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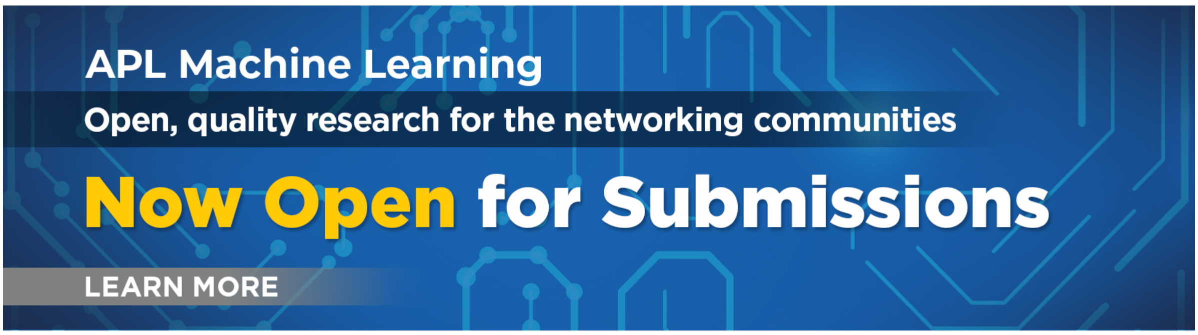

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TROMBE WALL'S THERMAL AND ENERGY PERFORMANCE – A RETROFITTING APPROACH FOR RESIDENTIAL BUILDINGS IN ARID CLIMATE OF YAZD, IRAN

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Abstract

A Trombe wall is a passive solar technology attached to the building envelope to reduce energy demands. In warm climates, due to overheating problems in the cooling season, its efficiency is limited and proper operation is required. In this study the thermal behavior of a bedroom of a house equipped with a Trombe wall in Yazd with a hot and arid climate under different design configurations, and various masonry materials were investigated using the dynamic simulation software DesignBuilder. Monthly ventilation strategies and a schedule of blinds for external glass cover throughout the year were proposed to optimize its energy efficiency. The blinds are applied for shading solar irradiance during summer. They also increase the system's thermal resistance during winter nights. According to the results, a concrete Trombe wall with 2/3 of the façade area is capable of reducing the heating load by 86%. However, its function for summertime is negative, and even in insulation mode, it can increase of the cooling load by 5 %. Natural ventilation with Trombe wall is applicable during moderate seasons; however, its cooling efficiency is limited compared with cross ventilation. The results also highlight that retrofitting a room with a Trombe wall can reduce the annual energy demand by 63%, equal to a reduction of 124 kg CO_2 emission.

Keywords: Passive Solar system, Trombe wall, shading and insulation, ventilation strategies, Low-energy, masonry materials, Low-cost.

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1. Introduction

Maintaining an appropriate indoor environment in the buildings results in a consumption of 30-40% of global energy [1]. The first step to minimize this energy consumption is to improve the thermal efficiency of the building envelope [2]. This improvement is feasible by applying passive or combined strategies. Different shapes of passive solar systems can be installed on the building envelope to benefit from solar energy and wind force as renewable energies. They also can be adopted in both new buildings and retrofits, without restricting daylight and the outdoor view. A Trombe wall is one of the favorable passive solar systems for cooling, heating, and ventilation of space with low cost, simple implementation geometry, and operating [3], resulting in a healthy and comfortable indoor environment [4].

Trombe wall can be divided into three main parts, including the massive wall, glass cover, and air cavity, which is left between the glass and wall [5]. The incident solar radiation is captured exploiting the greenhouse effect occurring in a cavity, and solar energy is absorbed and stored using a massive wall. The heat exchange between the Trombe wall and the indoor environment occurs in two ways: ventilation through the openings and transmission through the wall [6]. In the heating season, the cool air of the room enters the cavity via the lower opening of the wall, heated up by the wall, and flows upward due to the buoyancy effect. Then the warm air returns to the room via the upper opening of the wall. In the cooling season, the outdoor air enters the room through the window on the opposite side of the Trombe wall. It then cools down the room by natural ventilation and flows out through the upper vents of the wall and glass, respectively based on the stack effect [5]. Usually, the thermo-circulation by the airflow between the air gap and the room is critical, since the inversion of airflow could worsen the thermal loss in some conditions [7].

The role of the Trombe wall in achieving indoor thermal comfort was investigated during numerous investigations [8]. Then, different design parameters affecting the efficiency of the classic Trombe

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wall were assessed, such as the opening configurations impact on airflow rate [9, 10], the materials of a massive wall on maximizing solar energy absorption [7], and wall thickness on thermal insulation of Trombe wall [11]. Rabani and Rabani [12] proposed an innovative Trombe wall in Yazd with an arid climate to improve its heating efficiency. To have better heat storage and reduce indoor temperature fluctuations, the massive wall material was replaced with Phase Change Materials (PCM) [13]. Its efficiency was compared with traditional Trombe wall [14] in different new types of PCM, such as capsules [15] and stabilized PCMs panels with double layers [16]. The cooling efficiency of a novel ventilated Trombe wall combined with PCM was investigated in Ref. [17]. In this study, comparing the new with the classical Trombe wall system showed that the annual cooling energy usage was reduced by 18.6% with a maximum temperature of 24 °C.

The difficulties of using the Trombe wall in cold climate conditions were evaluated and summarized by Sergei, Shen [18]. A comparison of ventilated with non-ventilated Trombe walls shows the potential of ventilated ones in saving 62% of the heating energy demands of the room [19]. Applying external insulation components [20] and triple glazing filled with argon are recommended to reduce the glass wall's heat loss [21]. According to Elghamry and Hassan [22], a Trombe wall with a geothermal tube and solar chimney maximized heating and changed the air rate 58 times per day. Applying a thermo-diode Trombe wall provides consistent heat gains for the indoor environment even on cold days and hours after daylight's end [23]. In addition, using the water-flowing channel in the Trombe wall can obtain a desirable insulation efficiency in the heating season and allow excessive solar radiation to heat the water in cooling and moderate seasons [24]. According to Zhou, Huo [25], in comparison with the traditional Trombe wall, the Water Trombe wall can decrease the heat loss by 31% during the night.

The unwanted heat gain is the main problem of using the Trombe wall for cooling purposes [26]. Implementation of the roller shutters [27] and Venetian blind are the solutions to regulate shading and airflow in the cavity, resulting in air-conditioning effect [28]. The cooling efficiency of a Trombe wall was investigated in Ref. [28] using CFD and BES model. The authors concluded that a modification for slat geometry in the air gap is required to reduce solar heat gain of the external wall. An empirical study was conducted for a building in Yazd climate using a Trombe wall combined with a water spraying system and solar chimney [29]. Using a water spraying system showed that the cooling efficiency of the Trombe wall was enhanced by about 30%. Another study focused on a Trombe wall combined with an earth air heat-exchanger and the green wall for passively heating and cooling the temporary houses for refugees in Sweden [30]. This triple passive system compromised 88% of annually thermal comfort requirements with a 231.1 kg CO_2e/annum amount of CO_2 emissions, while the discount payback period of the system was 7.4 years.

As a cost-effective solution for better indoor climate, the Trombe wall was retrofitted to the residential units in off-grid desert areas in Sinai, Egypt [31]. In another study, field measurement and numerical simulation were carried out to optimize the energy efficiency of a Trombe wall as a low-cost strategy retrofitted in a master room. The results showed a 72% reduction in the total annual energy consumption compared to existing houses [32]. However, according to the study conducted by Agurto, Allacker [33], the heating efficiency of a low-cost prefab Trombe wall was three times more than its cooling. Other studies implemented the Trombe wall as assisting system [34] in keeping the indoor temperature within the desired range in the heating season [35] and enhance heat storage throughout the building [36].

Nevertheless, in combination with other strategies, the Trombe wall can be used for indoor air purification [37], [38], inactivation of the spatial virus [39], and domestic hot water [24]. The combination of photovoltaic (PV) modules and Trombe wall could increase thermal efficiency by 38% [40] and electrical efficiency values by 20 % [41] when used as photovoltaic power generation [42].

Its electrical efficiency could reach over 45% higher than existing PV Trombe walls when PV is used as a blind in Trombe wall [43].

This study proposed a low-cost retrofitting Trombe wall combined with masonry material as a passive heating and cooling system for existing residential buildings in Yazd city, Iran, with a hot and arid climate. To determine the optimum configuration, a parametric analysis for a Trombe wall attached to the south façade of a bedroom was conducted by examining different ratios of Trombe wall area and massive wall materials for various days. Then, to minimize annual cooling and heating requirements, a proper operation schedule for ventilation, mobile insulation, and external shading was determined. To conduct the analysis, the DesignBuilder simulation software was implemented.

2. Case study and climate

2.1. Climate

To investigate the Trombe wall system efficiency, a bedroom of a house in Yazd, Iran, was considered. Yazd is located in a latitude of 31.89 and a longitude of 54.35 [44], with a hot, dry summer and cold, dry winter [45]. The weather data provided by the EnergyPlus database was applied in the simulations. The monthly ambient air temperature and the global solar radiation on the vertical surface of the city are presented in Table 1. The high level of solar radiation available in Yazd and the high number of sunny days are due to its specific desert climatic conditions. The high fluctuation of ambient air temperature during the day and night and among various seasons allowed the investigation of the Trombe wall's energy efficiency with various scenarios discussed in the next sections.

Table 1. Weather data and room temperature settings.

Month	Global radiation daily total (kWh/m^2 day)	Peak (W/m^2)	Outdoor temp. Max. (°C)	Min. (°C)	Room temp. settings (°C)
January	3.102	549	19.3	-7	20
February	4.605	767	21.3	-4.5	20
March	4.691	718	28	-2.3	20
April	5.767	798	35	6.4	23
May	7.241	932	36.7	13.9	23
June	8.053	1005	41.7	18.8	26
July	7.834	993	42.2	18.3	26
August	7.317	980	42.3	17.5	26
September	6.603	965	38.2	9.6	26
October	4.797	775	34	4.7	23
November	3.583	620	28.1	-2.1	23
December	3.117	537	21.1	-4.7	20

2.2. Case study

The study examined a south-oriented bedroom of a one-story house to investigate the effect of the attachment of a Trombe wall on the indoor environment. The main focus was on retrofitting the Trombe wall, as a passive system, in the existing buildings to obtain sufficient comfort and energy performance. The reference room was 12 m^2 with a height of 3 m and surrounded by controlled spaces on two sides. Fig.1 shows that the room has a 2×0.5 m window on the north side and another 1×1.5 m on the south side, with polyvinyl chloride (PVC) frame, to take advantage of cross ventilation. The external walls and side walls are made of concrete blocks with low insulation, complying with Trombe wall insulation's attachment. The ceiling slab is made of reinforced aerated concrete with a thermal transmittance of 0.246 W/m^2.k and covered with clay tiles, as reported in Table 2. The external walls' thermal transmittance (U value) is 0.95 W/m^2.k.

Fig.1. The sectional perspective (a) and room plan (b).

Table 2. Thermal properties of the floor, roof, and wall layers.

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	Material layers	Thickness (m)	C_p (J/kg.K)	ρ (Kg/m^3)	K (W/m.K)
Roof	Clay Tile	0.020	800.000	2000.00	1.000
	Aerated Concrete Slab	0.200	840.000	500.000	0.1600
	XPS Extruded Polystyrene	0.090	1400.00	35.00	0.0340
Floor	XPS Extruded Polystyrene	0.030	1400.00	35.00	0.0340
	Cast Concrete	0.150	1000.00	2000.00	1.1300
External wall	Brick Outer	0.105	800.00	1700	0.8400
	Air gap	0.050	-	-	-
	Concrete block (Lightweight)	0.100	1000.00	600.00	0.1900
	Plaster (Lightweight)	0.0130	1000.00	600.00	0.1600

2.3. The Trombe wall operation modes

Three operation modes of the Trombe wall, for different seasons, are set and shown in Fig. 2. The Trombe wall operates in the passive heating mode during the heating season. The indoor air was entered into the cavity of the Trombe wall and heated up by stored solar energy. The warm air returned into the room and reduced the possible heating load. In the moderate seasons, when the ambient temperature was lower than the indoor temperature, the Trombe wall operated in the natural ventilation for cooling applications. In the cooling season, when the ambient temperature was more than the indoor temperature, the Trombe wall could notbe applied to improve natural ventilation for the building. Since entering the warm ambient air without pre-cooling can worsen indoor conditions besides increasing the cooling load. Hence, to prevent this phenomenon, the air entered into the Trombe wall cavity from the lower vent was exhausted to the outside via the upper vent. In these conditions, the Trombe wall operates in the thermal insulation mode to avoid a heat gain from the Trombe wall to the space. The seasonal operation was determined after a series of preliminary simulations based on the analyzed locality of Yazd to minimize the energy consumption.

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Fig. 2. The three annual operation modes of a Trombe wall; heating (a), moderate (b), and cooling (c) seasons.

2.4. Parametric study

To determine the appropriate Trombe wall configuration for the room in the hot and arid climate, parametric analysis was carried out. Therefore, the impact of different design parameters of the Trombe wall on indoor thermal conditions of the room on selected winter and summer days was assessed. Then, different schedules for vent activation and blinds operation were examined to decrease the annual cooling and heating demands. During the parametric analysis, the building only relies on a passive system. Whereas, to evaluate the saving energy, the HVAC system was assumed to be activated. The parametric study was developed based on the following parameters:

- The ratio of the Trombe wall to the total south wall area, considering 1/3 of the façade, 2/3 of the façade, and the entire facade;
- Massive wall materials, including brick, concrete, slate stone, adobe, and sandstone;
- Operation schedule of blinds and vents.

The Trombe wall efficiency is evaluated based on its cooling, heating, and ventilation functions compared with the reference room (without a Trombe wall). Since in Yazd, heat transfer was more sensible on the coldest day than the warmest day [46], the parametric study for Trombe wall configuration was conducted with particular attention to providing heating demand. Based on the preliminary simulations for different seasons, the Trombe wall could only exploit natural ventilation for cooling the room during moderate seasons. However, to more precisely evaluate the cooling efficiency of the Trombe wall, different natural ventilation scenarios were investigated and compared in the cooling season (worst conditions), as described in the following section.

3. Methodology

The simulations of this study were carried out by applying the DesignBuilder interface for the EnergyPlus engine, using the Trombe Wall algorithm. For a virtual building model, DesignBuilder as a dynamic simulation software calculates a broad spectrum of thermal performance statistics, including energy usage [47]. Ozdenefe, Rezaei [48], and Stazi, Mastrucci [49] validated this simulation tool by comparing the predicted temperature of the air gap with experimental data. Their results indicate that it is a reliable tool for evaluating Trombe wall efficiency. The Northumbria University has evaluated DesignBuilder's CFD three-dimensional flow solver against the commercial CFD Phoenics package [50].

Abdeen and Serageldin [47] designed a simplified analytical model of a Tromp wall for the winter period in Alexandria, Egypt as illustrated in Fig. 3. They examined the model under various design parameters to achieve indoor thermal comfort. DesignBuilder software was applied to predict thermal and airflow conditions of the model throughout the winter in a detailed illustration. Under the same operational conditions, a comparison between the recorded and predicted temperatures for the glass, the massive wall, and the airflow was undertaken (Fig. 4). According to the results, there was a good agreement between the predicted and experimental results since the comparison showed an average error (e) of approximately 3.93%.

