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A STUDY ON ENHANCING THE COMFORT AND ENERGY EFFICIENCY OF PASSIVE HOUSING THROUGH THE ARCHITECTURE DESIGN

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ABSTRACT

As population growth, urbanization, and increasing comfort expectations drive energy consumption higher, various strategies, plans, standards, norms, research studies, and product development efforts are being pursued under sustainable development policies to reduce energy use in the building sector and enhance energy efficiency. While the initial focus was on conserving energy in buildings, the push to decarbonize the building stock has led to the need for designing new buildings with exceptionally high energy performance. Concepts like the "zero-energy building," which generates its own energy from renewable sources, and the "plus-energy building," which produces more energy than it consumes and feeds the excess back to the grid, have emerged. Research and development in these areas are currently progressing rapidly.

In Mongolia, coal is the primary source of energy, making up over 90 percent of national energy production. Around 90 percent of the energy generated in the country is used for heating buildings. In Ulaanbaatar, over 210,000 households not connected to the central heating network rely on improved or other fuels for residential heating, with solid fuels contributing to 80 percent of the city's air pollution. In 2012, the Mongolian government introduced green development as a new economic strategy and adopted the "Sustainable Development Policy 2030" and "Vision 2050" policy documents. Mongolia has also committed to reducing greenhouse gas emissions under the Paris Agreement, with targets including a 40 percent reduction in building heat losses by 2030 and supplying 30 percent of total national energy production from renewable sources by 2030.

The study was motivated by the air pollution caused by solid-fuel use in Ulaanbaatar and other urban areas, as well as my personal interest as a researcher in exploring this topic in depth. The research aims to investigate the possibility of constructing single-family houses that offer indoor comfort in Mongolian climatic conditions while being energy efficient. Using dynamic energy simulation in the EnergyPlus software, commonly used for building energy calculations, the study aims to assess the potential reduction in energy consumption for heating, cooling, and ventilation.

International research suggests three main approaches to improving building energy efficiency: *Implementing passive design strategies to reduce energy consumption, using energy-efficient active systems to meet reduced energy demands and incorporating renewable energy sources to power these systems;*

Previous studies by international researchers have shown that passive design methods not only lead to economic benefits but also result in long-term energy savings. However, since most of these studies were conducted in regions with milder climates, the primary goal of this research is to determine the effectiveness of these strategies in Mongolia's harsh, cold-climate regions using established calculation methods.

Objective of Study: to investigate the potential for reducing energy consumption for heating and cooling in a single-family house in Ulaanbaatar by improving insulation and thermal protection of the building envelope, to examine the correlation between insulation levels and heating/cooling loads in Ulaanbaatar's climate and to assess the effectiveness of a Trombe wall in Ulaanbaatar's climate.

KEYWORDS

Single-family House, Zero-energy Building, Plus-energy Building, Passive Design Strategy, Energy-efficient Active System

CITATION

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Introduction

As a result of population growth and urbanization, people now spend 85 percent of their daily lives indoors. This highlights the significance of ensuring indoor environmental comfort and air quality, which is crucial for both new and existing buildings to protect public health, well-being, and productivity. Various countries have established standards and norms for indoor environmental comfort, focusing on measurable parameters that are acceptable to the general population. The main categories of indoor environmental comfort include thermal comfort, air quality, lighting, and acoustics, which are classified differently in international and national standards.

Internationally recognized standards, such as those from the International Organization for Standardization (ISO), the European Committee for Standardization (CEN), and the American National Standards Institute (ANSI), provide detailed information and calculation methods for indoor environmental comfort. The main standards related to indoor environmental comfort issued by these organizations are listed in Appendix 1. In ISO and EN standards, indoor air comfort is categorized as good, medium, acceptable, and poor, while the ANSI/ASHRAE standard specifies threshold values only within the "acceptable" category.

In Mongolia, indoor air quality standards for residential spaces are outlined in the standard MNS 4585:2016, which sets specific threshold values for airborne pollutants and physical factors. The Mongolian Building Code BNbD 25.01.20 "Thermal Protection of Buildings" includes guidelines for thermal comfort, while BNbD 23.02.08 "Natural and Artificial Lighting" and BNbD 23.04.07 "Solar (Insolation) Provision for Residential and Public Buildings and for Residential Zoning" address solar exposure and lighting requirements. BNbD 23.05.10 "Sound Insulation" covers acoustics regulations. Various advisory documents and building regulations complement these codes.

Table 1. Indoor air quality indicators currently enforced in Mongolia

The name of the parameter		Assessment conditions	Unit of measure	Maximum allowable amount
Temperature		By average measurement	degrees of Celsius	18-22
Airflow speed		By average measurement	m/s	0.2-0.4
Relatively humid		By average measurement	Percentage	30-60
Carbon dioxide (CO2)		24 hour average	mg/m³	1800
Lighting	People sit all the time	By average measurement	Luxury	150-300
	People don't sit all the time			50-150

Thermal Comfort. Thermal comfort in an indoor setting is achieved when occupants do not feel excessively hot or cold and are not affected by drafts or chilling sensations. It is assessed using the PMV (Predicted Mean Vote) to determine the average thermal sensation of occupants and the PPD (Predicted Percentage of Dissatisfied) to estimate the percentage of occupants likely to be dissatisfied with the thermal conditions. These metrics were established by Danish scientist Povl Ole Fanger (1934–2006).

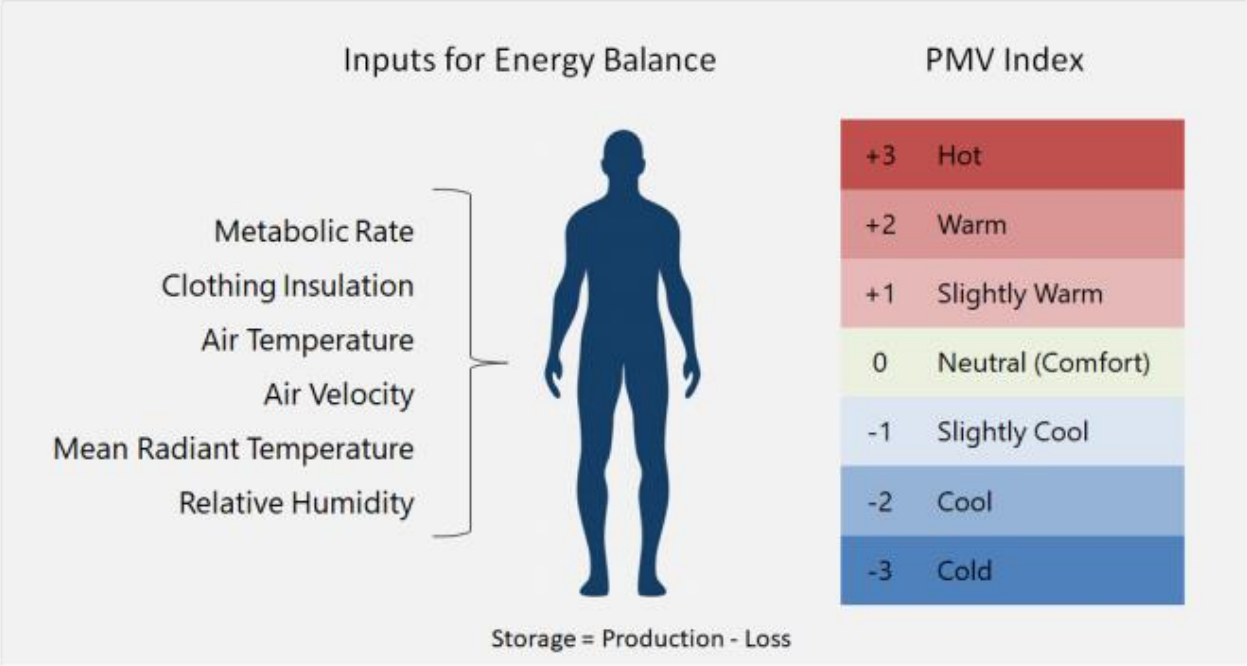


Fig. 1. *The PMV index and the factors influencing* ***in it***

Most standards not only define indoor thermal comfort in terms of PMV and PPD but also set upper and lower limits for indoor air temperature. These threshold values take into account factors such as air velocity, relative humidity, weather conditions, seasonal characteristics, building function, and ventilation system type. As a result, standardized temperature values differ based on building type and season, typically ranging from 18–28 °C.



Fig. 2. *Metabolic rate of the human body*

When assessing indoor thermal comfort, the standards mentioned above consider the impact of temperature on the entire human body. Along with setting suitable values for PMV, PPD, and air temperature, they also include measures that identify discomfort in specific body areas.

These factors include:

- Drafts caused by unwanted air movements;
- Variances in vertical air temperature between head and ankle levels;
- The impact of uneven radiation (resulting in cold or radiant-heat discomfort);
- The influence of excessively hot or cold floors.

Air Quality. The average person breathes around 12,000 liters of air daily. The atmosphere is composed of 78% nitrogen (N_2), 21% oxygen (O_2), and 1% other substances like carbon dioxide (CO_2) and VOCs (volatile organic compounds). These substances in the 1% category impact human health, comfort, and productivity. Air quality is considered satisfactory when pollutant levels are within acceptable limits and most occupants are content with the air quality. Poor indoor air quality can have negative effects on health, leading to allergies, mold-related illnesses, respiratory issues, heart disease, and even cancer.

Indoor air quality is influenced by outdoor factors, occupants, building activities, and emissions from materials and furnishings. Standards for indoor air quality vary for residential and public buildings based on their function. International guidelines specify acceptable levels of airborne pollutants and ventilation requirements, which can be based on floor area or number of occupants.

