SOLARWALL
ENERGY PERFORMANCE ASSESSMENT

by **Antonis M. Psarompas**

Thesis submitted for the degree of MSc in Energy Systems and the Environment

Department of Mechanical Engineering

Energy Systems Research Unit

University of Strathclyde

Glasgow

2001

"The 21st century will see a transition to a new energy source just as has happened in previous centuries. In the 19th century a transition occurred from wood to coal, the turn of the 20th century saw the transition from coal to oil, and the end of the century saw the rapid growth in the use of natural gas in the building sector. Which energy source will dominate as we move farther into the 21st century remains to be seen, but what is certain is that it must be a renewable source. And, the use of solar energy will surely be a major energy source, particularly in the building sector." IEA

Abstract

This work is concerned with the energy performance of a solarwall system. The main part of this thesis is divided into two chapters. The first, is concentrated in general on passive solar systems, it includes background information of what passive solar systems are and how they operate. Furthermore, the indirect gain passive solar system "solarwall" is analysed and its basic principles justified. Case studies of various applications around the world are presented, various points of their implementation listed, in order to examine what particular area needs to be refined further. Based on this final section of the literature study, the second part (research) of the thesis is carried out.

The research is derived from the need to assess the energy performance, potential of the solarwall (energy savings), prior to construction. A building simulation program is used, ESP-r, for the modelling and simulation of a solarwall model, where initial results indicated considerable energy saving potential. Hence, further analysis of the solarwall system with computer simulation follows.

The research part of this work is divided into five main sections. The first section is concentrated on the modelling work involved with ESP-r. First simulations and results are presented and analysed on the second[1] section. The third[2] part identifies and explains under what climatic circumstances the performance of the solarwall component deteriorates or improves considerably. On the following[3] section various modifications on the solarwall system have been applied in order to scrutinize whether its performance can be enhanced. Finally[4], the operation of the fan (required to ventilate the heated air in the solarwall) is taken into consideration and the impact of its energy consumption, on the energy savings contributed by the solarwall, is analysed.

[1] Energy savings in kWh have been calculated, presented. Comparison between the two initial models in ESP-r takes place. This comparison is achieved by picking a typical winter, summer day, for which typical parameters have been plotted for the initial models.

[2] In this section monthly energy savings, average values for solar gains and ambient temperature are plotted. Furthermore, individual days have been picked for various climatic cases for which the same parameters (as the monthly energy performance) have been plotted.

[3] The different models (initial models have been modified) created for this part are compared. Energy savings, heat flux (through the solarwall system into the living space), direct gains, heating load are some parameters used for the comparison.

[4] Annual energy consumption of the fan has been calculated, therefore final energy savings by the different modified models are presented for a final evaluation.

Acknowledgements

I would like to express my thanks to Mr. Christoph Morbitzer, PhD student in University of Strathclyde at ESRU, for his valuable effort to introduce me with the ESP-r building simulation tool and basic modelling techniques. Dr. Paul Strachan, Lecturer at University of Strathclyde Department of Mechanical Engineering, offered his expert advice on the subject during the completion of the thesis.

Finally, I would like to thank Ms. Lori McElroy, SESG Director at University of Strathclyde, for her guidance and help throughout the completion of this project.

Chapter 1. Introduction

1.1 General

"*Capturing the sun's warmth can help us to turn down the Earth's temperature.*" Bill Clinton, June 1997.

Each year, an enormous amount of solar energy reaches the earth's atmosphere. Much of this is reflected back into space by clouds before it reaches the planet's surface. Ninety-nine percent of the sunlight, which does reach the ground, is converted into heat (the other 1% is captured by plants through photosynthesis) and radiated back into space. If only a small fraction of this energy could be captured, the world's energy demands could be met. Even in cold climates like United Kingdom, the amount of useful solar energy reaching the ground in the winter is greater than the daily heating requirements of a well-insulated house. **[25]**

The capture of solar energy by passive solar technologies has almost no negative impact on the environment. Passive solar energy gives off no air or water emissions and therefore does not contribute to any of the environmental problems such as acid rain and global warming, which are associated with other source of energy. The sun is also a virtually inexhaustible source of energy, which is "renewable" and will never become depleted like fossil fuels.

There is nothing new about using the sun's energy to heat living spaces; humankind has used passive solar techniques for thousands of years. In the last century, cheap and abundant fossil fuels have led to the abandonment of passive solar building design. Rediscovering passive solar energy and incorporating technological advances can go a long way towards creating a more sustainable energy future.

Solar energy is a radiant heat source that causes natural processes upon which all life depends. Some of the natural processes can be managed through building design in a manner that helps heat and cool the building. The basic natural processes that are used in passive solar energy are the thermal energy flows associated with radiation, conduction, and natural convection. When sunlight strikes a building, the building materials can reflect, transmit, or absorb the solar radiation. Additionally, the heat produced by the sun causes air movement that can be predictable in designed spaces. These basic responses to solar heat, lead to design elements, material choices and placements that can provide heating and cooling effects in a building.

Passive solar energy has the potential to supply a large proportion of the energy needs for a properly designed building. Although retrofitting a building to incorporate passive solar is possible, it is often fairly expensive. The best opportunity for using passive solar is in new construction. Before the proliferation of fossil fuels, architects routinely designed buildings to utilize available solar energy for heating, cooling and lighting. Recent advances in technology and building materials have greatly expanded the tools for architects to work with, and thus the potential for passive solar energy. Passive solar energy, while often seen as "low-technology", represents in many cases, the cleanest, and least expensive possible source of useful energy for buildings. **[25]**

Buildings are estimated to be responsible for half of all energy consumption in the UK. Space heating accounts for the most significant part of this demand, and contributes around 25% of total UK CO_2 emissions. **[8]**

At the same time, concern for improving indoor air quality and avoiding temperature stratification and sick-building syndrome calls for an increased intake of fresh, outside air. Industrial building operators face a quandary regarding how to maintain combustion also generally means high-energy use for central heating plants and industrial furnaces.

The main problem in the use of solar energy for central heating or cooling purpose is that, in general, most solar heat is available in the season when least heating is required. Conversely heating is required when there are few hours of daily sunshine, so to be able to use solar energy when really needed; it must not only be collected but also stored so as to be capable of recovery when required.

1.2 Solar Resource

The sun showers the Earth with a nearly infinite supply of energy. It is roughly 100,000 times more than the present world output power from all the operating utility plants. Sabady shows that the earth surface at sea level on clear day receives between 850 W/m^2 to 1000 W/m^2 of surface area in some places, but the most recent value is 1373 W/m^2. **[28]**

The energy content of two days of solar radiation falling on the surface of the earth equals the world’s total fossil fuel reserves.

Most of the solar energy comes in the form of light, a short wave radiation, not all of which is visible to the human eye. When this radiation strikes a solid or liquid, it is absorbed and then transformed into heat energy. The material becomes warm, stores the heat and convects it to the surrounding materials (air, water, etc.).

In the USA a 25 percent of the total energy consumption goes into space heating, space cooling and water heating, which means that the rapid development of the solar heating and cooling industry could make a significant impact upon this country’s energy budget.

In the U.K. the variation in solar radiation is very great (a ratio of 10:1 between summer and winter) Turrent. In this country, incoming solar radiation varies between 0-600 W/m^2 depending on geographical location, orientation, time of day and year. **[59]**

Solar energy became economically competitive for space heating and cooling because of the escalation in fossil fuel costs, and as the cost of conventional energy rises the economic position of solar energy for space and water heating and air conditions should continue to improve in the future.

In addition to heating and cooling buildings, McVeigh, Kettani showed many other applications such as solar energy which can be converted into electricity and therefore used to operate engines, power refrigerators, pumps, etc. **[60], [61]**

The United National Industrial Development Organization mentioned that some countries might be able to provide nearly all their requirements from solar systems, but in U.K., which has about half the solar radiation of the USA or Australia, only 10-20 percent of the energy requirements may be satisfied in the long term. Buildings in the U.K. usually receive more than enough energy on their surfaces to match internal thermal demands, if this demand could be averaged over the year. **[62]**

1.3 Why Building Simulation

Approximately one third of primary energy supply is consumed in buildings. Buildings are consequently a primary contributor to global warming and ozone depletion. From the oil embargo in 1973, building energy efficiency has become one of the world's major concerns. As lighting, heating, ventilating and air conditioning of spaces consume most of the building energy, it is vital that thermal performance of buildings and mechanical systems is well understood and optimised in order to achieve energy efficient buildings (EEB).

Computer applications in building design can be categorized into three groups: (1) computerized documentation; (2) computer aided drafting; and (3) computer based calculation and simulation. Today, the first two applications are very popular, which often use personal computers to produce technical documents and drawings. The last application often includes the prediction of peak energy demand for sizing HVAC systems, equipment and plants. Computer aided documenting and drafting indeed improve the working efficiency of building designers, but have hardly impact on building performance. Only computer-based simulation can improve building energy efficiency.

Building simulation started in 1960s and became hot topics of 1970s from the energy research community. During these two decades, most research works related to studies of fundamental theory and algorithms of load calculation, which resulted in some simplified methods, e.g., degree-day method, equivalent full load hour method, and bin method, to predict the energy consumption of buildings, and some detail methods like weighting factors to predict peak cooling load.

Building simulation was expected to lower building energy consumption upon this period. Although the past of oil crisis in 1970s lessens the motive for energy efficiency, building simulation received growing attention during the 1980s due to the quick advance of computer technology. US Department of Energy funded more than one billion US$ for solar energy R&D projects from 1970s to early 1980s. Actually many popular detailed building and HVAC systems simulation programs (BSP) like DOE-2 [3], ESP [4] and TRNSYS [5] stand for the achievements of this period.

Despite the availability of BSPs, they were rarely employed in building design practice because of their hard-to-use and high-cost-to-use. The coming of 1990s reveals two important trends: the first is the widespread use of cheap powerful personal computers; the second is the global concerns of sustainable human settlement, which calls for green buildings that create healthy and comfortable built environment with less energy consumption and less negative impact on the ambient. The design of green buildings makes the application of building simulation a must rather than a need.

Thus, BSPs become routine design and analysis tools. It can be seen that the early 1990s is the real starting point to move BSPs from research community into design community, from the hands of scientists to the hands of professionals.

1.4 Objectives and Aims

The overall objective of this thesis is to assess energy performance of a solarwall system making buildings more reliable and less pollutant to the environment. In order to achieve these objectives the following specific aims are defined:

- Obtain background knowledge on passive solar systems.
- Understand and examine operation of the solarwall system.
- Create computer models and run simulations using ESP-r to assess energy performance of the solarwall.
- Calculate annual energy savings by the solarwall.
- Examine climatic conditions under which the performance of the solarwall is maximised.
- Investigate whether the solarwall model can be refined, by modifying the design, form, materials and operating characteristics of the system.

Chapter 2. Passive Solar Systems and Solarwall

2.1 Passive Solar Systems

The passive solar design term is used to include a wide range of strategies and options resulting in energy-efficient building design and increased occupant comfort. The concept emphasizes architectural design approaches that minimize building energy consumption by integrating conventional energy-efficient devices, such as mechanical and electrical pumps, fans, lighting fixtures, and other equipment, with passive design elements, such as building siting, an efficient envelope, appropriate amounts of fenestration, increased daylighting design, and thermal mass. In short, "passive solar design balances all aspects of the energy use in a building: lighting, cooling, heating, and ventilation. This is achieved by combining, in a single concept, the use of renewable resources and conventional, energy-efficient strategies." **[24], [31], [32]**

Watson gives the definition of a passive heating or cooling system as one in which thermal energy flows through the building (from collection to storage, to distribution) by natural means (radiation, conduction and natural convection) enabling the system to function without external power. Sometimes a fan or pump, for example, is added to assist natural energy flow. Using such a system, thermal energy transfer, in and out of buildings, in and out of the thermal storage, around and through an air conditioned space are achieved by natural means. **[29]**

The basic idea of passive solar design is to allow daylight, heat, and airflow into a building only when beneficial. The objectives are to control the entrance of sunlight and air flows into the building at appropriate times and to store and distribute the heat and cool air so it is available when needed. Many passive solar design options can be achieved at little or no additional cost. Others are economically viable over a building life cycle. **[24]** The purpose of designing a passive solar heating system, Sanford, is to achieve a net heat gain through the south wall and when this heat gain displaces part of the energy supply, this can be considered as "useful" heat gain. **[30]**

A passive solar system designed only for winter heating can inadvertently increase the cooling energy requirements in summer, especially if simple sunshading precautions are ignored. Passive solar systems for building therefore include winter solar gain and summer sunshading, winter wind protection and summer ventilation, as well as a related design of the building's envelope for thermodynamic efficiency resistance of insulation and thermal capacitance effects (for time lag heating and radiation cooling). **[28]**

The U.S. Department of Energy has shown that passive solar buildings use 47% less energy than conventional new buildings and

60% less than comparable older buildings. Passive solar design strategies can benefit most large buildings and all small buildings. It has been used effectively in an estimated 17,000 commercial buildings in the United States — ranging from offices and warehouses to schools, health care centres, libraries, and airport terminals. Passive solar design is best suited to new construction and major renovation because most components are integral elements of the building. Depending on siting, the range of improvements planned, and the building's characteristics, a number of passive strategies can potentially be incorporated into existing buildings. For example, designers can consider using advanced glazings when replacing windows during a renovation. **[24]**

Many different techniques can be used to convert sunlight into useful forms of energy. Active and passive solar energy technologies are generally used for space conditioning (heating and cooling), while solar electric technologies such as photovoltaic cells convert sunlight into electricity. Although the distinction between active and passive solar is blurry, the use of integral building components to capture the sun's energy is considered passive solar. Active solar technologies are generally add-on features, which utilize mechanical means to distribute captured solar energy. An example of active solar energy is a solar hot water heater, while passive solar features may be as simple as south facing windows. **[25]**

Passive solar features can often be included in new buildings without significantly adding to construction costs, while at the same time providing energy savings of up to 40%. Designing the buildings to capture the ambient energy of the sun through passive solar features is one of the least expensive and most environmentally friendly methods of providing for our energy needs. **[25]**

A solar energy system should seek to provide the optimal combination of efficient performance, low initial and running costs, robustness and durability. Successfully integrating passive solar design strategies require a systematic approach that begins in the pre-design phase and carries throughout the entire design process. It is critical that the building owners and the design team agree to integrate passive solar design considerations during the appropriate project phases. The passive solar design strategies discussed later should be included during the building-design process. **[24]**

2.1.1 Passive Solar Design

Optimum passive solar design begins with the layout of a building lot or subdivision. Buildings must be oriented so that they can take full advantage of available solar energy and subdivisions must be designed in such a way that all the new houses or buildings have equal access to sunlight. In the northern hemisphere, it is best to situate buildings with their long axis in an East-West direction. This configuration maximizes solar gain in the winter, when the sun is to the south, and minimizes it in summer afternoons when the sun is in the west. Solar subdivisions are generally laid out on East-West streets with lots, which are wider but less deep than traditional suburban lots. Sun path charts can be used to assess the solar access of buildings in a subdivision. **[25]**

One of the problems encountered during the design of a passive solar system for heating interior spaces is the fact that the sun only shines during the day. Although the amount of solar radiation in most parts of the world is great enough to meet all our heating needs, it is not evenly distributed, and therefore methods of storing the sun's energy for release at night are very important. The most common method of storing passive solar heat is increasing the thermal mass of a building or sunspace. Heat can be stored in concrete, brick, rock and water by simply increasing the temperature of these materials. Of these four, water can store the greatest amount of heat per unit volume. Other materials can store heat by changing their phase, rather than simply increasing their temperature. Calcium chloride hexahydrate is an example of a phase change material, which has a heat storing capacity 10 times that of water. **[25]**

The American Institute of Architects (AIA) **[33]** mentioned three basic solar concepts each involving different relationships between the sun, the storage mass, and the living space. The goal of all passive solar heating systems is to capture the sun's heat within the building's elements and release that heat during periods when the sun is not shining. At the same time that the building's elements (or materials) is absorbing heat for later use, solar heat is available for keeping the space comfortable (not overheated). Many other features exist, but are basically variations of the above. **[25]** These three basic concepts are:

- Direct Gain **[24], [26], [27]**

The direct gain is the most common passive solar system in architecture. In a direct gain structure, the actual living space is a solar collector, heat absorber and distribution system. Sunlight enters the building through the aperture, south-facing glazing material made of transparent or translucent glass. The sunlight then strikes masonry floors and/or walls, which absorb and store the solar heat. The surfaces of these masonry floors and walls are typically a dark colour so that they can absorb more heat. At night, as the room cools, the heat stored in the thermal mass convects and radiates into the room.

This approach works best when the south window area is double-glazed and the building has considerable thermal mass in the form of concrete floors and masonry walls insulated from the outside. The direct gain system will utilize 60 - 75% of the sun's energy striking the windows. The direct gain system is shown schematically in Figure 2.1.

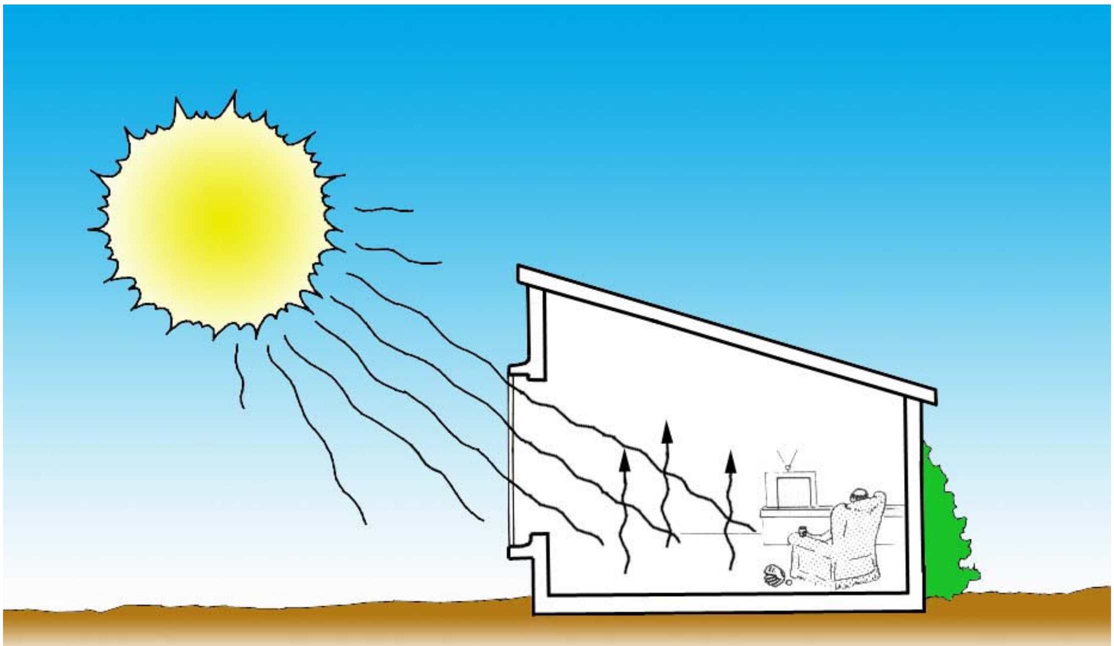


Figure 2-1: Direct gain passive solar system.

In some buildings there have been used water-filled containers inside the living space to absorb and store solar heat. Water stores twice as much heat as masonry materials per cubic foot of volume. Unlike masonry, water doesn't support itself. Water thermal storage, therefore, requires carefully designed structural support. Also, water tanks require some minimal maintenance, including periodic (yearly) water treatment to prevent microbial growth.

The amount of passive solar (sometimes called the passive solar fraction) depends on the area of glazing and the amount of thermal mass. The glazing area determines how much solar heat can be collected. And the amount of thermal mass determines how much of that heat can be stored. It is possible to undersize the thermal mass, which results in the house overheating. There is a diminishing return on oversizing thermal mass, but excess mass will not hurt the performance. The ideal ratio of thermal mass to glazing varies by climate.

<u>Requirements of Direct Gain System</u>

- Large south facing glazed (collector) area, with the living space exposed directly behind.
- A floor and/or wall storage mass of significant dimension for solar exposure and for capacity.
- A method for isolating the storage from exterior climate conditions.

Beyond these basic requirements, there are a series of variations and controls that demonstrate alternatives in passive solar heating by direct gain. The most common variations are found in the location and the materials of the thermal storage mass. The best location of storage mass is often decided by the physical laws governing natural heat flow by radiation and convection. For effective radiant distribution, physical proximity to the radiant body is an important factor in the location of the storage. In addition to storage location, there are significant variations in the storage materials and the massing of those materials, which provide different heat capacities and different time-lag properties. Storage materials vary from concrete, brick, sand, and ceramics, to water and other liquids, either singly or in various combinations.

Indirect Gain **[24], [26]**

The first indirect gain solar building type is the mass wall, in which the sun's rays are intercepted directly behind the collector glazing by a massive wall that serves as heat storage. Figure 2.2 shows the indirect gain mass wall system.

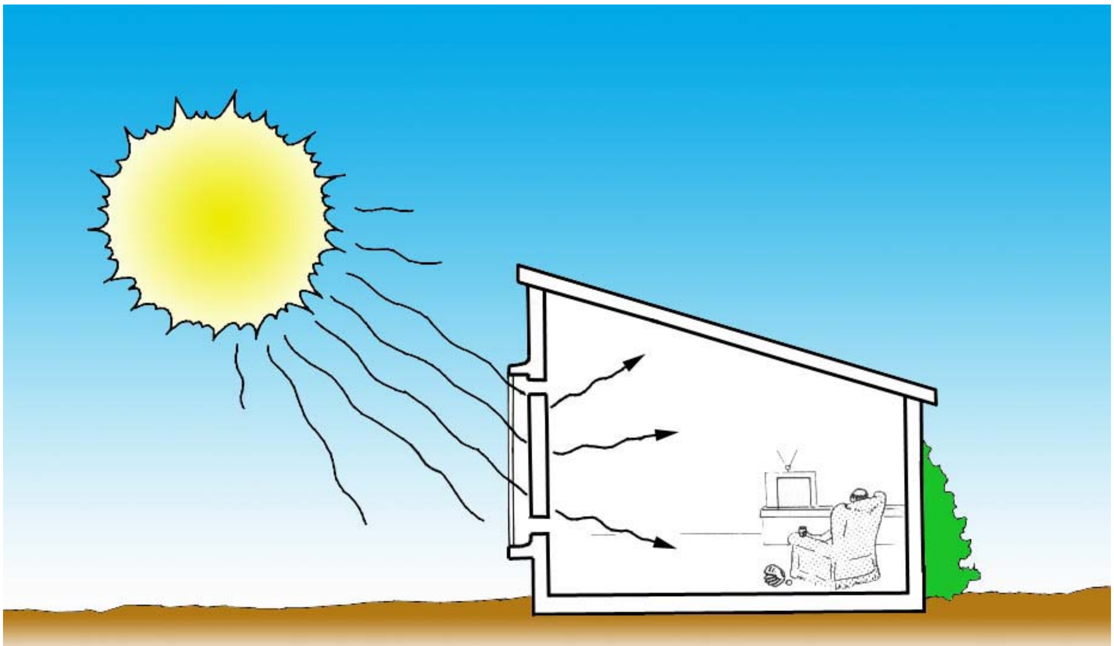


Figure 2-2: Indirect gain passive solar system

The required elements of the mass wall building type involve only a large glazed collector area and storage mass directly behind it. The material property to consider in deciding on storage construction is the method of distribution inherent in massing materials with different heat storage capacities and emission properties. Radiant distribution from a storage mass to an occupied space can be almost immediate, or it can be delayed up to 12 hours, depending on the depth and time lag property of the storage material chosen. Distribution of air by natural convection is also viable with the mass wall system since the volume of air in the space between glazing and storage mass is being heated to high temperatures and seeks constant means of escape.

In an indirect gain system, thermal mass is located between the sun and the living space. The thermal mass absorbs the sunlight that strikes it and transfers it to the living space by conduction. The indirect gain system will utilize 30 - 45% of the sun's energy striking the glass adjoining the thermal mass.

There are two types of indirect gain systems:

- Thermal storage wall systems (Trombe Walls) **[26], [27]**

Using a Trombe wall is the most common indirect-gain approach. The wall consists of an 8 to 16 inch-thick masonry wall on the south side of a house, called the thermal mass of the system. A single or double layer of glass is mounted about 1 inch or less in front of the surface of the wall. Solar heat is absorbed by the wall's dark-coloured outside surface and stored in the wall's mass, where it radiates into the living space.

The Trombe wall distributes or releases heat into the home over a period of several hours. Solar heat migrates through the wall, reaching its rear surface in the late afternoon or early evening. When the indoor temperature falls below that of the wall's surface, heat begins to radiate and transfer into the room. For example, heat travels through a masonry wall at an average rate of 1 hour per inch. Therefore, the heat absorbed on the outside of an 8 inch-thick concrete wall at noon will enter the interior living space around 8 p.m.

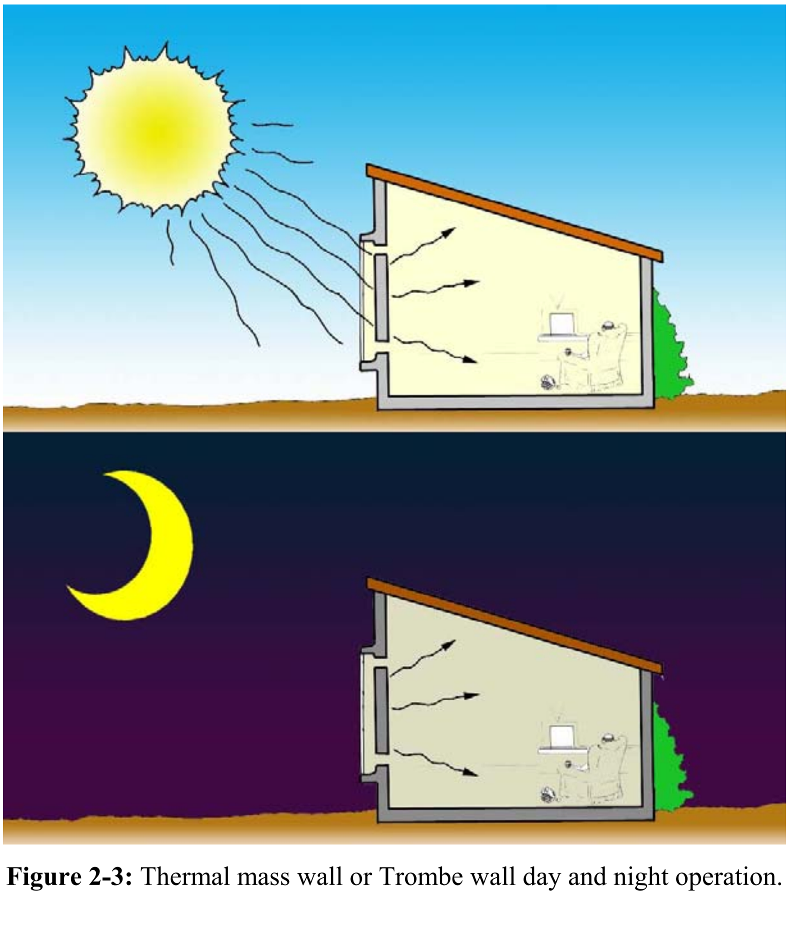


Figure 2-3: Thermal mass wall or Trombe wall day and night operation.

Operable vents at the top and bottom of a thermal storage wall permit heat to convect from between the wall and the glass into the living space. When the vents are closed at night radiant heat from the wall heats the living space. This type of heating is discussed in this project.

- Roof pond systems **[26]**

Six to twelve inches of water are contained on a flat roof.

This system is best for cooling in low humidity climates but can be modified to work in high humidity climates. (Effectively provides heat in southern U.S. latitudes during the heating season for one story or upper stories of buildings.)

Water is usually stored in large plastic or fibreglass containers covered by glazing and the space below is warmed by radiant heat from the warm water above.

These require somewhat elaborate drainage systems, movable insulation to cover and uncover the water at appropriate times, and a structural system to support up to 65-lbs/sq ft dead load.

- Isolated Gain Passive Concept **[25], [26], [27], [28]**

An isolated gain system has its integral parts separated from the main living area of the house. Examples are a sunroom and a convective loop through an air collector to a storage system in the house. The ability to isolate the system from the primary living areas is the point of distinction for this type of system. (See Figure 2.4)

The isolated gain system will utilize 15 - 30% of the sunlight striking the glazing toward heating the adjoining living areas. Solar energy is also retained in the sunroom itself.

Sunrooms (or solar greenhouses) employ a combination of direct gain and indirect gain system features. The living space is the collector of heat, and the mass of a Trombe wall system, which collects heat for indirectly heating the living space. The distribution of heat to the house can be accomplished through ceiling and floor level vents, windows, doors, or fans. Most homeowners and builders also separate the sunspace from the home with doors and/or windows so that home comfort isn't overly affected by the sunspace's temperature variations. **[27]**

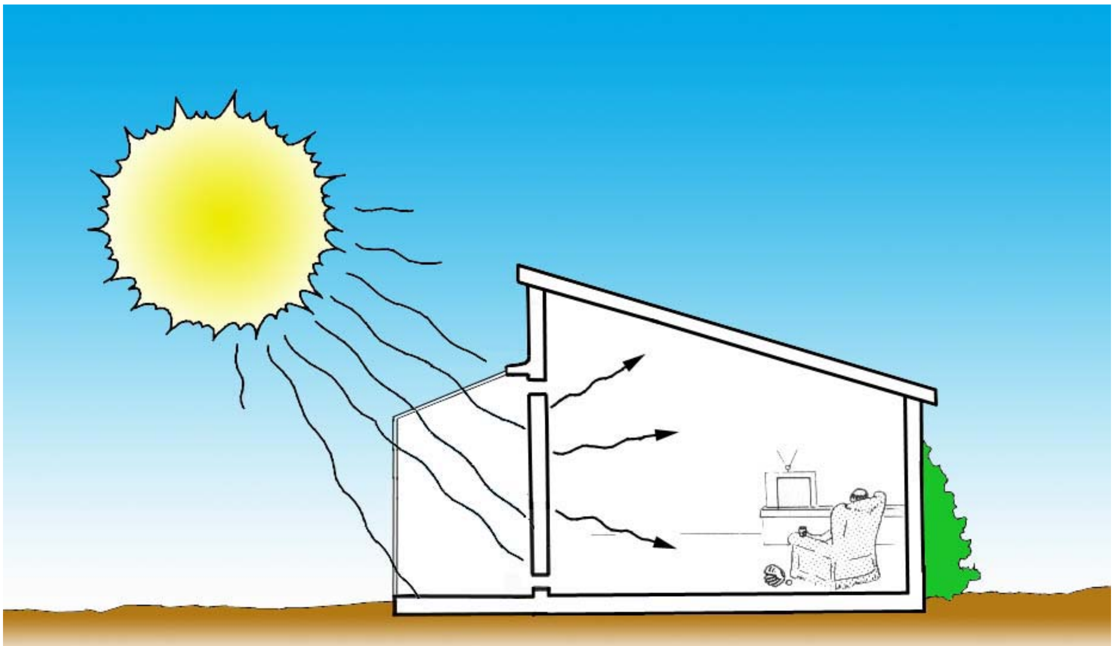


Figure 2-4: Isolated gain passive solar system.