Fig. 3. Experimental setup (a) and Trombe wall configuration model (b) of Abdeen, Serageldin [47].

Fig. 4. Comparing the measured and predicted airflow temperature results of Abdeen, Serageldin [47].

3.1. **Setting boundary conditions**

To evaluate the impact of the Trombe wall on the room indoor environment, the reference room integrated with TW with all the assumptions, such as the geometry, apertures, and materials, is simulated. The model is oriented to the south to receive the maximum solar radiation from the Trombe wall. The walls and floor surfaces of the model were simulated the same as the case study specifications. The model's boundary conditions have been achieved by setting actual ambient conditions provided by the EnergyPlus database. The thermal properties of walls and roof materials are set as described in Table 2.

To reproduce the actual operation of the reference room and solar radiation, internal gains via the room occupancy, lighting, and electrical appliances are set based on the usage schedule of the bedroom. For cooling and heating seasons, 26 °C and 20 °C were set as indoor set-point temperatures, respectively. To prevent excessive undercooling and overheating of indoor space, out of occupancy schedule, the minimum and maximum temperatures of 12 °C to 35 °C were set for activating the HVAC system in heating and cooling seasons, respectively. The constant pressure with zero initial velocity value is considered for inlet and outlet openings. Therefore, the flow occurs only by the stack effect.

3.1.1. The Trombe wall properties

The massive wall of the Trombe wall is made of Concrete block 1440, with the thermal properties illustrated in Table 3. The thickness of the massive wall was determined based on the corresponding reference, indicating that 0.3 m was the optimum value for the massive wall [47]. To have better solar absorption, the external surface of the massive wall was black. The thickness of the air gap between the massive and glass walls was selected according to the literature, indicating that increasing the distance higher than 10 cm doesn’t cause considerable enhancement [51]. The narrow thickness was also valuable for preventing unexpected backflow from the cavity during the heating season, which can be detrimental to indoor thermal conditions [52]. Therefore, different close dimensions were tested, and a thickness of 0.06 cm was chosen as the best one.

In the reference room, cross ventilation was provided by one opening on the north wall and another on the center of the south façade (Fig.1). For the room with the Trombe wall, airflow enters from the north opening, whereas the south opening is closed, and airflow exhausts via two vents located at the top of the massive wall containing two additional respective vents at the top of the glass wall. The dimensions of each vent, with a rectangular shape, are 0.65×0.20 m, as illustrated in Fig. 5. To accurately compare the room with the Trombe wall and the reference room in ventilation mode, the total areas of vents were assumed equal with the south window opening.

Fig. 5. The sectional perspective of a 2/3 area Trombe wall installed on the south façade of the room.

Table 3. Constructions with their layers are used in the Trombe wall.

	Layer	Thickness (m)	C_p (J/kg.K)	ρ (Kg/m^3)	K (W/m.K)
Window	Glass	0.003	840.00	2530-2600	0.9000
Air	-	0.06	-	-	-
Massive wall	Concrete block 1440	0.300	880.00	1440.00	0.3300

According to the literature, applying single or triple-glazed windows can cause reverse effects in some seasons [5]. Hence, a double-glazed window was selected to cover the Trombe wall. A PVC window frame with a 5 cm thickness and 3/13/3 clear double glass with an air gap was considered for windows. The central window was equipped with a fixed horizontal overhang, whereas Trombe wall glass had moveable shading devices and external blinds with high reflectivity slats installed at 1.5 cm from the external glass. In the cooling season, blinds are applied particularly for shading during the daytime. In the heating season, to improve the thermal resistance of the system during the nighttime, the blinds were opened. Therefore, they minimized the radiative thermal losses during the night between the external surface of the Trombe wall and the outdoor space.

4. Results and discussion

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In this section, first, the average indoor temperature of the reference room (without a Trombe wall system), and rooms with the three configurations of Trombe wall were evaluated and compared in the heating season. Then, the thermal efficiency of the selected Trombe wall geometry under different massive wall masonry materials was predicted for both heating and cooling seasons, and the most appropriate material was selected. Later on, various operation schedules of blinds and vents were set and compared to minimize the annual energy needs of the selected Trombe wall.

4.1. Trombe wall configurations

A traditional Trombe wall was assumed for the room, and indoor thermal conditions with different Trombe wall area ratios were evaluated. The arrangement of Trombe walls with three area ratios (1/3, 2/3, and total) is illustrated in fig.6. In the case with a total area ratio, the south window was omitted. Figure 7 shows the outdoor climatic conditions and the average indoor air temperature of the room with various Trombe wall areas compared to the average indoor temperature of the reference room for two winter days, a cold sunny day and a cold, mostly cloudy day.

Fig. 6. The arrangement of the Trombe wall with 1/3 (a), 2/3 (b), and total (c) area ratios.

Fig. 7. Comparing the average indoor temperature of the room with different Trombe wall areas on a winter's cold, mostly cloudy day (January 4) on the left and a winter's cold sunny day (February 2) on the right, (TW: Trombe wall, Ref.: reference).

As indicated in the graphs, the indoor temperature of the reference room was quite low and constant in both cases due to the limited incidence of solar radiation via the south window. While, in the presence of the Trombe wall, the room's temperature increased significantly (about 9 °C on a sunny day on average). Even in the mostly cloudy sky with a 2.8 °C lower average ambient temperature, the presence of the 1/3 area ratio Trombe wall causes increasing indoor temperatures ranging from 4.5 to

9°C. The noticeable difference between the reference room and the room containing the Trombe wall indicated the thermal efficiency of this wall. However, thermal comfort was not still achieved for most of the day and night time on the cloudy day and for a part of the night time on the sunny day. On both days, the maximum temperature difference between the reference room and the room equipped with a Trombe wall was observed during the noontime. In contrast, the outdoor temperature reached the top value during the late afternoon (4 p.m.). This temperature trend confirmed the significant role of solar radiation intensity on the performance of the Trombe wall.

Comparing three cases with the Trombe wall showed that, on both days, the total area with this wall acted better than others. However, the temperature difference of the room with the total area of the Trombe wall, compared to the Trombe wall containing 2/3 area, was insignificant (less than 1.5 °C difference during the night). Furthermore, even by specifying the total area to the Trombe wall, thermal comfort was not fully obtained during the night, and activation of the heating system was still required. Therefore, considering the similar indoor thermal conditions of cases during the night and the necessity of nocturnal heating due to the occupancy schedule of the bedroom mainly during the night, and at the same time, the critical role of the south window in providing daylight and external view, the room containing 2/3 area Trombe wall was selected for further tests.

4.2. Trombe wall Materials

In the previous section, the 2/3 area Trombe wall was determined as the wall with the best configuration. In this section, the indoor thermal conditions of the room containing the selected Trombe wall configuration with five masonry materials with large thermal mass [53] for massive walls, such as concrete, brick, Sandstone, adobe, and slate stone in winter and summer days, were investigated and compared on two days. Table 4 illustrates the thermal properties of selected materials.

Table 4. Thermal properties of the materials for the massive wall.

material	Cp (J/kg.K)	ρ (Kg/m3)	K (W/m.K)
Brick	500	700	0.27
Slate stone	1000	2400	2.2
sandstone	840	2150	5
adobe	573.2	1708.6	0.334
concrete	880	1440	0.33

4.2.1. Winter

Table 5 and Fig. 8 compare the heating efficiency of the Trombe wall with different materials on January 4 and February 2 as a cold, mostly cloudy day, and a cold sunny day, respectively, where the indoor and outdoor temperatures were shown along with solar incident radiation. According to the results, among all materials, slate stone and sandstone with close results had the highest thermal efficiency for both sunny and cloudy days, while concrete and abode with almost the same functions and partial difference with slate stone had the second-highest temperature. The comparison also shows that all the materials had similar behavior during the daytime (with a maximum difference of 2 °C on average), but they acted differently during the night (the difference reaches 4.6 °C on average). The slate stone had the highest efficiency during the night on January 4, which is attributed to its high specific heat and density (Table 4). Sandstone also had a close result to the slate stone for the nighttime on the same day but had less fluctuation daily. Then, concrete and adobe with almost the same functions had the third-highest temperature. However, their differences with slate stone (as the best case) were ignorable (1.1 ℃ on average). Although on a sunny day, the temperature difference of materials increases, they had the same trend, except for slate stone which had partially less daily function.

Table 5. The average indoor temperature of the room with different massive wall materials on two days; a winter's cold, mostly cloudy day and a winter's cold sunny day (January 4 and February 2 respectively) (Trombe wall with 2/3 area ratio).

Massive wall's material		Average temperature (°C)			
		January 4		February 2	
		Day	Night	Day	Night
Without Trombe wall (reference room)		6.7	6.2	10.1	8.3
With Trombe wall	Concrete	16.8	14.1	22.6	19
	Brick	15	11.8	21	16.6
	Slate stone	17.1	15.8	21.7	20.6
	Adobe	17.2	14.2	23	19.2
	Sandstone	16.1	15.3	22.9	21.2
Outdoor		2.9	-0.8	5.2	2.3

Day: 7 a.m.-6 p.m., Night: 7 p.m. -6 a.m.

Fig. 8. Outdoor climatic conditions and average indoor temperature trends of the reference room and the room with Trombe wall using different massive wall materials during cold, mostly cloudy days and cold sunny days (January 4 and February 2, respectively).

Compared to the reference room, all the cases with the Trombe wall had considerably increased temperatures during day and night (at least 6.9 °C on cloudy days and 9.6°C on sunny days on average) and low-temperature fluctuation during the night. In all cases with the Trombe wall, the highest and lowest average indoor temperatures were reported in the afternoon (2 p.m.) and early morning (6 a.m.), respectively. As Table 5 shows, on a sunny day, in the presence of slate stone and sandstone for the massive wall, the room temperature is within the range of thermal comfort, and assisting heating system is not required (21.2 °C and 22 °C on average, respectively). By implementing concrete and adobe for the massive wall, in the same outdoor conditions, thermal comfort is provided except early morning. In contrast, on the day mentioned above, the usage of brick for massive wall caused thermal discomfort for 6 hours of late-night (from 2 a.m. to 8 a.m.). However, on the cloudy and cold day (February 2), as the worst scenario with all materials, the room needs assisting heating system to provide thermal comfort.

4.2.2. Summer

The thermal behavior of the Trombe wall with various masonry materials for two days, a sunny hot day and a hot and partially cloudy day (June 26 and August 16), was investigated and compared with the reference room, as illustrated in Fig 9. To better analyze their cooling efficiencies, natural ventilation was activated for the reference room and room with the Trombe wall. According to the results, aside from the Trombe wall materials, the application of the Trombe wall in the summer ascertained a performance that was partially worse than the reference room during day and night (about 0.8 ℃ and 1℃ on average for June 26 and August 16, respectively). The temperature trends also show that with or without the Trombe wall, the indoor temperature was out of comfort limit and considerably higher than the outdoor temperature at night. Therefore, to compensate for overheating in all cases, activation of the cooling system is required.

Comparison of the cases with various materials showed that, on both days, the thermal behavior of the Trombe wall with concrete, brick, and adobe was almost the same; however, with concrete, the overall function of the Trombe wall was partially better (Table 6). Unlike winter, the thermal behavior of the Trombe wall with slate stone in the summer was not satisfying. However, the difference of cases values was not considerable (the concrete value was 0.7 ℃ lower than the slate stone value on average). Fig 9. shows that the Trombe wall has its lowest efficiency during the afternoon (from 1 p.m. to 3 p.m.) when the temperature of the reference room is about 1 ℃ lower than the room containing the Trombe wall. It is difficult to find a cloudy day during the summer in Yazd. August 16 is a hot day that experiences a cloudy sky during the afternoon. As Fig 9. illustrates, on this day during the morning time, regardless of the massive wall material, the indoor temperature of the room containing the Trombe wall is higher than the room on June 26. The reason refers to higher ambient temperature compared with June 26 (about 1 °C) and higher solar absorption by the massive wall due to low solar altitude angle during the daytime. It is while, during the afternoon, with less solar intensity attributed to a cloudy sky, decreasing in temperature is observed. Overall, the thermal behavior of all massive wall materials during the summer days is similar, and their difference reaches the highest value during the noontime, with the peak outdoor temperature. However, during the noontime, the room with a concrete wall possessed the most appropriate indoor conditions (1 °C lower than the room with a sandstone wall). The diagram also demonstrates that irrespective of the material, an auxiliary cooling system is essential to maintain a comfortable temperature within a space with Trombe walls during the warm summer months.

In contrast with the winter conditions, the indoor temperature of the summer day is mainly affected by outdoor temperature more than solar radiation intensity. It can be due to the introduction of warm outdoor air into the room by ventilation and high solar altitude angle during the daytime, decreasing solar absorption by a massive wall. Overall, the Trombe wall with slate stone shows better heating efficiency for the winter period. While, by selecting concrete for the massive wall, the Trombe wall acted better during the summer. In Yazd city, the cooling demand was predominant most of the year; therefore, concrete material was selected for the optimum model tested for the entire year.

Table 6. The average indoor temperature of the room with different massive wall materials on a summer's hot and sunny day and a summer's hot and partly cloudy day (June 26 and August 16 respectively) (Trombe wall with 2/3 area ratio).

Massive wall materials		Average temperature (°C)			
		June 26		August 16	
		Day	Night	Day	Night
Reference room		36.9	36.2	37.1	36.6
Room with Trombe wall	Concrete	37.5	36.5	38	37.1
	Brick	37.5	36.5	37.9	37.1
	Sandstone	38.2	37.1	38.9	37.9
	Adobe	37.5	36.6	38	37.2
	Slate stone	38	37	38.7	37.8
Outdoor		36.7	32.8	37.2	33.2

Day: 7 a.m.-6 p.m., Night: 7 p.m. -6 a.m.

Fig. 9. Outdoor climatic conditions and average indoor temperature trends of reference room and room with Trombe wall using different massive wall materials during hot and sunny days and hot and partly cloudy days (June 26 and August 16, respectively).

4.3. Operation schedules of vents and blinds

In the previous sections, the thermal efficiency of the Trombe wall system with different configurations and massive wall materials for winter and summer days was investigated. Also, a concrete Trombe wall with a 2/3 area ratio was selected as the optimum model. In this section, to optimize the thermal efficiency of the optimum Trombe wall, various operation schedules of blinds and vents for harsh seasons were investigated at first (Fig. 10). Consequently, a proper monthly schedule for shading and ventilation, as manually controlled systems, is recommended.

A: Blinds, **B:** Glass wall, **C:** Insulated cavity wall, **D:** Concrete wall, **E:** North opening, **F:** Trombe wall upper vents, **G:** Trombe wall lower vents.

Fig. 10. The components of the Trombe wall in the natural ventilation mode.

3.3.1. Investigating winter scenarios

To find the best performance of the solar system for the winter, various schedules of passive heating and mobile insulation were investigated by changing the vents and blinds modes. The different proposed schedules were determined according to the locality's climatic conditions and temperature fluctuation. For example, to control the unexpected night discomfort, in some cases, the passive heating was specified only for night time or insulation was activated during the night to prevent heat radiation loss from the glass wall.

