Sun House

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1 Background

Carbon dioxide is a greenhouse gas, which means it increases the ability of the earth's atmosphere to trap heat from the sun, which then increases the temperature of the planet. Increasing the average temperature of the earth will lead to sea levels rising and more intense weather, especially harsher storms.

How are we contributing to this problem? Well according to a UC Berkeley project, the average Needham household produces 63.6 metric tons[1] of carbon per year. Needham and surrounding suburbs aligned with the trend of suburbs producing much more carbon per household or capita than more urban areas. Urban centers produce far less carbon per household because of smaller house/apartment sizes (so less energy to heat residences), and use of public transportation and shorter commutes to work. For example, the average Cambridge household produced 35.7 metric tons per year, which is about average for the more urban parts of Boston.

What can we do to decrease global warming? The biggest contributor to household carbon emissions is heating and cooling of the house, which accounts for around 50% of a house's electricity consumption[2]. Which is why people are now building structures to harness the heat of the sun, by making passive solar houses. Passive solar houses take advantage of the sun's rays to heat houses through structural elements like south-facing windows to let in the winter sun, materials with a high heat capacity to store the heat, and insulation to prevent heat from escaping. Adding these elements to a house would vastly decrease the household's carbon footprint, which in the US, is more than twice the global average[3].

[1] https://coolclimate.org/maps
[2] https://paylesspower.com/blog/what-uses-the-most-electricity-in-the-house/
[3] https://www.sciencedaily.com/releases/2008/04/080428120658.htm

2 Design

As you can see in Figure 1, our house has several main features that help it to collect and store heat in the winter, but avoid letting heat in during the summer. The first feature is the big south-facing window, which lets in the lower-angled winter sun, while the overhang above blocks the higher-angled summer sun. The other feature that helps let the sun in during the winter but not during the summer is the deciduous tree planted south of the windows. This type of tree, common in New England, grows leaves in the summer but loses its leaves in the winter. This means that the winter sun can easily shine through the tree's bare branches, while in the summer the sun will be mostly blocked by the leaves.

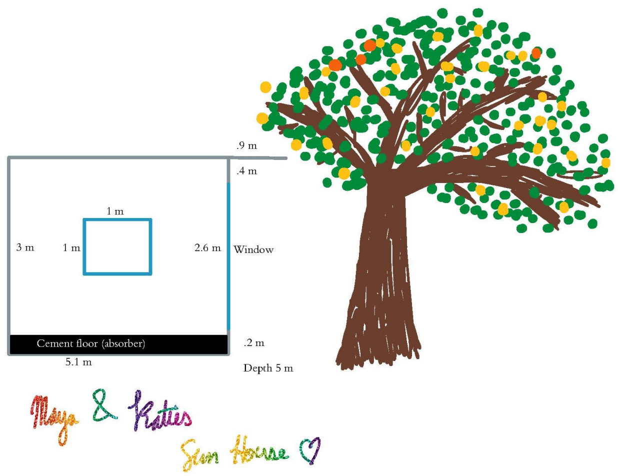

Figure 1: Design of Passive Solar House in Summer

Another way our house design keeps cool during the summer is through the placement of $1m^2$ double-paned glass windows on the East and West sides of the house. During the summer, these windows can be opened at night, when the outside air is coldest, which will promote airflow to cool the house down to the outside temperature. The average low during the night in July in Boston is a comfortably cool 19°C[4], so this approach would be effective. During the day, these windows can be closed and covered with curtains, keeping the cool air inside, while also keeping the sunlight out.

Some other design decisions that we made were to use concrete as the flooring, which we chose because it acts as both a good absorber, and a heat storage unit. We modeled the walls as fiberglass insulation, which was the default material in the project description. We chose this relatively simple design, as it

[4]https://www.currentresults.com/Weather/Massachusetts/Places/boston-temperatures-by-month-average.php

allowed us to focus on small changes that could affect our end goal. For example, we were able to test out different methods of keeping the house cool in the summer, since we knew reliably well that this design would work for the winter.

We used our model results to find the optimal floor thickness of 0.5m, and wall and window thickness of 0.03m. We tested different thicknesses before settling on these values, which optimized our passive solar house for comfort in all-seasons.

