineers and researchers to simulate the sizing, and studying the performance of photovoltaic systems. It has the capability of working with stand-alone, grid-connected, pumping and PV systems used for public transportation (DC-grid), as well as creating a database for the PV systems components. PVsyst can be implemented at any stage of the design process, giving approximated results according to the project stages. The database holds the whole system; PV components, PV modules, inverters, regulators, generators, and pumps for easy management (PVsyst SA, 2012).

CHAPTER 5

GENERATING MODELS FOR THE PASSIVE SOLAR ENERGY SYSTEMS

Simulation in the preliminary design stage became a necessity to have an established perception of the energy and thermal performance of the building, present software and tools facilitated the data gathering and analysis for the engineers or researchers through providing the essential data for the decision-making process. There are aspects that ought to be taken into consideration when attempting to simulate a building or a room, such as; heat loads, room conditions and geometry, materials applied, heat storage, climatic zone, thermal performance. The way each field approaches simulation tools differs, load profiles are the concern of an engineer as it fuels the system database, in the meanwhile architects are concerned with the flexibility it presents and illumination, and thermal comfort levels that assist in the architectural design process (Weiner, 1992).

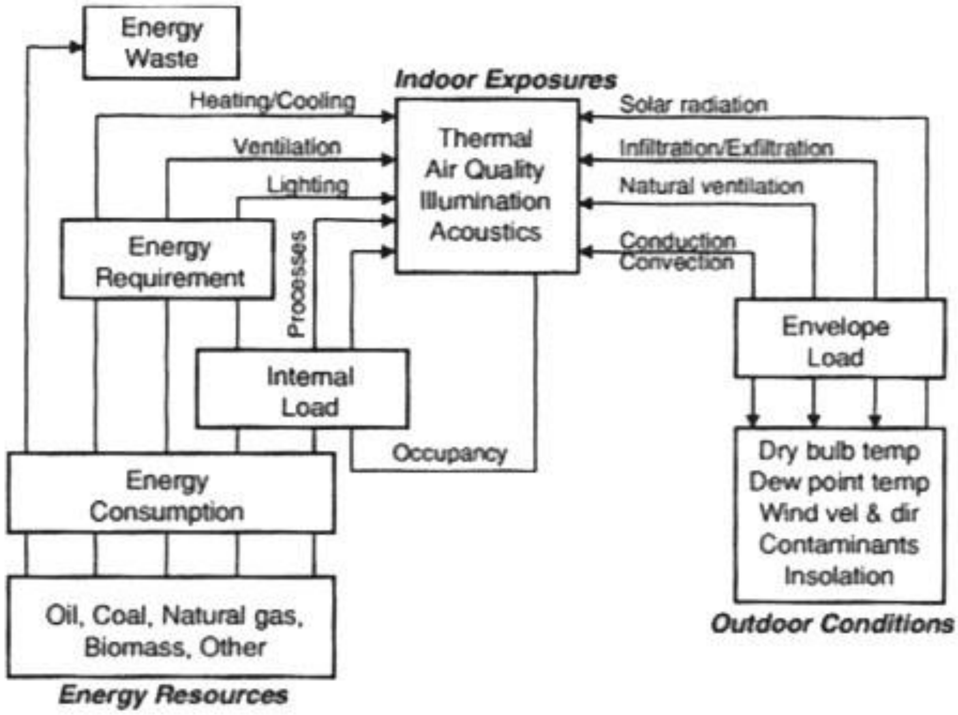


Figure 5.1 Building Energy Flow Diagram process **(Rallapalli, 2010)**

5.1 Location and Climate

This study has been conducted in the form of a comparative thermal performance analysis in two different climatic zones; hot and humid climatic region and semi-continental climatic region. City of choice for a hot and dry climatic region was Istanbul. It's population around 15 million people which makes it the most populated city in Turkey and it's an economic and historical hub, and the 6th largest in the world, it extends across Europe and Asia. The city has long, dry and hot summer period with up to 10 sunlight hours per day, while the winter period is cold and wet with some snowy days that happen usually in February and because of this rainy weather its mostly cloudy and dark, with months as December and January having 5 sunlight hours per day (Fig. 5.2). Istanbul's weather conditions as follows, July and August are the hottest most of the year with 28ºC, and the coldest one is February with 6 ºC (Fig. 5.3). in terms of the economy in Istanbul, it's growing by an average of 4.4% per year, with over 12 business districts that are supplied with all means of infrastructure and services (PROPIN, 2014). Turkey, in general, is mainly dependent imported fossil fuel, with the addition of 9% hydraulic energy production, the geographical location is a primary factor in the growing utilization of solar energy making Turkey one of the leading countries worldwide in photovoltaic technology manufacturing (Energypedia, 2016).

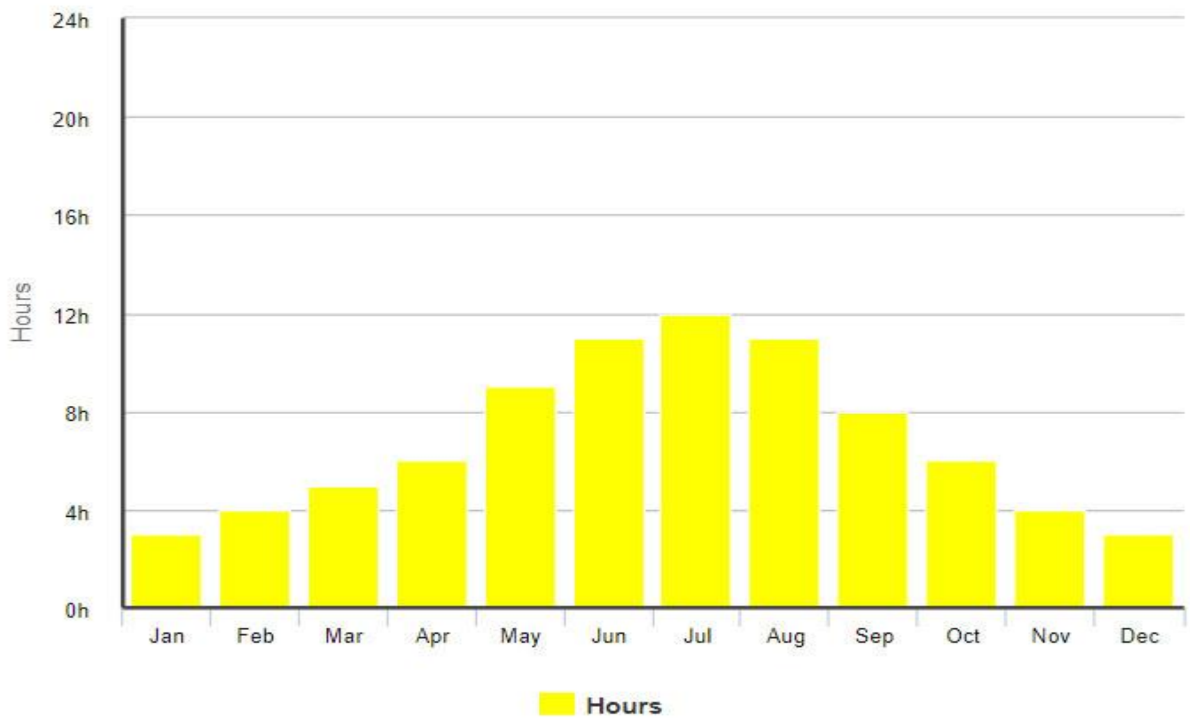


Figure 5.2 Average Sunlight Hours in Istanbul **(Holiday Weather, 2018)**

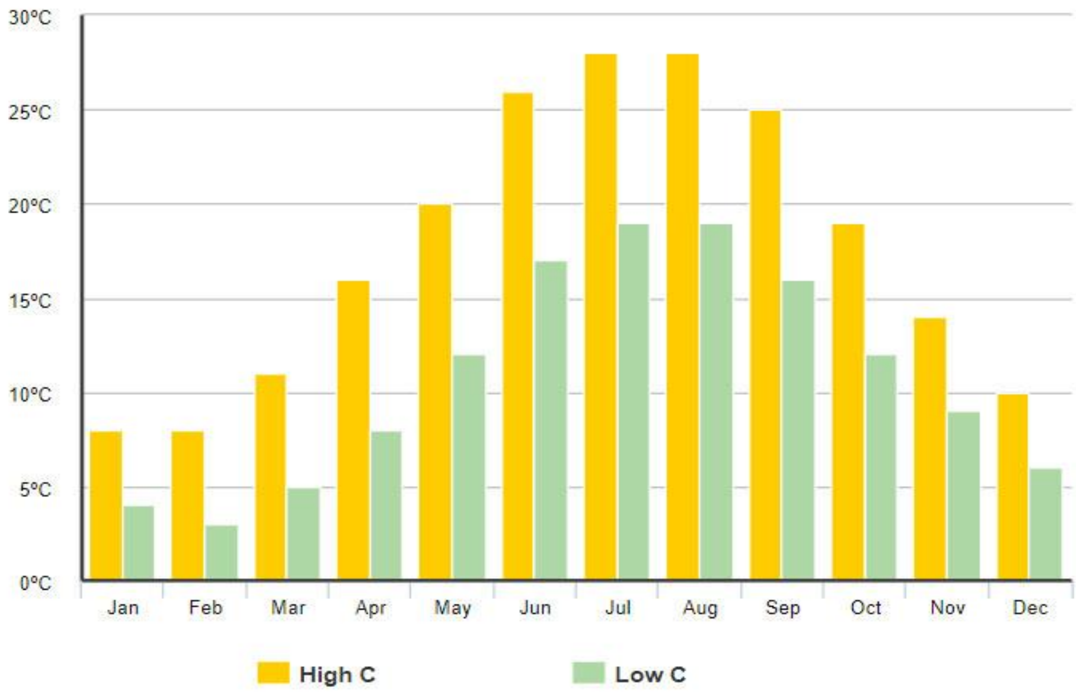


Figure 5.3 Average highs/ Lows Temperature in Istanbul in Celsius **(Holiday Weather, 2018)**

While for the semi-continental climatic, Stockholm was chosen. It is the capital of Sweden with the highest populated city in the Nomadic Countries, with a population of 9.5 million people living in it. The city is renowned for having long and dark winter days, with days that are as short as 6 hours, the darkest months are December and January with that have 2 hours of daylight, on the other hand, the dark hours in the summertime are a couple of hours long, with over than 12 hours of sunlight hours per day (Fig. 5.4). Stockholm's weather conditions are that July is the hottest month of the year with average temperature of 22ºC, and January is the coldest one with the temperature dropping to -3 ºC (Fig. 5.5). Stockholm is considered the center of the business hub of Europe that yet keeps growing, surpassed on by London, (Edwards, 2017) explains that the office rent in the city is considered the 2nd most expensive in Europe. With the growing efforts, Sweden is considered one of the leading countries in terms of using alternative energy resources such as nuclear power, wind and hydroelectric power plants, using only 20% of energy that is powered by fossil fuel, and as a result the CO_2 emissions are considered one of the lowest in comparison with the rest of the world (Fig. 5.6).

