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Ventilated Trombe wall as a passive solar heating and cooling retrofitting approach; a low-tech design for off-grid settlements in semi-arid climates

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Abstract

In the coming years, it is anticipated that if we continue with the same pace of energy consumption, communities will continue to face three major challenges; a mounting increase in energy demands, pollution, and global warming. On a local scale, Egypt is experiencing one of its most serious energy crises in decades. The energy consumed in indoor cooling and heating is the biggest portion of total energy consumption in residential buildings. This paper is an experimental simulation study for building retrofitting in off-grid settlements in semi-arid climates, using Trombe wall as a low-tech passive heating and cooling solution. In this study, we made developments to the conventional classic Trombe wall using occupant-centered design and living lab experimental methods. The thermal efficiency of the proposed Trombe wall design is simulated during winter and summer peaks. In the proposed design we used gray paint instead of typical black paint in addition to 15 cm reversible natural wool insulation and two 3 mm thick roll-up wool curtains. The new design reduced the heating load by 94% and reduced the cooling load by 73% compared to the base case with an annual energy savings of 53,631 kW h and a reduction in CO_2 emissions of 144,267 kg of CO_2. The living lab test proved that the proposed design of the Trombe wall is economically viable and the payback time is 7 months. It is recommended that the proposed design be monitored for a whole year to have an accurate assessment of its efficiency. A post occupancy evaluation is also needed to measure local residents' acceptance and perceived comfort after retrofitting.

Keywords: Trombe wall; Passive solar heating and cooling; Semi-arid climate; Energy consumption; Low-tech retrofitting; Occupant centered approach

1. Introduction

The world is experiencing one of its most serious energy crises in decades (IEA, 2014). By 2050, global temperatures are anticipated to continue to rise and greenhouse gas emissions are expected to be more than double if we carry on with our energy inefficient building methods (Hootman, 2013). Many countries have become more import reliant and gradually more effected by the problems associated with fuel poverty (Timilsina and Zilberman, 2014). Today's buildings consume more than 40% percent of the world's primary energy, which are responsible for 30% of greenhouse gas emissions (Heinberg and Lerch (red.), 2010). This is more energy than any other sector of the world's economy, including transportation and industry (IEA, 2013). Domestic heating and cooling alone consumes one

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fifth of total fossil fuel energy production worldwide (Lechner, 2009), meaning our homes add to many environmental problems like greenhouse gas emissions, which contributes to man-made global warming (Santamouris (red.), 2003). Accordingly, we pay a high environmental cost for our future.

Currently, Egypt unwisely produces about 94% of its electricity from fossil fuel sources (RCREEE, 2013a). Nevertheless, the government has recently begun making plans for investing in nuclear energy. The demand for thermal indoor comfort is increasing, which is consequently responsible for a higher demand for heating and cooling, which already accounts for 50% of energy consumption in Egypt (NREA, 2013; RCREEE, 2013b). This is due to the current inefficient housing stock. We indulge in our profligate lifestyles and are becoming less sustainable due to the government policy of providing subsidized electricity. Because of the recent mounting local energy crisis and electricity power cuts, energy conservation has slowly started to become a main concern. Energy efficiency has now gained a prominent role at the political level with the formulation of a quantitative target to save 20% of today's consumption by 2020 (NREA, 2013). However, the government's existing measures are mainly focused on new buildings, often ignoring the existing buildings that represent the largest share of the building stock, appeal to the majority of the consumers, and remain the least efficient. This conundrum tasks independent researchers to work on alternative retrofitting solutions that incorporate solar passive heating and cooling strategies in a country, which, according to RCREEE, has high potential in solar energy (RCREEE, 2013b).

In this study, the ventilated Trombe wall was simulated and experimented as a retrofitting low-tech, passive heating and cooling solution. Our proposed Trombe wall is considered a design development for the existing classic Trombe wall type found in discourse. The main objective of this study is to increase the building efficiency in achieving indoor thermal comfort while reducing the current energy load for heating and cooling. This will consequently reduce CO_2 emission during building operations. The simulation showed a higher percentage of efficiency in achieving indoor thermal comfort compared to recent studies, and the living lap experiment proved the ventilated Trombe wall be cost effective for Egyptian standards. In addition, there was an added contribution in applying an occupant-centered retrofitting approach in a living lab environment for remote off-grid settlements.

1.1. Trombe wall usage in passive solar heating and cooling

Unlike conventional heating and cooling strategies, passive solar and natural air conditioning methods achieve comfort through a knowledge of local climate and vernacular design (Anderson and Wells, 1981), showing us how to utilize natural elements to provide the amenities we need without negatively impacting the earth (Chiras, 2002). Earlier, Kreider and Kreith discussed how solar passive strategies can be economical for building thermal control (Kreider and Kreith, 1982), while Koch-Nielsen added later, that it is even more economical in hot climatic zones where both air conditioning for cooling and heating is required (Koch-Nielsen, 2002). Thorpe affirmed that, if suitable passive solar solutions are incorporated in existing buildings, building energy demands can drastically be reduced (Thorpe, 2011).

A Trombe wall is a system that makes use of indirect solar gain (Kachadorian, 2006). It is a thermal mass wall normally made from stone, brick, or adobe, painted in black, and placed behind south facing glazing (Saadatian et al., 2012). The immense thermal mass serves as heat storage from solar energy which is transferred to the interior of the building for winter heating or to evoke air movement for summer cooling (Gan, 1998). It stores daytime solar gain and releases it back at night when residents most benefit from the heat (Kachadorian, 2006). There are various Trombe wall systems from classic to composite ones, and their efficiency is discussed and compared in several works of research (Agrawal, 1989; Nahar et al., 2003). The Trombe wall is mainly used in cold and mild climates (Haggard et al. (red), 2009); however, for a long time there have been numerous studies on the Trombe wall for passive solar heating for arid climates (Tasdemiroglu et al., 1983; Boukhris et al., 2009), as well as several robust studies on reducing the drawback of the Trombe wall in summer for hot climates (Ghrab-Morcos et al., 1993; Soussi et al., 2013).

1.2. Previous studies

A considerable number of scholars have investigated glazed ventilated and non-ventilated Trombe walls by studying its steady state performance (Hami et al., 2012), modeling techniques (Bojić et al., 2014), thermal efficiency (Burek and Habeb, 2007), and in-situ performance (Rabani et al., 2015). Some strategies have been adopted to enhance the efficiency of Trombe walls in summertime, improving natural ventilation (Stazi et al., 2012a), the provision of shade (Chen et al., 2006) and proper insulation (Stazi et al., 2012b). Several researchers discussed that the main consideration in guaranteeing a successful retrofit using passive solar Trombe wall systems is to properly design the suitable size, position, and orientation of its components (Athienitis and Santamouris, 2002). It has been discussed thoroughly and proved that wall thermal storage, thermal insulation, black paint thermal properties, size of air vents, and glazing type are the main components that have significant effects on the efficiency of ventilated Trombe walls (Saadatian et al., 2012).