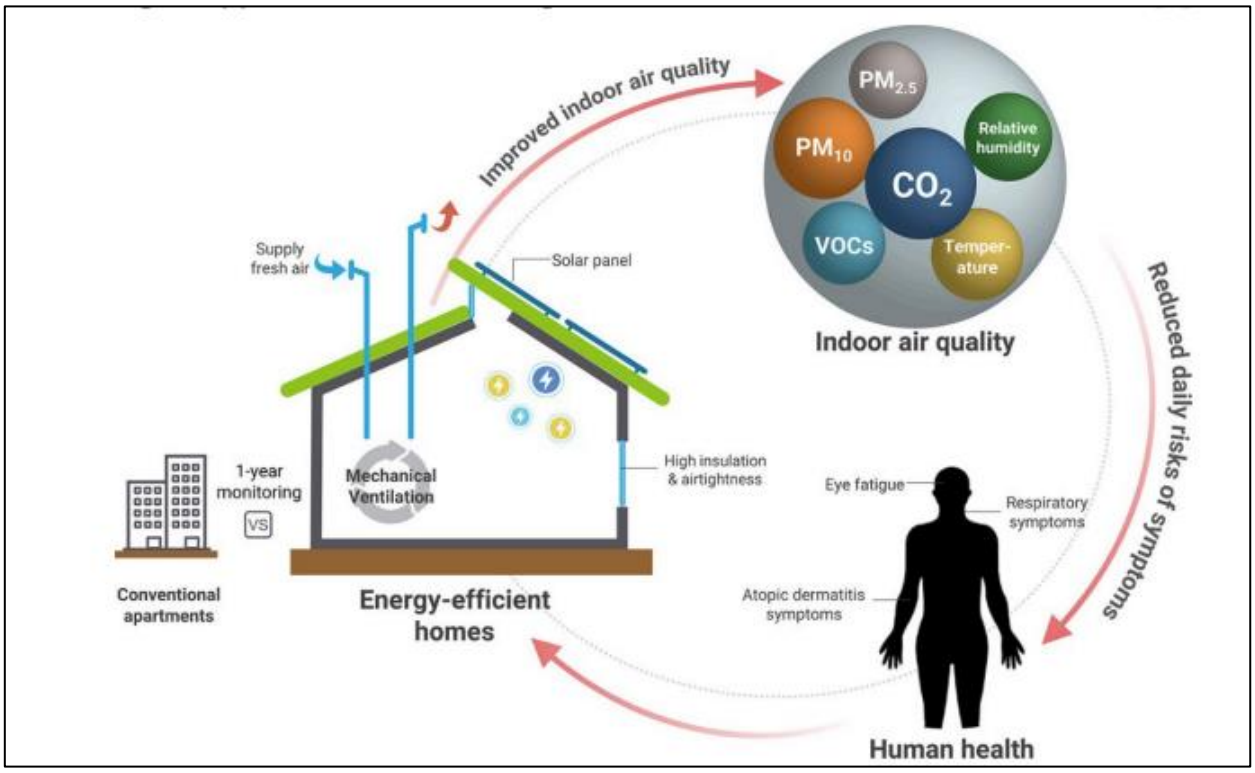


Fig. 3. *Indoor air quality and health*

The main measure used to assess the level of pollutants in indoor air is the concentration of carbon dioxide (CO_2), measured in parts per million (ppm), a unit established by the German scientist Max von Pettenkofer (1818–1901). Indoor CO_2 levels are categorized according to ISO 17772 and EN 16798 standards into four groups: up to 550 ppm; 550–800 ppm; 800–1,350 ppm; and above 1,350 ppm. Along with regulating air quality through mechanical ventilation systems, the ASHRAE 62.1 standard offers guidance on natural ventilation strategies.

These standards also outline filter requirements based on outdoor air quality. Relative humidity recommendations vary among standards, with ISO and EN suggesting 30–50 percent, 25–60 percent, and 20–70 percent for different comfort levels, while ASHRAE sets a maximum of 65 percent without a minimum. The Mongolian standard MNS 4585:2016 establishes acceptable 24-hour average concentrations for various indoor air pollutants: CO_2 at 1,800 μg/m³, radon at 0.005 μSv/m³, formaldehyde at 0.3 μg/m³, and air oxidizability at 4,000–6,000 μg/m³.

Lighting. Previously, the evaluation of lighting in living environments focused on indicators like protection against glare, effective distribution of illumination, and visibility of work surfaces. Recent research has revealed that light also impacts the human organism and psyche through its effects on the nervous system, circadian rhythm, pituitary gland, endocrine system, pineal gland, and alertness, in addition to its visual effects. Therefore, modern lighting design must consider not only light intensity but also the spectrum's oscillation.

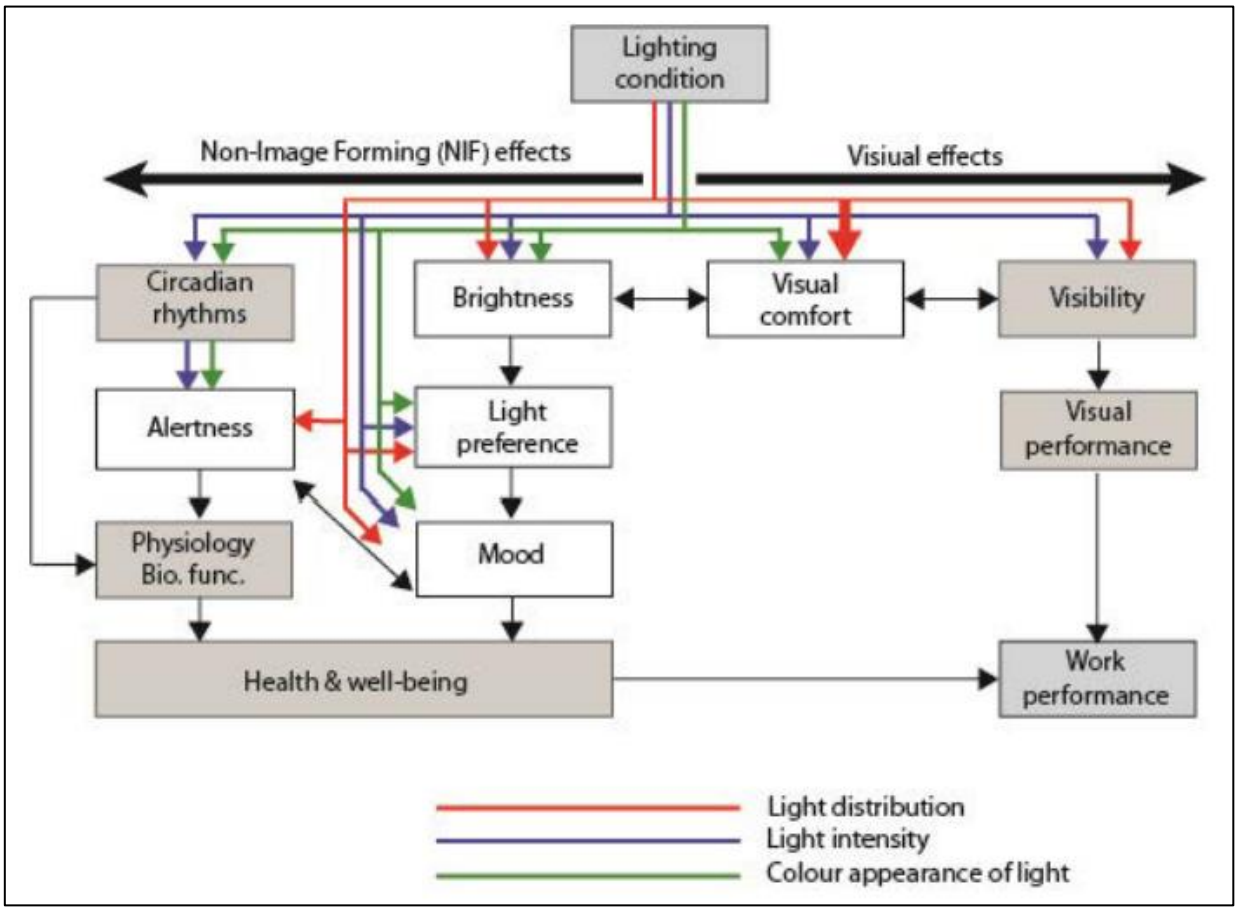


Fig. 4. *The influence of the light*

Light is assessed using factors like intensity, illumination, distribution, ambient light, color, glare, and flicker rate. The comfort of the observer and the task at hand play a crucial role in visual comfort. International lighting standards, such as ISO 8995-1:2002, BS EN 12464-1:2021, and ANSI/ASHRAE 90.1, establish the appropriate parameters for natural and artificial lighting to ensure comfort, safety, and energy efficiency in workspaces. Artificial lighting consumes 19 percent of global grid-connected electricity, making the shift to natural lighting a key focus in sustainability efforts. Natural lighting not only saves energy but also positively impacts the health, mood, and comfort of occupants in buildings.

The brightness on a specific surface is measured in "lux." Direct sunlight provides around 100,000 lux, while indirect daylight offers 3,000–18,000 lux. Television studio lighting necessitates 1,000 lux, while 200–500 lux is adequate for work and home settings. The color temperature of artificial lighting is indicated in Kelvin (K): below 2,000 K results in yellow light; 2,000–3,000 K produces warm white (soft amber) light; 3,000–4,500 K creates bright white; 4,500–6,500 K generates cool white with a bluish tint; and values above this range yield blue-tinted light. These two factors, in addition to energy usage, are the primary considerations in artificial lighting design.

Acoustics. A good acoustic environment is one where individuals can feel physically and mentally comfortable without experiencing any unpleasant sensations. Additionally, a favorable acoustic environment enables individuals to focus on their tasks and be in a positive psychological state. Prolonged exposure to disturbing noise can harm both hearing and mental well-being, impacting overall quality of life.

Every country around the world has specific regulations for acoustic comfort in buildings, outlined in norms and standards. International standards like ISO 717, ISO 12354, and ISO/TS 19488 detail how to assess the acoustic environment in building design and operation, as well as the criteria for building structures, rooms, and interior spaces.

In Mongolia, BNbD 23.05.10 “Sound Insulation” sets out regulations for building acoustics, including permissible noise levels based on building function, guidelines for creating a suitable acoustic environment, and general requirements for the sound insulation performance of building elements and components. Among indoor environmental comfort factors, thermal comfort is the most crucial, followed by indoor air quality.

Thermal comfort and air quality are essential for all occupants, while lighting comfort needs may differ based on the occupant's job and age. Acoustic comfort is influenced by geographic location and environmental factors. The use of intelligent systems for monitoring indoor environmental conditions greatly affects occupant’s satisfaction with indoor comfort.

The Energy Efficient Housing

The global population, which was 7.7 billion in 2019, is expected to reach 9.7 billion by 2050 and potentially 10.9 billion by the end of the century, according to some studies. This population growth will lead to increased demand for clean water, food, and energy, posing a threat to natural resources and the environment. The building industry is responsible for 30–40 percent of global energy consumption and one-third of greenhouse gas emissions, as well as producing significant amounts of waste that contribute to harmful emissions. Implementing a comprehensive sustainable development strategy in the building sector can help mitigate these negative effects. Sustainability in construction involves environmental, social, economic, and technological aspects.