Table 7 compares indoor thermal conditions of the room with the Trombe wall and the reference room on a winter's sunny and cold day under different vent and insulation settings. The results showed that the function of the selected Trombe wall in the winter was satisfying. Since, compared to the reference room, in all cases with the Trombe wall, a significant increase in indoor temperature was observed (about 11.6 ℃ on average). This is in agreement with the results of Ref. [54]. Among different cases, the Trombe wall with passive heating during day and night and nocturnal insulation had the best function. However, the indoor temperature did not change significantly in the absence of nocturnal insulation. By implementing the Trombe wall, comfort condition was reported during the daytime in all cases. However, during some nighttime parts, the indoor temperature was still lower than the comfort limit (from 4 a.m. to 7 a.m.). Therefore, during nighttime, activation of the heating system is required. The maximum temperature is reported in the early afternoon when the indoor temperature of the room with the Trombe wall reaches 26 ℃.

Table 7. The trend of indoor and outdoor temperatures of the room with/without Trombe wall under different vents and mobile insulation schedules for a sunny and cold winter day (February 2).

<table>
<tr><th colspan="2" rowspan="2">Hour / Case</th><th colspan="3">Daytime temperature (℃)</th><th colspan="3">Nighttime temperature (℃)</th></tr>
<tr><th>8-11</th><th>12-15</th><th>16-19</th><th>20-23</th><th>24-3</th><th>4-7</th></tr>
<tr><td colspan="2">Reference room</td><td>8</td><td>11.6</td><td>12</td><td>8.8</td><td>8.1</td><td>6.8</td></tr>
<tr><td rowspan="3">Room with Trombe wall</td><td>Day-night passive heating</td><td>20.1</td><td>25.9</td><td>23.3</td><td>20.5</td><td>18.5</td><td>16.6</td></tr>
<tr><td>Day-night passive heating & Night insulation</td><td>20.4</td><td>26.2</td><td>23.6</td><td>21.</td><td>19</td><td>17</td></tr>
<tr><td>Night passive heating & Night insulation</td><td>17.1</td><td>19.9</td><td>20.3</td><td>20.7</td><td>19.2</td><td>16.5</td></tr>
<tr><td colspan="2">Outdoor conditions</td><td>-0.2</td><td>9.4</td><td>9.5</td><td>4</td><td>2.9</td><td>-2.8</td></tr>
</table>

According to the data, by storing solar heating in the massive wall during the daytime and heating the room during the night, thermal comfort was not obtained. This undesired condition continued during the morning. Furthermore, compared to passive heating, the impact of using mobile insulation for nighttime was not significant. Since by activating nocturnal insulation, the indoor temperature increased partially (0.4 ℃ on average).

3.3.2. Investigating Summer scenarios

For the summertime, due to the high outdoor temperature of the locality and the risk of overheating, implementing natural ventilation during the daytime is not recommended. However, nocturnal ventilation and shading device can be influential in reducing the indoor temperature during the day in harsh climate conditions [55]. Therefore, this section investigates the thermal efficiency of the Trombe wall with various vents and blinds schedules for a hot and sunny day of the summertime as the worst scenario and compares the different ventilation strategies.

Fig .11 shows the hourly temperature of the room with or without a Trombe wall with different ventilation and blinds settings for a hot and sunny day during the summer. As the figure shows, in contrast to the winter, the function of the Trombe wall for the summer was not satisfying. Since, even in the insulation mode of the Trombe wall (without ventilation), the indoor thermal condition of the room was worse than the reference room. According to the data, with or without the Trombe wall, implementing natural ventilation reduced indoor temperature.

Reference room with cross ventilation acted better during the daytime among the different cases. While the room with the ventilated Trombe wall and open blinds acted better during the nighttime (Table 8). Hence, natural ventilation seems useful to increase the heat transfer from the room to the outdoor environment and reduce indoor temperatures. However, due to high outdoor temperature, thermal comfort was not achieved. The maximum effect of natural ventilation was observed in the early morning and the minimum in the evening. Although cool air from the outside was available during the nighttime, according to the data, relying on night ventilation was also not effective and can increase the temperature during the morning (up to 2 ℃).

Fig. 11. The trend of indoor and outdoor air temperatures of the room with/without the Trombe wall under different schedules of vents and blinds on a summer’s hot and sunny day (June 26), (NV: natural ventilation).

Table 8. The average temperature values of room with/without Trombe wall under different vents and blinds schedules for a summer’s hot and sunny day (June 26).

	Vent/Opening	Blind	Ave temp. (°C)		Strategies
			Day	Night	
Reference room	-	-	38.8	39.2	Thermal insulation
	* (Openings)	-	36.7	37.1	Cross ventilation
Room with Trombe wall	-	*	39.7	39.7	Thermal insulation
	*	-	38.4	36.7	Natural ventilation
	*	*	36.9	35.8	Natural ventilation & Shading
	* (Nighttime)	*	37.8	36.4	Night ventilation
Outdoor			36.7	32.8	

By deactivating the blinds system, the room temperature increased, especially during the daytime. The maximum increase in temperature was reported in the early morning, which was about 2 °C. As the graph illustrates, the cooling effect of natural ventilation seems higher than the blind's efficiency. By implementing natural ventilation, the room temperature reduced about 2.9 °C. However, by blinds' activation, 0.8 °C reduction was observed on average. The low efficiency of blinds in controlling indoor temperature might be due to the presence of the south window in all cases, causing solar heat penetration. As a result, activating natural ventilation and blinds for the room with the Trombe wall resulted in better performance among the cases investigated. Since indoor thermal conditions are out of the comfort range in all cases, HVAC system is required for the summer season. Hence, the insulation mode is selected for the summer season among various cases.

3.3.3. Investigating moderate seasons scenarios

During the moderate seasons, the relatively mild outdoor temperature of the locality is suitable for using natural ventilation and can be enough for cooling indoor space. However, according to the results of preliminary tests, due to high-temperature fluctuation during day and night, different strategies are required. In this section, based on the results of the previous section, the most efficient ventilation (and shading strategy) was selected and implemented for temperature analysis of two different days in moderate seasons, May 2 and November 2.

Fig. 12 shows the hourly temperature of the room with or without Trombe wall with different ventilation and blinds settings of a sunny day on the spring. The reference room was tested with and without cross ventilation throughout the day and night. Whereas the room with the Trombe wall was examined with natural ventilation and activated shading throughout the day and night. The graph illustrates that by implementing natural ventilation in cases with and without Trombe wall, indoor temperatures reduce considerably, especially during the night when the outdoor temperature reaches the lowest value (3.9 °C by cross ventilation and 3 °C by natural ventilation with Trombe wall on average). The cooling efficiency of natural ventilation in both cases (with or without Trombe wall) reached the lowest value during the peak outdoor temperature. Although the room with the Trombe wall was partially warmer than the reference room, the indoor temperature of the room was within the comfort range during the day and night.

Fig. 12. The temperature trend for the room with/without Trombe wall under different schedules of vents and blinds for a spring day (May 2).

In autumn, both heating and cooling might be required due to high-temperature fluctuation during day and night. Therefore, to find the best performance of the solar system for this season, various schedules of natural ventilation and passive heating were investigated. To control the unexpected night discomfort, passive heating was specified for nighttime. Also, natural ventilation was tested for some cases during the daytime to prevent overheating.

Fig. 13 compares indoor thermal conditions of the room with Trombe wall and reference room of a sunny day in the autumn under different vents settings (November 2). As Fig. 13 illustrates, during the autumn day, the indoor temperature of the reference room is appropriate, except for late night and early morning when a slight increment of the heating demands has emerged. By implementing the Trombe wall, the average indoor temperature of the room during the day increased dramatically (at least 3 °C). Implementing natural ventilation caused a temperature reduction of 1.7 °C during the day, but its impact was more evident during the night when a reduction of 4.8 °C was occurred on average. Therefore, it seems that natural ventilation during the daytime can ruin passive heating at night, resulting in high exposure of massive walls to the outdoor environment. However, the indoor temperature still was in the comfort range, indicating that activating the heating system was not required. The sharp change of temperature at 6 p.m. was due to changing the vent mode. As a result, the Trombe wall with natural daytime ventilation and passive heating for nighttime is recommended to be used for November.

Fig. 13. The trend of temperature for the reference room and the room containing Trombe wall with and without natural ventilation for an autumn day (November 2).

Comparing the graphs of spring and autumn showed, in the case with higher outdoor temperatures, natural ventilation induced by Trombe wall performed better than cross ventilation of the reference room. In lower outdoor temperatures, the efficiency of natural ventilation was reduced during the daytime, and it also increased the risk of overcooling during the night. The highest heating efficiency of the Trombe wall was reported at 7 p.m. (4 °C) on an autumn day, while its highest natural ventilation efficiency was observed at 9 p.m. (5 °C) on a spring day. As a result, natural ventilation is recommended to improve the thermal efficiency of the Trombe wall in moderate seasons.

3.3.4. The optimum monthly schedules

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Based on the results of previous sections, a series of preliminary simulations were carried out to determine the appropriate monthly shading and ventilation schedule under different outdoor conditions considering the number of sunny days throughout the year. The target was obtaining the optimum indoor thermal condition for the room with the Trombe wall. Tables 9 and 10 show the year's hourly vent and shading schedules. Fig. 14 shows that, in the summer the internal vents are closed, and external vents of the glass wall are open to prevent overheating. At the same time, blinds were activated during the daytime. Therefore, the Trombe wall acted as thermal insulation, and a HVAC system is required. During the moderate seasons, to take advantage of natural ventilation, the room north opening in addition with upper vents of the Trombe wall and upper and lower vents of the glass wall were open. In these moderate seasons, the shading system was not required, except in May and June, while the mobile insulation was only used for December nights. In the winter, passive heating was activated for the indoor space by closing the external vents and opening the internal vents of the Trombe wall. To prevent heat loss, blinds were applied during the nighttime as mobile insulation. As Table 10 shows, November is the only month with two different daily strategies (daily natural ventilation and nocturnal passive heating).

Table 9. The hourly schedule of blinds and mobile insulation for the Trombe wall during the year.

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00-06:00	[orange]	[orange]			[orange]	[orange]	[orange]	[orange]	[orange]			[orange]
07:00-17:00					[orange]	[orange]	[orange]	[orange]	[orange]			
18:00-24:00	[orange]	[orange]			[orange]	[orange]	[orange]	[orange]	[orange]			[orange]

Table 10. The hourly schedule of vents for the Trombe wall along with different thermal and ventilation strategies during the year.

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00-06:00	[orange]	[orange]	[orange]	[yellow]	[yellow]	[yellow]	[white]	[white]	[white]	[yellow]	[orange]	[orange]
07:00-17:00	[orange]	[orange]	[white]	[yellow]	[yellow]	[yellow]	[white]	[white]	[white]	[yellow]	[yellow]	[orange]
18:00-24:00	[orange]	[orange]	[orange]	[yellow]	[yellow]	[yellow]	[white]	[white]	[white]	[yellow]	[orange]	[orange]

Passive heating (orange), Natural ventilation (yellow), Thermal insulation (white)

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Fig. 14. The daily and nocturnal operation modes of the optimum Trombe wall during heating (a), cooling (b), and moderate (c) seasons.

4. Energy and CO_2 saving

In this section, the contribution of the Trombe wall in the reduction of cooling and heating loads due to implementing different strategies for each month was calculated and compared with the reference room using an HVAC system. Fig 15 illustrates the room with optimum Trombe wall monthly cooling and heating energy needs compared to the reference room. To more precisely evaluate the energy, similar ventilation modes during each month for the room with the Trombe wall and the reference room were assumed. It means that, for the summer and winter seasons, both rooms are insulated, while in moderate seasons, natural ventilation is applied for both cases (cross ventilation for the reference room and natural ventilation for room with Trombe wall).

In the winter, the Trombe wall was used for passive heating. As Fig. 15 shows, the application of the Trombe wall could almost fulfill the heating requirements of the room except for January, which still heating system is needed. However, this month also had the highest reduction of energy needs when the heating demand of 211 kWh dropped to 66 kWh. It confirms the high efficiency of the Trombe wall in conditions with high solar radiation intensity. A considerably various trend was observed in the summer. As indicated by the thermal analysis, the Trombe wall only could act as thermal insulation on days with hot outdoor temperature. The graph shows that even in insulation mode, the negative effect of the Trombe wall on the cooling load of the room is observed, since it was slightly higher than the cooling needs of the reference room in September.

Fig. 15. The monthly cooling and heating energy demands of the room with optimum Trombe wall relative to the reference room comparison.

During the moderate seasons, passive heating and natural ventilation were implemented. During this period, although by implementing the Trombe wall the room heating loads were almost fulfilled, a partial increase of the cooling demand was observed (especially in June). The natural ventilation reduced the cooling loads in the reference room and the room containing the Trombe wall in April, May, and October due to the relatively low ambient temperatures during the vents activation time. However, the efficiency of natural ventilation provided by the Trombe wall is not prominent compared to cross ventilation in the reference room. Therefore, according to the energy graph, the highest thermal performance of the Trombe wall belongs to the winter and after the autumn, when the Trombe wall is in the passive heating mode. In the presence of the Trombe wall, natural ventilation can be used for five months of a year during the moderate seasons.

As Table 11 shows, overall, the heating energy can be saved about 86% using the Trombe wall, while it slightly increased cooling energy by about 5%. Therefore, on average, the room's energy consumption was reduced by 63% per year (equal to 683 kWh), resulting in the CO_2 emission reduction by approximately 124 kg.

Table 11. The annual heating and cooling requirements of the room with Trombe wall (optimum case) compared to the reference room.

Case	Heating (Gas) kWh	Cooling (Electricity) kWh	Co2 Emissions (kg)
Room with optimum Trombe wall[1]	108.2	278.5	219.9
Reference room[2]	805	264	343.8

[1]Room with 2/3 area ratio concrete Trombe wall and scheduled ventilation and shading
[2]Room without Trombe wall with the same scheduled cross ventilation

5. Payback period calculation

To estimate the entire cost of retrofitting the Trombe wall to the room, considering the construction materials and installation costs, and external attachments such as blinds for shading and insulation, the total cost of the Trombe wall was equal to 160 Euros. Under real conditions, the heating season's energy need (from November to March) was 70.6 kWh/m^2. Regarding the amount mentioned above, the cost of natural gas, the cheapest and the most used fuel in housing, for the entire heating season was 6.4 Euros/year. The cost for gas was 0.083 Euro/m^3.

The same calculation was carried out for the room with Trombe wall incorporated, and the consumption was estimated equal to 9.5 kWh/m^2. Therefore, according to the data, the payback for the low-cost Trombe wall was around 28 years, considering the least favorable scenario (with the high performance, cheapest fuel, and masonry materials).

The energy values demonstrated in Tables 11, and 12 indicate the relatively high savings, whereas the payback period is quite long. It is because compared to the average world price, the price of gas in Iran is quite low (about one-tenth of the world prices) [33, 56]. Therefore, despite the high thermal performance of the Trombe wall, it is not assumed a low-cost retrofit action in the locality of Yazd, Iran.

