Evaluation of Retrofit Passive Solar Heating for Emergencies

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https://doi.org/10.52202/077496-0019

Abstract

During war or natural disasters, the heating infrastructure of a nation can be damaged, and temporary heating is necessary. Emergency generators are often employed until infrastructure restoration. This project proposes to add a simple and inexpensive passive solar Trombe water wall consisting of individual containers as an emergency energy option. An experiment determined that the conversion efficiency of solar radiation into stored heat was 60% for the water wall. The average yearly heating performance was then calculated at two locations: Morgan Hill, CA (37.1°N latitude) and Boseman, MT (45.6°N latitude). The performances were predicted using two methods that agreed with each other. The predictions show that the water wall can supply 98% of the yearly heating requirement for Morgan Hill and 85% for Bozeman. The heating performance can be improved if the containers are tilted so that the sun's rays are perpendicular to the absorbing surface on the winter solstice.

Keywords: passive solar; Trombe wall; retrofit; emergency heating

1. Introduction

In times of war and natural disasters, the heating infrastructure of a nation can be damaged. In these situations, there is a need for emergency heating of buildings. While some energy can be restored with backup solar or fossil fuel generators, this may only supply a few hours a day on a rotating basis. A temporary retrofit passive solar system could add to that emergency energy mix by providing a warm room(s) in unheated buildings. In addition, passive solar could reduce the load on power plants.

The first use of passive solar designs for heating date back to the Greeks, Chinese, Romans, and Anasazi (U.S. Department of Energy, 2004; Wikipedia, 2023). Passive solar heating is usually incorporated into the building structure (Wikipedia, 2023; U.S. Department of Energy, n.d.; Duffie & Beckman, 1974). However, this report evaluates a temporary retrofit system that can be added to existing buildings. The concept is to build a Trombe water wall out of inexpensive and easily available materials, such as wood, plastic, or metal containers; flat black paint; water; and polystyrene insulation (Wikipedia, 2024). Alternate materials can also be used. The materials need not be new either. They can be salvaged from landfills or damaged buildings.

The Trombe water wall would be built in front of an equator-facing (±30°) window. The water wall would consist of flat black-painted containers on a shelf. During the day, the sun's rays would warm the water in the containers. At night, insulation between the water wall and the window would direct the heat into the room. The advantages of the design are that it is: 1) decentralized, 2) inexpensive, 3) constructed of common materials, 4) electricity-free, 5) easy to assemble and disassemble, and 6) low in carbon emissions. It would take a semiskilled person 1 to 2 days to do the assembly.

2. Theory

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The Trombe water wall was analyzed as a flat-plate collector. According to Duffie and Beckman (1974), the solar energy balance equation for a flat-plate collector is given in eq. 1.

$$A(\tau\alpha)S = Q_U + Q_L + Q_S \quad (1)$$

A is the solar collector area, $(\tau\alpha)$ is the transmittance-absorptance product for the clear cover, *S* is the rate of total solar radiation per unit area, Q_U is the rate of useful heat transfer to a working fluid, Q_L is the rate of energy loss, and Q_S is the rate of energy storage. But Q_U is the same as Q_S in the case of the Trombe water wall since the heat stored in the water wall is the useful heat, so $Q_S = 0$. The modified balance equation then becomes eq. 2.

$$A(\tau\alpha)S = Q_U + Q_L \quad (2)$$

This modified energy balance equation was used to evaluate the Trombe water wall. Also, the rate of energy terms were converted to energy in kWh, a common unit used by utilities.

Q_U was determined by using the water's specific heat capacity as shown in eq. 3.

$$Q_U = 2.78x10^{-7}(mC\Delta T) \quad (3)$$

where *m* is the mass of the containers' water, *C* is the specific heat capacity of water, ΔT is the water temperature increase, and $2.78x10^{-7}$ *kWh/J* converts *J* to *kWh*.

The containers were isolated by setting them on four 7-mm diameter felt pads so the heat loss would be mainly by radiation. It was then assumed that conduction and convection heat losses were negligible. The radiation heat losses, Q_L, were calculated using eq. 4, which assumes that the six containers in this experiment are a small convex object surrounded by a large enclosure, the room (Duffie & Beckman, 1974).

$$Q_L = \frac{t_1 \varepsilon_1 A_1 \sigma\left(T_2^4 - T_1^4\right)}{1000} \quad (4)$$

where t_1 is the time of energy collection in hours, ε_1 is the emissivity of the flat black-painted containers, A_1 is the total surface area of the containers, σ is the Stefan-Boltzmann constant, T_1 is the average room temperature, T_2 is the average container temperature and *1000* converts *W* to *kW*.