The Trombe wall has many advantages. A study on life cycle costs shows major advantages in applying Trombe walls as a cost efficient solution for indoor thermal comfort in winter time, while reducing annual CO_2 emissions by approximately 455 kg CO_2 (Jaber and Ajib, 2011).

Moreover, Hordeski shows that the Trombe wall can reduce a building's energy consumption for residential heating by up to 30% (Hordeski, 2004). Chel et al. proved that it had a short payback time, which depends on the local economy, but can reach up to nine months (Chel et al., 2008), which Jaber and Ajib also assured in respect to life cycle costs (Jaber and Ajib, 2011). Besides all of the benefits of the Trombe wall, there are several drawbacks in using this system, especially when it comes to overheating in the summertime. Saadatian et al., mentioned four main shortcomings related to thermal resistance, inverse thermosiphon phenomena, heat transfer, and aesthetics (Saadatian et al., 2012).

We have found few studies dealing with year-round performance. In many cases we have not found enough discussion on how to make the compromise when cooling and heating are equally needed in hot and semi-arid climates. This is especially pertinent during extreme fluctuations between day and night temperatures, when cooling is needed in the morning and heating is needed at night. Also, very few cases were found for passive heating using solar walls in Egypt (Hassanain et al., 2011) outside of agriculture purposes in green houses. No robust studies were found for the applicability of solar walls for residential buildings in the Egyptian climate except for a numerical study for using a solar chimney in passive cooling (Abdallah et al., 2013) and some recommendations by individual practitioners for solar passive heating (Ibrahim, 2011). In addition, no reliable research was found on the economic feasibility of using passive solar techniques in heating and cooling or specifically using the Trombe wall in Egypt. This gap in research spurred our investigation of the efficiency of using the Trombe wall for passive heating and cooling in off-grid remote settlements in the Egyptian semi-arid climate.

2. The case study and the semi-arid climatic context

The selected case study is a residential building located in Saint Katherine in Sinai. It is located at a latitude of 28.7000° North and a longitude of 34.1000° East at an elevation of 1586 m. In terms of climatic characteristics, Saint Katherine is located in a semi-arid climate zone with extreme differences in temperature between the day and night in both summer and winter. It is characterized by hot dry summers with a maximum average temperature of 29.7 °C and a minimum average of 22.4 °C and mild to cold winters with a maximum average temperature of 18.6 °C and a minimum average of 5.2 °C. Summer midday temperatures can reach up to 34 °C, while in winter, night temperatures can fall to around 0 °C commonly accompanied by frost. The average solar radiation intensity is 5.4 W/m^2 and the average wind speed is 0.7 mph. The prevailing winds come from the Northwest. Saint Katherine is characterized by relatively low annual rain fall ranges from 7075 mm to 10,018 mm. Typically, snow falls from late December until mid-February (METEOTEST, 2014; EMA, 2014). A psychometric chart was used to show comfort ranges in Saint Katherine throughout the year, Fig. 1 following ASHRAE standards 55 for hot climates.

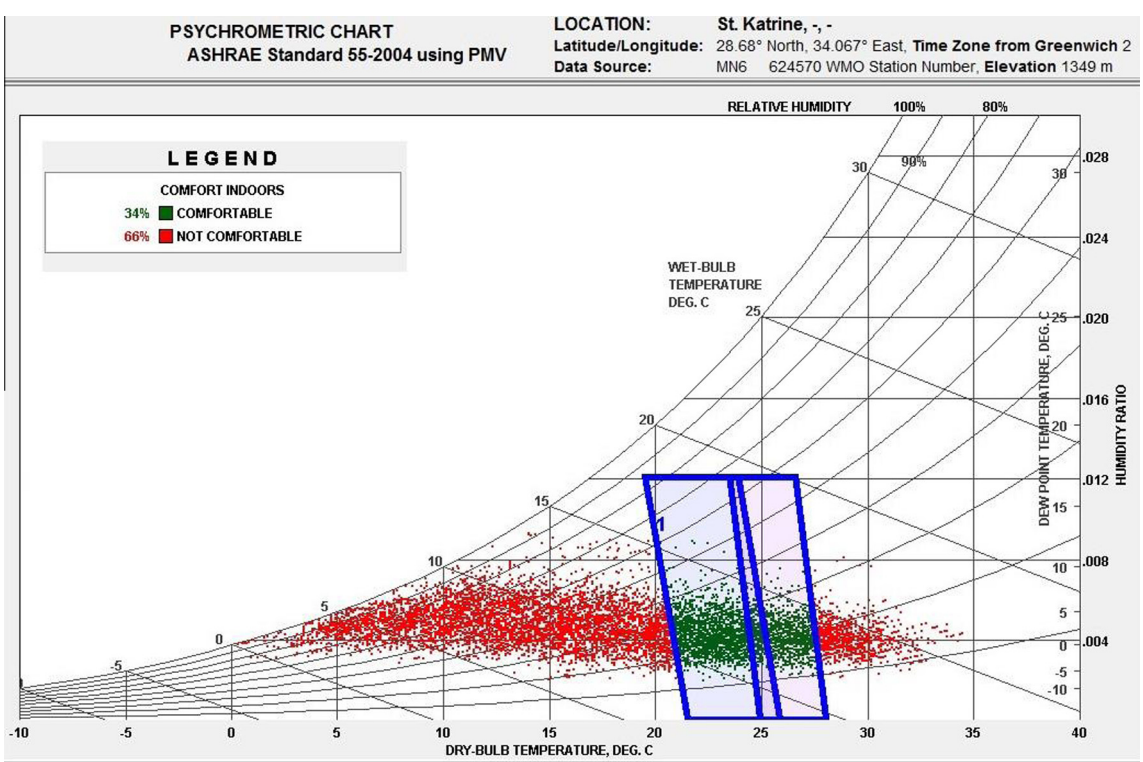


Fig. 1. Psychrometric chart of Saint Katherine's yearly temperature showing comfort range according to ASHRAE standard 55-2004, generated by climate consultant.

Generally, the temperature falls below the body's level of thermal comfort 66% of the year. In winter, 99% of the season is outside of the comfort range and requires heating strategies. In summer, 35% of the season is outside of the comfort rage and requires cooling strategies.

