ZNE Hop Kiln Design

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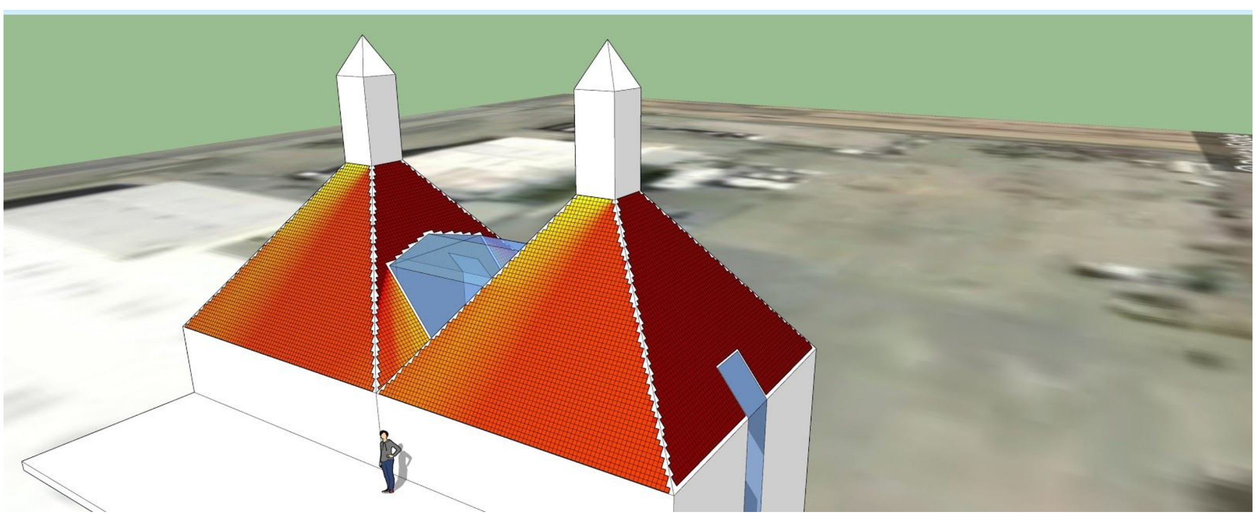
ABT 212



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1. Project background

1.1. Brief history and context

Historically, Sacramento's climate, soils, and railroad connectivity made it uniquely suited for the brewing industry. In fact, by 1881, Ruhstaller's brewery was the largest west of the Mississippi, surpassing other large companies like Anhauser-Busch. (History) Part of Ruhstaller's success then, as well as now, was that they grew their own hops, which is an essential part of their beer. Fast forward over 100 years, and although the beer industry has changed significantly, you can still find Ruhstaller growing their own hops in Dixon, brewing beer, and selling it in Sacramento. By now, Ruhstaller is the only brewer on the west coast that grows their own hops, and although it helps to create great tasting beer, it introduces a set of challenges that many other breweries don't have to conquer. Additionally, Ruhstaller wants to use the kiln as a tap room when they are not drying hops which adds additional complexity.

Before hops are used in brewing, they have to be processed, the main stage of which is drying in a kiln. This removes excess moisture so that the hops can be stored without rotting. A hop kiln of the design that Ruhstaller wants to build has three main parts and is pictured in Figure 1 on page three. First, the kiln has a heat source that is placed near the ground. Often, these are gas furnaces which generate hot air and convective airflow. Two, the kiln has a slatted, open ceiling which is located at the top of the wall where the wall meets the roof. Burlap is placed on this slatted surface. The hops are then placed on top of this burlap. The burlap and open spaces between the floor slats allows the hot air to move freely through the hop bed. Lastly, hop kilns often have a steeply pitched roof with an exhaust vent at the top which allows the air to escape after it has moved through the hop bed and slatted floor. Currently, Ruhstaller uses a modified 27'x8' storage container and propane furnace to heat the hops to the required temperature and supply the needed airflow so that the hops dry to the desired humidity of 3-5%. With the new kiln construction, they hope to increase the kiln size to a total of 1,458 square feet, fulfilled by two 27'x27' kilns. This would increase the square footage for hop drying by over six fold. We were given some basic schematic drawings of the hop kiln they plan on building, and based our calculations and models on this design.