The heat stored in the containers at the end of the day H_b is given in eq. 5. The heat loss from the containers was added to the heat gain since that heat loss is heat gain to the room.

$$H_b = \frac{Q_U + Q_L}{A} \quad (5)$$

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The predicted heating performance *P* is given in eq. 6.

$$P = \frac{100SEA_W}{Q_r} \tag{6}$$

P is the percentage of heating supplied by solar, *E* is the conversion efficiency of solar radiation into heat in the containers, A_w is the total window area, and Q_r is the space heating requirement.

In addition to the above method, the Trombe water wall was analyzed by a second method (Mazria, 1979). The method is not reproduced here but the source is listed in the references.

Finally, the predicted daily average indoor temperature t_i is given in eq. 7 (Mazria, 1979).

$$t_i = \frac{HG_{sp}}{U_{sp}} + t_0 \tag{7}$$

HG_{sp} is solar heat gain, U_{sp} is the overall coefficient of heat transfer, and t_0 is the average daily outdoor temperature.

3. Methodology

Equipment

The experimental setup is shown in Figure 1 and is a scaled-down version of a Trombe water wall. The containers on the lower shelf are tilted at 60° and those on the upper shelf are tilted at 90°. The equipment was set up in an unheated room of a house where the equator side of the house faced 160° south. The house is located near Morgan Hill, CA at 37.1°N latitude. Even though the room was unheated, two adjacent rooms were heated. Prior to setup, the containers were painted with a flat black paint. The containers were placed on the wood shelf 28 cm from a double-pane window that is made of standard window glass. A single container's fluid capacity is 3.875 L (1 gallon). Calibrated thermocouple temperature meters measured the water, room air, and outside air temperatures. Calibrated solar power meters measured cumulative solar radiation at 60° and 90° tilts.

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Fig. 1. Experimental setup showing six flat black painted and water-filled containers on a shelf. The containers on the lower shelf are tilted at 60° and those on the upper shelf are tilted at 90°. (Photo credit: Martin Smallen)

The equipment list is shown in Table 1.

Table 1. Equipment List

Item	Manufacturer Model Number
Solar Power Meter (2 ea)	TES-132
Thermocouple Thermometer (3 ea)	Perfect Prime TC41

Procedure
In the morning of each day, the polystyrene insulation was removed from the space between the water containers and the window. The initial temperature and solar radiation measurements were recorded in the morning and the final measurements were recorded in the afternoon. There were no measurements in between. At the end of the day, the polystyrene insulation was placed back between the containers and the window. A typical data sheet is shown in Table 2.

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Table 2. Typical data sheet.

Site Info.	Tilt (°)	Date	Start and Stop Time	Bottle Temp. 1 (°K)	Bottle Temp. 2 (°K)	Bottle Temp. 3 (°K)	Bottle Temp. 4 (°K)	Avg. Bottle Temp. (°K)	Room Temp. (°K)	Outside Temp. (°K)	Cum. Solar Rad. (kWh/m^2-Day)	Heat Gain in Bottles (kWh)	Heat Loss From Bottles (kWh)	Net Heat Gain to Bottles (kWh)	Norm. Heat Gain in Bottles (kWh/m^2-Day)
Morgan Hill, CA	90	4/9/23	9:30	291.6	291.8	291.5	291.1	291.5	291.3	283.0	0	0	0	0	0
Collector Facing 160° South			15:30	300.8	300.6	301.8	300.8	301.0	298.3	298.0	3.069	0.250	0.029	0.279	1.552

Constants used in the calculations are given in Table 3.

Table 3. Constants used in calculations.

Constant	Symbol	Value
1. Solar collector area (6 containers)	A	0.180 m^2
2. Heat capacity of water	C	4182 J/Kg-°K at 20°C
3. Mass of water (6 containers)	m	22.86 Kg
4. Emissivity of flat black paint	ε_1	0.95
5. Area of containers subject to radiation losses	A_1	0.510 m^2
6. Stefan-Boltzmann constant	σ	5.67x10^{-8} W/m^2-°K
7. Window area of test room	A_w	2.90 m^2

The predicted heating performance of the Trombe water wall was determined for two locations, one in Morgan Hill, CA (37.1°N latitude) and one in Bozeman, MT (45.6°N latitude). To do this, E was obtained from Figure 2 and was used along with National Renewable Energy Laboratory historical solar data (Marian & Wilcox, 1990) plus historical heating data from Morgan Hill (23 years) and Bozeman (3 years). In addition to this, the performance in Morgan Hill was predicted using as a check on the Duffie & Beckman method, except that actual coefficient of heat transfer (U_{sp}) was used for the Mazria method instead of the calculated U_{sp} (Mazria, 1979). The predicted room temperatures were calculated per the Mazria method. Finally, the cost was determined to build a water wall.