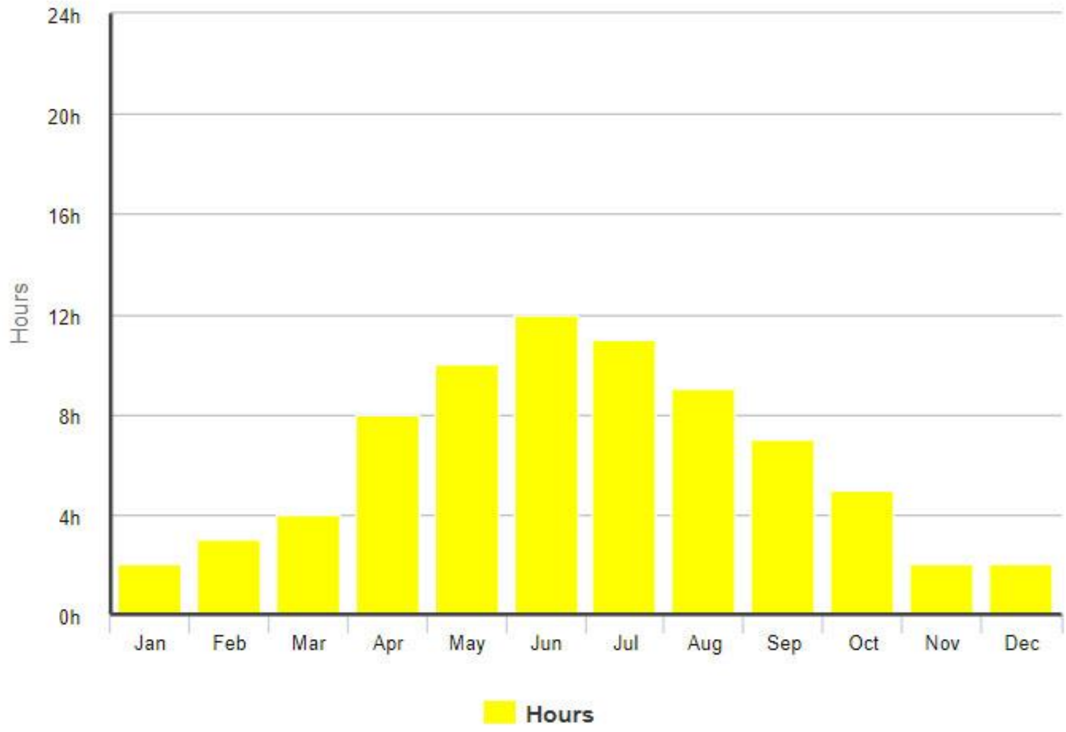


Figure 5.4 Average Sunlight Hours in Stockholm **(Holiday Weather, 2018)**

Figure 5.5 Average highs/ Lows Temperature in Stockholm in Celsius **(Holiday Weather, 2018)**

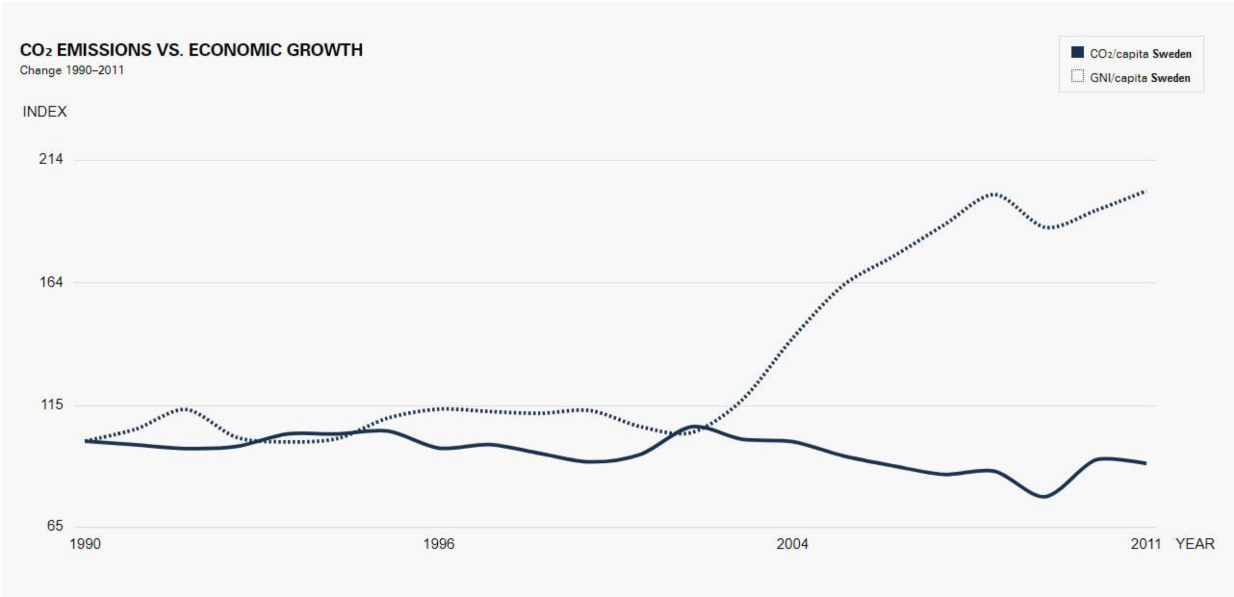


Figure 5.6 Co^2 Emissions Levels in Sweden in 10 years **(Sweden.se, 2016)**

5.2. Space Selection

An office space was used as a base for this study. With the upraise in the business sector and their reliance on mechanically managed environment using HVAC systems, that's besides the fact that humans spend most of their waking hours in offices. Active engagement and interaction with the designed space beyond passive presence stimulates a greater over all sense of satisfaction that increases the occupant's productivity levels.

5.3. Problem Definition

The comparative analysis of different types of indirect solar gain systems and a direct solar gain system, in terms of minimizing total energy consumption for HVAC system and thermal comfort level in an office space. According to this problem the systems were tested in different climatic zones to observe which one is more suited for each weather conditions.

5.4. Variables

The variables in this study are the solar energy systems, with a common factor which is that they are located on the south façade. The climatic zones presented are different as well.

5.5. Limitation

The common façade element for an office space is a glass surface, usually in the form of floor to ceiling window which increases natural lighting but results in an increase of solar heat gain resulting from solar infiltration to the space. As a result, glass façade was chosen as a base system in the comparative analysis with the other indirect solar gain energy systems.

5.6. Objective

The objective of this study is a reduction of total energy consumption, stable indoor temperature, and reaching thermal comfort level needed for office space tenants. According to ASHRAE Standards 55-1992, thermal comfort is archived in average temperature of 23-26 ºC, with 26 ºC being the comfort temperature for an office space.

5.7. Energy Objective

The base model of this study total energy consumption which includes heating and cooling was calculated using Grasshoppers' Ladybug + Honeybee plugin which is a calculative interface for total energy consumption. This plugin uses EnergyPlus format and infrastructure.

5.8. Base Model

The base model is for a conceptual office space, with 5m width, 10m length, and 5m height. The longest side facing the south direction where the direct and indirect solar energy gain systems are located. The chosen systems are; Single Glazed Wall, Transparent Water Wall, Concrete Water Wall, Trombe Wall, Gazbeton Water Wall (Fig. 5.7).

5.9. Generating Model

The model generation in Rhino, the Ladybug + Honeybee Tools plugin was added to Grasshopper Environment. Honeybee components were used to define the geometries, this process is divided into two parts, one which is identifying building structural and nonstructural elements (walls, flooring, ceiling, window, and thermal storage wall), this is followed by assigning the building materials along with their physical characteristics. Then weather data files (EPW files) which is in an EnergyPlus weather format, for Stockholm and Istanbul are then identified in separate Rhino files into the Honeybee component (EnergyPlus, 2018).

5.8 Performance Evaluation

Energy simulation model was created using Ladybug + Honeybee, Information regarding the plugin was provided in the previous chapter.

5.9 Parametric Definitions of the Solar Gain Energy Systems

First of all, the model is constructed in Rhino (Fig. 5.7) with that is followed by assigning materials to each construction element in the model to specify its function and composition such as; walls, floor, ceiling. The main façade with the variable wall compositions is the South facing façade as shown in (Tables 5.1 - 5.2 – 5.3 - 5.4, and 5.5), as for three other sides they are assigned the same materials as shown in (Tables 5.7 – 5.8 and 5.9) represent the materials assigned to the ceiling and flooring consequently. The physical characteristic that was needed to assign water as a material in the Honeybee material component is in (Table 5.6). In (Fig. 5.8) shows the overall Honeybee material assignment the detailed parametric material assignment of each building component for the model was created in the Grasshopper environment.

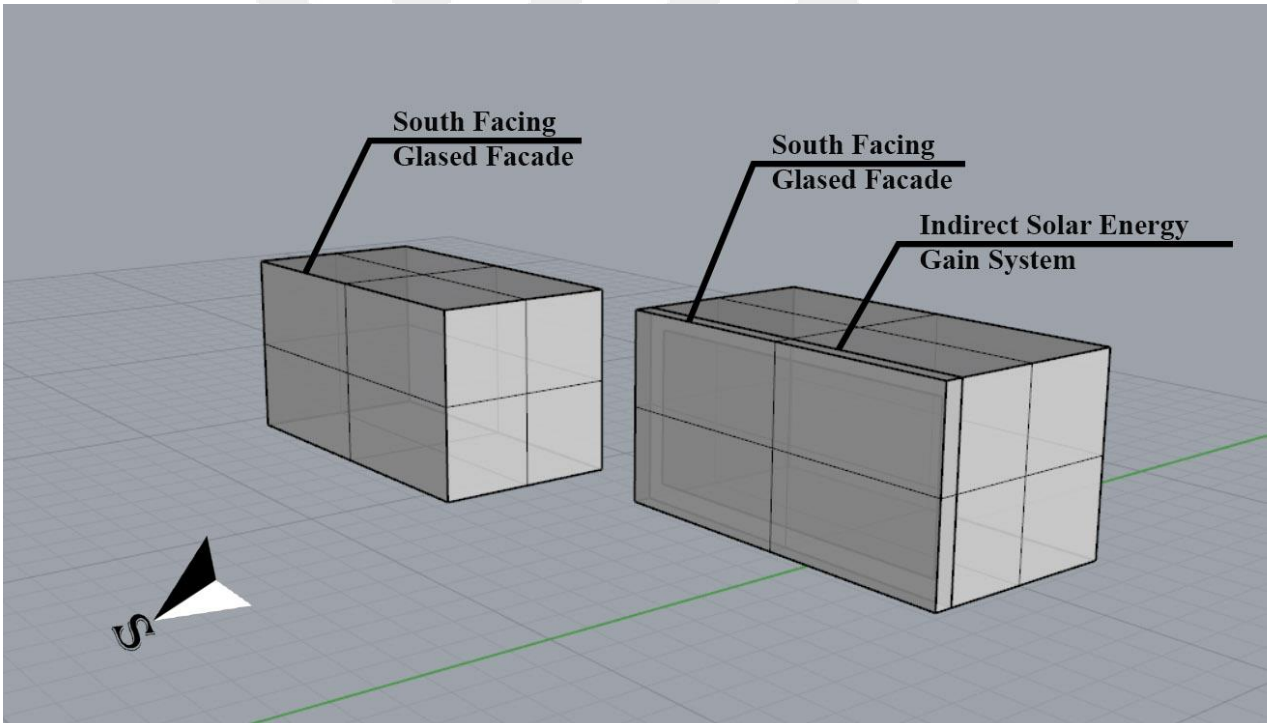


Figure 5.7 Rhino Base Models for Direct and Indirect Solar Gain Systems

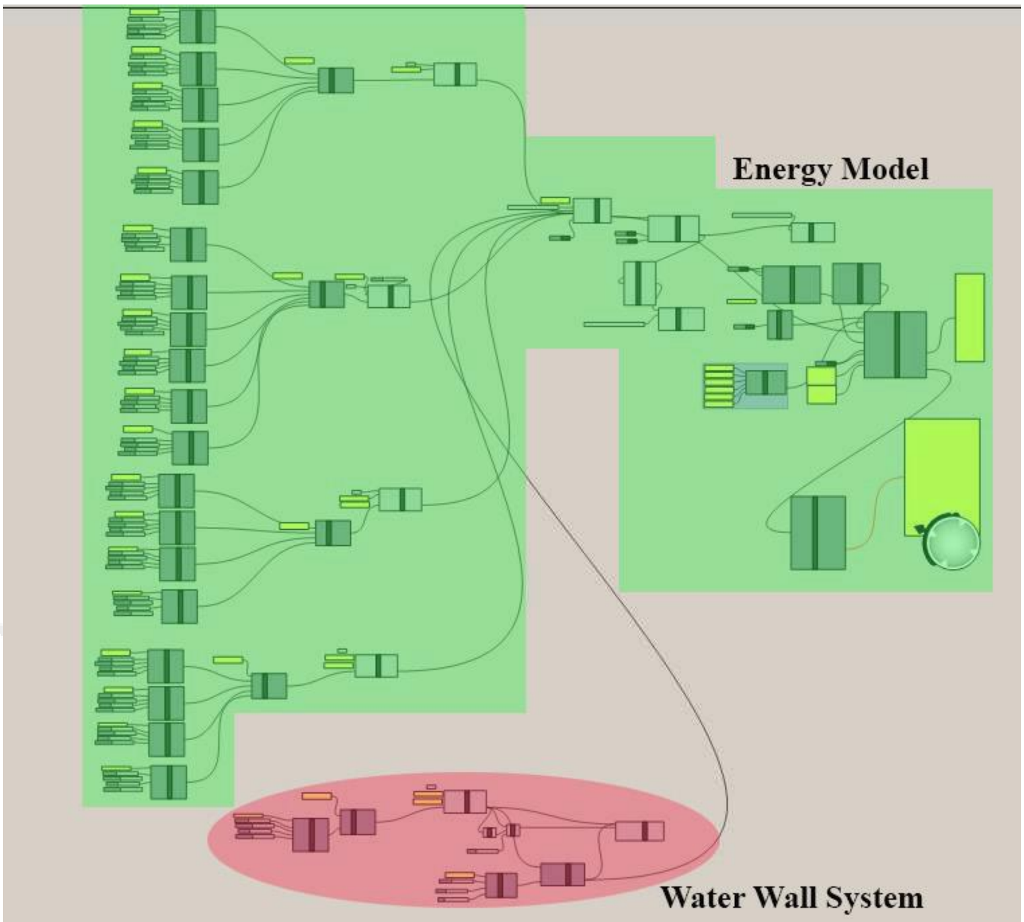


Figure 5.8 Overall Grasshopper Model for the Material Assignment for the WaterWall System

