University Honors House: Going Solar in 2016

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University Honors House

Going Solar in 2016

Gabrielle McMorrow
Group Members: Donald Kennedy Aidan McDonald, and Gabriela Volpato
5/14/2016
Abstract

A group of students in the ME 4460: Solar and Geothermal Engineering at the University of Wyoming were tasked with designing a solar heating system for a residential building in Laramie, WY in the fall 2015 semester (McMorrow et al. 2015). As a group project, the team was expected to work together to learn and implement the design process for designing a solar system. The deliverables for the project included a plan of steps to implement the project, a six-page report (with appendices), and a self-assessment. A team of four students were grouped, including Donald Kennedy, Aidan McDonald, Gabriela Volpato, and myself, Gabrielle McMorrow. Together, throughout the semester, we worked hard to design a solar heating system for the very first time.
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Appendix I: Savings Calculation
Introduction

“Solar thermal energy seems to be growing, and growing fast. The vast amount of information, research, and other studies available in the field are evidence of this, and it seems there is still room to grow. Many technical papers are from the last two years, showing that demand for solar water heating system is big” (McMorrow et al. 2015).

“Solar thermal energy has many advantages and few disadvantages....With this energy from the sun, less fossil fuels are used, which is much better for the environment and more sustainable. Solar technology is becoming increasingly more advanced. With time, system efficiencies are increased, while cost decreases. This is essential for solar to become more mainstream and widely used. While solar systems have a high upfront cost, their continued energy savings are beneficial” (McMorrow 2016).

The Challenge

Students of ME 4460: Solar and Geothermal Engineering at the University of Wyoming were tasked with designing a solar heating system for a residential building in Laramie, WY in the fall 2015 semester (McMorrow et al. 2015). As a group project, the team was expected to work together to learn and implement the design process for designing a solar system. The deliverables for the project included a plan of steps to implement the project, a six-page report (with appendices), and a self-assessment.

A team of four students were grouped, including Donald Kennedy, Aidan McDonald, Gabriela Volpato, and myself, Gabrielle McMorrow. Together, throughout the semester, we worked hard to design a solar heating system for the very first time. In order to begin to
understand the process of designing a solar heating system, the group first had to understand what a solar heating system was. The team asked themselves a series of questions posed by the instructor, Yuan Zheng, in order to begin this process. I have added more information in addition to the brainstorm the team did in order to make the answers to the posed questions more complete.

**What is a solar heating system for?**

“There are three major applications of solar water heating systems: domestic hot water, space heating, and combisystems, which combine domestic hot water and space heating (Streicher 2016)” (McMorrow 2016). Heating water is currently the most widely used application of solar energy (Goswami 2015). “As Mazarrón et al. puts it, “solar water heaters (SWHs) are the most popular way to use solar energy,” which is somewhat due to their simplicity and potential financial savings (Mazarrón et al. 2016). Even further, solar water heating systems are used for domestic hot water 85% of the time (Camargo Nogueira et al. 2016). Solar water heating systems are used to reduce the use of fossil fuels (Wang et al. 2016), and thus can be very economical and sustainable” (McMorrow 2016).

Systems can either use natural circulation (passive solar systems) or forced circulation (active solar systems) (Goswami 2015). Photovoltaic panels (PV) could also be used to convert solar energy into electricity to heat and cool as well.

**What does a solar heating system look like?**

There are many different variations of solar heating systems, and some are simpler than others. The principle is similar in both passive and active systems; heat is absorbed from the
sun into a heat transfer fluid, then moved to the system’s distribution system (i.e. water tank/storage to radiator, baseboard heaters, etc.). The collectors are usually dark in color in order to absorb more heat from the sun.

“An active solar water heater absorbs energy from the sun and circulates a heat transfer fluid within the system. This heat transfer fluid then delivers heat to a building in the form of domestic hot water or space heating. There are two main circulation patterns of active solar water heaters, those that are passive-circulation, or thermosiphon systems (circulate due to natural physics), and those that are active-circulation, or forced-circulation (circulate with a pump) (Mazarrón et al. 2016). With a solar water heating system, there are three main types of solar collectors used: flat plate collectors, evacuated tube collectors, and compound parabolic collectors (Streicher 2016; Mazarrón et al. 2016). Flat plate and evacuated tube collectors are most commonly used for residential water heating (Camargo Nogueira et al. 2016). Looking even closer at a solar water heating system, the system can be described as either direct, where fluid that flows through the collectors is the same as the tank fluid, or indirect, where the fluid flowing through the collectors is used to transfer heat to another fluid in the tank (Camargo Nogueira et al. 2016)” (McMorrow 2016).