A sustainable building encompasses various measures, such as the efficient use of natural resources, decreased energy usage, lower greenhouse gas emissions, waste reduction, recycling promotion, and improved building safety and indoor air quality. Energy efficiency is a crucial aspect of sustainable construction, and recent efforts have focused on developing products and conducting research to lower energy consumption in buildings. Heating, cooling, and ventilation account for 42–68% of energy use in an average building, while domestic hot water, household appliances, and lighting make up the remaining percentages. Passive design strategies, along with technological advancements and smart systems, are key in reducing energy consumption in buildings.

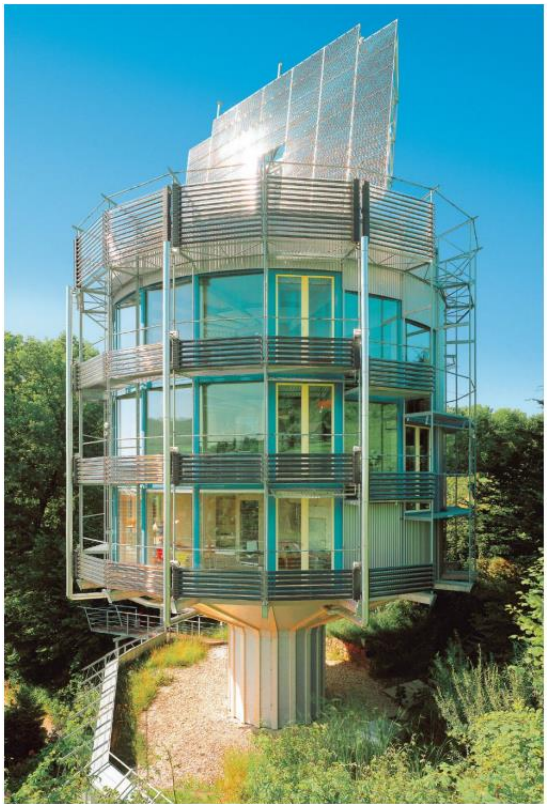


Fig. 5. *The first plus-energy building*

Norms, standards, and globally recognized sustainability certifications are crucial in the development of energy-efficient buildings. This is why energy-efficient buildings are now assessed based on specific, internationally recognized standards. This approach is essential for ensuring adherence to standards developed by experts, establishing formal classifications, and instilling public trust.

Energy-efficient building standards are not solely a result of modern technology but are rooted in centuries-old regional vernacular architecture and design principles that have influenced modern architectural development. The goal of building energy efficiency is to minimize energy consumption for indoor comfort and to meet that demand using renewable energy sources, thereby conserving natural resources, reducing greenhouse gas emissions, and slowing environmental degradation.

The first Passive House, built in Darmstadt, Germany, in 1990, and the founding of the Passivhaus Institute in 1992. Source: www.ofhouses.com. Figure 1.7 DTH Zero Energy House (1975). Examples also include the Fraunhofer Institute's "Solar Building" in Freiburg, Germany, which produces more energy than it consumes.

Building Energy Efficiency. Two primary strategies are employed to enhance building energy efficiency: reducing energy consumption and increasing the utilization of renewable energy sources. In addition to the building energy regulations, standards, and codes established by various countries, there are globally recognized organizations that issue green-building certifications. Techniques for improving building energy efficiency can be categorized into two main groups based on their operational principles: passive and active. Passive techniques involve utilizing natural energy through the building's design and orientation, thermal insulation, solar energy utilization, natural ventilation, and shading to enhance energy efficiency without the need for additional equipment.

Passive systems involve design elements that utilize natural resources like sunlight and ventilation to reduce energy consumption in buildings. On the other hand, active systems involve additional equipment such as solar panels, wind turbines, heat-recovery ventilation, geothermal energy, and heat pumps to generate energy. Combining passive and active systems can enhance efficiency, known as the "hybrid" method. Designing high-performance energy-efficient buildings requires consideration of climatic and microclimatic data, precise calculations, and coordination of systems with local conditions to achieve tangible results.

Energy-efficient housing typically combines various measures such as high thermal resistance building envelopes, high-performance windows and doors, airtight construction, heat-recovery ventilation systems, high-efficiency heating and cooling equipment, active solar-energy systems, and the use of low-energy appliances. Buildings are often categorized based on their annual heating, cooling, and ventilation load per unit floor area (E): $E \leq 65$ kWh/m²•yr for a standard building, $E \leq 40–50$ kWh/m²•yr for an energy-saving building, $E \leq 20–30$ kWh/m²•yr for a highly energy-efficient building, and $E \leq 15$ kWh/m²•yr for a Passive House. To be a viable economic investment, the incremental cost of an energy-efficient building should typically be recouped within 16–30 years.

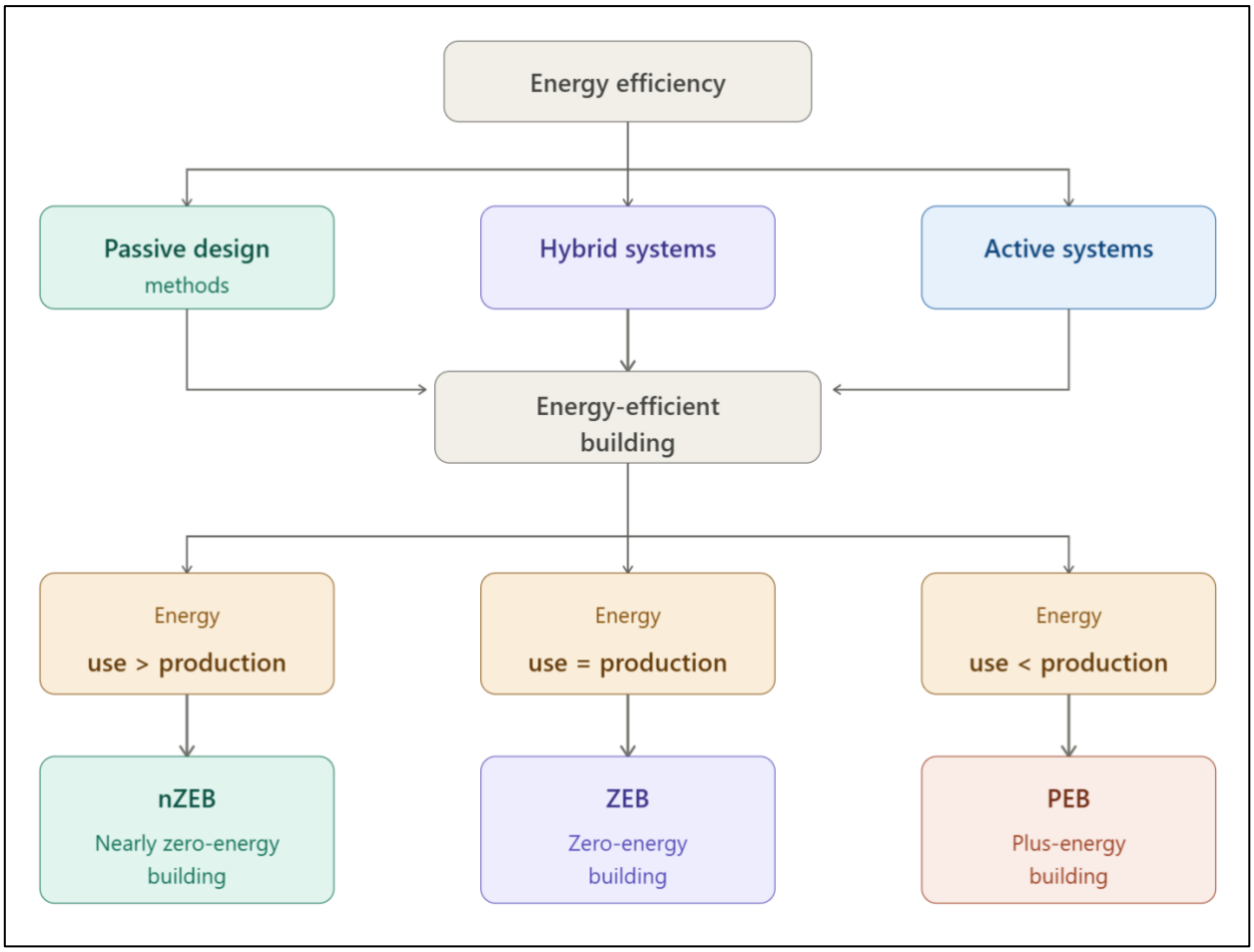


Fig. 6. *Diagram of an energy-efficient building*

Passive House. The Passive House standard, established in 1995 by the Passivhaus Institute in Germany, aims to enhance building energy efficiency by reducing heating loads through super-insulation. While originally designed for the European climate, the standard has been adopted in cold-climate countries like Denmark, Sweden, Norway, Estonia, and Canada, making it the most widely used standard globally. Various countries have tailored the standard to suit their specific climatic conditions, supported by numerous research studies. The core principles of the Passive House standard include super-insulation, efficient windows, airtightness, elimination of thermal bridges, and the use of heat-recovery ventilation systems. Indoor air quality is maintained through a mechanical ventilation system with heat recovery. Energy consumption for heating and cooling in a Passive House is estimated to be 80 percent lower than in a conventional building. While the initial investment is 5-15 percent higher than for a conventional building, the long-term energy savings and environmental benefits make it a cost-effective choice.



Fig. 7. *The first Passive House*

The key requirement of the Passive House is high levels of insulation, with the U-value of the external building envelope set between 0.1 and 0.15 W/m²•K based on regional climate conditions. There are no strict guidelines on the materials used for construction. Thermal bridges are minimized, and there is a strong focus on achieving airtightness. The air-change rate (n50) is specified as 0.6 at a pressure differential of 50 Pa between indoor and outdoor air, in contrast to the 3.0 rate in the standard German building code.

In mild climates, achieving the 15 kWh/m²•yr target solely through airtight insulation is not feasible; a mechanical ventilation system with a heat exchanger of at least 75 percent efficiency must be installed at a minimum. Solar radiation is crucial in a Passive House, with calculations ensuring that one-third of the heating energy comes from solar radiation through the windows.

As a result, the design includes large south-facing windows with a heat-transfer coefficient of 0.8 W/m²•K, as specified for European climates (Source: www.passiv.de; The first Passive House, p. 28). This standard also applies to window frames. By selecting highly energy-efficient domestic hot-water boilers and other household appliances, it is feasible to maintain total consumption, excluding heating, below 120 kWh/m².

