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REVIEW

Review of passive heating/cooling systems of buildings

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Abstract

In this review, an attempt has been made to analyze passive solar heating and cooling concepts along with their effects on performance of a building's thermal management. The concepts of Trombe wall, solarium, evaporative cooling, ventilation, radiative cooling, wind tower, earth air heat exchanger, roof pond, solar shading for buildings, and building-integrated photovoltaic thermal (BiPVT) systems are extensively covered in this review. Comparison of results by various heating and cooling concepts has been made. It has been observed that direct heating through double-glazed window saves maximum conventional fuel for thermal heating during winter months. Further, an evaporative cooling is one of the best cooling concepts which is economical too in summer period.

Highlights

1. Double-glazed window for thermal heating.
2. Combination of evaporative cooling and wind tower for passive cooling.
3. Trombe wall for both passive heating and cooling.
4. BiPVT system for thermal heating and electricity production.

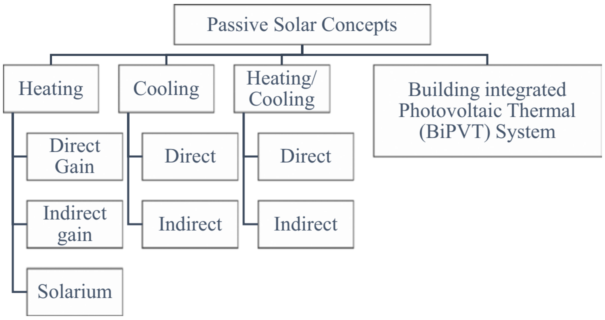
Introduction

An estimated 6.7% of the global energy requirement is used for thermal management of buildings for which precise Arab data are not available [1]. As per an estimate, at least 35% of the total building's energy requirements may be satisfied by using alternative resources [1]. The world's total energy requirement may be reduced by 2.35% at an approximate incremental cost of 15% over the total construction and planning cost [1, 2]. As a proof of concept, the solar H.P. Co-operative building in India was able to reduce heat loss by 35% by using double-glazing solar passive design for thermal heating [3]. Different physical processes for providing thermal comfort for passive buildings include solar radiation, long-wave radiation exchange, radiative cooling, and evaporative cooling. Solar radiation and radiative cooling are the processes used for both thermal heating and cooling purposes [1].

Passive solar design is used as a cost and resource efficient method for achieving natural harmony between climate, architecture, and people. The building structure should be self-sustainable that is generating the energy for its own consumption.

Classification of various heating, cooling, and heating/cooling passive concepts has been done in Table 1 including building-integrated photovoltaic thermal (BiPVT) systems.

Table 1. Classification of heating and cooling concepts.



Passive solar design strategies for passive house

Passive design strategies are related to various aspects of a building like shape, size, orientation, form, site, layout etc. Their impact can be easily seen in the performance of the building's energy use. This is because the massing and layout of the buildings can generate self-shading effects and can enhance the ventilation and natural lighting. At hardly any additional cost in adapting design strategies like building orientation**,** we can significantly achieve an effect on the building's thermal performance. Depecker et al. [4] investigated the relationship between shape coefficient and heating loads. The study revealed that the heating load in cold climatic conditions was directly proportional to the shape coefficient, the reason being that the solar gain through the glazing was low. The study also suggested that opaque walls do not have any association with either heating load or shape coefficient, thus bearing less importance in mild and sunny climatic conditions. Stevanović [5] reviewed the heat flow across a building envelope and revealed that an optimized building form can reduce the heating load up to 12% per total volume of the building. Aldawoud [6] discussed different geometries of the atrium for the energy saving performance and concluded that square-shaped atrium has the best performance. The results also suggested that more energy savings can be achieved in low rise structure with an atrium which has a larger glazing to roof ratio for temperate and cold climatic condition. However, for hot and dry climatic conditions, high structure with a low glazing to roof ratio is preferred. An algorithm based on self-shading building envelopes for reduction in cooling and lighting loads integrated with different façade types, glazing, orientations, shapes, and life cycle costs has been developed [7, 8]. Square shape was found to give better results for all climate types. Stevanović [5] discussed that the detached units placed in curved road configurations requires large heating and cooling when compared to the attached units placed in straight layout. The latter saving up to 30% cooling and 50% heating requirements. Energy savings of 1–5% may be achieved just by changing the orientation, aspect ratio, and shape factors [9, 10]. The study concluded that the aspect ratio has very less influence on the building's energy use. The study also concluded that with increase in the size of south-facing window, there is corresponding decrease in the total annual load in cold climatic conditions and the same increases in warm climatic conditions.

Passive Heating Concepts

The various heating concepts in brief have been summarized in Table 2 with remarks. Few concepts have been discussed in detail as follows:

Direct gain

In this case, solar radiation is directly transmitted through glazed window into the living room for thermal heating. During the day, the whole building structure collects, absorbs, and stores the heat and releases the heat at night for thermal heating as shown in Figure 1.

The rate of heat transfer into the room can be expressed as follows,

$$\dot{Q} = \left(\frac{1}{U_t} + \frac{L}{K} + \frac{1}{h_i}\right)^{-1} (T_{sa} - T_r) = U_L (T_{sa} - T_r) \qquad (1)$$

where,

$$T_{sa} = \frac{\tau I(t)}{U_t} + T_a \text{and} U_t = \left(\frac{1}{h_0} + \frac{1}{h_i}\right)^{-1}$$

Balcomb et al. [11] suggested that single-glazed south-oriented system without storage mass is comparatively incompetent, whereas double-glazed system along with night insulation and soundly storage mass heat capacity proves to be efficient in meeting the heating requirements. Percentage of solar annual heating with storage heat capacity of 400 kJ/m^{2}gC for single-glazed system, double-glazed system, single-glazed system with night insulations and

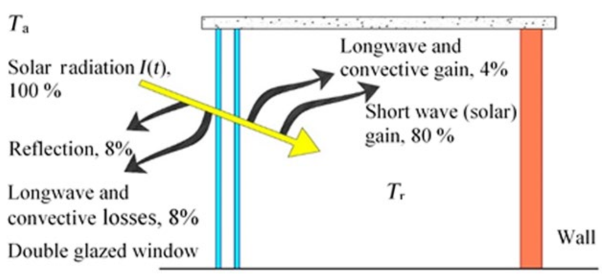


Figure 1. Direct gain during sun shine hour.

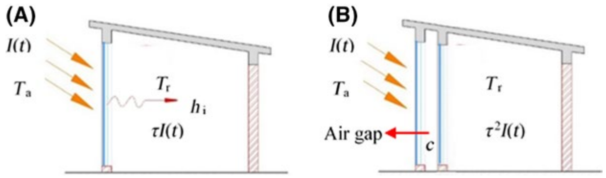


Figure 2. (A) Single glazing. (B) Double glazing.

double-glazed system with night insulation was observed to be about 10, 65, 80, and 90%, respectively. For 45° tilt, percentage of annual storage heating turns out to be nearly 87, 80, 58, and 18% for active system, double-glazed system with night insulation, double-glazed system and single-glazed system, respectively, with ratio of glass area to house area of 0.4 [1]. This means that double-glazed with night insulation is as good as active system tilted near the optimum angle. According to the authors, double glazing should be used in order to reduce heat loss from room to outside air, and windows should be covered by insulation at night to solve the same problem. Single-glazed system and double-glazed system are shown in Fig. 2A and B, respectively.

Rate of useful energy for single-glazed system,

$$\dot{q}_u = \tau I(t) - U_t(T_r - T_a) \tag{2a}$$

where,

$$U_t = \left[\frac{1}{h_0} + \frac{L_g}{K_g} + \frac{1}{h_i}\right]^{-1} = \left[\frac{1}{5.8} + \frac{1}{2.8}\right]^{-1} = 1.88\ \mathrm{W/m^2}, \left(\text{neglecting}\,\frac{L_g}{K_g}\right)$$

Rate of useful energy for double-glazed system,

$$\dot{q}_u = \tau^2 I(t) - U(T_r - T_a) \tag{2b}$$

where,

$$U = \left[\frac{1}{h_0} + \frac{1}{c} + \frac{1}{h_i}\right]^{-1} = \left[\frac{1}{5.8} + \frac{1}{4.8} + \frac{1}{2.8}\right]^{-1} = 1.35\ \mathrm{W/m^2}$$

Reduction of losses can be calculated as $\left[\frac{1.88 - 1.35}{1.88}\right] = 28\%$ (2c)

The air gap reduces the heat transfer by conduction since air is a poor conductor. This proves that a reduction of 9% in heat gain and a reduction of 28% in losses can be achieved by using double-glazed system when compared with single-glazed system.

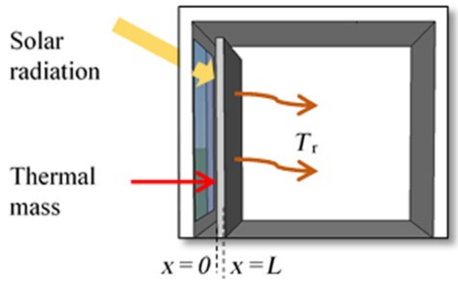


Figure 3. Indirect gain during sunshine hours.

Indirect gain

In indirect gain, the heat is allowed to enter through glazing and is stored in the thermal mass. The heat is then transferred to the room via conduction and convection (Fig. 3).

Indirect gain concepts include Trombe wall, water wall and trans wall.

The rate of heat transfer into the room can be expressed as follows,

$$\dot{Q} = \left(\frac{1}{U_t} + \frac{L}{K} + \frac{1}{h_i}\right)^{-1}(T_{sa} - T_r) = U_L(T_{sa} - T_r) \tag{3}$$

where,

$$T_{sa} = \frac{\alpha\tau I(t)}{U_t} + T_a$$

The thickness, surface area, material, and thermal properties of the thermal mass controls the heat flow inside the room. The thermal mass is dark colored for maximum efficiency and promote absorption of solar radiation. Reduction in building's heating demands with use of passive heating concepts has been reported to be about 25% annually in various studies [12].