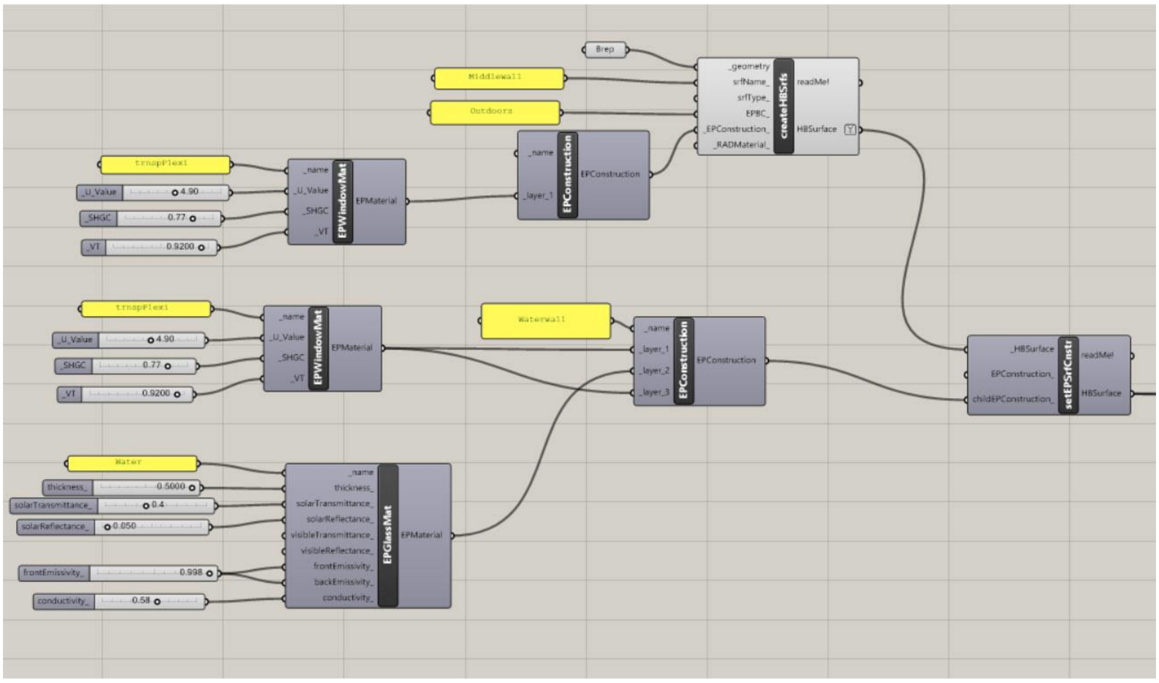


Figure 5.9 Grasshopper Model for The Transparent WaterWall System

5.12. Water as a Material

As there is no previous reference that could be used in this situation, and with the few available studies that have been conducted concerning Water Wall System, it presented a problem. The problem was faced during a material assignment in terms of identifying water as a construction element in Honeybee component to be simulated and analyzed. This has been solved in two different ways, one is to identify and treated water as if it's glass material which happened in the case Transparent Water Wall System, using Honeybee_PlusEnergy Glass Material (Fig. 5.10), meanwhile in the case of having an opaque envelope (Concrete, Gazbeton) for the Water Wall System, its identified as an opaque material using Honeybee_PlusEnergy Opaque Material (Fig.5.11) as its reflective and visual transmittance aren't hindered by the opaque envelop.

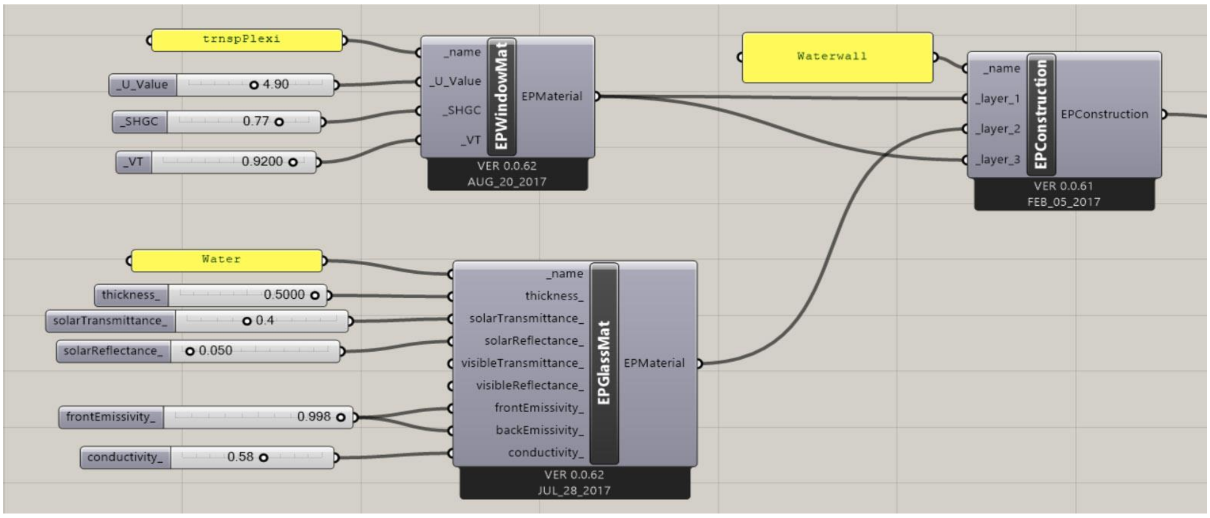


Figure 5.10 Detailed indication of Water in Transparent WaterWall System

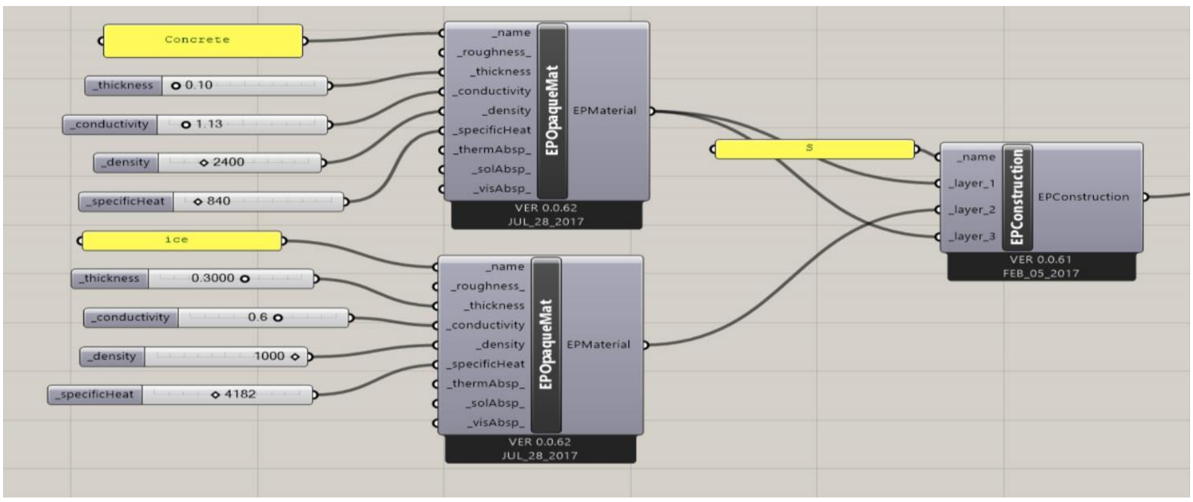


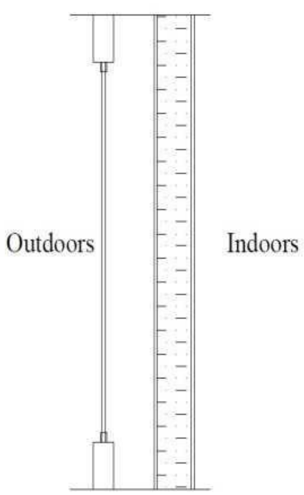
Figure 5.11 Detailed indication of Water in Opaque Water Wall System

5.11. Solar Gain Energy Systems Section Compositions

The following tables provide sections and physical characteristic that were used to identify direct and indirect solar gain systems in the energy models.

Table 5.1; Display Transparent Water Wall material configurations, in terms of each material used and its physical properties as identified in the Grasshopper simulation components.

Table 5.1 Transparent Plexiglass Water Wall Configuration

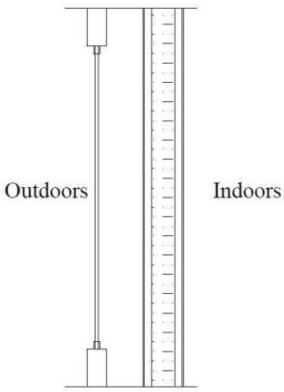
Transparent Water Wall Section	**N**	**Material**	**D** *(m)*	**U-Value** *(W/m2)*	**SHGC**	**VT %**
	1	Single Glazing	0.04	5.2	0.88	0.9
	2	Air Gap	0.5	-	-	-
	3	Transparent Plexiglass	0.04	4.9	0.77	0.92
	4	Water	0.42	-	-	-
	5	Transparent Plexiglass	0.04	4.9	0.77	0.92

D (Distance), U-value (Thermal Transmittance), SHGC (Solar Heat Gain Coefficient)

VT (Visible Transmittance), SH (Specific Heat)

Table 5.2; Display Concrete Water Wall material configurations, in terms of each material used and its physical properties as identified in the Grasshopper simulation components.

Table 5.2 Concrete Water Wall Configuration

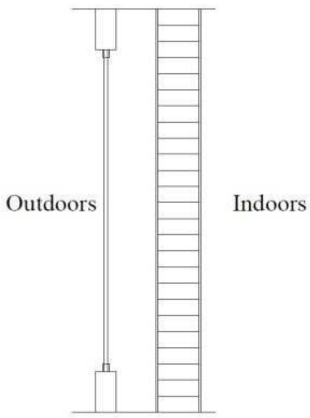
Concrete Water Wall Section	**N**	**Material**	**D** *(m)*	**U-Value** *(W/m2)*	***SHGC***	**VT** *%*	**ƙ** *(kA/L)*	**ρ** *(kg/m³)*	**SH***(J/kg-K)*
	1	Single Glazing	0.04	5.2	0.88	0.9	-	-	-
	2	Air Gap	0.5	-	-	-	0.025	-	-
	3	Concrete Block	0.1	1.13	-	-	2.5	2400	840
	4	Water	0.3	-	-	-	993	-	-
	5	Concrete	0.1	1.13	-	-	2.5	2400	840

U-value (Thermal Transmittance), SHGC (Solar Heat Gain Coefficient), VT (Visible Transmittance)

ƙ (Thermal Conductivity), ρ (Density), SH (Specific Heat)

Table 5.3; Display Trombe Wall material configurations, in terms of each material used and its physical properties as identified in the Grasshopper simulation components.