The sunroom has some advantages as an isolated gain approach in that it can provide additional usable space to the house and plants can be grown in it quite effectively.

The convective air collector by comparison becomes more complex in trying to achieve additional functions from the system. This is a drawback in this area where space heating is less of a concern than in colder regions where the system would be used longer. It is best to use a system that provides more than one function if the system is not an integral part of the building. The sunroom approach will be emphasized in this information since it can provide multiple functions.

Sunrooms can feature sloped and/or overhead glass, but is usually not recommended. A sunroom will function adequately without overhead or sloped glazing. Due to hot summers in most areas, it is important to use adequate ventilation to let the heat out. Sloped or overhead glazing is also a maintenance concern. Due to the intensity of weather conditions for glazing facing the full ventilation, passive design and burnt of the sun and rain, seals between the glazing panels need to be of extremely high material and installation quality.

Finally it should be noted that direct solar gain, or heat from thermal storage, could be distributed throughout a building by either natural convection currents or mechanical ventilation. Hot air naturally rises and cold air sinks. These facts can be used to distribute passive solar heat in a building (Figure 2.5). Depending upon climate, design and the existence of backup heating, it may be necessary or advantageous to distribute passive solar energy by mechanical means such as fans and ductwork. Although this may seem "active", such systems are often classified as passive solar because the distribution system is an integral part of the building.

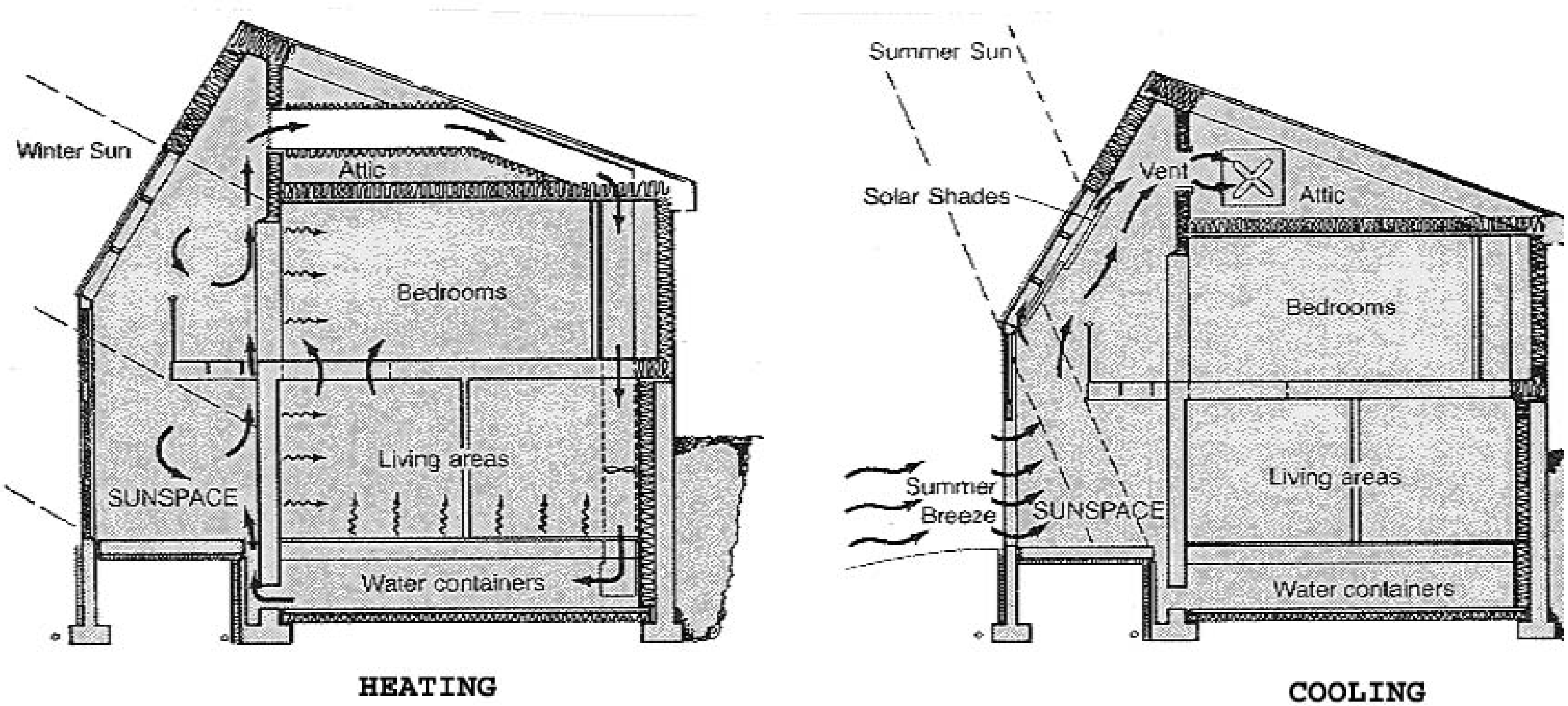


Figure 2-5: A passive solar home in Montgomery County, Pennsylvania. Heating distribution system. **[25]**

All passive solar heating systems are based on the principle of using the south facing elevation as the solar collector. The main objective in passive solar design is to maximise the useful solar heat gain and minimise the conductive losses back through the fabric. In general the main elements of passive heating or cooling are, the collector, which will be described later, the storage material (storage mass), and the space to be heated or cooled. **[28]**

The storage material consists of a dense, heavy material that:

a) Receives and holds heat and later releases the heat to the interior of the structure.

b) Is of sufficient volume, depth, and thermal energy capacity to store and deliver adequate amount of solar heat for the structure.

c) Is located so that it is capable of distributing the stored heat directly to the different areas of the structure through heat distribution methods.

d) Has an area of directly irradiated material equal to or greater than the solar collection area.

The outside of the storage mass, which is the surface facing the sun, is normally dark in colour to increase the amount of absorbed radiation (the amount of heat stored) to increase the efficiency of the system. The heat collected depends upon the location and the construction of the storage material, and typical locations are:

a) External building walls.

b) Internal building walls.

c) Floor surfaces.

d) Free standing masses.

In passive solar energy systems it is most common to use the south facing walls and windows for energy collection. This, however, is only one component of a “system” which requires storage media and night window insulation to perform effectively.

Every type of storage system requires considerable insulation to reduce its heat loss to the surrounding environment. For example, in the fourth Massachusetts Institute of Technology (MIT) **[34]** solar house which was built in 1959, about 43 million kJ during the six month heating season were collected, about 6.8 million kJ were lost from the warm tank of water located in the unheated basement, and only 36.2 million kJ were used.

The sequence of sunny and cloudy days is important to storage sizing. The solar system (including solar heat gain and the thermal mass of the house) could be sized to collect heat for one sunny day and for the following cloudy day, and 100 percent of the heating demand could be provided by solar energy if the system is sized for the coldest two days period.

South facing rooms are much warmer than north facing rooms in most passive solar buildings, and upper spaces in a building are generally warmer than lower spaces due to temperature stratification. Conventional building materials and products can be used for passive solar applications. The storage material varied from concrete, brick, sand and ceramics, to water and other liquid, either singly or in various combinations, Pinto. **[35]**

One of the most common features in the storage material is the time lag, which is beneficial because the material delays the arrival of heat at the indoor surface until it is needed. Also, the most efficient storage container is the material, which is incorporated into the building as walls, floors, roofs and partitions.

2.1.2 Passive solar heating in the UK

Ferraro shows most research and development on solar applications in U.K. buildings has been concentrated on the development of active systems, as shown by the Department of Energy. **[36], [37]**

Passive systems, however, have many advantages for example, lower capital costs and greater reliability. Initial estimates indicate that they can yield useful amounts of energy and show considerable promise for becoming cost-effective in the near future.

All passive solar heating systems are based on the principle of using south facing materials as solar collectors. Passive systems appropriate for the U.K. climate fall into four main categories:

a) **Direct gain**: using south facing double-glazing window where the area of south facing glazing is increased to the maximum practical limit, and using insulated shutters at night.

b) **Conservatories**: Single (or double) glazed, lean-to conservatories can be considered as passive solar collectors. The main problem in this is the poor resistance to conduction losses.

c) **Trombe wall**: This will be discussed later.

d) **Roof space collector**: The south facing roof surface is glazed and energy is collected in the roof space and then transferred by fan to the rooms below.

One of the most technically interesting developments, Ferraro, at the present time involves the application of low emissivity coatings on glass. Long wave radiation is reflected back into the interior space and heat losses are reduced. **[36]**

Another development is the investigation of new building material, which incorporates phase change material for heat storage.

In some passive system designs, Anderson and AIA showed that thermal storage could be located on the roof by using a roof pond that contains water stored in large plastic bags. These are dark coloured bags, which absorb the heat during the day and then at night conduct it through the roof and radiate it from the ceiling to the space below. **[34], [38]**

An insulating panel covers the roof pond at night to reduce heat losses. This system is called “skytherm” Anderson that can be used also for cooling during summer. In this case the water absorbs heat from the space below and radiates the heat to the outside through the process called nocturnal radiation cooling Anderson. **[34]**

2.2 Solar Walls

Since ancient times, people have used thick walls of adobe or stone to trap the sun's heat during the day and release it slowly and evenly at night. Today's passive solar buildings often improve on this ancient technique by incorporating a thermal storage and delivery system called a Trombe wall (solarwall). Named after French inventor Felix Trombe in the late 1950s, the Trombe wall continues to serve as an effective feature of passive solar design. **[23]**

The solarwall can be located between a wall of glass (or plastic) and the space to be heated. All existing solar wall designs are variations of the systems depicted in Figure 2.6 **[20]**. Although the above fact, there are two basic types of thermal storage walls.

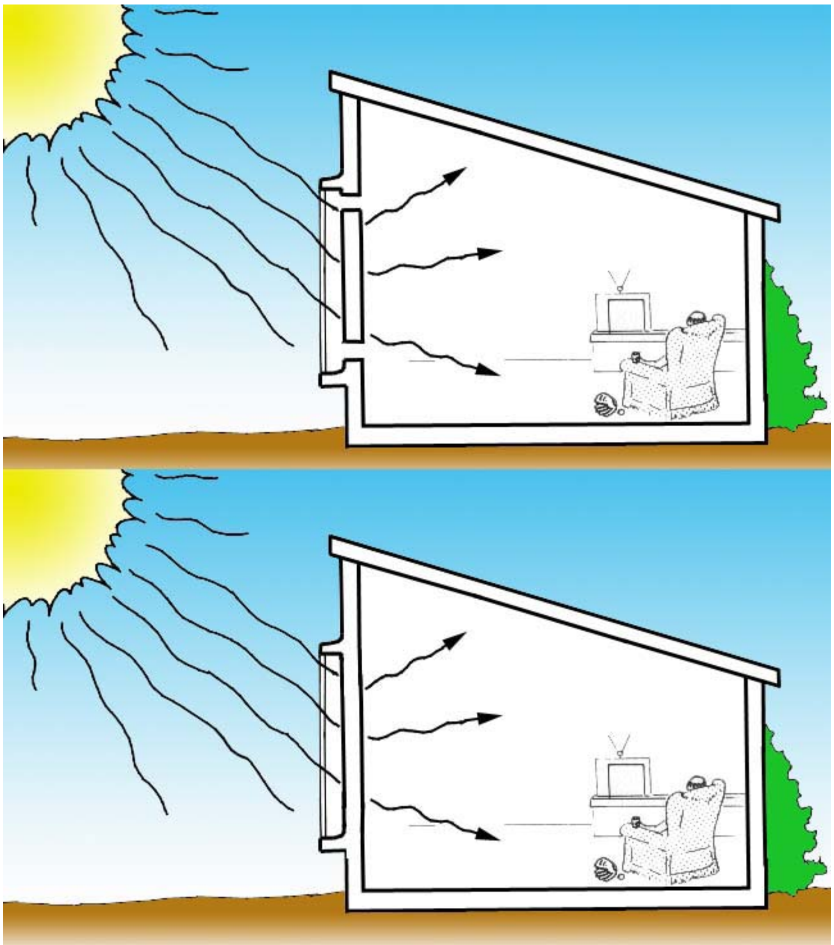


Figure 2-6: Two basic types of the solar wall.

The first one uses heavy masonry materials, the surface of which is painted a dark colour (sometimes black), which absorbs the solar energy passing through the glass and converts it to heat. A fluid (generally water or air) is used to transfer heat from the storage material to the living space. The most effective place to build the wall is directly inside the window, thus the sunlight strikes the wall instead of directly heating the house as solar window. This has a great disadvantage of limiting the amount of light entering the room. This wall is called the “Trombe Wall”, Anderson, and Dickinson, related to Professor Felix Trombe in France. Figure 2.7 shows the details of the Trombe Wall. **[34], [39]**

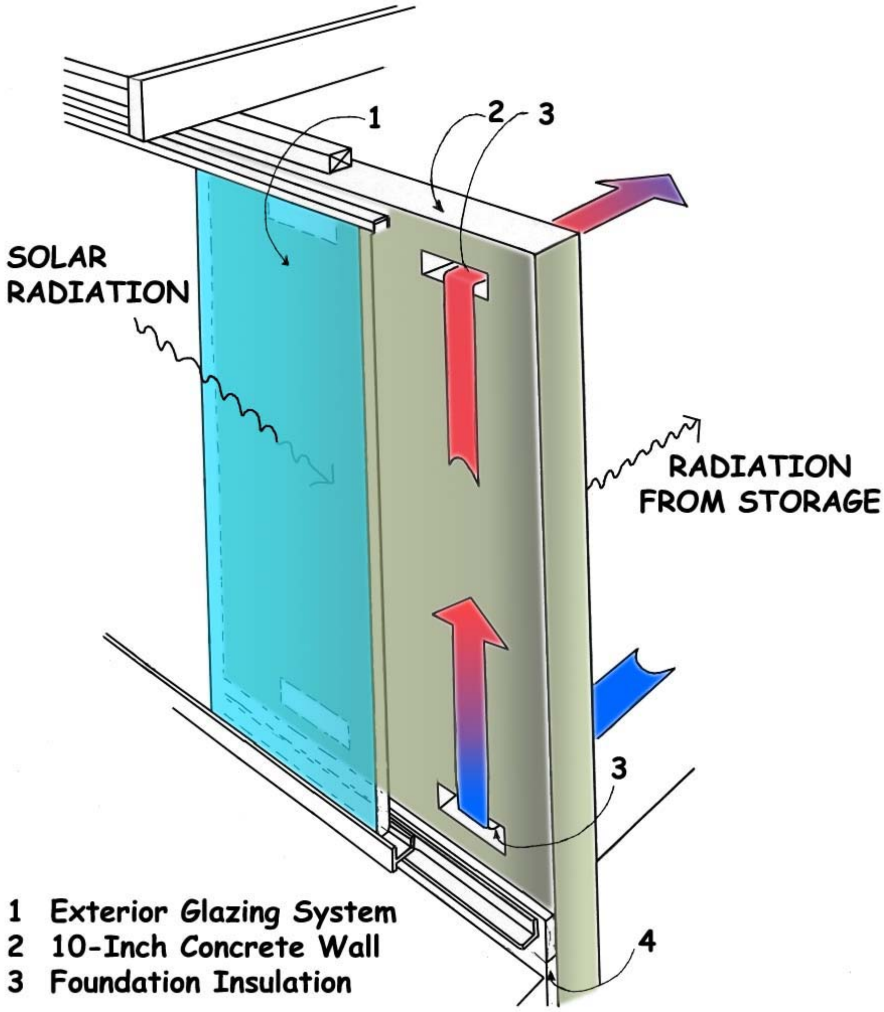


Figure 2-7: Trombe wall details. **[34]**

In this Trombe wall, airspace runs between the wall and the glass, the chimney effect, Anderson, causes the heated air to rise during the day. Openings at the bottom and top of the Trombe wall are provided to allow the cold air along the floor to enter the airspace, as shown in Figure 2.8 Anderson. **[34]**

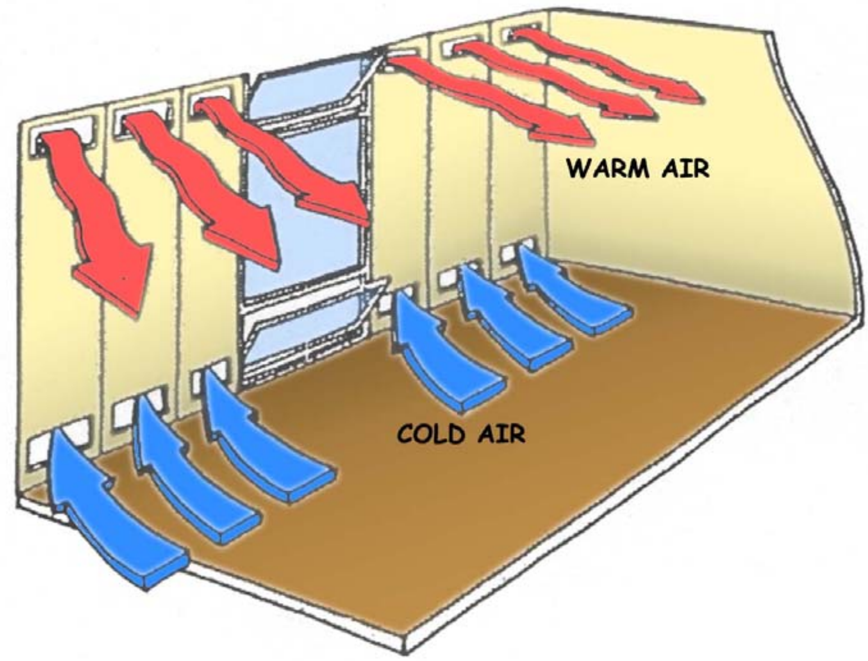


Figure 2-8: Air movement between air space and room. **[34]**

For an 8-inch-thick Trombe wall, heat will take about 8 to 10 hours to reach the interior of the building (heat travels through a concrete wall at rate of about one inch per hour). This means that rooms remain comfortable through the day and receive the heating slow for many hours after the sunset, greatly reducing the need for conventional heating. Rooms heated by a Trombe wall often feel more comfortable than those heated by forced-air furnaces because of the radiantly warm surface of the wall, even at lower air temperatures. **[23]**

Heat is transmitted to the living space by natural convection (sometimes by forced convection when a fan is added to the system) through the openings in the top and bottom of the concrete wall. Heat is also transmitted by conduction through the wall because, on a sunny day there is a temperature gradient between outer and inner surface of the wall, causing a rise in temperature at the wall interior surface, and this causes heat transfer to the living space by radiation, convection at night (or in cold climates) after removing the insulation which is sometimes added between the wall and living space.

Manual or automatic dampers can be installed in the openings to prevent the nighttime reverse flow of air, which can cool the space.

The other type of wall uses containers of water to substitute the masonry materials or water filled Trombe wall is also sometimes used instead of mass Trombe wall (concrete). The natural flow of air is from the room to the space between the glass and the water wall or the containers of water, then back to the room.

It is common for water Trombe walls to use either containers of water such as tubes of water or barrels, of fabricated water walls. In these walls, the solar heat is transferred quickly through the water containers, which then radiated and convect heat directly to the living space.

The water Trombe wall tends to be slightly more efficient than the solid wall because it absorbs heat faster due to convective currents of water inside the containers as they are heated. This causes immediate mixing and quicker transfer of heat into the house than solid walls can provide, and the water wall is called "drumwall", as shown by Bear. Figure 2.9 shows the water Trombe wall. **[34]**

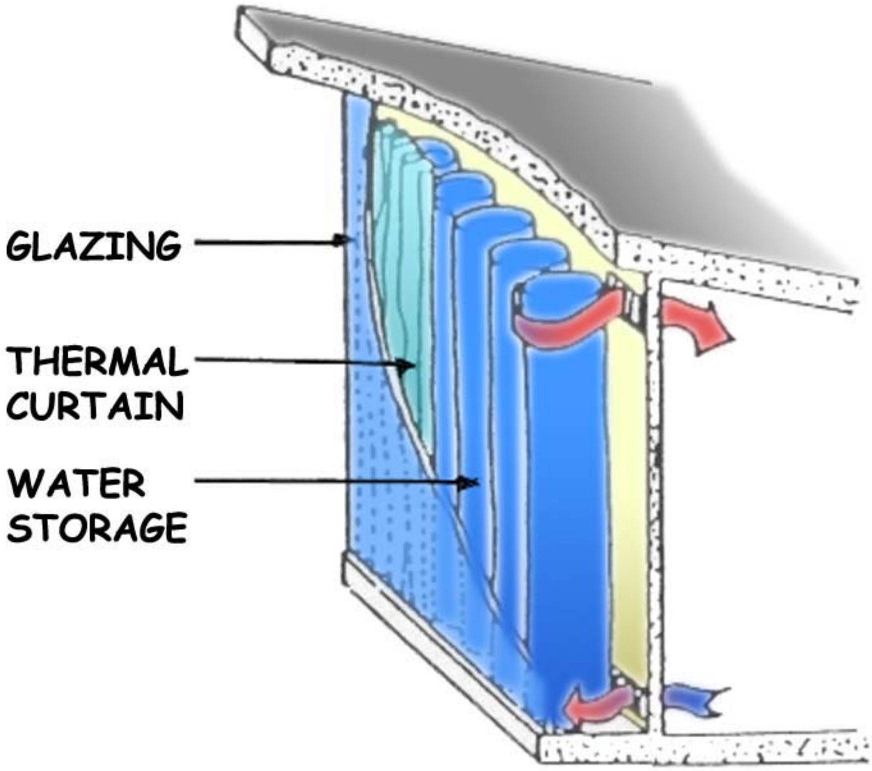


Figure 2-9: Water Trombe Wall. **[34]**

Buildings with large windows facing the equator (south in the northern hemisphere, or north n the southern hemisphere) are arranged to admit solar radiation into the building when the sun is low in the winter sky, and these buildings are called (solar houses). When the sun is available the heat gain from radiation is significant, but in the other condition where the sun is not available, i.e. cloudy weather or at night, or in cold climates, in these circumstances the losses from the walls should be reduced by the provision of insulation, and an auxiliary heating system is necessary.

Thermal storage walls perform both functions of collection and storage in a simple way. Usually they constitute the buildings south façade, having a dark surface, external glazing and moveable insulation, which can cover the outside surface whenever weather conditions are unfavourable.

During the day solar energy is absorbed at the outer surface and conducted through the wall providing heat to the room with a time delay characteristics of the wall material and its thickness.

One of the main problems in the design of the Trombe wall has been matching the wall properties (its thickness and thermal properties), to the location in which the house is to be built. If the wall is too massive to be sufficiently heated by the sun, then it will place an extra load on the building heating system. Conversely, if it is too thin, too much solar energy may enter the room, overheating it and making uncomfortable conditions for the occupants. Also, the heat storage capacity of different materials varies according to their specific heats.

Most walls are designed to release collected energy gradually to the building's interior. Massive walls continue giving off heat 8 or more hours after the sun has set, thus helping to keep the house at a comfortable temperature throughout the night. **[20]**

Trombe walls are often designed to serve a load-bearing function as well as to collect and store the sun's energy and to help enclose the building's interior spaces. Multiple uses of solar energy components help greatly to reduce the overall labour and material cost of constructing a passively heated building. **[20]**

A critical part of solar wall design is choosing the proper thickness. Excessively thick walls take too long to transmit the thermal energy they collect. A typical result of this might be a living space that does not receive enough heat during the evening hours when it is needed most, for the energy is still working its way through the wall. Walls that are too thin, on the other hand, transmit energy too rapidly, resulting in overheating of the living space during the day and little energy left for the evening. The solar savings fraction, the percentage of the building's heating needs that are met by the sun's energy, is also decreased in poorly designed wall systems. **[20]**

The optimum thickness of a Trombe wall is to a great extent dependent on properties of the material from which it is made such as thermal conductivity and heat capacity. The higher the conductivity, for instance, the faster heat flows through the walls made of a variety of commonly used materials. **[20]**

Solar walls made of different materials lead to different levels of performance, whether the walls are optimally thick or all of equal thickness. **[20]**

2.2.1 Solarwall©

Solarwall© is a product developed by Conserval Systems Inc. An 18-month, $80,000 Inventions and Innovation grant, along with additional funding provided by the Department of Energy's Office of Power Technologies and the Office of Building Technology State and Community Programs, allowed Conserval to improve the efficiency of this indirect gain solar wall system.

Solarwall© is an unglazed transpired solar collector (absorber) whose convection losses are reduced, because the external boundary layer is pulled in through the perforations Figure 2.10. The National Renewable Energy Laboratory made significant contribution as to the understanding of transpired solar collector, which is used to heat large quantities of ventilation or process air. The design is cost effective because there is no glazing and the transpired collector can easily be integrated with the building structure. **[13]**

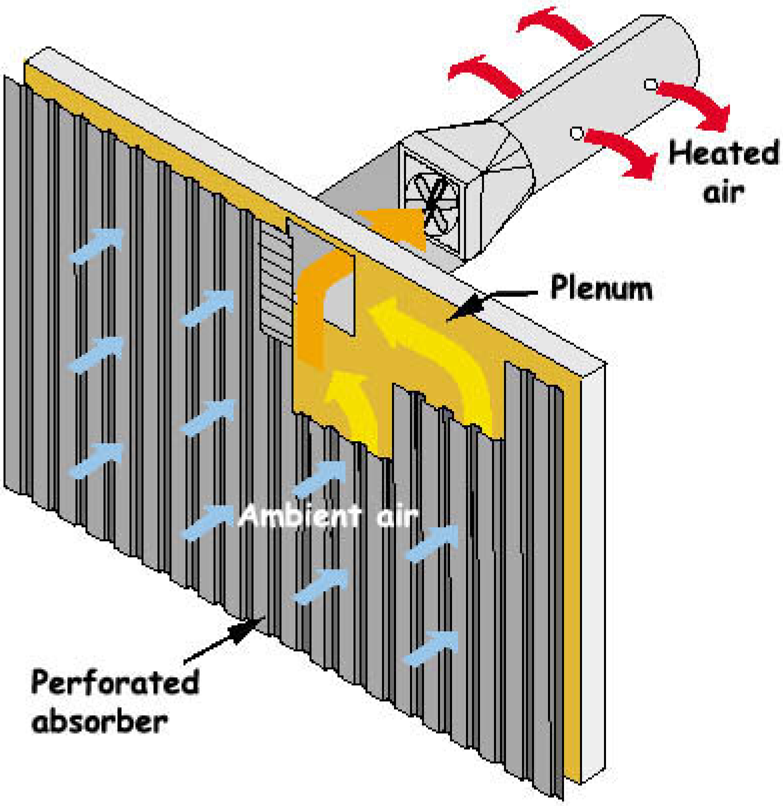


Figure 2-10: Solarwall© system developed by Conserval Inc. **[63]**

Solarwall is an unglazed aluminium surface perforated by small holes (the holes 1.6mm in diameter consist the 2% of the total collector surface). The surface is painted with black colour to maximise the absorption of solar energy (although any dark colour can be used, but there is an efficiency penalty of approximately 10% for the use of a non-black surface on the panels **[1]**). As outside air is drawn through the air space, the absorbed solar heat is transferred from the metal to the air. The pre-heated air is collected in a canopy plenum and then ducted into the normal heating system of the building. **[5]**

Glazed solarwalls have great disadvantages compared to this perforated plate system. Glazing is expensive and fire concerns are raised. Some incoming solar energy is lost due to the reflection of the glazed surface. Moreover, it provides a cost effective alternative for retrofit applications. **[5]**

There is a basic distinction between the perforated plate solarwall and a Trombe wall. The performance of the aluminium plate solar collector does not rely on the storage of the thermal energy. **[1]**

2.3 Thermal Protection

As with all passive systems, the aim of a solar wall is to collect the maximum amount of solar energy while losing a minimum amount of heat to the outside. Two heat-retention options to be considered are: increasing the number of glazings beyond the two typically used and adding a selective surface to the wall. **[20]**

Additional Glazing

Each layer of glazing added to system increases the thermal resistance of the south wall, but it also decreases the amount of transmitted sunlight. The difference in solar savings fraction between pone glazing and two is very large, which is why double-glazing is standard in the solar industry. But as successive glazing layers are added, the increment in performance becomes steadily less. The addition of the third layer of glazing has far more effect in cold climates like Madison, Wisconsin, than it does in a gentle one like Santa Maria, California.

Adding multiple layers of glazing to a system can be an expensive undertaking unless thin films as Mylar or Teflon are used for at least some of the layers. The advantages of installing multiple glazing layers for thermal protection, is that once in place they require no user participation. Night insulation, on the other hand, requires daily installation and removal (unless automatically operated), but it also provides higher insulating values.

Selective Surfaces

A less expensive and more efficient alternative to movable insulation is a selective surface applied to the good absorber of sunlight, but it is unfortunately a good emitter of thermal energy as well. As a flat black wall's surface temperature rises, much of its energy is given off in the form of infrared "heat" radiation that is absorbed by the glazing and eventually lost to the outside. A selective surface is able to reduce these emissions radically.

Selective surfaces for solar applications are made of materials that absorb sunlight nearly as well as flat black paint while, for reasons related to their ability to carry electric current, have a low emissivity of energy in the infrared wavelengths. Since infrared energy flow makes up a large part of the total energy loss of the system through the glazing, selective surfaces can be quite effective in improving performance.

"Black chrome" commonly called, is a very effective selective surface. Numerous experiments have confirmed that selective surfaces can dramatically reduce heat losses.

2.4 The Effect of Wall Colour

For aesthetic reasons, solar walls are sometimes coated with colours other than black. While this can be done in direct gain systems with little overall impairment of performance, solar walls are somewhat more sensitive, due to the fact that reflected sunlight is not reabsorbed by other surfaces but is for the most part lost through the glass.

Most of the sunlight that is reflected from a solar wall is lost out though the glazing. Dark colouring should thus be used on a solar wall to reduce reflection and improve absorption as much as possible.