Solarium

Solarium is a unification of direct gain and thermal storage concepts. Solarium consists of three sections namely

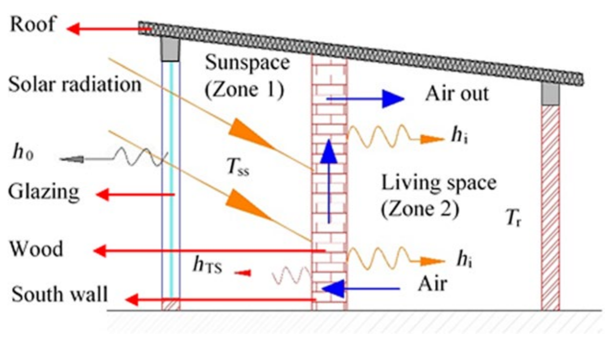


Figure 4. Cross-section view of solarium-cum-passive solar house.

sunspace with thick mass wall on the south side (for Northern hemisphere), linking space, and living space as shown in Figure 4. The thermal wall between the living space and sunspace helps in heat retention and distribution, thus improving the efficiency. The sunspace collects the energy through the glazing, absorbs it, and prewarm air for the living space. The sunspace works on the direct gain principle, in which the heat is used to maintain the temperature suitable for its transfer to the living space.

The rate of heat transfer into the living zone can be expressed as follows,

$$\dot{Q} = \left(\frac{1}{h_m} + \frac{L}{K} + \frac{1}{h_i}\right)^{-1} (T_{sa} - T_r) = U(T_{sa} - T_r) \tag{4}$$

where,

$$T_{sa} = \frac{\alpha\tau I(t)}{U_t} + T_a \text{and} h_m = \left(\frac{1}{h_0} + \frac{1}{h_{TS}}\right)^{-1}$$

Tiwari and Kumar [13] have presented a thermal analysis of a solarium-cum-passive house as represented in Figure 4. The findings of the study were based on the energy balance of different components, link walls (like air collector, trans wall, water wall, metallic sheet). The findings have been based on best Thermal Load Levelling (TLL).

Variation in room air temperature and ambient temperature were noticed due to the solar intensity necessitating an estimate of the room temperature variations. TLL can be calculated using the following expression:

$$\text{TLL} = \frac{(T_{r,\max} - T_{r,\min})}{(T_{r,\max} + T_{r,\min})} \tag{5}$$

Decrement factor (*f*) can be defined as the reduction ratio of inside surface temperature of a room to the outside surface temperature of the room and can be expressed as follows:

$$f = \frac{(T|_{x=L})_{\max} - (T|_{x=L})_{\min}}{(T|_{x=0})_{\max} - (T|_{x=0})_{\max}} \tag{6}$$

Temperature fluctuations in the living room were noticed in case of air collector as link wall and resolved using an additional thermal mass. With use of air collector as link wall, along with effect of isothermal mass in living space and presence of movable insulation, drop in maximum temperatures of both the zones were found to be 3–4°C.

Based on Table 2, one can observe that direct gain is more convenient for sunshine hours heating (office) and rest of the concepts are used for residential buildings. Solarium will be useful for both the applications.

Passive Cooling Concepts

To maintain comfortable indoor environment, there should be reduction in rate of solar heat gains (by using solar devices, insulation, appropriate building materials and colors, decrease in thermal heat gains by lighting controls etc.) and removal of excess heat from the building via convection, evaporative cooling, radiative cooling, air movement, cool breezes, earth coupling, reflection of radiation etc. Passive cooling concepts channel the airflow, thus removing the heat. The various cooling concepts in brief have been summarized in Table 3 with remarks. Few concepts have been discussed as follows:

Wind tower

Hot ambient air is allowed to enter the wind tower during the day. Transferring heat to the walls upon contact creating a cool downward draft. The heat stored in the walls warms the cold night air. Low pressure at the top leads to an upward draft.

Saffari and Hosseinnia [18] suggested that drop of 12°C in indoor temperature and relative humidity increased by 22% can be achieved with use of wet columns 10 m in height. Hughes et al. [19] underlined various cooling techniques integrated with wind towers. The key parameters considered include the ventilation rate and temperature to determine the feasibility of implementing the devices for their respective use. The temperature decrease was found to be in the range of 12–15°C by incorporating evaporative cooling with wind towers. The addition of the cooling devices reduces the air flow rates and the overall efficiency of the wind tower. This temperature drop was found to be greater than a solitary wind tower arrangement. Montazeri et al. [20] examined two- sided wind tower. The maximum performance was achieved during an experiment at 90° angle. Chaudhry et al. [21] investigated a novel closed-loop thermal cycle embedded inside a circular wind tower with internal cross-sectional area of 1 m^2 with 1 m height installed at the roof top to achieve internal thermal comfort. Louvers present at the wind tower openings were angled at 45°. The study concluded that the exit temperature using traditional cooling was increased up to 4°C without any impact of the height in case of the proposed heat pipe design with water and ethanol as working fluids.

Evaporative cooling

The interior spaces are cooled by passing the hot ambient air over damped surface to cool an air stream (by evaporating the water) before its introduction to the interior spaces. Amer [22] reported that evaporative cooling is one of the most oldest, effective, and efficient technique with the potential to reduce indoor temperature by about 9.6°C. Heat transfers for evaporative cooling have been shown in Figure 5.

Table 2. Various passive heating concepts (for thermal heating).

S. No.	Concepts	Results	Ref.	Climatic conditions	Remarks	Applications
2.1	Direct gain (Figs. 1, 2A and B)	i 80% solar gain for double-glazed window. ii Use of double-glazed system leads to reduction of losses by 28% when compared with single glazed system (Equations 2a–2c).	[14]	Very cold.	i No phase change. ii Day lighting	Office building
2.2	Indirect gain (Fig. 3)	25% reduction in heating load. (Equation 3)	[12]	South China.	i Phase change. ii No day lighting	Household
2.3	Solarium (Fig. 4) (Equation 4)					
a.	Link walls iAir collector iiTrans wall iiiWater wall ivMetallic sheet	Maximum room temperature achieved: i Air Collector: 23–24°C (Zone 2) ii Trans wall: 21–22°C (Zone 2): better performance iii Water wall: 17–18°C (Zone 2) iv Metallic sheet: 30–31°C (Zone 1)	[13]	Srinagar, India.	i During the day time, the temperature of zone 1 is greater than living room but reduces at night	Sun space: Glass construction (except for the roof) Living space: Wooden construction
b.	Water wall as link wall	i The variation in living space was observed to lie within the range of 18–20°C. ii For a 5 cm thick water wall, the average temperature for Zone 1 was found to be 35°C and 30°C for Zone 2 with water temperature of about 40°C. iii Best TLL in the living space achieved	[15]	Srinagar, India	The thickness of the water wall was found to be inversely proportional to the temperatures of the sunspace and the living space	i Glass construction for wall and roof with movable insulation east and west face of sunspace. ii Only valid for wooden construction
c.	Combination of water wall and Phase Change Component Material as link wall	i Best TLL along with comfortable temperature (approx. 20°C) for the zone 2 was achieved. ii With decrease in thickness of PCCM from 10 to 5 cm, the heat flux transmitted from the link wall to the living space increased by about 35%	[16]	North America (Boulder)	Zero ventilation rate	Household
d.	An attached solarium with motorized shading devices	i Reduction of about 76% in the heating demands. ii 134 kWh/m^2 of excess heat can be collected and stored by solarium. iii 70% reduction in case plants are grown inside the solarium	[17]	Montreal	Combined interior and exterior motorized shading	i Greenhouses. ii Solar houses. iii High-efficiency buildings where solar gains are priority

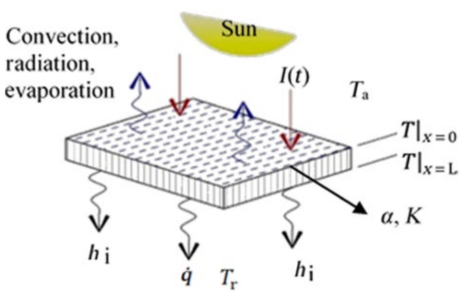


Figure 5. Evaporative cooling: Wetted surface exposed to solar radiation.

The rate of thermal energy per unit area can be expressed as follows,

$$\dot{q} = U_L(T_{sa} - T_r) \quad (7)$$

where,

$$T_{sa} = \frac{\alpha I(t)}{h_1} + T_a - \frac{\varepsilon \Delta R}{h_1}, h_1 = h_{rw} + h_{ew} + h_{cw} \text{ and}$$

$$U_L = \left(\frac{1}{h_1} + \frac{L}{K} + \frac{1}{h_i}\right)^{-1}$$

In the Middle East, evaporative cooling is combined with wind towers to channel the cool wind passed over water cisterns into the interiors to produce cooling and refreshing effect [23]. The evaporative cooling is extensively used in the form of dessert coolers in arid areas in sun light hours (ambient temperature between 37 and 42°C), despite leading to increased indoor air humidity. The method is limited to the regions with low outdoor humidity with 0.3–0.5 m^3 water per dwelling availability [1]. Kamal [24] discussed a passive downward evaporative cooling system consisting of downward tower with wetted cellulose pads installed at the top of the tower with inside temperatures ranging between 29 and 30°C while the outside temperature ranged from 43 to 44°C with 6–9 number of air changes. Roof surface evaporative cooling was also discussed where the water was sprayed over suitable water-retaining materials like gunny bags laid over the roof. The results showed that the wetted roof temperature was 40°C with ambient temperature of 55°C. Qingyuan and Yu [25] concluded that the potential of evaporative cooling is subjective to the difference between humidity ratio of outdoor air and wet bulb temperature at saturation.

Solar shading techniques

Solar shading devices reduce the heat gains and thus provide comfortable indoor temperature, reducing the cooling costs. They can also function as an esthetic element aside from day lighting if properly designed. Drop of almost 6 °C in the room temperature has been observed [26]. Kumar et al. [27] evaluated various passive cooling techniques and found that solar shading alone is responsible in reducing the inside temperature by about 2.5–4.5°C. Further drop of 4.4–6.8°C was observed with insulation and controlled air exchange rate.