2.1. The test room description

The case study is a courtyard building with a total area of 378 m^2, currently used for residential purposes (plan is shown in Fig. 2). The choice of this rammed earth residential building for the study was based on available data and documentation for a building in a remote and off-grid settlement in a semi-arid climate in Egypt. There are six total occupants in the building. The room chosen for retrofitting is 4.9 × 5.4 m with a height of 3.3 m, two windows in the south wall and three ventilation openings in the north facade. The walls are 40 cm thick and constructed from rammed earth with a stone foundation. The ceiling is made from local wood and the floors are made from local stone. The main room façades face north and south and side façade faces west. The Trombe wall is proposed on the south façade to maximize capture of sun rays. The Trombe wall covers an area of 10.2 m^2. The proposed design of the Trombe wall is shown in Fig. 3 and its material properties in Table 1.

3. Methodology

This study applied an experimental simulation method for retrofitting using parametric simulation modeling by means of DesignBuilder software. As aforementioned, the southwest room was selected for retrofitting. The thermal performance of the room was simulated first as a base case, then when using a classic Trombe wall and when using our proposed ventilated Trombe wall. The classic Trombe wall was used as a point of reference for assessing the design development. The winter and summer performance for the test room were simulated using both the classic Trombe wall and the proposed design.

First, we ran the simulation using a typical design for a classic Trombe wall. Then we developed our design

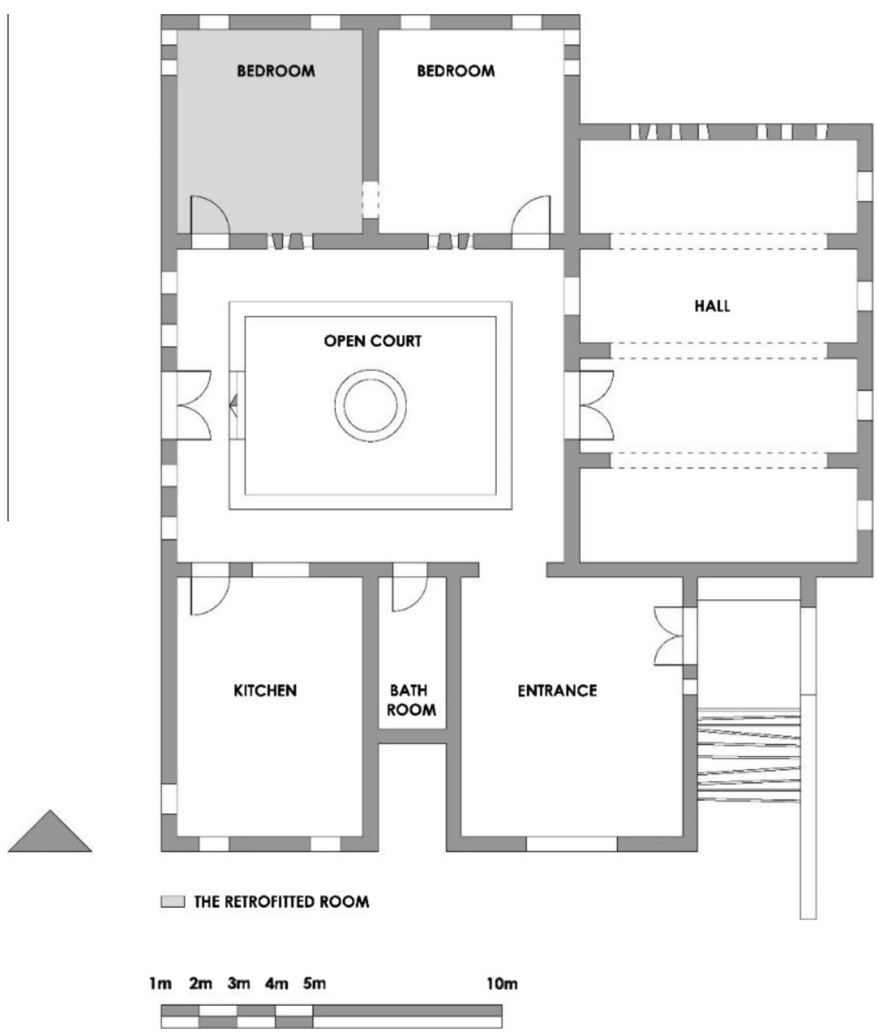


Fig. 2. Ground floor plan for the case study showing the test room location and orientation.

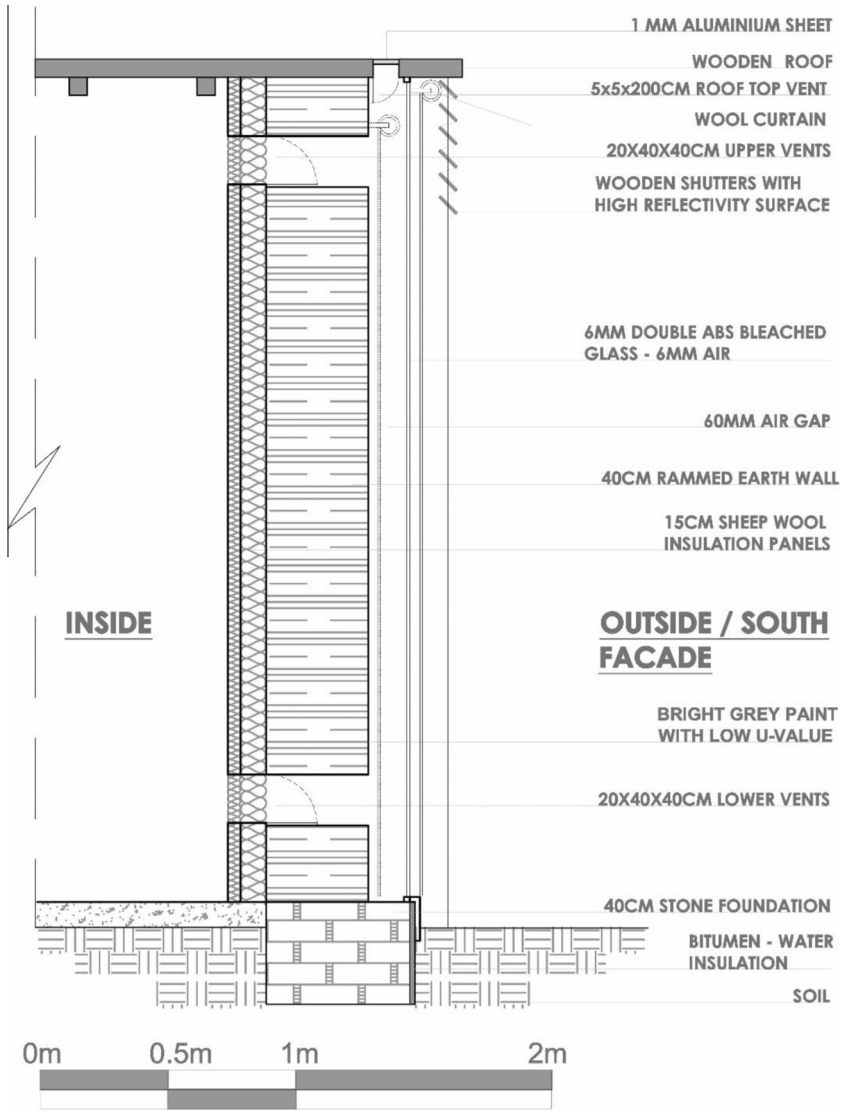


Fig. 3. Cross section in the proposed Trombe wall.

