Solar Concentration Strategies for Evacuated Tubes: A Comparison Between a Compound Parabolic Reflector and a Linear Fresnel Lens

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ABSTRACT

Evacuated tubes are glass tubes coated with Aluminum Nitrate that trap incoming radiation without letting energy escape due to convection or conduction. They are commonly used in solar cooking to heat food or water or in domestic hot water systems.These tubes also have potential to be used as solar water pasteurizers, although it is not currently considered a viable solution. To demonstrate this potential, two identical evacuated tubes were equipped with either a linear Fresnel lens or a compound parabolic reflector to concentrate sunlight and heat the water filling both tubes. The temperature of the water was monitored in each tube and the time was recorded for the water to reach 80℃. This temperature was chosen because it is well above the 65°C necessary to kill Hepatitis A, the most heat resistant virus, in contaminated water. The hope of this research is to bring this technology into the solar water pasteurization field, inspired by a students research in the previous year with a parabolic reflector and evacuated tube. This method was criticized as being impractical for implementation in developing countries, so this current study aimed to make a more practical and more efficient system with the use of an enclosed box with Fresnel lens to concentrate irradiance on the evacuated tube. The results show that the Fresnel lens is much more efficient in sunny conditions, while the reflector is more efficient under cloudy conditions.

INTRODUCTION

This thesis will investigate two different solar concentration methods for heating water in evacuated tubes. The goal is to heat the water to a safe pasteurization temperature and compare efficiencies for each concentration method. Two identical tubes will be heated on each test run, one with a compound parabolic reflector and the other with a linear Fresnel Lens to concentrate sunlight. These two systems will be compared in order to apply the results to the potential for a more efficient and durable method of solar water purification. Since most evacuated tubes on the market today use compound parabolic reflectors, this model will be used as a control. While compound parabolic reflectors are effective, the reflector itself is both fragile and due to its reflective coating, appealing to steal in low-income environments where shiny surfaces are rare may be more valuable as a mirror than a reflector. A linear Fresnel lens is being used as a comparison because these lenses have an impressive concentration strength, are more durable, and are not being used widely with evacuated tubes.

Water contamination is a global cause for concern but disproportionately affects developing countries and regions of lower socioeconomic status around the world. Many of the countries most in need of clean water are also exposed to large amounts of sunlight. The recommended method for purifying contaminated water is currently to boil the water, which takes a large amount of fuel, whether that be gasoline or biomass. Evacuated tubes require no fuel input, which largely cuts down on the deforestation effects that can occur as a result of cutting biomass to boil water and cook. There are many different methods of water pasteurization in place today, the most common of which being thermal pasteurization. The common practice in areas with contaminated water today is to bring the water to a rolling boil. Hepatitis A, the most heat-resistant disease found in water, is killed at temperatures of 65°C and higher, so boiling water is not necessary for it to be safe to drink. This also tremendously decreases the energy required. The data from heating water with these two different concentration strategies will illuminate alternate methods of heating water and show that evacuated tubes can play a large role in solar water pasteurization.

Evacuated Tube Background and Application

Evacuated tubes are made with two layers of vacuum sealed glass. This manufacturing method creates an inner glass tube that can be filled with water, a small cooking tray, or other heat transfer fluids. Borosilicate glass is commonly used because it is resistant to high temperatures, relatively durable, and has a high transmissivity. A high transmissivity and low emissivity value is needed to ensure that the majority of solar radiation incident upon the tube is trapped inside to heat the water, or other materials, efficiently. The inner tube is coated to maximize absorption of incoming radiation. Aluminum-nitrate is commonly used due to its low emissivity rate, allowing none of the captured radiation to emit from the inner tube.[1] The vacuum seal prevents heat loss due to conduction and convection. These evacuated tubes are traditionally mounted with a compounded parabolic reflector, which focuses sunlight on a center point in the tube. The main use for these systems today is in domestic water heating. There are a few companies that specialize exclusively in producing evacuated tubes for cooking uses, but since these systems cost $100 or more, they are often used for fun on camping trips or for affluent population's emergency backup cooking.