As our client, JE and his team develop the site, they want to do it in such a way that they limit their reliance on the power company, imported fossil fuels, and achieve some level of environmental stewardship. Given the size of their company, they also have financial constraints. Fortunately, many of these went hand in hand for the kiln design. For example, limiting the reliance on the power company meant that we needed to choose an energy source that could be generated reliably onsite, which in turn excludes the use of fossil fuels, which then further achieves a “Zero Net Energy” status which ensures a certain level of environmental stewardship through the use of renewables.

1.2. Problem description

The main problem we tried to solve with this project could be distilled into the following. How can we work within existing schematics and principles of classic hop kiln design and apply energy systems that allow the client to dry their hops optimally and provide HVAC without importing energy? In this case, “imported energy” would be in the form of fossil fuels, or non-offset grid electricity (leaving open the option of a net metered grid connection).

1.3. Literature review

In the early stages of this project, we looked into many options for heating the kiln and conducted a qualitative analysis to figure out which combination of technologies made the most sense in the site context. The results of this analysis were that electrical and thermal energy were the most feasible forms of energy for utilization at the site. Furthermore, a heat pump in conjunction with a solar thermal pre-heat system was the system we settled on.

2. Methodology

2.1. System Design

During the drying season the drying season the temperature of the hop kiln needs to be maintained at approximately 120°F to guarantee sufficient drying and a high quality of the hops. Additionally, the air flow should be around 1.35 ft/min per inch of hop-bed(Hop Drying). Assuming a hop-bed-thickness of 20 inches this leads to a required air-flow of 25 ft/min. With an area of 729 ft² per Hop-Kiln the required volume-flow can be estimated to 18225 cfm. Extreme high and low temperatures, as well as an insufficient air-flow can lead to lupulin losses or extensive hop cone shattering (Hop Drying). This leads to two constraints for the system: the max heating load [BTU] and the air-flow [cfm].

2.1.1. Calculating the Heating and Cooling Load of the Hop Kiln

In general, it can be assumed that the heat addition of a building needs to meet the heat loss of a building in order to keep the temperature constant. From Figure 1 the following equation can be derived:

(2.1) $Q_{in} = Q_{out}$

(2.2) $Q_{in} = Q_h = \sum_i^N A_i * U_i * HDD * 24 \frac{h}{day} \qquad i = 1, \ldots, N$

(2.3) $Q_{in} =- Q_c =- \sum_i^N A_i * U_i * CDD * 24 \frac{h}{day} \qquad i = 1, \ldots, N$

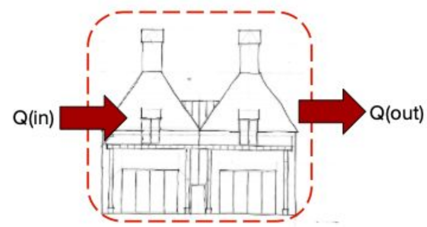


Figure1: System Boundaries

For the following work it was assumed that if Q_{in} is greater than zero, the building was heated and, vice versa if Q_{in} was smaller than zero the building was cooled. The heating and cooling load could then be calculated using equations (2.2) and (2.3) whereas,

Q_h Heating Load [BTU]
Q_c Cooling Load [BTU]
A_i Area of the building part i [ft²]
U measure of the heat transmission through a building part [BTU/(ft²*h*°F)]
HDD Heating Degree Day [°F*day]
CDD Cooling Degree Day [°F*day]
N number of building parts (Floor, Roof, Walls, Windows, Doors,...).

As of now the building design of the Hop-Kiln is not complete which leads to certain assumptions regarding the areas of the building aspects and their U-Values. The U-Values, are used to determine the heat transmission through single building aspects. In order to estimate the U-Values for the roof, walls and foundation of the Hop-Kiln, the insulation fact sheet which is published by the DOE (Department of Energy), was used. The fact sheet contains recommendations for new as well as existing buildings depending on their location . Using the Zip Code of the Brewery the Insulation Zone of the Hop Kilns could be determined. Since the Hop-Kiln is not build yet, the recommended values for a new building were used. As for windows, skylight and doors average values from website recommended from the DOE were used(Efficient Windows Collaborative), whereas the U-Values of the windows and skylights take size and shading into consideration. In Table 1 the assumed U-Values for the single building parts are listed as well as the area of the building parts.