proposal according to the results from the simulation. To reduce the parametric study time, we designed the proposed Trombe wall based on previous research outcomes for optimizing the air vents, the air gap, the properties of the paint and the glazing. The simulation mainly revealed the indoor room temperature and the heat flows when using the classic and the proposed Trombe wall. Then the indoor thermal comfort ranges both in summer and winter for the three cases (base case, using a classic Trombe wall and using the proposed Trombe wall), were analyzed and compared in reference to the average outdoor temperature. Reduction in heating and cooling loads, energy consumption and CO_2 emissions were then calculated for before and after the use of the Trombe wall. Finally, a cost analysis was prepared to calculate the payback time and assess the cost efficiency of our proposed passive Trombe wall system.

3.1. Occupant centered design approach and living lab experiment

We started with an onsite test cell experiment for the classic Trombe wall concept. Local representatives from Saint Katherine were involved in the building process. They were also involved in the monitoring process of the test cell for one week in February. We measured indoor temperature and humidity and compared it to outdoor temperature and humidity. The outcome of one week of monitoring was discussed with local residents. Unstructured interviews in semi-structured local meetings asking mainly about residents' acceptance of retrofitting their homes with the Trombe wall were conducted. In our design development phase we worked on the drawbacks deduced from the simulation and the test cell experiment of the classic Trombe wall and what was found in literature

Table 1
Material properties of the classic and the proposed Trombe wall.

Classic Trombe wall	Single T.W. glass	T.W. air gap $R = 0.21$ m^2 K/w	Black paint with high reflectivity factor	Wool insulation panel	Outdoor wooden shutter – medium reflectivity	Wool curtain
Density (kg/M^3)	–	–	600	–	–	–
Specific heat capacity (J kg/K)	–	–	100	–	–	–
Conductivity (W/M K)	1.875	28.5	0.16	–	0.9	–
Reflectivity	–	–	–	–	0.5	–
Total solar transmission	0.858	–	–	–	0.5	–
Light transmission	0.898	–	–	–	–	–
Thickness (cm)	0.3	6	1	–	1	–
U-value (W/m^2 k)	6.257	4.75	0.16	–	0.9	–
Proposed Trombe wall	**Double T.W. glass**	**T.W. air gap $R = 0.21$ m^2 K/w**	**Bright gray paint with high reflectivity factor**	**Wool insulation panel**	**Outdoor wooden shutter – high reflectivity**	**Wool curtain**
Density (kg/M^3)	–	–	600	25	–	160
Specific heat capacity (J kg/K)	–	–	1000	710	–	1360
Conductivity (W/M K)	1.07	28.8	0.16	0.39	0.9	0.04
Reflectivity	–	–	–	–	0.8	–
Total solar transmission	0.739	–	–	–	0.8	–
Light transmission	0.752	–	–	–	–	–
Thickness (cm)	0.6	6	1	15	1	0.3
U-value (W/m^2 k)	1.77	4.75	0.16	0.026	0.9	0.008

(discussed above in Section 1.2). The proposed Trombe wall was simulated to test the efficiency. It was followed by an experimental prototype as a proof of concept with local involvement in building process, shown in Fig. 4. This entailed testing the proposed Trombe wall in its real environment and local acceptance. This part of the methodology informed feasibility and cost.

4. Simulation results

The results of this study show how retrofitted buildings using a low-tech resilient Trombe wall design can increase its efficiency and reduce cooling and heating loads. Our proposed Trombe wall design showed a significant improvement in indoor temperature that affected thermal comfort range both in summer and winter compared to both the base case and the classic Trombe wall. The proposed Trombe wall ensured a satisfactory thermal comfort with minimal temperature difference to the standard comfort. 16% of the year is outside the comfort range for the proposed Trombe wall compared to 66% for the base case and 62% when using the classic Trombe wall. During spring and autumn the room retrofitted with the proposed Trombe wall showed no need for heating or cooling. Cold nights in autumn and hot days in spring were still within the comfort range. The results of the simulation for the three cases compared to the outdoor temperature for winter and summer performance are shown in Figs. 5 and 6.

During winter, the simulation for our proposed Trombe wall showed 152 h outside the comfort range during January and February with average lowest temperature 19.1 °C, compared to 2566 h outside the comfort in the case of the classic Trombe wall with average lowest temperature 16.5 °C. During peak winter days, the measurements on the 16th of January, when the lowest outdoor temperature was 4.7 °C, the lowest recorded temperature indoors for the proposed Trombe wall was 17.6 °C, compared to 13.9 °C for the classic Trombe wall and 13.1 °C for the base case, where the minimum comfort in winter according to ASHRAE standard 55 is 20.3 °C. For summer performance, the base case was outside the comfort range for the whole summer season with an average temperature of 29.4 °C and the same for the classic Trombe wall with an average of 29.6 °C. The proposed Trombe wall reduced the total number of cooling hours to 1072 h with an average temperature of 26.3 °C. The highest indoor temperature recorded for the new Trombe wall proposal case on the 24th of July was 28.7 °C compared to 30.1 °C for the classic Trombe wall and 32.3 °C for the base case when the outdoor temperature was 35 °C. The highest comfort summer temperature according to ASHRAE standard 55 is 26.7 °C.

The average heating load in winter season when using the classic Trombe wall is 20,160 kW h compared to significant difference in heating load reduction for the proposed Trombe wall to be 202 kW h, when the average heating load for the base case is 33,256 kW h. The average cooling load in summer season was reduced when using the proposed Trombe wall to be 1814 kW h compared to the classic Trombe wall which is 23,970 kW h when the existing cooling load for the base case is 22,391 kW h with marginal small difference to the classis Trombe wall operation. This reduction in heating and cooling loads was accompanied

Fig. 4. Proof of concept test for the proposed Trombe wall on site.

by a significant reduction in energy consumption in the case of the proposed Trombe wall is 2016 to kW h to reach an energy savings of 53,631 kW h and reduction in CO_2 emissions of 144,267 kg of CO_2. The classic Trombe wall's energy consumption is 42,551 kW h, with an energy saving potential of 13,096 kW h and a 35,228 kg reduction in CO_2 emissions (see Table 2).