Shading devices

They can be classified as vertical (vertical louvers, projecting fins), horizontal devices (canopy, awnings, horizontal louvers, and overhangs), egg crate devices (concrete grille blocks, metal grills), and screenings (venetian blinds, double glass windows, window quilt shade, movable insulation curtains, natural vegetation etc.). Various roof shading techniques have been shown in Figure 6. Horizontal shading devices are best suited for south-oriented openings, whereas vertical shading devices for east- and west-facing facades.

Kima et al. [28] studied the impact of four shading types – overhangs, blind system, light shelf, and experimental shading device. Maximum cooling energy saving was determined to be 11% for experimental shading with 76° of solar altitude. Grynning et al. [29] conducted a study in which it was found that solar shading systems are necessary to reduce the need of artificial cooling of an office block. Simulations for north- and south-oriented cubicles with different floor areas, openings, and shading schemes were run. The simulations revealed that the shading systems contribute toward lowered transmittance value of the window. It was found that the cooling load increases with increase in the window size from 41% to 61%, therefore, there was a decrease in the heating demand. Energy demands were found to be larger in north-facing offices as compared to south facing. Shading devices, if improperly used, can increase the energy demands by 5%, hence they should not be installed on north-oriented workspaces. The results also show that by using a proper and correct shading technique, energy demands can be reduced for south-facing facades by 9%, whereas an improper technique may lead to an increase of 10%. It was also found that four pane glazing is beneficial as compared to two or three pane glazing and can reduce the energy demands as high as 20% and 7% if two pane and three pane glazing is replaced by four pane glazing, respectively.

Shading devices have been in use since ancient times. The Mughal architecture (India) used these in the form of inclined and deep shades to cover more surface area with deep carvings on building exteriors. These carvings help create mutual shading and the extended surface helps to increase the convective heat transfer [30] (Fig. 11).

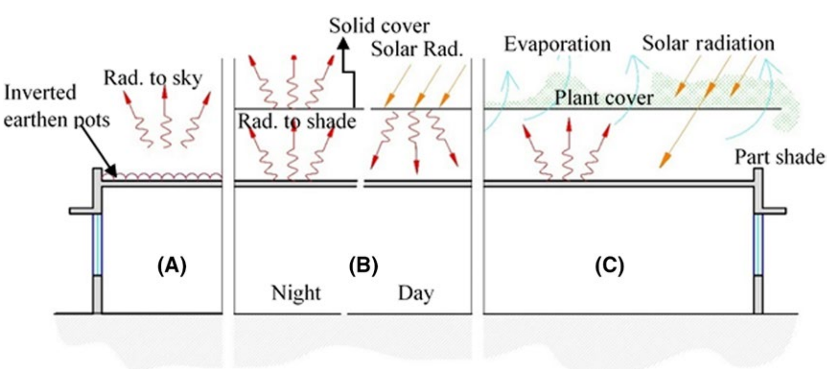


Figure 6. Roof shading by (A) earthen pots, (B) solid cover and (C) plant cover.

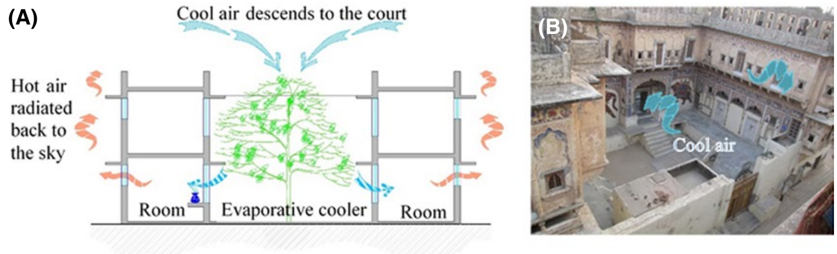


Figure 7. Radiative cooling (A) Schematic section and (B) Haveli in Shekhawati, Rajasthan.

Radiative cooling

Effective radiation from the exposed horizontal surface to ambient air via convective and radiative heat transfer is termed as radiative cooling. Roof transfers heat to the night sky via long wave radiation exchange and convection (Fig. 7A).

The radiant heat exchange between sky and a body/surface can be expressed as:

$$\dot{q}_r = \varepsilon\sigma(T_{sky}^4 - T^4) \tag{8}$$

Rate of long-wavelength radiation exchange between ambient air and sky can be expressed as:

$$\Delta R = \sigma[(T_a + 273)^4 - \left(T_{sky} + 273)^4\right] = 60\ \mathrm{W/m^2} \tag{9}$$

Courtyard planning

Localized heating within buildings may be reduced to large extent by exploiting the thermal interaction due to the difference in temperature of courtyard and the building core depending upon the aspect ratio of the court, wind speed, and direction [31] (Fig. 7A and B). In vernacular architecture, the courtyards were integrated with vegetation and water bodies to enhance the humidity, evaporative cooling, and provision of shade.

Infiltration/Ventilation

Energy conservation and natural ventilation should be the prime concern of any building design as the buildings are often planned as sealed and well insulated, with low heat gain or loss, the extreme use of HVAC systems to improve air quality and to dilute the VOCs emitted by the building materials and furniture [32]. In buildings, there are two types of airflows induced due to pressure difference leading to natural air flow. Infiltration occurs from adventitious openings that are present in every building in the form of interfaces, cracks, or any gaps etc. Infiltration can be minimized with draught sealing, air locks, airtight and quality construction of doors and windows. Wang et al. [33] suggested that airtightness alone can have a significant impact on the heating and cooling performance of the building. In the study, infiltration of hot and humid air led to an increase of 9.4% and 56% in total cooling load and latent load, respectively. Reduction of 1.4% in heating load was observed due to higher outside temperature. The other type of airflow is ventilation. Windows play an important role for air circulation within the building premises with recommended value of air movement being 0.2 and 0.4 m/s during winters and summers, respectively [14].

The ventilation losses can be given by:

$$Q_v = 0.33\,NV(T_r - T_a) \tag{10}$$

Rate of heat transfer from roof bottom to room air is,

$$M_a C_a \frac{\mathrm{d}T_r}{\mathrm{d}t} = h_i\left(T_{|x=L} - T_r\right)A_r + A_{win}U_t\left(T_{sa,win} - T_r\right) - 0.33\,NV(T_r - T_a) \tag{11}$$

Based on Table 3, one can observe that the combination of evaporative cooling and wind towers is able to reduce the temperature by up to 12–17°C. Evaporative cooling is the most economical concept for cooling of a building.

Passive Heating and Cooling Concepts

These are the concepts that can be used for both seasons for heating and cooling purposes. The various heating/cooling concepts in brief have been summarized in Table 4 with remarks. Few concepts have been discussed as follows:

Trombe wall

Trombe wall is a large (at least 400 mm thick) mass (material – stone, brick, reinforced cement concrete, mud, etc.), exposed to sunlight through south-facing exterior glazing in northern hemisphere. The thick walls transfer

Table 3. Various passive cooling concepts.

S. No.	Concepts	Results	Ref.	Climatic Conditions	Remarks	Applications
3.1	Wind Towers					
a.	Proposed improvements: i Integrated with evaporative cooling concept. ii Tower heads capable of trapping wind from any direction. iii One-way damper with large screen openings	i 306 kg of mass storage material is used per cubic meter of tower, capable of storing 36 m^2 heat. ii The above proposed design increases the efficiency of heat transfer by 5–10 times without a penalty in the total mass of the thermal material used	[34]	Hot arid areas (Areas with variable wind directions)	i Wind towers are capable of releasing air at higher flow rates to the buildings. ii An energy storing system (long conduits made of baked non-glazed clay) was also introduced to increase the heat transfer area	i Residential. ii Commercial. iii Analysis may be used as guideline for natural ventilation and passive cooling systems
b.	Two novel designs: i Wetted columns with cloth curtains. ii Wetted surface with evaporative cooling pads	i High wind conditions: Wetted column tower design. ii Low wind conditions: Wetted surface tower design. iii The design released air at much lower temperature to the interior space as compared to the conventional design. iv Wet columns with 10 m height can reduce the indoor temperature by 12°C and RH by 22% [35]	[35–37]	Hot arid regions (Middle East)	Integration of cooling devices with the conventional wind towers is beneficial with air exiting the towers at significantly lower temperature than the outside temperature	–
e.	Proposed design includes: i Clay conduits. ii Water pool	i Air flow induced by the tower has direct impact on the reduction of internal temperature. ii Increasing the number of conduits results in better efficiency than a wetted column. iii Wetted surface deign is able to reduce the temperature by up to 17.6°C	[38]	Hot dry region of Ouargla (maximum temperature 47–52°C)	i Clay conduits mounted to improve mass and heat transfer. ii Water pool introduced to increase the humidification	i Residential. ii Bio climatic housing
f.	Wind towers installed at the roof top.	i The proposed tower can rotate and align itself in the direction of the predominant wind to compensate for low wind speeds. ii Natural day light inside the premise can be improved by using transparent construction material for the wind catchers	[39]	Windy regions	The proposed wind towers could be used in various configurations such as wind tower with windows, a wind tower and a solar chimney/heater or two wind towers in different directions	i Residential. ii Closed arenas. iii Commercial buildings. iv Administrative buildings
3.2	Evaporative cooling (Fig. 5; equation 7)					
a.	Passive evaporative cooling.	Effective for metal ceiling and thus reduces the room temperature.	[40]	Hot humid climate (Thailand)	Higher solar radiation and ambient temperature gave better results	All building types