For space heating in liquid systems, heating load devices are used to transfer the heat from solar heat storage to the space (Goswami 2015). These include forced-air systems, baseboard convection systems, and heated floors/ceilings (Goswami 2015).
Why does a solar heating system vary from house to house?

Solar system design varies widely from house to house. This is for a number of reasons. Location matters a great deal when designing a system. A location’s climate, weather, elevation, amount of incoming solar irradiation, and even amount of shading on the collector surface are all influencing factors on the design. A solar system’s size also depends on the demands of the building, including number of people, activity happening within the building, thermal comfort preferences of the occupants, and building construction. Finally, the building itself influences the design. The roof angles, roof area, roof directions (if collectors are to be located on the roof) all influence the placement and design of the system.

What are the criteria for the design?

Ideally, the group would like to have an adequate number of solar collectors in order to meet the demands of the Honors House residence. Some demands are defined as water source temperature and delivery temperature, and energy for space heating. Demands would be determined by analyzing one year’s utility data (and using calculation methods as described in subsequent sections of this report). The group also wanted to create an economical design.

What knowledge do we already have to complete the design problem?

As the team quickly discovered, they did not know very much about designing a solar heating system going into the design process. The team determined that they had three main skills: the ability to convert utility data into useful parameters, the ability to determine the Honors House location (Laramie’s latitude and longitude), and the knowledge of many software that could help in the design of the system (Revit, MATLAB, Excel, etc.).
What knowledge do we need to learn to complete the design problem?

As the group did not know exactly which direction to go in in order to design their solar heating system, it was somewhat difficult to determine what exactly they needed to learn in order to complete the project. The team determined that they needed to learn to apply the correct equations and to apply them in the correct order, select a type of solar collector based on economic analysis and efficiency of the collectors, pick a solar model based on the orientation of the solar collector (tracking, fixed, South, etc.), and calculate irradiation for a specific roof. These are just a few of the steps necessary to designing a solar heating system.

What assumptions would you like to make?

In order to design the solar heating system, a lot of assumptions were made. The first assumption is that the residence has a constant temperature and humidity setpoint. This simplifies the calculations. The second assumption is that heat loss and heat gain is constant. In reality, this is not true: these parameters change by the second, however we will assume each month, a constant amount of heat exits the building. The third assumption is that the effect of solar flares will be neglected. Finally, monthly average water consumption and electricity usage will be treated as constant in order to determine the number of panels needed. Many other assumptions were made during the design process, most of which are described in subsequent sections of this report.
Design Process

The design process for creating a solar heating system is very complex. The subsequent sections of this report will attempt to explain the process of designing a solar heating system for the Honors House.

Building Facts

First, the team had to gather information on the University Honors House. This information could be used in their calculations. “The University of Wyoming Honors House is located at 1501 Fraternity Row in Laramie, WY. The house is residential and features 17 bedrooms, some of which are shared between roommates, for a total of 29 residents at maximum occupancy. Floor plans can be seen in Appendix A” (McMorrow et al. 2015).

“Historical energy data was gathered from the University of Wyoming Physical Plant. Within this data, two years’ worth of water, electricity, and steam usage data were provided. This data can be viewed in Appendix F. Electricity and water usage values are accurate to the Honors House. However, the university uses a square footage estimate for steam usage, which is served square footage divided by MMBTU input, so the estimate is not very accurate. This makes it difficult to estimate the actual building heating load based on the provided information” (McMorrow et al. 2015).

Solar Irradiation

Solar irradiation was calculated by another group member. Solar irradiation is the amount of incoming solar energy in units of energy per area. For this project, incident solar irradiation on the solar collector surface was calculated using the LJ method (McMorrow et al.
This method can be used to calculate monthly solar radiation on a tilted surface (McMorrow et al. 2015). Calculations can be seen in the MATLAB code located in Appendix D written by another group member. The results of the calculations can be found in Figure 1 (McMorrow et al. 2015).

![Figure 1. Monthly Solar Irradiation. Source: McMorrow et al. 2015](image)

The group chose the LJ method for two reasons: because it uses monthly averaged data and because it is based on historical data (McMorrow et al. 2015). Other solar models, such as the CPR, CPRG, and DI models use daily or hourly data, whereas the LJ model uses monthly averaged data (McMorrow et al. 2015). In addition, the LJ method uses historical weather data, whereas the ASHRAE Clear Sky model uses the assumption that the sky is clear every day (McMorrow et al. 2015). Using the LJ model over the Clear Sky model will ensure more accurate results (McMorrow et al. 2015).
The group chose south facing fixed collectors with a tilt angle of 56.3° and solar irradiation calculations are based off these facts (McMorrow et al. 2015). A fixed solar collector will absorb the most thermal energy from the sun when it is south facing. The tilt angle was chosen as the latitude of Laramie, WY, plus 15 degrees (McMorrow et al. 2015). This is typical in cold climates where there is a high heating demand while the sun is lower in the sky (winter) and there is risk for snow build up (McMorrow et al. 2015).