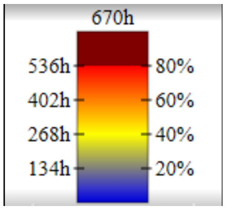
Building Part	U-Value [BTU/(ft²*h*°F)]
Roof	0,026
Floor	0,04
Walls	0,053
Slab foundation	0,125
Windows	0,3
Skylight	0,65
French Swing Wood Doors	0,3
Entrance Door	0,3
Doors Inside	0,3

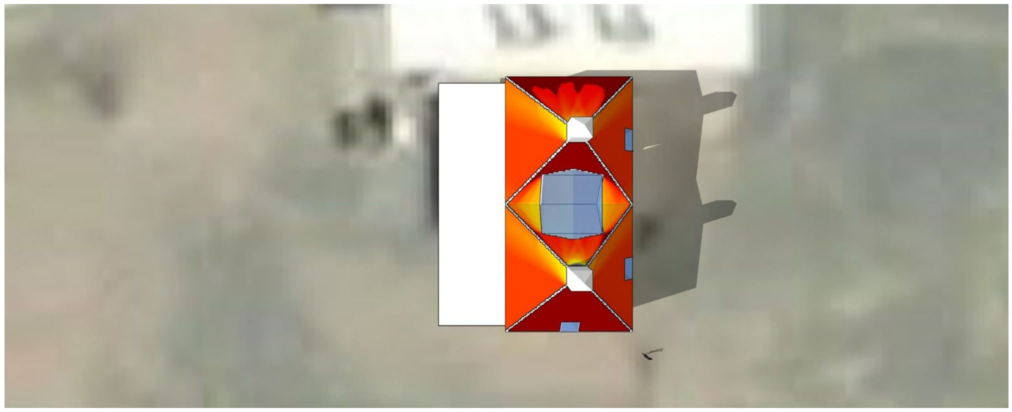
Table 1: U-Values of the different building Parts

The values of the degree days were researched online as well(BizEE). The location was set to the weather-station of the University of Davis (KEDU). For heating a target-temperature of 68°F was assumed, for cooling 70°F and for drying 120°F. The HDD and CDD were then calculated using the daily average of the last 5 years. Since the drying of the hops only occurs in August or September, the heating load for drying was only calculated for those months.

2.1.2. Solar Thermal

To get an estimate of the amount of energy we could harvest from the solar thermal system, as well as establish where collectors should be placed, we built a geo-referenced 3D model of the proposed hop kiln in Google Sketchup. We then utilized an extension called SunHours which calculates how many hours of direct sun a certain face of a building receives in a specified amount of time (SunHours). For our analysis we specified the two months in which drying would occur (August and September), and selected the faces of the roof for analysis.





2.1.3. Heat Pump Requirements

The Heat Pump needs to be able to provide sufficient kiln drying and HVAC for both the hottest and coldest days of their respective periods, thus the first constraint is given by the day with the highest heating or cooling load. Additionally a certain air-flow is required in order to ensure a high-quality of the hops after the drying process. Generally, it can be assumed that per ton a air-flow of 400 cfm can be provided(Cabrillo). The following three equations were used to estimate the size of the Heat-Pump:

(2.4) $Heat-Pump\ size\ (load)\ = \frac{max(Load\ [BTU])}{1200\ BTU} * tons$

(2.5) $Heat-Pump\ size\ (air-flow)\ = \frac{required\ air\ flow\ [cfm]}{400\ cfm} * tons$

(2.6) $Heat-Pump\ size\ = \ max\ (Heat-Pump\ size\ (load), Heat-Pump\ size\ (air-flow))$

2.1.4. Estimating the PV-Array-size

In order to estimate the size of the PV-Array the maximum electricity load needs to be determined. With the heating season performance factor (HSPF) and the seasonal energy efficiency ratio (SEER) the electricity demand of the heat pump can be estimated. While the HSPF is defined as the BTU of heating per Wh of electricity consumed, the SEER describes the BTU of cooling per Wh of electricity consumed. After calculating the max electricity load that needs to be supplied by the PV array, the size of the PV array can be estimated with Formula (2.7). One PV-cell was assumed to provide 2.6 kWh of Electricity.