Table 3. Continued

S. No.	Concepts	Results	Ref.	Climatic Conditions	Remarks	Applications
b.	Solar air heater design along with the concept of evaporative cooling	Responded well during the winters but was not effective for summer cooling	[41]	Composite climate	Changes (like addition of wetted south wall collector and roof duct at the top) were made to the model in order improve performance in both seasons	–
c.	Performance of various roof materials on evaporative cooling effect	Siliceous shale itself is capable of reducing the roof surface temperature up to 8.63°C due to its high evaporation rate as compared to mortar concrete (0°C). This material releases more latent heat while silica sand, volcanic ash and pebbles yield more sensible heat of about 0.62, 0.18 and 0.18, respectively	[42]	–	Siliceous shale with adsorption rate of 0.07 $kg/m^2/h$ is found to have the greatest evaporation performance (0.3 $kg/m^2/h$)	All building types
d.	Passive evaporative cooling wall based on various porous layers	Porous pipe surface temperature and the air flow of about 4–6°C and 3–5°C, respectively below the ambient can be attained, thus meeting the cooling demand	[43]	Shanghai, China (October).	i Porous ceramic pipes with high water sucking ability were used as construction material for the evaporative wall. ii Not suitable for extreme humid climate and locations with shortage of water for evaporation.	Hot and dry climates or locations while the design of outdoor or semi enclosed spaces in parks, pedestrian areas and residential courtyards aims at controlling increased surface temperature.
e.	Indirect evaporative cooling	i There was drop of 1°C in mean daily temperature [44], ii There was an average drop in indoor temperature of up to 2.5°C compared to the outside temperature [44], iii This system is capable of reducing the thermal discomfort due to excess of heat in about 95–100% of the year [44], iv Capable of reduction of the energy demand of HVAC by 20% in next 20 years [45]	[44, 45]	Maracaibo, Venezuela (average daily temperature ranged between 26.5–27.6°C) [44], Dry and hot climate [45]	i Metallic water tank with thickness of 3–4 cm was laid over concrete slabs. Insulated high reflectance sheets of 1 cm thickness were used as roof element and fans were used in order to enhance the evaporation [44]. ii Strong potential for improving indoor comfort conditions	The system can be employed in various Brazilian territories, irrespective of the arid climate [44]
f.	Evaporative cooling through a fountain	i The resultant inside temperature was observed to fall within the comfortable zone of 20°C. ii There is a potential for reduction of the cooling load by 9% and the annual energy consumption by 23.6%	[46]	Hot and arid regions (Dubai)	Outside temperature was about 45°C	All building types

Table 3. Continued

S. No.	Concepts	Results	Ref.	Climatic Conditions	Remarks	Applications
3.3	Solar Shading Techniques					
a.	Shading of roof	High indoor temperature can be controlled by providing a roof cover made from locally available material like hay, terracotta tiles, inverted earthen pots, solid cover (sheets), plants, thermal insulation. (Fig. 6)	[24]	–	Masonry and RCC constructions tend to make the indoor temperature as high as 41°C when the roof top temperature is about 65°C	All building types
b.	Shading by trees and vegetation	i The ambient temperature near the outer wall may be substantially reduced by 2–2.5°C without excess use of supplementary energy [26]. ii Deciduous trees should be used on the south and southwest of buildings [47]. iii Evergreen trees should be used on the south and west side of the façade [47]. iv Shading and evapotranspiration from trees can reduce the surrounding temperature as much as 5°C [47]. v The air temperature can be reduced by 2°C in the surrounding area with presence of a nearby park [48]	[26, 47, 48]	–	Deciduous trees provide summer shading and daylight in winters by shedding the leaves	i Energy savings. ii Overall benefits for environment (reduced emissions). iii All building types
c.	Tree buffering as solar control in a south- east oriented building	i The solar irradiation peak in the non- shaded area and the shaded area at the same time was observed to be 600 W/m^2 and 100 W/m^2, respectively. ii Solar radiation exceeded on the shaded wall on the mid-day and reached 180 W/m^2 as the sun was at high horizon	[49]	Agricultural University of Athens	Parameters like air and wall surface temperatures, wind speeds, humidity, heat exchange between the wall surface and surrounding environment were measured in the shaded (by deciduous trees) and unshaded areas for a hot summer period	i Energy savings. ii Overall benefits for environment (reduced emissions). iii All building types
d.	Roof solar collector	Roof thermal comfort cannot be effectively achieved by only roof solar collector system and it should be installed along with Trombe wall	[50]	Hot and humid climate	The roof solar collector design used: CPAC Monier concrete tiles and gypsum board	Housing
e.	Ventilated roof	As the ventilated roof provides insulation along with the protection against the solar gains, it is more advantageous during the summer season. No clear improvement in winters	[51, 52]		The proposed setup consisted of air gap sandwiched between the reinforced concrete prefabricated slab and the insulation for both the seasons	–

Table 3. Continued

S. No.	Concepts	Results	Ref.	Climatic Conditions	Remarks	Applications
f.	Cool roof (37 roof designs)	i About 10–40% reduction in air conditioning energy. ii Flat roof: Heat gain and average indoor temperature were 414 kWh and 32.5°C, respectively. iii Domed roof: Heat gain and average indoor temperature were 310 kWh and 32.2°C, respectively. iv Vaulted roof: Drop of 1.5°C in the average indoor temperature. Fall of 53% and 826 kWh savings during summers in discomfort hours with rim angle of 70° with high albedo coating as compared to the reference case of the conventional noninsulated roof	[53]	Cairo, hot dry climate	The typical roof temperature can reach up to 37°C above the ambient for hot dry climate and can exceed by about 20°C when compared to the surroundings covered by vegetation	Low and medium rise residential buildings
3.4	Radiative Cooling (Fig. 7A and B; equations 8 and 9)					
a.	Correlation between the radiative cooling power and the temperature difference between the ambient and the sky	Radiative cooling has the potential to save up to 25% of the power consumption independent of all location	[54]	Tropical climate (Malaysia)	The cooling power decreases with decrease in the difference between the ambient and sky temperature	–
b.	Radiative cooling applications	The specific cooling power measurements ranges from 20 to 80 W/m^2	[55]		Movable insulations, air-based systems and open or closed water-based systems	–
c.	Water-based radiative cooling plate	Net cooling power of 81 W/m^2 was achieved by removing the cover for 7 h of operation	[56, 57]	Israel	Flat plate collector attached to a storage tank was used	Conventional space cooling
d.	Open water-based system	The plant showed a specific cooling power of 120 W/m^2 as achievable	[58]	Würzburg, Germany	Cooling outputs are higher for the closed system because of the absence of the thermal resistance between the water and the ambient	–
e.	Regional characteristics	With increase in elevation, there is a decrease in the cooling load but the potential of radiative cooling is large	[59]	China	The long wave terrestrial radiation shows no correlation with the elevation while the short wave incoming radiation shows a proportionate decrease at the normal lapse rate. Thus, leading to an increase in the value of radiative cooling	Residential buildings

Table 3. Continued

S. No.	Concepts	Results	Ref.	Climatic Conditions	Remarks	Applications
3.5	Infiltration/Ventilation (Equations 10 and 11)					
a.	Building design	i Window to ground ratio for residential buildings lies in the range of 0.33–0.58 (average 0.44). ii The mean window to wall ratio for like dining/living, bed room and are 0.34 and 0.27, respectively	[60]	Hong Kong	–	High- rise residential buildings
b.	Hybrid ventilation and night ventilation	i Natural ventilation should not be disturbed by the additional mechanical airflow in hybrid ventilation. ii Minimize HVAC system, solar loads and artificial lighting	[61]	Germany	Architectural solutions were used which solutions included thermal insulation, moderate window dimensions, central atrium, shading systems and cross ventilation	Office buildings

the absorbed solar energy to the interiors by conduction and convection. Trombe wall reduces the heat flux from the exposed outer surface wall to the interiors of the building. Thermal mass reduces the temperature fluctuation peaks (decrement factor) and shifts the peak to a later time than the air temperature peaks (time lag) due to a lower overall heat transfer coefficient.

Energy balance for Trombe wall are as follows:

Solair temperature,

$$T_{sa} = \frac{\propto I(t)}{h_0} + T_a - \frac{\in \Delta R}{h_1} \tag{12}$$

Heat flux (W/m^2),

$$\dot{q} = U_L(T_{sa} - T_r) \tag{13}$$

where,

$$U_L = \left(\frac{1}{h_0} + \frac{L}{K} + \frac{1}{h_i}\right)^{-1}$$

Energy balance for bare surface (Trombe wall) with insulation of thickness L_i, having thermal conductivity of K_i during the night time can be expressed as follows:

$$\dot{q} = U_L(T_{sa} - T_r) \tag{14}$$

where,

$$U_L = \left(\frac{1}{h_0} + \frac{L}{K} + \frac{L_i}{K_i} + \frac{1}{h_i}\right)^{-1}$$

Trombe wall may have two different types of exposed surfaces for passive buildings:

a). Bare exposed surface (unglazed Trombe wall) with absorptivity, $\alpha \le 0.4$. This surface is used for thermal cooling (Figs. 8 and 11; equation 16).

b). Blackened and exposed surface (glazed Trombe wall) with absorptivity ≥ 0.9. This surface is used for thermal heating (Fig. 9; equation 15).

Trombe wall – Passive heating

Blackened and glazed surface (Fig. 9) of the Trombe wall should be considered for passive heating.

Energy balance for blackened and glazed surface are as follows:

Heat flux (W/m^2),

$$\dot{q} = U_L(T_{sa} - T_r) \tag{15}$$

where,

$$T_{sa} = \frac{\propto \tau I(t)}{U_t} + T_a, \text{and} U_L = \left(\frac{1}{U_t} + \frac{L}{K} + \frac{1}{h_i}\right)^{-1}$$

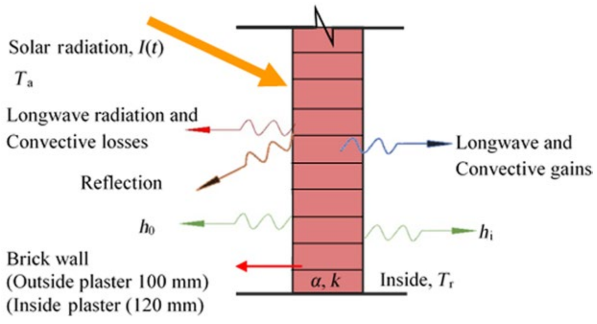


Figure 8. Energy flow diagram for Trombe wall (unglazed).