Table 5.3 Trombe Wall Configuration

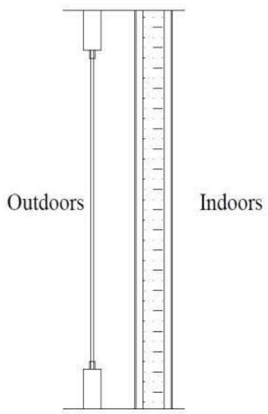
Trombe Wall Section Section	**N**	**Material**	**D** *(m)*	**U-Value** *(W/m2)*	***SHGC***	**VT** *%*	**ʎ** *(kA/L)*	**ρ** *(kg/m^3)*	**SH***(J/kg-K)*
	1	Single Glazing	0.04	5.2	0.88	0.9	-	-	-
	2	Air Gap	0.5	-	-	-	0.025	-	-
	3	Sandstone	0.5	2.33	-	-	-	2650	920

U-value (Thermal Transmittance), SHGC (Solar Heat Gain Coefficient),

VT (Visible Transmittance), ʎ (Thermal Conductivity), ρ (Density), SH (Specific Heat)

Table 5.4; Display Gazbeton Water Wall material configurations, in terms of each material used and its physical properties as identified in the Grasshopper simulation components.

Table 5.4 Gazbeton Water Wall Configuration

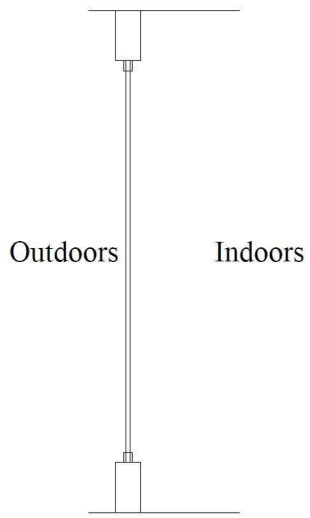
Gazbeton Water Wall Section	N	Material	D *(m)*	U-Value *(W/m2)*	*SHGC*	VT %	ʎ *(kA/L)*	ρ *(kg/m³)*	SH*(J/kg-K)*
	1	Single Glazing	0.04	5.2	0.88	0.9	-	-	-
	2	Air Gap	0.5	-	-	-	0.025	-	-
	3	Gazbeton	0.1	0.16	-	-	-	500	1000
	4	Water	0.3	-	-	-	-	993	-
	5	Gazbeton	0.1	0.16	-	-	-	500	1000

U-value (Thermal Transmittance), SHGC (Solar Heat Gain Coefficient),

VT (Visible Transmittance), ʎ (Thermal Conductivity), ρ (Density), SH (Specific Heat)

Table 5.5; Display Single Glazed wall material configuration, in terms of each material, used and its physical properties as identified in the Grasshopper simulation components.

Table 5.5 Single Glazed Wall Configuration

Single Glazing Section	N.	Material	D (m)	U-Value (W/m2)	SHGC	VT %	ρ (kg/m³)	SH(J/kg-K)
	1	Single Glazing	0.04	5.2	0.88	0.9	-	-

U-value (Thermal Transmittance), SHGC (Solar Heat Gain Coefficient),

VT (Visible Transmittance), ƙ (Thermal Conductivity), ρ (Density), SH (Specific Heat)

Table 5.7 - 5.8, and 5.9; Display the material configuration of the model components; 3 Exterior walls, Ceiling, and Flooring, in terms of their position and their physical properties as identified in the Grasshopper simulation components.

Table 5.6 Water Physical Characteristic

Material	Solar Transmittance	Solar Reflectance	Emissivity	Conductivity
Water	0.4	0.05	0.998	0.58

Table 5.7 Wall Material Configuration

	Layer	Material	D (*m*)	ƙ (*kA/L*)	ρ(*kg/m*^{3})	SH (*J/kg-K*)
Wall Layers	Layer 1	gypsum plaster	0,01	0.35	1680	1085
	Layer 3	XPS	0,03	0,04	28	1200
	Layer 2	Brick	0,19	0,30	1922	840
	Layer 4	lime plaster	0,01	0.35	1680	1085

Table 5.8 Ceiling Material Configuration

	Layer	Material	D (*m*)	ƙ (*kA/L*)	ρ(*kg/m*^{3})	SH (*J/kg-K*)
Ceiling Layers	Layer 1	Leveling concrete	0,05	1,4	2300	750
	Layer 2	XPS	0,12	0,034	28	1200
	Layer 3	Leveling concrete	0,03	1,4	2300	750
	Layer 4	RC Slab	0,12	2,5	2400	840
	Layer 5	lime plaster	0,01	0.35	1680	1085

U-value (Thermal Transmittance), SHGC (Solar Heat Gain Coefficient), VT (Visible Transmittance), ƙ (Thermal Conductivity), ρ (Density), SH (Specific Heat)

Table 5.9 Flooring Material Configuration

	Layer	Material	**D** *(m)*	**ʎ** *(kA/L)*	**ρ***(kg/m³)*	**SH** *(J/kg-K)*
Flooring Layers	Layer 1	Blockade	0,15	1.74	1500	960
	Layer 2	Lean Concrete	0,10	1,10	1100	750
	Layer 3	leveling concrete	0,02	1,40	2300	750
	Layer 4	XPS	0,08	0,04	28	1200
	Layer 5	leveling concrete	0,03	1,40	2300	750
	Layer 6	Laminate	0,02	0,19	545	2385

U-value (Thermal Transmittance), SHGC (Solar Heat Gain Coefficient),

VT (Visible Transmittance), ʎ (Thermal Conductivity), ρ (Density), SH (Specific Heat)

CHAPTER 6
RESULTS AND DISCUSSION

In this study, a passive design solution which is water wall system has been applied to 2 different cities which are Istanbul and Stockholm that are located in different climatic regions. The energy performance of transparent water wall system, concrete water wall system, gas concrete water wall system; single glazing direct gain system and Trombe wall system has been done for 2 different cities in 2 different climatic regions which are hot and humid climatic region and semi-continental climatic region respectively.

Istanbul has a hot and humid climate with hot and humid summers and warm winters.

Stockholm has a semi-continental climate with cold winters and warm and sunny summers (https://www.climatestotravel.com/climate/sweden).

(Fig. 6.1, and 6.2) display the hourly indoor air temperature variations for 1 month and for 1 day in January for Istanbul. During night time when heating is needed, the indoor air temperature variations from highest to lowest are concrete water wall system, gas concrete water wall system, transparent water wall system, Trombe wall system and single glazing direct gain system respectively.

During daytime when the sun is high in the air and there is solar radiation, the indoor air temperature variations from highest to lowest are single glazing direct gain system, concrete water wall system, gas concrete water wall system, transparent water wall system and Trombe wall system respectively. The indoor air temperatures in the single glazed direct gain system are higher in the daytime when there is solar radiation due to the higher heat transfer coefficient it has. The concrete water wall system, gas concrete water wall system, transparent water wall system, and Trombe wall system are indirect gain systems which transmit heat with a time lag. Thus, in these systems, the indoor air temperature neither rises nor drops that rapidly compared to the single glazed direct gain system. The minimum and maximum indoor air temperatures are 3.16C and 36.48C throughout January.

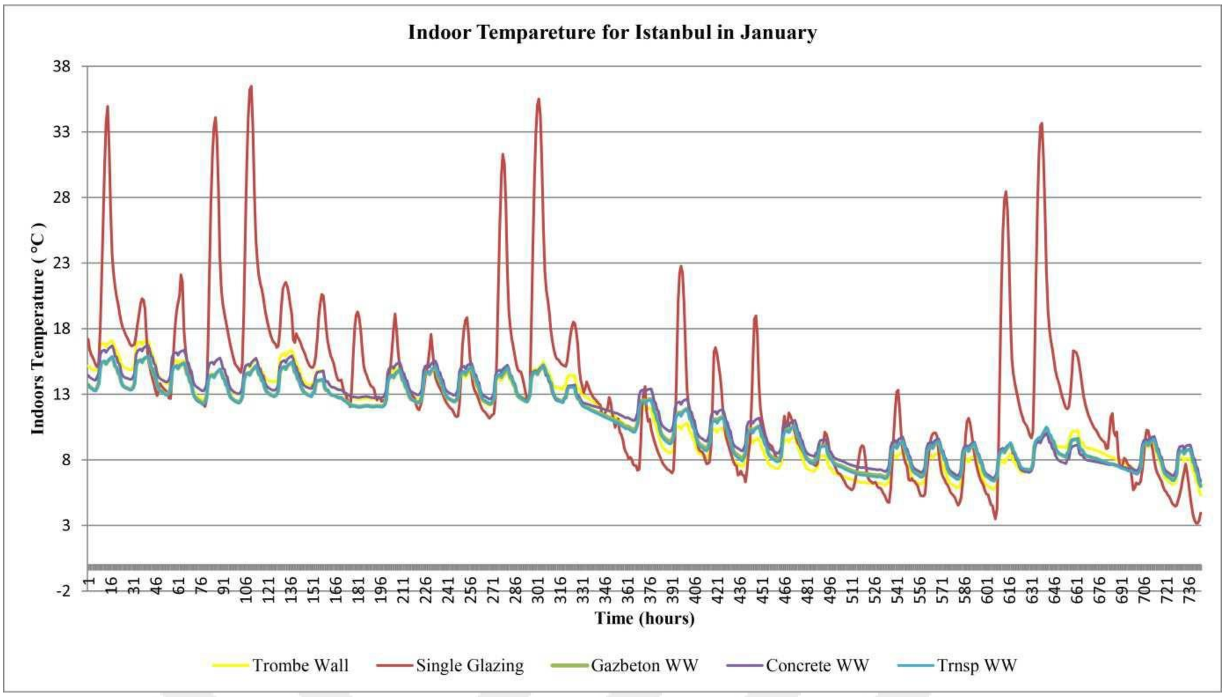


Figure 6.1 Hourly indoor air temperature variations for Istanbul on January

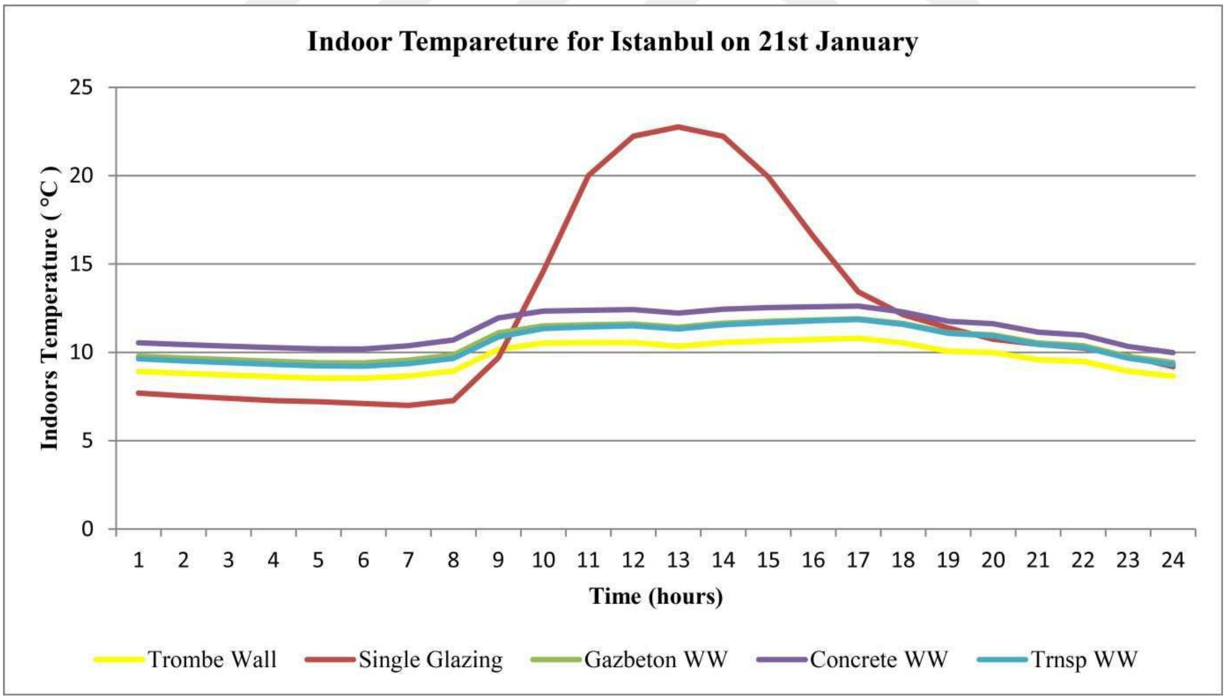


Figure 6.2 Hourly indoor air temperature variations for Istanbul on January, 21st

In (Fig. 6.2), it is seen that the indoor air temperatures at 01.00 are 7.69ºC, 10.54 ºC, 9.79 ºC, 9.63 ºC, 8.92 ºC for single glazing direct gain system, concrete water wall system, gas concrete water wall system, transparent water wall system and Trombe wall system respectively. The

indoor air temperatures drop down to 7.10 ºC, 10.19 ºC, 9.41 ºC, 9.22 ºC, and 8.53 ºC at 06.00 respectively. Then, they start increasing up to 16.56 ºC, 12.58 ºC, 11.83 ºC, 11.78 ºC, and 10.73 ºC at 16.00 respectively. Then, they start decreasing up to 9.19 ºC, 9.98 ºC, 9.43 ºC, 9.31 ºC, and 8.65 ºC at 00.00. As seen from the graphs, the indoor air temperature fluctuation is so high in the alternative with single glazing direct gain system. This affects the thermal comfort of a room for the occupants in a negative way.