ZEB – Zero Energy Building. Due to rapid technological advancements and population growth, global energy consumption has been increasing annually, leading to changes in the climate. In response to these challenges, various strategies are being devised to promote energy efficiency, decrease fuel consumption, and boost the utilization of renewable energy sources. One such strategy is the concept of zero-energy buildings, which aim to minimize energy consumption and reduce environmental impact. This goal can be achieved through implementing technical specifications and regulations throughout the building's lifecycle, including design, construction, and operation. Emphasizing the use of sustainable energy sources and eco-friendly building materials is a key aspect of the zero-energy building concept. A building that is highly energy-efficient and either uses renewable-energy systems to meet its own energy needs or is connected to a renewable-energy source can be considered a “zero-energy building.”

PEB – Plus Energy Building. The building sector accounts for 40 percent of total energy consumption and 30 percent of greenhouse gas emissions, making it a significant contributor to global warming and the energy crisis. Various strategies, plans, and standards are being developed to reduce energy consumption and improve efficiency in buildings. One such initiative is the decarbonization program for the building sector, which aims to transition the entire building stock to be more energy efficient. This has led to the emergence of the zero-energy building concept as a reform strategy in many countries.

Since 2021, new buildings in EU member states have been required to meet the standard of "nearly zero-energy buildings," with the goal of decarbonizing the entire building stock by 2050. To accomplish this, new buildings must go beyond zero-energy status and aim to become "plus-energy buildings." These buildings are not only highly energy efficient but also generate more energy than they consume through on-site renewable sources, feeding the surplus back into the central grid. By functioning as independent energy producers, plus-energy buildings help reduce the strain on centralized energy generation and play a crucial role in lowering greenhouse gas emissions, thus supporting the building sector's decarbonization objectives.

The Passive Design Strategy

The initial step in creating an energy-efficient building involves minimizing its energy consumption, with the primary source of energy usage being active systems that regulate indoor comfort. However, the strain on these systems can be lessened through passive design techniques. These strategies are crucial in enhancing indoor comfort, reducing heating and cooling demands, and ultimately boosting energy efficiency. Passive design methods encompass thoughtful building form and orientation based on climate and site specifics, thermal protection via the building envelope, leveraging direct solar heat gain, utilizing natural ventilation through windows, and implementing shading to prevent solar overheating.

These methods utilize the building's structural components to utilize natural energy and achieve energy efficiency without the need for extra equipment. While passive design alone may not consistently maintain indoor comfort, active systems are incorporated as a complement. In colder climates, a wider range of technological solutions is required to enhance building energy efficiency.

Energy efficiency is primarily achieved by utilizing passive design methods. After reducing energy consumption through passive design, it is important to incorporate advanced active systems to meet the reduced demand. In cold regions, the thermal transmittance of the building envelope and the solar-heat-gain coefficient of windows have a significant impact on energy-efficient dwellings. Additional measures to decrease heating loads in cold climates include implementing a cold roof with an air space, sunspaces, Trombe walls, window shutters, wind protection, thermal mass, and utilizing underground space for geothermal heat.

Another study conducted in a cold region found that buildings with dark-colored facades can save energy. In rural areas without access to infrastructure, buildings like schools that are only used during the daytime can benefit from passive solar energy. By designing the form and orientation correctly, adjusting the thermal transmittance of the envelope to suit the local climate, using high-efficiency south-facing windows, and providing shading to prevent window heat loss and overheating, buildings can achieve optimal daytime thermal comfort. In cold, remote small settlements in China, schools that incorporate these passive design strategies are already in operation.

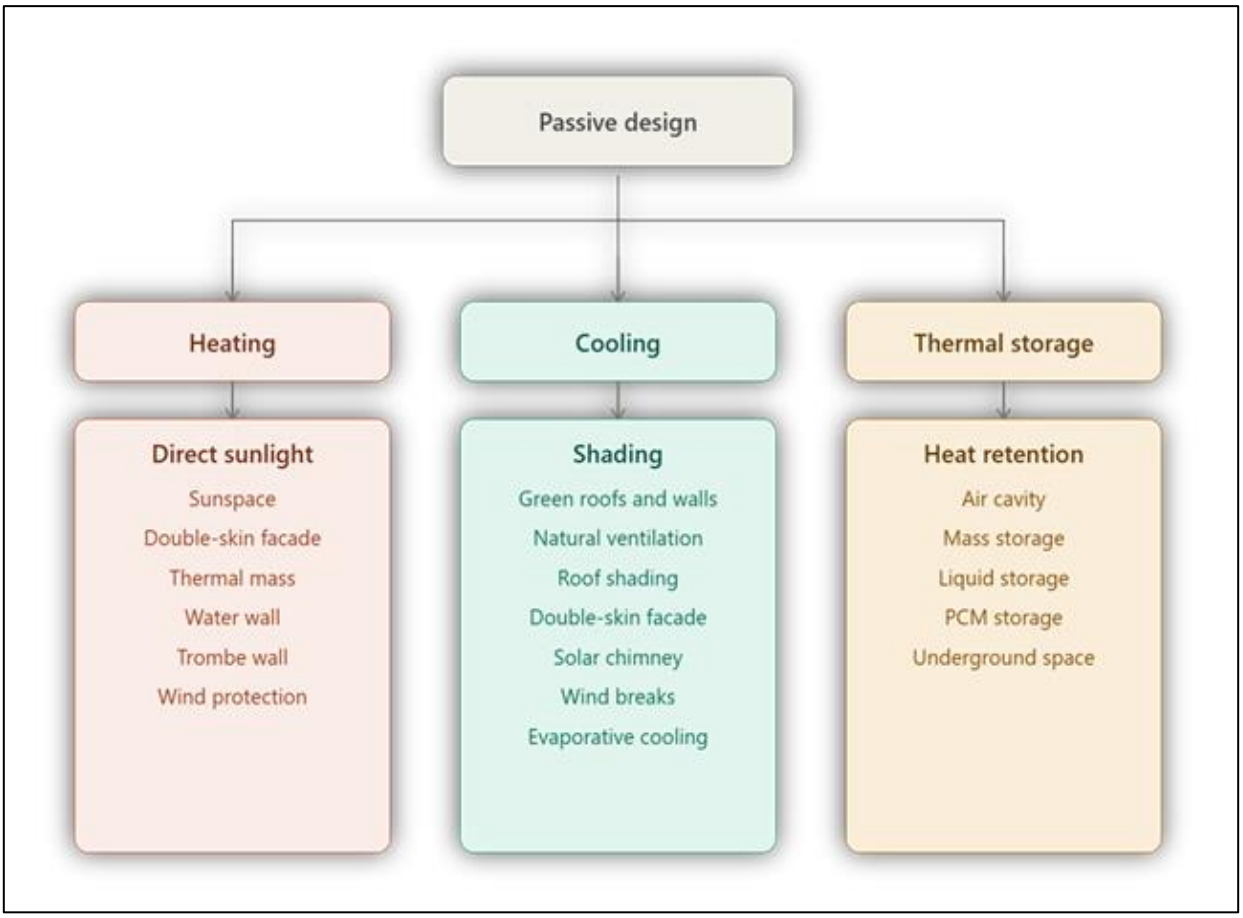


Fig. 8. *Passive design diagram*

Passive design methods can also be used on existing buildings to lower their energy usage. For instance, many historic buildings have had their energy consumption decreased by simply upgrading their windows, while maintaining their historic look. Altering the exterior color of a building can impact its absorption of solar radiation and help decrease energy usage. Facade renovation can also lower the energy consumption of older buildings.

The Innovative Design Solution

The Trombe Wall. The Trombe wall, a passive solar system, has been in use since the nineteenth century. Edward Morse patented a device in 1881 that utilized solar radiation to heat air and warm a room. Fred Keck, in 1940, discovered a method of storing solar radiation as thermal energy by painting interior walls and floors black in a house he designed. Arthur Brown, in 1946, created a space for storing solar energy by installing a glass wall on the outer side of the south wall and painting the interior walls and floors black in a house he designed. Félix Trombe and Jacques Michel developed the first model of the “Trombe wall” in 1967 based on these experiments as a way to passively utilize solar energy, and patented it.