**Building Loads**

Building loads were calculated by myself, Gabrielle McMorrow. “Building loads were calculated for the Honors House using the equations presented in Chapter 5 of the course textbook (Goswami 2015)” (McMorrow et al. 2015). The wall areas were calculated using the length of the walls as shown in the plans given by Physical Plant multiplied by the floor to floor height (9, 10, 9, and 9 feet for basement, first, second, and third floor, respectively) (McMorrow et al. 2015). “The wall type was divided into categories based on wall construction” (McMorrow et al. 2015). Wall U factors for these wall constructions were estimated based on residential energy efficiency guidelines for zone 6, the zone in which Laramie is situated; these values were at 0.36 for basement walls and 0.06 for all other walls as found in “Residential Energy Efficiency” (2006) (McMorrow et al. 2015). “Additionally, floor and roof U factors were also estimated as 0.033 and 0.035 respectively (“Residential Energy Efficiency” 2006)” (McMorrow et al. 2015).

“Building load for each month was calculated using the mean monthly temperature and the estimated U factors and areas. It was estimated that windows took up 20% of the wall
area, and the other 80% was the wall materials. It was also assumed an indoor temperature setpoint of 70 degrees F, or 21.1 degrees C. Table 1 shows the results of the heat loss calculations. See Appendix E for detailed calculations. It is acknowledged that the U factors are not exact to the construction of the walls in the building. Without detailed wall constructions within the building plans, it is difficult to estimate the complete materials or amount of insulation used in each wall, floor, or roof” (McMorrow et al. 2015).

Table 1. Monthly heat losses (in W). Source: (McMorrow et al. 2015)

<table>
<thead>
<tr>
<th>Month</th>
<th>Wall Heat Loss</th>
<th>Window Heat Loss</th>
<th>Floor Heat Loss</th>
<th>Roof Heat Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>1117.4947</td>
<td>1986.362</td>
<td>10.000313</td>
<td>310</td>
</tr>
<tr>
<td>February</td>
<td>1053.6306</td>
<td>1862.209</td>
<td>10.000313</td>
<td>291</td>
</tr>
<tr>
<td>March</td>
<td>925.90238</td>
<td>1613.904</td>
<td>10.000313</td>
<td>252</td>
</tr>
<tr>
<td>April</td>
<td>776.88614</td>
<td>1324.214</td>
<td>10.000313</td>
<td>207</td>
</tr>
<tr>
<td>May</td>
<td>564.00579</td>
<td>910.3711</td>
<td>10.000313</td>
<td>142</td>
</tr>
<tr>
<td>June</td>
<td>351.12544</td>
<td>496.5284</td>
<td>10.000313</td>
<td>77.5</td>
</tr>
<tr>
<td>July</td>
<td>180.82117</td>
<td>165.4543</td>
<td>10.000313</td>
<td>25.8</td>
</tr>
<tr>
<td>August</td>
<td>265.9733</td>
<td>330.9914</td>
<td>10.000313</td>
<td>51.7</td>
</tr>
<tr>
<td>September</td>
<td>457.56562</td>
<td>703.4498</td>
<td>10.000313</td>
<td>110</td>
</tr>
<tr>
<td>October</td>
<td>713.02203</td>
<td>1200.061</td>
<td>10.000313</td>
<td>187</td>
</tr>
<tr>
<td>November</td>
<td>883.32631</td>
<td>1531.135</td>
<td>10.000313</td>
<td>239</td>
</tr>
<tr>
<td>December</td>
<td>1160.0708</td>
<td>2069.131</td>
<td>10.000313</td>
<td>323</td>
</tr>
<tr>
<td>Total</td>
<td>8449.8242</td>
<td>14193.81</td>
<td>120.00376</td>
<td>2216</td>
</tr>
<tr>
<td>Grand Total</td>
<td></td>
<td></td>
<td></td>
<td>24,980 W</td>
</tr>
</tbody>
</table>
Collector Type

Collector type was explored by another group member.

Collector Efficiency

“Based on efficiency, heat transfer, and performance in cold weather, we determined that evacuated tube solar collectors, rather than flat plate collectors, should be used for our design” (McMorrow et al. 2015). The conclusion in McMorrow et al. was reached with the following analysis of collector efficiency at varying temperatures (2015).

For flat plate collectors, instantaneous efficiency can be found by Equation 1 (McMorrow et al. 2015).