(Fig. 6.3) displays the hourly indoor air temperature variations for 1 month in July for Istanbul. During night time, the indoor air temperature variations from highest to lowest are single glazing direct gain system, transparent water wall system, gas concrete water wall system, concrete water wall system and Trombe wall system respectively. There is not much difference between transparent water wall system, gas concrete water wall system, and concrete water wall system results.

During daytime when the sun is high in the sky and there is solar radiation, the indoor air temperature variations from highest to lowest are single glazing direct gain system, transparent water wall system, gas concrete water wall system, concrete water wall system and Trombe wall system respectively. The indoor air temperatures in the single glazed direct gain system are higher in the daytime when there is solar radiation due to the higher heat transfer coefficient it has. In a similar way, the single glazed direct gain system loses heat more rapidly compared to Trombe wall and water wall systems. Thus, the temperature fluctuation in the single glazed direct gain system is the highest during 1 day in the cooling period as it is in the heating period. The minimum and maximum indoor air temperatures are 27.57 ºC and 45.74 ºC throughout July in Istanbul.

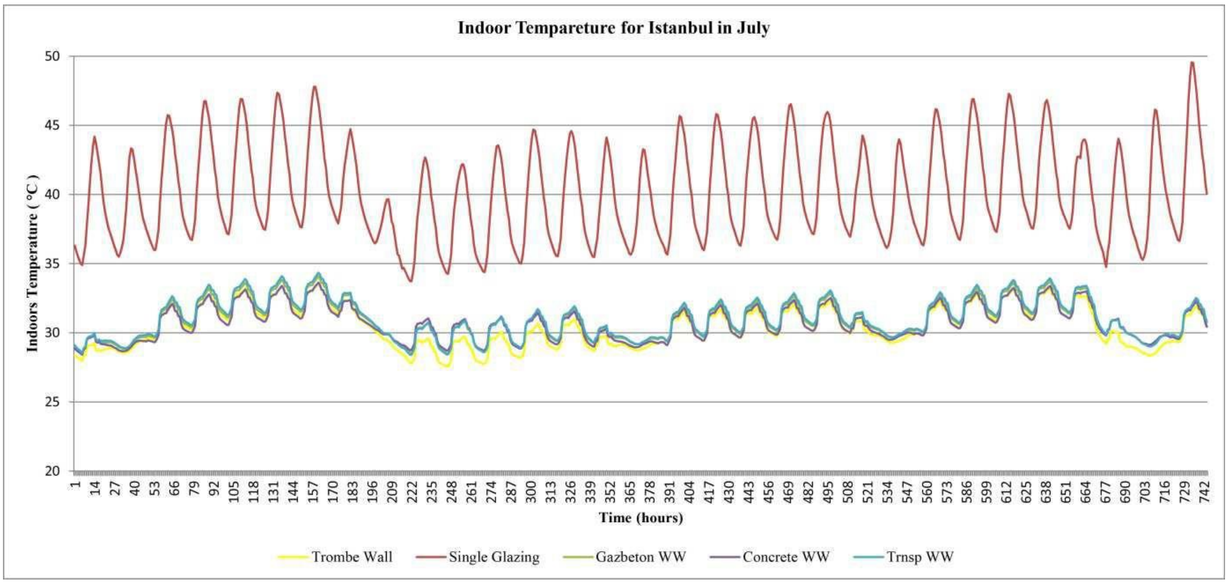


Figure 6.3 Hourly Indoor Air Temperature Variations for Istanbul on July

In (Fig. 6.4) it is seen that the indoor air temperatures at 01.00 are 35.40 ºC, 28.97 ºC, 28.90 ºC, 28.90 ºC and 27.96 ºC for single glazing direct gain system, concrete water wall system, gas concrete water wall system, transparent water wall system, and Trombe wall system respectively. The indoor air temperatures drop down to 34.39 ºC, 28.72 ºC, 28.64 ºC, 28.59 ºC, and 27.76 ºC at 06.00 respectively. Then, they start increasing up to 43.18 ºC, 31.06 ºC, 31.02 ºC, 30.98 ºC and 29.95 ºC at 16.00 respectively. Then, they start decreasing up to 36.47 ºC, 29.37 ºC, 29.31 ºC, 29.22 ºC, and 28.46 ºC at 00.00 respectively. As seen from the graphs, the indoor air temperature fluctuation is so high in the alternative with single glazing direct gain system. This affects the thermal comfort of a room for the occupants in a negative way in cooling period.

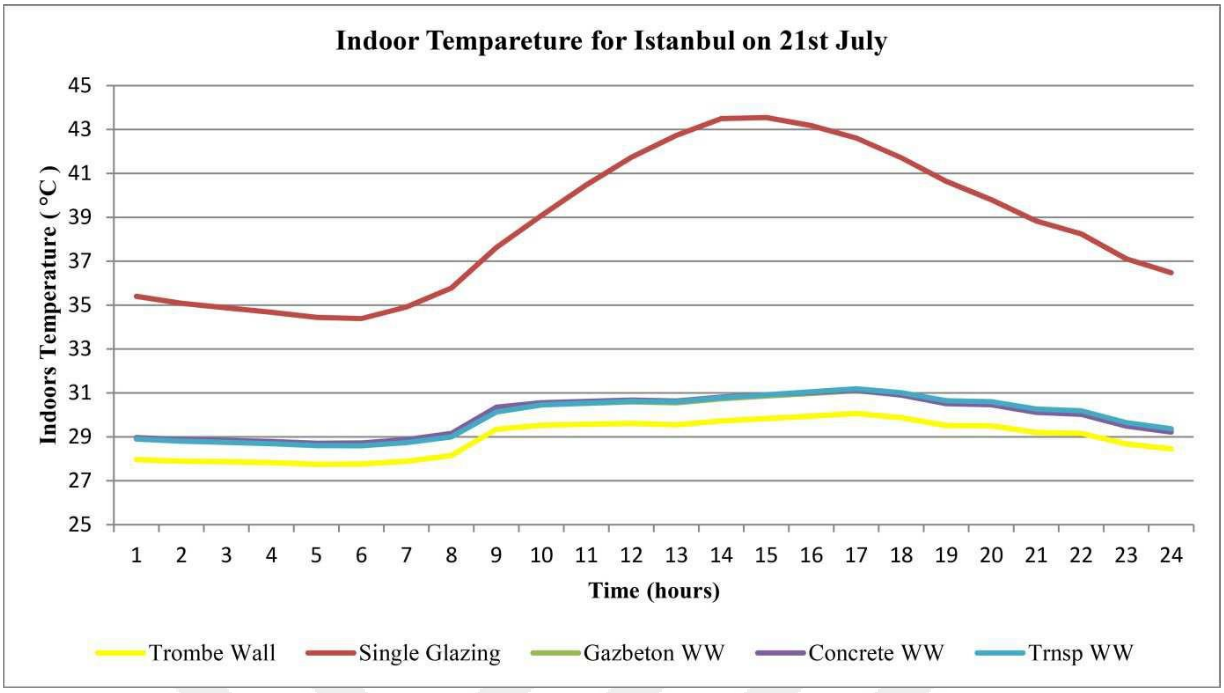


Figure 6.4 Hourly Indoor Air Temperature Variations for Istanbul on July, 21st

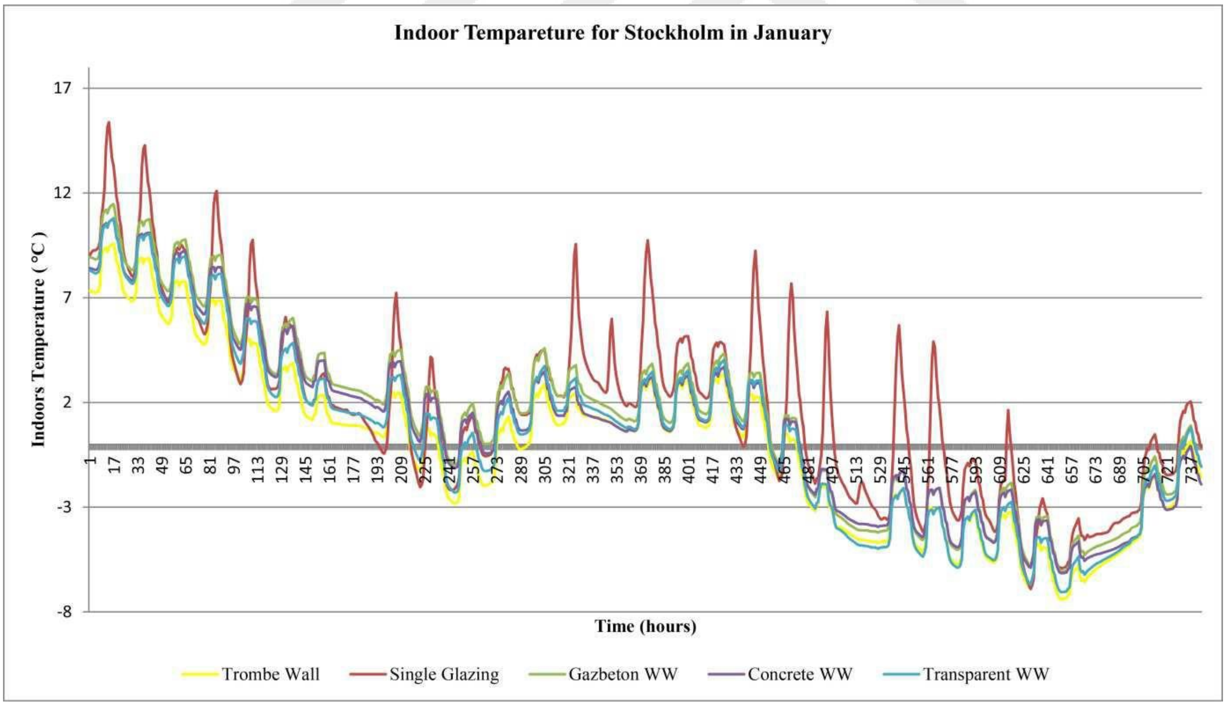


Figure 6.5 Hourly Indoor Air Temperature Variations for Stockholm on January

(Fig.6.5) displays the hourly indoor air temperature variations for 1 month in January for Stockholm. During night time when heating is needed, the indoor air temperature variations from highest to lowest are gas concrete water wall system, transparent water wall system, concrete water wall system, Trombe wall system and single glazing direct gain system respectively. The minimum and maximum indoor air temperatures are -6.90 ºC and 15.38 ºC throughout January in Stockholm.

(Fig. 6.6) displays the indoor air temperature variation in Stockholm on January 21st. In Figure 6.2, it is seen that the indoor air temperatures at 01.00 are 1.52 ºC, 1.30 ºC, 1.12 ºC, 0.82 ºC, and 0.78 ºC for gas concrete water wall system, transparent water wall system, concrete water wall system, single glazing direct gain system, and Trombe wall system respectively. The indoor air temperatures drop down to 1.1C, 0.80 ºC, 0.72 ºC, -0.11 ºC and 0.34 ºC at 06.00 respectively. Then, they start increasing up to 3.41 ºC, 3.05 ºC, 2.92 ºC, 6.63 ºC, and 2.25 ºC at 16.00 respectively. Then, they start decreasing up to 0.10 ºC, -0.20 ºC, -0.19 ºC, 0.20 ºC and -0.71 ºC at 00.00. As seen from the graphs, the indoor air temperature fluctuation is so high in the alternative with single glazing direct gain system that is applied to a south façade in Stockholm like in Istanbul. This affects the thermal comfort of a room for the occupants in a negative way.