3 Modeling

Our basic model was two ordinary differential equations - one to model the concrete floor absorber, and one to model the air inside the house. Both equations followed the form

$$mC_v \frac{\delta T}{\delta t} = Q_{in} - Q_{out} \tag{1}$$

where m is mass, Cv is specific heat, T is temperature, and t is time, but the equations for concrete and air each had different values for Qin and Qout.

3.1 Equation for Concrete

For the concrete, we modeled Qin as the solar flux from the sun hitting the concrete, and Qout as convection from the concrete to the air inside the house.

The heat transfer rate (Qin) to the cement is due to radiation from the sun hitting the concrete, which can be represented as:

$$Q_{in} = (-.361 \cos \frac{t\pi}{12 * 3600} + .2243 \cos \frac{t\pi}{6 * 3600} + .2097) * Aw \tag{2}$$

where t is time in seconds, and Aw is the area of the window.

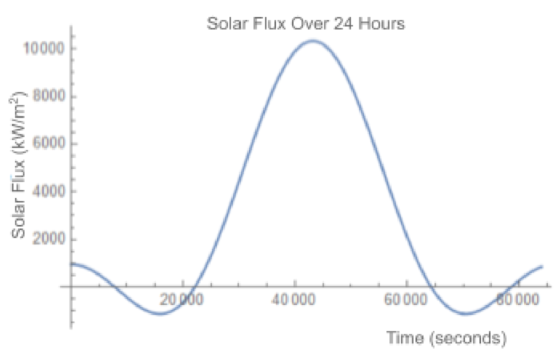

Figure 2: Graph of sinusoidal function that represents solar flux over one day in Winter

As you can see in Figure 2, this equation is a sinusoidal function that peaks at midday. In the winter, we modeled the area of the window as $13m^2$, since sunlight is entering through the entire window. In the summer, however, the vast majority of solar flux is being blocked by either the sun shade overhang on the roof, or the deciduous trees planted in front of the windows. We estimated an area of window of $2m^2$ to model the amount of area through which solar flux entered in the summer, taking into account that is is possible one or both of the side windows might be open, or that sunlight could reflect in from other surfaces.

Qout of concrete is modeled as convection from the cement to the air in the house. We used the equation

$$Q_{out} = hA_f(T_c - T_a) \tag{3}$$

where Tc is the temperature of the cement, and Ta is the temperature of the air inside, h is the heat transfer coefficient of air, $20W/m^2 - K$, and Af is the surface area of the floor.

3.2 Equation for Air

Our equation for air inside the house followed the same basic form as equation 1, shown above, with both a Qin, and a Qout. In this equation, Qin is convection to the air from the concrete, and Qout is modeled as conduction between the inside air and outside air, which represents the walls.

The Qin in the air equation is the same as the Qout in the equation for concrete, including the same coefficients,

$$Q_{in} = hA_f(T_c - T_a) \tag{4}$$

which makes sense as they are both the same phenomenon, just viewed from different sides.

Qout is the conduction to the outside through the insulated walls, modeled as,

$$Q_{out} = (\frac{k_w A_w}{L} + \frac{k_{wi} A_{wi}}{L})(T_a - T_{out}) \tag{5}$$

where Aw is the area of the walls, k is the thermal conductivity, and L is the thickness of the walls, also known as length of conduction. Because our system has walls and windows, which have different thermal conductivities, our has different values of k and A for walls and windows. For the sake of simplicity, we chose to only use a thickness of 0.03m for both the walls and the windows.

Tout is the temperature of the outside air, which is modeled in the winter using a sinusoidal equation

$$T_{out}(t) = -3 + 6\sin\frac{2\pi t}{24 * 60 * 60} + \frac{3\pi}{4} \tag{6}$$

which ranges between -6°C to 6 °C over the course of the day, which is typical weather for February in Massachusetts. To model the outside temperature during summer months, we modified the equation by multiplying the above equation by .8, then adding 23°C. The resultant equation has a range of 19°C to 27°C, which is typical for an average July day in Massachusetts.