Equation 1. Source: McMorrow et al. 2015

\[ n_c = F_R \tau \alpha - F_R U_L \left( \frac{T_i - T_a}{T_c} \right) \]

where:

- \( F_R \): collector heat removal factor;
- \( \tau \): transmission coefficient of glazing;
- \( \alpha \): absorption coefficient of plate;
- \( U_L \): collector overall heat loss coefficient;
- \( T_i \): inlet fluid temperature;
- \( T_a \): ambient temperature;
It is assumed that $F_R$, $\tau$, $\alpha$, and $U_L$ are constants for a given collector and flow rate for the project. Then the efficiency will only depend in the following parameters: Solar irradiance, fluid inlet temperature and ambient air temperature” (McMorrow et al. 2015).

For evacuated tube collectors, instantaneous efficiency can be found by Equation 2 (McMorrow et al. 2015).

\[ n_c = \frac{D \left[ \tau \alpha_r I_{eff} - \pi U_c (T_r - T_a) \right]}{A_c I_c} \]

“Solving the equation for both types of solar collector yields Table 2, which compares efficiency at different temperatures, assuming an ambient temperature of 23.33°C and $I_c$ of 1000 W/m².” (McMorrow et al. 2015).

<table>
<thead>
<tr>
<th>Collector</th>
<th>System Operating Temperature( °C )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>21.1</td>
</tr>
<tr>
<td>Flat Plate $n_c$(%)</td>
<td>56.4</td>
</tr>
<tr>
<td>Evacuated Tube $n_c$(%)</td>
<td>73.2</td>
</tr>
</tbody>
</table>

Appendix G shows a typical evacuated tube efficiency curve (McMorrow et al. 2015). “When it is compared to the flat plate curve efficiency, is notable that for application that demands low heat
loss, such as really cold weather, the evacuated tubes are great choices for the project. Also, evacuated tubes are recommended for heating applications where the outdoor temperatures are about -20 degree C. This recommendation is perfect for the weather in Laramie” (McMorrow et al. 2015).

Performance in Cold Weather

“Using evacuated tubes can bring advantages such as low heat loss at high temperatures relative to ambient temperatures. Table 2 shows that the best choice for the designing project is evacuated tube, since the efficiency in the operating temperature is relatively greater when we compare to the same operating temperature for flat plate collectors. Therefore, the collector that will be used in the project design will be evacuated tubes.

Also, due to their cylindrical absorber surface, evacuated tubes passively track the sun throughout the day, which is another advantage comparing with flat plate collectors, as the round absorber is facing the sun from sunrise to sunset. This is another advantage over flat plate collectors that only have maximum sun exposure at midday” (McMorrow et al. 2015).

Design of System Components

The design of the system components was looked at by another group member. The group chose to use a design as shown in Figure 2. “Residential > Water Heating – Flat Plates” posts this image on their webpage; McMorrow et al. 2015 uses it as a model for design of their system.
In order to implement this design the team would have to install a series of system components and complete a series of steps. These include:

- Install a 119 gallon solar storage tank in the mechanical section of the Honors House
- Pipe the supply and return water lines from the convertor to the solar storage tank
- Install and pipe the solar pump near the storage tank
- Install and wire up the solar controller, also near the solar storage tank
- Mount the solar collectors on the roof of the east section of the Honors House (See Appendix A)
• Pipe and insulate from the evacuated tubes to the solar pump
• Fill the piping going to the evacuated tubes with Ethylene Glycol
• Connect an injection quill going to the evacuated tube piping for glycol make-up”

(McMorrow et al. 2015)

“Using the existing plumbing and energy (from steam generated by the Physical Plant), our group will adapt the existing system to include Evacuated Solar Tubes as a way to limit the amount of coal burned at the Physical Plant, save money, and save energy. The lowest temperature in Laramie (2014) was -34°F with a wind chill of -55°F. Because of such a low temperature an indirect circulating system (closed system) will be used in our solar circulating system, and to prevent freezing, Ethylene Glycol will be used. The Ethylene Glycol is already part of the existing system and is controlled in a 50 gallon Polyethylene tank…. However, due to the Ethylene Glycol being used as a make-up pressure system (where the pump only operates at low pressure to restore the systems pressure) a new solar water tank and controls will be needed…. The make-up pressure system, controlled by the solar pump and control, will be used to keep the Ethylene Glycol at a constant rate of approximately 1 Gallon/Minute. The make-up glycol will be piped from the 50 gallon polyethylene tank to the solar storage tank using an injection quill. The injection quill acts like a check valve, not allowing liquid to flow back to the 50 gallon tank” (McMorrow et al. 2015).

“Instead of running all new plumbing in the Honors House, our group will be able to tie into the existing lines of the ‘Hot Water Return from System’ and ‘Hot Water Supply to System,’” (McMorrow et al. 2015).