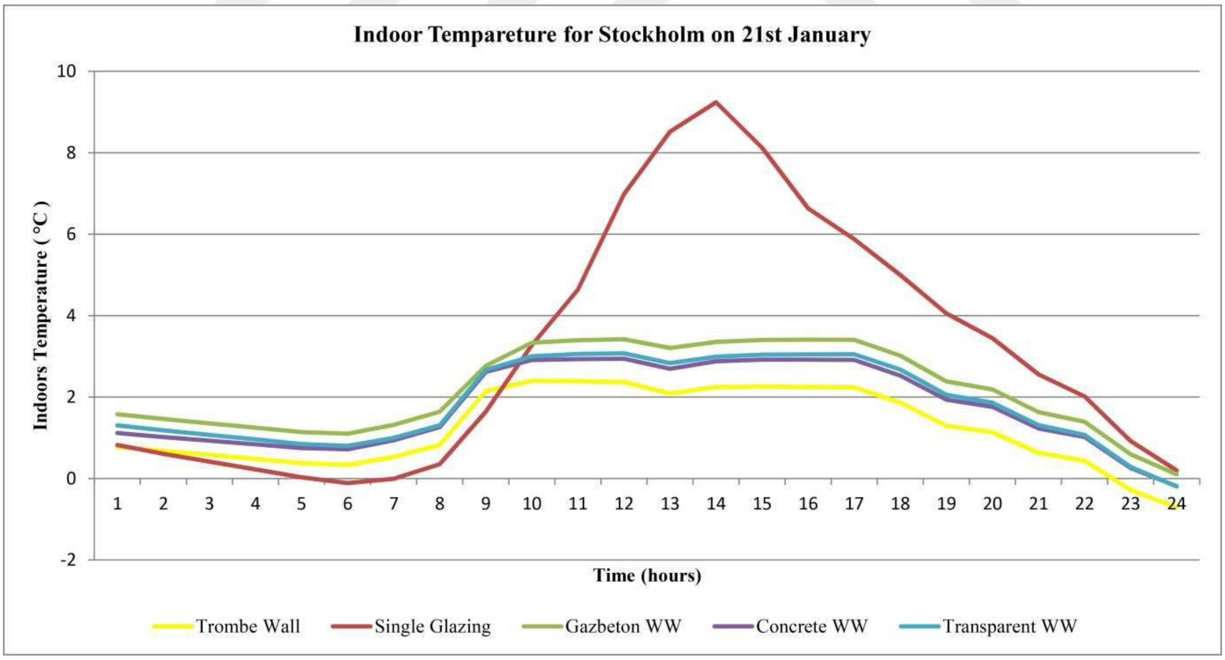


Figure 6.6 Hourly Indoor Air Temperature Variations for Stockholm on January, 21st

(Fig. 6.7) displays the hourly indoor air temperature variations for 1 month in July for Stockholm. During night time, the indoor air temperature variations from highest to lowest are single glazing direct gain system, concrete water wall system, gas concrete water wall system, transparent water wall system and Trombe wall system respectively.

During daytime when the sun is high in the sky and there is solar radiation, the indoor air temperature variations from highest to lowest are single glazing direct gain system, concrete water wall system, gas concrete water wall system, transparent water wall system and Trombe wall system respectively.

The indoor air temperatures in the single glazed direct gain system are higher in the daytime when there is solar radiation due to the higher heat transfer coefficient it has. In a similar way, the single glazed direct gain system loses heat more rapidly compared to Trombe wall and water wall systems. Thus, the temperature fluctuation in the single glazed direct gain system is the highest during 1 day. The minimum and maximum indoor air temperatures are 19.95 ºC and 48.21 ºC throughout July.

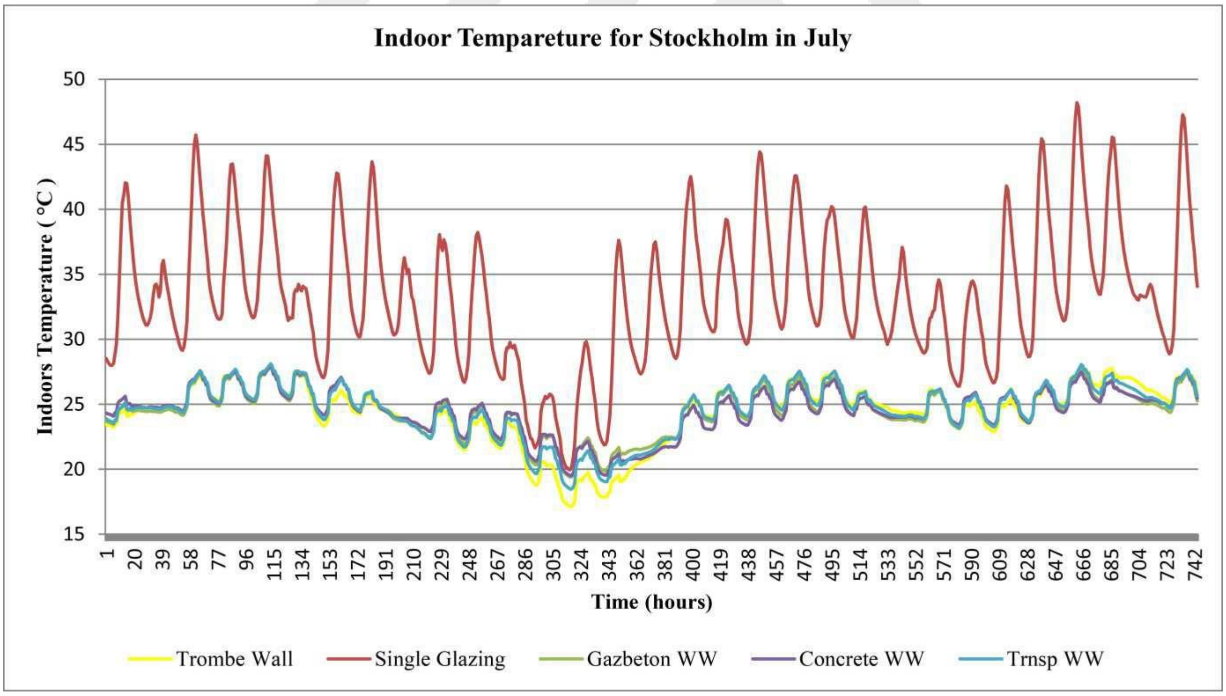


Figure 6.7 Hourly Indoor Air Temperature Variations for Stockholm on July

(Fig.6.8) displays the indoor air temperature variations for 5 different south façade alternatives applied in Stockholm on July 21st. It is seen that the indoor air temperatures from highest to lowest are seen in single glazing direct gain system, concrete water wall system, gas concrete water wall system, transparent water wall system and Trombe wall system respectively.

Transparent water wall alternative provides the best thermal conditions for a cooling period even if the indoor air temperature variations in Trombe wall alternative are lower than the transparent water wall alternative.

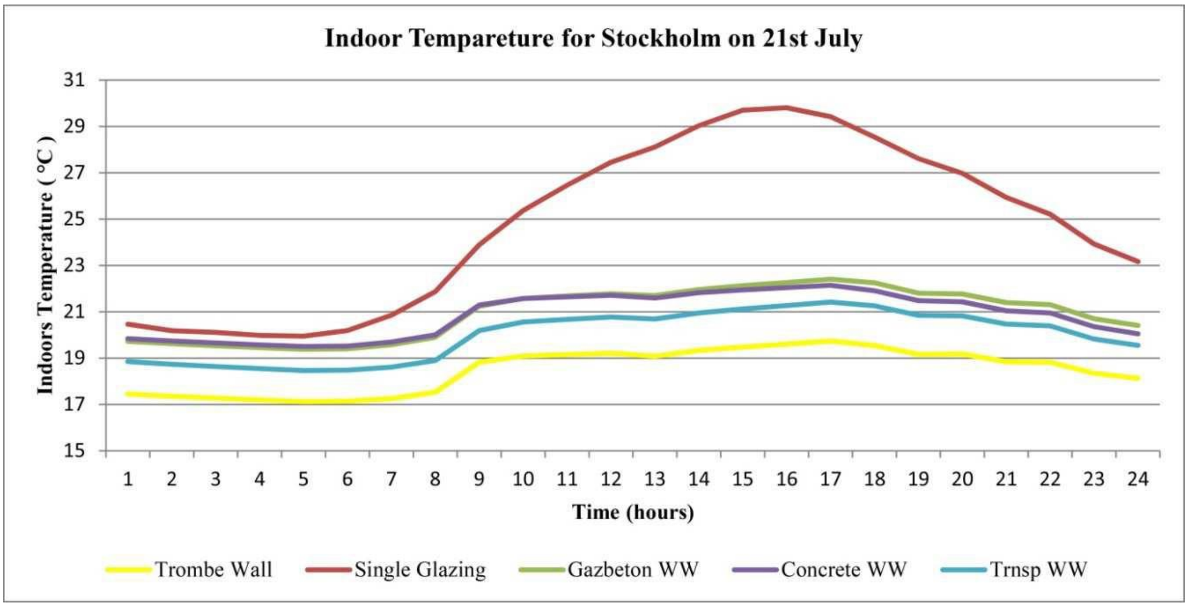


Figure 6.8 Hourly Indoor Air Temperature Variations for Stockholm on July, 21st

(Fig. 6.9, and 6.10) display the hourly surface energy flow through the inner envelope of the south facade for indirect gain system alternatives and the envelope itself for the single glazing direct gain system. The maximum and minimum hourly heat gains for 5 different wall alternatives that are applied to south façade throughout January are 23.06kWh and -2.72kWh respectively.

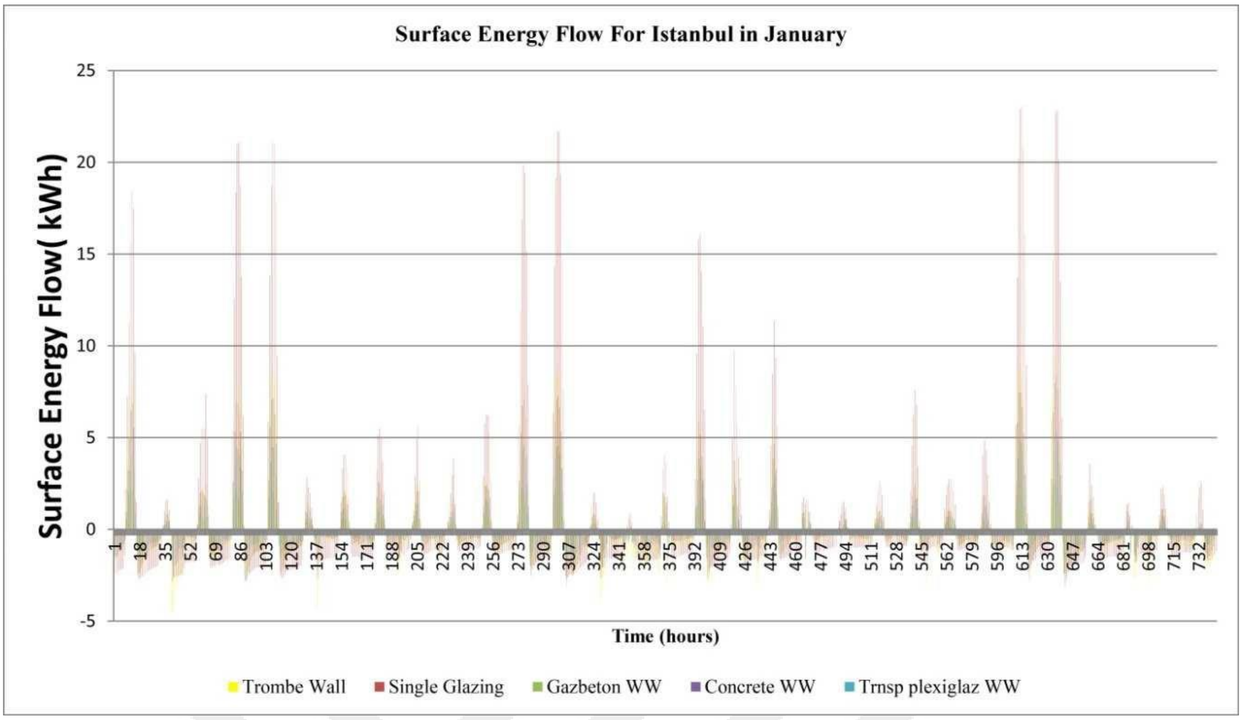


Figure 6.9 The Hourly Surface Energy Flow Through the Envelope for Istanbul on January

In (Fig.6.10, 6.13) all the envelope alternatives lose heat to outside during night time on January in Istanbul and in Stockholm; while they gain heat during the daytime when there is solar radiation heating up the volume. As seen from the graphs, the maximum heat loss to outside and maximum heat gain to the inner volume occur in single glazing direct gain system both in Istanbul and Stockholm but as the temperature fluctuation inside the volume during the whole day is too much, it is not preferable for the thermal comfort of occupants. Similar comments can be made for the heat gains and losses in Istanbul and in Stockholm in July.