Table 12. Summary of cost evaluation for implementing Trombe wall.

Item	Reference room	Room with Trombe wall	Unit
Initial investment	-	160	Euros
Heating demands (per meter)	70.6	9.5	kWh/m^2
Unit price per m^3	0.083	0.083	Euro/m^3
Annual expenditure in Heating	6.44	0.86	Euros
Payback period	-	28	Year

6. Conclusion

This study presented the annual efficiency of a Trombe wall attached to a bedroom façade, as a retrofitting system, in Yazd with a hot and arid climate. Different Trombe wall configurations and materials were investigated for the selected days of winter and summer seasons. A concrete Trombe wall with 2/3 of the façade area was determined as the optimum model. Then, to improve the yearly thermal efficiency of the Trombe wall, various ventilation strategies and shading and mobile insulation modes for the external glass wall were examined. It was determined by setting a schedule for vents and blinds for each month separately. The blinds were applied to avoid solar radiation penetration during the summer and enhance the thermal resistance of the system during winter nights.

According to the results, three operational modes are proposed for the Trombe wall during the year, including passive heating and nocturnal mobile insulation for winter, insulation mode with shading for summer, and natural ventilation for moderate seasons. Trombe wall has its highest efficiency in passive heating mode during the heating season with an 86% heating load reduction. While its lowest efficiency is reported during the cooling season when even in insulation mode, the presence of the Trombe wall increases the cooling load by 5%. A combination of natural ventilation and shading can control overheating of the room with the Trombe wall during the moderate seasons. However, compared to cross ventilation in the reference room, the cooling efficiency of natural ventilation provided by the Trombe wall was not significant. In addition, the shading effect of blinds covering the external glass wall of the Trombe wall in summer was more significant than its insulation effect for the winter night.

In the winter, the passive heating provided by the Trombe wall is enough to obtain comfort conditions except for limited hours of night time which activation of the heating system is required. In the summer, the activation of HVAC is needed to keep the indoor temperature within the comfort limit. For moderate seasons, natural ventilation is influential for most of the time (four months), except for December with passive heating and November with various day and night strategies (natural ventilation and passive heating, respectively). In conclusion, retrofitting the Trombe wall in the room reduced the annual energy demand by 63% (equal to 683 kWh), equal to a reduction of 124kg CO_2 emission. Despite its high heating efficiency, the estimated payback period is prolonged due to low fuel prices in Iran compared with the world fuel prices. Therefore, the selected Trombe wall cannot be assumed as a low-cost strategy in the locality.

6.1. Future studies:

The impact of radiation temperature on comfort conditions of the room with the Trombe wall needs to be investigated. In addition, to achieve better natural ventilation, further studies on the vents design of the Trombe wall are required. Different mobile insulations for the external glass wall should be compared.

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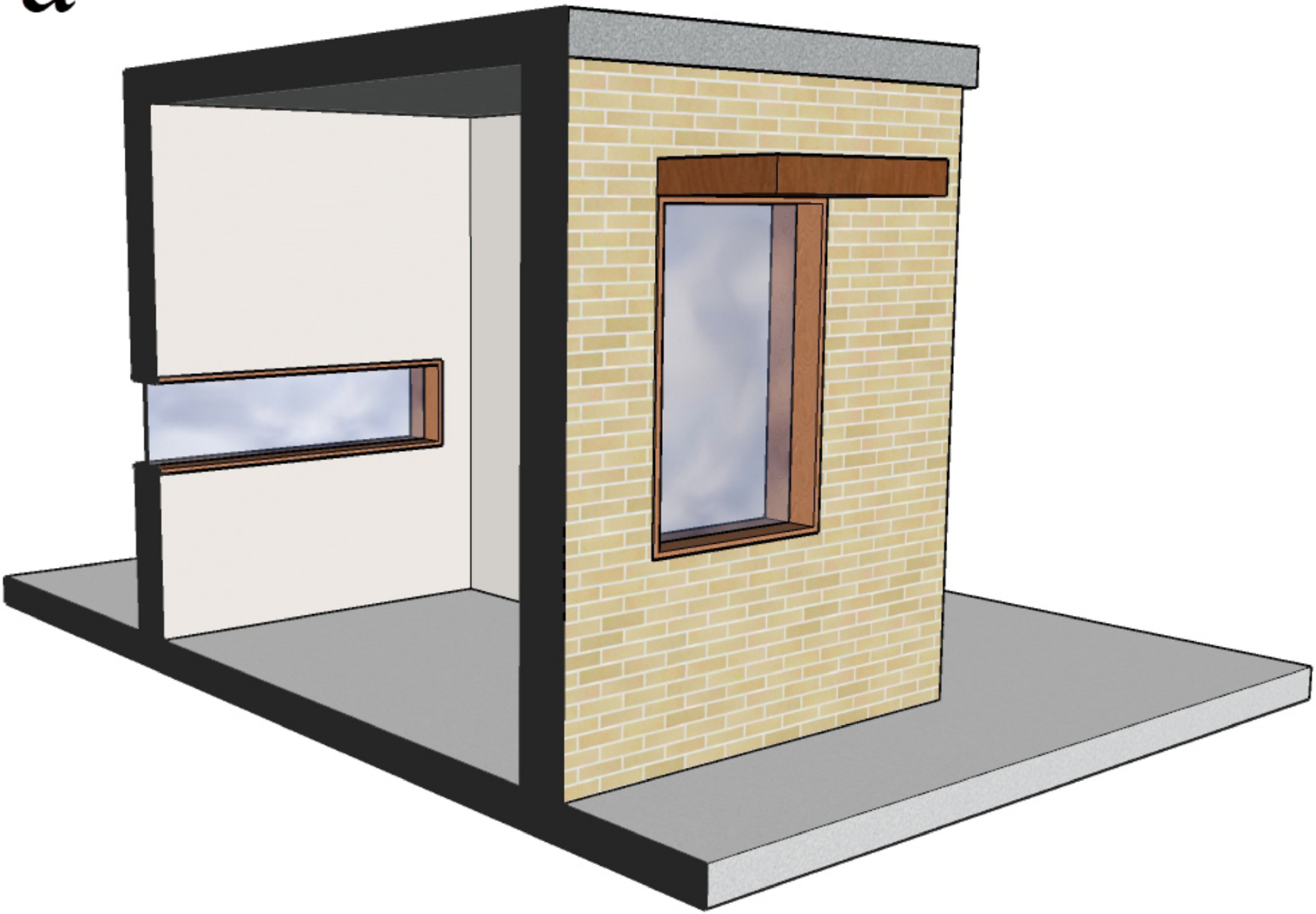
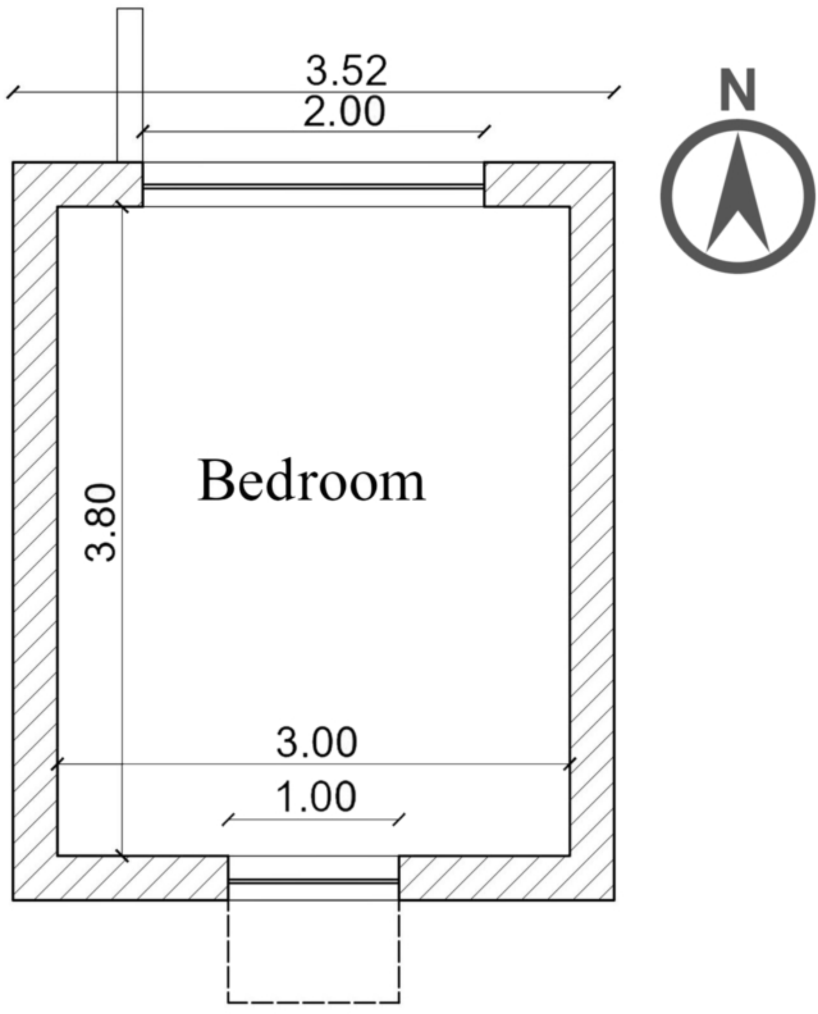
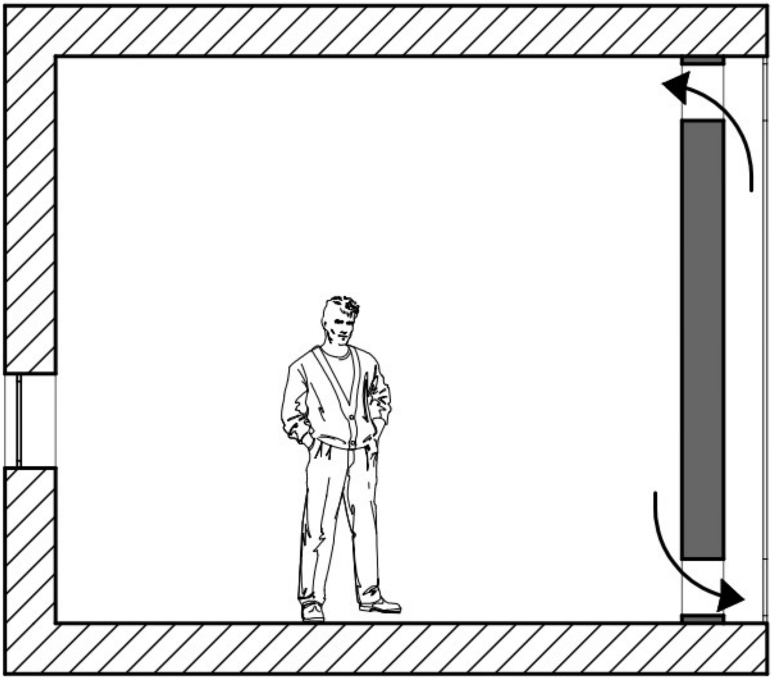
a