(2.7) $Number\ of\ PV-Cells \geq \frac{Max(Electricity-Load)}{2.6\ kWh}$

2.2. Economics

Currently the heat-demand for the hops-drying-process is generated by burning natural-gas. Assuming that 1 ft^3 of natural gas provides 1,037 BTU the consumption of NG was calculated to be around 23,000 ft^3 for the month of drying(EIA, *Energy Units and Calculators*). Using the price of natural-gas and the price of electricity published by EIA the operational cost of the two systems could then be compared(EIA, *California Natural Gas Prices*).
The capital expenditures for the installation of the heat-pump, PV-array and the solar-thermal application national averages were researched online.

3. Results & Discussion

3.1. System Design

3.1.1. Heating and Cooling

Figure 2 shows the Heating and Cooling Load over the course of one year. While Heating is required almost all year, cooling is only needed during the summer months. The highest load appears in January, where up to 400 MBTU are required for heating the Kiln. Figure 3 shows the heating load during the drying-months as well as the reduction-potential from solar thermal. The highest load is 1200 MBTU without the solar-thermal installation and 476 MBTU including the reduction potential of a solar thermal installation. Since the highest loads are found during the drying-process, the drying process determines the size of the system.

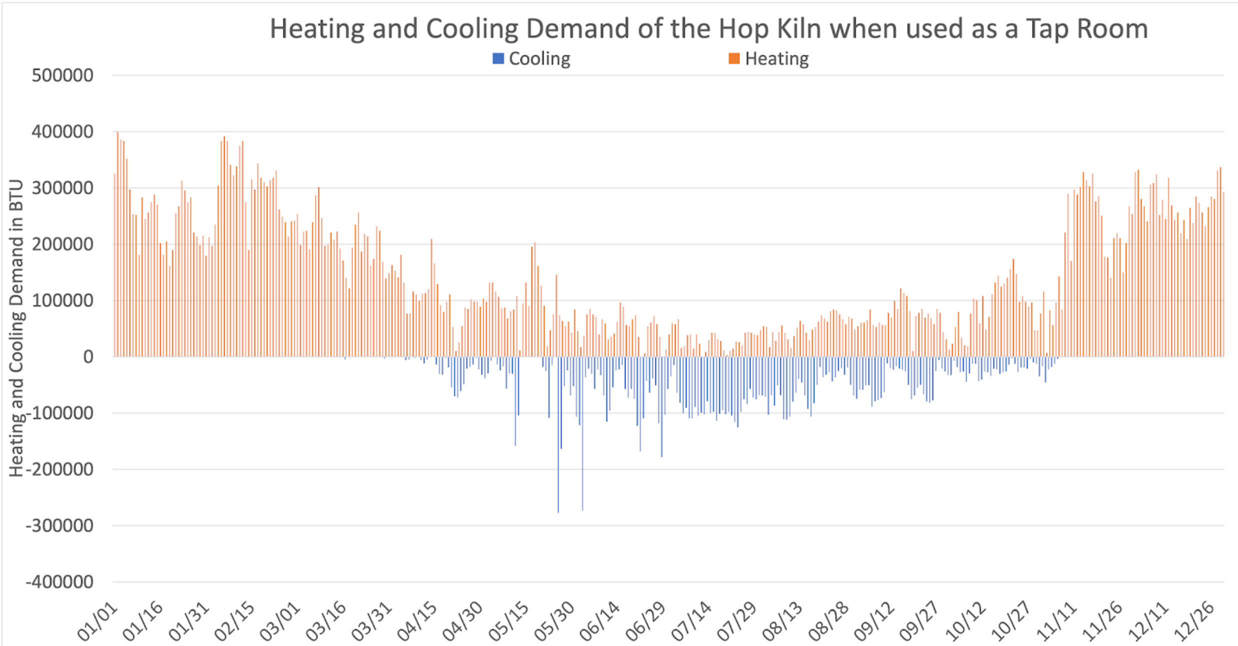


Figure 2: Heating and cooling load of the hop kiln during the year

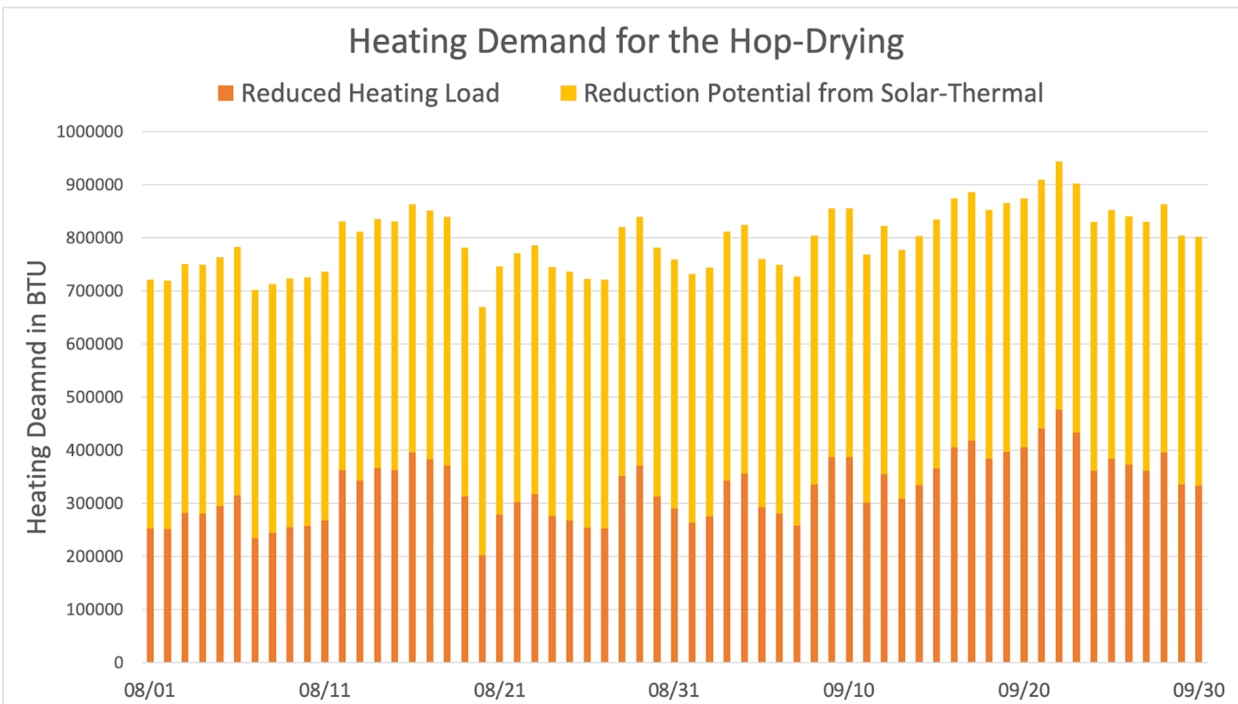


Figure 3: Heating demand of the hop-drying process with and without the reduction potential of a solar thermal application

It is important to note that when calculating the reduction potential from solar thermal, it was assumed that only 2 rooftops are going to be covered with solar thermal. If the amount of ft² that is covered by solar thermal increased to more roof panels, the majority of the heat could be supplied from the solar-thermal application - at least during the day. A case study on the drying of walnuts was performed by Solar Wall(Solarwall Europe). The results showed that not only could the Solar Wall installation provide the required 110 °F, which is a similar temperature to what is needed for the hop-drying process, but an air-flow of 25,000 cfm could be provided. If solar-thermal would cover all the roof sections, up to 450 MBTU/h can be produced. Figure 4 shows the potential heat production for each roof section.