Pricing for system components can be found in Table 3.
Table 3. Pricing of Solar Heating System Design Source: McMorrow et al. 2015 Appendix C

<table>
<thead>
<tr>
<th>Part</th>
<th>Manufacturer/Vendor</th>
<th>Quantity</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>HHNS-Solar Evacuated Tube Kit</td>
<td>Houseneeds</td>
<td>4-30 Tube Collectors</td>
<td>$3799.00</td>
</tr>
<tr>
<td>119 gal Solar Water Tank</td>
<td>Caleffi</td>
<td>1</td>
<td>$2369.75</td>
</tr>
<tr>
<td>Solar Pump</td>
<td>Caleffi</td>
<td>1</td>
<td>$929.00</td>
</tr>
<tr>
<td>Solar Controller</td>
<td>Caleffi</td>
<td>1</td>
<td>$379.75</td>
</tr>
<tr>
<td>Ethylene Glycol</td>
<td>Existing system</td>
<td>50 gal tank</td>
<td>Existing system</td>
</tr>
<tr>
<td>Injection Quill</td>
<td>Cole-Palmer</td>
<td>1</td>
<td>$183.00</td>
</tr>
<tr>
<td>Piping/Insolation</td>
<td>Local Contractor</td>
<td>250 ft</td>
<td>approx. $3000.00</td>
</tr>
<tr>
<td>Electrical</td>
<td>Local Contractor</td>
<td>small run</td>
<td>approx. $1000.00</td>
</tr>
<tr>
<td>Total</td>
<td>Local Contractor</td>
<td></td>
<td>approx. $11,660.50</td>
</tr>
</tbody>
</table>

Results

Table 4 “shows the fraction of the Honors House’s heating energy that will come from solar energy each month with our design. The calculations for these values are located in Appendix H” (McMorrow et al. 2015).

Table 4. Fraction of heat load supplied by solar energy for each month Source: McMorrow et al. 2015

<table>
<thead>
<tr>
<th>Monthly fs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.6089</td>
</tr>
<tr>
<td>Month</td>
<td>Value</td>
</tr>
<tr>
<td>----------</td>
<td>-------</td>
</tr>
<tr>
<td>February</td>
<td>0.7729</td>
</tr>
<tr>
<td>March</td>
<td>0.8264</td>
</tr>
<tr>
<td>April</td>
<td>0.912</td>
</tr>
<tr>
<td>May</td>
<td>1.0709</td>
</tr>
<tr>
<td>June</td>
<td>1.3145</td>
</tr>
<tr>
<td>July</td>
<td>2.7935</td>
</tr>
<tr>
<td>August</td>
<td>1.4338</td>
</tr>
<tr>
<td>September</td>
<td>1.2949</td>
</tr>
<tr>
<td>October</td>
<td>1.0334</td>
</tr>
<tr>
<td>November</td>
<td>0.7929</td>
</tr>
<tr>
<td>December</td>
<td>0.5884</td>
</tr>
</tbody>
</table>

“These values were calculated assuming $F_r U_c = 1.7$ and $F_r \tau \alpha = 0.83$ for the collectors, which were derived from the typical evacuated tube efficiency curve in Appendix G. Unfortunately, we were unable to obtain data from the manufacturer for the specific collectors we chose” (McMorrow et al. 2015).

**Discussion**

“This design would provide all of the necessary heating for the Honors House for May through October, and would cut the necessary energy input from the Physical Plant by more than half even during the coldest months. Assuming a constant cost of energy from the Physical Plant of 10 ¢/kWh, the design would result in $1,470 in annual savings (See Appendix I for calculations). Therefore, given the initial cost of $11,660.... the solar system would pay for itself in about 8 years. We believe that this is a reasonable payoff period for a solar heating system, and we
recommend that the Honors House seriously consider employing this design” (McMorrow et al. 2015).

**Improvements**

There is ample room for improvement in the calculations for the design of the Honors House solar heating system. First, the building load calculations could use some tweaking, as there is a much more sophisticated way to calculate building loads, which includes internal heat gains. Also, the solar system should have been designed for the maximum month, and not the sum of all the months, as was presented in this report. This would result in a solar heating system nearly a fourth of what it was design as. In addition, average monthly temperature was used as the outdoor temperature in calculations for heat transfer. Really, the maximum temperature difference should be used in order to design for the worst case scenario.

Second, the $f_s$ calculations would then be adjusted because the newly sized system would have different percentage values. Also, the $f_s$ values should be no greater than one since a system cannot go above 100%. Finally, the estimated cost seems low. In reality, the installation of a system would probably be slightly higher due to engineering fees and other labor costs.