Outside of cooking, evacuated tubes are used in larger systems for heating domestic water. These systems typically consist of multiple evacuated tubes hooked up to a water storage tank. A heat pipe is inserted in the glass evacuated tube that contains a heat transfer fluid. This fluid is heated with solar radiation and releases heat into a tank with water flowing through, heating the water for domestic use.[2] A diagram of the system can be seen in Figure 1. In this system, no water fills the evacuated tube since the heat pipe is surrounded by an absorber fin to transfer heat from the glass surface to the water tank. This method ensures that cold water does not come in contact with a pre-heated tube which could cause thermal shock which may shatter the glass inner tube. This thesis is examining the use of a fully filled evacuated tube, which is a unique approach when compared to most research studies.

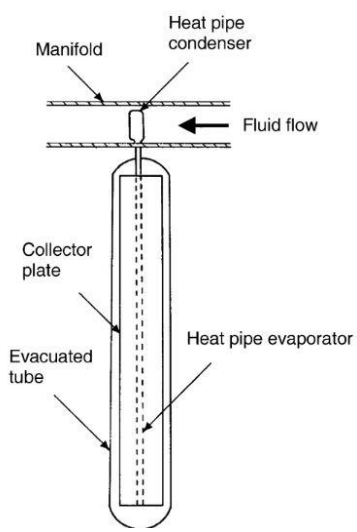

Figure 1. Diagram of an evacuated tube with a pipe inserted to transfer heat for a domestic hot water system.[2]

Though evacuated tubes can be used without any extra concentration accessories, they are more efficient when paired with a reflector or other concentration mechanism. A study was conducted in Heifei, China that examined a rooftop system of an evacuated tube with and without a mini-compound parabolic concentrator. The water was heated in each system from 26.9 to 55, 65, 75, 85, and 95°C and data was tracked for two days.[3] The inner tube of each system had a copper U-tube pipe with an inlet and outlet for the heated water. A pyranometer was used to measure irradiance and a thermocouple was placed in the water storage tank for each system. This study found that when the temperature of the water reached 65℃ or higher, the system with a compound parabolic concentrator was more energy efficient than the system without.[3] This study gives credibility to the use of a compound parabolic reflector for water pasteurization purposes.

For this thesis, a Fresnel lens was chosen as the concentration method for the other tube because the plastic of the lens is more durable than the reflector, it has a high concentration ratio, and is not commonly used outside of utility scale projects. Linear Fresnel lenses have been used in photovoltaic concentrations to focus a greater intensity of sunlight on the solar cells, typically deployed with a tracking system in order to keep the lens in line with the incident radiation.[4] Fresnel reflectors are also often used with evacuated tubes in a parabolic trough concentrator. The reflectors are broken up into many flat rectangles and arranged to mimic how a parabolic reflector would be shaped. An evacuated tube in the middle is used to create steam for power generation.[5] There are no evacuated tube systems on the market that come with a lens instead of a reflector, as the Fresnel lens approach is almost exclusively used by power plants for power generation. This is the reason why the current experimental design was made to directly compare a compound parabolic reflector with a linear Fresnel lens; to the best of our knowledge, the direct comparison has not been studied previously.

Fresnel Lens and Compound Parabolic Reflector Optics introduction

The lens used for this current study is a non-imaging Fresnel lens, which is traditionally recommended for concentrated solar applications. The goal of producing an image makes imaging lenses more sensitive to aberrations when misaligned with the sun, so tracking systems are almost always needed if the lenses are being deployed on a large scale.[4] Fresnel lenses focus incident light from a variety of angles into a straight focal line with the ridges that are etched into the plastic, but only when the center of the lens is parallel to incoming radiation. If the lens is misaligned, the focal line is spread out and less focused, and could shift entirely to the left or right and not focus on the tube at all depending on the angle of misalignment.