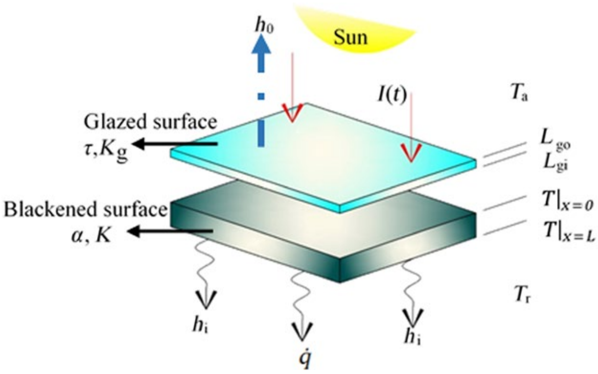


Figure 9. Blackened and glazed surface.

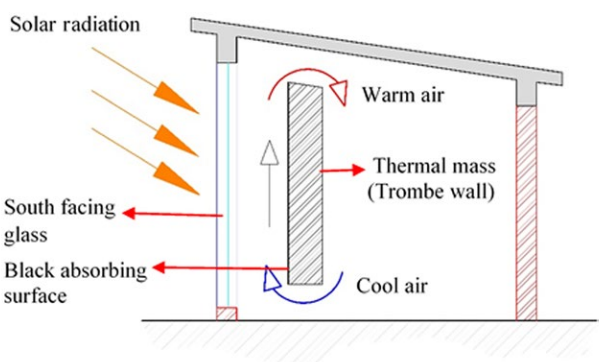


Figure 10. Trombe wall with vent openings.

Figure 10 shows simple passive heating technique using Trombe wall, with vent openings provided near the floor and the ceiling to allow convective heat transfer. These concepts have been applied in Pyrenees Orientales district of France and in the U.S. southwest.

For heating purposes, thermal resistance of glazing is proven to be more beneficial because glazing minimizes the heat loss through itself. A solar house based on this concept has also been constructed in Jordan (1983–1984) with two sections, namely the heated section and the non-heated space. Ta'ani et al. [62] reported that it is possible to meet 54% of the building's heating demands by solar energy with collector array efficiency with proper retrofitting. Tyagi and Buddhi [63] proposed a filling of phase change materials (PCM) to enhance the storage of latent heat in the masonry wall. These units are lighter in weight and require less space as compared to the massive thermal mass. Nwachukwu et al. [64] found that heat storage capacity along with the heat transfer through a Trombe wall can be improved by coating the exteriors of the thermal mass with superior absorption vigor. Balcomb and McFarland [65] found that Trombe walls with vented openings proved to be 10–20% more efficient, especially in extreme climatic conditions like Boston. Saadatian et al. [66] discussed different types of Trombe walls, viz. classical and modified, zigzag, composite, fluidized, solar water wall, solar trans wall, solar hybrid wall, Trombe wall with PCM and PV-Trombe wall. The efficiency of Trombe wall can be improved by 8% by using a fan. The optimal size (i.e., ratio of Trombe walls area to area of rooms with other walls) should be 37% with 300–400 mm thickness. The insulation increases the efficiency by 56% and also decreases the size of the thermal wall. The energy and environmental performance has been compared with and without Trombe wall in the study by Bojić et al. [67]. The research is based on two cases: the first case, without any Trombe wall and the second case, with installations of two Trombe walls at the south side of Mozart house located in Lyon, France. A 450 mm layer of clay brick 1220 has been used as the Trombe core material. The second case uses the solar energy captured to save around 14% of all electricity and 20% of annual energy as compared to the first case. The energy ratio is around 6 with the energy payback time of around 8 years for the electrical heating with optimum core thickness. The above values are around 3 and 18 years, respectively, for natural gas heating. The savings can further increase with increase in the thickness of Trombe wall layer. The optimum thickness of clay brick is around 0.35 m and 0.25 m for electrical heating and natural gas heating, respectively. The study also reveals that lower density material like clay brick save more operating energy as compared to higher density material like concrete.

Trombe wall – Passive cooling

A thick thermal mass used as the exterior facade reduces the decrement factor and leads to a time lag. A heavy structure is preferred for thermal cooling as the mass acts as an insulator and a heat storage medium. The unglazed Trombe wall may be constructed with different materials like stone, brick, reinforced cement concrete, mud, etc. This is a very old technique and is clearly

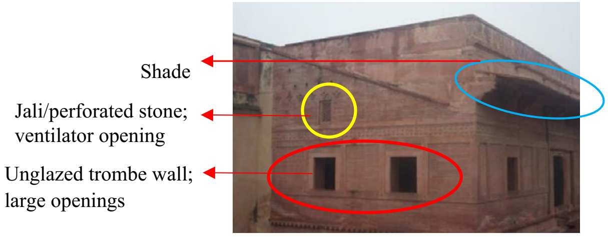


Figure 11. Trombe wall, openings, shades (passive cooling) Fatehpur Sikri, Agra, India.

visible in historical buildings like Humayuns Tomb, Qutub complex, Fatehpur Sikri (Fig. 11) etc. The ventilation system, as marked, has been arranged above the lintel level of the windows and the inside temperature is found to be comfortable all year round.

A bare surface (Fig. 8) should be considered for passive cooling purpose. Expression of solair temperature for bare surface Trombe wall can be written as:

$$T_{sa} = \frac{\alpha}{h} I(t) + T_a - \frac{\varepsilon \Delta R}{h} \tag{16}$$

An innovative approach of combining unglazed Trombe wall (Bare surface) with storage facility was evolved by Tiwari et al. [68] as shown in Figure 12A and B.

Trombe wall – Passive heating and cooling

Shen et al. [69] discussed the installation of adjustable dampers at the glazing and adjustable vents at the wall. This system is favorable for both heating and cooling purposes. During winters, the upper damper closes while the lower damper and both vents are open, although in summers, lower damper along with upper vent are closed. It was also discussed that the composite wall has better energetic performances than the classical wall in cold and/or cloudy climatic conditions. Krüger et al. [70] analyzed the heating and cooling potential of Trombe wall by installing two test cells of 5.4 m^3 internal volume and 2.6 m^2 floor area for a subtropical location. One of them was a naturally ventilated Trombe wall and the other one was without it (reference test cell). Higher performance was seen in the reference test cell under cold conditions. For heating purpose, three operation modes were tested – air vents 1 and 3 closed (case 1); air vent 3 closed (case 2); and air vents 1 and 3 closed with dampers installed in the storage wall openings (case 3). For weekly averages and clear sky conditions, the smallest average difference was recorded in case 3 and the highest in case 2, from the control test cell. Case 2 was considered the best configuration for the weekly period data, but case 1 proved to be better in clear day conditions with slightly higher temperature difference to the exterior (5.2°C against 4.5°C). Case 2 was considered to be a better option for winters. For summers, four operation modes were used – all air vents shut (operation mode 1); air vents 1 and 4 shut (operation mode 2); air vent 2 shut (operation mode 3); air vents 2 and 4 shut (operation mode 4). Mode 3 is considered to be the best option in summers.

Roof pond

In earlier studies, it has been seen that about 50% of the heat gains for single-story buildings is received via roof [71]. The conventional approaches to reduce the heat flux via roof includes false ceilings, insulations, increasing the roof thickness, roof shading, or using roof coatings. Roof pond is another technique found in 1920s and was first investigated at the University at Texas [72]. Sutton [73] observed that the roof surface temperature might reach 65.6°C without any treatment. By installing an open roof pond, the above temperature can be dropped down to 42.2 and 39.4°C with 0.05 and 0.15 m depths of the pond, respectively [74]. A drop of 20°C in the room temperature can be achieved by using the roof pond in arid regions [75]. Kharrufa and

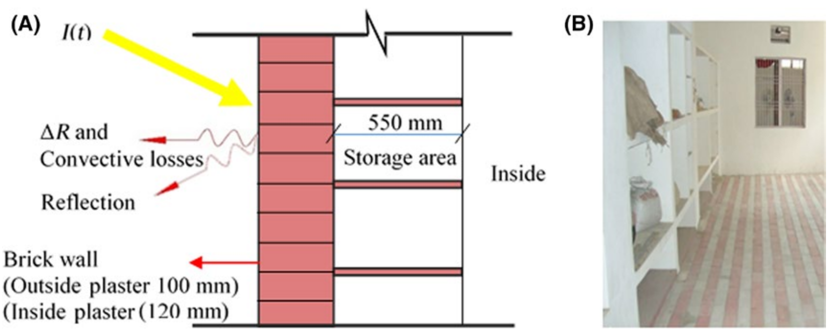


Figure 12. Unglazed Trombe wall (Bare surface) with storage (A) Section and (B) Sodha BERS Complex, Varanasi.

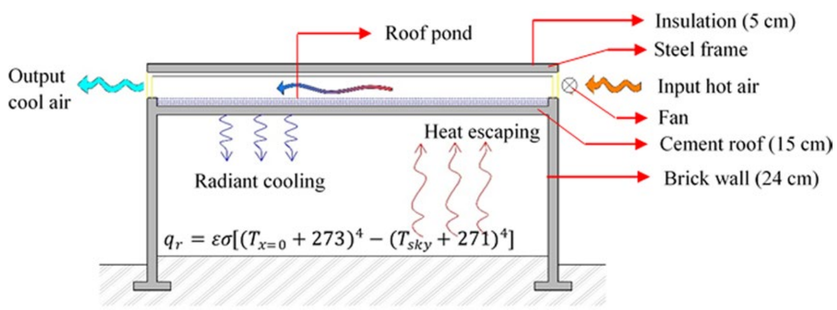


Figure 13. Schematic section of roof pond with forced electric ventilation.

Adil [76] tested one room (4 × 7 × 2.75 m) to check the effectiveness of the roof pond which was mechanically ventilated (Fig. 13) for cooling in hot dry summer of Baghdad.

Earth air heat exchanger

The air is allowed to pass through a tunnel or a buried pipe at least 1–3 m below the surface for both heating and cooling purposes. A depth of 2–3 m is generally considered since at that depth, it is cooler than the outside in summers and warmer in winters [35]. Figure 14 shows the scheme of Earth air heat exchanger (EAHE).

Thermal energy gained by the flowing air can be expressed as:

$$\dot{Q}_u = \dot{m}_a C_a (T_{fo} - T_{fi}) \tag{17}$$

$$\dot{Q}_u = \dot{m}_a C_a (T_0 - T_{fi}) \left[1 - e^{\frac{-2\pi r h_c}{\dot{m}_a C_a} L}\right] \tag{18}$$

where,

T_0 is the ground temperature outside pipe (°C).