It is suggested that if the flat black colour of a painted or selectively surfaced wall is not aesthetically pleasing to the designer, it would be advisable to use translucent glass to hide the wall rather than change its colour. **[20]**

2.5 Solar heating experiments

Many experiments have been made on solar heating and various buildings have been carefully engineered using advanced instrumented systems based on solar water heating, water storage. Others have also investigated the use of different fluids, some of them with different Trombe wall materials and thickness.

Some of these are mentioned here and many others can be found in the literature. Many tests have been done using different kinds of passive systems.

2.5.1 Residential case studies

In 1948 Telkes and Raymond described a solar house with vertical south facing air heater collectors and energy storage using the heat of fusion of sodium sulphate decahydrate. This house was constructed a t Dover, Massachusetts, and the capacity of the storage system was to carry the design heating load for five days. **[34]**

In Arizona (1955), Bliss used a matrix type of air heater and rockpile energy storage unit in solar houses. Bliss used a rockpile type storage system containing 10cm diameter fieldstones, weighing 65 ton, in an insulated underground structure. The building heat load was 8440 kJ/DD and the system was completely adequate for heating the building. The rock-pile was cooled by radiant cooling during the summer night and also helped to air-condition the building. **[41]**

Lof designed an air heating system using overlapped glass plate collector and a rockpile exchanger for energy storage. **[34]**

Dunkle and Robinson, in 1968, described a heating system used for partial heating of laboratory buildings in Australia. This system used 56m^2 veer groove air heaters and rockpile storage unit. **[42]**

Thomason (1973) described large capacity water storage tanks with rockbeds surrounding the tanks for additional storage uses as water heating system. **[43]**

In 1973 Boer used photovoltaic cells as a part of the energy absorbing surface in the lower temperature portion of flat plat air heaters and based on this he built a solar heated structure. **[41]**

Solar heat from a convective loop collector can be stored in rock bins located inside the house. Figure 2.11 is the Hammond design which shows the heated air rising through the collector, and then through a vertical rock storage bin in the house, air flow passes through the living space between the storage bin in the house, air flow passes through the living space between the storage bin and the collector. In this design, the wood stove flux is imbedded in the storage bin to provide auxiliary heating during periods of cold, cloudy weather. **[44]**

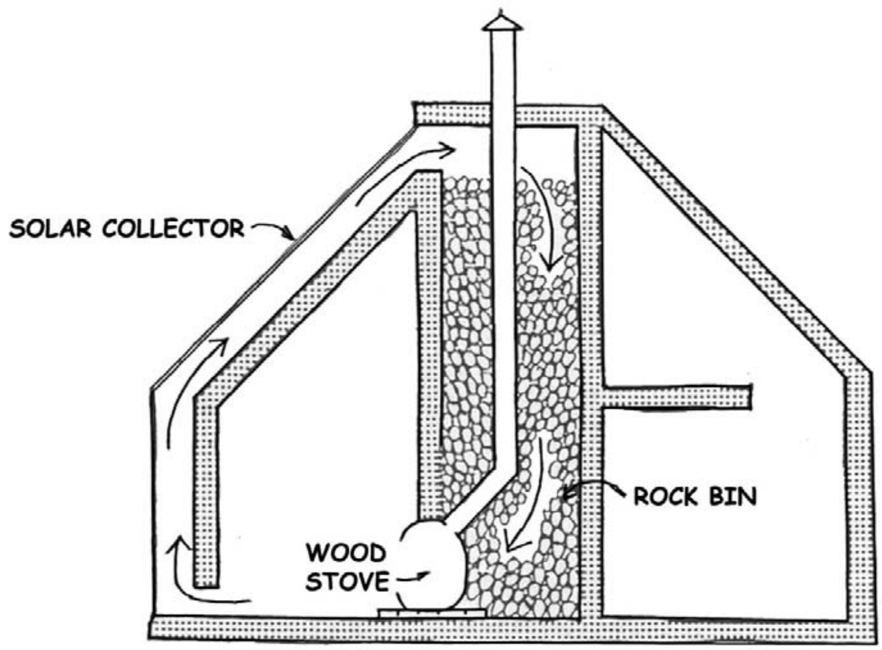


Figure 2-11: A rocking storage system for solar heating a house. **[44]**

Hays "solarchitecture" house was built in1973 in Atascadero, California. An equal area of roof pond covers the $100m^2$ of floor area. Nine flat, insulating panels slide horizontally in tracks above the roof ponds. The water is contained in four 2.4 by 11.6m transparent plastic bags, the volume of water used was $26.5m^3$, above these bags an inflatable transparent serves to reduce heat loss from the bags, increasing solar heat collection. During summer, heat from the house rises and is absorbed by the roof pond. The warm bags radiate their heat to the cool night sky, Figure 2.12. Concrete block exterior wall and interior partitions are filled with sand to increase the thermal mass of the house. This house is 100 percent solar heated and cooled. **[39]**

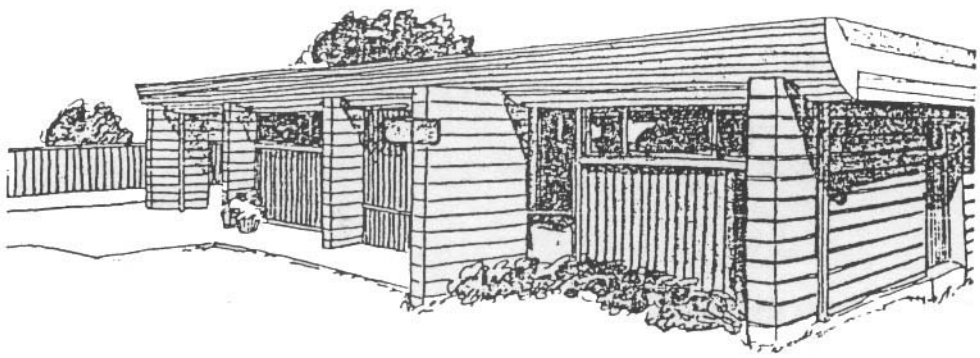


Figure 2-12: Harold Hay's house. **[39]**

The Davis house has used a thermosiphoning collector in combination with a thermosiphoning rock bed since 1972. Figure 2.13 shows that the heated airflow raises through the collector to the rock bed located below the porch. Heat rises through registers, also cooled air from the house is provided by a passive movement of air. **[45]**

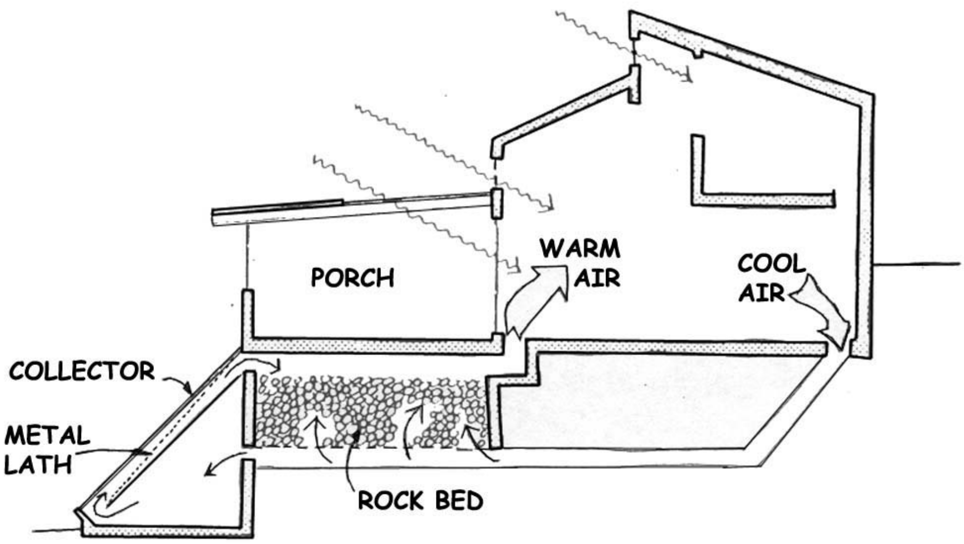


Figure 2-13: Paul Davis house. **[45]**

Figure 2.14 shows the Jackson house (sunroom), the 33m^2 of south glazing can collect 500MJ on a clear winter day in 5.5^{o}C temperature rise, this heat is stored in the 10cm thick floor slab of the house, and in the 0.5m of dirt beneath it, and these are insulated from the ground. In summer excess hot air is vented at the peak of the house, the air is replaced by earth-cooled outdoor airflow through buried pipes. **[39]**

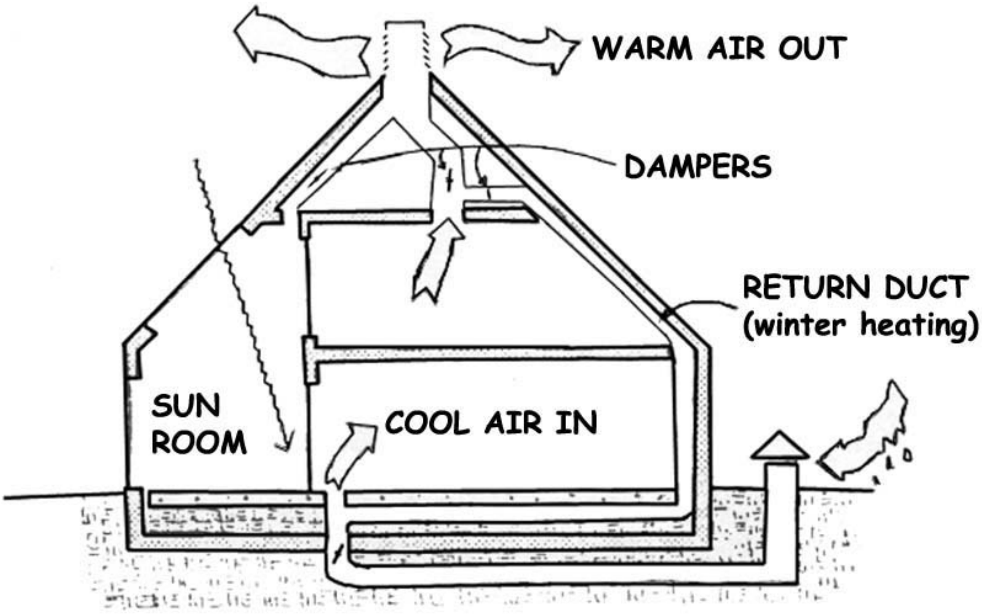


Figure 2-14: Jackson house (sunroom). **[39]**

Many experiments and houses have been made using a Trombe wall for solar collection; some of them are the following:

In 1967, an experiment on a Trombe wall building shows that for 0.6m wall thickness, one third of the solar radiation incident on the south wall during the winter months was transferred into the house, about 70 percent of the space heating load was provided by solar energy, 20 percent of the amount was transferred into living space by convection and 50 percent by conduction through the wall, and then to the air by convection.

The conclusion, reached by Balcomb and colleagues, in an analytical study of Trombe walls was as follows: **[42]**

a) Double-glazing on night insulation (or both) is needed.

b) Best performance is obtained with 20-50cm thickness of Trombe wall

c) To increase the performance of the wall, vents at the top and bottom of the wall must be provided to allow natural circulation of air.

Anderson shows that in France several heated houses have been constructed by Trombe and his associates. These houses utilized a south wall of glass, behind which was a black painted concrete wall about 20cm thick, used for energy absorption (collector) and storage. The walls are vertical and the angle of incidence of the solar radiation on them is high in winter and low in summer, and the system is for winter operation only. **[34]**

Some of the most significant work in thermosiphoning air collectors is being done at the (Centre National Research Scientific) CNRS in Odeillo, France under the direction of Professor Felix Trombe; this Centre has developed several approaches to solar heating. These thermosiphoning air collectors, Figure 2.15, supply about half of the building winter heat. Figure 2.16 shows the cross section of the CNRS wall collector. **[34]**

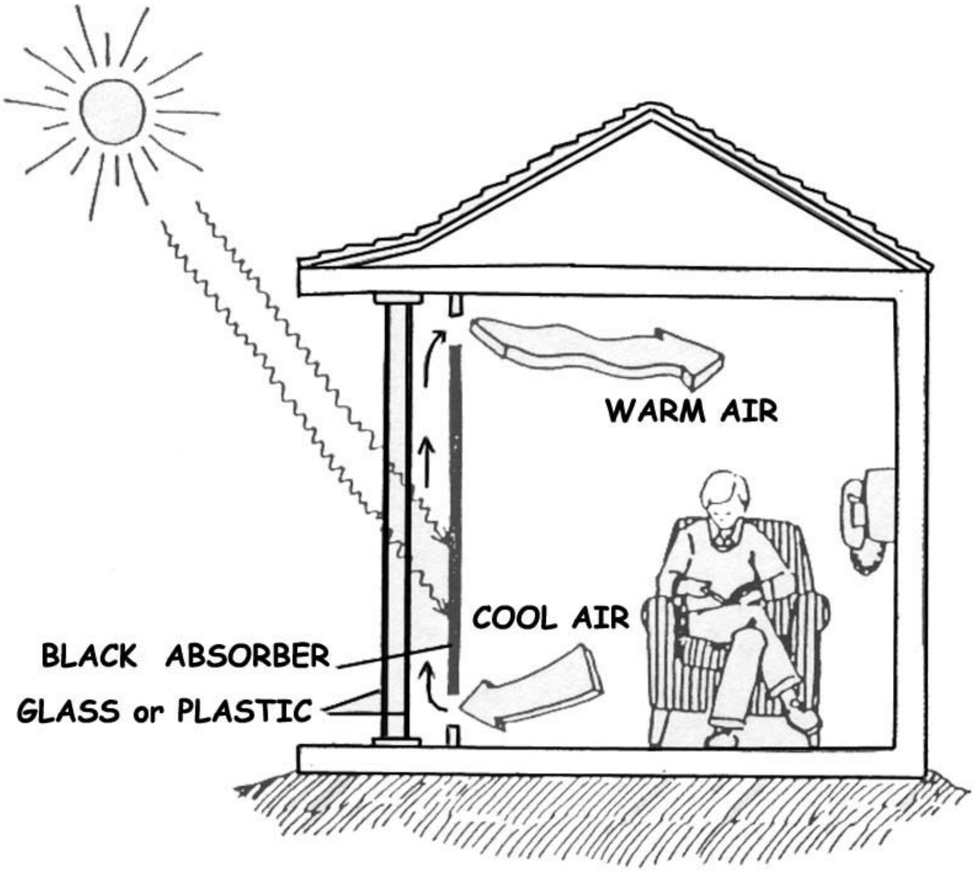


Figure 2-15: Thermosiphoning air collector. **[34]**

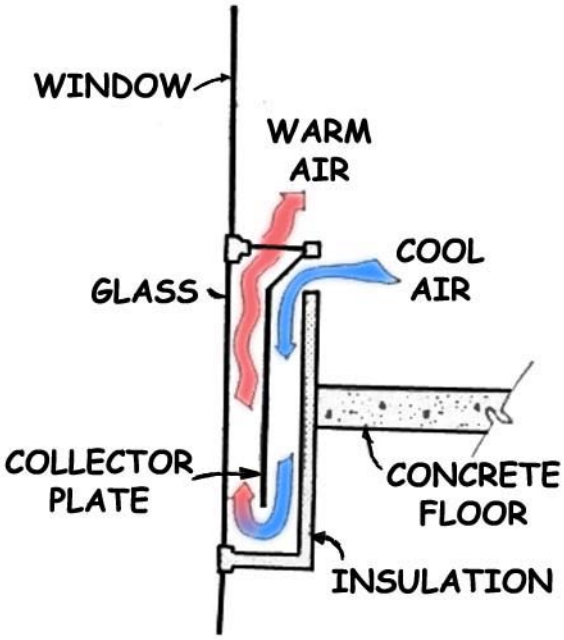


Figure 2-16: CNRS wall collector. **[34]**

In New Jersey, Kelbaugh used a 12m long, two storey-high-concrete Trombe wall, Figure 2.17 incorporating a large green house and several windows. This wall provides 70 percent of the heating requirements of the house. **[44]**

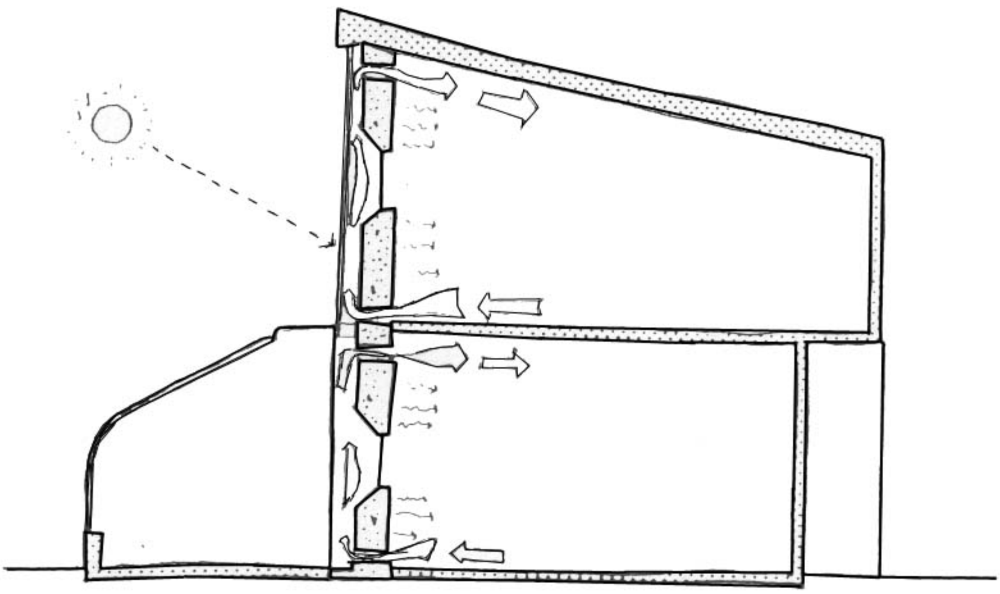


Figure 2-17: Two-storey high concrete wall. **[44]**

Figure 2.18 shows the water thermal storage wall. This system developed by Baer uses 55 gallon drums filled with water, insulating panels hinged at the base of each wall can cover a single layer of glass at night to reduce heat loss. When the shutters open and lie flat on the ground, the aluminium surface reflects additional sunlight on to the drums. During summer the shutters, in a closed position, shade the glass. **[44]**

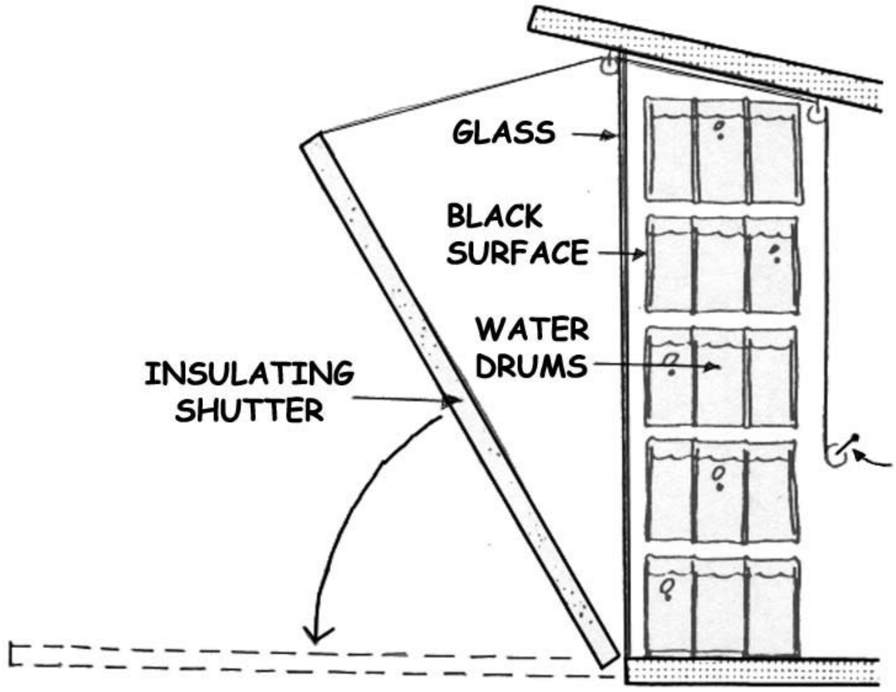


Figure 2-18: Hand operated insulating shutter and drum wall. **[44]**

Kalwall Corporation provides another example of water Trombe wall, as shown in Figure 2.19. In this wall, vertical tubes of water which are insulating from the living space by a wall through which air from the room can pass and contact the warm tube. The thermal curtain closes between the tubes and the glass at night to reduce heat loss. **[39]**

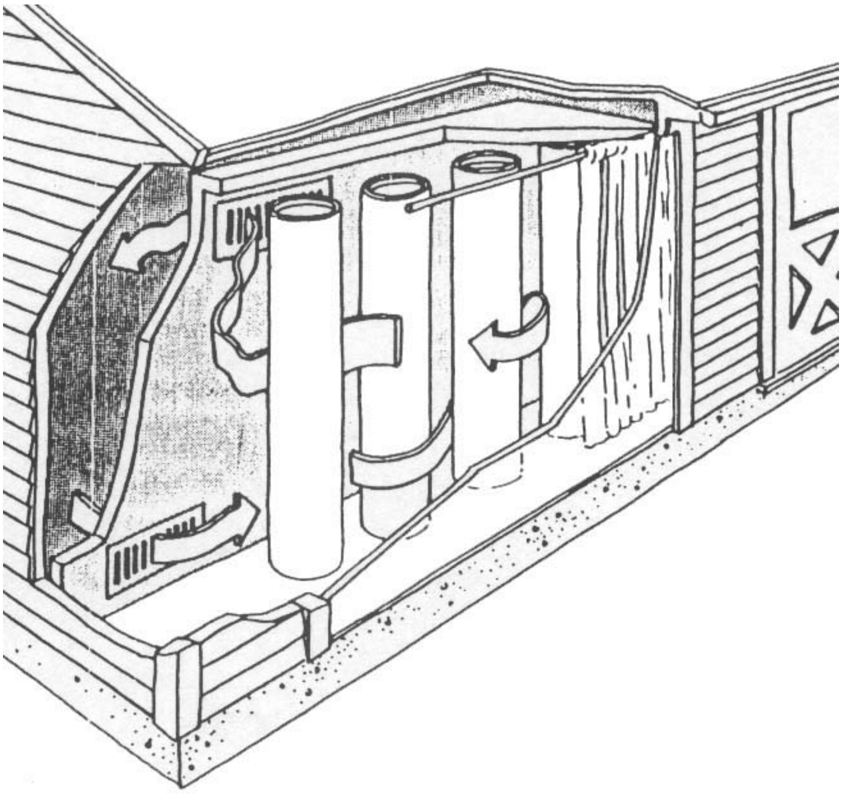


Figure 2-19: Vertical water tubes thermal storage wall. **[39]**

Figure 2.20 shows a water-Trombe-wall was used in the Odeillo house and the heat was transferred to water heat storage taken by the natural convection of the water between the collector and the storage tank.

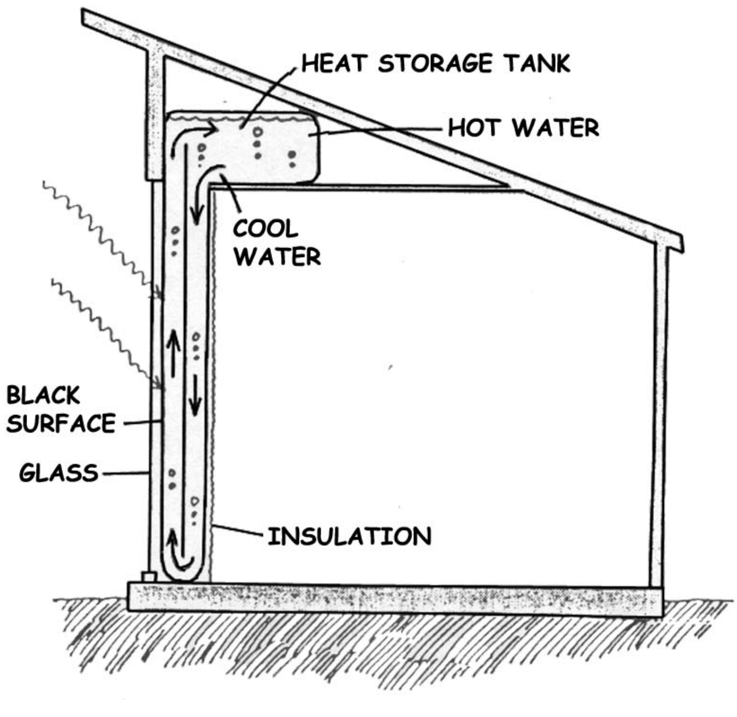


Figure 2-20: Water Trombe wall used in Odeillo house.

2.5.2 Commercial case studies

Some other recent case studies are analysed below in more detail. The following are concentrated mostly on the commercial level.

Participation in the Building 2000 programme enabled passive solar techniques to be incorporated successfully in these projects.

High Tech Laboratory

This building, located in Belgium, has been used for the application and research of various passive solar systems, including a solar wall.

The east and west external walls are solarwalls. They are constructed from an outer wall of heat-absorbent single glazing and an inner wall made of clear glass and insulated solid panels Figure 2.21.

During winter, the solar walls serve as buffer spaces between the outside environment and the building interior. Solar gain in the glazed areas is distributed evenly over the buffer spaces by fans. Fresh air is introduced into the bottom of the solar walls, pre-warmed by passage through the concrete mass of the air ducts in the crawl space and then warmed further in the solar walls by solar radiation and conduction heat losses from the laboratories. The warmed air is taken into the air-handling units to reduce the load on the heating plant.

With the louvers at the top of the solar wall shut, the double wall acts as additional insulation.

The glazed solar walls maximize daylight entry into the building. Automatic switching of the artificial lighting in the atria, conservatory spaces and external zones of the laboratory floors is achieved by means of photocells.

In summer, existing trees and service runs serve as a sunscreen in the solar walls. Natural stratification of warm air in the buffer zones prevents the laboratories from overheating. Motorized vents open at the top of the solar walls and atria so that unwanted heat can be vented to the outside by the stack effect.

The total annual consumption of fuel for heating the building is 405kWh/m^2. Useful solar gains amount to about 70 kWh/m^2 a year and compensate for most of the efficiency losses of the heating system.

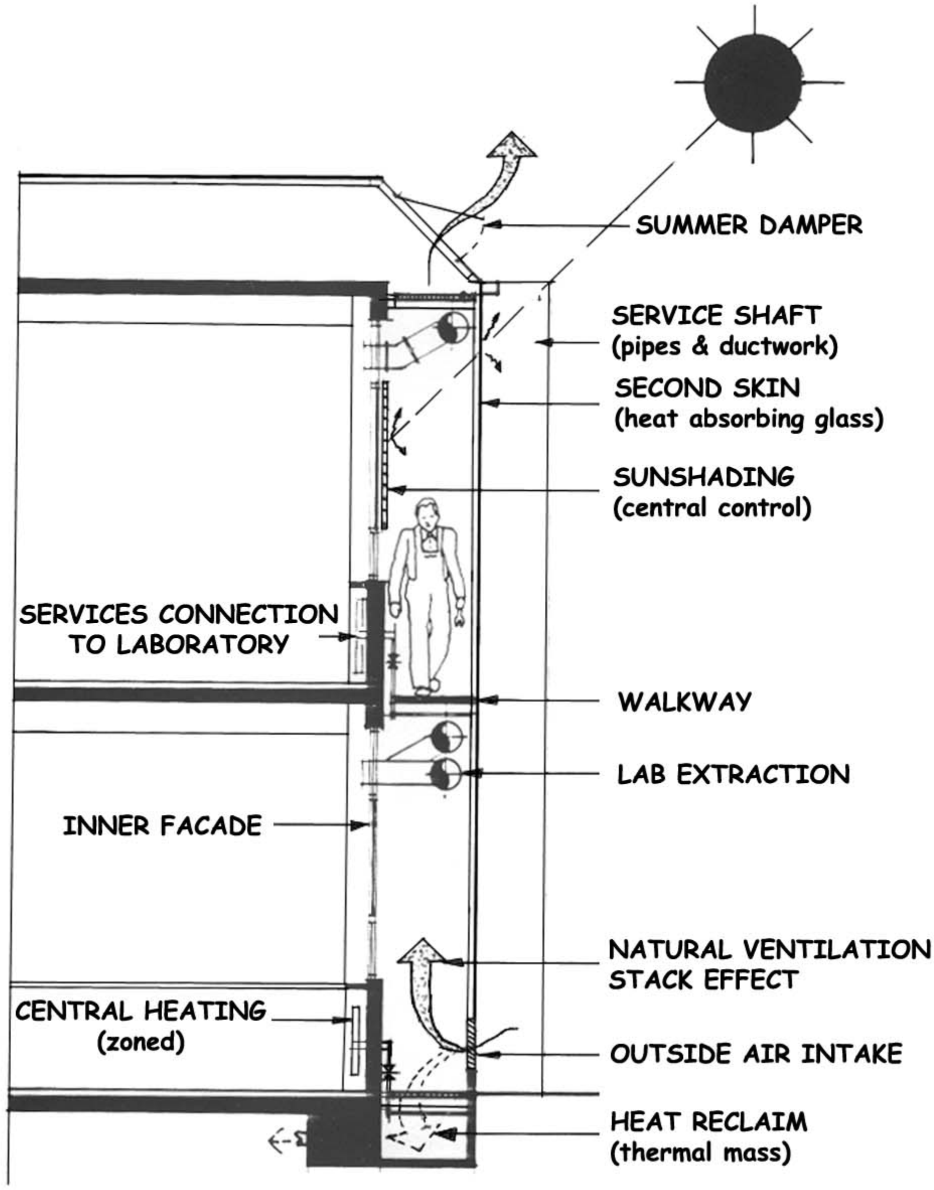


Figure 2-21: Section through solar wall. **[9]**

High School

This case study is concentrated on a high school of 1,600m^2 total area, located on the island of Andros (latitude 37.3^{o}N, longitude 24.8^{o}E).

The building has been designed to be in keeping with the traditional architecture of the island and yet to take into account bio climatic principles and the needs of the school.

Heating requirements are met in a number of ways. The glazed roof has turned the entrance hall in to a sunspace. Glazing covers 85m^2

(30%) of the south facade and there is a direct solar gain of this. Trombe walls occupy 70 m^2 (25%) of the south side of the classrooms.

Because of high levels of direct solar gain through south facing windows, the total area of Trombe wall is only needed in extreme winter conditions. To prevent overheating at other times using external roller blinds can reduce the area of Trombe wall exposed to the sun.