The goal of this project was to learn the process, which the team did quite well. It is recognized that there could be a number of improvements in order to make this project better and more accurate for the University Honors House solar heating system.
Resources


Resources (McMorrow et al. 2015)

“Arctic Cold Wraps Up 2014: Wyoming Village Records Lower 48’s Coldest Temperature of the Year.”


NASA Atmospheric Science Data Center. 2015. Available at https://eosweb.larc.nasa.gov/sse/

“Residential Energy Efficiency.” Available at

https://www2.iccsafe.org/states/Virginia/Energy/PDFs/Chapter%204_Residential%20Energy%20Efficiency.pdf

“Residential > Water Heating – Flat Plates.” *Solar Panel Plus* Available at


“The Energy Store.” 2015. Available at


*The Weather Channel*. 2014. Available at


**Resources (McMorrow 2016)**


Selected Appendices from McMorrow et al. 2015

Appendix A: Honors House Floor Plans

Source: McMorrow et al. 2015
Appendix D: Solar Irradiation Calculation Code

Source: McMorrow et al. 2015

I_c monthly calculation (LJ method)

```matlab
clear all;
clc;
format compact;

Inputs

% Pick day from each month
for n = [16,46,75,105,136,166,197,228,258,289,319,350]

Angles

% Latitude
L = 41.3167;

% Panel azimuth angle
a_w = 0;

% Panel tilt angle
beta = L+15;

% Solar declination angle (2.23)
delta_s = 23.45*sind(360*(284+n)/365);

% Sunset hour angle (2.30)
h_ss = acosd(-tand(L)*tand(delta_s));

Radiation

% Long-term avg daily total and diffuse radiation from NASA-SSE
% (http://eosweb.larc.nasa.gov/sse/)

% Total (in kwh/(m^2 day))
H_h_Jan = 2.10;
H_h_Feb = 2.99;
H_h_Mar = 4.19;
H_h_Apr = 5.16;
H_h_May = 6.21;
H_h_Jun = 6.91;
H_h_Jul = 6.67;
H_h_Aug = 5.82;
H_h_Sep = 4.86;
H_h_Oct = 3.59;
H_h_Nov = 2.34;
H_h_Dec = 1.91;

% Diffuse (in kWh/(m^2 day))
H_d_Jan = .70;
H_d_Feb = .97;
H_d_Mar = 1.37;
H_d_Apr = 1.86;
H_d_May = 2.14;
H_d_Jun = 2.19;
H_d_Jul = 2.12;
H_d_Aug = 1.87;
H_d_Sep = 1.43;
H_d_Oct = 1.02;
H_d_Nov = .76;
H_d_Dec = .61;

% Select monthly data based on n
if 1<=n && n<31
    H_h = H_h_Jan;
    H_d = H_d_Jan;
elseif 31<=n && n<59
    H_h = H_h_Feb;
    H_d = H_d_Feb;
elseif 59<=n && n<90
    H_h = H_h_Mar;
    H_d = H_d_Mar;
elseif 90<=n && n<120
    H_h = H_h_Apr;
    H_d = H_d_Apr;
elseif 120<=n && n<151
    H_h = H_h_May;
    H_d = H_d_May;
elseif 151<=n && n<181
    H_h = H_h_Jun;
    H_d = H_d_Jun;
elseif 181<=n && n<212
    H_h = H_h_Jul;
    H_d = H_d_Jul;
elseif 212<=n && n<243
    H_h = H_h_Aug;
    H_d = H_d_Aug;
elseif 243<=n && n<273
    H_h = H_h_Sep;
    H_d = H_d_Sep;
elseif 273<=n && n<304
    H_h = H_h_Oct;
    H_d = H_d_Oct;
elseif 304<=n && n<334
    H_h = H_h_Nov;
    H_d = H_d_Nov;
else
    H_h = H_h_Dec;
    H_d = H_d_Dec;
end

% Convert H_h and H_d to Wh/m^2 day
H_h = H_h*1000;
H_d = H_d*1000;

% Ground reflectivity
rho = .2;

% Beam radiation on a horizontal surface
H_b = H_h - H_d;

% Tilt factors
R_b = (cosd(-beta)*cosd(delta_s)*sind(-h_ss)+pi()/180*-h_ss*sind(L-beta)*sind(delta_s))/(cosd(L)*cosd(delta_s)*sind(-h_ss)+pi()/180*-h_ss*sind(L)*sind(delta_s));
R_d = (cosd(beta/2))^2;
R_r = rho*(sind(beta/2))^2;

% Total radiation on tilted surface (2.82) in kwh/m^2 day
I_c = (H_b*R_b + H_d*R_d + H_h*R_r)/1000

end
Appendix E: House Model and Energy Calculations

Source: McMorrow et al. 2015

U Factor Assumptions

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Minimum U factor requirement</th>
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<td>A 12&quot; Concrete</td>
<td>0.36</td>
</tr>
<tr>
<td>B 10&quot; Concrete</td>
<td>0.36</td>
</tr>
<tr>
<td>C 8&quot; Concrete</td>
<td>0.36</td>
</tr>
<tr>
<td>D not used</td>
<td>not used</td>
</tr>
<tr>
<td>E CMU and 4&quot; brick</td>
<td>0.06</td>
</tr>
<tr>
<td>F New Frame Wall</td>
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<tr>
<td>G Frame Wall and brick veneer</td>
<td>0.06</td>
</tr>
<tr>
<td>h CMU</td>
<td>0.06</td>
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<tr>
<td>I Stud and Brick and White</td>
<td>0.06</td>
</tr>
<tr>
<td>J CMU and brick and white</td>
<td>0.06</td>
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Summary of Areas and Construction

<table>
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<tr>
<th>Area Sums</th>
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<th>Non-Basement</th>
<th>Window Area</th>
<th>Wall Area</th>
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<tr>
<td>A</td>
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<td>171.345</td>
<td>SM</td>
<td>0 SM 34.268992 SM</td>
<td>137.08 SM</td>
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<tr>
<td>B</td>
<td>87.28098</td>
<td>87.281</td>
<td>SM</td>
<td>0 SM 17.456196 SM</td>
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<tr>
<td>C</td>
<td>7.239623</td>
<td>7.23962</td>
<td>SM</td>
<td>0 SM 1.4479245 SM</td>
<td>5.7917 SM</td>
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<tr>
<td>D</td>
<td>not used</td>
<td>not used</td>