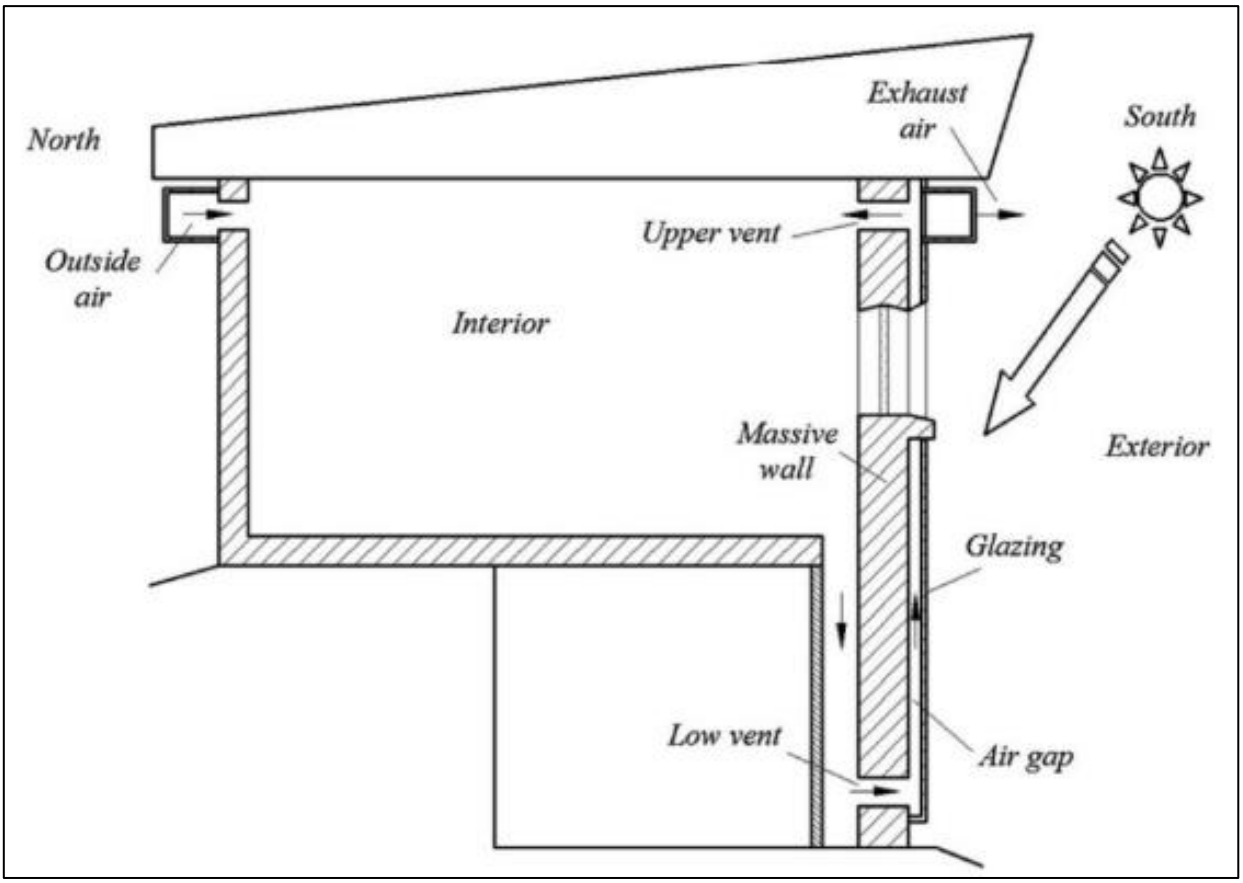


Fig. 9. *Classical Trombe wall*

A traditional Trombe wall is a south-facing wall that is painted black on the front surface and has glazing on the outside. It absorbs heat from the sun during the day and creates airflow through the stack effect to warm the interior. The heat stored in the wall during the day is released into the interior at night, acting as a thermal reservoir that helps regulate the impact of solar radiation. During the summer, it can function as a method to enhance ventilation and cooling by expelling hot air outside. Various researchers worldwide have experimented with and refined different versions of the original Trombe wall concept. Sergey Kostikov categorizes these variants into nine types based on their operational principles, including a hybrid system that integrates a Trombe wall with a mechanical ventilation system, while the other eight are passive Trombe wall designs (*Source: Sergey Kostikov; Classical Trombe wall, p. 44).* Lily Zhang also organizes Trombe walls into eight similar types, as depicted in Figure 10.

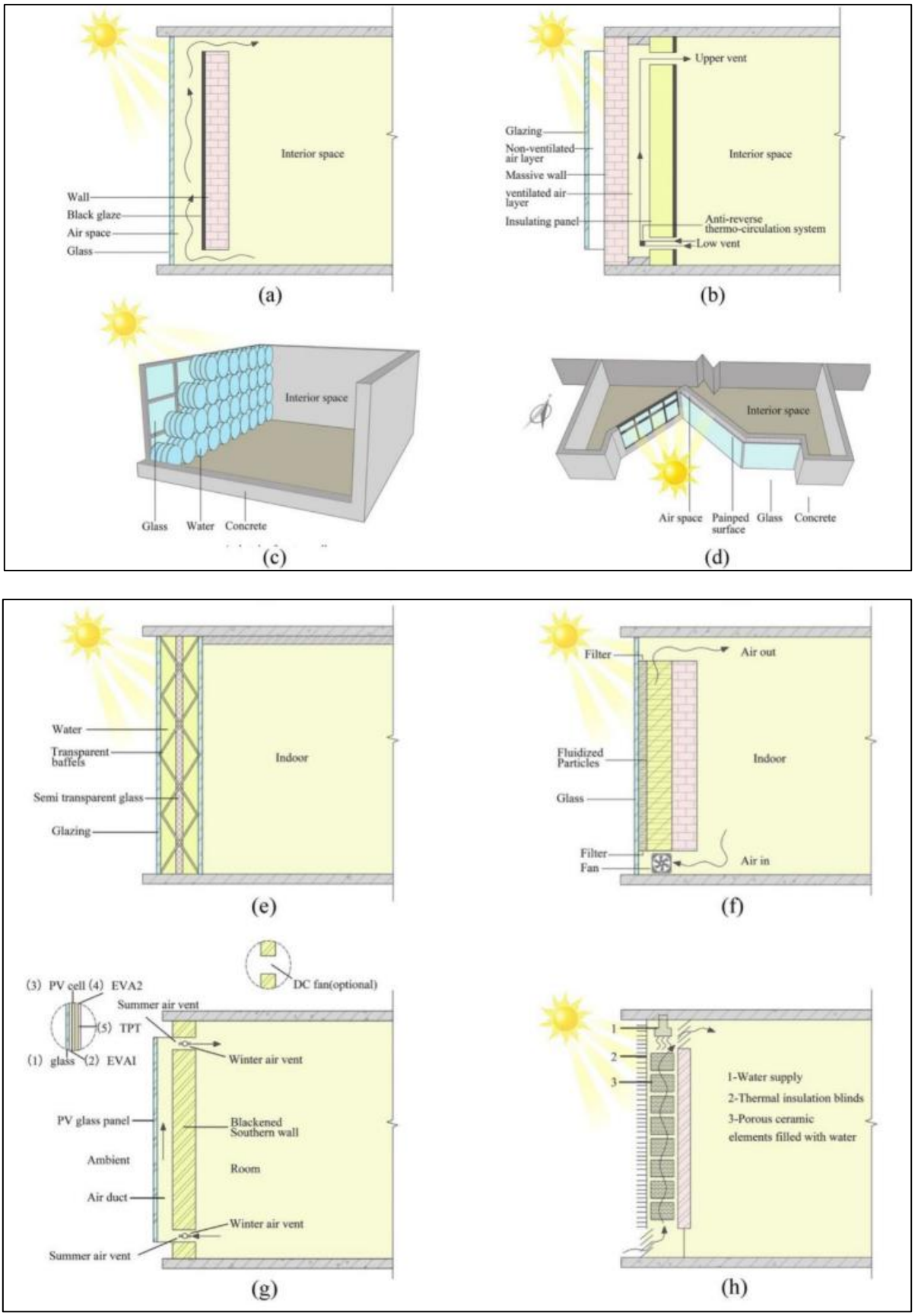


Fig. 10. *Types of Trombe walls: a) classical, b) composite, c) water, d) zigzag, e) transparent, f) fluid-filled, g) photovoltaic, h) porous ceramic*

a) The traditional Trombe wall design includes a south-facing glazed surface, an air cavity, an absorber surface, and a mass wall. Various modifications have been made to enhance its thermal performance, such as changing the material of the mass wall, incorporating fans, and adding dampers to the ventilation openings. One drawback is the heat loss during winter, which can be partially mitigated by installing shutters in the ventilation openings. This type of wall is easy to build, requires minimal extra costs, and can be customized to fit local climate conditions. In some instances, ventilation openings in the mass wall are omitted, relying solely on the thermal mass effect.

b) The composite Trombe wall features a glazed outer surface and a mass wall without ventilation openings on the exterior, along with an insulated wall containing air-exchange openings on the interior. This configuration aims to reduce nighttime heat loss; although its direct daytime efficiency is lower than that of a classical Trombe wall, it is better suited for cold climates due to reduced heat loss. The thickness of the mass wall and insulated wall can be adjusted based on climate conditions, and proper protection against moisture is essential for the wall insulation.

c) The water Trombe wall functions similarly to the traditional Trombe wall but uses a water tank instead of a mass wall. Water, with its high thermal mass, was chosen for testing this system. However, due to water's high thermal conductivity, there is significant heat loss at night. Moreover, during winter nights, the water in the tank freezes, requiring a substantial amount of the next day's solar energy to melt the ice.

d) The zigzag Trombe wall design involves constructing the south-facing facade of the building in a zigzag pattern, with windows on the southeast-facing sections and Trombe walls on the southwest-facing sections. This design aims to allow morning sunlight through the windows and store afternoon sunlight in the Trombe wall. However, the increased exterior wall area in this design leads to a 12-15% rise in total heat loss, making it an energy-inefficient solution.

e) The transparent Trombe wall is a variation of the water wall, using a glass structure instead of a water tank to store heat and allow daylight in. However, heat loss at night increases due to water's thermal conductivity, leading to conditions that promote the growth of organisms and algae within the glass.

f) The fluid-filled Trombe wall involves placing a high heat-storage capacity fluid between the glazed surface and the air cavity. This enhances the heat-absorption capacity of the Trombe wall, but its complexity in execution and operation has limited its practical adoption.

g) The photovoltaic Trombe wall combines photovoltaic panels with a traditional Trombe wall design, allowing for electricity generation in addition to heat absorption. However, this design significantly reduces the thermal energy production capacity. In a 65 m² dwelling, the wall generated 16,209 kWh of electricity per year but only 1,531 kWh of heat. This results in low thermal efficiency and high costs.

h) The porous ceramic Trombe wall is designed for cooling purposes. It includes porous ceramic material within the air cavity that is moistened with water. As air passes through this section, it is cooled and then enters the interior space.

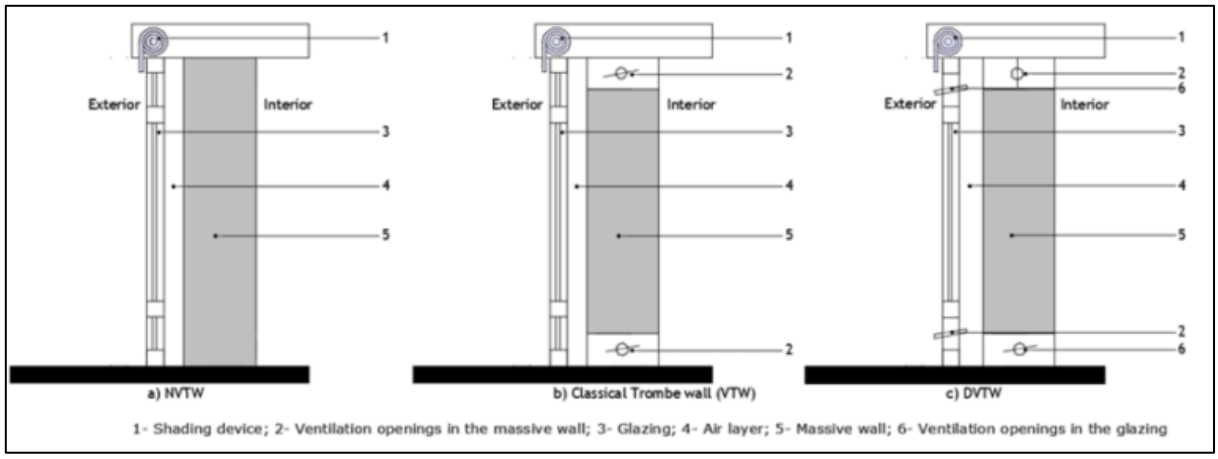


Fig. 11. *Modes of use of the classical Trombe wall*

In certain situations, Trombe walls are built without ventilation openings to maximize their heat-storage capabilities and can be utilized for both heating in winter and cooling in summer (acting as a solar chimney). The choice of glazed layer for the Trombe wall is based on the specific climate of the area. In colder climates,

it is advisable to use double glazing with high thermal resistance to minimize heat loss at night. However, this type of glazing limits the amount of solar radiation transmitted, resulting in decreased daytime efficiency of the Trombe wall.