Cooling is also achieved by cross ventilation between the skylights on the north side of the rooms and the windows on the south side. Reverse functioning of the Trombe walls also helps the ventilation process.

Calculations showed that, because of the mild climate and relatively short occupancy period (9 am to 4 pm, September to June), the passive solar systems would supply almost all the heating needs of the building. They also indicated that the natural ventilation and shading systems would be sufficient to cool the building in the warmer months. **[10]**

West Berlin Innercity

This case study consists, the renovation of two multi-storey inner city buildings, located in Berlin, originally constructed in the middle of 19th century (latitude 52.4^{o}N).

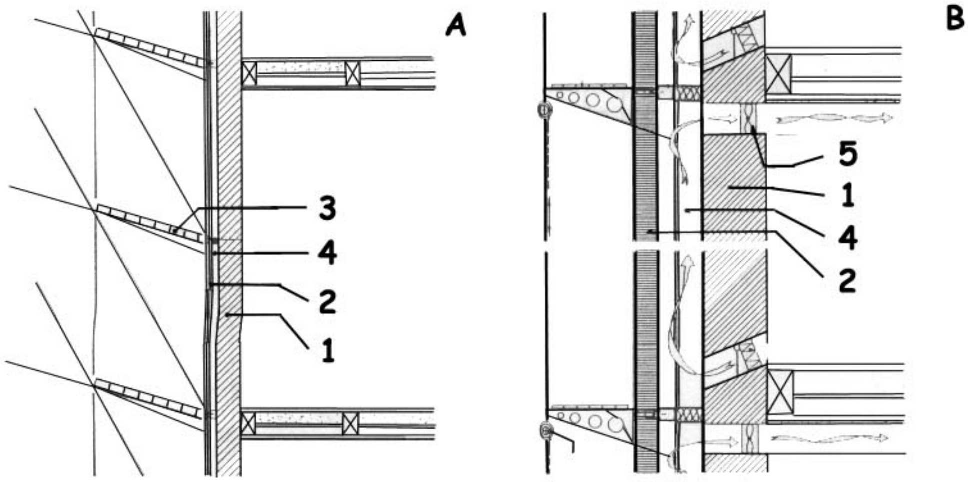
The restoration of the building was carried out as part of a publicly financed urban renewal programme where prototype ecological features are incorporated. Various passive solar systems were installed, including a transparent insulation system (TIS) on the side wing end wall. The TIS will be used in conjunction with a gas-fired central heating system to heat the building.

The idea of the TIS was suggested by B.u.L. Energieplan and developed further by the Weidlich engineering company. It consists of a transparent layer of insulation, which is fitted to a southerly-facing end wall of a building. There is a gap between the insulating material and the wall, which is sealed off from the outer air. The insulation slows down heat loss from the adjacent rooms. In addition, the layer of air between the insulation and the wall of the building warms up when the sun shines and can be used for heating the building.

The system has three variations. In the simplest form (the solar wall without convection – Figure 2.22), the wall of the building serves as the medium for transporting the radiant heat from the sun. The heat of the warmed air in the gap is absorbed by the wall, which acts as a thermal store, heating up the rooms adjacent to it. To prevent overheating, the insulated wall must be shaded once the heat requirements of the building have been met. This variation of the TIS is not as effective in using the available solar radiation as the other two versions described below.

In the solar wall with convection (Figure 2.22) direct use is made of the air warmed by the sun. Vents in the building wall permit warm air to be conveyed into the building with the assistance of fans so that it can heat the rooms. Cooler air is directed back into the air gap behind the insulating façade by means of door cracks and return vents in the end wall. It is then warmed up again. Like the solar wall without convection, this version of the TIS requires a shading facility as a protection against overheating. The advantage of the open loop system is that, with suitable piping, more rooms can be heated than just those adjacent to the insulated façade. However, a means of cleaning the inside of the insulation must be provided in the open version because impurities can get into the gap between the wall and the insulating facade.

In the third version of the TIS (the flat collector system with transparent insulation – Figure 2.22), water is the heat transfer medium. This is warmed in flat collectors located between the wall of the building and the insulating layer and collected in a storage tank, which, by means of heat exchangers, preheats the water for the conventional domestic hot water and space heating systems. The presence of a storage tank helps to smooth out the minute-by-minute changes to the solar radiation incident on the building facade. Solar energy is used more effectively in this version of the TIS than in the others. On the other hand, the system is more complex, has higher capital costs and requires supplementary energy for circulation of the water.



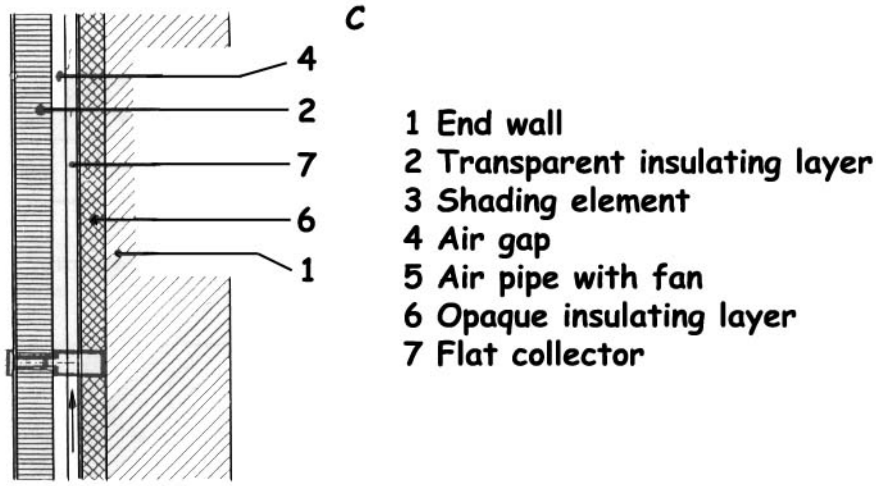


Figure 2-22: Various TIS designs. **[11]**

It was decided to install the simplest version of the TIS (the solar wall without convection), because of its low capital costs.

The insulating elements consist of light-permeable honeycomb or capillary 870mm polycarbonate sheets protected from contamination on both sides by sheets of glass. They are mounted on a load-bearing system of thermally separated sections at a distance of 150-200mm from the outer wall of the building.

To maximize the energy savings achieved by the TIS, the rest of the building is well insulated. The other exterior walls of the side wing are insulated with conventional materials.

The local climate conditions are such, however, that it is not possible to heat the rooms by the TIS alone – the solar system has to be augmented by a gas-fired low temperature central heating system.

In summer, no heating is generally required in the building. Therefore the solar wall will as a rule, be shaded.

The thermal performance characteristics of the TIS were established using various computer modelling and energy calculation procedures.

The calculations showed that the annual energy savings of the TIS would amount to 7,900 kWh some 20% of the energy required for a conventional heated insulated side wing. The cost saved annually is DM 800. The additional cost of installing the TIS compared with traditional opaque insulation is estimated to be DM 50,000. The final chargeable investment costs to DM 18,000 (because of local fiscal instruments). This will enable the system to pay for itself in about 22 years. **[11]**

Secondary School

This building has a 2000 m^2 floor area and is situated 50 km from the sea in Portugal (latitude 40°35').

The design aims to use passive solar and other energy-saving features to provide lighting and thermal comfort in the building throughout the year.

Thermal comfort in winter is achieved by direct solar gains, storage and carefully controlled auxiliary heating system. Overheating in summer is prevented by shading and cross ventilation.

South facing non-absorbing transparent glazing is provided on the south side with the aim of providing just enough direct gains to maintain comfortable internal conditions in the classrooms (Figure 2.23).

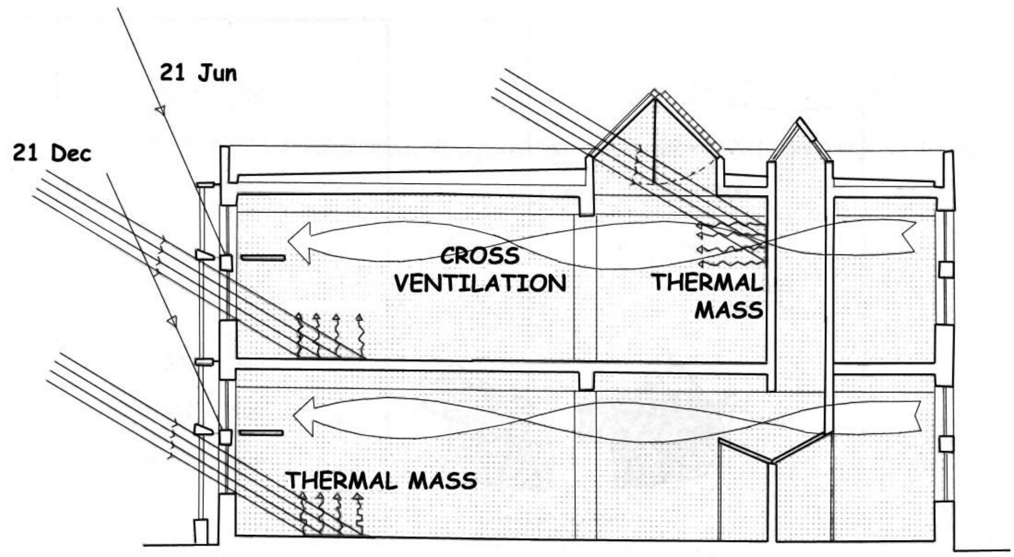


Figure 2-23: Mode of operation of passive solar heating systems. **[12]**

The thermal energy is stored in the mass of the building (220mm dense brick internal wall and 200mm concrete floor) so that large temperature swings are avoided and a steady optimum temperature is maintained. The thermal mass consists of classroom floors (which are made of concrete), the internal walls (which are heavy brick) and the external walls (which are well insulated).

To prevent entry of direct radiation into the classrooms in the warm periods of the year, horizontal external overhangs are provided above the glazing to prevent all but diffuse radiation entering the building.

The upper parts of the classroom windows and doors are provided with opening panels to allow adequate cross ventilation to be achieved without draughts. Periodic air renewal can thus be affected quickly and efficiently.

Thermal performance of the space heating passive solar components was carried out using a simplified computer method. The passive solar gains contribute by 64% of the annual space heating requirements of the building. The rest 36% is provided by the auxiliary system.

Thermal optimisation was ensured by well insulating the building, particularly around the region of thermal bridges. Overhangs prevent direct solar gains during summer. Walls and floors made of heavyweight material so solar energy can be stored. North and south-facing windows and doors were given opening panels at the top to allow cross ventilation. **[12]**

2.5.3 Solar heating experiments in the U.K.

A passive solar house was constructed by Sadler and family by convecting an old Suffolk barn to be used with direct gain via windows. Internal walls and floors were constructed to absorb and store solar heat. The sun supplies 58 percent of the heating required. One wood stove supplies the balance at the annual cost of £30. The house collects heat from the sun in two main ways; firstly, solar radiation through $16m^2$ double glazed windows on the SW side of the main barn is absorbed by a 300mm thick brick faced concrete floor slab. They absorb about 55 percent of solar radiation incident on them. Secondly, one wing was converted to form a glass roofed conservatory, and solar radiation through the $15m^2$ glazing in SE roof and $4m^2$ in the SW wall heat the insulated 100mm concrete floor and NW wall. The total volume of the interior brick walls, the insulated brick and concrete floor slab 300mm thick is equal to $33m^3$ and the total capacity of all thermal mass is $23kWh/^oC$. The author believes that passive solar heating is feasible in Britain provided there are suitable massive interior surfaces to absorb and store heat for short periods, and the addition of insulating shutters over large window. **[46]**

The conversion of a barn into a solar house was not an ideal demonstration project; better results could have been achieved with a purpose-built passive house, making use of the same principles but with relatively larger window and conservatory area.

Direct gain, of passive solar heating systems are applicable in a wide variety of house types. For effective passive systems design the following factors must be investigated, internal planning, sizing of windows, provision of heat storage and selection of appropriate materials and finishes.

More work is needed on the development of low cost controls (shutters, blinds, etc.) and new building materials.

Because of the relatively poor performance of Trombe walls, there will be a limited application to new housing.

Keable developed another method in distributing solar heat which is to excavate a hollow space on the four sectional faces of the building (that is, walls at back and front, roof and under floor), interconnected in such a way that a convection current can flow, thus channelling heat collected on the south face to the thermal mass represented by the floor slab. **[45]**

On a sunny day a greenhouse receives much solar radiation. The air in the greenhouse becomes very hot, and rises and flows northward along the roof space, flows downward in the north wall, flows southward in the crawl space then completes the circle.

The author proposed a modification, which included.

a) Restricting the width of air passageway, thus increasing the contact with storage mass.

b) Controlling the airflow, by placing one or more fans within the circuit.

c) Increase the thermal mass in the north wall.

The above principles were used in the house in Berkshire, Reading.

In general, in Western Europe, especially on the Atlantic seaboard, the variable weather conditions make it desirable to trap solar energy as rapidly as possible and convey it to store.

The passive system can lead to overheating at different times through the year, and the Trombe wall can be used to overcome this disadvantage, but the Trombe wall itself is poor in controlling the thermal gain.

One passive application of solar heat was the study in Milton Keynes by Horton to evaluate the thermal characteristics of the attached greenhouse and passive components and their relationships to the building. **[47]**

2.5.4 Solarwall© Case Studies

The Solarwall© has been great interest from various industries in the past few years.

Weledeh Catholic School

This case study consists of the installation of 200 m^2 black metal perforated collectors onto the exterior wall of the gymnasium, with southwest orientation.

The total cost of the Solarwall system was approximately CAD$70,000, with energy savings of $12,300, giving a payback period of six years.

The system is designed to provide its contribution to the heating load during the shoulder seasons of August to October and February to May, when outdoor temperatures are colder than indoor comfort levels. During those periods, the sun can deliver 1.2GJ/m^2 of the collector wall. In the spring, the snow on the ground combines the low azimuth of the sun to reflect up to 70% additional solar radiation onto the collector wall. The school is located at 62°N, 114°W.

A school demands a large volume of heated air during the day only, and is considered to be an ideal application for passive solar building technology. **[1]**

General Motors Battery Plant

In 1991, a 420 m^2 Solarwall was erected at the General Motors of Canada Battery Plant in Oshawa, Ontario.

The installed system has actual flow rates of 68,000 m^3 per hour. The temperature of the delivered air is controlled by mixing solar heated air with recirculated indoor air. The lower the temperature of the air from the collector, the greater the proportion of recirculated air.

When outside temperature is above 18°C, the system is designed to bypass the Solarwall completely. Automatic dampers in the canopy allow air to be drawn directly from the building exterior.

The total cost of supplying and installing the perforated plate solarwall system was about CAD 92,000. Energy savings amount to an estimated annual total of 755kWh/m^2 of collector area (based on an eight month heating season). Annual energy cost savings provided by the Solarwall rise to CAD 12,200 (compared to a steam-operated fan coil unit). Thus the payback period is 8 years. **[5]**

Leadville Water Treatment Plant

The water treatment plant in Colorado has been retrofitted with a high performance solarwall that provides space heating and preheats air for ventilation heating at an altitude of about 3,000m.

The building is located in a very cold region. Water, from the mine, flows through the building at a flow rate of 126litres/sec at a temperature of 7°C, constantly drawing heat from the air. The building therefore has to be heated all year round and the plant also requires a large volume of air to ventilate noxious vapours from chemicals used to treat the contaminated water. These conditions made the plant a particularly suitable application for transpired air collectors.

The solarwall is installed on a south-southeast-facing wall. The fan, mounted at the top of the collector wall, pulls outside air through the absorber perforations and distributes the warmed air through flexible ducts mounted near the ceiling. The system is equipped with recirculation and summer by-pass dampers. However, the designers subsequently decided that dampers are probably unnecessary in such as cool climate.

Operating at 70% efficiency, the solarwall installation produces about 768GJ/year. The project cost of $31,000 provides annual savings of $3,057, giving a payback period of 10 years. **[14]**

Canadair facility

The installation of the Solarwall at the Canadair facility was completed in October 1996. The system covers a total area of 8,826m^2. It operates 24 hours a day, with approximately half the system operating at a constant airflow and the remainder at a variable rate. Lightweight precast concrete panels in a complementary colour were installed on the north facing walls of the facility where the Solarwall would not be effective.

The total installed price of the Solarwall, including labour and all hardware, was CAD 2,575,000. The conventional alternative system amounted to CAD 2,290,000. The Canadair Solarwall delivers 23,000 GJ annually. At a fuel cost of CAD 0.25/m^3, the annual savings amount to CAD 167,000, resulting in a simple payback period of 1.7 years. **[16]**

The solarwall technology can capture as much as 80% of available solar energy, avoiding some of the resource depletion, pollution, and greenhouse gas emissions associated with conventional heating. Additionally increased ventilation improves indoor air quality and worker comfort, increasing productivity. **[4]**

It is of particular interest to large warehouse type facilities that require significant amounts of air, such as airplane hangers, plants, which must exhaust process fumes. Standards for air quality are increasingly being revised to recognise this need for clean ventilation air, which increases the heating requirements and financial costs for companies.

Solar air heating is being exploited as a cost-effective technology for crop drying of tea, coffee, rice and timber, and the use of solar heat is often preferred over fuels since it will not burn or damage delicate foods.

Another application under development in Canada is the integration of the solar thermal collectors with a building-integrated photovoltaic system. If a PV façade can be designed to allow a solar thermal air gap behind the solar panels, energy savings can quadruple if the air system captures the heat emanating from the PV modules. At the same time, the airflow provides uniform cooling for the PV component, allowing the solar cells to generate electricity more efficiently.

Chapter 3. Energy Performance Assessment

3.1 General

Going through the previously analysed case studies it is clearly noticed that energy performance assessment was not a point of interest for the most passive solar projects. In section 1.2 it was suggested that computer simulation is an essential tool for the design and construction of buildings in residential, commercial and industrial sectors. Therefore, the main work of this thesis is concerned about computer building simulation.

More specifically a building system case study with a solarwall passive solar component is selected. For this chosen building, energy performance assessment is carried out using a sophisticated computer modelling and simulation program ESP-r.

3.2 Computer modelling and building performance

3.2.1 About building performance

The term building performance implies that an object, i.e. building, can be defined and its performance measured. A building is the result of a distinct activity that transforms or alters people's environments. This broad definition permits buildings to be perceived and elaborated from different points of view: a designer may see buildings as objects by means of which he can seek beauty, an engineer as the assemblage of systems while workings should be examined and optimised, an investor as a saleable product, a user as a space wherein he can live or work comfortably, and so on. Hence, depending on a person's point of view, buildings have to perform various functions.

To examine how well buildings perform these functions, scientists have attempted to devise performance-measuring models. The Building Performance Research Unit (BPRU) at the University of Strathclyde has undertaken systematic studies to develop methods for appraising existing or proposed buildings. They have devised a conceptual model for examining building performance in association with passive solar systems and the people living or working in a building. Other researchers have focused their work on one aspect of building performance and for specific purposes such as design, management, operation, etc. of buildings. **[48], [49]**

3.2.2 Modelling and energy performance of buildings

There are, however, aspects of building performance that can be examined and assessed more thoroughly than others, by employing scientific methods. Such an aspect is the energy performance[1] of

[1] Energy performance may be assessed relative to: the total energy input for all processes involved in the making of a product; the energy input for servicing, maintaining and disposing a product; the energy in use, i.e. the energy consumed by components of a product to accomplish specific functions. Building performance is examined here relative to the energy use to obtain thermal comfort.

buildings, whose importance is rising due to the global need of reducing energy use. Clarke provided an analysis of the energy flow paths in buildings and devised dynamic energy modelling techniques to describe them analytically. These techniques have been incorporated, by ESRU at the University of Strathclyde, in a computer based dynamic tool (ESP-r), which allows mathematical representation (simulation) of a building's energy system. **[50]**

The choice of a computer based tool was a major element of this part of the research since it would both determine the type of data to be collected for modelling, elaboration and analysis and drive the evaluation process. The chosen tool (ESP-r), which is a complex building energy simulation program, has been selected by the Commission of the European Communities as the European reference simulation software for passive solar systems.

ESP-r can simulate energy flows inside and at the building envelope under the impact of real weather conditions, including the thermal behaviour of building components, occupant presence, and air movement and heating/cooling plant contribution. Such a tool for energy simulation can effectively be used to validation preconditions and test-prove of building models used.

For the former, the ESRU Unit of Strathclyde of University has collaborated with research teams from EC member countries in the PASSYS project funded by CEC; this validation work has resulted in several improvements to the program described elsewhere **[53]**. For the latter, building models generated to be used with ESP, for the purpose of this thesis[2], were based on modelling knowledge acquired from the PASSYS project and had to be tested using parametric analysis and undergo checks against some practical criteria. (Section 3.4) **[51], [52]**

3.2.3 Classification of energy related building systems

The higher demands that buildings are expected to meet today compared to earlier times make building costs increase[3] continuously. Such demands include, for example, electric and plumbing services, HVAC and telecommunications. Some of them were available only in palatial or luxurious buildings few decades ago; today they are a necessity and have made buildings more complicated and costly.

In the case of a complex building it is possible to resolve it into subsystems, sub-subsystems, and so on, by appropriately combining various building components. A component may consist part of more than one systems; for example, a concrete storage wall between a

[2] The building models described in this thesis are available in digital format so that they can be used as exemplars by other researchers who would find in them complete building descriptions for analysis in their own areas of interest, or who may wish to pursue the matter further.

[3] There are other reasons to increased costs such as inflation, decrease of the purchasing power of money etc., but they are generally applicable to all design products and not to buildings only.

sunspace and a living room is a component of a passive solar heating system (solarwall), it is also part of the building envelope providing shelter and privacy, and perhaps a bearing element of the building structural system.

It is practically difficult to optimise a complete system, such as a building, by combining optimum components, because usually components are interrelated and impose restrictions on each other.

The latest version of ESP-r (version 9 series) is used in this study to examine the role of solarwall behaviour on the energy performance of buildings for space heating/cooling. To do so, the building energy related processes are seen here as an assemblage of a finite number of components and/or subsystems grouped together to form the following systems:

- A system directly related to energy processes.
- A system indirectly related to energy processes.
- A user related activity system.

The first system involves space heating, cooling and lighting components, electrical and mechanical equipment, metabolic mechanisms, etc. Common characteristic of the subsystem/components of this system is that they can inject or extract energy to/from the building

The second system comprises mainly the building fabric: walls (external & internal), roof, doors, floor, passive solar components, etc. Hence components of this system are involved in energy exchange processes relative to the building but to do not produce energy themselves.

The third system represents energy related human activity i.e. describes actions that the users of a building perform and which may have consequences on energy related mechanisms.

The classification of the building energy system into three subsystems is done in order to enable:

- An effective analytical description of a complicated energy mechanism to a simulation tool.
- An analysis and attribution of the ensuing results to the energy related systems.
- A building energy performance assessment.

3.2.4 Energy Systems Analysis

At this point, it is appropriate to discuss what is to be examined, using simulations, before approaching the workstation. This is considered a vital step before a thorough examination can commence since simulation is only an approximation to reality and certainly not a solution to all energy systems related design questions. Careful planning is needed before any such work can commence so that the confusion of the load of simulation data and results can be avoided. ESP offers a variety of ways to simulate a building system, thus allowing the user to analyse the problem according to the specific answers required. However, this uncertainty leaves the responsibility of model to the user. It would therefore be unjustifiable to create models and run simulations at this stage. Firstly, the energy related questions that need to be answered by using ESP have to be discussed.

Primary aim of computer-aided analysis undertaken for this thesis is to test the solarwall interaction with building energy to building energy performance.

3.3 Modelling the solarwall

Information used in the modelling work is obtained from Mr. Christoph Morbitzer PhD student at the University of Strathclyde. Additional modelling work includes, modifications to the design, form, ventilation rate and materials of the thermal mass and glazing of the solarwall model.

By carefully examining the required output of the research it was decided to create the models represented on the following section.

3.3.1 Geometrical characteristics

The models developed in ESP-r are based on a real case study. It involves the erection of a new hospital in Derbyshire. However, it was decided that the computer models should not match the exact dimensions of the real building neither the size of the actual solarwall. A more general view was required about the potential benefits of the solarwall system in the cold climate of Glasgow. The solarwall modelled is a glazing type.

Simple Model

The first model created, includes a three-storey building without the solarwall (Figure 3.3). These three zones are the corridors of the hospital. They are not in scale with the real case, but this model can still be used to analyse the behaviour and effect of the solarwall on its adjacent rooms.

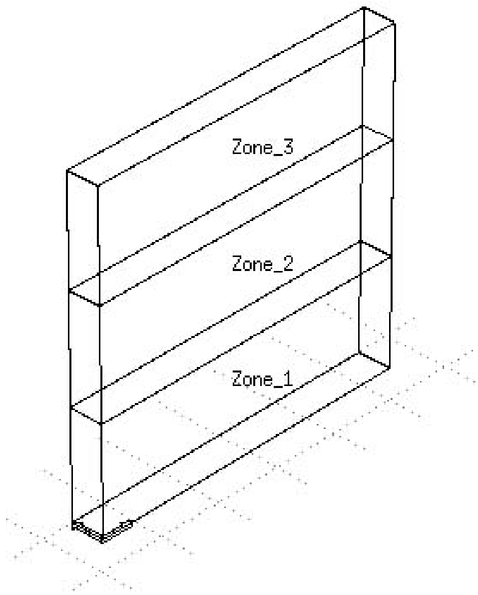


Figure 3-1: Simple three-storey model without the solarwall system.

Solarwall Model

This is the basic model used for the energy assessment performance of the solarwall (Figure 3.4). A non-scale image is provided so that a better view/understanding for the operation of this model can be gained (Figure 3.5).

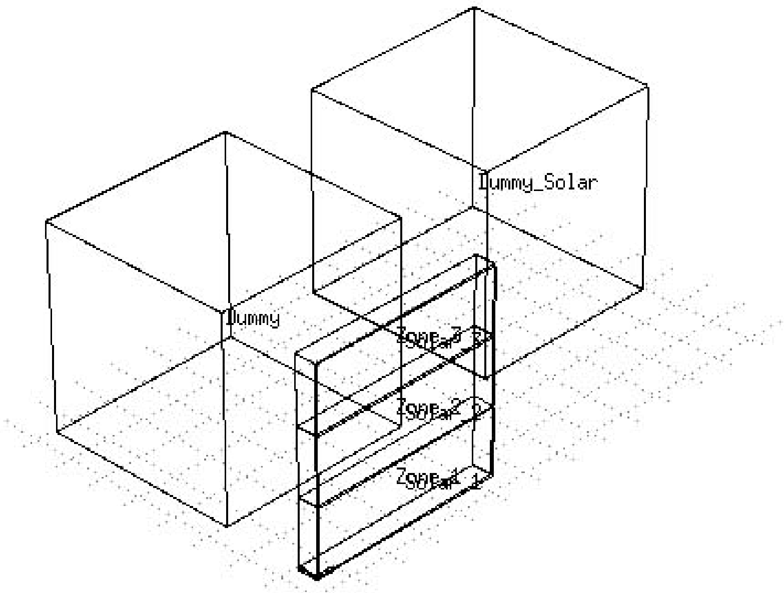


Figure 3-2: Three-storey solarwall model.

The only differences between the solarwall and simple model are:

- The solarwall zones, located in front of the corridors.

- The black colour concrete used as the material for the surface between the glazing of the solarwall and the corridors (south external surface of the simple model).
- The two *dummy* zones.

One *dummy* zone is called *Dummy_Solar* zone and is heated by the warm air coming from the solarwall and the HVAC system (heating load configured in ESP-r). The *Dummy* zone is heated using the HVAC system only and is also infiltrated at the same rate as the warm air of the solarwall heats the *Dummy_Solar* zone.

The two *dummy* zones are used to calculate the energy savings that are contributed by the solarwall system. More specifically, these savings are calculated by subtracting the energy required to heat the *Dummy_Solar* zone from the energy required to heat the *Dummy* zone.

The difference between the two energy consumptions is derived by the fact that the infiltrated air (ambient temperature) is colder than the warm air (temperature of the heated air inside the solarwall) ventilated in the *Dummy_Solar* zone. Therefore, the HVAC system in the *Dummy* zone has to consume more energy in order to keep the space at a comfortable temperature. On the other hand, the HVAC system in the *Dummy_Solar* zone does not consume so much energy because the air coming from the solarwall is already warmer than the ambient air.

The solarspace of the solarwall, Figure 3.3 is in fact divided into three zones in ESP-r. This detail is not clear in the ESP-r Figure 3.2; also their height is the same as the corridors. This is a basic assumption made in the solarwall model, so that the airflow inside the solarspace could be modelled. Section 3.3.4 provides further discussion of these assumptions.

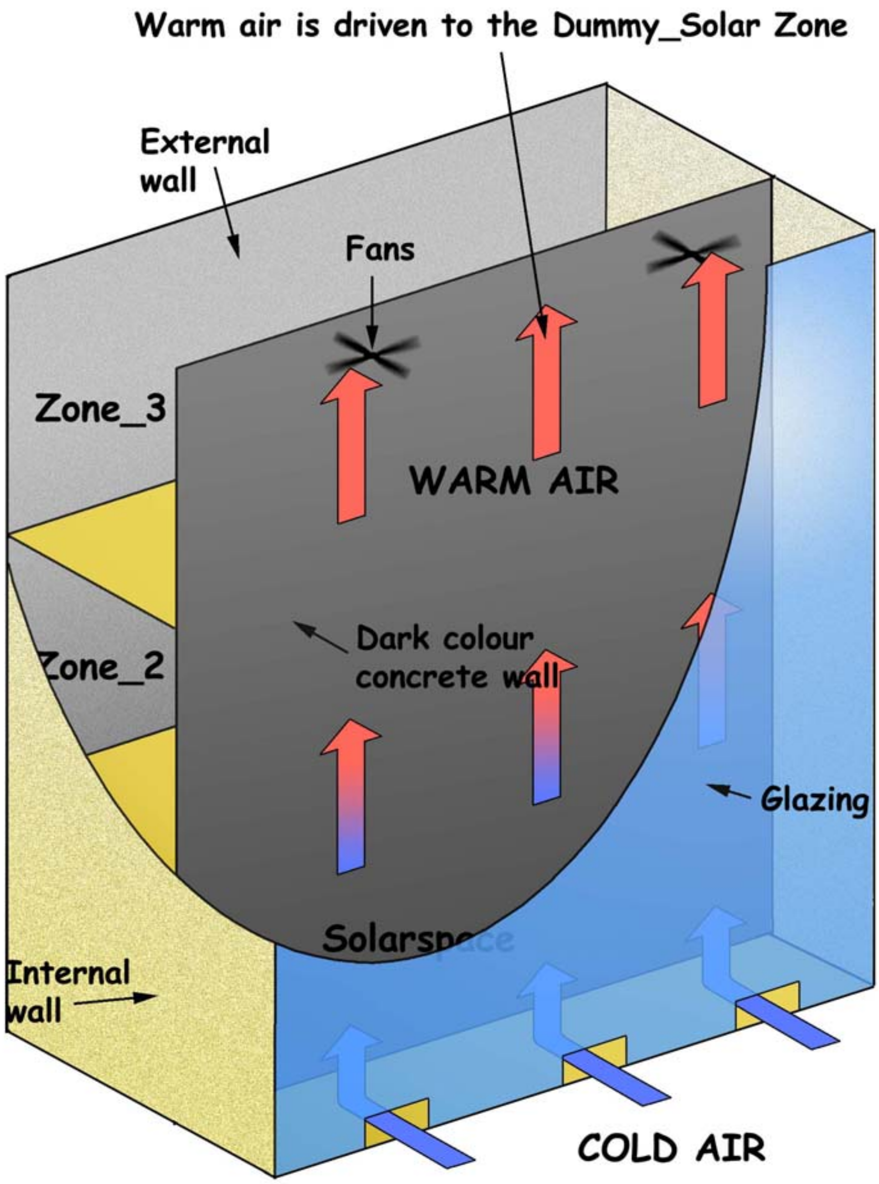


Figure 3-3: Graphical representation of the solarwall model.