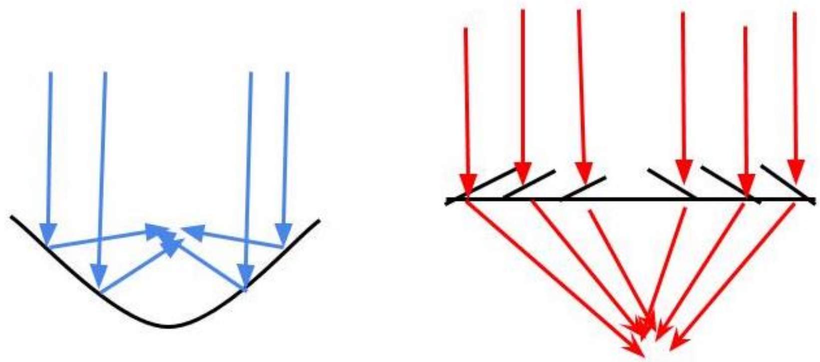

Figure 2. A visual representation of the optics of a parabolic reflector (left) and the optics of a Fresnel lens (right). The focal point is where all of the arrows converge in the middle of the reflector or behind the lens.

This misalignment is mitigated in utility scale applications by employing tracker systems or using many lenses at varying angles, similar to the trough technique mentioned previously. In the current study, a solar pathfinder is mounted to the enclosure and manual adjustment is carried out to ensure the lens is properly aligned so that incoming rays are perpendicular with the lens surface.

Parabolic reflectors are used instead of spherical reflectors to decrease spherical aberration. When parallel light rays hit the edge of a spherical reflector, they focus closer to the reflector than light rays that bounce off near the center. This causes two different focal points to appear, which would cause an evacuated tube placed in a spherical reflector to heat unevenly or be missed by the focused solar radiation. The shape of a parabolic reflector corrects for this spherical aberration by focusing light rays that hit the edge and the center at the same focal point. The compound parabolic reflector used in the current study follows this same principle but creates two focal points instead of one. There is a focus from each of the two parabolas that are combined to make the single reflector. This creates two focal points on each side of the evacuated tube. Reflectors are less sensitive to sun-tracking than lenses because they accept a wider angle of incident light without shifting the main focal point. However, to maximize the efficiency of each system and make an equal comparison, the reflector system was adjusted accordingly each time the lens system was repositioned with the solar finder.

Current study and water pasteurization applications

This project is a continuation of a past project from Professor Ramsdell's and her student, Lucy Barron.[6] A water pasteurization system was constructed of a small evacuated tube, a reflector, and a dirty and clean water reservoir. The tube and reflector system was always horizontal, so it was not lined up to make the most efficient use of incident irradiance. This design was presented to a water non-profit, Wine to Water, who voiced concern about the impracticality due to the shiny and fragile components of the evacuated tube and the reflector. This feedback prompted this experiment and research into Fresnel lens as a possibility. The enclosure designed for these tests is a wooden box that contains the evacuated tube so that it is less likely to be damaged, and less likely to be attractive for thievery. The lens itself is plastic, so it is less desirable and less fragile than the reflector. If the lens can outperform the parabolic reflector, then this system could have very real potential to be used for water pasteurization in refugee camps, developing nations in the world, or as another method of cooking for hobbyists.

EXPERIMENTAL METHODS

Design and Set-up

The design for this experiment was driven by the 30 cm focal length of the Fresnel lens being used. The lens needs to be suspended 30 cm above the evacuated tube in order to properly concentrate the solar radiation. Many Fresnel systems use metal rods to attach to lens above the tube that can be rotated so that the lens can always be tracking the path of the sun.[6] The goal of this project is to keep the cost low and use easily accessible materials to build a durable system for water pasteurization. In order to achieve these goals, particle board was used to create a box that would enclose the evacuated tube while supporting the Fresnel lens above it. The box design was chosen to protect the evacuated tube from being jostled and make transporting and adjusting the system easier. The five-sided particle board box was designed so that the focal length of the lens would focus in the center of the evacuated tube, in order to heat the water most effectively. The box is 30.0 cm wide, 70.0 cm long, and 33.4 cm deep. The depth of the box aligns the focal line in the center of the evacuated tube once it is mounted on the clamps. The lens is installed to cover the box and the evacuated tube is centered in the box and secured with clamps from an old SolarCooker model. Figure 3 shows the finished product for the Fresnel lens enclosure.