Such significant difference in heating and cooling loads was clear when calculating the contribution of using the proposed Trombe wall in only one room in the entire house. Summer cooling load for the entire house without using the proposed Trombe wall is 34,553 kW h/m^2 and the winter heating load is 32,402 kW h/m^2. While the summer cooling load is 30,438 kW h/m^2 and the winter heating load is 25,791 kW h/m^2 when using the proposed Trombe wall. That reflects the effect of the design modifications on enhancing efficiency of the proposed system which will consequently enhance the performance of the entire building. While for the results of the heat loss and heat gain of the proposed Trombe wall compared to the classic. In summer season, heat gain for the proposed Trombe wall is 116 W during day-time and 51 W during night-time. While the heat loss is 834 W during winter day-time and 1895 W during winter nigh-time. Compared to classic Trombe wall which shows heat gain of 885 W during summer day-time and 5535 W during night-time while heat loss is 972 W during winter day-time and 1555 W during winter nigh-time. We used Eq. (1) for calculating heat loss and gain.

$$Q = U * A * \Delta T \tag{1}$$

where are A is the surface area of each component of the Trombe wall, U is the U-value of the materials and ΔT is the difference in temperature between inside the building and outside.

5. Discussion and analysis for design development performance of the proposed Trombe wall

In this study, the Trombe wall works as a method of passive heating in winter and is adjusted to act as a solar chimney for passive cooling in summer. It is important to mention that the computer simulation results have been obtained under the assumption that the building would

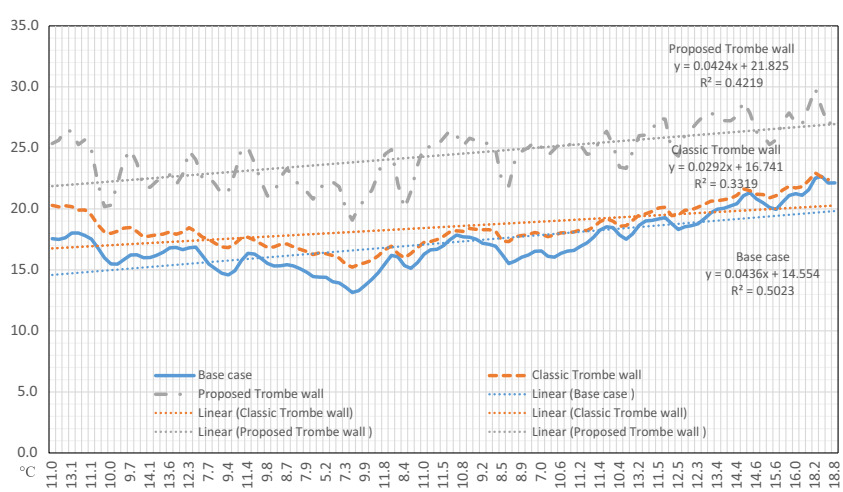


Fig. 5. Winter average daily indoor and outdoor temperature showing the performance of the proposed Trombe wall compared to the classic Trombe wall and the base case.

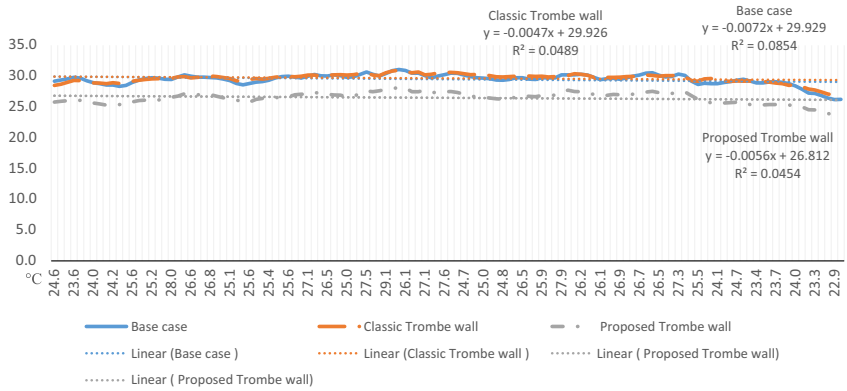


Fig. 6. Summer average daily indoor and outdoor temperature showing the performance of the proposed Trombe wall compared to the classic Trombe wall and the base case.

Table 2
Comparison between the classic Trombe wall and the proposed one in terms of energy consumption, energy saving and CO_2 reduction.

Type of Trombe wall	Energy consumption (kW h)	CO_2 emission (kg of CO_2)	Energy saving compared to base case (kW h)	CO_2 reduction (kg of CO_2)	Heating load (kW h)	Cooling loads (kW h)
Classic Trombe wall	42,551	114,462	13,096	35,228	20,160	23,970
Proposed Trombe wall	2016	5423	53,631	144,267	202	1814

be operated correctly; especially when it comes to opening and closing the Trombe wall air vents. It is assumed that the windows in the room will be opened when the indoor temperature is above 24 °C. In this study the heat gains and losses of the spaces around the simulated room were considered in the simulation for accurate results. A shading reduction factor for external obstacles, like mountains, were also taken into consideration in calculations of the solar effective area of the Trombe wall.

To overcome the inverse thermosiphon phenomena and heat transfer from inside to outside especially during winter nights, we introduced several solutions like thermal insulation, using goat wool curtains and sheep wool insulation for the upper and lower vents. External insulation is an applied solution tested in previous research work (Chel et al., 2008). In our design we proposed a thick layer of 15 cm local sheep wool insulation to be used indoors, in the form of reversible and mobile folded panels to cover the internal Trombe wall surface. The wool helped to trap the indoor heat during the night, with average 3 °C difference in indoor temperature compared to the classic Trombe wall, and reduce the heat loss through the wall from inside to outside the building envelope. During summer, the wool is folded to the sides of the wall, which reduced the overheating effect by an average of 1.5 °C indoors when compared to the performance of the proposed Trombe wall with insulation in summer.

The second solution we proposed was to cover the exterior surface of the wall with 3 mm local goat wool in the form of a roll-up curtain. It is to be placed in the Trombe wall air gap (see Fig. 4). The curtain will be used only during winter nights and it assesses the reduction of the reverse effect for heat transfer when the outdoor temperature drops during winter nights. Using shading devices in the air gap with low emissivity was introduced by other researchers (Chen et al., 2006) as a useful tool for reducing summer overheating and improving insulation in winter. In our design, we proposed a wooden shutter built on the outside. In addition to covering the glass surface from the outside with a mobile 3 mm goat wool roll-up curtain placed behind the shutters during winter nights, the wooden shutter helps keep the Trombe wall glass surface temperature equal or slightly lower than the air temperature inside the air gap. Other studies suggested that in winter the upper and lower vents should be closed in the evening and reopened during the day (Saadatian et al., 2012). In our proposal, in winter, the vent frames are also covered from the inside using the same sheep wool insulation layer when closed overnight. This is to reduce infiltration and keep heat from escaping.