The air cavity serves to transfer heat, with fans in the ventilation openings and the cavity size controlling air velocity and temperature. Typically constructed from concrete, brick, or stone, the mass wall's thickness is determined through calculations considering heat retention and release timing, in conjunction with local climate factors.

In recent times, there have been numerous experiments conducted utilizing phase-change materials (PCMs) with high thermal mass that undergo phase changes at small temperature differentials, serving as thermal storage units. This innovation allows for the substitution of heavy mass walls with lighter alternatives. PCMs can be categorized into two primary groups: organic and inorganic. Organic PCMs, such as paraffins and fatty acids, offer high thermal resistance but are flammable, while inorganic PCMs, like “hydrated salts,” are more cost-effective but lack resistance to cold and moisture. Incorporating these materials into a Trombe wall is projected to decrease energy consumption by 10–30 percent, although the design and implementation processes are intricate and costly.

To address the primary issue of nighttime heat loss with Trombe walls, various additional strategies such as insulation and shutters have been explored to enhance their effectiveness in colder climates. Research and experiments have also been conducted to investigate the feasibility of implementing Trombe walls in tall buildings. Another approach to improve the performance of Trombe walls involves integrating them with active systems, such as combining them with mechanical ventilation systems. This hybrid system can provide heating during winter and cooling during summer, effectively mitigating the summer overheating issues often associated with traditional Trombe walls.

In this system, a perforated metal plate with corrugations and small holes that have high thermal absorption is used instead of the outer glazed structure. During winter, the metal plate is heated by solar radiation, and the heated air is drawn through the small holes by the mechanical ventilation unit to warm the interior. In summer, outside air enters the ventilation section directly without passing through this heated zone. Furthermore, any heat that has escaped through the mass wall to the outside is recirculated back in.

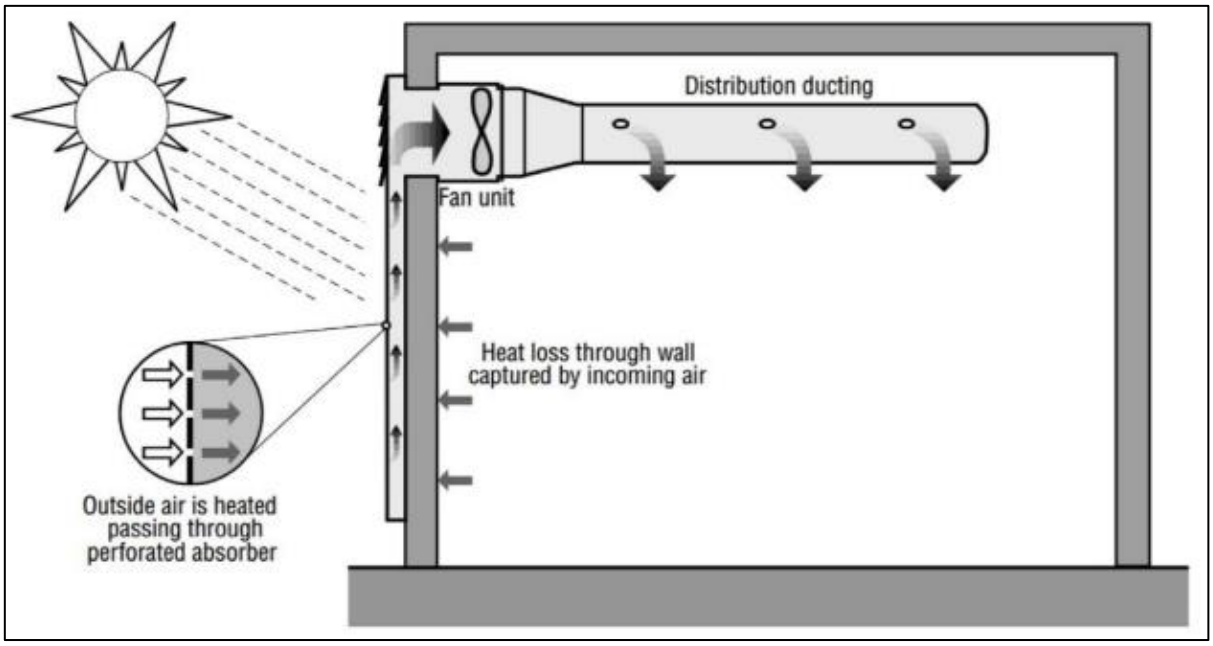


Fig. 12. *Example of a hybrid Trombe wall*

A similar concept to the Trombe wall is the “green wall,” which is another passive design method that enhances indoor air quality by creating a vertical greenhouse on the exterior wall. Air is filtered through the plants in the greenhouse before entering the interior, maintaining the basic principle of the Trombe wall. The Trombe wall is an effective solution for improving the energy efficiency of a building by incorporating an additional air space within the envelope. Other solutions, such as sunspaces, attic spaces, basements, and

vestibules, create buffer zones between the indoor and outdoor environments. These solutions significantly impact energy savings, with calculations showing that utilizing an air space in the roof structure can reduce solar heat gain by up to 95 percent. A double vestibule can also help reduce heat loss through doors during cold seasons. Sunspaces can be seen as larger versions of the Trombe wall, while basements, with their stable air temperatures due to geothermal effects, can be used as a cooling source in the summer.

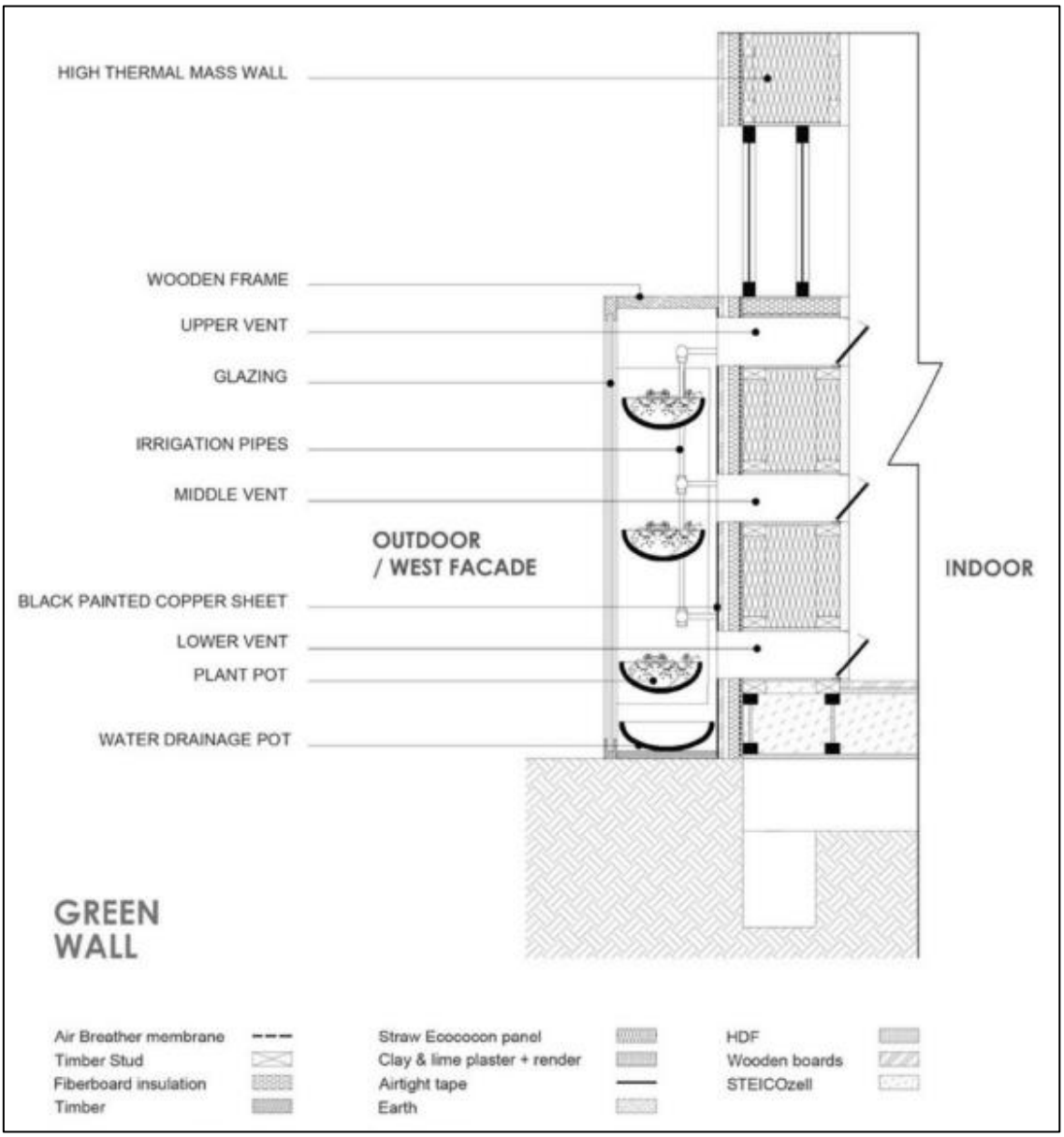


Fig. 13.Green wall

The Trombe Wall Experiment

The goal of the fifth experiment in Phase 1 is to test the effectiveness of a passive Trombe wall in reducing heating loads during the cold season in Ulaanbaatar. The experiment aims to investigate whether the Trombe wall can serve as a thermal store for a single-family dwelling. The test model used in the experiment is similar to previous Phase 1 experiments, featuring a concrete floor, brick walls, and a pitched roof with "U"values of 0.13 Bt/m² C⁰, for the roof and walls, and 0.2 Bt/m² C⁰ for the floor. To compare the heat-gain and heat-loss properties of the Trombe wall with a window, the Trombe wall was positioned in place of the window on the south-facing facade, occupying 30 percent of the facade.