b

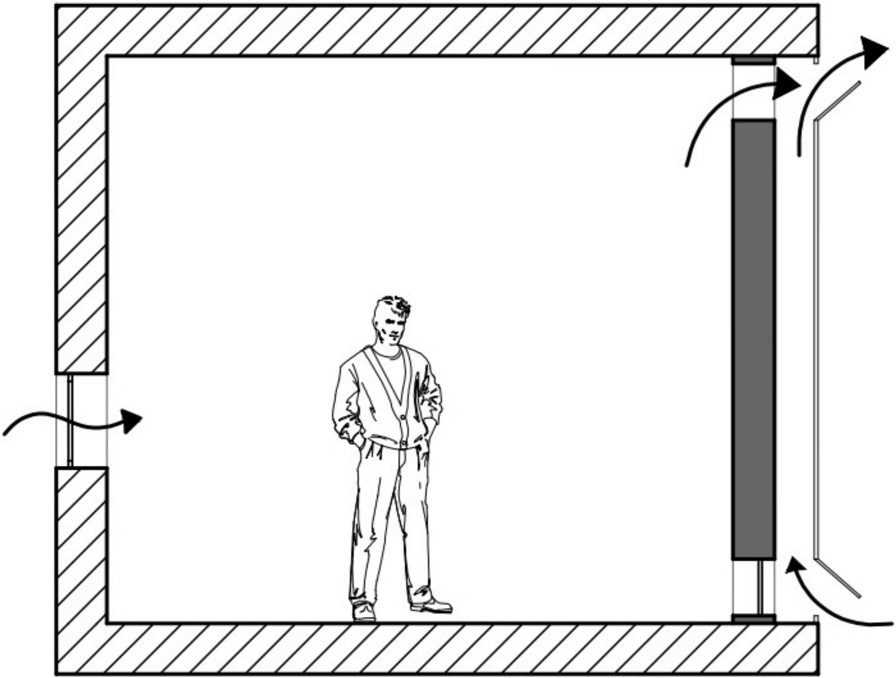


a

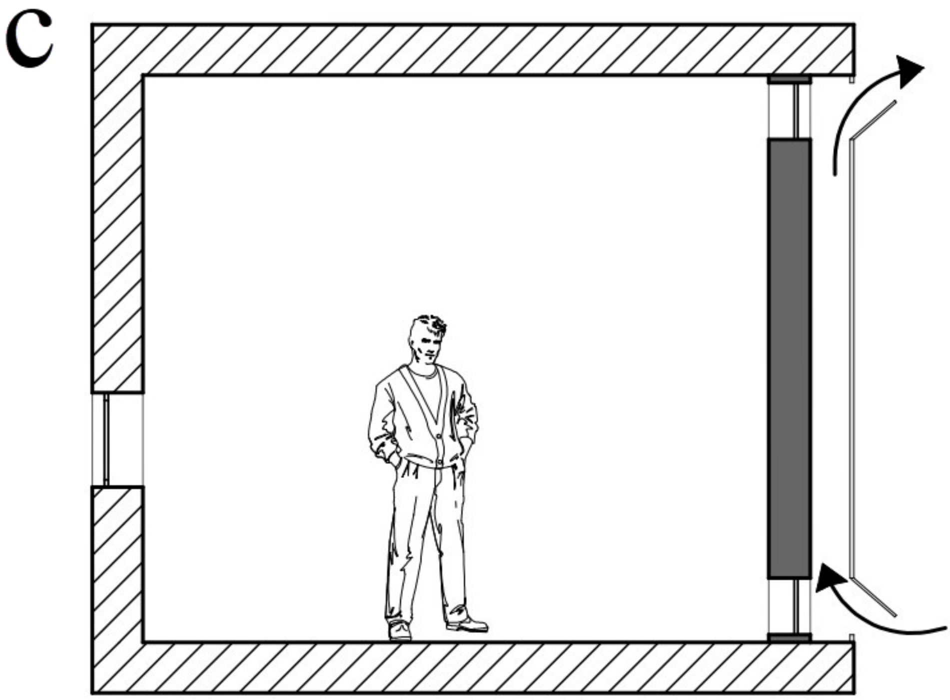


Passive heating mode

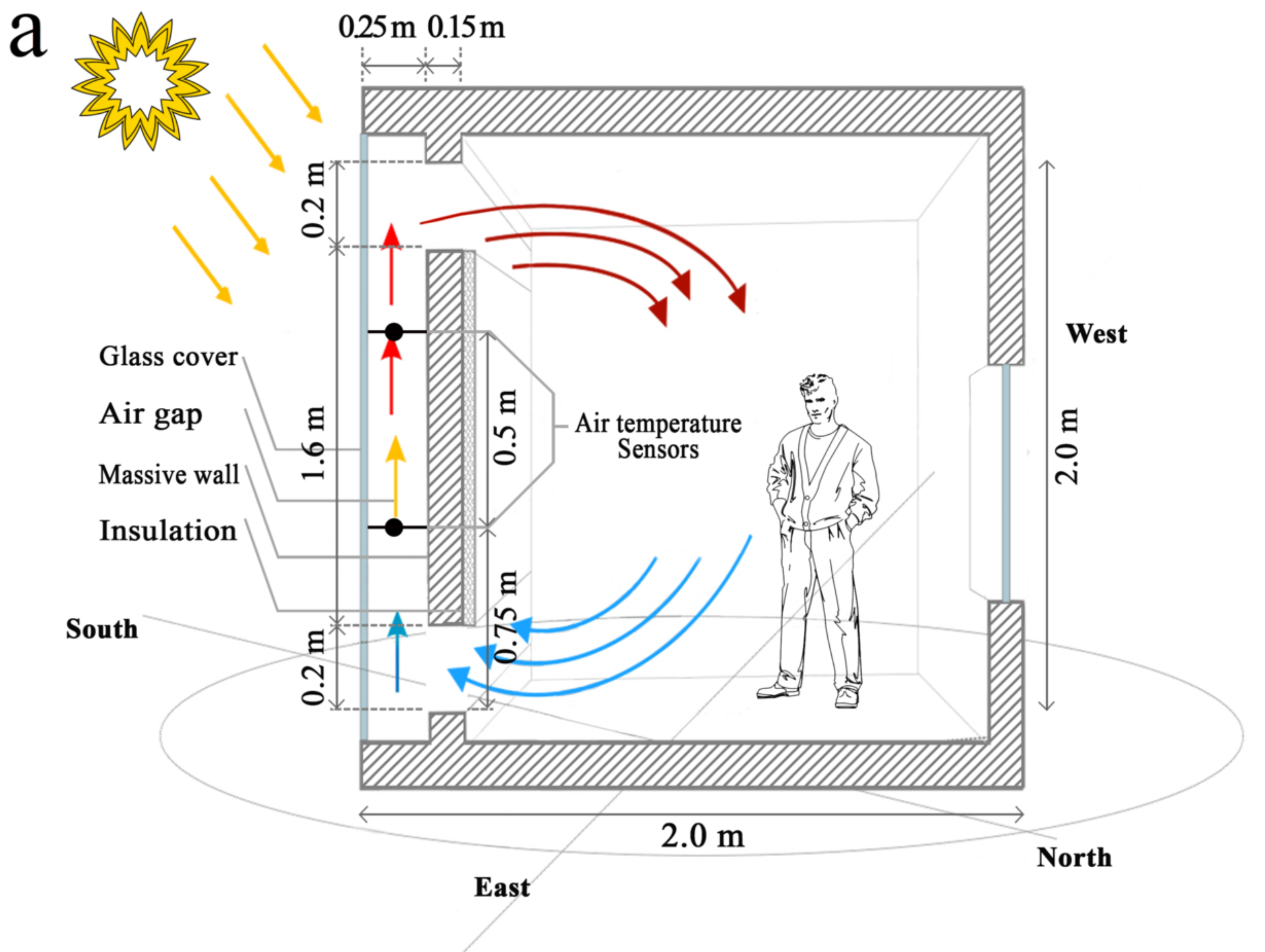
b



Natural ventilation mode

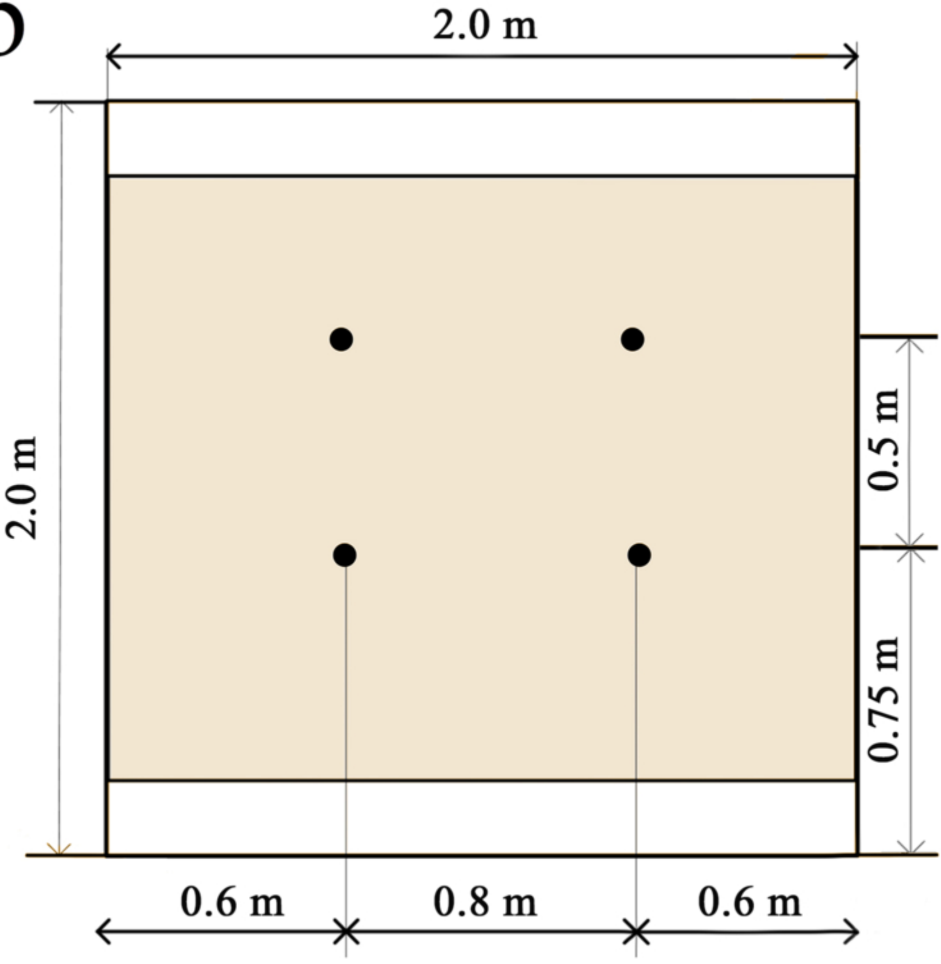


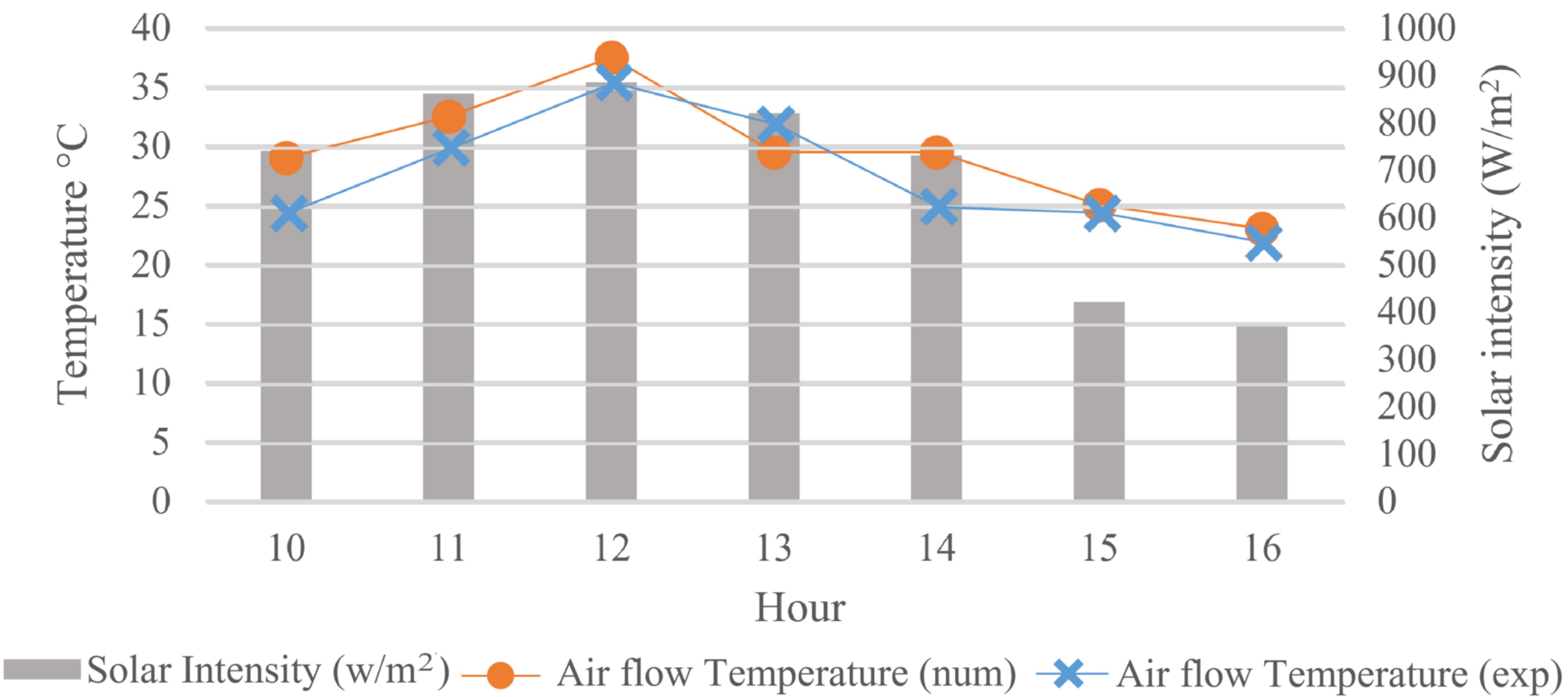
Thermal insulation mode



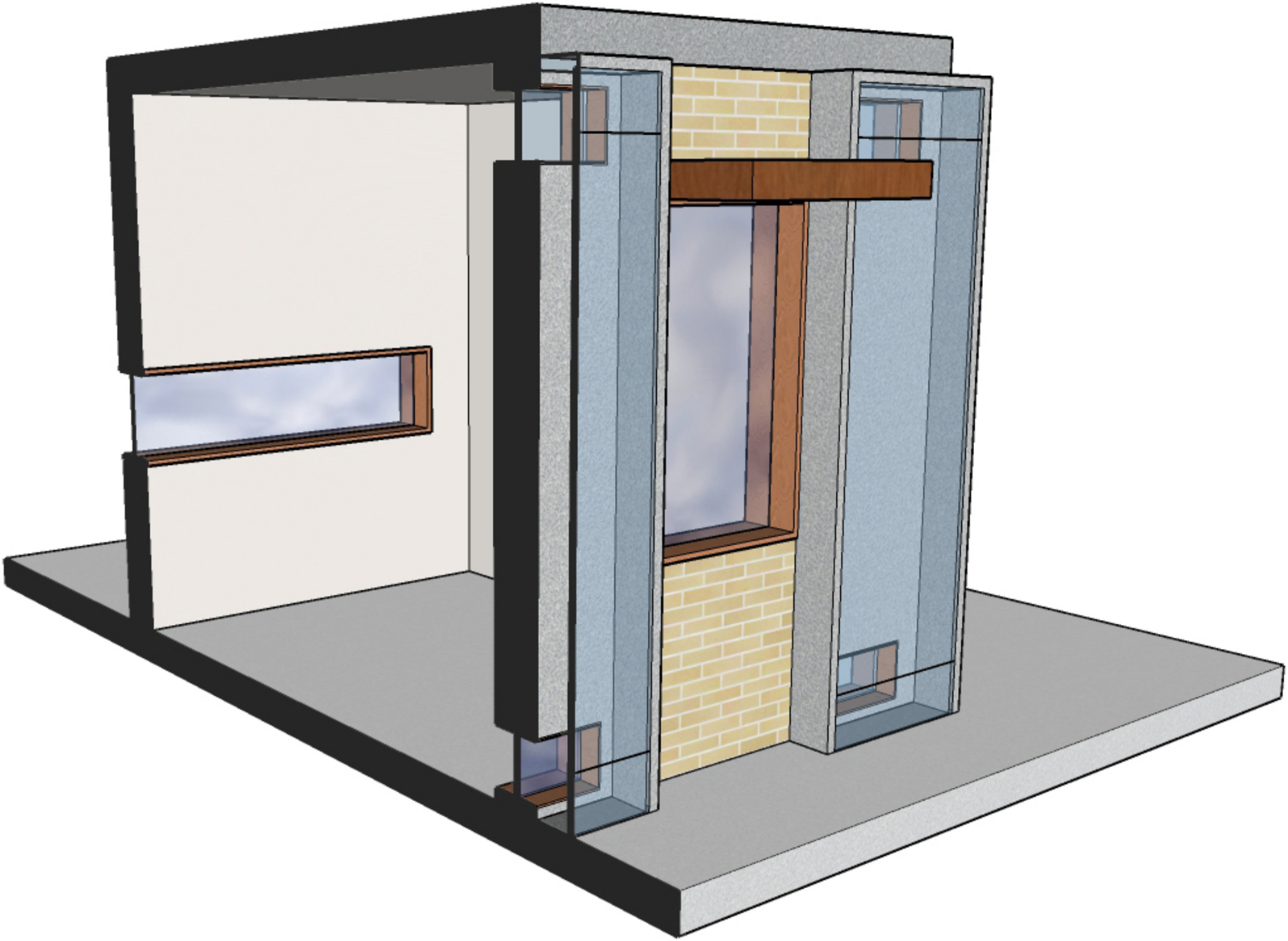
a
0.25 m
0.15 m
0.2 m
1.6 m
0.2 m
Glass cover
Air gap
Massive wall
Insulation
0.5 m
0.75 m
Air temperature
Sensors
West
2.0 m
South
2.0 m
North
East