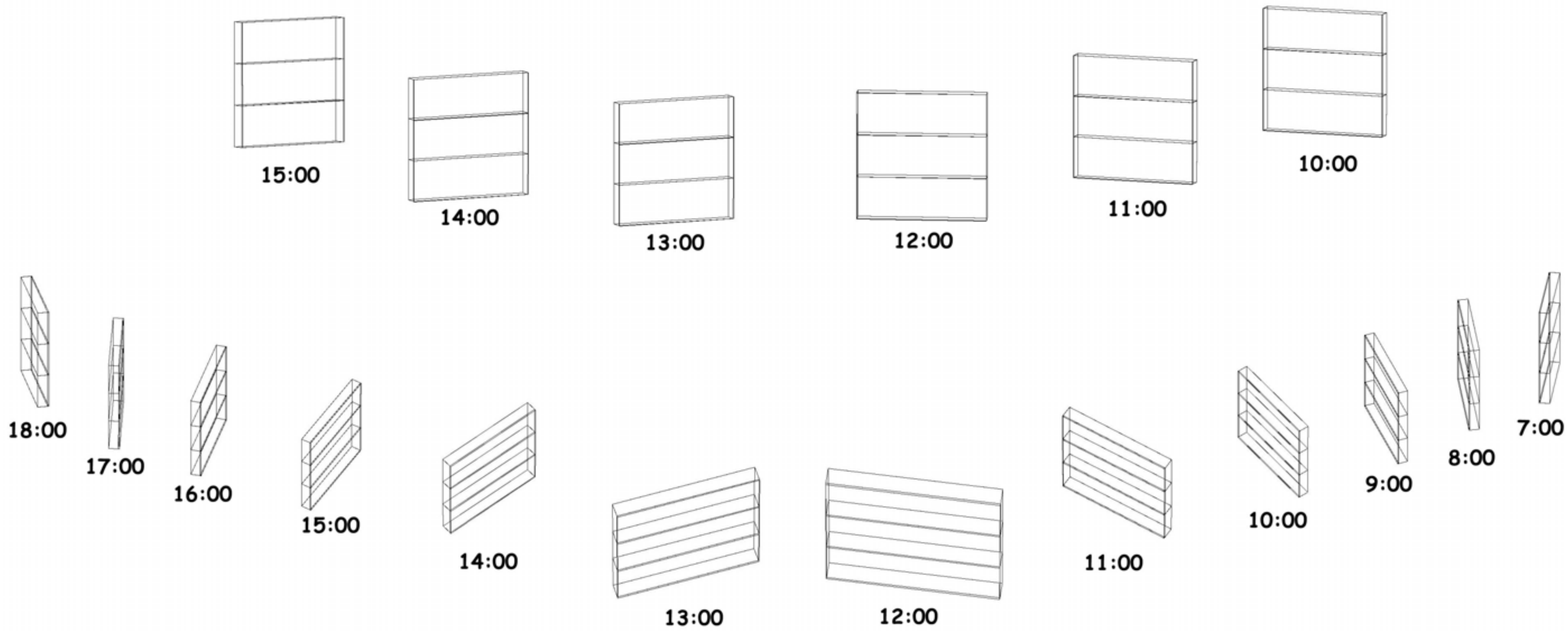


Figure 3-4: Views from the sun of the solarwall model at winter (a) and summer (b) solstice.

3.3.2 Constructional characteristics

Building plans, including information on materials used such as conductivity, density, specific heat and thickness, together with a standard construction materials database available with ESP-r are used to describe the two models' fabric. Differential sensitivity analysis (DSA) is undertaken for those factors whose value was not known but expected to be within a range. This is a technique used in the CEC PASSYS project to examine the effect of an input parameter whose value is known to be within a range of uncertainty (e.g. heat transfer coefficient, thermal conductivity, etc.) on building energy performance.[1] This done by running simulations of a basic building model and the same model with the maximum or the minimum expected values for that parameter, and testing the results on an output parameter. DSA is applied here to test the effects of the value of the convection heat transfer coefficient, only for the absorbent wall (thermal mass), which is located between the glazing, solar space and the building space.

Calculated energy consumption for space heating is chosen as the output parameter. Simulations have been carried out using the solarwall model for a period of a mid winter week (12-18 Jan. 1967) with the standard British climate file. The three models tested differ only in the convective heat transfer coefficient value of the thermal mass material.[2] For the base case model, heat transfer coefficient[3] gets the value of 5.24W/m^{2}K. Heat transfer coefficient value for the other two models is the base case value ±2.5%. Table 1 shows that the effect of this variation to thermal performance is relatively small and the uncertainty of the coefficient value does not introduce significant differences to calculated energy consumption during winter.

	-2.50%	**Base case**	***2.50%***
***h* (W/m^{2}K)**	5.1	5.24	5.4
KWh	12457.21	12528.15	12665.21
%	0.57%	0%	1.08%

Table 1: Influence of convection heat transfer coefficient value of the thermal mass.

It is essential to note that the calculated heat transfer coefficient has been applied only to the one side of the thermal mass wall. This is the side facing the glazing of the solarwall; because of the high-speed

---

[1] Such parameters are "passive" i.e. usually related to the building fabric rather than to design options. They are generally engaged in the simulation models with the mean value from their uncertainty range.

[2] The convective heat transfer coefficient values have been applied only to the surface (of the thermal mass wall) that faces the glazing. The material databases of ESP-r have standard values of this coefficient. However, because of the high speed of the airflow in the solar space the value of this coefficient will differ. The side of thermal mass wall facing the corridors have been given the default value of convective heat transfer coefficient.

[3] Look appendices for more details.

airflow. On the other side, facing the corridors, the heat transfer coefficient has been given the default ESP-r value for the specific material.

Further details about the constructional characteristics of this model, including materials used, can be found in Appendices.

3.3.3 Operational characteristics

Human behavioural patterns are the most difficult to predict and describe in a computer model with certainty and it is subject to daily, weekly and seasonal variations, parametric analysis is used to test the influence of a variety of occupancy patterns as well as operational schemes to building energy performance. However, occupancy patterns and operational regimes are not important aspects for the models developed. The output/results (e.g. energy saved by the solarwall, which is the energy consumed by the *Dummy* zone minus the consumption of *Dummy_Solar*) described, are not affected by internal gains (e.g. occupants, equipment, lights).

On the other hand, internal gains have been considered for the three *Zones_1,2,3* as they do affect the performance of the solarwall, more specifically the energy loss through the thermal mass of the system can alter the energy consumption of *Dummy_Solar* zone.

3.3.4 Air infiltration – ventilation

Air movement close to human body is important to thermal comfort since it affects convective exchange and the rate of moisture evaporation from the skin.

Renewing indoor air results in energy losses[4] from buildings since replacing it is usually colder. It is therefore appropriate to establish minimum desirable levels of air exchanges between indoors and outside so that acceptable levels of air quality are obtained inside the building with minimum energy expenditure.

Recent work by Fanger and Leaderer & Cain focusing on occupant perception about acceptable odour levels, have resulted in revision to CIBSE recommendations and ASHRAE standards (minimum of 8 l/s per person and 7.5 l/s per person respectively). **[57], [58]**

Infiltration rates used for the ESP-r models inside the corridors were taken by CIBSE recommendations. The infiltration/ventilation rates in the two dummy zones depend on the speed of the airflow inside the solarwall. It is not necessary to apply the CIBSE recommendations in the dummy zones because in a following section various speeds have been tested to check if there can be a more effective fan operation. Therefore, the ventilation/infiltration rates will vary accordingly.

---

[4] During summer, this may also result to energy gains. At this point, however, air infiltration is considered as an energy loss from buildings (through convection) during winter.

For the *Dummy_Solar* zone the outside air is initially passed through the solarspace of the solarwall, so that it can be warmed up. However, the *Dummy* zone is infiltrated[5] from the ambient air that is taken directly from the outside. That is the only difference between the two dummy zones, which results in the calculation of the energy savings contributed by the solarwall, as mentioned previously. Also the infiltration rate of *Dummy* zone has been kept the same with the ventilation rate of the *Dummy_Solar* zone as the airflow speed changes, so that energy consumption can be compared. **[56]**

It is essential to mention at this stage that the models produced for this work, do not control the volume of the warmed air and there are not any control strategies developed to prevent summer overheating. These are necessary assumptions that were considered during the development of these ESP-r models. In fact the results presented later (energy savings) are not affected by these assumptions.

The following Figure 3.5 is provided in order to view all the assumptions considered in ESP-r for the solarwall system only.

Infiltration has been set for the bottom solarspace zone (Solar_1). Zone Solar_2 is ventilated by zone Solar_1 and Solar_3 from Solar_2. These settings in the ESP-r solarwall model represent the airflow inside the solarspace. In addition, a high conduction material has been used for the surfaces that divide the solarspace zones. Thus heat can transfer between the solarspace zones without a detrimental effect on the heat loss due to heat resistance.

[5] Infiltration is the renewal of the indoor atmosphere by the outside air. Ventilation is the indoor air coming from another zone of the building.

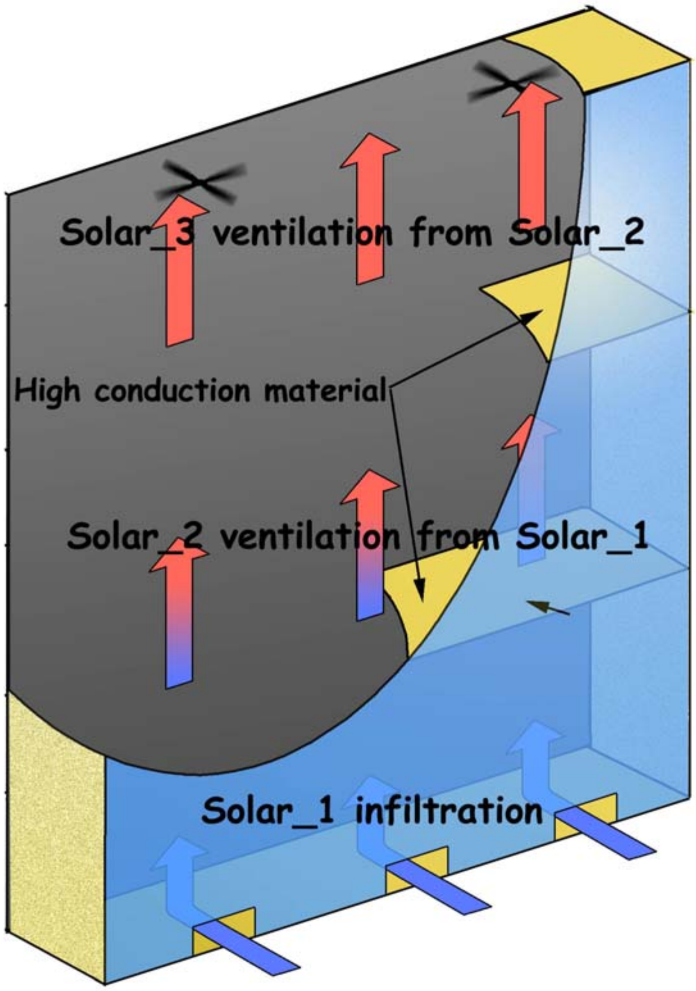


Figure 3-5: Solarwall system and ESP-r assumptions.

3.3.5 Modified models

These models have been used in order to examine whether the solarwall system can be refined. The various modifications that have been applied on the original solarwall model, and for each case simulation has taken place, are:

- Thickness.

In the first case the thickness of the concrete wall (thermal mass of the solarwall system) has been increased to 30cm from 15cm. This modification is considered to give higher energy savings from the solarwall because higher thermal mass volume results to a higher amount of heat stored.

- Airflow speed.

The airflow speed of the original solarwall model has been decreased to 0.5m/s and increased to 1.5m/s, where 1m/s is the original airflow speed value. It is believed that this modification can alter the amount of warm air entering the *Dummy_Solar* zone thus affecting the energy performance of the solarwall.

- Solarspace.

The specific modification of the original solarwall model involves the increase of distance to 20cm between the glazing and thermal mass (concrete wall) of the solarwall. The initial distance is 10cm. Making the above variation might increase the volume of warmed air, but there is a possibility that this higher volume might not be heated enough from solar gains, due to high airflow speed 1m/s.

- Absorbent/Airflow/Solarspace.

For this case the thickness of the thermal mass wall (concrete wall) has been set to 30cm, the speed of the airflow to 0.5m/s and the solarspace distance to 20cm. This modification is applied due to the fact that lower airflow speed and increased solarspace volume might heat the incoming ambient air higher so that energy savings increase. The thicker concrete wall can assist to higher insulation of the corridors.

- Airflow/Solarspace.

According to the two last variations it is necessary to observe what the effect the original concrete wall thickness can have, providing lower airflow speeds and wider space between solarwall glazing and thermal mass wall. The additional volume of concrete in the previous case might be unnecessary.

- Insulation and low-e glazing.

This last modification includes the addition of insulating materials on the surface of the concrete wall that faces the corridors. This variation can result to lower energy losses from the corridor zones. Also, the use of a low emissivity glass, instead of the simple double-glazing used on the initial solarwall model, can improve the performance of the solarwall. Less heat escapes from the low-e glass; therefore higher solarspace temperatures can be achieved. This will increase energy savings.

Finally, for this last modification the airflow has been increased to 1.5m/s. Because of the higher solar gains inside the solarspace (cause of the low-e glass) the increase of the airflow speed can result to higher amounts of heat ventilated to the *Dummy_Solar* zone.

All modifications described have the main objective of improving the solarwall system.

3.4 Energy savings

The first results are listed in Table 2. For *Zones_1,2,3* the values listed are the energy consumptions for each zone. The energy performance of the solarwall is calculated by subtracting the different amounts of energy required to heat the two dummy zones. Energy savings by the original solarwall model reach 12,528kWh.

It is observed that energy required to heat the three zones (1,2,3) is increased with the solarwall system, because of the high ventilation rates during the solarwall operation and low insulating performance of the concrete (thermal mass). Some part of the heat escaping from the corridor, through the concrete, is trapped inside the solar space of the solarwall system; therefore it is ventilated to the *Dummy_Solar* zone. So the total energy saved by the solarwall taking into consideration the energy consumption from Zones_1,2,3 is 12,075kWh.

		SIMPLE MODEL kWh	SOLARWALL kWh
Energy Consumed	Zone_1	2,448.68	2,776.95
	Zone_2	2,165.06	2,509
	Zone_3	2,965.65	3,090
Energy Saved			12,528

Table 2: Annual energy consumption and savings comparison between the simple and solarwall model. The same table format is used on the following similar tables[6].

The above fact is investigated by applying some insulation on the concrete wall on the corridor side. The results shown on the following table indicate that heat lost from the concrete wall is less.

Lesser amount of heat escapes from the corridors through the concrete, and because of that, lower energy savings are contributed by the solarwall system. Therefore, the insulating material has a negative impact in the performance of the solarwall, as it now provides less energy savings.

On the other hand, taking into account energy savings resulted by the smaller amount of energy required to heat zones 1,2,3 there is a total of 12,670kWh conserved.

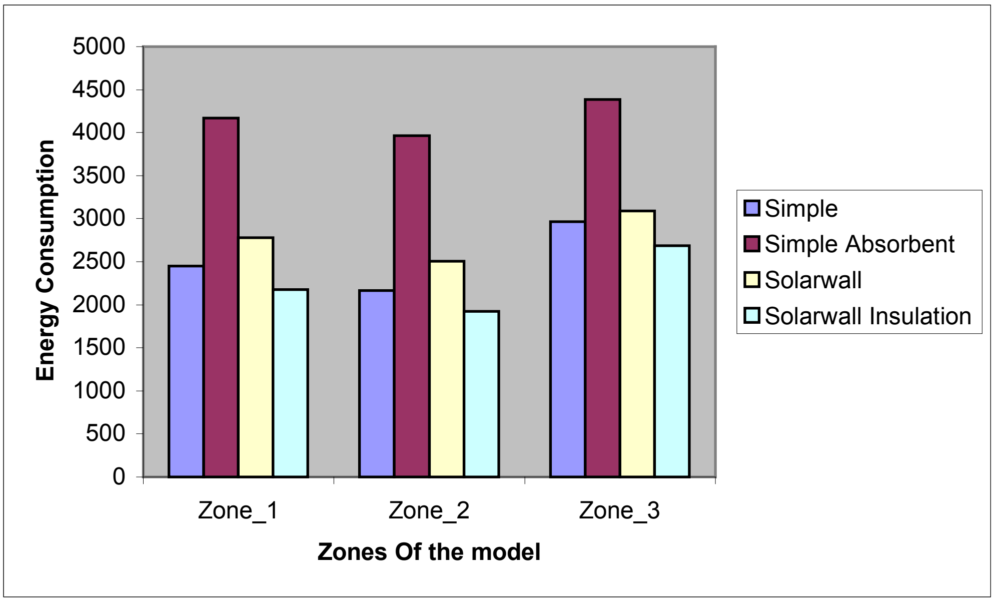
	Solarwall with insulation kWh
Zone_1	2,180
Zone_2	1,922

[6] The kWh values on the tables for the corridor zones (Zone_1, Zone_2, Zone_3) are energy consumption values.

Zone_3	2,686
Energy Saved	**11,880**

Table 3: Annual energy consumption and savings when insulating material is applied on the concrete wall.

The following graph represents the effect of different models in the energy performance of zones 1,2,3. The *Simple Absorbent* series corresponds to the energy consumption values provided when the south external surface of the simple model is considered to be the concrete wall (thermal mass of the solarwall model) instead of the common external wall construction material[7]. More specifically the simple absorbent model is a modification of the simple model. The only modification is that a black coloured plain concrete wall has been selected as the material of the south surface of the model. When the additional double-glazing is applied in front of the thermal mass wall there is a 33% reduction in the energy consumption of the three zones/corridors (solarwall model). If the insulating material is applied the reduction increases to 46% (solarwall insulation).



Graph 1: Energy consumption comparison for zones 1,2,3.

Considering the simple absorbent model as the base case, the actual energy savings[8] made by the other three models, is shown on the following table.

[7] Look appendices constructional characteristics for the specific materials.
[8] In this comparison energy savings resulted in the corridors (zones 1,2,3) have also been considered.

	SIMPLE MODEL kWh	SOLARWALL kWh	SOLARWALL INSULATION kWh
Energy Saved	**4,936**	**16,667**	**17,607**

Table 4: Annual energy savings comparison.

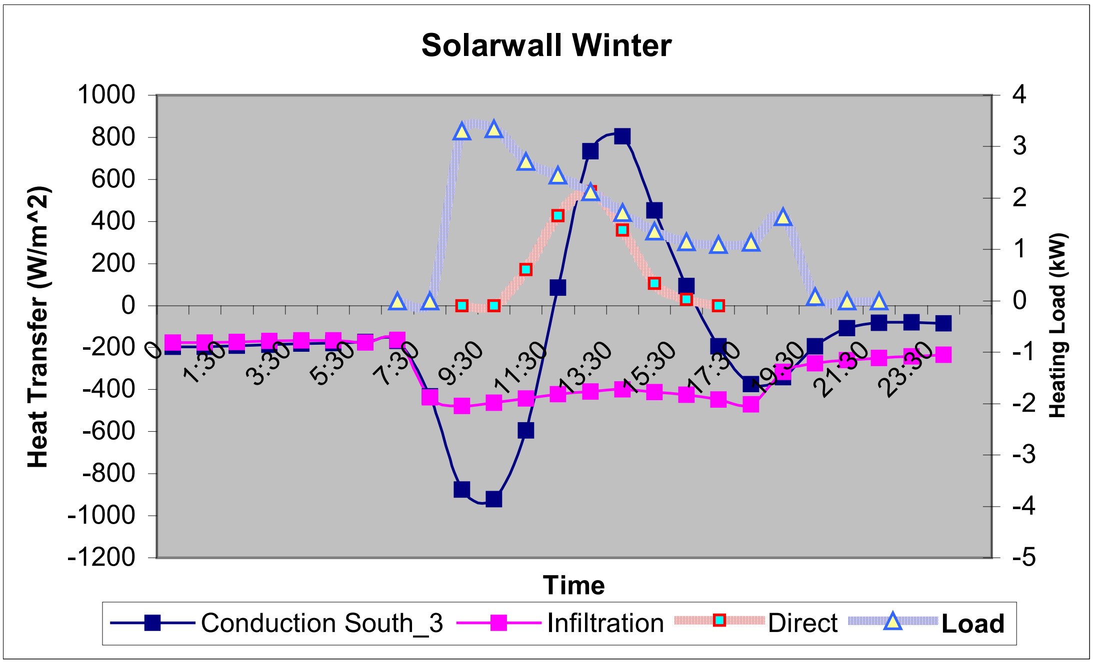
In order to understand the basic difference between the two main models, simple and solarwall, the following graphs are provided. The values are based on *Zone_3*. The *conduction south_3* series represents the heat flux that takes place in the inside south surface of *Zone_3*. *Infiltration* corresponds to the heat lost from *Zone_3* due to infiltration. The *load* series symbolizes the heating load required to heat *Zone_3*, and that is the only series using the scale on the right side of the graphs.

A typical winter (1^{st} of January) and summer (10^{th} of July) day is picked up for these results.

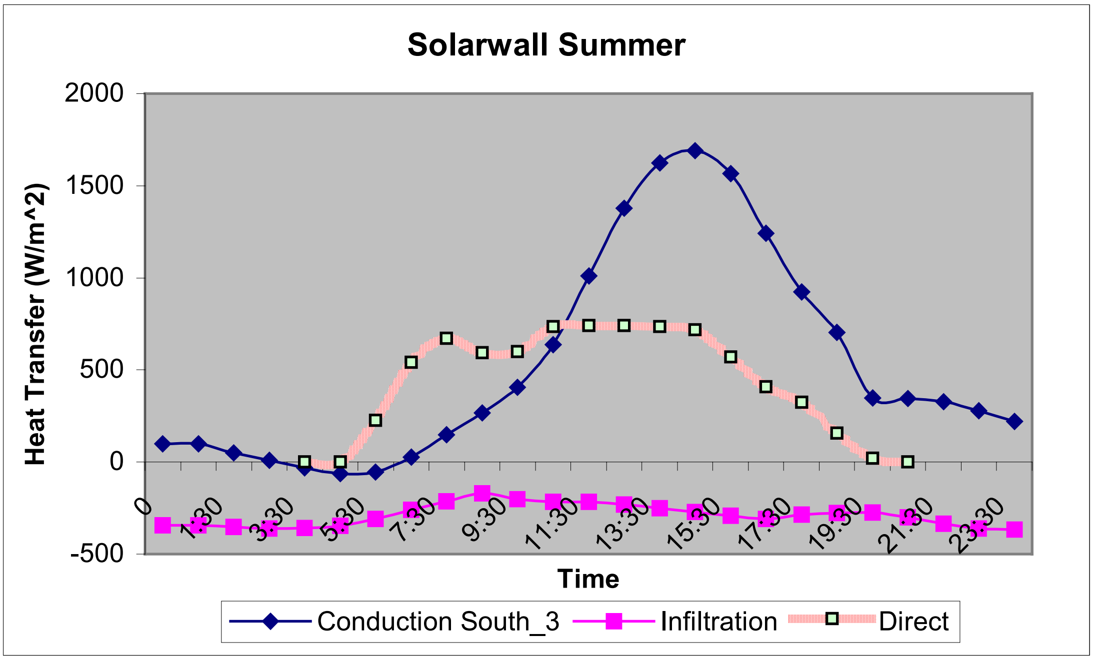
The basic difference between summer and winter is that a heating load is not required during summer to warm[9] the corridors.

The effect of the solarwall system is noticed in the two winter graphs 2,3 between the two models. For the solarwall model heat is gained by conduction through the thermal mass (concrete) after 11:30 hours. However, in the simple model there are no heat gains associated with the south surface of *Zone_3*. In addition solar heat gains become zero around 17:00, the solarwall is still in operation and that is why heat flux at 18:00 hours reaches a minimum value.

[9] In fact, zones 1,2,3 overheat during summer. The solarwall model developed is not capable of shutting down the fans when the ambient temperature has reached the maximum value allowed. In general, summer cooling has not been investigated in this thesis, but it can be an area where another project could be based on.

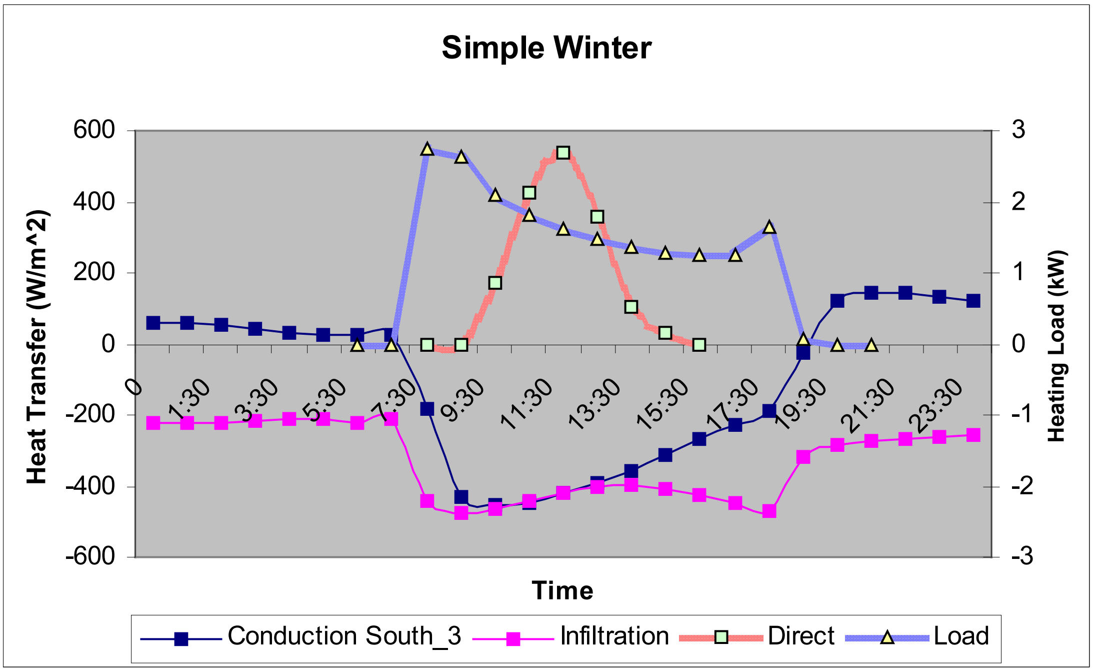


Graph 2: Original solarwall model heat exchange on the inside face of the south surface in Zone 3 during winter.

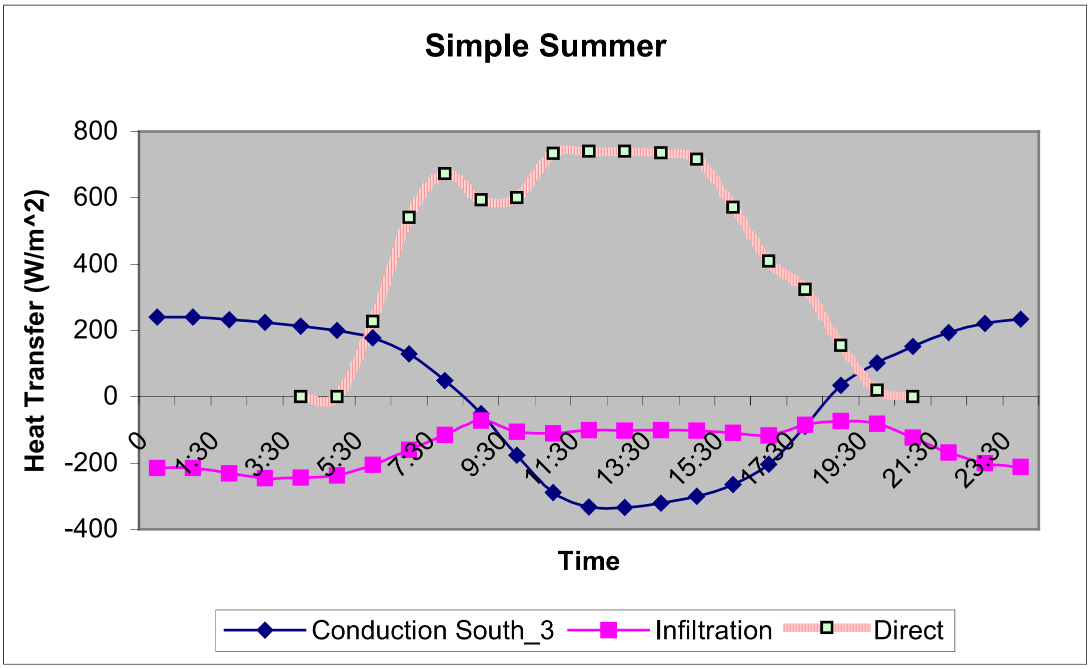


Graph 3: Original solarwall model heat exchange on the inside face of the south surface in Zone 3 during summer.