For the given design parameters by Tiwari et al. [77], a drop of 5–6°C in the outlet air temperature in summers was noticed, using five air changes with 100 mm diameter and 210 mm length of the pipe.

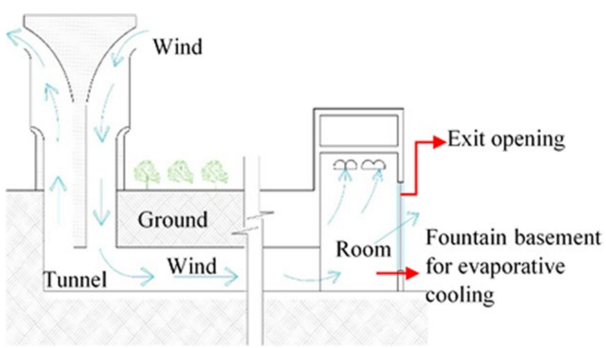


Figure 14. Scheme of Earth air heat exchanger.

Combination of various passive heating and cooling concepts

Various passive solar strategies have been discussed and it is evident that the energy use can be reduced to some extent with the above discussed strategies individually. To achieve a high level of energy performance, a combination of different passive solar techniques is necessary. The various heating/cooling concepts in brief have been summarized in Table 4 with remarks.

Based on Table 4, one can observe that unglazed Trombe wall can be used for both heating and cooling, whereas glazed Trombe wall can be used for heating purpose only. Combination of Trombe wall, cool roof, and thermal insulation proves to be very effective and can achieve 46% and 80% of savings in winters and summers, respectively.

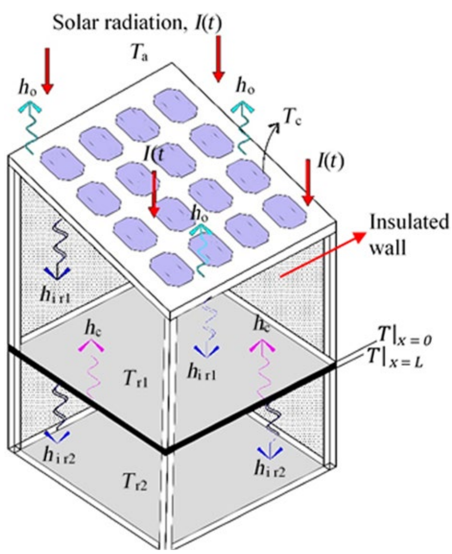


Figure 15. Building-integrated semitransparent photovoltaic thermal (BiSPVT) system.

Table 4. Passive heating and cooling concepts.

S. No.	Concepts	Results	Ref.	Climatic Conditions	Remarks	Applications
4.1	Trombe wall (Fig. 8; equations 12–14)					
4.1.1	Trombe wall – Passive heating (Fig. 9; equation 15)					
a.	PV- Trombe wall Case 1: with openings and heat storage. Case 2: With DC fan. Case3: Performance evaluation by varying air flow for 3 types of glazing. Case 4: Installation over the glazing. Case 5: Thermal insulation	Case 1 [78]: i Indoor temperature can be increased by 7.7°C. ii The Daily average electrical efficiency can reach up to 10.4%. Case 2 [2]: i Indoor temperature can be increased by 14.42°C. ii The daily average electrical efficiency can reach up to 10–11%. Case 3 [79]: i The effect of airflow on the performance stagnates when the air velocity reaches the value of 1 m/s. ii The maximum PV efficiency (of about 0.185) was achieved in the double glass with argon. iii Highest reduction in cooling load at air velocity of 1.75 m/s was achieved in double glass with argon (about 160 W/m^2). iv The study concluded that double glass filled with argon and double glass PV-Trombe wall is preferable over the single glass at air velocity of 1.5 m/s. Case 4 [80]: i The thermal performance of the Trombe wall can be reduced by up to 17%. Case 5 [81]: i The room temperature can be increased by 2.36°C with use of thermal insulation in cold climatic conditions and decreased by 2.47°C in hot climatic conditions. For the same electrical efficiency decreases by <2%. ii The room temperature can be decreased by 2°C with use of curtain shading in hot climatic conditions and electrical efficiency increases by 1%	[2, 78–81]	Case 1 and 2: China. Case 3: Universiti Teknologi Petronas. Case 4: South China. Case 5: Composite climate	Case 2: Reduces the PV temperature simultaneously. Case3: i PV- Trombe wall glazing types: single glass, double glass and double glass with Argon. ii Double glass shows 18% less reduction in cooling load as compared to double glass with argon. iii Ventilated double glass offers more insulation Case 5: It is recommended that thermal insulation in both winter and summer and appending a shading curtain in summer are adopted, especially for the diurnally used PV-Trombe wall.	PV Trombe wall can provide feasible solutions for high energy consumption and environmental degradation especially for tropic region
b.	Opening and closing modes in the management of air vents	i The best time to open the air vent is 2–3 h after sunrise and the best time to close it is 1 h before sunset. ii The heat storage capacity of the Trombe wall is fully released at 7:30 a.m. and it reaches its maximum value of 10.6 MJ/m^2 at 4:00 p.m. At 7:30 a.m., the heat release reaches its maximum value of 10.4 MJ/m^2	[82]	GangCha country, China	Conclusion i is appropriate for almost all type of Trombe wall heating system. Conclusion ii is case specific	–

Table 4. Continued

S. No.	Concepts	Results	Ref.	Climatic Conditions	Remarks	Applications
4.1.2	Trombe wall- Passive cooling (Figs. 8 and 11) (Equation 16)					
a.	Thermal behavior of Trombe wall in summers	i A decrease of 1.4°C in the internal surface temperature of the wall was observed and 0.5 MJ/m^2 in daily heat gains was observed with the use of rolling shutters as screening. ii The heat gains of the screened Trombe wall were about 18 times lower than those of the unscreened. iii A reduction of 72.9% and 65% in cooling energy needs was observed with the combination of overhangs, rolling shutters and cross ventilation, respectively, in comparison with unvented Trombe wall without solar shadings	[83]	Mediterranean climate	A comparative analysis of difference between the thermal behaviors of two Trombe walls was carried by varying the screening, ventilation, occupancy and internal heat gains	Low or highly insulated building
4.2	Roof pond					
4.2.1	Roof pond – Passive cooling					
a.	Experimental roof pond building	i The vapors were discharged from the pond in order to improve the building's summer performance whereas the same will reduce the efficiency of the system in winters. ii Cooling load (500 KJ/m^2) is at its maximum at noon because the most significant component of the cooling load is the direct heat gained through the south glazing. iii There is a significant sensible heat contribution at 11.00 am, which is responsible for the cooling. At noon, cooling is due to the latent heat of evaporation	[84]	Baghdad (July and August)	i 3 × 2.5 × 2 m room with pool depth of 60 mm. ii There is a need to design the vapor leakages from the pond to prevent them from winter heating and rains	Increased effectiveness of roof ponds in high- humidity regions
b.	Site experiments for: Case 1: roof with moist soil Case 2: Walkable roof pond along with night water circulation	Case 1: Reduction of 5°C in indoor temperature. Case 2: Reduction of 6°C was seen in the indoor temperature compared to the outdoor temperature	[85]	Hot dry climate of Saudi Arabia	Case 1: Roof was shaded by 10 cm of pebbles. Case 2: Roof pond was filled with pebbles with an insulation layer and thin tiles over the layer	Not suitable for low cost housing since dead load of water needs to be considered in the roofing structure
c.	Roof pond with gunny bags (RPWGB) floating on water surface	i This technique is better than the roof pond with wetted gunny bags (RFWWGB) in terms of cooling performance of room temperature and heat flux through the roof into the pond. ii This technique has better performance when compared to movable insulations. iii The optimum water depth for the RPWGB should be 200 mm and 50 mm for concrete and metal-decked roofs, respectively	[72]		The technique is better than RPWWGB because of thermal satisfaction inside the pond during daytime irrespective of the building type	Further field examinations are required before putting this system into practical use

Table 4. Continued

S. No.	Concepts	Results	Ref.	Climatic Conditions	Remarks	Applications
d.	Roof pond with forced electric ventilation (Fig. 14)	i The indoor temperature was better stabilized (with fan) as compared to the pond without fan and cover. The variations became limited to 3.5°C without a fan and 3°C with one. ii The average temperature reduction with the pool alone lowered the room temperature by 3.36°C compared to the roof without a pond. iii A substantial reduction of 6.0°C in the peak external temperature at 15:00 between the room without a pond and the room with a ventilated pond was achieved. iv There was also a substantial reduction of 6.5°C in the peak internal temperature at 6:00. v With a larger percentage of roof to wall, the roof pond cooling will be more effective and the drop in the cooling load will be around 29%		Hot dry climate (Baghdad, Iraq)	–	–
e.	Ventilated pond protected with a reflecting layer	i There was a reduction of 30% in the maximum indoor air temperature compared to the corresponding temperature of a building without any roof cooling technique. ii The proposed system has a 24 h cooling effect because the ceiling temperature is higher than that of the water. At night, the water better prevents the heat loses compared to a bare concrete roof	[86]	Crete, Greece	In the setup, a pond with 1.10–1.12 m depth was filled with water and covered with an aluminum layer at 1.15 m height from the free water surface	Small buildings
4.2.2	Roof pond – Passive heating and cooling.					
a.	Skytherm	Room temperature achieved was 27°C and 22°C when the outside temperature was 37°C and 5°C for summers and winters, respectively	[1]	Different weather types with various means of modulating ambient conditions	Use of metallic plate at bottom of the pond with blowers in summers and pond covered with transparent plastic in winters	–
4.3	Earth Air Heat Exchanger (EAHE) (Fig. 14; equations 17 and 18)					
4.3.1	Earth Air Heat Exchanger (EAHE) – Passive heating					
a.	EAHE coupled with a solar air heating duct	i The proposed design was connected at the exit end with a solar air-heating duct to increase the heating capacity by 1217.625–1280.753 kWh. ii There was a substantial rise in the inside temperature and the coefficient of performance (COP) of 1.1–3.5°C and 4.57, respectively. iii With 34 m of tunnel length, more than about 82–85% iv of total rise in air temperature can be achieved which means that by reducing the length of the tunnel to 34 m, the cost of the installation was optimized. v The COP increased up to 4.57 when assisted with solar air heating duct	[87]	Northwestern India, arid climate of Ajmer during winters	Thermal performance of EAHE with a 60 m long, 100 mm diameter horizontal polyvinyl chloride pipe buried 3.7 m deep configurations	–