Figure 3. The Fresnel box enclosure built with particle board. The five-sided box has a fold-down door that can be secured with a latch shown on the upper left corner of the box. The lens is drilled to the top so that the focal line falls in the center of the evacuated tube. The silver clamps were removed from an old SolarCooker reflector and drilled to the bottom of the box. A SunFinder can be seen mounted to the top of the box above the latch; this is used to align the lens with the sun's position. A hole was drilled on the same side as the SunFinder to ventilate the box and run the thermocouple wires from the tube to the datalogger.

A drawback of a Fresnel lens is that it is much less effective than the reflector at concentrating solar radiation that is not directly perpendicular to the lens surface. In order to correct this drawback, a SunFinder was mounted to the top of the box in line with the center of the Fresnel lens. A metal stand with an adjustable ledge was used to angle the box so that the lens is perpendicular to the incident solar radiation at the sun's altitude angle. The brackets used to hold the evacuated tube in the lens box were removed from the reflector system, so a spring was used to hold the evacuated tube in the center of the reflector. A spring of the same size was placed on the evacuated tube in the lens box to ensure the area of the evacuated tubes that were receiving solar radiation was equivalent across the two different systems.

Data Collection Procedure

The goal of this study is to calculate the efficiencies of each system, where the goal is to heat the water sample to 80℃, a temperature known to pasteurize water.

- Each evacuated tube has three thermocouples submerged in the water sample at different depths that are attached to a sheet of wire mesh for structural support.
- The values from the top and bottom thermocouples in each tube were recorded with a data logger that saves the temperature reading every minute. The middle thermocouple values were manually recorded to check the values of the top and bottom readings.
- The mass of the water in both evacuated tubes was measured before and after the data collection time period to ensure there was no mass loss due to steam.

The Fresnel box was set up first, and the SunFinder was used to find the correct angle for the solar radiation to be perpendicular to the lens and focus correctly. The reflector was then set up next to the Fresnel box and the height was adjusted so that both systems were at the same angle. During this set-up process, both systems were covered with a black cloth until everything was ready for data collection. This was done to prevent one tube from starting at a higher temperature than the other or receiving more undocumented solar radiation and skewing the results. A Vernier data logger with a pyranometer was used to record irradiance levels during the data collection period. The irradiance measurement was updated and saved every minute to correspond with the sample rate of the temperature data.

The data collection process lasted until the thermocouple near the bottom of each tube reached near 80°C or two hours had passed.

The bottom thermocouple is monitored because a natural temperature gradient arises due to the angle of the evacuated tubes and this causes the water on top to heat up much quicker and circulate slower within the system. The water at the bottom of the tube should be the coldest so once this has reached pasteurization temperature, the whole sample should be safe to drink. Once a temperature near 80°C has been reached, both data loggers were stopped and the systems were disassembled.

DATA ANALYSIS AND RESULTS

The efficiency of a system is determined by comparing the energy output with the energy input. In this study, the energy output is the heat required for the change in temperature of the water and the energy input is the effective irradiance of the system. The effective irradiance is calculated by multiplying the measured irradiance by the area of the solar collector. This value is measured in Watts after being normalized with the area. A Watt is a Joule per second, so the effective irradiance is multiplied by the measurement time period, 60 s, to calculate the energy input in Joules. The energy output uses Equation 1 to determine how much energy is needed to heat the water sample.

$$Q = mc\Delta T \quad (1)$$

The mass of the water in kg is m, $\Delta T$is the change in temperature, $c$is the specific heat of water, and Q is the heat required for that particular temperature change. This value is measured in Joules. The specific heat of a material is quantity that represents how resistant it is to temperature change. The specific heat of water is defined as the amount of energy that raises one gram of water one degree celsius, which equates to 4,186 $\frac{J}{kg\cdot°C}$. Water has at least twice as high of a specific heat than any other material, making it vary thermally intensive to get a significant change in temperature. The average efficiency for each system was calculated, but due to potential lags in the thermocouple and some outliers, these values do not tell the best story of how these solar collectors compare to one another. Temperature curves were graphed for each trial run and were superimposed onto one graph of temperature vs. time for all three trials. The data is color-coded so that red lines are the Fresnel lens results and the blue lines are the reflector results. The different dashes of the lines indicate the date the trial was run.The temperature curves can be seen below in Figure 4.