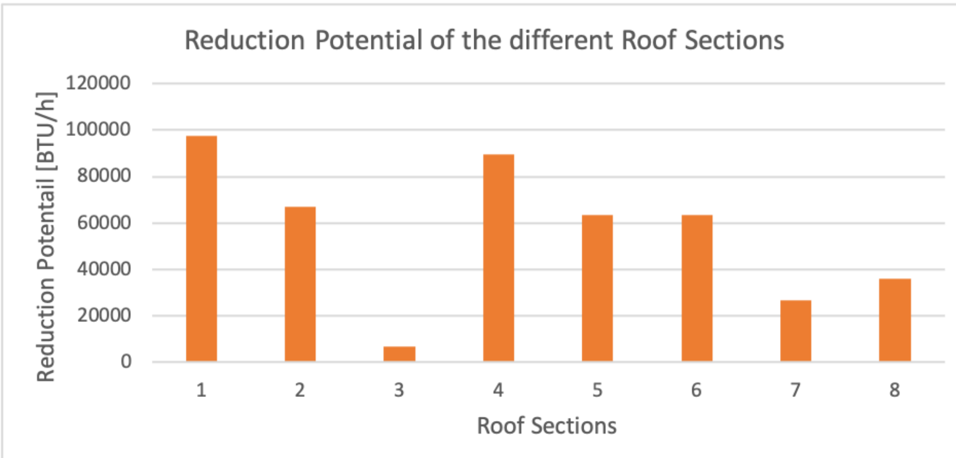


Figure 4: Potential heat production of each roof section

3.1.2. System Layout

In order to meet the heating and cooling loads a heat pump with at least 3 tons is needed. However, in order to meet the air-flow-requirements a heat pump of 45 tons is needed. We reached out to Daikin and Trane in search of a model that could fulfill the demand however we either never heard back or were not able to find a model with the required tonnage.

Assuming a HSPF of 8.5 and a SEER of 10, as recommended by ENERGY STAR, a program of the EPA and the DOE(ENERGY STAR), the electricity demand of the heat pump can be calculated. Table A3 of the Appendix gives an overview of the electricity load for heating, cooling and drying. The size of the PV-Array is depends on the highest electricity-load that needs to be provided. Table 2. shows the results for the scenario with or without a solar thermal installation. Thus, including a solar-thermal application can decrease the size of the required array by 50%

Scenario	**Electricity Load**	**Number of PV-Cells**
Electricity Load	111 kWh	43
Electricity Load with utilization of Solar Thermal	56 kWh	22

Table 2: Estimation of the PV-Array

3.3. Economic Assessment

With an average cost of \$ 3.05 per kWh of Electricity installed the cost of the PV-Array can be estimated to be either \$17446 with the solar thermal and \$ 34099 without. Assuming that the installation cost of the solar thermal is similar to that of a solar ventilation preheat application, the installation cost for an area of 241 ft^2 would be around \$ 7476. The average installation cost of a 3 ton heat pump is around \$ 5740(ENERGY STAR). Unfortunately, it was not possible to find industrial heat pumps that meet the constraints of the system and thus, their cost remained determined.

Currently the heating load is provided by burning LPG (liquified natural gas). The cost of LPG was assumed to be \$ 2.4 per $gallon^3$ of LPG, whereas the cost of electricity was estimated to be \$ 0.16 per kWh of electricity. In Figure 5 the operational cost of the electricity-based heat pump system are compared to the cost of the LPG based system.