Table 4. Continued

S. No.	Concepts	Results	Ref.	Climatic Conditions	Remarks	Applications
4.3.2	Earth Air Heat Exchanger (EAHE) – Passive cooling					
a.	Analytical model to calculate the cooling potential	i The results validated that EAHE can provide 30% of the cooling energy demand. ii There was a reduction o 1700 W in the peak cooling load and 2.8°C in the indoor temperature during summers	[88]	Dessert climate (hot and arid)	Thermal resistance of the material of the pipe was neglected	Domestic buildings
b.	Explore the effect of geometrical and dynamical parameters on thermal performance of EAHE	i With increase in the length of the pipe: • The air outlet temperature decreases. • The daily mean efficiency increases. • The coefficient of performance falls. ii When pipe length changes from 10 to 30 m: • For an inlet temperature of 29°C, there was a reduction of 2°C in the outlet temperature. The reduction rate was not found to be constant. • The COP falls by 10.5% and the daily mean efficiency rises by 142%. iii With increase in cross section and air velocity: • The air outlet temperature increases. • The daily mean efficiency decreases. • A rise of 1.2°C was noticed in the ambient temperature and a drop of 31.6% in the daily mean efficiency was observed when the air velocity changed from 1 to 3 m/s	[89]	Algerian Sahara conditions	i A pipe with 5 mm thickness was buried in soil with 22.27°C temperature. ii The ambient temperature was the same as the air inlet temperature i.e., 29°C	–
4.3.3	Earth Air Heat Exchanger (EAHE) – Passive heating and cooling.					
a.	EAHE assisted by a wind tower (Fig. 14)	i Unlike the pipe dimensions (length and diameter), the height and cross section of the tower had no influence on the performance. ii A tower with 5.1 m height and 0.57 m^2 of cross-sectional area generates 592.61 m^3/h of airflow. iii The air velocity increases and the maximal gradient of temperature decreases with the increase in the pipe diameter. iv With a pipe length of 70 m, the daily cooling potential reached a maximum of 30.7 kWh and that the daily cooling potential was proportional to the pipe diameter. v This scheme is more efficient than the conventional	[35]	Hot and arid regions of Algeria	Ambient temperature more than 45°C	–

Table 4. Continued

S. No.	Concepts	Results	Ref.	Climatic Conditions	Remarks	Applications
b.	Energy conservation potential of EAHE	i A 19 kW cooling potential was recorded to maintain an average room temperature 27.65°C for the proposed design with 80 m of pipe length, 0.53 m^3 of cross-sectional area and 4.9 m/s air flow velocity ii An auxiliary energy load of 1.5 kW for winter season is required in achieving comfort conditions affecting an average room temperature of 24.48°C	[90]	Mathura, India	–	i Non- air conditioned building. ii Can be coupled to greenhouse and building simulation codes
c.	Photovoltaic- thermal collector accompanied with an EAHE	i Capable of increasing the indoor temperature by 7–8°C at night during winters. ii The hourly thermal energy generated, during day and night is 33 MJ and 24.5 MJ, respectively. iii The yearly thermal energy generated has been calculated to be 24728.8 kWh, while the net annual electrical energy savings is 805.9 kWh and the annual thermal exergy energy is 1006.2 kWh	[91]	New Delhi, India	–	Green house
d.	Improvement of the EAHE thermal potential	The thermal performance of an EAHE can be improved by 73% and 11% for cooling and heating purpose, by increasing the number of ducts, while keeping the area occupied by the ducts and the mass flow rate of air fixed	[92]		In all proposed installations the thermal potential for cooling was higher than the thermal potential for heating	–
e.	Evaluation of EAHE	80 m long tunnel with 0.528 m^2 of cross-sectional area has 512 kWh and 269 kWh cooling and heating capacity, respectively	[93]	India	The heating capacity was found to be inadequate for providing the necessary comfort conditions	Hospital complex
4.4	Combination of various passive heating and cooling concepts.					
a.	Trombe wall, ventilated walls, glazed walls, fenestration, green roof, PV roofs, evaporative roof cooling along with thermal insulation and PCM	i Thermal mass is more effective when the outside ambient temperature difference between days and nights are high. ii Size of the mechanical devices can be reduced by incorporating a holistic energy efficient design which compensates for the additional capital investment for the energy efficiency features	[94]	–	Various building envelope components were studied to review the potential of passive energy savings	–
b.	Window size on each facade, shadings on south façade and thermal insulation on both roof and walls	About 25.31% of the energy consumption and 11.67% of the lifecycle costs can be reduced using these variables	[95]	Mediterranean region	Jaber and Ajib performed a study to minimize the energy consumption and lifecycle cost	Residential building

Table 4. Continued

S. No.	Concepts	Results	Ref.	Climatic Conditions	Remarks	Applications
c.	Building orientation, thickness of external wall, air infiltration, wall and roof insulation, lighting, windows to wall ratio, glazing type	About 50% of the annual energy use can be minimized when compared to the existing design practices. This can be achieved mostly by integrating the roof insulation, reducing the air infiltration and using energy efficient lighting and other electrical equipment	[96]	Tunisia	Ihm and Krarti performed a research in order to reduce the energy consumption and life cycle costs	Single family houses
d.	Wall and roof insulation, shading style, thermal mass, night ventilation, air change rate	Use of an optimal solution can reduce the building energy requirement by 94% when compared to the actual design practices adopted in Sydney	[97]	Sydney	Design optimization for lifecycle heating and cooling costs	Low energy home (detached, single story house)
e.	Thermal insulation, Trombe wall and cool roof	i 46% and 80% of savings can be achieved in winters and summers, respectively, in comparison to an ordinary building. A reduction of 5.41 kW was also achieved in the peak cooling load. ii About 20.7% was contributed alone by the storage capacity of the Trombe wall. iii 60.3% and 47.7% savings in heating and cooling, respectively, can be achieved by integrating the movable overhangs, internal curtains and low emissive argon coating loads	[98]	Tunisia	Analyzed the impact of architectural characteristics and passive techniques on its energy requirements	–
f.	Passive cooling techniques: Ground cooling, solar control, night ventilation, evaporative cooling, night sky infrared radiation, infiltration control and thermal insulation	i The results confirmed the effectiveness of the earth pipes. ii With the application of a conductive thermal control in the west wall and the roof slab, a reduction of temperature fluctuation from 24.07 of the outside conditions to an average DBT of about 21°C was noticed. iii The DBT inside the setup for evaporative cooling remained in a comfortable zone i.e., 22.86°C. iv The shading devices blocked any direct sun gain and avoided overheating the interior improving the indoor comfort conditions and thus reducing the energy consumption	[99]	Hot and dry regions (Mexico)	To achieve hygrothermal conditions for occupants and reduce the energy consump-tion of air- conditioning	New and existing buildings

Table 4. Continued

S. No.	Concepts	Results	Ref.	Climatic Conditions	Remarks	Applications
g.	Louver shading devices, double-glazed, natural ventilation: wind catcher, cross ventilation, green roofing, evaporative cooling via fountain, insulation, indirect radiant cooling, light color coatings with reflection	i The solar heat gain coefficient was about 17% and a reduction of 55% in energy was noticed with the use of solar control film. ii A reduction of 23.6% in annual energy consumption can be achieved with use of solar passive cooling strategies. iii A 220 m^2 green roof with sprinklers was used and it was estimated that the green roof reduces the energy demand by 6% and drops the roof temperature by 30°C	[100]	Hot and arid regions (Dubai)	To study the effectiveness of various passive cooling techniques to enhance the thermal performance and to decrease the energy consumption	Residential buildings
h.	Night ventilation, roof insulation, shading devices, courtyard planning, micro climate modifications	i The indoor temperatures of the Chinese houses were higher by 1°C than the outdoor temperatures during the day under open window conditions and by 2°C at night under closed window conditions. ii The outdoor temperature of Malay house was recorded to be 1.7°C higher than the terraced house. iii The indoor temperature was 5°C lower than the outdoor temperature in case of courtyard planning at the peak period whereas the values for both indoor and outdoor temperatures were same during the night. iv The periods of indoor operative temperatures exceeding the 80% comfortable upper limit in Malay houses, Chinese shop houses, daytime ventilated and night ventilated terraced houses were 47%, 7–8%, 91% and 42%, respectively	[101]	Hot and humid (Malaysia)	Field studies were conducted in two traditional timber Malay houses and two traditional masonry Chinese shop houses	Modern terraced houses
i.	Orientation, cross ventilation, day lighting, unglazed Trombe wall, earth sheltering, wind towers, solar water heater system, roof top PV system and PV thermal greenhouse dryer	i During the extreme weather conditions in both summers and winters, all the floors were in comfortable range of temperature. ii The temperature recorded for the basement (earth sheltering) was 28°C, for ground and first floor it was recorded at approximately 18–20°C. iii The basement temperature was found to be 7–8.65°C lower than the ambient temperature during harsh summers. iv A rise of 2–3°C in the indoor temperature was found during harsh winters on the first floor due to the presence of a clerestory window. v The total energy saving due to the thermal heat gain and day lighting to be 34,445.568 kWh, out of which 5852.93 kWh accounts for day lighting only	[68]	Composite climate (India)	–	All building types

Table 5. Building integrated Photovoltaic Thermal (BiPVT) system.