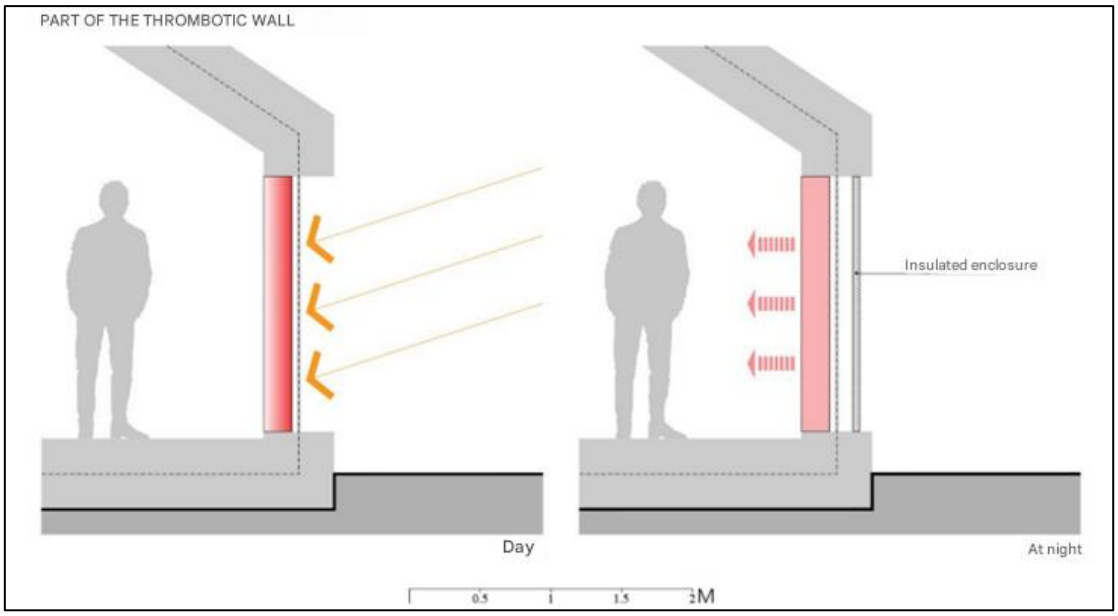


Fig. 14. *Trombe wall used in the experiment*

For this experiment, a passive Trombe wall without ventilation openings was chosen from various types of Trombe walls. The design aimed to absorb solar energy during the day, release the stored energy to the interior after sunset, and maintain a balance where the heat absorbed during the cold season exceeds the heat lost at night for optimal functionality. The Trombe wall was built with a concrete structure, a high thermal absorbance copper absorber surface, a 10 cm air cavity, and a glazed surface.

In order to analyze the impact of the Trombe wall in depth, the wall construction was simulated in various configurations and comparisons were made regarding heating and cooling loads, heat loss through the glazing, and air-cavity temperature. Initially, the glazed layer was examined in two different setups. Since the light transmittance and thermal transmittance of a glazed surface are directly related (higher light transmission results in higher heat loss), a Trombe wall with a 6 mm single-glazed surface was contrasted with a Trombe wall featuring the same construction as the window is a double-glazed surface with a "U"value of 1.507 W/m²•K, filled with 13 mm argon, and equipped with a low-emissivity ("LoE") coating on the inner pane.

In the following step, the impact of varying thicknesses of the concrete wall on the performance of the Trombe wall was examined. Concrete wall thicknesses of 10 cm, 20 cm, 30 cm, and 40 cm were simulated, and the results of the measurements were analyzed. To minimize heat loss through the glazed surface during the night, a 5 cm thick movable insulated shutter was placed on the exterior of the glass and programmed to close after sunset when the outdoor temperature drops below 0 °C. In the final phase of the Trombe wall study, the heating and cooling loads of the modeled Trombe wall were compared with those of a window of the same size, based on the findings from the previous experiments. This comparison was made through hourly simulations to assess the varying impacts on the indoor environment of (a) a window covering 30 percent of the south-facing facade and (b) a Trombe wall of equivalent dimensions.

Reducing Heating Load with the Trombe Wall

The purpose of the experiment was to investigate the potential of reducing heating loads in a single-family dwelling in Ulaanbaatar during the cold season by designing a thermal-storage passive Trombe wall. The study aimed to determine the percentage of reduction in heating loads achieved. The experiment involved using a 45 m² brick-walled dwelling, similar to Phase 1 experiments. The Trombe wall was positioned in the place of a window in the test model to compare its heat-gain and heat-loss characteristics with that of a window. The passive Trombe wall was designed to store solar energy during the day and release it into the interior for a set period after sunset, while also ensuring that the heat absorbed through solar radiation in the cold season exceeds the heat lost at night. The Trombe wall included a concrete wall, a copper absorber surface with high thermal absorbance, an air cavity, and a glazed surface. Heating and cooling systems were simulated to maintain indoor temperatures between 20 and 26 °C in all test models, and the results were compared. Initially, the impact of the glazed layer construction was assessed by testing two different configurations.

The first option was a 6 mm transparent single glazing with a “U” value of 5.78 W/m²•K, offering low thermal resistance but high light transmittance. The second option was a 6 mm double glazing filled with argon, featuring a low-emissivity coating and a “U” value of 1.507 W/m²•K, providing high thermal resistance but lower light transmittance. After conducting the experiment and analyzing the results, it was determined that the annual heating and cooling load per unit area was 35.58 kWh for the dwelling with 6 mm single glazing on the Trombe wall, and 32.54 kWh for the variant with double glazing. In other words, the double-glazed option was 9 percent more efficient.

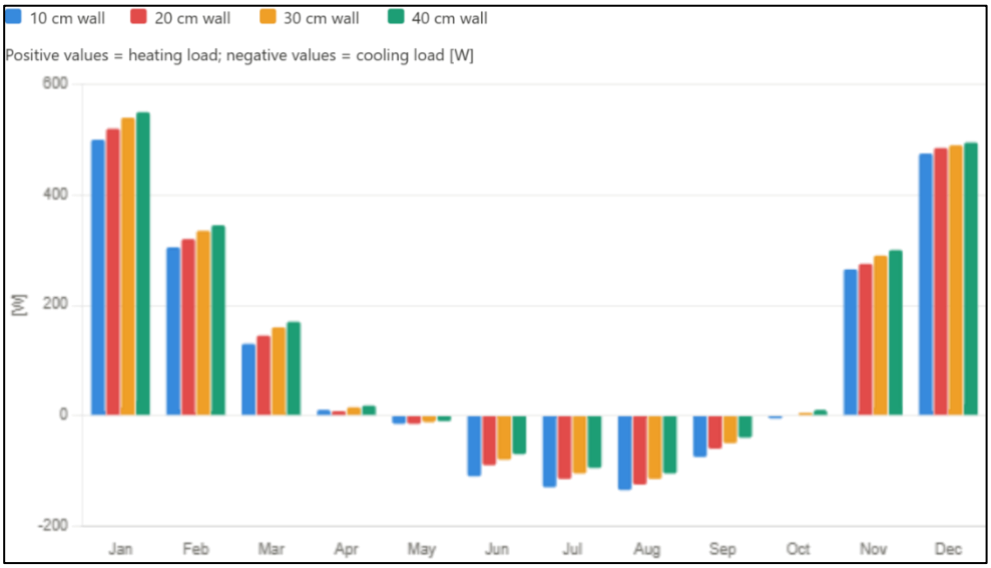


Fig. 15. *Trombe wall variants and monthly average heating and cooling loads*

The total annual heating energy consumption was 1,297.31 kWh for the single-glazed dwelling and 1,308.7 kWh for the double-glazed dwelling, showing a 1 percent difference. In terms of total annual cooling energy consumption, the single-glaze dvariant used 290.51 kWh, while the double-glazed variant used 143.67 kWh, resulting in a 51 percent reduction. The main distinction between the two lies in the cooling load. By utilizing shading to reduce the cooling load, there is no necessity to use multi-layer, high-thermal-resistance glass for the glazed layer of the Trombe wall; instead, using single glazing with high light transmission seems to be more effective.

Table 2. Annual heating and cooling loads for Trombe mass wall variants [kWh]

Variant	kWh/m²·year	Total (kWh)	Heating (kWh)	Cooling (kWh)
10 cm concrete wall	35.81	1,598.23	1,247.39	350.83
20 cm concrete wall	35.58	1,587.82	1,297.31	290.51
30 cm concrete wall	35.80	1,597.66	1,348.09	249.57
40 cm concrete wall	36.07	1,609.63	1,393.60	216.03

In the next phase of the Trombe wall experiment, the impact of the heat-storing concrete wall was studied by modeling it in four different thicknesses: 10 cm, 20 cm, 30 cm, and 40 cm. The results were then analyzed and compared. The 20 cm thick concrete wall was found to be the most effective in terms of total annual performance. As the thickness of the wall increased, the heating load also increased while the cooling load decreased. Thicker walls retain heat absorbed from the sun during the colder months more effectively, but some heat is lost to the outside. In contrast, during the summer, thicker walls absorb heat and reduce cooling requirements. Monthly average heating and cooling loads were further examined to better understand this phenomenon.

Table 3. Annual heating and cooling loads for Trombe wall variants with insulated shutters [kWh]

Variant (with insulated shutters)	kWh/m²·year	Total (kWh)	Heating (kWh)	Cooling (kWh)
10 cm wall	26.81	1,196.50	834.74	361.76
20 cm wall	26.09	1,164.14	871.06	293.08
30 cm wall	26.23	1,170.61	919.73	250.88
40 cm wall	26.52	1,183.36	966.47	216.90

To minimize heat loss through the Trombe wall during the night, a 5 cm thick movable insulated shutter, similar to those used on windows, was installed on the exterior of the wall. The shutter was programmed to close after sunset when the outdoor temperature dropped below 0 °C. The experimental results showed a significant improvement in energy efficiency. For the 20 cm concrete-wall version, the energy load decreased from 35.58 kWh/m²•yr without the shutter to 26.09 kWh/m²•yr, representing a 27 percent reduction. In the final phase of the study, the impact of the Trombe wall on heating and cooling loads was compared to that of a window of the same size in a similarly designed house. The Trombe wall, comprising 6 mm single glazing, a 10 cm air cavity, a black copper absorber surface, and a 20 cm thick concrete wall, covered 30 percent of the south facade of a 45 m² single-family home.

Table 4. Annual heating and cooling loads for variants with Trombe wall versus window [kWh]

	Energy consumption [kWh]			
	m²·year	Total	Heating	Cooling
30% Trombe wall	35.81	1,598.23	1,247.39	350.83
30% Window	35.58	1,587.82	1,297.31	290.51

The window was designed as an argon-filled double glazing with a low-emissivity coating and a U-value of 1.507 W/m²•K. The total annual heating and cooling energy consumption of the two configurations were similar; however, the Trombe wall variant had a 3 percent lower heating load and a 12 percent higher cooling load compared to the window variant. To further analyze the results, the monthly average heating and cooling loads for both variants were compared. Both variants required heating from October to April, with the Trombe wall variant using an average of 91.36 W/h less heating energy than the window variant. Cooling was needed from May to October, with the Trombe wall variant consuming an average of 10.41 W/h more cooling energy than the window variant. The Trombe wall was more effective in reducing heating load during the cold season compared to the window, while shading against direct solar radiation could help reduce the summer cooling load.