4. Results

Figure 2 shows that the heat stored in the containers at the end of a day is a linear function of the solar radiation. Approximately 60% of sunlight is stored as heat in the containers for both tilt angles (E = 60%). This curve is used to predict the performance of the Trombe water wall.

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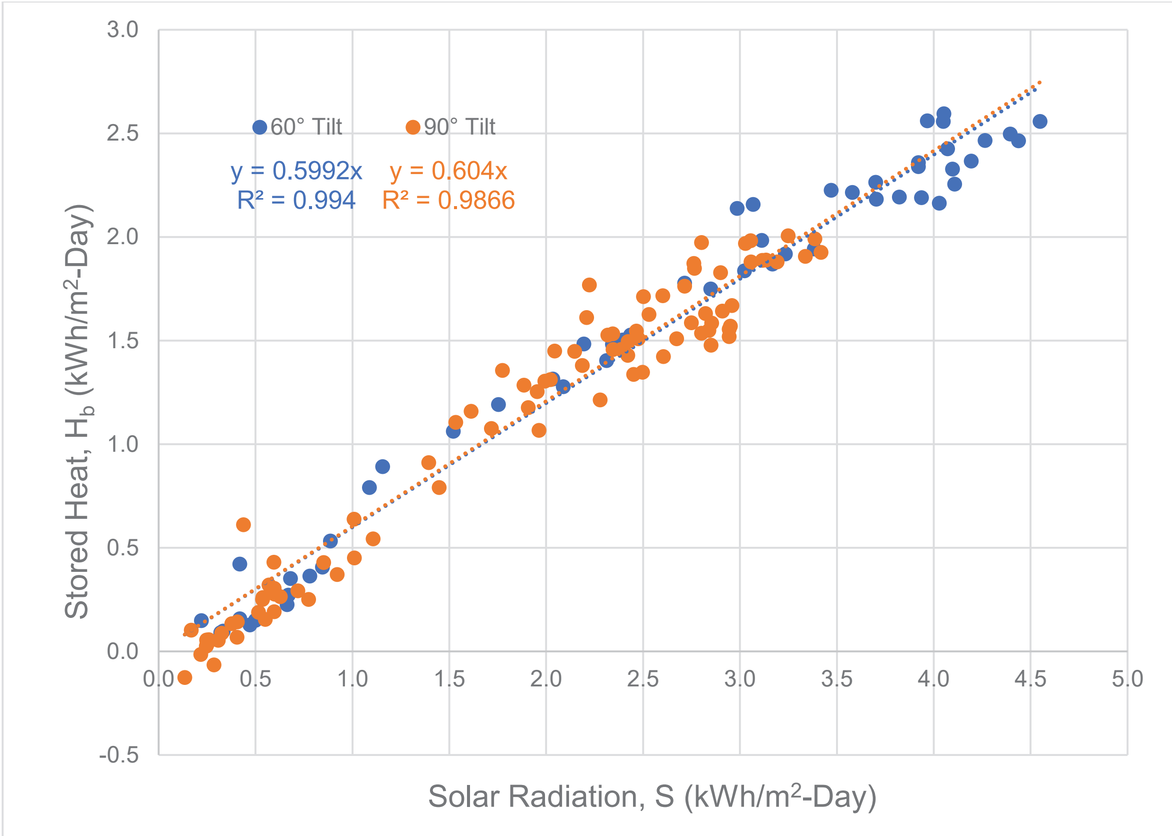

Fig. 2. Heat stored in containers at the end of each day as a function of solar radiation. S is shown in Eq. 1 and comes from solar energy meter measurements. H_b is shown in Eq. 5 and comes from temperature measurements. The slope gives E in Eq. 6.