<td>SM</td>
<td>not used SM</td>
<td>not used SM</td>
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<tr>
<td>E</td>
<td>343.4104</td>
<td>0 SM</td>
<td>343.4104 SM</td>
<td>68.682088 SM</td>
<td>274.73 SM</td>
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<tr>
<td>F</td>
<td>105.2468</td>
<td>0 SM</td>
<td>105.2468 SM</td>
<td>21.049358 SM</td>
<td>84.197 SM</td>
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</tbody>
</table>
Roof Area Floor Area
3577 SF 3262 SF
332.3 SM 303.04 SM
0.035 (U) 0.033 (U)

Equations to Calculate Heat Flow

\[ q_{walls,window,ceiling} = U \times F \times (T_i - T_o) \]  \hspace{1cm} (Eq.5.1)

\[ q_{floors,basement walls} = U \times A \]  \hspace{1cm} (Eq. 5.2)

Monthly Breakdown of Heat Flow

<table>
<thead>
<tr>
<th>Monthly Average T</th>
<th>F</th>
<th>C</th>
<th>Wall</th>
<th>Windows</th>
<th>Floor</th>
<th>Roof</th>
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<td>January</td>
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<td>1986.4</td>
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<td>925.90238</td>
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<td>564.00579</td>
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<td>Month</td>
<td>N</td>
<td>Mean</td>
<td>Median</td>
<td>SD</td>
<td>N</td>
<td>Mean</td>
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<td>14.4444</td>
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<td>18.8889</td>
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<td>11.6667</td>
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<td>-6.6667</td>
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# Appendix F: Historical Energy Data

**Source:** McMorrow et al. 2015

**Source:** University of Wyoming Physical Plant

<table>
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<td>23</td>
<td>24</td>
<td>56</td>
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Appendix G: Typical Evacuated Tube Efficiency Curve

Source: McMorrow et al. 2015

Source: Brunold 2012
Appendix H: Fraction of Heat Load Provided by Solar Calculation Code

Source: McMorrow et al. 2015

\( f_s \) Calculation

clear all;
clc;
format compact;

Inputs

% Month
for n = [1:12];

% Total monthly load (J/month)
if n==1
    L = (1117.4947+1986.362+10.000313+310)*3600*24*31;
elseif n==2
    L = (1053.6306+1862.209+10.000313+291)*3600*24*28;
elseif n==3
    L = (925.90238+1613.904+10.000313+252)*3600*24*31;
elseif n==4
    L = (776.88614+1324.214+10.000313+207)*3600*24*30;
elseif n==5
    L = (564.00579+910.3711+10.000313+142)*3600*24*31;
elseif n==6
    L = (351.12544+496.5284+10.000313+77.5)*3600*24*30;
elseif n==7
    L = (180.82117+165.4543+10.000313+25.8)*3600*24*31;
elseif n==8
    L = (265.9733+330.9914+10.000313+51.7)*3600*24*31;
elseif n==9
    L = (457.56562+703.4498+10.000313+110)*3600*24*30;
elseif n==10
    L = (713.02203+1200.061+10.000313+187)*3600*24*31;
elseif n==11
    L = (883.32631+1531.135+10.000313+239)*3600*24*30;
else

\[
L = (1160.0708+2069.131+10.000313+323)*3600*24*31;
\]

end

% Collector area (m^2)
\[ A_c = 4*4.54; \]

% Heat Exchanger efficiency
\[ F_{hx} = 1; \]

% Fr*Uc (W/m^2 K)
\[ FrUc = 1.7; \]

% Fr*tau*alpha (dimensionless)
\[ FrTauAlpha = .83; \]

% Time range (s)
if \( n==1|n==3|n==5|n==7|n==8|n==10|n==12 \)
  \[ \text{delta}_t = 31*24*3600; \]
elseif \( n==2 \)
  \[ \text{delta}_t = 28*24*3600; \]
else
  \[ \text{delta}_t = 30*24*3600; \]
end

% Reference temperature (deg C)
\[ T_R = 100; \]

% Monthly average ambient temperature from
% http://www.areavibes.com/laramie-wy/weather/ (deg C)
if \( n==1 \)
  \[ T_a = -5.56; \]
elseif \( n==2 \)
  \[ T_a = -3.89; \]
elseif \( n==3 \)
  \[ T_a = -.56; \]
elseif \( n==4 \)
  \[ T_a = 3.34; \]
elseif \( n==5 \)
  \[ T_a = 8.89; \]
else \( n==6 \)
\begin{verbatim}
T_a = 14.44;
elseif n==7
    T_a = 18.89;
elseif n==8
    T_a = 16.67;
elseif n==9
    T_a = 11.67;
elseif n==10
    T_a = 5.00;
elseif n==11
    T_a = 0.56;
else
    T_a = -6.67;
end

% Solar irradiation (kJ/m^2/day)
if n==1
    I_c = 4.2955*3600;
elseif n==2
    I_c = 4.8629*3600;
elseif n==3
    I_c = 5.1641*3600;
elseif n==4
    I_c = 4.8015*3600;
elseif n==5
    I_c = 4.619*3600;
elseif n==6
    I_c = 4.555*3600;
elseif n==7
    I_c = 4.6441*3600;
elseif n==8
    I_c = 4.9554*3600;
elseif n==9
    I_c = 5.441*3600;
elseif n==10
    I_c = 5.4838*3600;
elseif n==11
    I_c = 4.5245*3600;
else
end
\end{verbatim}
\[ I_c = 4.2859 \times 3600; \]
end

**f-chart method**

\[
\text{\% Loss Parameter} \\
P_L = A_c \times F_h \times Fr \times Uc \times \delta_t \times (T_R - T_a) / L; \\
\]
\[
\text{\% Solar Parameter} \\
P_s = A_c \times F_h \times Fr \times TauAlpha \times I_c \times 31 / (L/1000); \\
\]
\[
\text{\% Fraction of Load Supplied by Solar Energy} \\
f_s = 1.029 \times P_s - 0.065 \times P_L - 0.245 \times P_s^2 + 0.0018 \times P_L^2 + 0.0215 \times P_s^3
\]
end

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Appendix I: Savings Calculation