S. No.	Concepts	Results	Ref.	Climatic conditions	Remarks	Applications
5.1	Building integrated Opaque Photovoltaic Thermal System (BiOPVT) System					
a.	Integrated with façade with air duct	Minimum 2.3°C rise in room temperature	[107]	Srinagar, India with (although valid for different climatic conditions)	i Rise in room temperature is comparatively lesser than SPVT because of low conductivity of tedlar. ii Ambient temperature 4.4°C	i Electricity generation. ii Thermal heating
b.	Installed on the roof top	45% energy produced	[111]	Brazil	Installation on the roof top yields more energy than on any vertical façade	i Multi- family dwellings. ii Thermal and electricity generation
c.	Installed on roof	3.19 kW annual electrical energy can be saved	[112]	Las Vegas	South orientation	Residential buildings
5.2	Building-integrated Semitransparent Photovoltaic Thermal (BiSPVT) System (Fig. 15; equations 19–23)					
a.	Installed on the roof top without air duct	i Maximum 18°C rise in room temperature [107]. ii Air mass flow rate (0.85–10 kg/s) through duct increases the room air temperature from 9.4 to 15.2°C [107]. iii 1203 MWh of electricity can be saved annually [113]	[107, 113]	Srinagar, India (although valid for different climatic conditions)	i Non- packing area (i.e., glass area) increases the heat gain. ii Double glazing reduces the heat loss. iii Better performance when compared to BiOPVT system	i Day lighting. ii Thermal energy. iii Electricity production. iv Office buildings
b.	Integrated to a roof	i 47°C achieved at first floor. ii The optimum roof thickness for the above study was found to be 300–400 mm to minimize the decrement factor	[102]	Varanasi, India	The effect of number of air changes per hour through the room on the inside temperature, decrement factor and TLL of the building for thermal comfort were considered	Crop drying

Building-Integrated Photovoltaic Thermal (BiPVT) System

Solar energy is converted to electrical energy by photovoltaic (PV) modules with efficiency of 10–15%. The rest of the energy is radiated back to the atmosphere or absorbed as heat. Photovoltaic thermal system (PVT) refers to the extraction of this absorbed energy and bringing it into use. Integration of PVT with a building (façade, roof, windows etc.) is referred to as building integrated photovoltaic thermal system (BiPVT). The efficiency of BiPVT system is much larger, since it produces electricity and also provides the building with thermal energy. In case, the PV modules are opaque type, the system is termed as building-integrated opaque photovoltaic thermal system and if the PV modules used are semitransparent, the system is referred as BiSPVT (Fig. 15).

Following [102] (Fig. 15), energy balance for solar cell is,

$$\alpha_c\tau_g I(t)\,\beta A_m = \left[U_{tca}\left(T_c - T_a\right) + U_{bcr1}\left(T_c - T_{r1}\right)\right]A_m + \tau_g I(t)\beta A_m \eta_c \tag{19}$$

Energy balance for roof of room 2 at $x = 0$ is

$$\alpha_R \tau_g^2 (1-\beta)\, I(t) A_m = h_c A_R \left(T|_{x=0} - T_{r1}\right) - kA_r \left.\frac{dT}{dx}\right|_{x=0} \tag{20}$$

Energy balance for room 1 air temperature:

$$M_{a,1}C_{a,1}\frac{dTr_1}{dt} = h_c\left(T|_{x=0} - T_{r1}\right)A_R + U_{br1}\left(T_c - T_{r1}\right)A_m - 0.33N_1V_1(T_{r1} - T_a) \tag{21}$$

Energy balance for roof to room 2 at $x = L$ is

$$-K\left.\frac{dT}{dx}\right|_{x=L} = h_{ir2}(T|_{x=L} - T_{r2}) \tag{22}$$

Energy balance for room 2 air temperature is

$$M_{a,2}C_{a,2}\frac{dTr_2}{dt} = h_{ir2}\left(T|_{x=L} - T_{r2}\right)A_{r2} - 0.33N_2V_2(T_{r2} - T_a) \tag{23}$$

Joshi et al. [103] have found that exergy efficiency of PVT system (11.6–16%) is higher than that of the PV system (8–14%) by using Petela's formula [104]. Joshi and Tiwari [105] have found that the monthly energy and exergy of a 1.2 m PVT module lies between 35–60 kWh and 7–16 kWh, respectively, for different months and cities of India. Chen et al. [106] have found that BiPVT system with 64 m^2 surface area can produce 8.5–10 kWh of thermal output.

Vats and Tiwari [107] have derived analytical expressions for room air temperature of BiSPVT and BiOPVT system integrated to the roof of a room and facade with and without air duct. It was found that the room air temperature for façade and roof in SPVT and OPVT systems with air duct is lower than without an air duct. The reason behind the finding was that there was indirect heating due to the presence of insulated façade/roof between the PV module and the room air. The difference between the room air temperature in SPVT and OPVT façade with and without air duct was found to be 1.46°C and 9.80°C, respectively. The same for SPVT and OPVT roof with and without air duct was found to be 1.13°C and 9.55°C, respectively. Further, the results have been tabulated in Table 4. Vats and Tiwari [108] evaluated the energy and exergy performance of BiSPVT system with roof and found that HIT PV module (heterojunction comprised of a thin amorphous silicon PV cell on top of a crystalline silicon cell) has maximum overall thermal energy of 2497 kWh, maximum annual electricity of 810 kWh, and maximum exergy of 834 kWh. The authors also found that the efficiency of HIT and a-Si is 16% and 6%, respectively, varying inversely with the solar cell temperature, while maximum annual thermal energy of 464 kWh was observed in case of thin amorphous silicon cell (a-Si). An a-Si has maximum thermal energy of 79 kWh with packing factor of 0.62 [109].

Vats et al. [110] evaluated the energy and exergy performance of BiSPVT system to roof with and without ducting for cold climatic conditions. It was observed that HIT accounts for maximum overall thermal energy and a-Si for minimum in both cases with and without an air duct. Annual overall exergy in HIT with duct was 643 kWh and without duct was 610 kWh. The study concluded that with duct, approximately 15% overall thermal energy is greater than without duct. Vats et al. [109] studied the influence of packing factor of SPV module integrated to the roof on the room temperature, module, and electrical efficiency of the module. The study concluded that the temperature of the module decreases with decrease in the packing factor. With decrease in the packing factor, there is an increase in its electrical efficiency and rise in the room air temperature by 3°C due to increase in the nonpacking factor. The authors found that HIT PV module has maximum annual electrical energy of 813 kWh and a-Si has maximum thermal energy of 79 kWh with packing factor of 0.62. Efficiency increases by 0.2–0.6% with a corresponding decrease in the module temperature by 10°C if packing factor is reduced from 0.83 to 0.62. The results of few studies have been summarized in Table 5.

Based on Table 5, one can observe that BiPVT system can be used for thermal heating and electricity generation. In addition, semitransparent PV module is also an effective heating technique to sustain design, which not only produces electricity and provides thermal energy but also allows day lighting, reducing the energy demands.

Conclusions and Recommendations

- For passive heating, direct gain is more convenient for sunshine hours heating (office) and rest of the concepts are used for residential buildings. Solarium will be useful for both the applications. Use of double-glazed system leads to reduction of 9% of heat gain and reduction of losses by 28% compared to single-glazed system. Exposed walls should be double glazed to trap maximum solar radiation inside the room with minimum *U*-value.
- For passive cooling, the combination of evaporative cooling and wind tower proves to be very effective and can reduce the temperature by up to 12–17°C. Evaporative cooling is the most economical concept for cooling of a building.
- For passive heating/cooling, combination of Trombe wall, cool roof, and thermal insulation can achieve 46% and 80% of savings in winters and summers, respectively.
- BiSPVT system gives better result in terms of efficiency, thermal environment, space heating, day lighting, and electricity use. Photovoltaic systems are among the most promising alternative energy source. Building-integrated photovoltaic systems can provide savings in electricity costs, reduce pollution, and also add to the architectural appeal of the building.

Nomenclature

A	Area	m^2
C_a	Specific heat of air	J/kg K
c	Air conductance	W/m K
h_0	Outside heat transfer coefficient	W/m^2 K
h_1	Total heat transfer coefficient	W/m^2 K
h_c	Convective heat transfer coefficient	W/m^2 K
h_{cw}	Convective heat transfer coefficient (wetted surface)	W/m^2 K
h_{ew}	Evaporative heat transfer coefficient (wetted surface)	W/m^2°C
h_i	Inside heat transfer coefficient	W/m^2 K
h_m	Top losses of solarium	W/m^2 K
h_r	Radiative heat transfer coefficient	W/m^2 K
h_{rw}	Radiative heat transfer coefficient (wetted surface)	W/m^2 K
h_{TS}	Convective and radiative heat transfer coefficient from wall's outer surface to sunspace	W/m^2 K
$I(t)$	Solar intensity	W/m^2
k	Thermal conductivity	W/m K
L	Thickness	m
M_a	Mass of air	kg
$\dot{m}_a$	Mass flow rate of air in pipe (EAHE)	kg/s
N	Number of air changes	–
T	Temperature	°C
T_{fo}	Air temperature at the outlet of EAHE	°C

Continued.

T_{fi}	Air temperature at the inlet of EAHE	°C
T_p	Temperature of metallic surface of water containers	°C
T_r	Room air temperature	°C
T_{sa}	Solair temperature	°C
T_{ss}	Temperature of sunspace (solarium)	°C
T_w	Water temperature	°C
U_{bcr1}	Overall heat transfer coefficient from solar cell to room 1 through glass cover	W/m^2 K
U_L	Overall heat transfer coefficient	W/m^2°C
U_t	Total heat transfer coefficient	W/m^2 K
U_{tca}	Overall heat transfer coefficient from solar cell to ambient through glass cover	W/m^2 K
V	Volume of room	m^3
$\dot{Q}$	Rate of heat transfer	W
$\dot{q}$	Rate of useful energy gain	W/m^2
$\dot{q}_r$	Radiant heat exchange between sky and a surface	W/m^2
Q_v	Ventilation losses	W
Greek symbols		
α	Absorptivity	–
β	Packing factor	–
ΔR	Rate of long wavelength radiation exchange between ambient air and sky	W/m^2
ε	Emittance	–
σ	Stefan-Boltzmann constant	$W/m^2/K^4$
τ	Transmissivity	–
Subscript		
1	Room 1	
2	Room 2	
a	Ambient air	
c	Solar cell	
g	Glass	
m	PV module	
R	Roof	
r	Room	
win	Window	

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Conflict of Interest

None declared.

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