Figure 3 shows the predicted heating performances in Morgan Hill, CA and Bozeman, MT. In Morgan Hill, the Trombe water wall supplied 66%, 71%, and 98% of the heating requirement for December, January, and the total heating season, respectively when the container tilt angle was 90°. Those numbers increased to 97% for both months and 162% for the total heating season when the container tilt angle was 60°. A 60° tilt makes the sun's rays perpendicular to the absorbing surface of the containers on December 21st, the winter solstice. Figure 3 also shows the predicted heating performance in Bozeman, MT. Here the Trombe water wall supplied 56%, 50%, and 85% of the heating requirement for December, January, and the total heating season, respectively when the container tilt angle was 90°. Those numbers increased to 66%, 61%, and 108% when the container tilt angle was 69°. A 69° tilt makes the sun's rays perpendicular to the absorbing surface of the containers on December 21st. The asymmetric shape of the curves is due to dividing a large number (stored heat) by a small number (heating requirement) in November and March compared to the rest of the heating season. The reason the water wall exceeds 100% for the total heating season is that some months exceed 100%.

In Mazria's method, the solar contribution is truncated for those months when it exceeds the heating requirement. If that is done with the Duffie and Beckman method, then the percentage of the yearly heating requirement supplied by solar for Morgan Hill is 87% for the Duffie and Beckman method and 79% for the Mazria method.

The predicted average daily indoor temperature for the rooms at each location is given in Table 4. In Morgan Hill, monthly temperatures range from 18.1°C to 27.0°C for a 90° tilt and 19.0°C to 30.3°C for a 60° tilt. In Bozeman, monthly temperatures range from 8.7°C to 27.0°C for a 90° tilt and 9.4°C to 31.2°C for a 60° tilt. The December and January indoor temperatures are cool in Bozeman but still substantially warmer than outside, which is -4.4°C to -5.6°C.

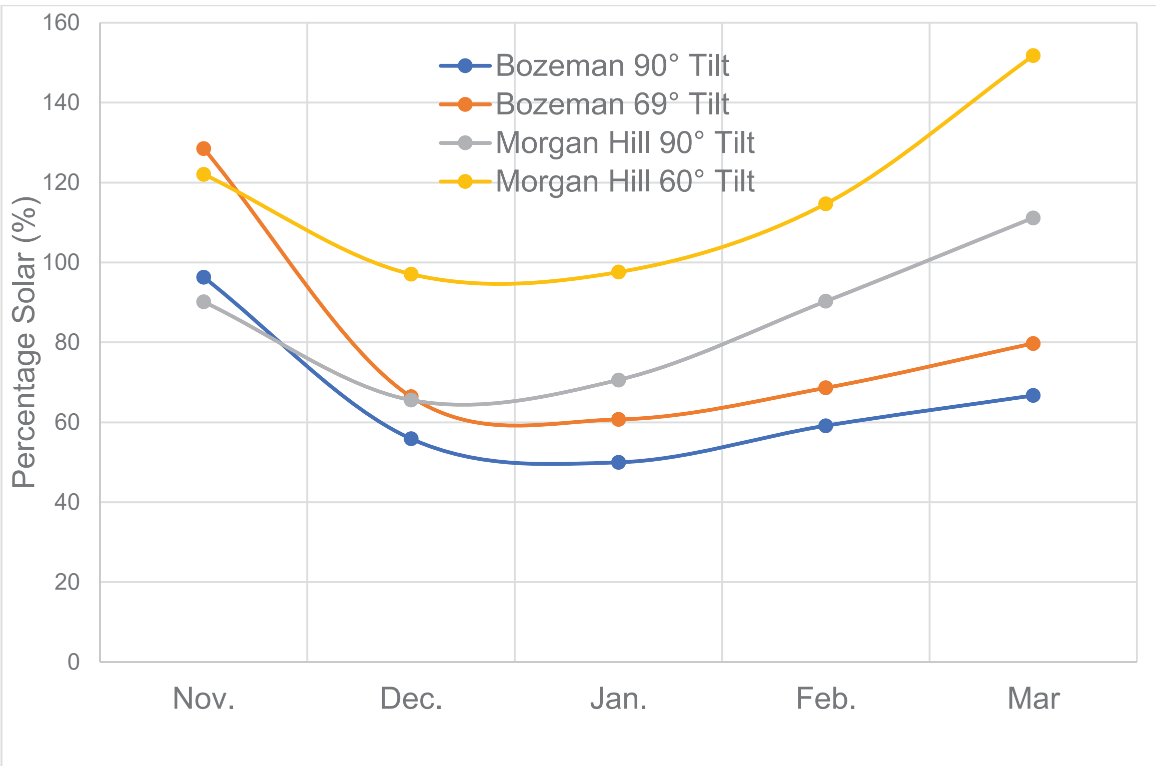

Fig. 3. Predicted heating performance for Morgan Hill, CA, USA (37.1°N latitude and window area = 2.90 m^2) and Bozeman, MT, USA (45.6°N latitude and window area = 1.78 m^2).