Our design develops the use of external blind shutters in response to the undesirable heat gain over summer. The reason for adding blind shutters in front of the glass surface is to act as a buffer for heat transfer and reflect sunlight (Saadatian et al., 2012). In our proposal, an external wooden shutter, to be made from local palm-tree wood and painted with a double layer of white albedo paint with a high reflectivity, is proposed for summer sun protection. Moreover, using the Trombe wall as a solar chimney in summertime proved to be applicable and efficient in enhancing ventilation, which is also discussed in recent studies (Rabani et al., 2015). We added a thin layer of 1 mm aluminum sheeting on the top vent. This enhanced the stack effect for air movement upwards. This is due to

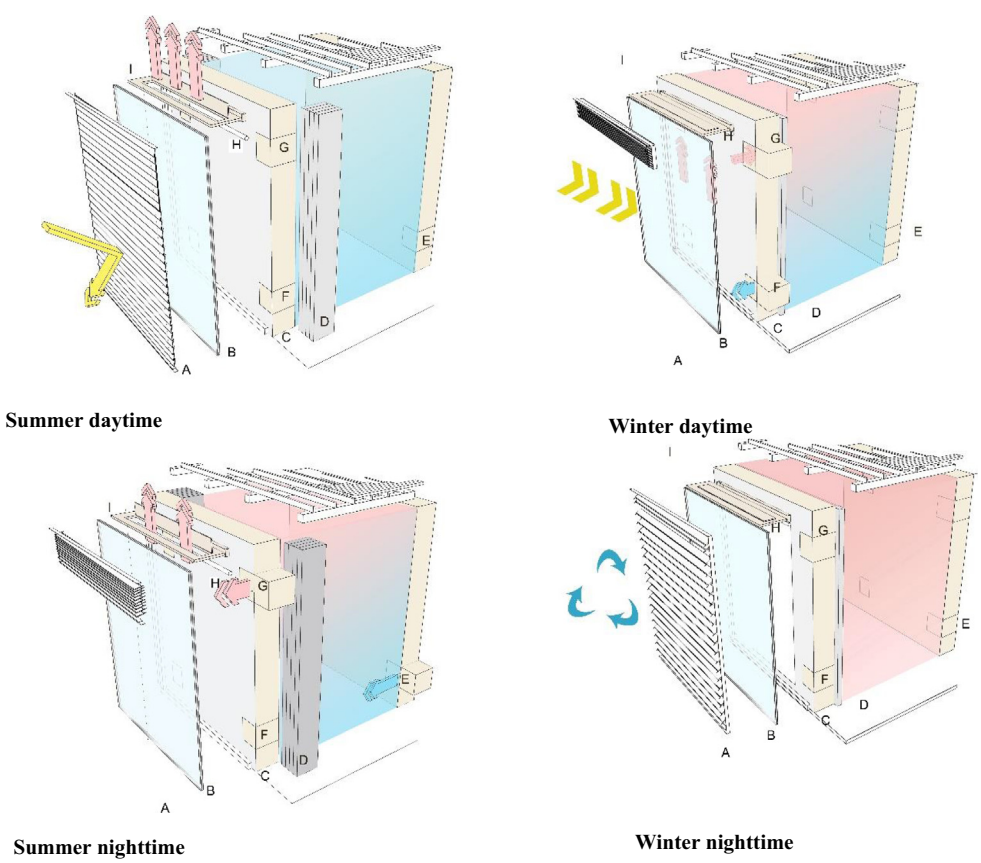
the difference in pressure created by the aluminum sheet when exposed to direct sunlight. Such solutions reduced the indoor air temperature by an average of 1.5 °C during the daytime.

The issue of aesthetics was also discussed in the literature as a major challenge in using Trombe walls (Saadatian et al., 2012). We tried to pay attention to the design features along with the functionality and efficiency of the system. Recent studies have still focused on the efficiency but ignored the aesthetics (Rabani et al., 2015), which is sometimes considered a barrier in users' acceptance of Trombe walls. Our Trombe wall proposal is integrated into the façade. The wool curtains are placed underneath the wooden shutters so they are not visible. The gray wall paint used reduces the dull look of the black wall when the exterior wooden stutters are opened during the daytime in winter.

Other aspects of the design development are considered, for example the air gap and the wall thickness. A study on Trombe wall use for passive heating proved that the air gap width does not have a major effect on the thermal performance of the Trombe wall (Yilmaz and Basak Kundakci, 2008). For this reason, we kept the standard width of 6 cm. The optimal thickness of the Trombe wall is normally related to the latitude, climatic conditions and heat loss (Lebens, 1980). In our case, width was not possible to control as we were retrofitting rooms. However, the existing rammed earth wall with a 40 cm thickness was suitable, even assisting the performance of the Trombe wall. The glazing material used is typical in the Egyptian market. The indoor sheep wool insulation panels and the goat wool curtains are available at the local market in Saint Katherine, where locals mainly work with weaving wool. The morning and night modes in winter and summer for the proposed Trombe wall are illustrated in detail in Fig. 7. The analysis of winter and summer efficiency of the newly proposed Trombe wall is discussed in the sub sections below.

5.1. Thermal performance and efficiency analysis of proposed Trombe wall in heating operation

Natural convection and radiation were key factors in the winter performance of the proposed Trombe wall. Solar gains are calculated by taking into account the effective collecting area of the Trombe wall glazing surface. Trombe wall heat flux has a horizontal direction and value of 6.8 kW h. In the simulated room, the rammed earth wall has a radiative factor of 5.13 W/m^2 k and a conductive factor of 19.8 W/m^2 k. We primarily used two main equations in our analysis and understanding of the simulation results for heating during the winter performance of the Trombe



A: Wooden shutters, **B:** Glass panel, **C:** Rammed earth wall, **D:** Wool insulation panel, **E:** Lower vent for north cool air, **F:** Trombe wall lower vents, **G:** Trombe wall upper vents, **H:** Wool curtain, **I:** Trombe wall top vent.

Fig. 7. Different modes and adjustments of the Trombe wall during summer and winter days and nights.

wall. According to (Garg, 1987; Balcomb, 1992), Eq. (2) is used to understand solar load ratio (SLR), which is the ratio of solar energy absorbed by the Trombe wall. Eq. (3) was used to understand the solar heating fraction coefficient (SHF) and the energy saving percentage, when calculating energy consumption.

$$\mathrm{SLR} = \frac{\overline{S} \cdot N \cdot A_r}{L_{\mathrm{TW}}} \tag{2}$$

where $\overline{S}$ is the net solar intensity which the Trombe wall absorbs, N is number of days in winter and A_r is the Trombe wall receiving surface area in m^2, L_{TW} is the monthly thermal load of the Trombe wall system measured in GJ (Fares, 2012).

$$\begin{aligned} \mathrm{SHF} &= 0.7197(\mathrm{SLR}) && \text{for SLR} \leq 0.5 \\ \mathrm{SHF} &= 1.007 - 1.119[-1.0948(\mathrm{SLR})] && \text{for SLR} > 0.5 \end{aligned} \tag{3}$$

During day, heat is transmitted by convection through the air vents. The cold air inside the room is replaced by warm air from the air gap inside the Trombe wall. As explained by Santamouris, this natural convective loop allows the cool air to be drawn into the heating space, thereby replacing the outflowing hot air, and allowing the cold air to start drawing in heat (Santamouris, 2007). The top and the bottom vents continue to circulate the air as long as the air entering the bottom vent is cooler than the air leaving the top vent. At night, the solar heat gained through direct solar radiation that was stored inside the wall as thermal energy is transferred to the internal space through radiation. The rammed earth walls generally had a low R value, but studies show that a thermal mass of rammed earth would help due to its high thermal storage capacity (Taylor and Luther, 2004). The rammed earth wall's lag time ranges from 6 to 7 h, which helped prolong the time the heat is stored in the wall during the day.