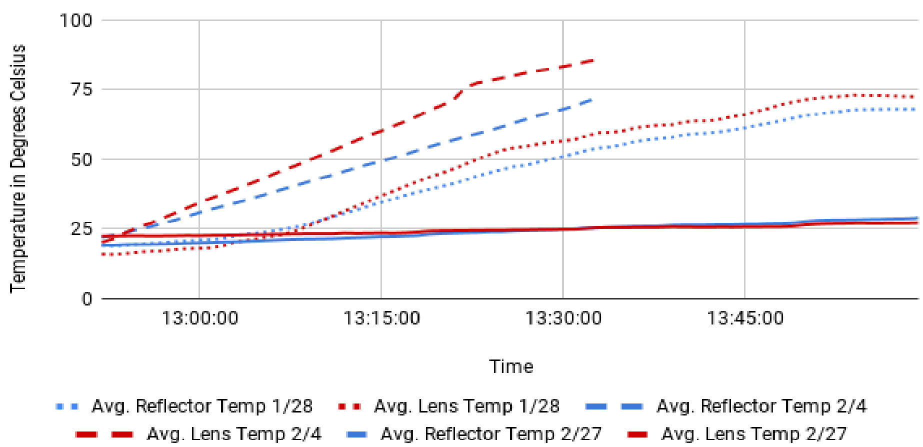

Figure 4. The temperature curves for each trial graphed against the total time data was logged. The 2/4 trial was logged under sunny conditions, the 1/28 trial was logged under partly cloudy conditions with erratic irradiance levels, and 2/27 was logged under full cloud cover.

It can be seen in Fig. 4 that the Fresnel lens apparatus gets to higher temperatures than the reflector in sunny conditions, but the reflector is more effective in cloudy conditions. However, this gap between the two systems is not nearly as large on cloudy days as it is in sunny trials, suggesting that the advantage of having a Fresnel lens system in sunny conditions might outweigh the slight loss in efficiency in cloudy conditions. The calculated efficiency values can be seen below in Table 1.

Table 1. Each trial date has an average irradiance and efficiency for the lens and reflector associated with it. The date of the trial is listed in the legend of Fig. 4. The efficiency for 1/28 is unusually high for the irradiance measured, which may be due to scattered irradiance and a lag in temperature readings.

Trial Date	Average Irradiance (W/m^2)	Average Lens Efficiency	Average Reflector Efficiency
2/4	930 (Sunny)	0.39	0.32
1/28	130 (Partly Sunny)	1.36	1.35
2/27	140 (Cloudy)	0.34	0.35

The trial on January 28th had very scattered irradiance levels, which are displayed in Figure 5. These sharp spikes in irradiance resulted in a low average irradiance value, which made the tubes appear to be more efficient during analysis. There was a brief, 5-10 minute period of full sun that increased the water temperature significantly, which can be seen in Fig. 4 between 13:15 and 13:30. The possible lag in the thermocouples means that this is not good data for analysis, but the irradiance graph overlaid with the temperature curves can be used to confirm the other trials