b

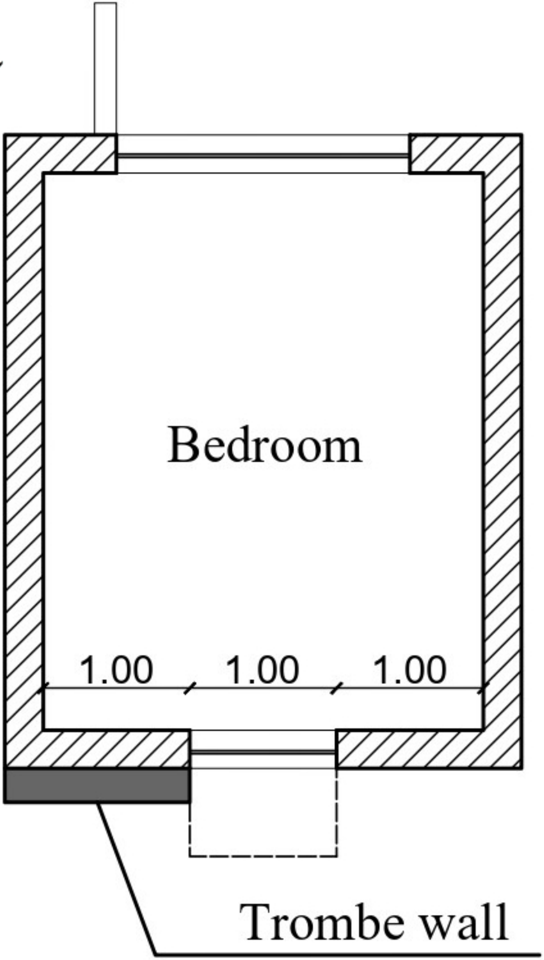




Temperature °C
40
35
30
25
20
15
10
5
0
1000
900
800
700
600
500
400
300
200
100
0
Solar intensity (W/m2)
10
11
12
13
14
15
16
Hour
Solar Intensity (w/m2)
Air flow Temperature (num)
Air flow Temperature (exp)



a



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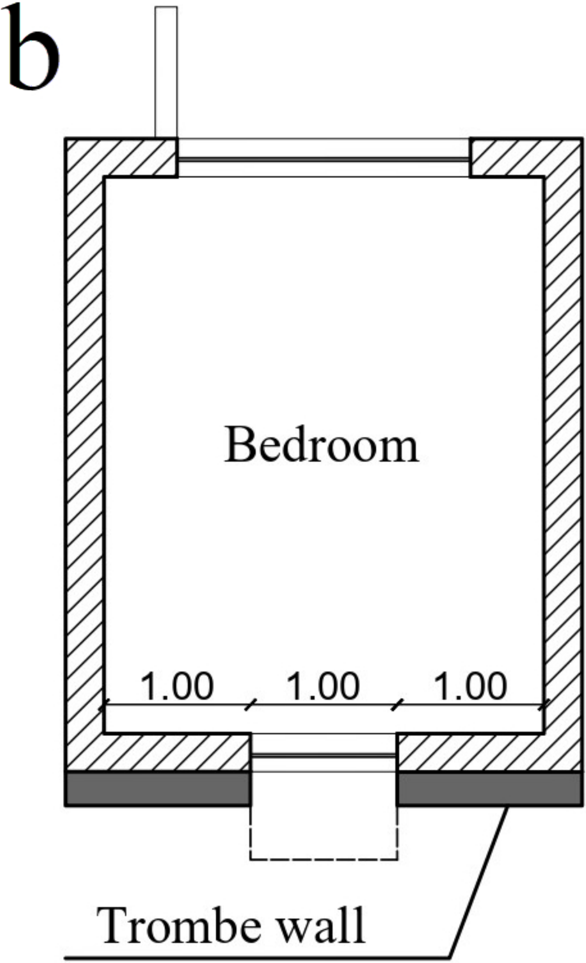
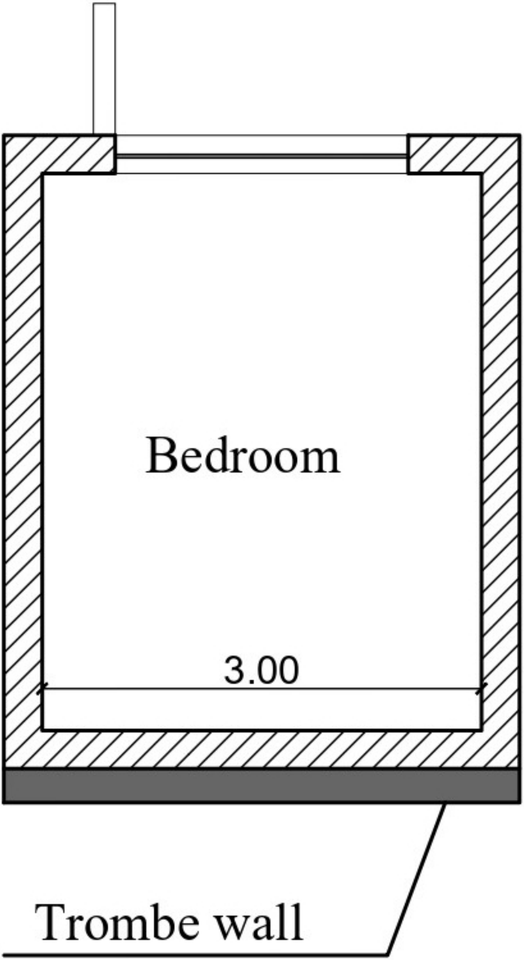
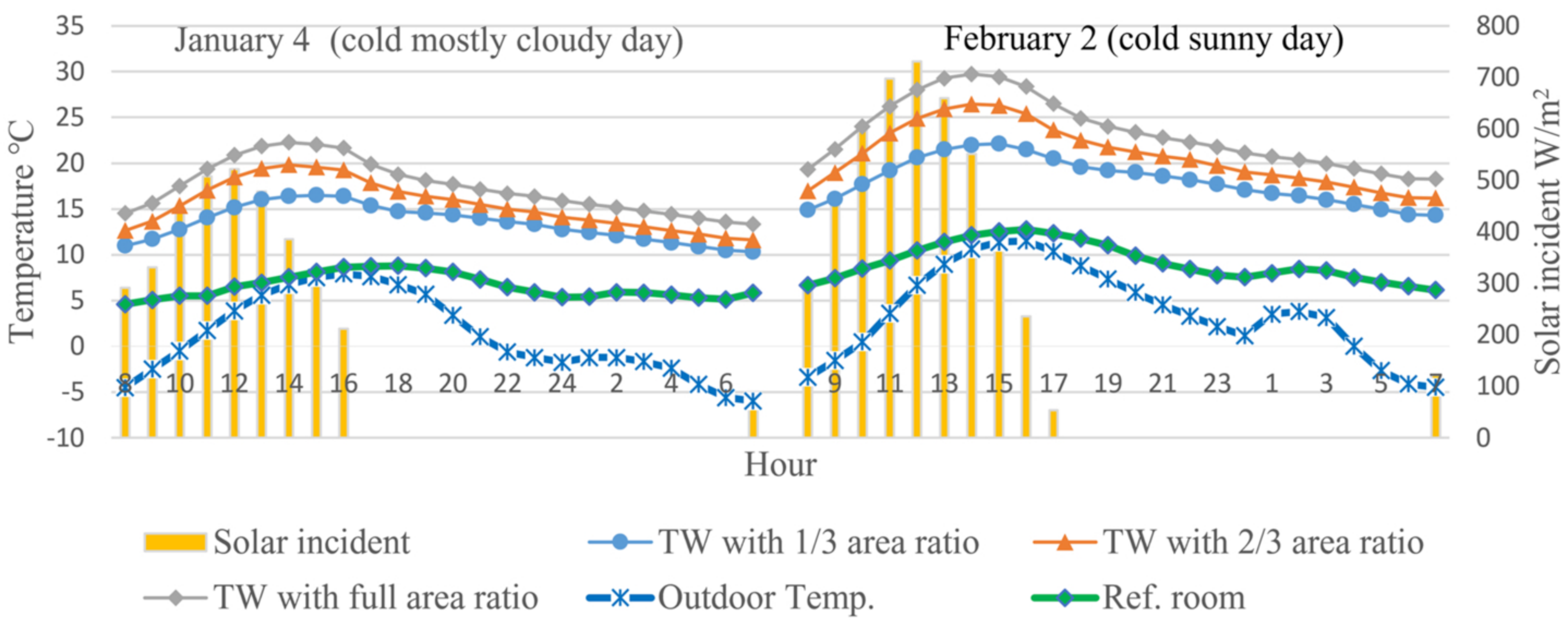
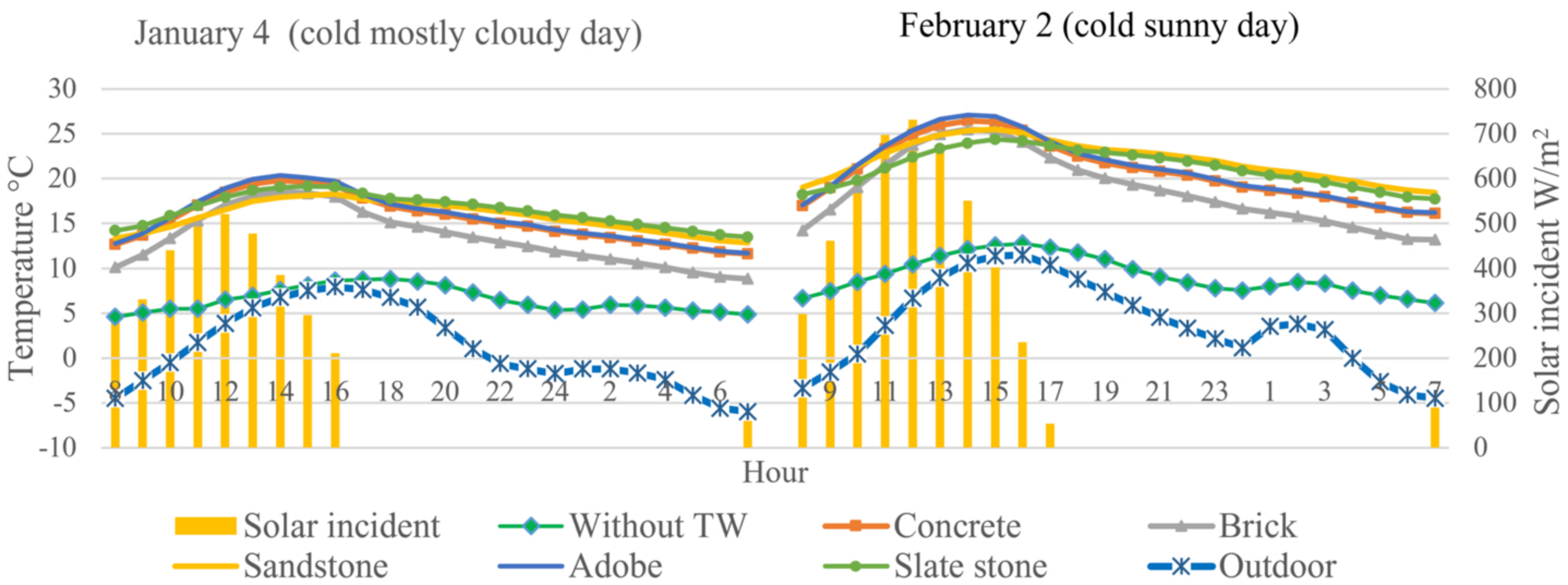
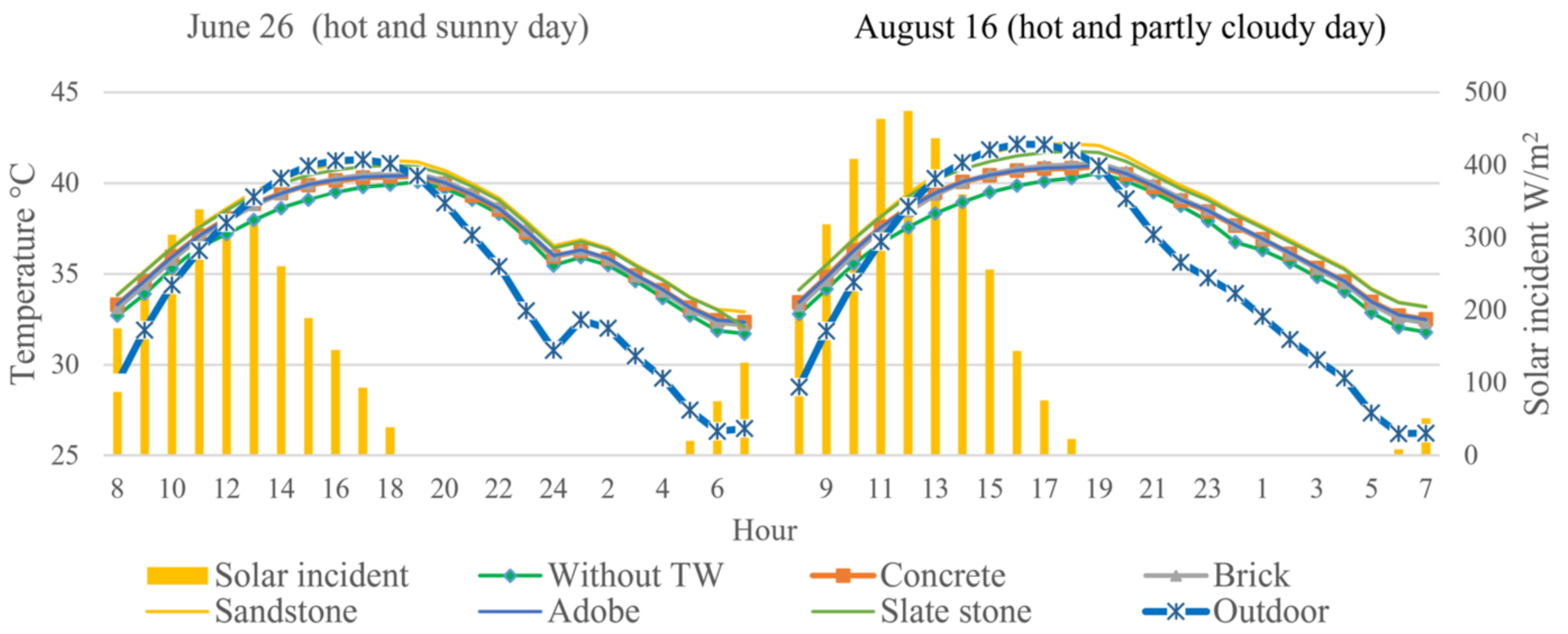