```matlab
clear all;
clc;
format compact;

% Convert 10 cents/kwh to dollars/J
X = 10/3600000*.01;

% Monthly Savings
S1 = (1117.4947+1986.362+10.000313+310)*3600*24*31*X * .6089;
S2 = (1053.6306+1862.209+10.000313+291)*3600*24*28*X * .7729;
S3 = (925.90238+1613.904+10.000313+252)*3600*24*31*X * .8264;
S4 = (776.88614+1324.214+10.000313+207)*3600*24*30*X * .912;
S5 = (564.00579+910.3711+10.000313+142)*3600*24*31*X;
S6 = (351.12544+496.5284+10.000313+77.5)*3600*24*30*X;
S7 = (180.82117+165.4543+10.000313+25.8)*3600*24*31*X;
S8 = (265.9733+330.9914+10.000313+51.7)*3600*24*31*X;
S9 = (457.56562+703.4498+10.000313+110)*3600*24*30*X;
S10 = (713.02203+1200.061+10.000313+187)*3600*24*31*X;
S11 = (883.32631+1531.135+10.000313+239)*3600*24*30*X * .7929;
S12 = (1160.0708+2069.131+10.000313+323)*3600*24*31*X * .5884;

% Annual Savings
Savings = S1+S2+S3+S4+S5+S6+S7+S8+S9+S10+S11+S12

% Years for savings to equal initial cost
Payoff_Period = 11660.5/Savings

Savings = 1.4697e+03
Payoff_Period = 7.9342

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