However, more energy is required to heat the corridor in the solarwall model than in the simple model. And that happens because of the low insulation specifications of the thermal mass (concrete). The heating load reduces more rapidly in the solarwall model, since there are heat gains from the south surface.



Graph 4: Simple model heat exchange on the inside face of the south surface in Zone 3 during winter.



Graph 5: Simple model heat exchange on the inside face of the south surface in Zone 3 during summer.

3.5 High end performance

The purpose of this section is to examine the climate circumstances under which the performance of the solarwall is improved or deteriorated.

3.5.1 Monthly energy performance

The following graphs 6,7 show the monthly energy savings contributed by the solarwall system. Average values for direct solar gains and ambient temperatures are plotted for a more in depth analysis.

The highest energy savings occur during March, April and May.

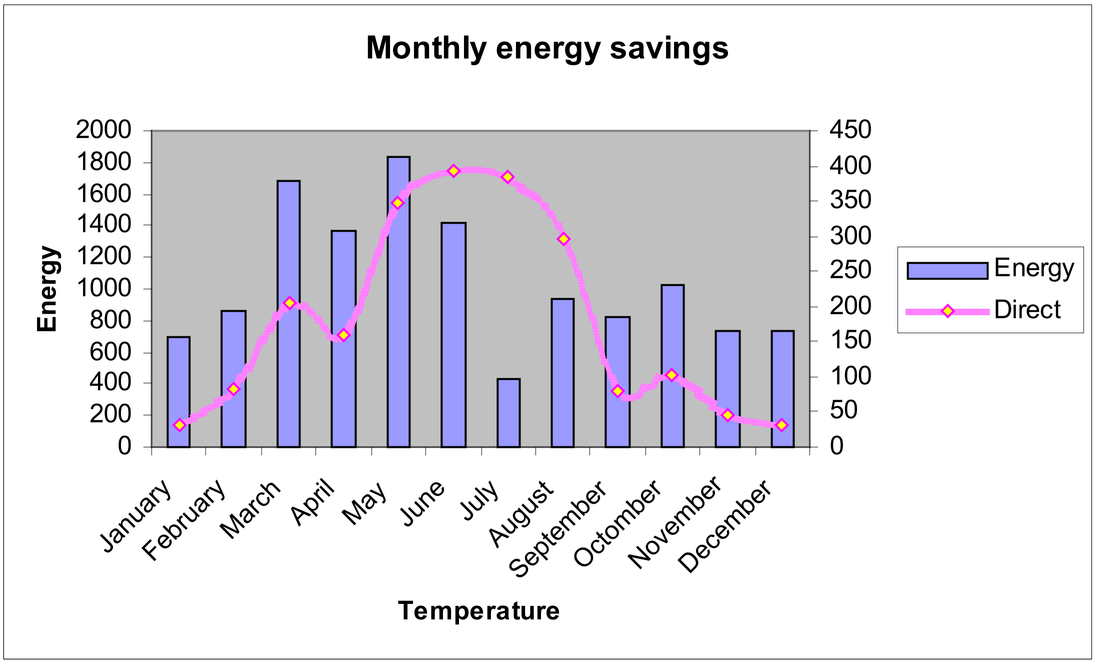
During March the average ambient temperature and solar direct gains are 8.9C^{o} and 205.5W/m^2 respectively. The resulted energy savings are the second highest during the year.

In April the average direct gains fall to 159W/m^2 and ambient temperature has a minor increase. It is observed that energy savings follow the path of the solar gains.

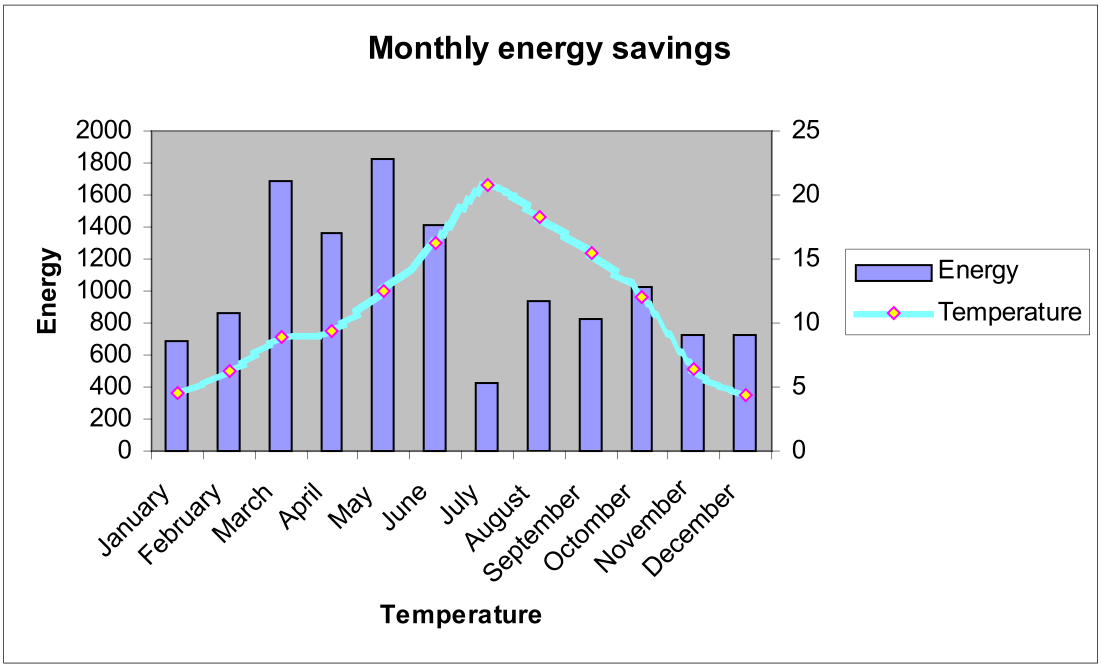
In May the solar gains almost double to 346.6W/m^2, although the energy savings do not increase significantly. That is because of the relatively high ambient temperature during this month. During the following three months of summer, where direct solar gains and ambient temperatures are very high the performance of the solarwall system is declined.

On the other hand when ambient temperatures are low and direct gains high, the performance of the passive solar system is enhanced.

Further investigation follows in the next section 3.6.2.



Graph 6: Monthly energy savings and direct gains.



Graph 7: Monthly energy savings and ambient temperature.

3.5.2 Per day energy performance

In order to analyse further the performance of the solarwall and the climatic conditions, individual days have been picked up with different characteristics (climatic).

The following three cases have been considered:

- Low ambient temperature with high direct gain.
- Low temperature and low solar gain.
- High temperature and high solar gain.

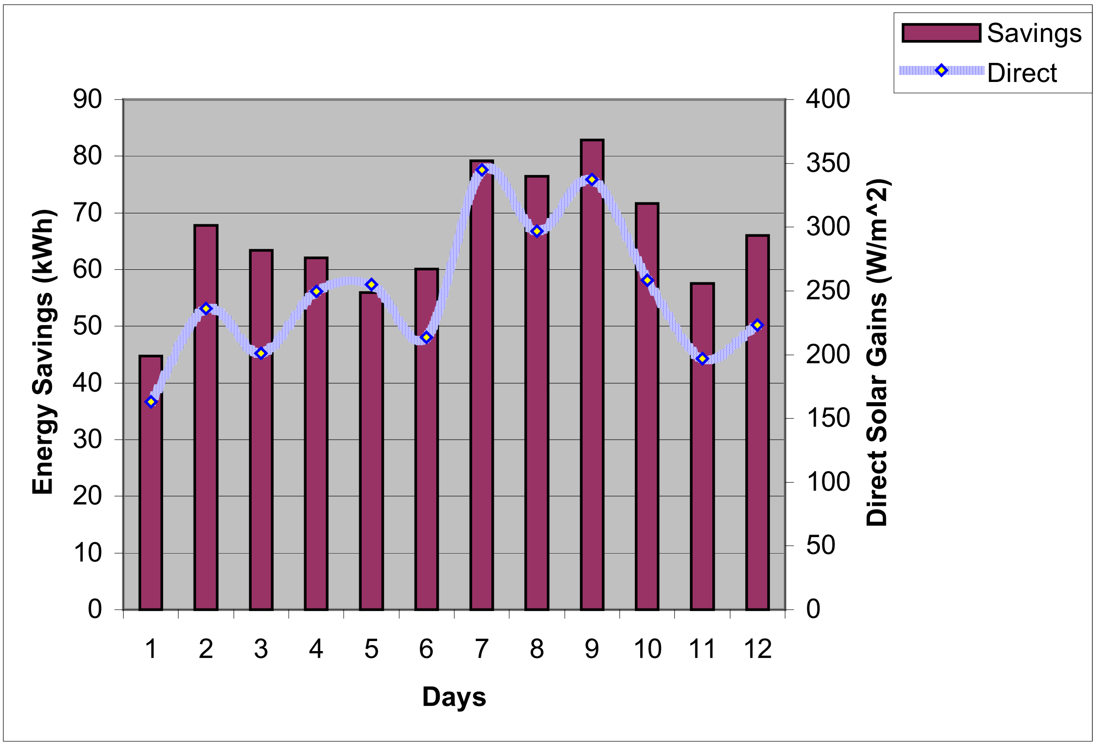
For each case various individual days are chosen from the climate database of ESP-r and energy savings were calculated.

Low ambient temperature with high solar direct gains

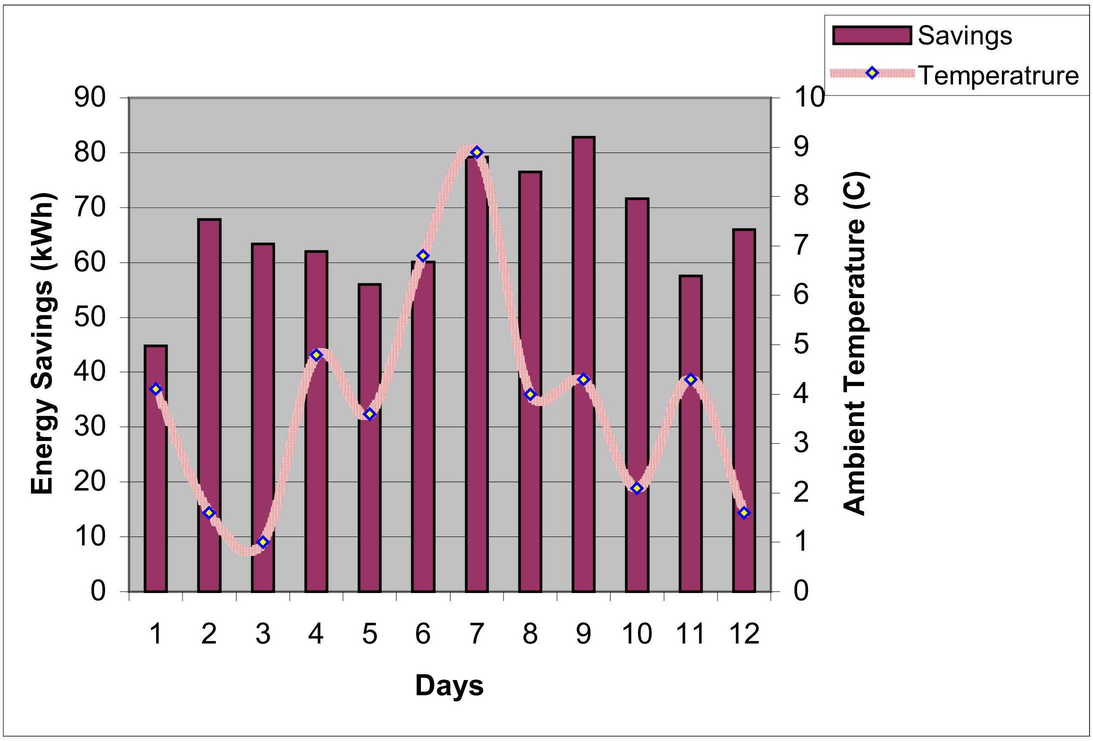
On the following graphs 8,9 are represented 12 different days[1] whose main characteristics are high ambient temperatures and high solar direct gains during the operation of the solarwall (9-18hours).

From the two graphs, the operation of the solar system during the 9th day contributes to the highest performance of the solarwall. Very low ambient temperatures and high direct gains are the main requirements for high-energy savings.

[1] Look appendices for more information about these days, the energy consumption and savings contributed by the passive solar system.

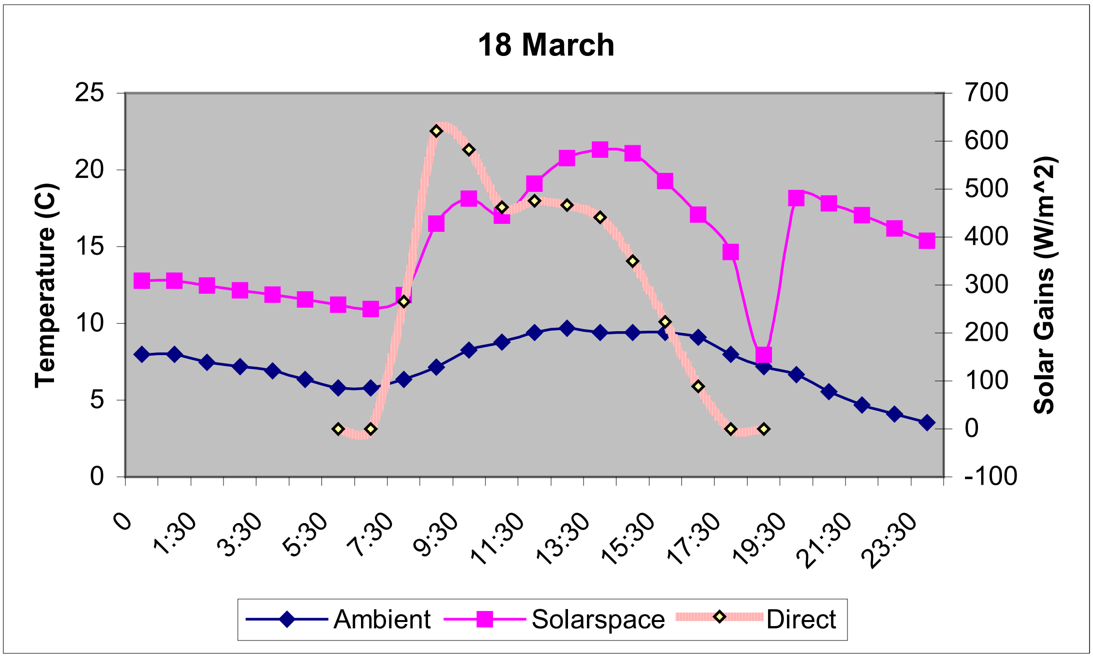


Graph 8: Low temperature, high solar gains energy performance and direct solar radiation.



Graph 9: Low temperature, high solar gains energy performance and ambient temperature.

From graph 10 it can be seen that the difference between solarspace and ambient temperature is high during the operation of the solarwall. The temperature inside the solarspace is reduced slowly because of the high solar direct gains. As soon as the sun's radiation decreases the temperature inside the solarwall falls rapidly.

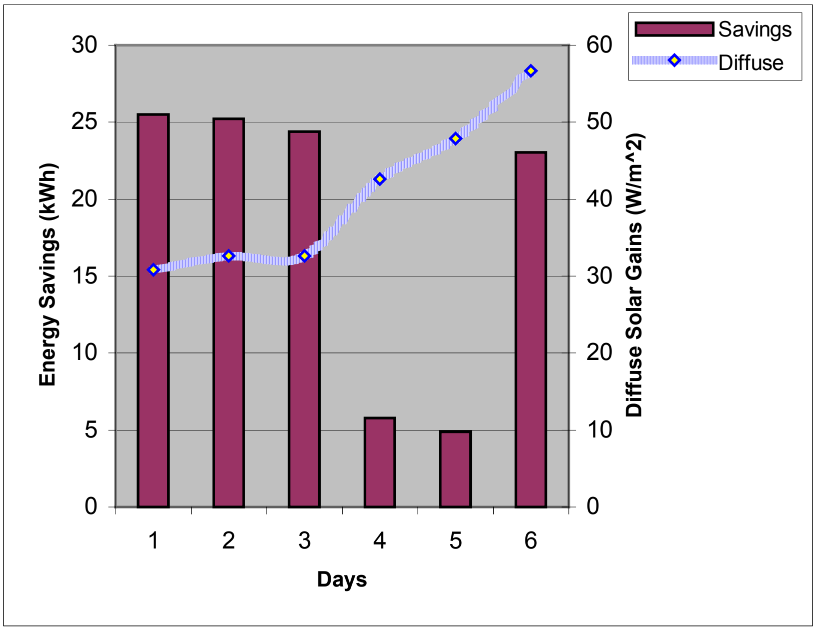


Graph 10: Comparison between solarspace and ambient temperature of the original solarwall model.

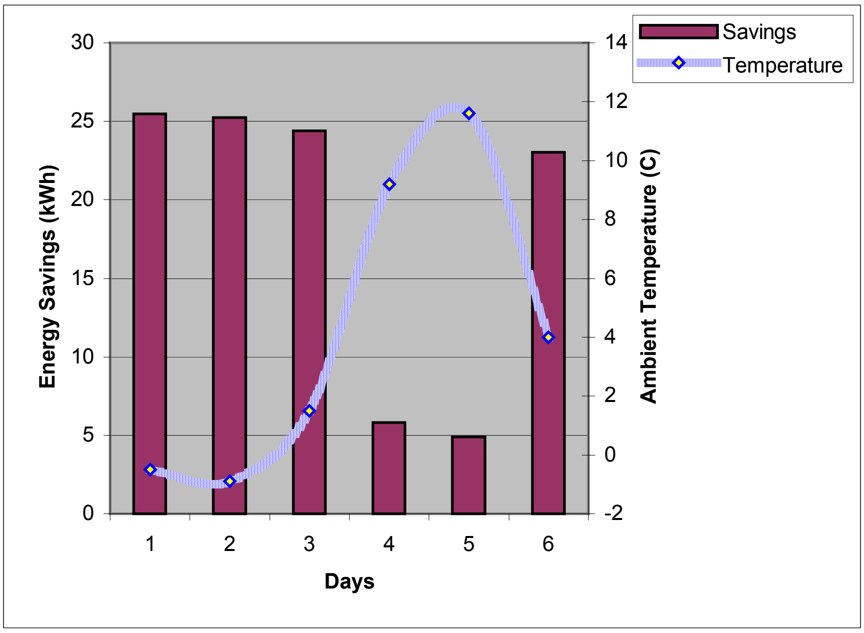
Low temperature and low solar gains

For this type of climate, 6 different days have been picked up[2]. Comparing with the low temperature and high solar gains climate the energy performance of the solarwall system has deteriorated. In fact there are not any direct gains during the operation period of the solarwall and that is the main reason for this poor performance.

[2] Look appendices for more information about the specific days and the energy performance of the solarwall model.



Graph 11: Low temperature, low solar gains energy performance and diffuse solar radiation.

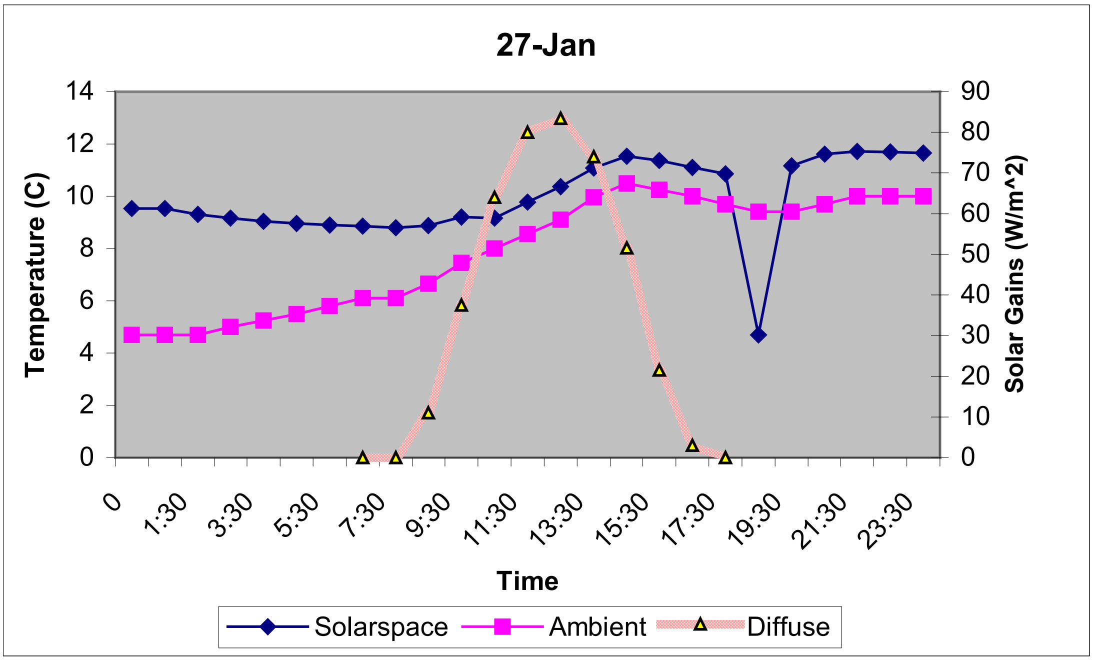


Graph 12: Low temperature, high solar gains energy performance and ambient temperature.

During days 4 and 5 the energy savings are considerably lower. This is explained with the following graph, which represents the ambient temperature and the temperature inside the solar space. Specifically these days are 27th of January and 2nd of February[3]. It is observed that the difference between the two temperatures always remains small during the solarwall operation. That happens because of the low solar gains. Additionally, at 17:30 hours diffuse solar gains become zero, therefore the solar space cools down rapidly as there is

[3] Look appendices for more details in the performance of the solarwall during these days.

no additional heat to be gained by the sun. That is why energy savings by the solarwall during these two days are considerably small.



Graph 13: Comparison between solarspace and ambient temperature of the original solarwall model

High temperature and high solar gains

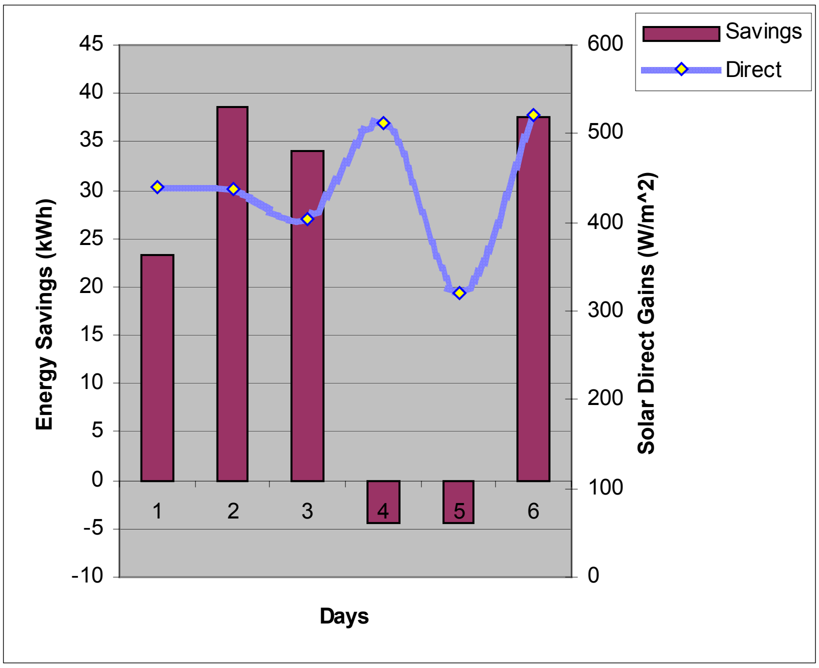
For this climate energy savings have improved slightly (comparing with the last case).

On the other hand there are two specific days 4 and 5 where energy losses take place. These two cases are the warmest days of the year.

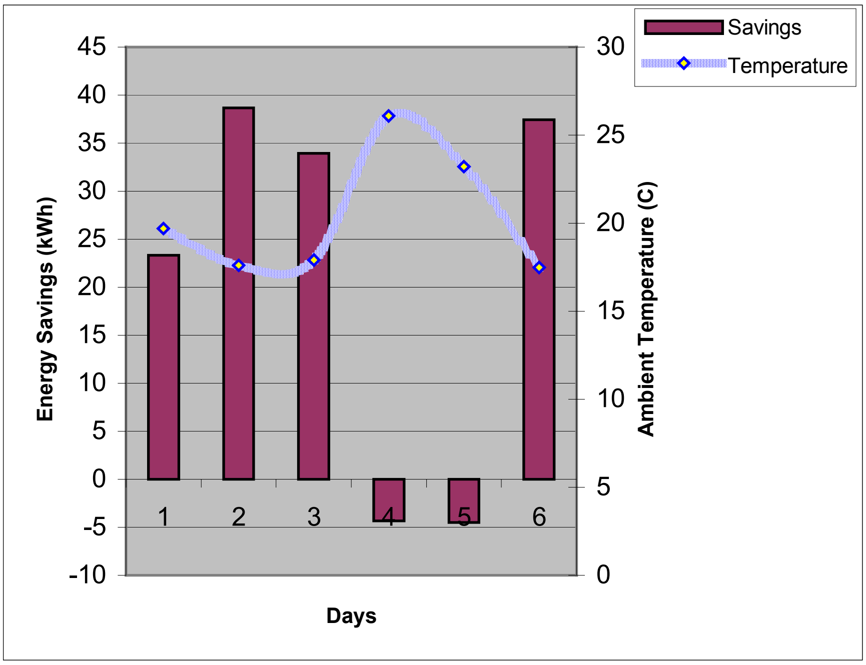
These specific energy losses contributed by the solarwall system are explained with graph 16. It is noted that during 9-18 hours the temperature inside the solar space of the solarwall is lower than the ambient air temperature and even lower than 22°C[4]. Therefore, when *Dummy* zone is infiltrated by the ambient air with a 22°C temperature, the *Dummy_Solar* zone is ventilated by the solarwall whose temperature is lower than 22°C so a heating load will be required to take the temperature of this dummy zone to the required specifications.

These results can be avoided if a control flow network is created for the solarwall model in ESP-r. However, it was not proven necessary because the required outcome is not greatly affected by the above low energy performance cases.

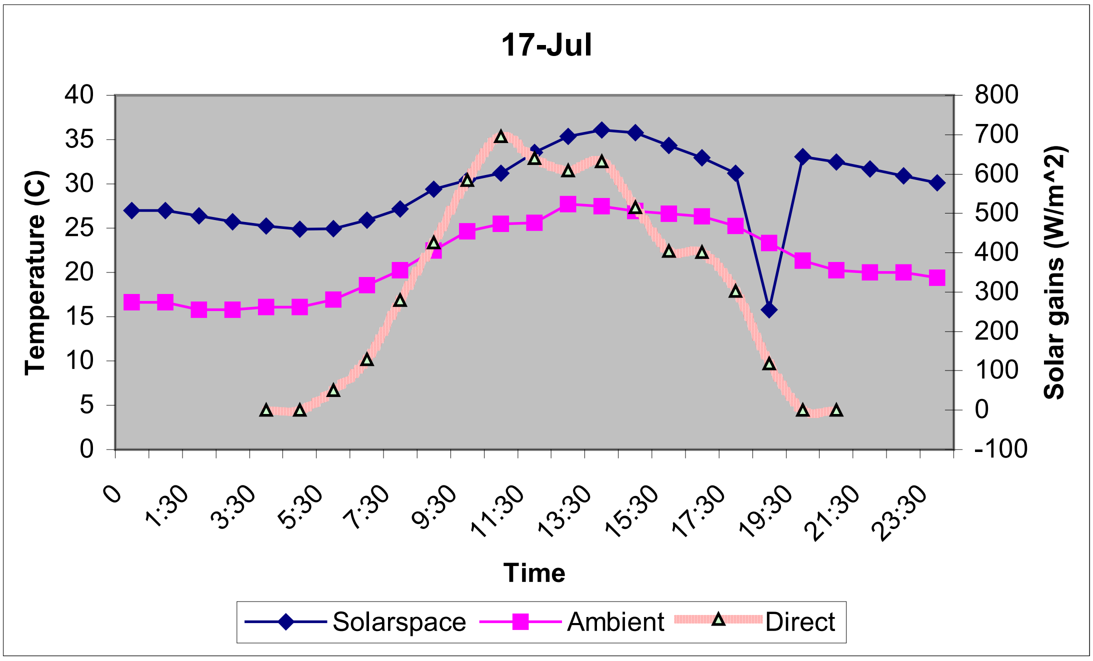
[4] This is the temperature that was set up in the model to be reached by the HVAC system during 7-19 hours inside the dummy zones.



Graph 14: High temperature, high solar gains energy performance and direct solar radiation



Graph 15: Low temperature, low solar gains energy performance and ambient temperature.



Graph 16: Comparison between solarspace and ambient temperature of the original solarwall model

3.6 Modifications

In this section various modifications have been applied to the solarwall model in order to find out whether the performance of the passive solar system can be refined.

3.6.1 Absorbent (Thickness of thermal mass)

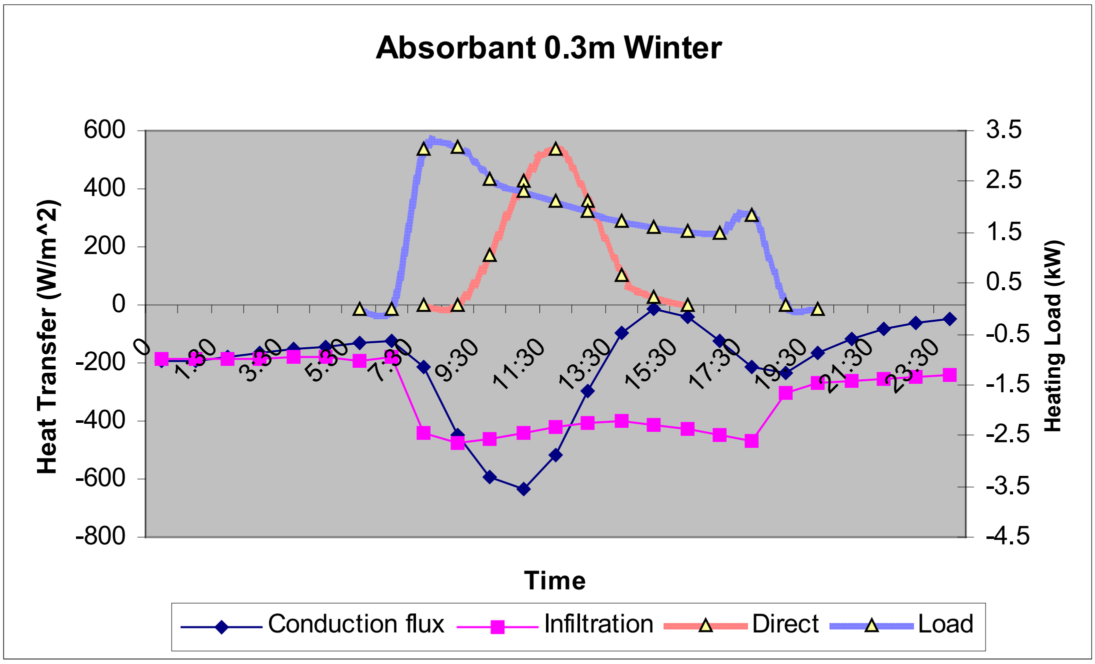
The first modification that was applied on the original solarwall model was the increase the thickness of the thermal mass (concrete wall) to 30cm.