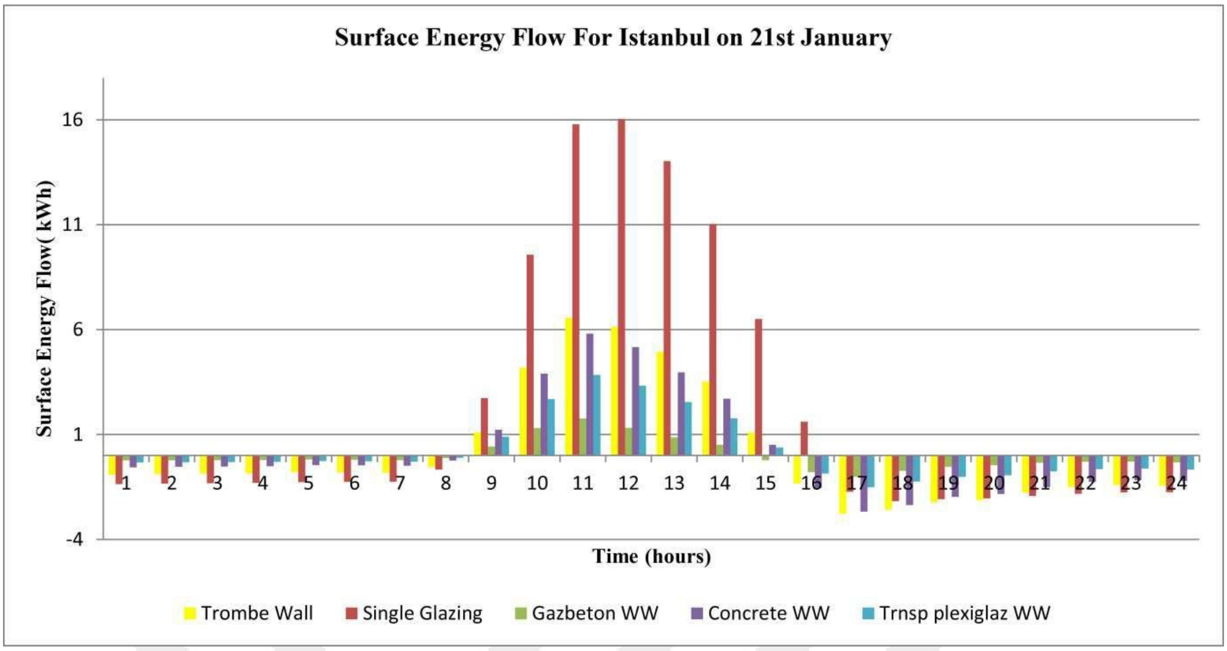


Figure 6.10 The Hourly Surface Energy Flow Through the Envelope for Istanbul on January, 21st

(Fig. 6.11, and 6.15) display the hourly surface energy flow through the envelope for Istanbul and Stockholm in July. The volume loses heat to outside as the indoor air temperature is higher than the outdoor temperature during night time. The exact opposite occurs in daytime where the volume gains heat during the day as the outdoor temperature is higher than the indoor air temperature.

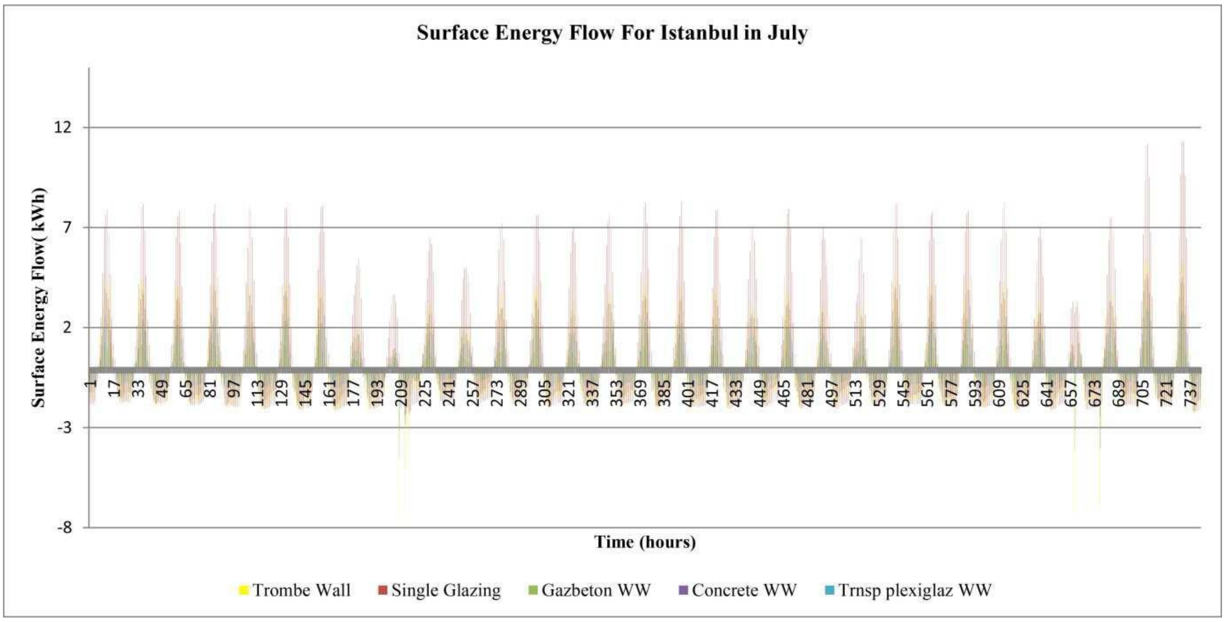


Figure 6.11 The Hourly Surface Energy Flow Through the Envelope for Istanbul on July

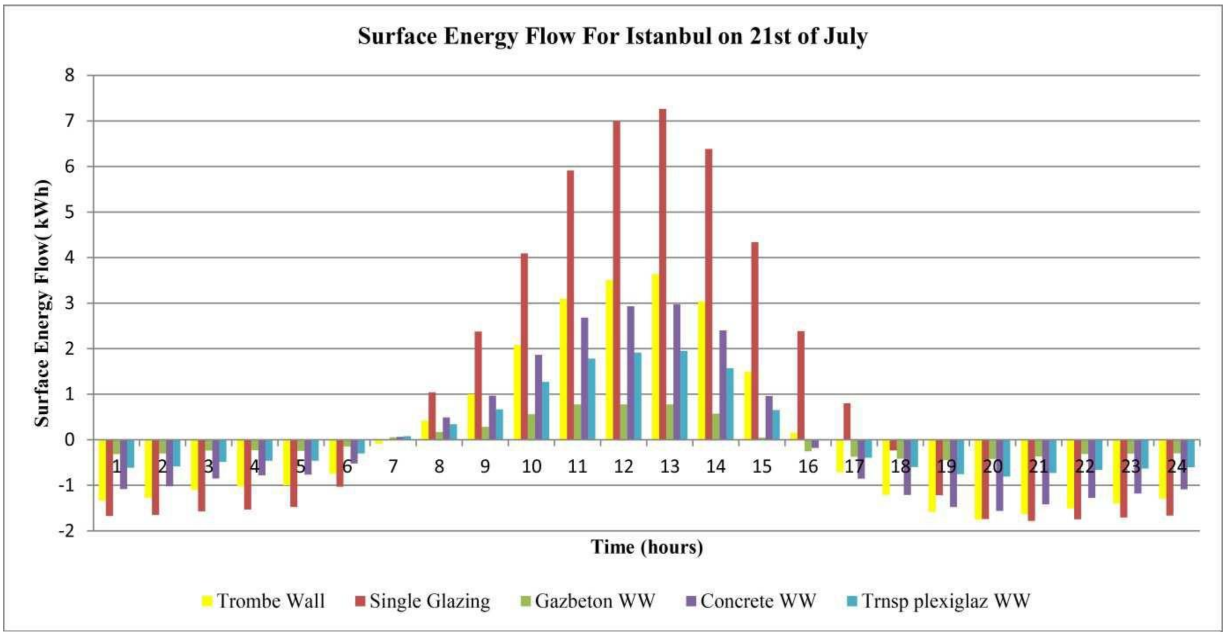


Figure 6.12 The Hourly Surface Energy Flow Through the Envelope for Istanbul on July, 21st

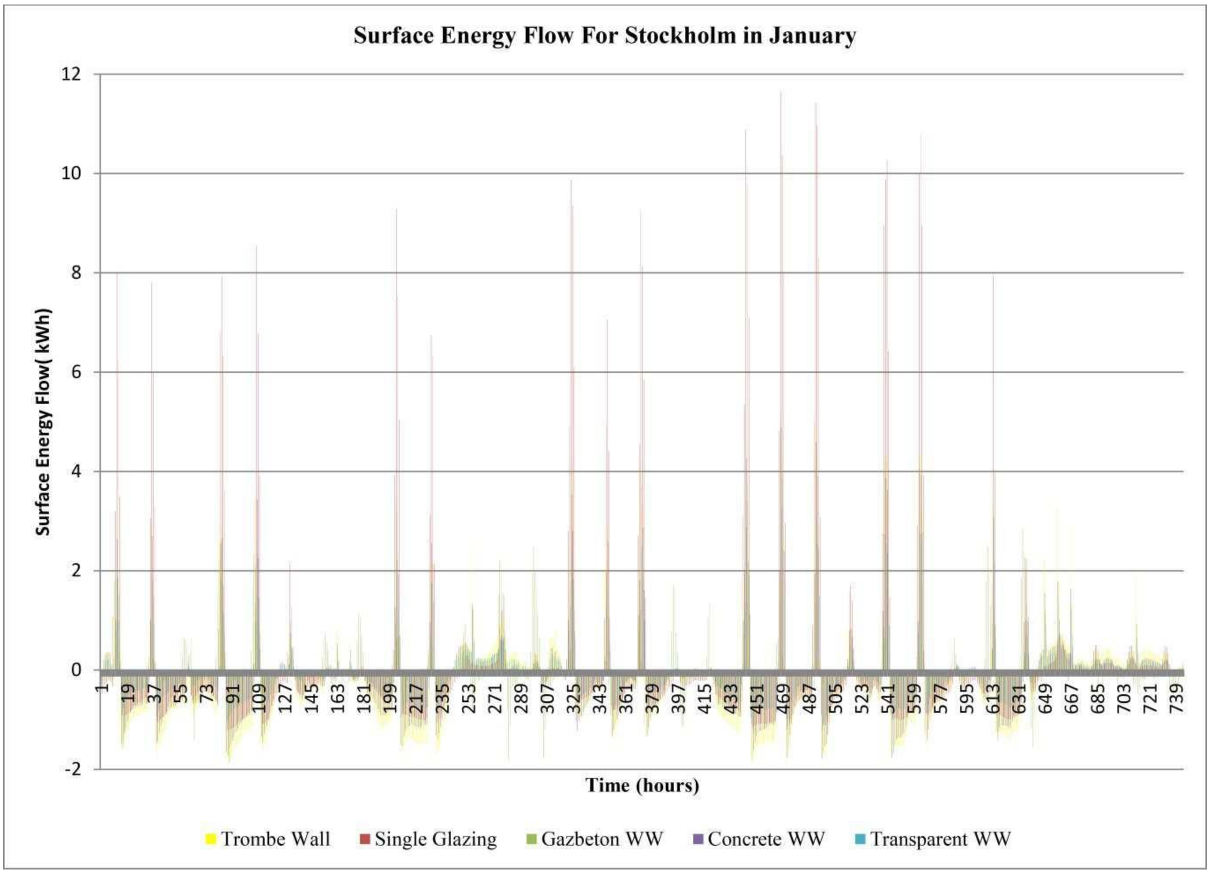


Figure 6.13 The Hourly Surface Energy Flow Through the Envelope for Stockholm on January