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Table 4. Predicted daily average indoor temperature for each month

Month	Room Temperature (°C)			
	Morgan Hill, CA		Bozeman, MT	
	60° Tilt	90° Tilt	69° Tilt	90° Tilt
Sept.	30.3	27.0	31.2	27.0
Oct.	27.7	25.6	25.1	22.8
Nov.	22.3	21.1	16.1	15.0
Dec.	19.0	18.1	9.4	8.7
Jan.	19.7	18.5	12.3	11.2
Feb.	21.7	19.5	16.2	13.8
Mar.	22.9	19.4	20.6	16.3
Apr.	23.8	19.4	22.3	16.4

The cost to construct a passive solar Trombe water wall was determined from 2023 USA prices and comes to \$221/m^2, excluding labor. The price can be lowered by using second-hand or salvaged materials.

5. Discussion

This project evaluated a Trombe water wall that would provide a warm room(s) in nations where the heating infrastructure has been damaged by war or nature. The water wall was designed so that it would be 1) decentralized, 2) inexpensive, 3) constructed of common materials, 4) electricity-free, 5) easily assembled and disassembled, and 6) a low-carbon emitter.

To evaluate the water wall, a curve was generated to determine the conversion efficiency of sunlight into stored heat. With that curve plus the sites' solar radiation, heating requirement and window area, the percentage of heat supplied by the water wall was calculated for each month of an average heating season in Morgan Hill, CA, USA and Bozeman, MT, USA. The same was done for the predicted room temperatures.

As expected, the predicted heating performance and room temperatures were better for Morgan Hill because it was at a lower latitude and had a larger window area. In addition, the performance improved when the container tilt angle was decreased from 90° to 60°. The water wall provided more than 100% of the heating requirement for some months of the heating season. Shading, insulation, or fewer containers would be needed for those months.

The predicted heating performance and room temperatures for the higher latitude site, Bozeman, was not as good because of the lower solar radiation and smaller window area. There was not as much performance improvement in Bozeman for December and January by decreasing the container tilt angle. That is because the solar elevations are ~9° lower in Bozeman and the sun's rays are closer to perpendicular to a 90° tilt.

https://doi.org/10.52202/077496-0019

The Mazria method was used as a check on the Duffie and Beckman method for both locations. It was found that both methods gave fairly similar results for the yearly solar contribution to the heating requirement. The differences are due to the literature sources for solar radiation.

There are several ways to improve the performance at higher latitudes. They are by adding another window, using a reflector, or applying a selective surface to the containers. Of course, these techniques increase the complexity and cost of the water wall.

There are several disadvantages of the Trombe water wall. The first is that the containers will block a substantial amount of sunlight from entering the rooms. But some containers can be removed to allow sunlight to enter the room(s). The second disadvantage is appearance. But maybe this is a small price to pay for warmth in an emergency.

One also must be aware of the loading of the water wall on the floor. The wall could weigh 227 to 454 kg (500 to 1000 lbs.) so the weight distribution on the floor needs to be considered. Lastly, the water wall should be anchored to the wall that borders the window.

6. Conclusion

Approximately 60% of sunlight can be stored as heat in a retrofit, passive solar Trombe water wall that is both simple and inexpensive. With that high conversion efficiency, two methods predict that a water wall could supply a substantial portion of the heating requirement in rooms with equator facing windows. The predictions show better results at lower latitudes. Nevertheless, enhancements can be made to improve the performance at higher latitudes such as by adding windows, reflectors, or selective surfaces.

It is proposed that this retrofit be used in countries where their heating infrastructure has been damaged by war or nature to supplement other emergency energy sources. Government policies could aid in the implementation of such a system. Those policies could include tax incentives and storage facilities with water wall kits available for emergencies.

Some limitations of this concept are loading considerations on wood floors, room sunlight blockage and aesthetics. Future work could entail comparing room temperatures with and without the water wall. Also, detaching the collector from the storage unit to alleviate overloading wood floors could be another future research topic.

Acknowledgement

I would like to thank William D. Smallen for supplying his historical heating data for Bozeman, MT, USA.

https://doi.org/10.52202/077496-0019

Conflict of Interest

The author does not report any conflicts of interest.

https://doi.org/10.52202/077496-0019

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https://doi.org/10.52202/077496-0019