C

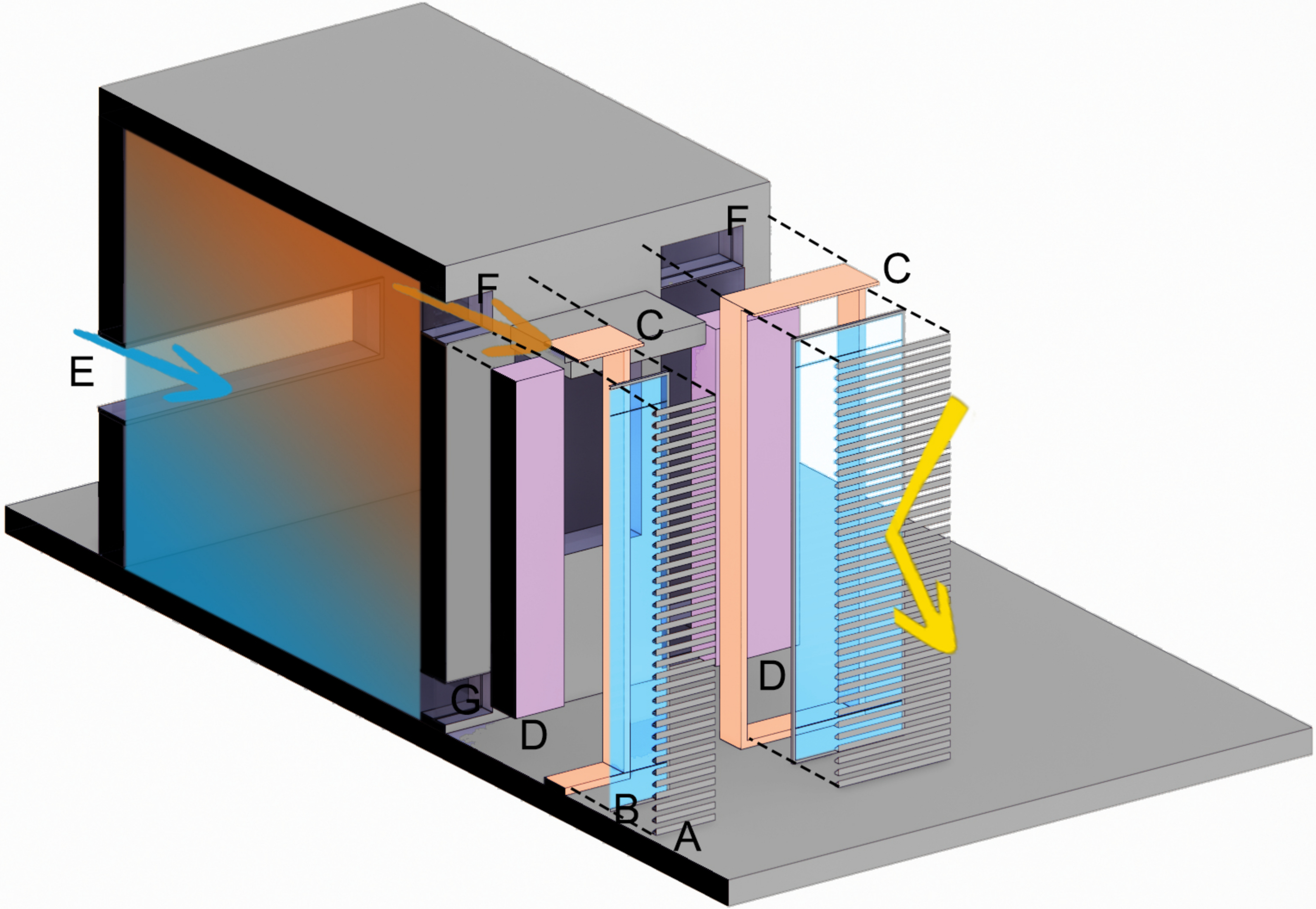



January 4 (cold mostly cloudy day)
February 2 (cold sunny day)
Temperature °C
Solar incident W/m2
Hour
35
30
25
20
15
10
5
0
-5
-10
800
700
600
500
400
300
200
100
0
8
10
12
14
16
18
20
22
24
2
4
6
9
11
13
15
17
19
21
23
1
3
5
7
Solar incident
TW with 1/3 area ratio
TW with 2/3 area ratio
TW with full area ratio
Outdoor Temp.
Ref. room

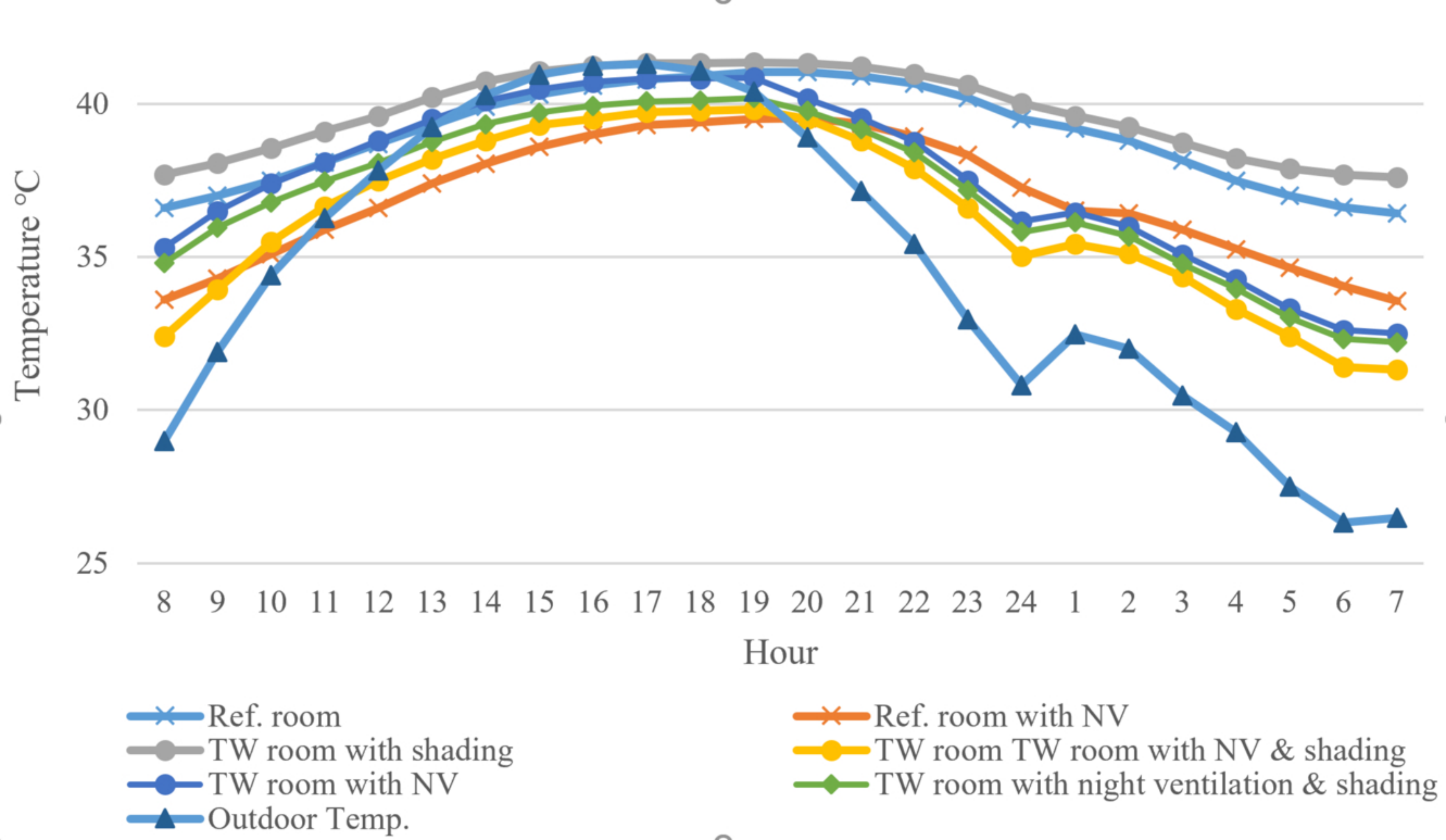

January 4 (cold mostly cloudy day)
February 2 (cold sunny day)
Temperature °C
Solar incident W/m2
30
25
20
15
10
5
0
-5
-10
800
700
600
500
400
300
200
100
0
8
10
12
14
16
18
20
22
24
2
4
6
9
11
13
15
17
19
21
23
1
3
5
7
Hour
Solar incident
Without TW
Concrete
Brick
Sandstone
Adobe
Slate stone
Outdoor

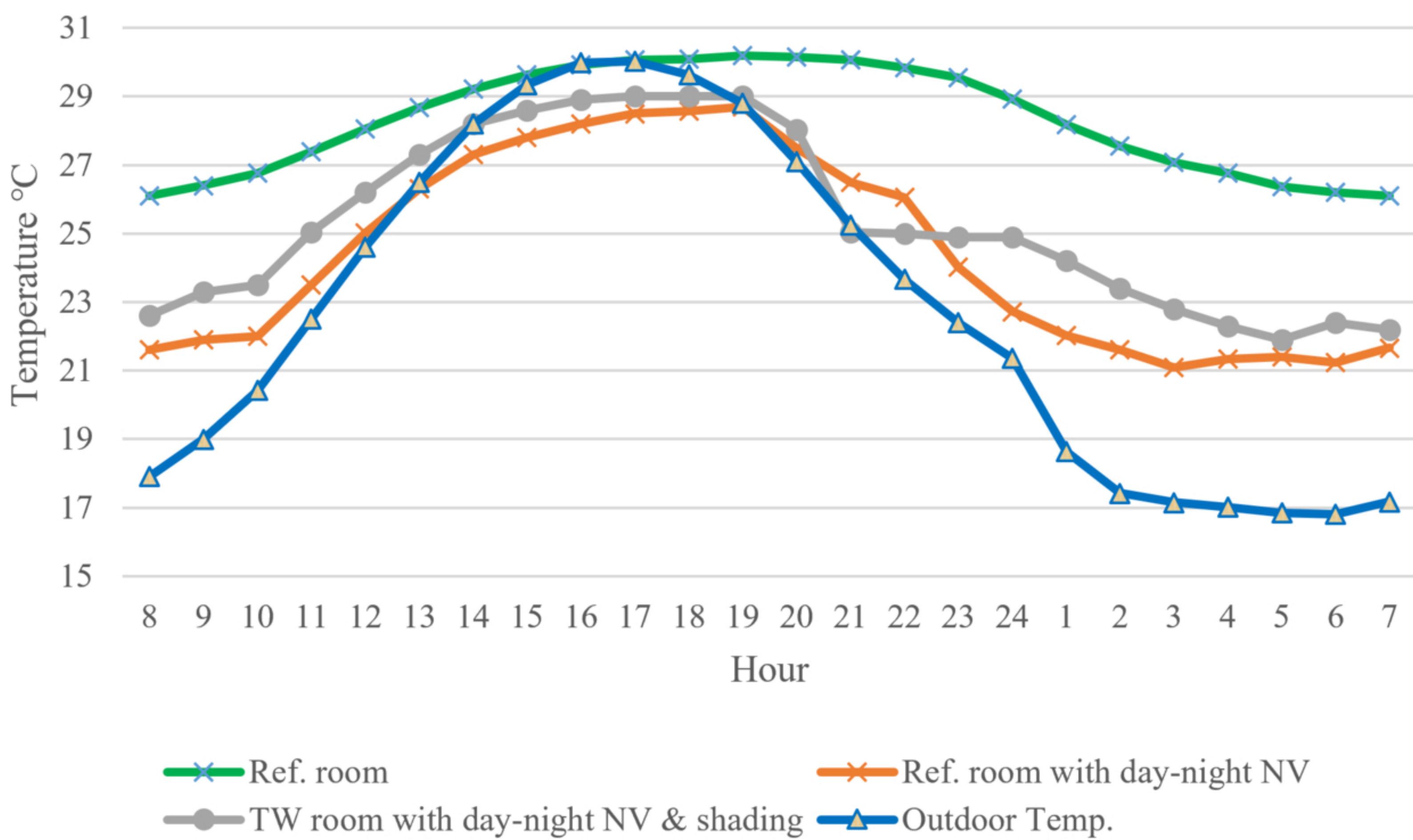


June 26 (hot and sunny day)
August 16 (hot and partly cloudy day)
Temperature °C
Solar incident W/m²
Hour
45
40
35
30
25
500
400
300
200
100
0
8
10
12
14
16
18
20
22
24
2
4
6
9
11
13
15
17
19
21
23
1
3
5
7
Solar incident
Without TW
Concrete
Brick
Sandstone
Adobe
Slate stone
Outdoor

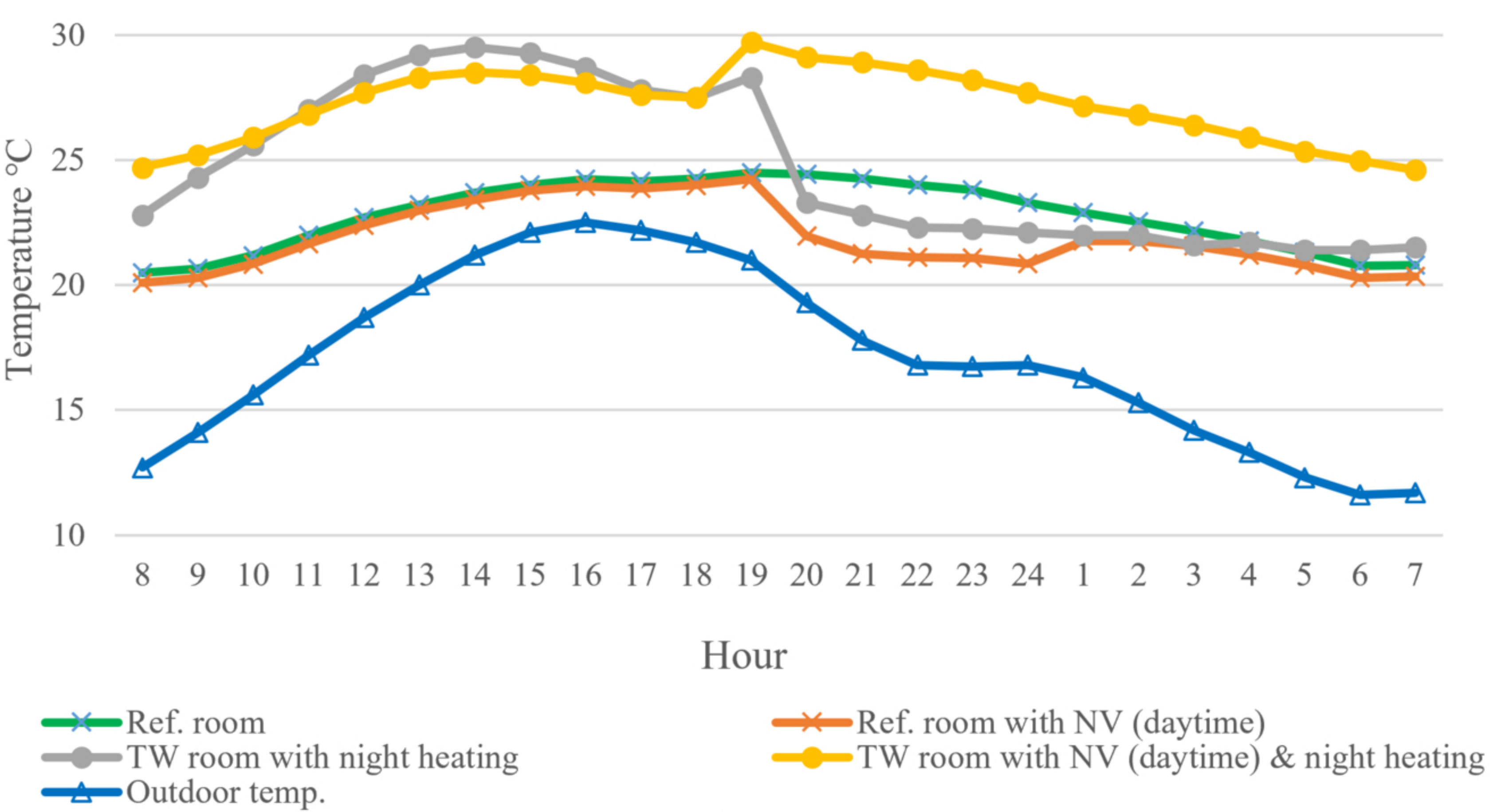


A: Blinds, **B:** Glass wall, **C:** Insulated cavity wall, **D:** Concrete wall, **E:** North opening, **F:** Trombe wall upper vents, **G:** Trombe wall lower vents.