Energy consumptions, resulted by this alteration, are listed on the following table. Lower energy savings take place due to higher insulation of the thicker concrete wall, thus lower amount of heat is lost from the corridors (lower energy consumption in the corridor zones).

	SOLARWALL (kWh)	**Absorbent 30cm** (kWh)
Zone_1	2,777	2,637
Zone_2	2,509	2,372
Zone_3	3,090	2,998
Energy Saved	**12,528**	**12,154**

Table 5: Original solarwall model vs. solarwall with 30cm thickness thermal mass

On the following graph is noted that the heat travelling through the concrete wall takes longer time to reach the inside surface because of the thicker material. In fact heat gains do not take place because solar radiation is minimised just before heat starts entering zone_3.



Graph 17: Solarwall model absorbent 30cm heat exchange on the inside face of the south surface in Zone 3 during winter.

3.6.2 Air Flow (Speed)

For this case, the airflow inside the solar space of the solarwall is modified to 0.5m/s and 1.5m/s[5].

Table 6 lists the results of the simulations for the different models.

When the speed of the ventilated air inside the solarspace is set to 0.5m/s the energy required to heat the corridor is slightly decreased, because of the lower convection heat transfer coefficient. Also the savings contributed by the solarwall decline significantly.

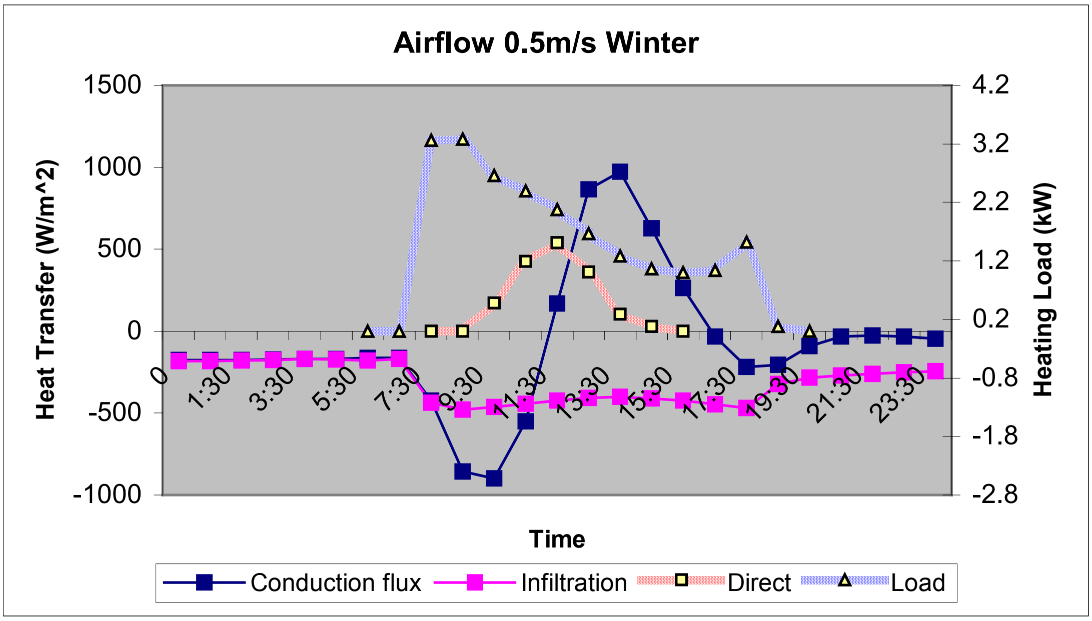
For a speed of 1.5m/s the convection heat transfer coefficient increases, therefore heat loss from the corridor is increased. There is also a small decline in the energy savings of the passive solar system.

[5] Look appendices for the corresponding convection heat transfer coefficients.

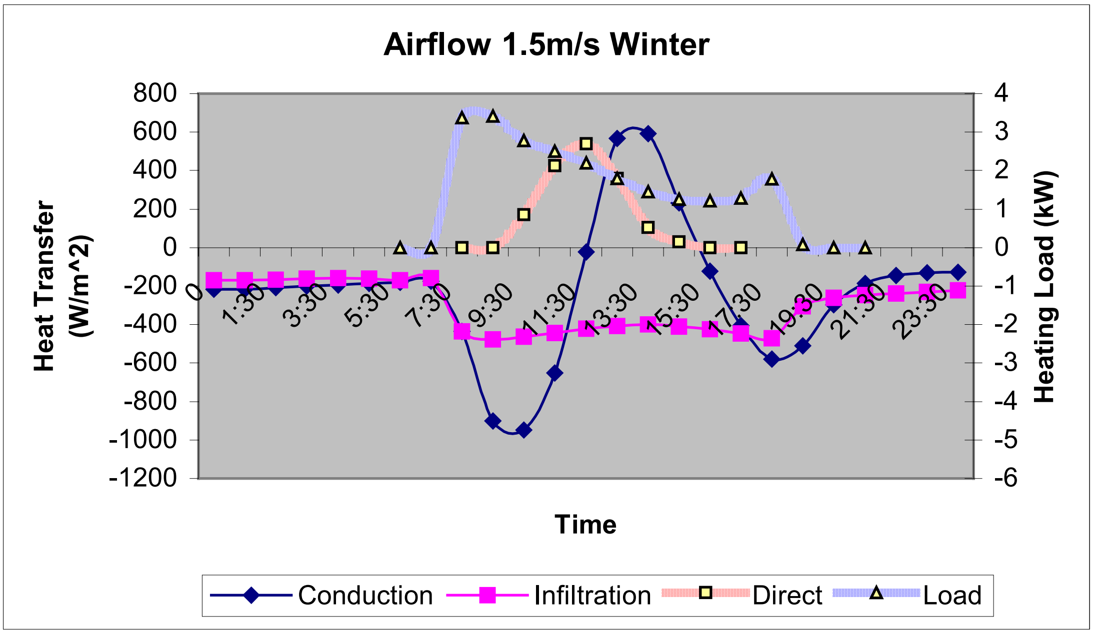
	SOLARWALL (kWh)	Airflow 0.5m/s (kWh)	Airflow 1.5m/s (kWh)
Zone_1	2,777	2650.77	3042.61
Zone_2	2,509	2346.58	2771.9
Zone_3	3,090	2921.94	3317.82
Energy Saved	**12,528**	**10,450**	**12,021**

Table 6: Energy performance of solarwall models with various airflow speeds.

The effects that the different airflows have on the heat exchange on zone 3 during the solarwall operation are shown on the following graphs.



Graph 18: Solarwall model airflow 0.5m/s heat exchange on the inside face of the south surface in Zone 3 during winter



Graph 19: Solarwall model airflow 1.5m/s heat exchange on the inside face of the south surface in Zone 3 during winter.

Firstly, the heating loads in the 1.5m/s speed case are higher than the 0.5m/s case. And that is why more energy is required to heat the corridors when the airflow speed is 1.5m/s. Also, heat gains in the corridor through the concrete are higher when the airflow is slow (0.5m/s).

3.6.3 Solarspace (Distance)

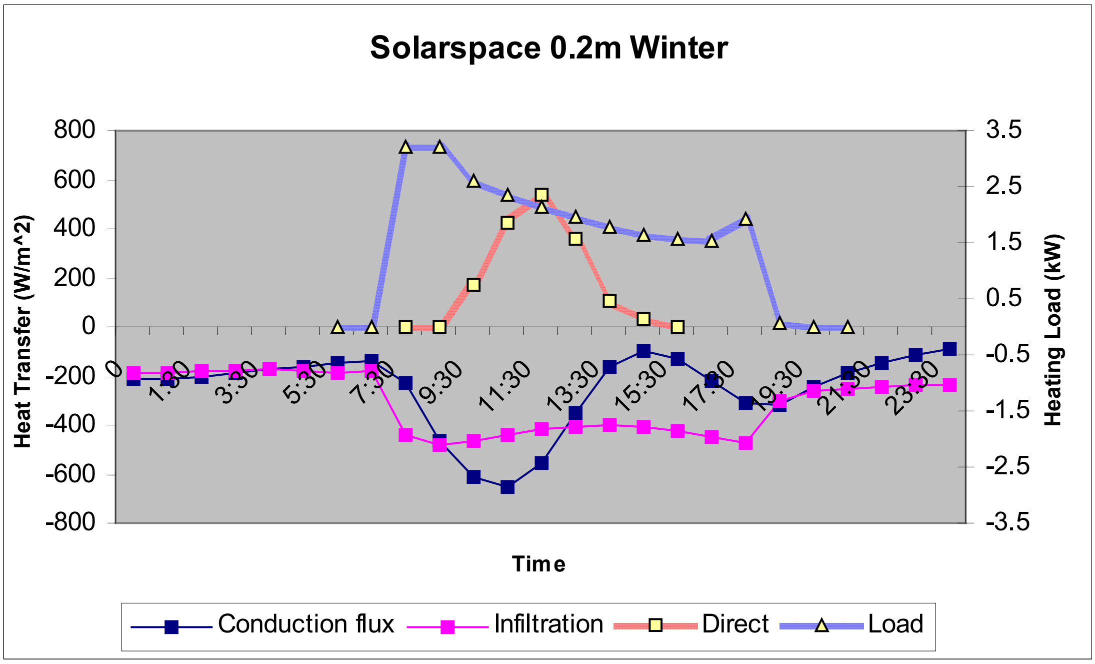
Another modification is applied to the width of the solarspace. That is the distance between the concrete wall and the glazing of the solarwall, which is increased to 0.2m.

Simulations of this new model give the following results.

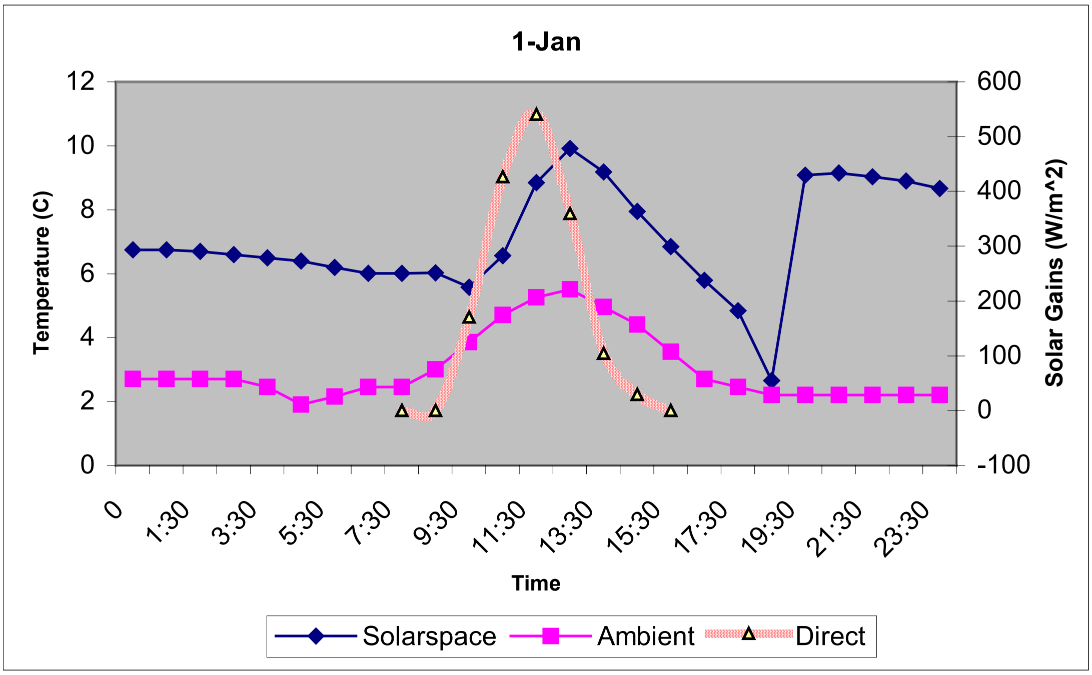
	SOLARWALL (kWh)	Solarspace 0.2m (kWh)
Zone_1	2,777	2897.73
Zone_2	2,509	2666.41
Zone_3	3,090	3264.02
Energy Saved	**12,528**	**3,394**

Table 7: Energy performance of the solarwall-modified model.

The energy performance of the passive solar system has declined to 3,394kWh. The reason for this significant low performance is explained on Graph 21. The difference between the ambient and solarspace temperature is very low, thus energy required to heat the *Dummy* zone is almost equal with the energy demanded to heat *Dummy_Solar* zone.



Graph 20: Solarwall model solarspace 0.2m heat exchange on the inside face of the south surface in Zone 3 during winter.



Graph 21: Comparison between solarspace and ambient temperature of the solarwall with 0.2m solarspace model

3.6.4 Absorbent/Airflow/Solarspace

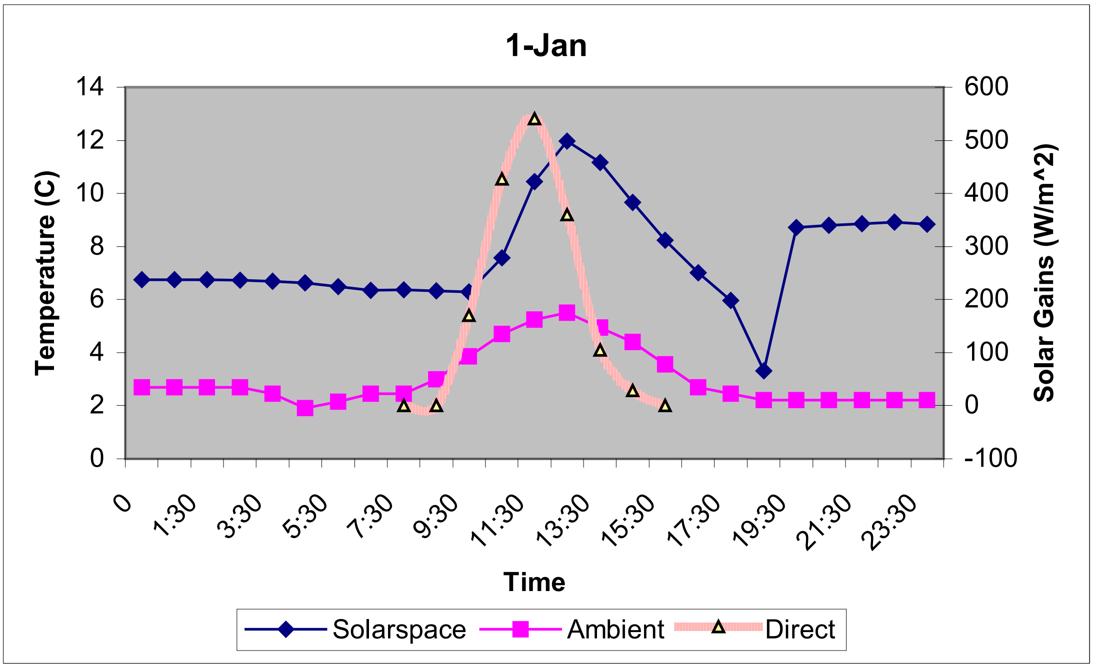
Examining the results of the last modification, this case might improve the energy savings. The thickness of the absorbent has been set to 0.3m, the airflow to 0.5m/s and the solarspace to 0.2m. The slow airflow should allow the temperature of the solarspace to increase, therefore the performance of the solarwall to improve.

Looking on the table with the new results, it is observed that in fact the energy savings have increased significantly, but not enough to be implemented in the design of the system. The net energy savings[6] achieved by this modified design are 109kWh only.

	SOLARWALL (kWh)	**Abs 0.3m Air 0.5m/s Solar 0.2m** (kWh)
Zone_1	2,777	2669.02
Zone_2	2,509	2406.07
Zone_3	3,090	3039.11
Energy Saved	**12,528**	**12,375**

Table 8: Energy performance of the modified solarwall model.

[6] This value includes the energy consumed to heat the corridors.



Graph 22: Ambient temperature, solarspace temperature in a typical winter day.

The temperature difference has now increased, because of the low speed of the airflow. Lower operation of the fan has increased energy savings, but the additional concrete volume is a great disadvantage on the cost of the system.

3.6.5 Airflow/Solarspace

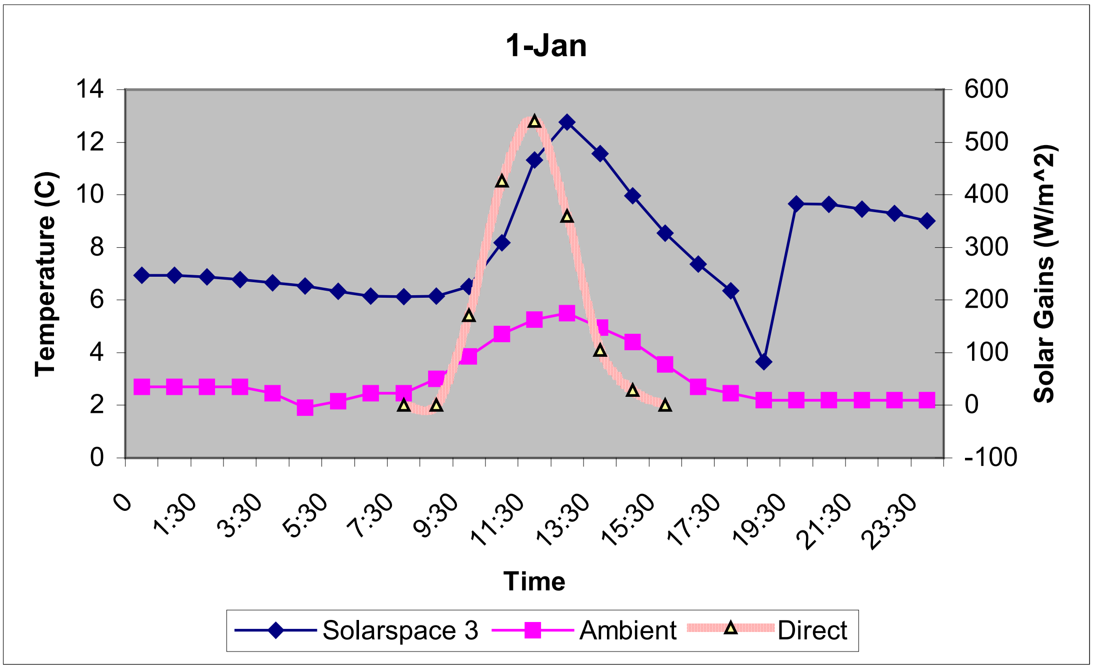
Considering the results from the previous section, another case is created to check whether the additional volume of the concrete is necessary.

The results on table 23 indicate that there are only 119kWh saved. So the only difference between the two models is the additional concrete volume of the previous case.

	SOLARWALL (kWh)	Airfow 0.5m/s Solar 0.2m (kWh)
Zone_1	2,777	2811.31
Zone_2	2,509	2546.59
Zone_3	3,090	3134.63
Energy Saved	12,528	12,762

Graph 23: Energy savings by the modified solarwall model.

Comparing the temperature profiles of the solarspace during the typical winter day (1st January), is observed that for the thinner thermal mass, slightly higher maximum value is achieved. This small dissimilarity corresponds to higher energy savings by the solarwall in the *Dummy_Solar* zone as shown on the table above.



Graph 24: Comparison between solarspace and ambient temperature of the modified solarwall model.

3.6.6 Insulation and low-e glazing

This is the final modification applied on the original solarwall model. Insulation has been applied on the thermal mass wall facing the corridor, thus heat losses are minimised. Low-e glazing has been used for the glazing material of the solarwall, so more heat can be captured inside the solarspace; therefore energy savings can be increased further.

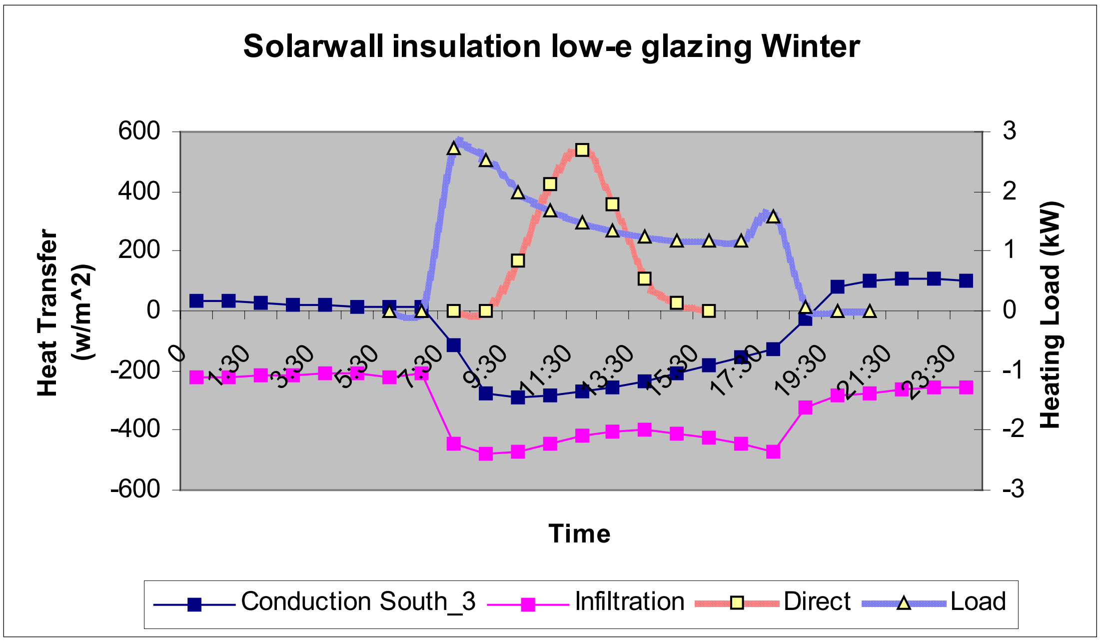
Simulations specify that in fact the performance of the solarwall has improved considerably, table 25.

	SOLARWALL (kWh)	**Insulation and low-e glazing** (kWh)
Zone_1	2,777	2034.8
Zone_2	2,509	1773.29
Zone_3	3,090	2536.91
Energy Saved	**12,528**	**16,984**

Graph 25: Energy savings by the solarwall model with insulation and low-e glazing.

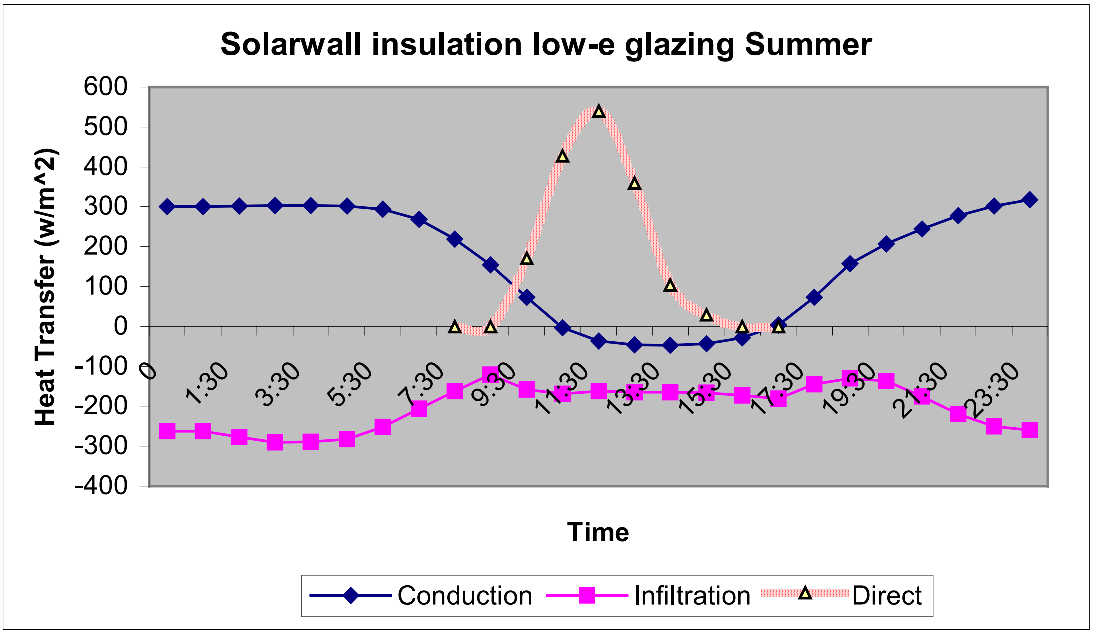
The way this alteration has affected the operation of the solarwall is shown on the two following graphs.

The heat lost from the south surface of zone 3 reaches a minimum of $-290 W/m^2$, where the original solarwall model reaches at the same time of the day $-920 W/m^2$. For the solarwall model, later during the day, heat enters the corridor graph 2. For this modified case heat transfer values still remains negative because of the insulation.

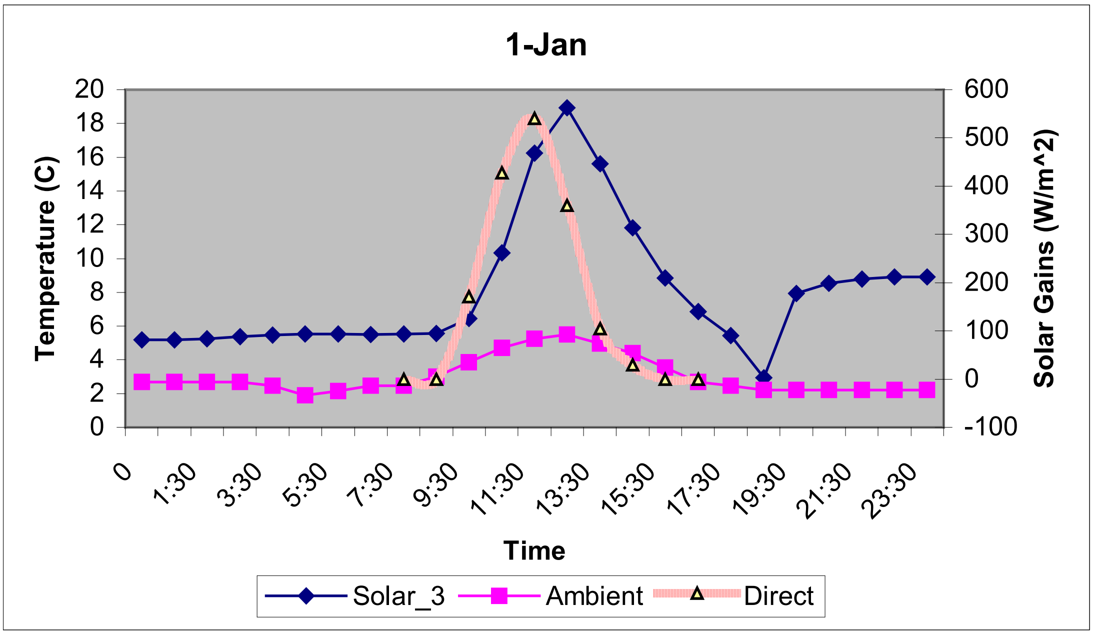


For the typical summer day the insulation prevents again incoming trapped heat from the solarspace of the passive solar system. This is a great advantage because during summer temperatures inside the corridors must remain low. On the other hand, all other models including modified and original, have this great disadvantage of allowing a lot of unwanted heat from the solarspace during summer[7].

[7] Heat flux diagrams for all models during summer can be found in appendices.



The effect of the low-e glazing material is shown on the following graph. The temperature of the solarspace has increased substantially so energy savings have also improved.



Now that the temperature inside the solarspace has improved significantly it is important that a final modification is applied to this already modified model. More specifically, increasing the speed of the airflow inside the solarspace might improve further the performance of the solarwall.

The following results correspond to the solarwall model with insulation and low-e glazing but with 1.5m/s speed of airflow.

	Insulation and low-e glazing (kWh)	**Insulation and low-e glazing airflow 1.5m/s** (kWh)
Zone_1	2034.8	2062.75
Zone_2	1773.29	1805.39
Zone_3	2536.91	2570
Energy Saved	**16,984**	**16,684**

Energy consumption increases for higher airflows. Thus far the solarwall model with insulation and low-e glazing consists the higher energy performance system modification. Additional insulation and low emissivity glazing add significantly to the cost of the passive solar system. Therefore, a cost analysis is required in order to make the final comparison between the various designs presented.

3.7 Fan operation

Energy consumed by the fan operation is an important factor that has to be considered during the comparison of the various models discussed in the previous section.

The first step is to find how many hours the fan will not operate during one year. From the climate database of ESP-r the days that the ambient temperature reaches 22^{o}C are found. Looking at the ambient temperature profile for each individual day it is found that 99hours during the solarwall operation reach 22^{o}C and over. So the annual operation time of the fan is 365 days * 9 hours – 99 hours = 3186hours.

The following table gives the final energy savings made by each model taking into consideration the operation of the fan and energy utilisation for zones 1,2,3.

Model	Airflow (m/s)	Air Capacity (m^3/s)	Motor Power[1] (kW)	Fan Energy Consumption (kWh)	Energy Saved	Final[2]
Solarwall	1	1	0.1	318	12,528	**11,415**
Absorbent 30cm	1	1	0.1	318	12,153	**11,835**
Airflow 0.5m/s	0.5	0.5	0.08	254	10,449	**10,194**
Airflow 1.5m/s	1.5	1.5	0.25	796	12,021	**11,224**
Solarspace 20cm	1	2	0.75	2,389	3,393	**1,004**
Airflow 0.5m/s Solarspace 0.2m	0.5	1	0.1	318	12,761	**12,443**
Abs. 30cm Air. 0.5m/s Solar. 20cms	0.5	1	0.1	318	12,375	**12,056**
Insulation low-e	1	1	0.1	318	16,984	**16,665**
Insulation low-e Air. 1.5m/s	1.5	1.5	0.25	796	16,684	**15,887**

Table 9: Fan energy consumption solarwall energy savings per solarwall model.