Depending only on the heat conduction from the wall was not enough to heat the rooms at night. Thermal insulation was also essential for reaching the desired thermal comfort range. A reversible 15 cm internal thermal insulation layer made from local natural sheep wool was used as a folded wall curtain to help trap the heat inside the room and reduce any heat loss through the inverse thermosiphon phenomena. Using the sheep wool insulation layer was a key factor in reducing the number of days requiring heating in winter and late autumn. The average indoor temperature using the proposed Trombe wall is 24.4 °C compared to 17.5 °C for the classic Trombe wall and 16.7 °C in the base case. When the outdoor temperature between 5 pm and 7 am, which is the average time between sunset and sunrise in winter, ranges from an average minimum of 6.6 °C to an average maximum of 11.4 °C degrees, the temperature using the proposed Trombe wall ranges between an average minimum of 18.9 °C and an average maximum of 24.5 °C degrees. This means that, except for the 152 h outside comfort levels, the evening and night temperatures are within the comfort range and there is a minimal reverse of the air flow at night. Several studies explained that the open vents produce a reverse flow at night and that reduces the efficiency of the Trombe wall system (Jaber and Ajib, 2011; Zalewski et al., 2012). For this reason, dampers are used for closing the air vents at night, as shown in Fig. 7, to prevent the reversal of the air cycle when the air temperature inside the air gap starts to be lower than the indoor air temperature. Additionally, a layer of thermal insulation is used around the upper and lower vent frames to reduce infiltration.

During autumn nights heating is required; however, the upper and lower vents will be closed so that the Trombe wall will behave as unventilated wall. The heat stored in the wall during day will heat the space through radiation and convection. The wool curtain inside the air gap is rolled down at night to act as a thermal insulation layer. This helps keep the wall surface temperature stable for a longer period. The wooden shutters are closed at night which also helps in reducing the rapid loss of heat from the glass surface, thus reducing the heat loss from the air gap through the glass surface. Flexibility in the proposed design and manual adjustment according to occupants needs helps achieve comfort all year round.

In order to avoid overheating in summer, the wall is proposed to be painted in a bright gray color and not in black as the classic Trombe wall design. This proposed paint color was effective in winter and helped to reach the required comfort range. The reflective double glass also played a role in speeding the process of heating up the air inside the air gap. The glass panel blocked the transfer of thermal energy back to the outdoor environment because it is impermeable to long wave thermal radiation, so most of the heat stored in the air gap is conducted to the inner surface. The heat gain from the high reflective glazing is 13 kW h. The 3 mm goat wool curtain used in the air gap was an asset in keeping the indoor surface of the glass and the outdoor surface of the wall with a minimal gradual loss of heat at night, when the outdoor temperature drops. The efficiency of the combination of solutions, was meant to enhance its performance compared to the classic Trombe wall. According to ASHRAE standard 55, the lowest winter temperature for comfort should be 20.3 °C. There is a 1.4 °C difference between the recorded indoor temperature and the thermal comfort range during the 152 h of discomfort. This is mainly during late night hours, which is normally when occupants are in bed, thus having little effect on their comfort as they have an extra layer of bed covering.

5.2. Thermal performance and efficiency analysis of proposed Trombe wall in cooling operations

The major challenge we faced in this study was to prevent summer overheating while at the same time using the Trombe wall to reduce cooling demands. Natural ventilation was one of the key players in the summer performance of the proposed Trombe wall. The idea of using

the Trombe wall for summer cooling depends on two basic ways for enhancing the convective cooling rate and the induced ventilation (Givoni, 1998). The influences of the ventilation and the air flow rate due to air convection through the Trombe wall air vents were considered. The main aim was to increase the volume of hot air flowing out while bringing in cooler air. If Delta T is the temperature difference between the existing indoor air and the incoming outdoor air, the overall cooling rate in kW per hour can be calculated by Eq. (4), where V is the volume of air escaping in cubic feet per minute (Givoni, 1994).

$$\text{Cooling rate} = 1.08 \times V \times \text{DT} \quad (4)$$

If air flows at a velocity of 1–2 m/s through the vent of 0.04 square meters, air flow rates will be between 20 and 400 cubic meters per minute. If incoming air is 10° cooler than the indoor air, the overall cooling rate will be about 0.2–0.4 thousand kW per hour. This was confirmed by the simulation and showed a decrease during peak time in July of up to 4 °C indoors compared to the classic Trombe wall and 4.5 °C to base case.

The combined use of exterior wooden shading shutters with a reflective surface and allowance of ventilation reduced indoor temperatures. Using only the shutters reduces the heat gain on the glass surface by 70%, and after reversing the behavior of the Trombe wall to act as a solar chimney for passive cooling, the indoor temperature was reduced by another 12% and indoor thermal comfort was enhanced. Shading was not only important in the summer but also proved critical in improving temperature monthly. Using shutters was essential from May through August. The gray paint was effective in summer compared to the typical black paint used in classic Trombe walls. It did not affect the winter heating as much as it reduced the heat gain in summer, even when simulated with shutters that totally covered the glass and reduced the induced direct sunlight on the glass surface.

As it is a hot arid climate in Saint Katherine, there is a difference between day and night temperatures in summertime which facilitates the possibility for night cooling using the night flush effect. The difference between the day and night can reach up to 10°. The hottest day is the 24th of July at an average temperature of 34.1 °C in the day and 24.1 °C at night time. At night, air movement is induced by the warm air inside the Trombe wall air gap. The air gap sucks the cool outdoor air into the interior space, replacing the warm indoor air through natural convection. Therefore, the Trombe wall is used for increasing the air flow that enhances the cross ventilation for cooling. However, heating is needed at night for 6.5% of days in the summer. The Trombe wall was effective in this respect. It behaves very similarly in winter aside from the fact that the thermal insulation wool layer is not applied in summer. There is a delay in the time it takes for heat to transfer from the walls until 7 pm, after which heating is required.