Temperature °C
40
35
30
25
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
1
2
3
4
5
6
7
Hour
Ref. room
Ref. room with NV
TW room with shading
TW room TW room with NV & shading
TW room with NV
TW room with night ventilation & shading
Outdoor Temp.



31
29
27
25
23
21
19
17
15
Temperature °C
8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 1 2 3 4 5 6 7
Hour
Ref. room
Ref. room with day-night NV
TW room with day-night NV & shading
Outdoor Temp.



Temperature °C
30
25
20
15
10
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
1
2
3
4
5
6
7
Hour
Ref. room
Ref. room with NV (daytime)
TW room with night heating
TW room with NV (daytime) & night heating
Outdoor temp.

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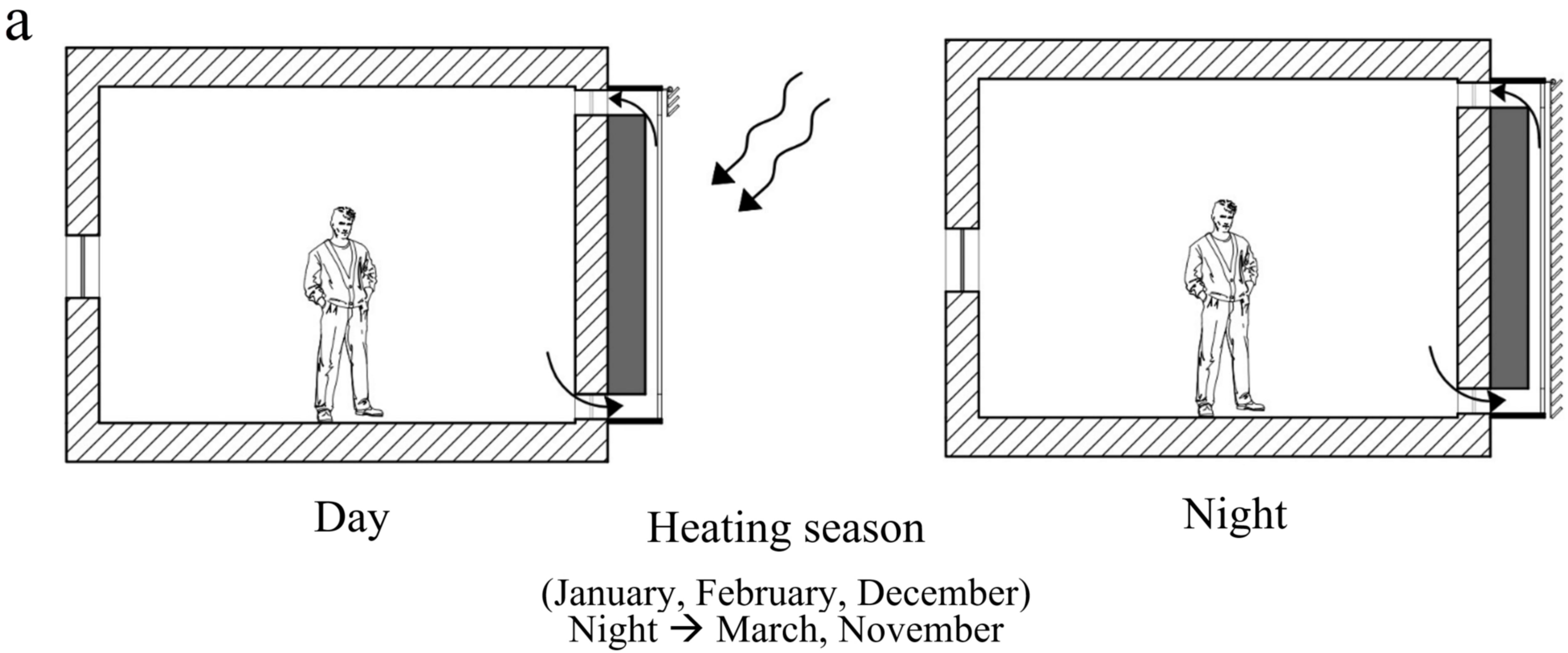
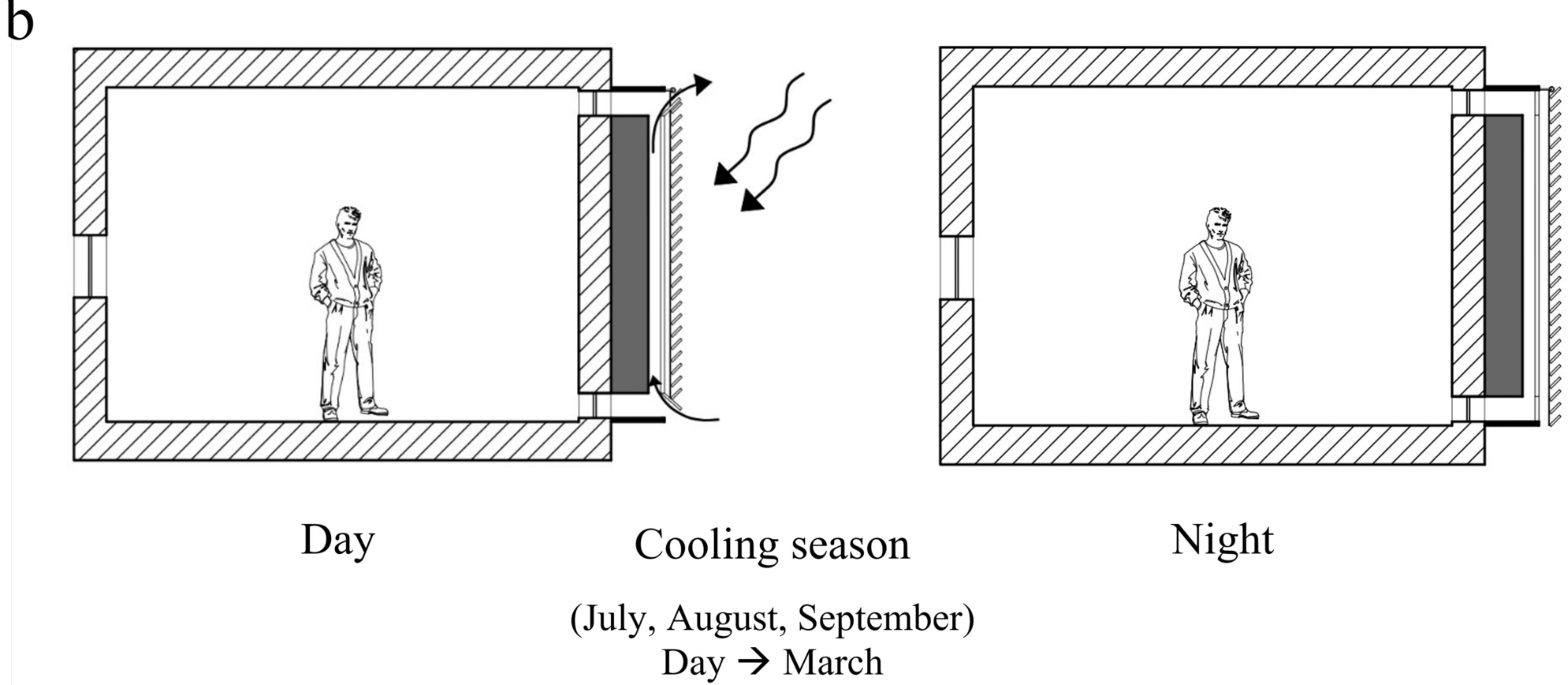
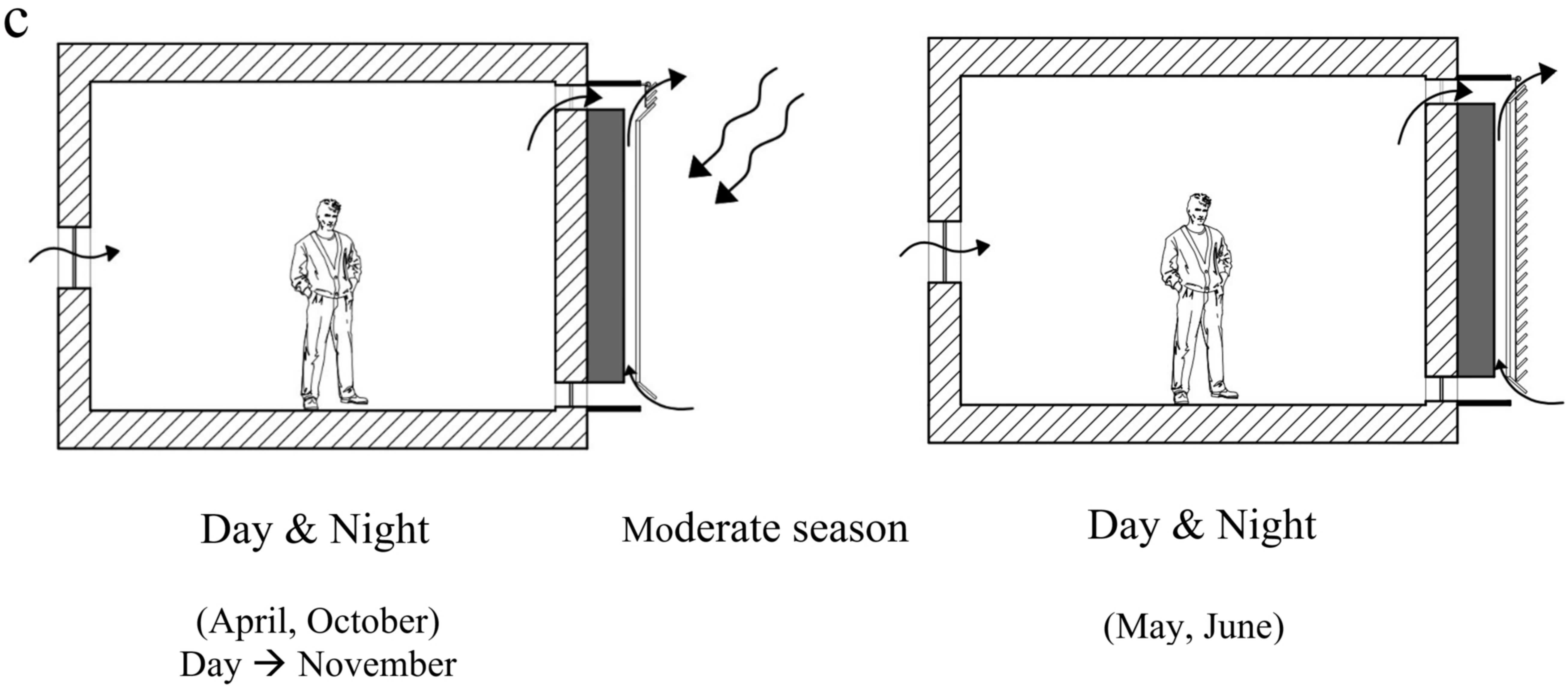
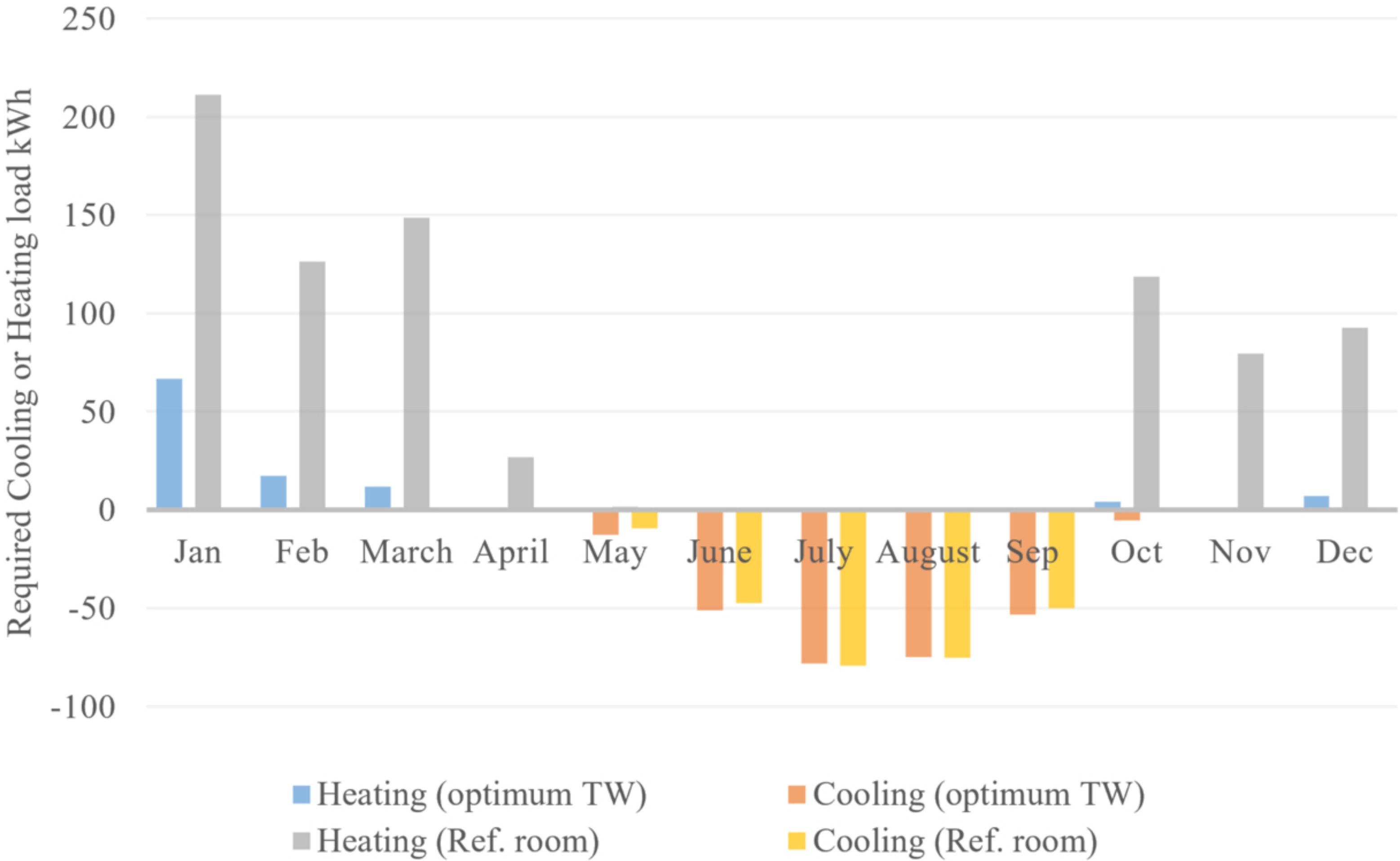


Accepted to J. Renew. Sustain. Energy 10.1063/5.0089098




c
Day & Night
Moderate season
Day & Night
(April, October)
Day → November
(May, June)


Required Cooling or Heating load kWh
250
200
150
100
50
0
-50
-100
Jan
Feb
March
April
May
June
July
August
Sep
Oct
Nov
Dec
Heating (optimum TW)
Cooling (optimum TW)
Heating (Ref. room)
Cooling (Ref. room)