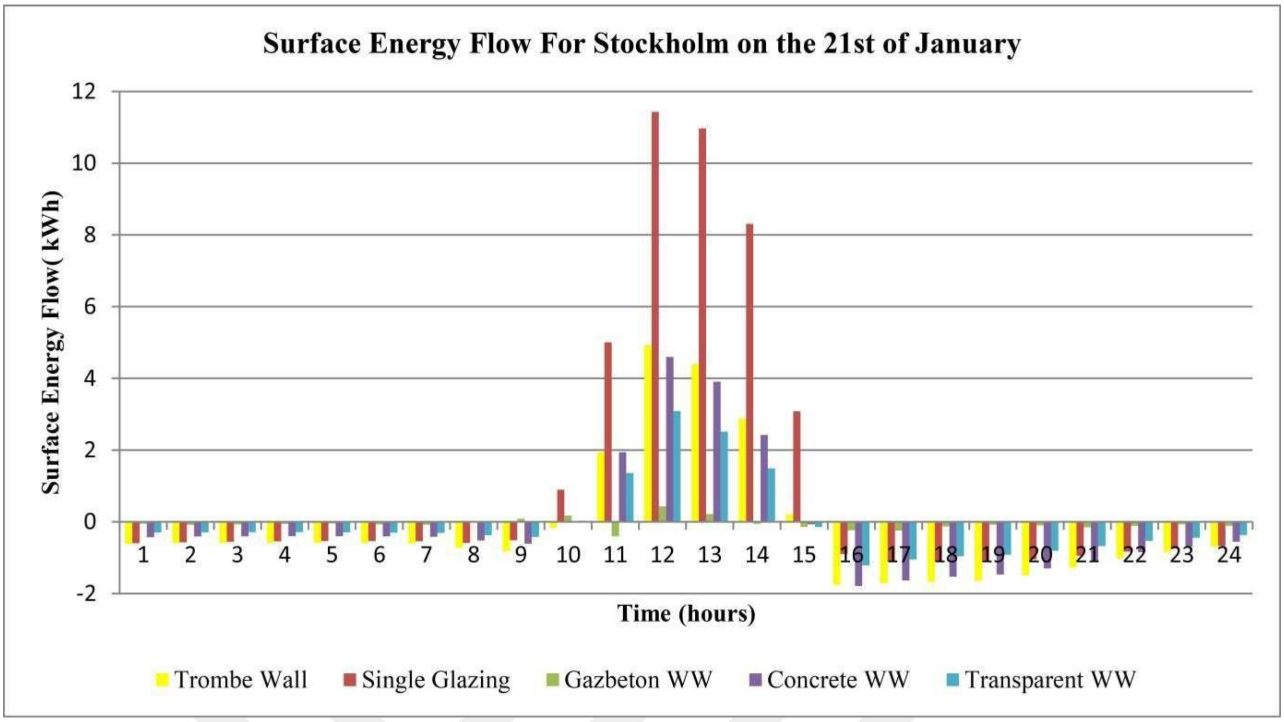


Figure 6.14 The Hourly Surface Energy Flow Through the Envelope for Stockholm on January, 21st

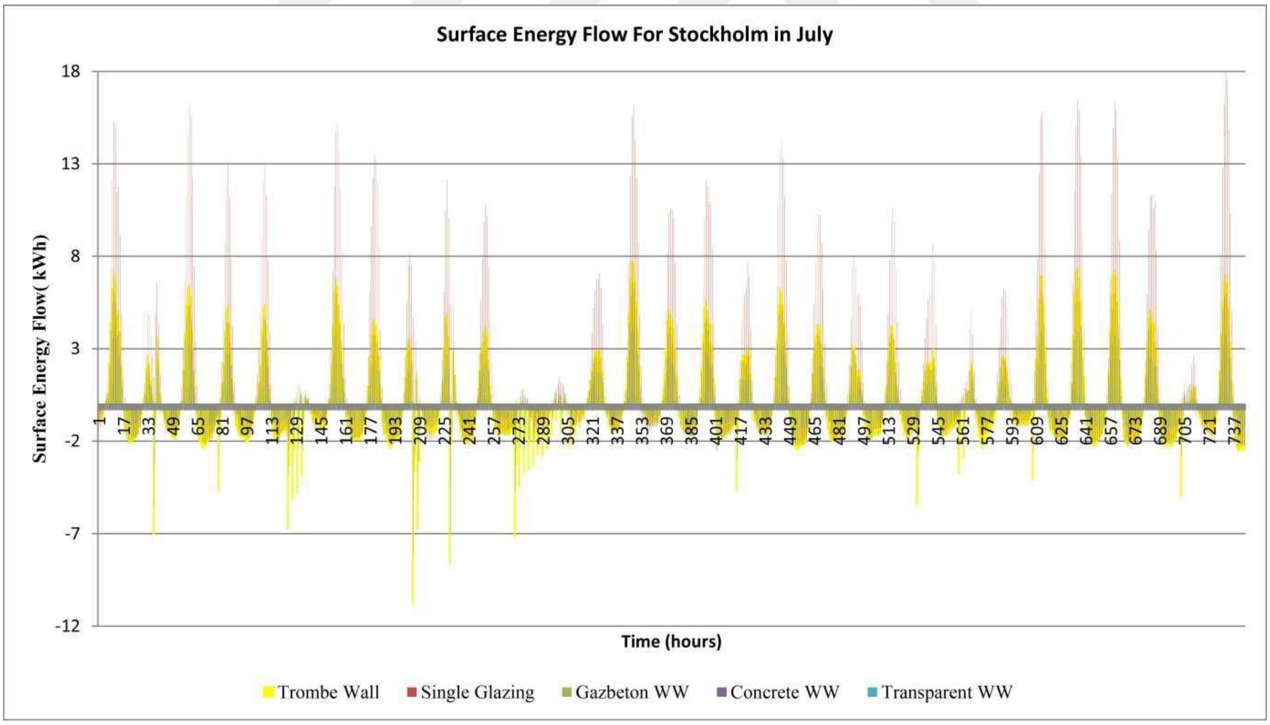


Figure 6.15 The Hourly Surface Energy Flow Through the Envelope for Stockholm on July

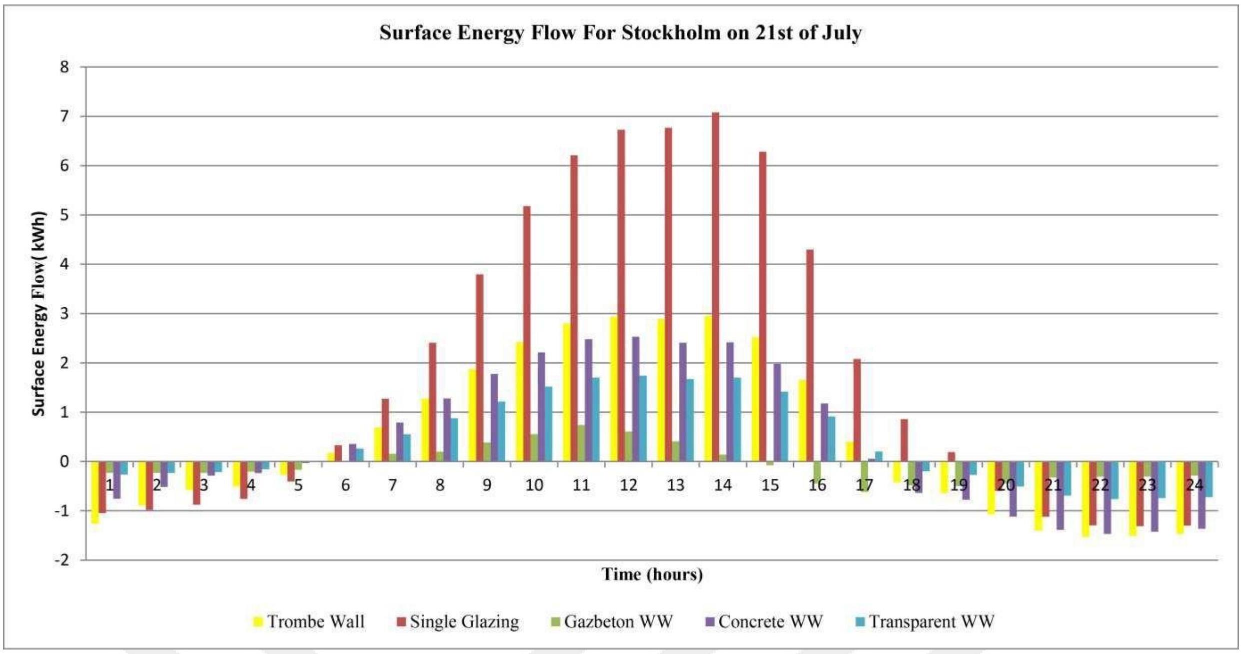


Figure 6.16 The Hourly Surface Energy Flow Through the Envelope for Stockholm on July, 21st

(Table 6.1) shows the number of heat gains and losses for 5 envelope alternatives of the south façade for the whole year in Istanbul and in Stockholm. The results show that the water wall alternatives perform better than the Trombe wall and single glazing direct gain alternatives for the heating period when applied to south façade of a room that is located in Istanbul. Transparent water wall alternative performs the best in Istanbul in the heating period.

Single glazing direct gain alternative performs the worst both in Istanbul and in Stockholm.

Trombe wall performs slightly better than concrete water wall alternative in Stockholm in the heating period. Thus, the occupant should decide which one to apply according to cost or manufacturing benefits.

Table 6.1 The Energy Performance (*kWh*) for 5 South Facade Envelope Alternatives in Istanbul and Stockholm for The Whole Year.

	Istanbul	Stockholm
Single glazing	-6106,4	-4071,44
Trombe wall	-494,8	117,24
Gazbeton WaterWall	-170,46	-23,51
Concrete WaterWall	-179,31	114,33
Transparent WaterWall	-87,17	12,2

Measuring Unite (kWh)

CHAPTER 7
CONCLUSION AND FUTURE RESEARCH

Energy became the increasing trend in the world as it is hard to find and expensive. It shapes the strategic development and the policies of countries. The improvement level is defined by the use of energy amount for each country in both for industry and for residential uses. This necessity for energy leads countries to use fossil fuels. Unfortunately, fossil fuels have a great negative impact on the environment, the living creatures and the world. It causes pollution, which leads to diseases, geographical change, climate change, erosions, a decrease in the efficiency of the land, a decrease in water sources, lack of energy, a decrease in biological variety and lack of food. Precautions should be taken not to face these.

It is possible to decrease the amount of energy consumed in a building from the early design stage. Architects may design the buildings in a passive way. These passive strategies have been used across the globe for centuries.

In this study, a passive design solution which is water wall system has been applied to 2 different cities which are Istanbul and Stockholm that are located in different climatic regions. The comparison of transparent and opaque water wall systems; Trombe wall system and the direct gain system has been done for 2 different cities in 2 different climatic regions.

The results show that the energy performance of the water wall alternatives in Istanbul performs better than Trombe wall alternative in the heating period. Among the water wall alternatives, transparent water wall alternative performs the best in Istanbul.

In Stockholm, the Trombe wall alternative performs the best throughout the whole year. Then, the concrete water wall, transparent water wall, and gas concrete water wall come in sequence. The single glazing performs the worst both in Istanbul and in Stockholm in the heating period.

As a result, water wall system performs better in the hot-humid climatic region but the system should be retrofitted by using vents or/and shading devices in a cooling period. In continental climate, Trombe wall and concrete water wall have close results and better than the other alternatives.

The proposals have been made above according to the simulation results but it should be left to the occupant to pick the alternative as the inner comfort conditions differ according to each person.

In this study, the invented version of water wall system has been analyzed and compared with different system alternatives. The vented water wall system for heating and cooling periods will be analyzed as a future study.

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