4 Optimization

In our model, we varied the thickness of the walls and windows, and the thickness of the concrete to achieve a comfortable inside temperature inside our passive solar house. The values we ended up choosing were 0.5 m for the thickness of the concrete, and .03 m for the thickness of both the walls and windows. We started off with reasonable estimates for what the thicknesses should be, then kept adjusting until the temperature of the house was comfortable. The starting estimates were 1m for the thickness of concrete, and 0.5 meters for the thickness of the walls, which made the house too warm. Once we'd lowered those values, and the temperature of the house started to be livable, we refined them until we reached our current values. If we'd had more parameters to vary, we may have used the Manipulate function in Mathematica, rather than just employing reason and guess-and-check, however this situation was simple enough to just use guess-and-check.

5 Model results

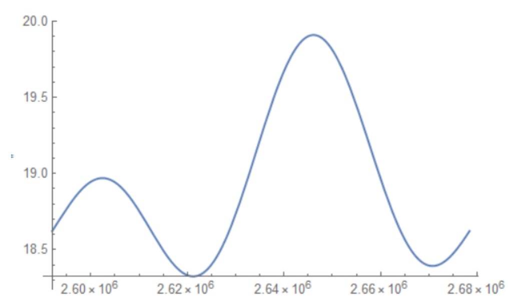

Figure 3: Inside temperature of air in winter from day 30 to day 31

As you can see in figure 3, during the winter, the air inside the house ranges from approximately 18.3°C to 19.9°C, which is comfortably cool.

In the summertime, the temperature of the house varies depending on what the inhabitant chooses to do. If they don't open the East and West facing windows, the air temperature in the house is between 24.6°C and 26°C, which is on the warmer side, but still not uncomfortable or uninhabitable. This can be seen in Figure 4.

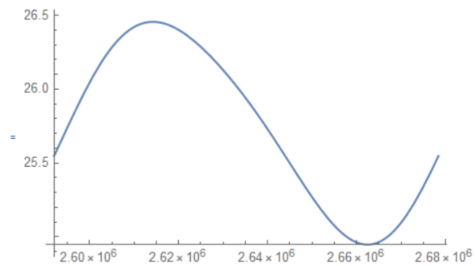

Figure 4: Inside temperature of air in summer, no window open from day 30 to day 31

If, however, the inhabitant of the house opens the window overnight, it sets the inside air temperature to the overnight outside air temperature, which generally is much cooler than the daytime temperature. The house in figure 4 remains warm due to the heat leftover from the previous day in the concrete absorber, which remains in the house since the air has no way to escape. When the inhabitant instead chooses to open the window overnight, the starting temperature of the house is much cooler (20°C). The stored heat in the concrete still plays a role, and doesn't completely dissipate, but the air flow from the windows allows the system to get much cooler before the sun can start to heat it up again. So when the windows are opened overnight but closed in the morning, the air inside the house over the course of the day is within the cool and comfortable range of 20°C to 22°C.

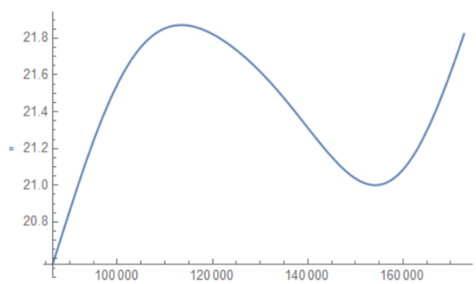

Figure 5: Inside temperature of air in summer with window open from day 1 to day 2

Adding more insulation would help the house to stay a couple degrees warmer in the winter, but then the house would become too warm in the summer, as it is unable to lose heat. Increasing the thickness of the concrete absorber helps the inside temperature of the house to stay more stable with less variation over the course of the day, but also can lead to the house retaining too much heat and becoming too warm.

6 Experiment

6.1 Motivation

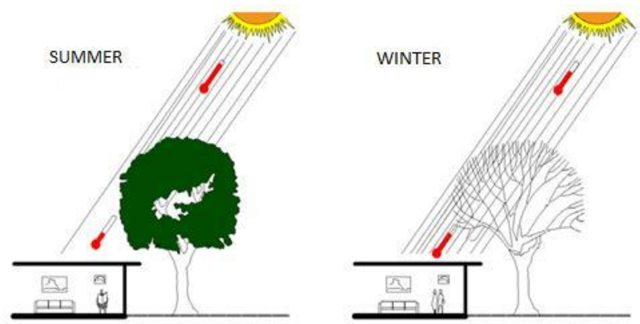

Figure 6: Illustration of how planting deciduous trees helps to warm houses in winter while keeping houses warm in summer

Our goal was to design a house that would be comfortable in both the summer and winter, and one of our ideas was planting deciduous trees. These are trees that lose their leaves in the winter, so the sun would shine freely through the branches in the winter, but would mostly be blocked during the summer. For our experiment, we tested the effect of shade from trees by comparing the temperature over time of tile in the sun and shade.