[1] Specifications of the power motors are taken from the product catalogue of POWERMATIC High Velocity Powered Extraction Units.
[2] The final energy savings have been calculated considering the energy consumption in the three zones 1,2,3, where the base case model is the simple.

Chapter 4. CONCLUSION

The main findings and conclusions of this work are:

- The simple solarwall design (original solarwall model) attains potential energy savings, which exceed 12,000kWh or 121.2kWh/m^2 per year. Therefore, lower energy bills can be achieved year-round.
- Insulation is required to prevent heat loss from the corridors through the thermal mass.
- Highest energy savings occur during the months March, April and May. High solar gains and average ambient temperatures are the main climatic conditions.
- This fact is further supported from the results in the per day performance section. More specifically, ambient temperatures of 10^{o}C or lower together with solar direct gains of 450W/m^2 or higher ensure high-end performance of the solarwall system.
- The solarwall should not operate when ambient temperatures reach the lowest allowable limit of indoor temperature for a specific part of the building.
- The only modified design of the solarwall that ensures higher energy savings with low construction and lower operating cost is the solarspace width of 20cm with low speed of airflow 0.5m/s. (12,443kWh or 125.7kWh/m^2)
- The other alternative option to ensure even higher energy savings is the additional insulation layer on the concrete wall and low-e glazing instead of the normal double-glazing. Energy savings reach 16,700kWh or 168.7kWh/m^2 annually.
- Fan energy consumption is not a critical parameter when assessing the annual energy performance of the solarwall (fan consumption 318kWh annually for the original solarwall model).
- However, fan operation affected significantly the modified models whose airflow speed was higher than the original 1m/s. Additionally, solarspace 0.2m modified model has high fan energy consumption because of the increased volume rate.

Some more critical assumptions that have been considered during the interpretation of the solarwall system's energy performance and not mentioned in a previous section are:

- Utilization of the warm air.

It is already clear that when the solarwall is in operation the heated air is taken into the *Dummy_Solar* zone. That is between 8:00a.m – 7:00p.m everyday of the year, without taking into consideration climatic conditions (ambient temperature, or temperature of the warmed air entering the *Dummy_Solar* zone. This important assumption has improved the simplicity of the ESP-r models, but has also assured inaccurate results.

The per day energy performance section analyses two cases (days) where energy savings become negative. In such cases though the solarwall will not operate in the real life, therefore the actual energy savings should be greater. There are also additional circumstances where the warmed air's temperature becomes lower than the ambient temperature during the solarwall operation. Similarly, these cases have resulted on calculating lower energy savings. Finally, energy savings of the solarwall system should be greater in real life.

- Airflow speed.

The speed of the airflow inside the solarspace is not uniform along the length of the solarwall. More specifically the speed decreases to zero close to the surfaces of the solarwall system. This fact has a great effect on the heat transferred to the fluid (air) by the solar gains. In addition the actual volume rates inside the solarspace will be lower with the same fan consumption.

Finally, it is of interest to note that there is more work to be done for further analysis of the solarwall system. There are many ways with which the results can be extended and provide a more overall view of the solarwall passive solar system and its capabilities. The first step should be the development of the solarwall model, include flow networks and control the operation of the fan by monitoring the ambient temperature. Develop or remodel the solarwall in ESP-r to provide strategies to avoid summer overheating, ensure occupant comfort and indoor air quality.

Another way should concentrate towards the cost effectiveness and economic analysis of this passive solar system. Investigate whether it is more economical to retrofit the solarwall on already existing buildings or invest money on the initial stages can assure prevention of higher budgets or even constructional complexities.

References

[1] *"Heating arctic air with solar energy",* Bill Eggertson.

[2] *"Totally transparent*", Building Services Journal, pp30-31, 1997.

[3] *"Active and passive lab design"*, Barrie Evans, aj® technical.

[4] "*A Fresh Way to Cut Combustion, Crop, and Air Heating Costs Avoids Million Btu Purchases*", John Hollick, Office of Industrial Technologies, Energy Efficiency and Renewable Energy.

[5] "*Solar collector system for heating ventilation air*", CADDET, International Energy Agency.

[6] *www.solarwall.com*, Conserval Engineering Inc.

[7] "Passive solar design for the home", Energy Efficiency and Renewable Energy (EREN).

[8] *www.latymer-upper.org*, Latymer Upper School.

[9] "*High Tech Laboratory, Leuven/Belgium*", Building 2000, Commission of the European Communities.

[10] "*High School, Gavrion, Andros Island/Greece*", Building 2000, Commission of the European communities.

[11] "*Innercity studios and offices, West Berlin/Federal Republic of Germany*", Building 2000, Commission of the European Communities.

[12] "*Secondary School, Valdingo Do Vouga, Agueda/Portugal*", Building 2000, Commission of the European Communities.

[13] "*Solar Energy-Where Does It Fit In?*", The Consultant, Volume 17, May 2000.

[14] "*Solar Wall Provides Economic Heating and Ventilation*", CADDET, International Energy Agency.

[15] "*The Power of Solar – Integrating Solar Energy Into Today's Buildings",* International Energy Agency Solar Heating and Cooling Programme.

[16] "*World's largest solar wall at Canadair facility*", CADDET, International Energy Agency.

[17] "*Strathclyde University Health Sciences Building EDAS Computer Simulation*", Hulley and Kirkwood.

[18] "*Bringing Solar Energy to the Planned Community*", A Handbook on Rooftop Solar Systems and Private Land Use Restrictions, Thomas Starrs – Les Nelson – Fred Zalcman.

[19] "*Solar Heat Technologies: Fundamentals and Applications*", Bruce Anderson, MIT Press.

[20] "*Passive & Active Solar Heating Technology*", Michael Meltzer, Prentice Hall, 1985, ISBN:0-13-653114-8.

[21] "*Passive Solar Schools*", Building Bulletin 79, Department for Education Architects and Building Division, ISBN: 0 11 270876 5.

[22] www.eren.doe.gov, Energy Efficiency and Renewable Energy Network (EREN).

[23] www.nrel.gov, National Renewable Energy Laboratory (NREL).

[24] "*Passive Solar Design in Architecture*", Faculty of Engineering, University of Hong Kong.

[25] "*Passive Solar Energy*", Energy Educators of Ontario, Energy Fact Sheet, 1993.

[26] "*Passive Solar Guidelines*", Sustainable Building Sourcebook, Green Building Program.

[27] "*Passive Solar Design for the Home*", Consumer Energy Information, Energy Efficiency and Renewable Energy Network (EREN), 2001.

[28] "*The Analysis of the Modified Trombe Wall and its Application to the Heating and Cooling of the Buildings*", Ali R. Dalal, University of Strathclyde.

[29] "*Passive Solar Update: Present Status and Future Goals*", D. Watson, Solar World Forum: Proceeding of the International Solar Society Congress, Volume 3, August 1981, pages 1762-1792, Pergamon Press.

[30] "*Solar Power a Place in the Sun*", L. Sanford, The Heating and Air Conditioning Journal, Volume 49 No. 570, July 1979, pages 22-38.

[31] "*Energy and Architecture: The Solar and Conservation Potential*", Christoper Flavin, Energy and Architecture, Wordwatch Institute, 1980.

[32] "*Solar energy in architecture and urban planning*", Prestel Verlag, 1996.

[33] "*A Survey of Passive Solar Buildings*", American Institute of Architects (AIA) Research Corporation, pages 25-27, 69-70 ands 121-122.

[34] "*The Solar Home Book: Heating, Cooling and Designing with the Sun*", B. Anderson & M. Riordan, Brick House Publishing Co. Inc., 1976.

[35] "*Experimental work on a Paraffin Trombe Wall*", R. Pinto, Y. Body, C. Bernard and D. Goblin, Variable Parameter Test Cell, Solar World Forum: Proceeding of the International Solar Energy Society Congress, Volume 3 August 1981, pages 1889-1895, Pargamon Press.

[36] "*Passive Solar Heating in the UK*", R. Ferraro, Solar World Forum: Proceeding of the International Solar Energy Society Congress, Volume 3, August 1981, pages 1959-1967, Pergamon Press.

[37] "*Active Solar Heating in the UK*", Energy Technology Support Unit, pages 1977-1984, Chapters 2 and 3, Watkiss Studios Ltd., 1985.

[38] "*Solar Dwelling Design Concepts*", American Institute of Architects (AIA) Research Corporation, pages 27-30, U.S. Government Printing Office, March 1977.

[39] "*Solar Energy Technology Handbook*" , W.C. Dickinson & P.N. Cheremisinoff, Part B, Applications, Systems Design, and Economics, Marcel Dekker, IND., Butterwoeths,1980.

[40] "*Solar Energy: Fundamentals in Building Design*", B. Anderson, McGraw-Hill Book Company, 1977.

[41] "*The Solar House: A Guide to Solar Energy Utilisation in Domestic, Industrial and Commercial Building*", P.R. Sabady & D. Arch, Newness-Butterworth, 1978.

[42] "*The Sun: Our Future Energy Source*", D.K. McDaniels, John Wiley and Son, 1979.

[43] "*Solar Energy and Building*", S.V. Szokolay, Architectural Press, John Wiley and Son.

[44] "*Introduction to Solar Heating and Cooling Design and Sizing*", U.S. Department of Energy, U.S. Government Printing Office, 1978.

[45] "*The Development of Double Envelop Concept*", J. Keable, Solar World Forum: Proceeding of the International Solar Energy Society Congress, Volume 3, Pergamon Press, 1981.

[46] "*Experience with a Passive Solar House in Britain*", R. Sadler, Solar World Forum: Proceeding of the International Solar Energy Society Congress, Volume 3, 1981.

[47] "*Linford Passive Solar Houses*", A.R. Harton, Solar World Forum: Proceeding of the International Solar Energy Society Congress, Volume 3, 1981.

[48] "*Building Performance*", Building Performance Research Unit, School of Architecture, University of Strathclyde, Applied Science Publishers Ltd., 1972.

[49] "*Building for Energy Conservation*", P. W. O' Callaghan, Pergamon Press.

[50] "*Energy Simulation in Building Design*", J. A. Clarke, Adam Hilger Ltd., 1985.

[51] "*The PASSYS Test Cells*", P. Wouters, L. Vandaele, Summary Report of the PASSYS Project, 1993.

[52] "*The PASSYS Services*", P. Wouters, L. Vandaele, Summary Report of the Passys Project, 1993.

[53] "*Whole Model Validation*", A. Pinney, P. Strachan, PASSYS Model Validation and Development Subgroup Final Report, Chapter 15.

[54] "*Energy Analysis and Management*", R. C. McLean, MSc Energy Systems and the Environment, Course notes.

[55] "*Introduction to Heat Transfer*", F. P. Incropera, D. P. De Witt, John Wiley & Sons, 2^{nd} Edition, 1990.

[56] "*Environmental Design*", The Chartered Institution of Building Services Engineers London, CIBSE Guide A, 1999.

[57] "*Body odour and carbon dioxide, minimum ventilation rates*", P. O. Fanger, IEA Energy Conservation in Buildings and Community Systems Programme, Annex IX final report.

[58] "*Air quality in buildings during smoking and non-smoking occupancy*", B.P. Leaderer & W. S. Cain, ASHRAE Trans. 89, 2A&2B, pp. 601-623.

[59] "*Passive Solar Housing in the UK*", D. Turrent, J. Doggart, R. Ferraro, Harwell, 1980.

[60] "*Sun Power, An Introduction to the Applications of Solar Energy*", J. C. McVeigh, Pergamon Press, 1977.

[61] "*Solar Energy Engineering*", Academic Press, 1977.

[62] "*Technology for Solar Energy Utilisation*", United Nations Industrial Development Organisation (UNIDO), 1978.

[63] "*Solar Buildings, Transpired Air Collectors, Ventilation Preheating*", National Renewable Energy Laboratory, 2001.

APPENDICES

Convection Heat Transfer Coefficient

Convection heat transfer occurs between a fluid in motion and a bounding surface when the two are at different temperatures. Convection is the energy transfer due to random molecular motion and energy being transferred by the motion of the fluid.

The coefficient (h) expresses the rate of convection heat transfer. This coefficient takes into account all the factors, which influence the convection transfer process. Accordingly, the value of h is dependent on various parameters, such as the system geometry, the flow velocity and the specific heat, viscosity and other physical properties of the fluid. Moreover, any study of convection ultimately reduces to a study of the means by which h may be determined.

Convection heat transfer is difficult to approach analytically and it is more readily solved by dimensional analysis and experiment. **[54]**

Using the above technique empirical correlations have been derived that can be used to calculate the convection heat transfer coefficient. There are various correlations used for laminar and internal flows, for circular and non-circular cross sections.

For the case of the solarwall model and more specifically the airflow (1m/s) inside the solar space, the following convection correlation was chosen:

$$Nu_D = 0.023 \mathrm{Re}_D^{4/5} \mathrm{Pr}^{0.4} \quad \textbf{[56]} \qquad (1)$$

Where:

$Nu_D = \frac{hD_h}{k}$ The Nusselt number, where h is the convection heat transfer coefficient, $D_h = \frac{4A_C}{P}$ hydraulic diameter, k thermal conductivity, A_C is the flow cross-sectional area and P is the wetted perimeter.

$\mathrm{Re}_D = \frac{\rho u D_h}{k}$ The Reynolds number, where ρ is the density of the fluid, u is the speed of the fluid and μ the viscosity.

Pr is the Prandtl number.

To calculate the properties of the fluid (in this case air) its temperature has to be given. The ambient temperature is not constant and impossible to forecast. Therefore, some arbitrary values have been considered to determine the heat transfer coefficient but also to find out what will be the effect on its value.

Table 1 shows that the influence of ambient temperature variation has a very small effect on the value of the heat transfer coefficient.

T (K)	Re	Pr	*h* (W/m^2K)	Nu	k (W/mK)
268	15540	0.715	5.37	45.35	0.0237
273	15044	0.714	5.3	44.17	0.024
278	14562	0.713	5.28	43	0.0245
283	14094	0.711	5.23	41.85	0.025
288	13633	0.71	5.17	40.73	0.0254
293	13186	0.705	5.09	39.55	0.02574

Table 10: Influence of ambient temperature on the value of convection heat transfer coefficient.

Taking the average h (5.24 W/m^2K) as the base value, the differential sensitivity analysis can commence in Section 3.4.2.

For various speeds of the airflow inside the solar space the following convection heat transfer coefficients result:

u (m/s)	Re	*h* (W/m^2K)	Nu
0.5	6,816	3	23.4
1	13,633	5.24	40.73
1.5	20,449	7.25	56.34

Constructional characteristics

The construction materials used for the models developed in ESP-r are listed on the following table:

CONSTRUCTIONAL MATERIALS		
External Walls	*Layer 1*	Outer leaf brick 0.1m
	Layer 2	Glasswool 0.075
	Layer 3	Air 0.17 0.17 0.17 0.05m
	Layer 4	Breeze block 0.1m
Internal Walls	*Layer 1*	Breeze block 0.15m
	Layer 2	Perlite plaster board 0.012m
Ground Floor	*Layer 1*	Common earch 0.25m
	Layer 2	Gravel based 0.15m
	Layer 3	Heavy mix concrete 0.15m
	Layer 4	Air 0.17 0.17 0.17 0.05m
	Layer 5	Chipboard 0.019
	Layer 6	Wilton 0.006m
Floors	*Layer 1*	Common earch 0.1m
	Layer 2	Red granite 0.1m
	Layer 3	Heavy mix concrete 0.05m
	Layer 4	Cement screed 0.05m
Top Roof	*Layer 1*	Roofing felt 0.012m
	Layer 2	Light mix 0.05m
	Layer 3	Air 0.17 0.17 0.17 0.05m
	Layer 4	Ceiling (Plaster) 0.008m
Glazing	*Layer 1*	Plate glass 0.006m
	Layer 2	Air 0.17 0.17 0.17 0.012m
	Layer 3	Plate glass 0.006m
Thermal mass	*Layer 1*	Heavy mix black colour concrete 0.15m

Thermal mass insulation	*Layer 1*	Heavy mix black colour concrete[1] 0.15m
	Layer 2	Polyurethane foam board 0.05m
	Layer 3	Perlite plasterboard 0.01m
Low-E Glazing	*Layer 1*	Plate glass 0.006m
	Layer 2	Air 1 1 1 0.05m
	Layer 3	Plate glass low[2] E 0.006m

[1] Black colour concrete absorptivity is set to 0.91
[2] Emmissivity of the low-glazing is set to 0.15

Energy performance of the solarwall

	Energy Saved	Ambient Temperature	Direct Gain
January	690.91	4.6	31.5
February	862.25	6.2	82.8
March	1684.97	8.9	205.5
April	1365.48	9.4	159
May	1830.82	12.5	346.6
June	1415.4	16.3	393.5
July	430.95	20.8	385.8
August	934.5	18.3	296.5
September	826.51	15.5	78.9
Octomber	1027.12	12.1	101.7
November	729.38	6.4	46.3
December	729.86	4.3	32.6

Table 11: Monthly energy performance evaluation.

	1-Jan	2-Jan	3-Jan	8-Feb	12-Feb	12-Mar	18-Mar	17-Nov	18-Nov	26-Nov	16-Dec	18-Dec
	Climate Characteristics 9-18											
Average Direct Gains (W/m^2)	163.1	236.1	201.1	249.4	255	213.7	344.7	296.9	337.4	258.2	196.9	223.3
Average Temperature (C^o)	4.1	1.6	1	4.8	3.6	6.8	8.9	4	4.3	2.1	4.3	1.6
	Energy Performance (kWh)											
Zone_1	20.39	18.23	18.58	16.71	19.16	7.3	5.83	14.31	11.31	17.07	15.45	19.6
Zone_2	19.55	17.05	16.99	15.37	17.89	5.22	4.42	13.63	10.29	16.64	14.68	18.39
Zone_2	22.1	20.27	21.6	17.8	20.7	7.95	6.12	16.73	13.05	19.37	16.51	22.3
Energy Saved	**44.76**	**67.81**	**63.37**	**62.03**	**55.94**	**60.07**	**79.21**	**76.46**	**82.83**	**71.66**	**57.54**	**66.04**

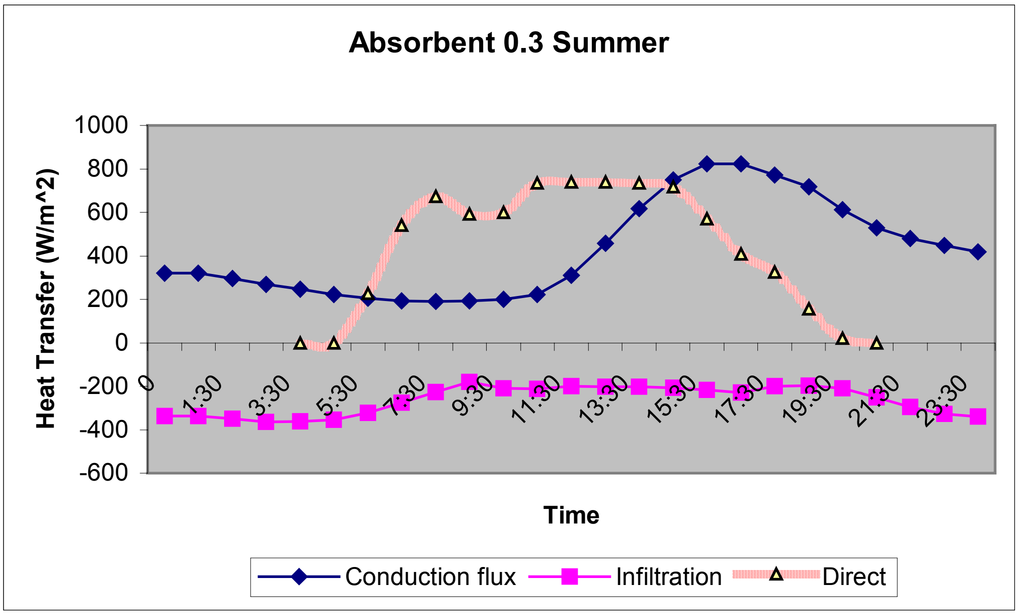
Table 12: Low temperature and high solar direct gain, individual day performance and climatic characteristics.

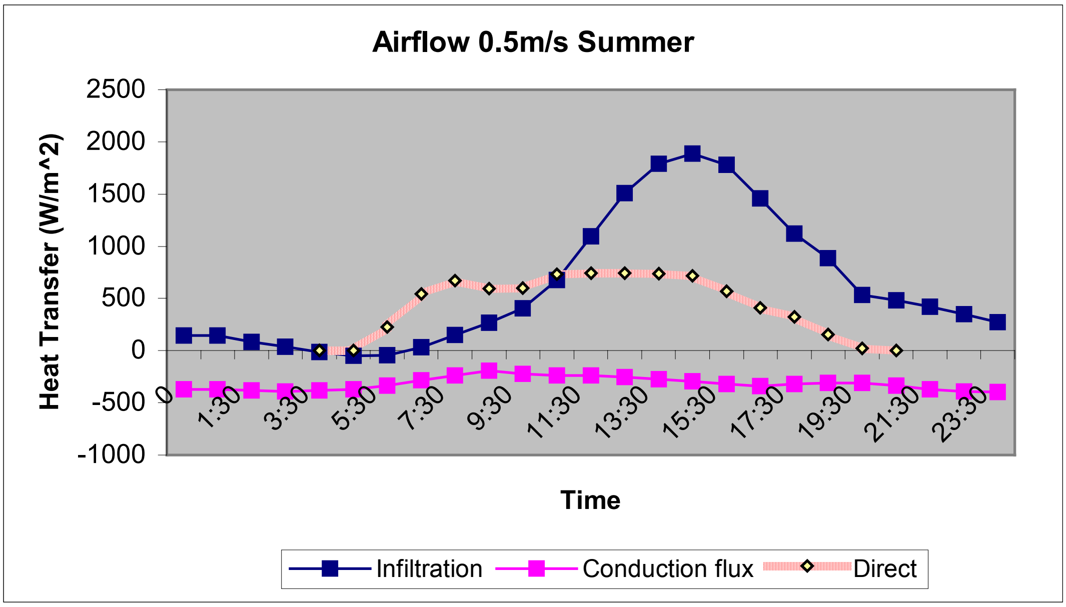
	7-Jan	9-Jan	15-Jan	27-Jan	2-Feb	9-Feb
	Climate Characteristics 9-18					
Average Direct/Diffuse Gains (W/m^2)	0/30.8	10.1/32.6	0/32.6	0/42.6	0/47.9	0/56.7
Average Temperature (C^o)	-0.5	-0.9	1.5	9.2	11.6	4
	Energy Performance (kWh)					
Zone_1	28.04	31.81	22.03	17.21	11.75	17.46
Zone_2	27.13	30.91	20.71	16.05	10.47	15.73
Zone_2	31.55	36.03	24.89	18.22	11.42	19.36
Energy Saved	**25.48**	**25.23**	**24.4**	**5.8**	**4.9**	**23.03**

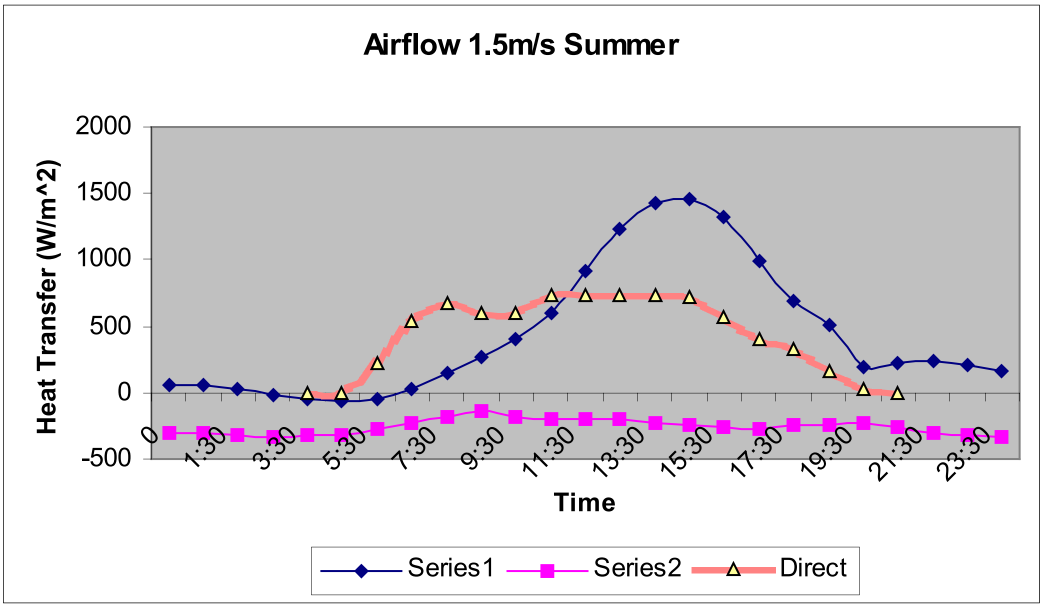
Table 13: Low temperature and low direct/diffuse solar gains.

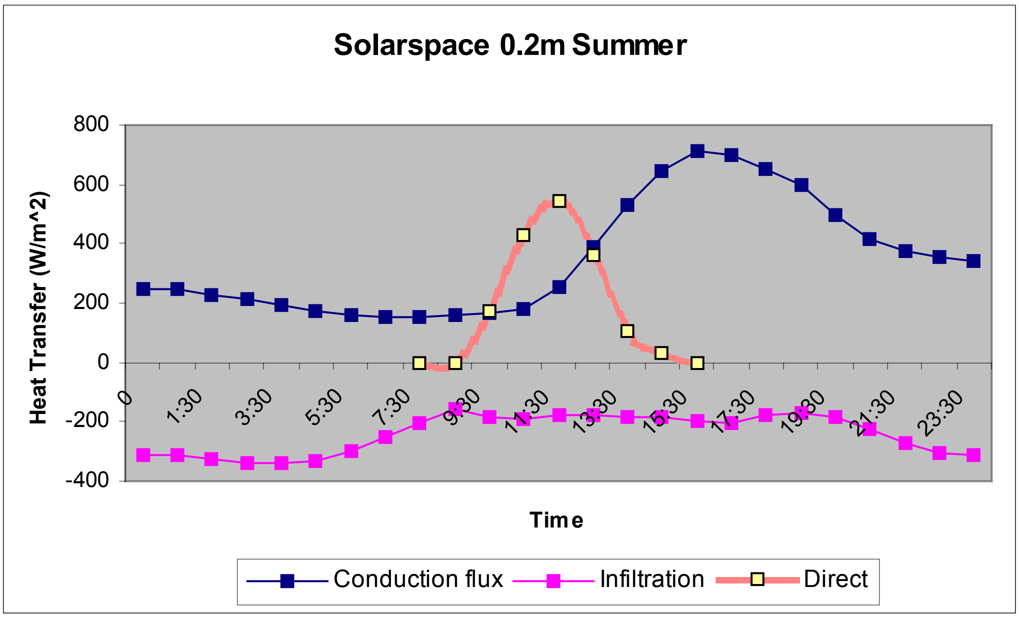
	6-Jun	21-Jun	8-Jul	17-Jul	1-Aug	20-Aug
	Climate Characteristics 9-18					
Average Direct Gains (W/m^2)	440.5	437.7	404.5	512.8	320.9	522
Average Temperature (C^o)	19.7	17.6	17.9	26.1	23.2	17.5
	Energy Performance (kWh)					
Zone_1	0	0	0	0	0	0
Zone_2	0	0	0	0	0	0
Zone_2	0	0	0	0	0	0
Energy Saved	**23.36**	**38.67**	**33.94**	**-4.34**	**-4.5**	**37.46**

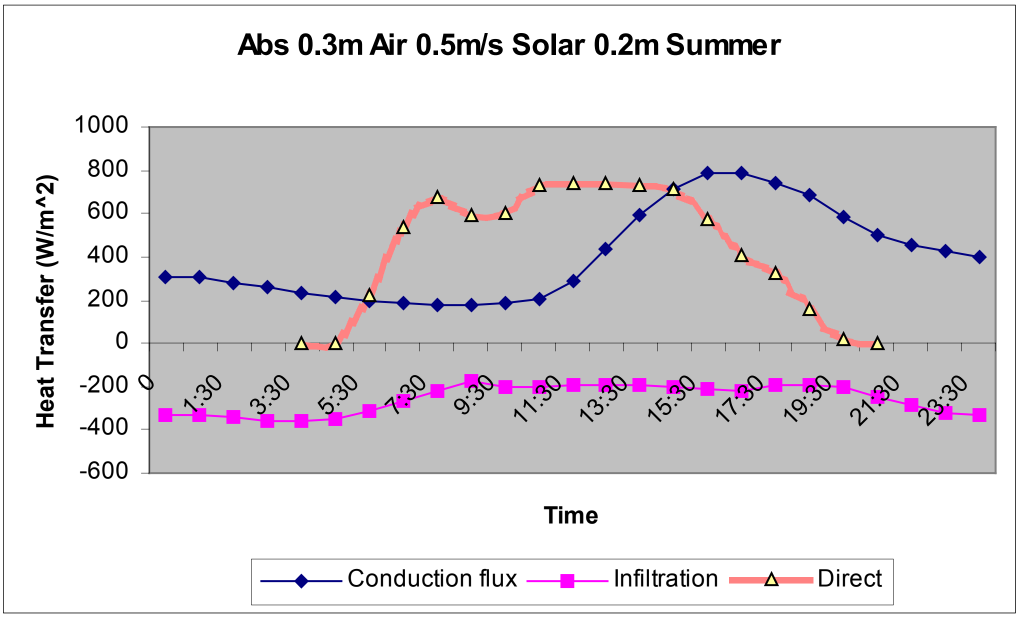
Table 14: High temperature and high direct solar gains.






Airflow 1.5m/s Summer
Heat Transfer (W/m^2)
2000
1500
1000
500
0
-500
0
1:30
3:30
5:30
7:30
9:30
11:30
13:30
15:30
17:30
19:30
21:30
23:30
Time
Series1
Series2
Direct


Solarspace 0.2m Summer
Heat Transfer (W/m^2)
800
600
400
200
0
-200
-400
0
1:30
3:30
5:30
7:30
9:30
11:30
13:30
15:30
17:30
19:30
21:30
23:30
Time
Conduction flux
Infiltration
Direct



Abs 0.3m Air 0.5m/s Solar 0.2m Summer
Heat Transfer (W/m^2)
1000
800
600
400
200
0
-200
-400
-600
0
1:30
3:30
5:30
7:30
9:30
11:30
13:30
15:30
17:30
19:30
21:30
23:30
Time
Conduction flux
Infiltration
Direct