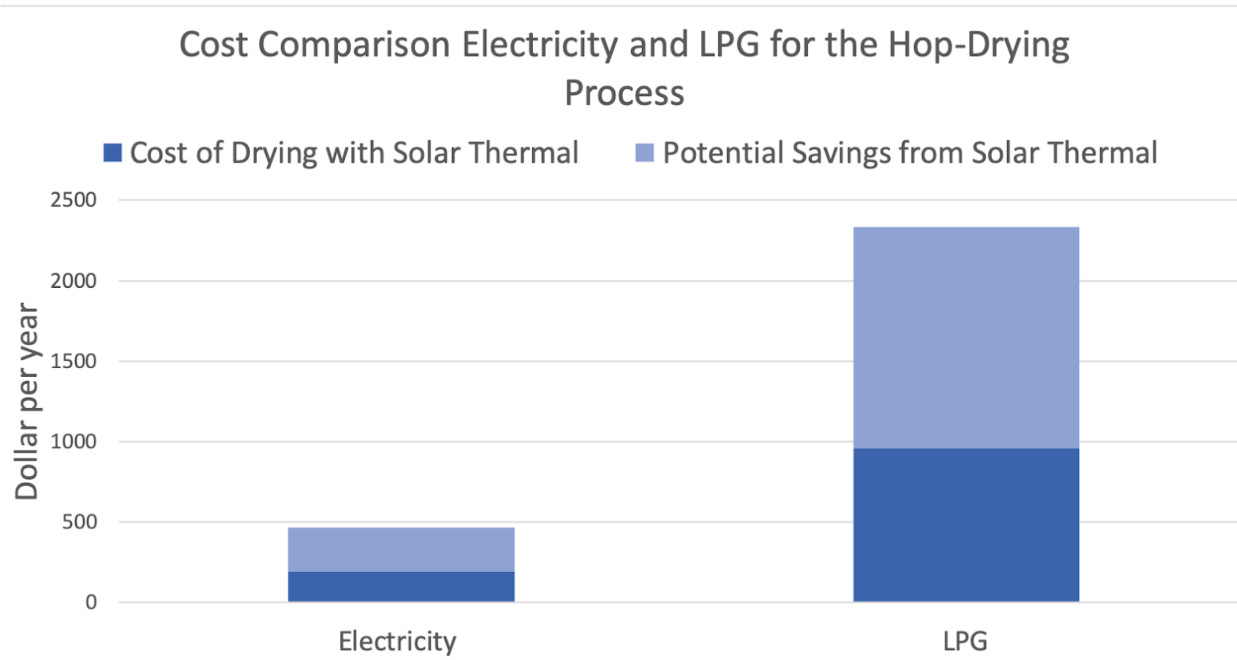


Figure 5: cost comparison of the electricity based to the natural gas based system

While the operational cost of the LPG system with the heat pump is significantly higher than the electricity system it is important to take into consideration the larger capital expenditures of an electricity-based system. However, the electricity can potentially be generated on-site through a solar PV-array, thus potentially providing independence from the grid.

Considering the high capital expenditures of an electricity-based system to provide for the entire load, a mix of an electricity-based system with the addition of a boiler seems most feasible.

3.4. Sources of Uncertainty

The heating and cooling loads of the system were estimated without taking factors like solar radiation or the number of people in a room into consideration. Therefore, the numbers should only be used as rough estimates. Since the design of the Hop-Kiln is not finalized, the U-Values had to be estimated and they might not match the actual U-Values of the material used in the final design. This adds additional uncertainty to the calculated heating and cooling loads and it might be necessary to re-calculations the loads.

3.5. Additional/follow-up work

For future work additional, more accurate calculations of the loads associated with the Hop-Kiln should be made as soon as the building design is finalized. This could lead to more accurate results and a more accurate system layout. In addition, heat recovery options should be researched. The brewing process requires a significant amount of process heat, which could be re-used for the drying process e.g. to pre-heat the air. The large air-flow required turned out to be difficult to provide with a heat-pump. More research could be done in order to find different technologies or system additions to meet this constraint of the system

4. Recommendations & Conclusions

Our recommendations fall into four categories. Firstly, we believe it is very important to first focus on the efficiency of the building construction. While the client expressed an interest in our efforts being focused on the energy aspect, rather than the efficiency aspect of the design, we recommend taking a hard look at aspects of the design like orientation, window placement, design, and construction, as well as other aspects like lighting and insulation.

Secondly, we recommend looking into decreasing the thickness of the hop bed. Given that airflow scales with hop bed thickness, the thinner the hop bed, the less airflow is needed. If less airflow is needed, a heat pump of fewer tonnage could be utilized which would save the client significant capital in both up front, and operating costs.

Thirdly, the solar thermal preheat system has significant potential. While our analysis only utilized the two roof panels which caught the most direct sun, utilization of the other panels could allow for even more heat load alleviation and the possibility that during the day, the entire load could be satisfied. Also, the system is simple, efficient, is low maintenance, and is easy to install by the client.

Finally, if the client does not have the flexibility to change the thickness of the hop bed or modify the design of the hop kiln, we found that the airflow needed to optimally dry the hops would be inefficiently supplied by a heat pump of the necessary size and would introduce a slew of other issues related to energy use, large size, and noise concerns. Requiring 18,000 cfm of airflow as would be needed by a 20 inch bed thickness would be better satisfied with a gas furnace and fan system.

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