Figure 7: Picture of our experimental setup

6.2 Setup

As you can see in figure 7, our setup was that we placed several pieces of tile on top of styrofoam, and attached a thermistor to the tile using a rubber band and tape, and used thermal paste to increase the conductivity between the tile and thermistor. We placed this entire setup under a clear plastic bin, which mimicked the windows of the solar house, because they let in sunlight but protected the inside of the house from the wind.

6.3 Results of Experiment

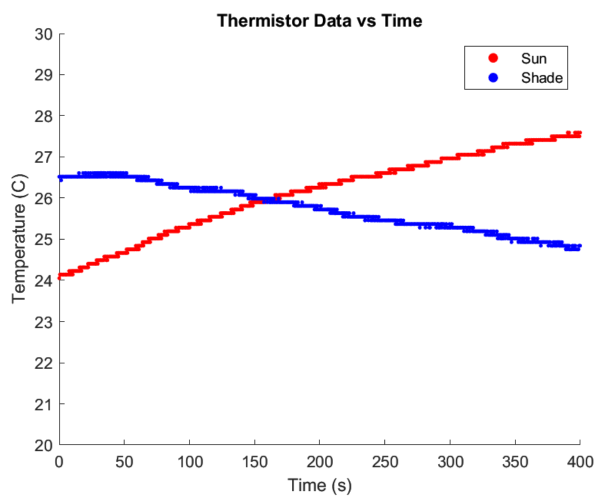

Figure 8: Graph of temperature of tile vs time for both sun and shade experiments

As you can see in the figure 8, putting our setup in the sun made the temperature of the tile warm up by approximately three degrees in 400 seconds, while putting the setup in the shade made the tile cool about the same amount in the same time. Our results indicate that whether the house is in the sun or shade significantly affects the temperature of the inside of the house. Therefore, our idea of planting deciduous trees would be a very helpful element of keeping the house warm in the winter and cool in the summer. Although summer sun should ideally not be getting through the main front windows anyway, due to the shade on top, it is logical to expect that some would get in anyway through light bouncing around. Another thing that our model did not take into consideration is the solar flux hitting the roof and walls of the house. Although we did not model this, it is a fair assumption that this solar flux would heat up the outside walls, and therefore the inside air, and that avoiding heating up the walls and roof would lead to a cooler house.

7 Discussion

Our design is overall very comfortable and practical. The inside temperature throughout the year is quite cool, which is especially impressive in the summer. During the winter, the temperature is a little bit colder than typical dwelling temperatures, but should still be comfortable while wearing a sweater or sweatshirt, and maybe a cozy pair of socks. Due to the thickness of the concrete, the house might require a small set of stairs, so the inhabitants can enter comfortably. It's also worth noting that although we assumed the system to be perfectly sealed so that there is no outside air entering the house, we did not mention in our design how we could ensure that. Future research on that may be useful. And while we accounted for the separate thermal conductivities of the walls and windows, we didn't include a door in the model. The last thing we could look into would be shades, rather than planting a tree. While planting a tree would do good for the environment as well as our house, deciduous trees take anywhere between 10 to 30 years to reach full maturity, so we would need to build the house in relation to already existing trees.

In relation to fossil fuel free living, there are still many devices that take place within the house besides heating the air, that require energy. Some of these include hot water heaters, refrigerators/freezers, dishwashers, cooking appliances, TVs/computers, clothes washers/dryers, and lights. In order for our passive solar house to become completely fossil fuel free, it would need to depend on an off-grid source of power. The most popular solution is solar panels. Although Massachusetts does not have an ideal climate for solar power, solar panels would still be the most practical solution to avoid being on an electrical grid that uses power from fossil fuels. Since about half of electricity use in a house goes towards heating and cooling, and our house does not use electricity for either, we would only need to install about 15 solar panels, half of what a normal house would use. This installation would cost just over $6,000 USD.

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