As mentioned in the results section, 1072 h in summer is outside comfort standards. According to ASHRAE standard 55, the highest comfort summer temperature is 26.7 °C. The difference in temperature to reach the comfort level is between 0.5 and 2 °C. As the range is small, using one of the evaporative cooling techniques can help reduce this range of discomfort. In addition, solar shading for window glazing using similar shutters applied in the Trombe wall, roof shading or insulation or by wall shading using deciduous trees, all such solutions can reduce heat gain. Such strategies have not been simulated for their efficiency as they are outside the scope of this study.

Comparing outcomes of our proposed new Trombe wall to the base case, only 3 days are within comfort rage in the base case, while the remaining days in summer range from average minimum of 27.8 °C to a maximum of 30.9 °C. The classic Trombe wall shows no improvement in summer comfort levels, even with using shutters to reduce the direct heat gain on the glass surface. On the contrary, the indoor temperature increased by an average of 0.5° throughout the summer season compared to the base case. This explained the recommendation by Gan, advising that the Trombe wall be insulated and the ventilation rate be maximized to prevent overheating in summer (Gan, 1998). This recommendation was applied in our proposal.

The air vents were essential for summer cooling ventilation when the Trombe wall functions as a solar chimney for passive cooling at night as shown in Fig. 7. The upper wall vent is 20 × 20 cm and the top vent size is 5 × 200 cm as shown in Fig. 3. The upper wall vent acts as an air exhaust opening and facilitates the air suction upwards while the lower vent is closed to prevent the air from flowing in reverse. The heat trapped in the air gap is higher in temperature than the air inside the room. This helps drag the colder air at night from the window opening on the northern side of the room. Hami et al. confirm this, when discussing the importance of a control mechanism for opening and closing vents to control both heating and cooling. They explained that opening and closing the vents changes the heat transfer coefficient between the air in the gap and the wall and glazing (Hami et al., 2012). Additionally, using a metal sheet to cover the frame of the top vent increased the difference in air pressure inside the Trombe wall air gap and the outside pressure, which accordingly increased the air movement upwards.

The insulation layer caused over heating in spring and summertime, and raised the indoor temperature by an average of 2.5 °C. For this reason, the thermal insulation is reversible so it can be folded away from the wall easily in summer and late spring to avoid overheating.

5.3. The cost and operating energy consumption analysis of the Trombe wall

In this section we tried to show the cost benefit and emissions reduction analysis when using the proposed Trombe wall design compared to the current state of the building and when using the classic Trombe wall. We took into account all costs of acquiring, owning, and disposing

of the Trombe wall system in the two cases. We applied life cycle cost (LCC) analysis in comparing the two Trombe wall alternatives in terms of performance with respect to initial costs and operating costs. We assumed that the life span of this building and the Trombe wall system is 30 years. In addition to the cost, the function, efficiency, energy savings and payback time are also criteria in the comparison. We have followed the equations applied by Jaber and Ajib in their economic model (Jaber and Ajib, 2011) and further developed the equations used by Irshad and his research colleagues in their studies in order to calculate life cycle cost (Irshad et al., 2014).

Some information is needed for the calculations. Some were assumed and others were obtained based on the local market in Egypt. According to the Central Bank of Egypt, the inflation rate is 8.95% with a recent increase to 11.4% and interest rate 9.25% (CBE, 2014) such increase is due to the government cut energy subsidies in July of 2014 for leading cost of gasoline and diesel. The salvage factor is set at 10% of the capital cost. As the Trombe wall system is low-tech with manual operation, the maintenance factor is estimated to be 3%. The life time span of the Trombe wall material components are calculated separately. The fuel price is 0.285 Euros.

$$\mathrm{LCC} = (C + M + R - S)/E \tag{5}$$

where C is the total initial capital, M is the total maintenance cost, R is the replacement cost anticipated for the whole life of the Trombe wall, S is the Salvage or scrap value at the end of system's life, and E is the amount of energy for heating/cooling produced (kW h/annum) (Irshad et al., 2014).

$$\begin{aligned}\mathrm{LCC} = {} & (\text{cost of existing system} \\ & + \text{maintenance cost for existing system} \\ & - \text{existing system salvage cost}) \\ & + (\text{cost of existing wall} + \text{cost of Trombe wall}) \\ & + (\text{annual current energy cost} \\ & - \text{annual cost of saved energy due to Trombe wall})\end{aligned} \tag{6}$$

The annual heating energy load for the base case is 33,256 kW h. This value is obtained by assuming that the starting point of using a heater is 20.3 °C. The heaters in Saint Katherine are powered by electricity in some houses and connected to the main grid; whereas, in remote areas, the majority of homes are powered by diesel or charcoal depending on local availability. In such remote areas, 1 kg of diesel is needed to produce 10 kcal (1 kW h = 0.866 kcal) and emits 2.69 kg CO_2. The total cost of the proposed Trombe wall when manufactured locally is calculated to be 3600 EGP, while the classic Trombe wall costs 2300 EGP, including materials and labor (equivalent to 420 and 270 Euro, respectively, at the time of this study). According to our calculations, the proposed Trombe wall is a reasonable investment relative to its efficiency. It has a comparatively short payback, 7 months, in relation to a building's 70 year average lifespan. Which is less than what other researchers have reached (Chel et al., 2008). This calculation has been made only for the retrofitted room and not for the entire building.

6. Conclusion and recommendation for further research

Building retrofitting represents the largest unexploited source of energy savings and CO_2 reduction potential in Egypt at this moment. Using Saint Katherine in Egypt as a case study, a modified Trombe wall technique is applied to offer an efficient low-tech solution for off-grid residential buildings in semi-arid climates. Our proposal aimed to introduce an economically viable, energy efficient Trombe wall design with a low carbon impact.

In the occupant-centered approach, we concluded from this living lab site experiment that upon real implementation of the system, training is needed for occupants to be better educated about their building's passive controls system. Residents' social acceptance of passive technologies is also a key aspect for the success of our proposal. This is especially pertinent when it comes to manually adjusting the system in different seasons (i.e. opening and closing the air vents, blind shutters, top vent, wool curtains, hanging and dismantling the sheep wool insulation boards and other accessible manual controls).

The methodology applied in this study should also be followed by a best practice manual that integrates applicable passive and low-tech, cost-effective retrofitting strategies for off-grid settlements. In addition, monitoring is recommended after one year in order to assess the Trombe wall before introducing it to the local market. A post-occupancy evaluation is also needed as it is not only important to measure users' satisfaction with the system's efficiency and whether it fulfills their thermal comfort standards, but also whether it provides validation to subjective evidence of occupants' knowledge gaps when it comes to green building performance. The cost of the system should be affordable and the technical know-how should be simple enough to encourage further implementation as well as offer potential novel business opportunities for local communities.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.solener.2015.10.005.

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