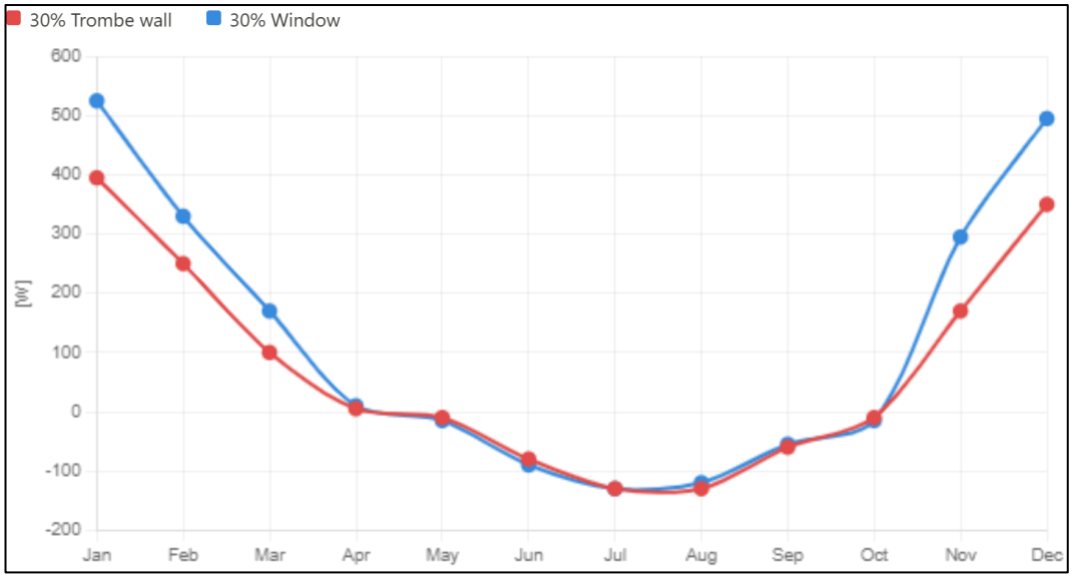


Fig. 16. *Comparison of monthly average loads between Trombe wall and window variants*

The study also analyzed the impact of the Trombe wall and window on an hourly basis during the coldest and warmest days of the simulation. On the coldest day, the total heating energy consumption was 21.37 kWh for the window design and 22.83 kWh for the Trombe wall design. When looking at the hourly heating load, the window design shows a gradual increase until sunrise, a sharp decrease due to solar radiation reaching a minimum of 469.99 W at 13:00, followed by a rapid increase, and then a gradual rise from sunset.

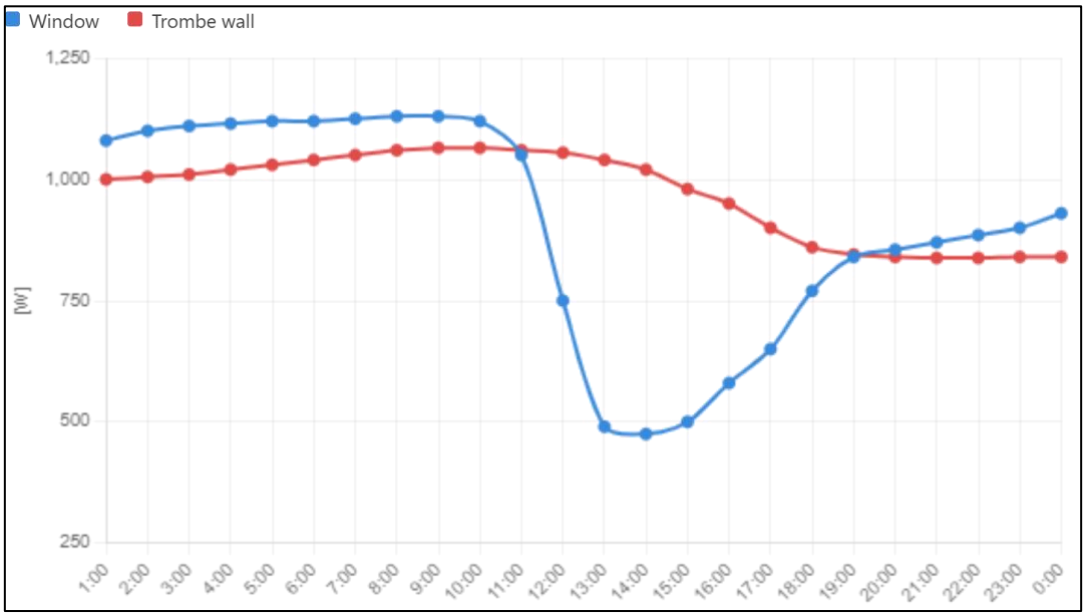


Fig. 17. *Simulated heating load on the coldest day for Trombe wall and window variants*

The heating load of the Trombe wall variant increases gradually, but starts to decrease around two hours after sunrise and continues to decrease for three hours after sunset, reaching its lowest point of 827.72 W at 21:00. After that, it gradually starts to increase again. This shows that the Trombe wall delays the impact of solar radiation by 2-3 hours and its effect lasts through the night. During the night, the heating load for the Trombe wall variant is 7% lower than for the window variant, but during the day it is 29% higher. The Trombe wall also helps to reduce the direct impact of daytime solar radiation and stabilize temperature fluctuations. On the hottest day, the Trombe wall variant used 5.48 kWh for cooling, while the window variant used 6.44 kWh.

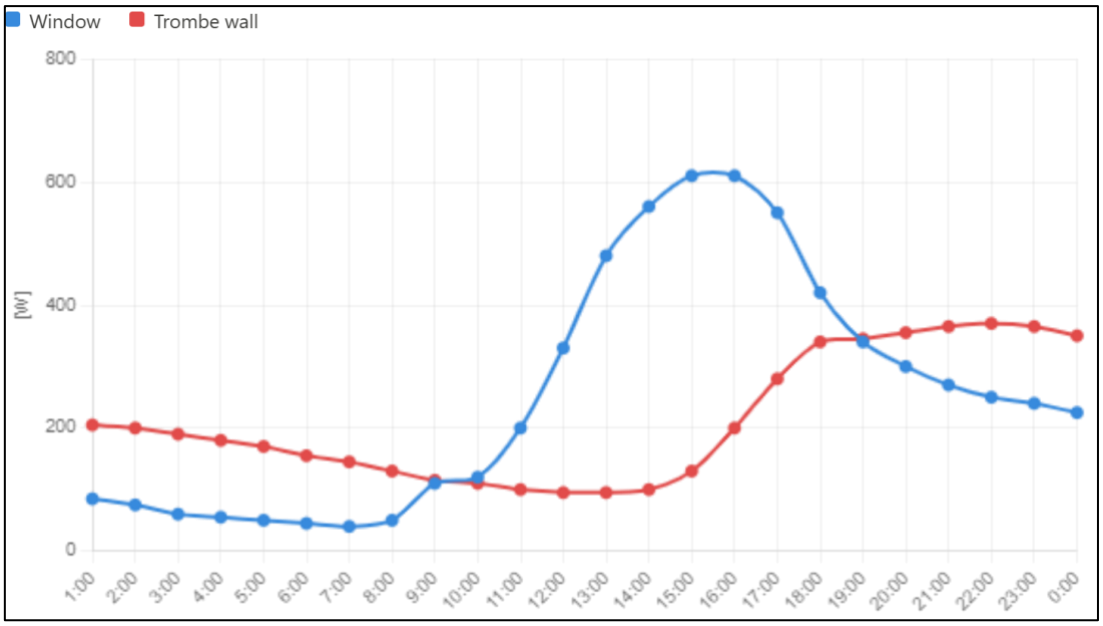


Fig. 18. *Simulated cooling load on the warmest day for Trombe wall and window variants*

When the hourly cooling load is analyzed, the window variant shows a gradual decrease until sunrise, followed by a sharp increase due to solar radiation, peaking at 617.09 W around 15:00. It then decreases rapidly and stabilizes from 18:00 onwards. In contrast, the Trombe wall variant experiences a gradual decrease until sunrise, continues to decrease for two hours after sunrise, then steadily rises to reach its peak of 372.6 W between 21:00 and 22:00 before gradually decreasing again. The Trombe wall helps to mitigate solar radiation overheating and distributes heat more evenly throughout the day. Consequently, its nighttime cooling load is 38 percent higher than that of the window variant, while its daytime cooling load is, on average, 55 percent lower.

Conclusions

The study utilized dynamic numerical simulation in EnergyPlus software to assess the potential for minimizing heating, cooling, and ventilation loads in a small single-family house in Ulaanbaatar through various architectural design strategies. Four passive design strategies for heating were tested, including thermal protection, thermal mass utilization, nighttime window heat loss reduction with insulated shutters, and a passive Trombe wall. For cooling, two passive strategies were examined: window shading to reduce overheating and natural ventilation for summer cooling. Mechanical ventilation with a heat exchanger and optimizer, along with active heating and cooling systems, were employed to maintain indoor comfort levels. The impact of each passive design strategy on the indoor environment was analyzed based on hourly dynamic simulation results. The study yielded insights into designing highly energy-efficient buildings in Ulaanbaatar's climate.

The study aimed to investigate the effectiveness of a thermal-storage passive Trombe wall in reducing heating loads in a single-family dwelling in Ulaanbaatar during the cold season. The Trombe wall, occupying 30 percent of the south facade, was compared to a window to analyze heat-gain and heat-loss characteristics. To minimize heat loss at night, a 5 cm thick movable insulated shutter was placed on the outside of the wall and programmed to close after sunset when the outdoor temperature dropped below 0 °C. This reduced the load from 35.58 kWh/m²•yr to 26.09 kWh/m²•yr, a 27 percent decrease. The total annual heating and cooling energy consumption for both the window and Trombe wall variants were similar. However, the Trombe wall delayed the direct impact of solar radiation by 2–3 hours and provided continuous thermal benefits throughout the night. It also helped moderate overheating from daytime solar radiation, stabilized temperature fluctuations, and reduced peak loads.

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