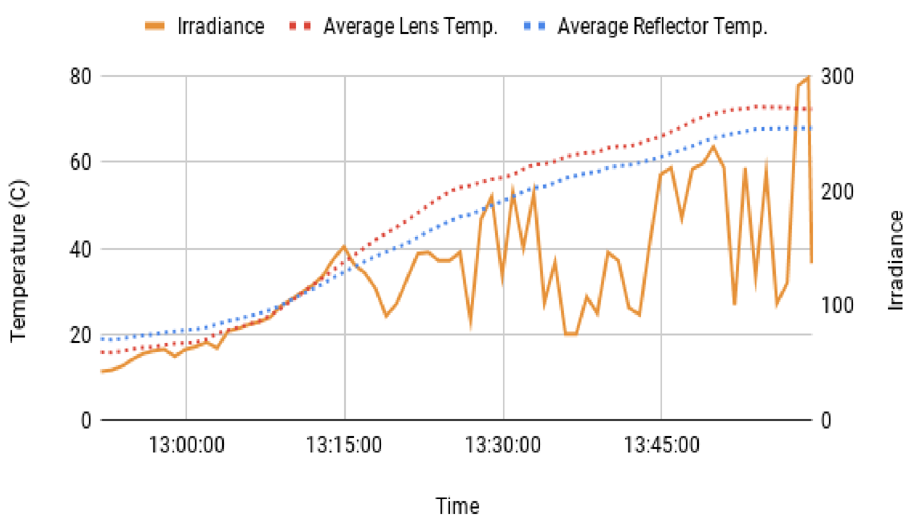

Figure 5. The temperature curves for the Fresnel lens and parabolic reflector on 1/28 with the irradiance data on a secondary axis. This shows the fluctuation in irradiance levels that are likely the cause for the high efficiency values recorded in Table 1.

DISCUSSION

The trials on February 4th and February 27th were days with consistent irradiance, so the efficiencies are representative of the actual system and likely not skewed by any equipment lags or anomalies in the data. The data on January 28th was not valid data because of the varied irradiance. The high specific heat of water means that it's resistant to temperature change, so once the spike in irradiance started heating the water more, it stayed at a higher temperature, even when the irradiance dipped low again. The temperature probes also only logged the temperature at each minute mark, so it's possible that these readings could have lagged and not accounted for all changes in temperature due to irradiance. Because of this disconnect in the reaction time of the temperature with the irradiance levels, both the lens and reflector appear to have efficiencies higher than 1, which should be thermally impossible. Although this data was not valid for calculating an efficiency, it is useful in confirming the results of the other trials. When the irradiance spiked for an extended time, the temperature curves had a steeper slope that matched the trend of the data for sunny conditions. When there was a period of low irradiance, the slopes of the temperature curves became more shallow, similarly to the cloudy condition data. This confirms that the systems are acting as expected and shows that the other data sets are valid. As displayed in other trials, the Fresnel lens started increasing in temperature rapidly when exposed to direct sun and created a larger gap from the reflector. The higher efficiency of the Fresnel lens on the sunnier days could make up for the slight lower efficiency on cloudy days. When irradiance is low, each system is going to struggle to some degree, so having a system that is more efficient under full irradiance would benefit individuals more in the long run.

Both of these systems were able to reach water pasteurization temperatures on sunny days, making them candidates for use as solar water purifiers. This research is significant because in today's society, the only market for these solar cooker systems is as a novelty item to cook dinner for friends while camping. There are multitudes of practical applications for evacuated tubes, one of the largest ones being water pasteurization. The biggest barrier for the implementation of these systems is the upfront cost it takes to purchase the materials. In many cases, wood is not expensive enough that there will be an immediate profit from buying an evacuated tube pasteurization system instead. In order to address this factor, a cost analysis was conducted that looked at firewood prices in Nepal and estimated how much a family would spend on using this fuel source to boil water. This will be compared with the estimated price of the Fresnel lens system and the parabolic reflector system. There has already been pushback from Wine to Water, an organization working to provide clean water in Nepal and other countries, about the use of a reflector due to its shiny nature. The cost analysis for both systems will show whether the lens could be a viable replacement for not only using firewood to boil water, but also the parabolic reflector.

Cost Analysis of Water Pasteurization Practices

This cost comparison will be conducted by using the price for firewood in Nepal and determining how much firewood is needed to boil water. This country was chosen because it is in the top ten list of countries with the greatest need for clean drinking water [10] internationally and because the organization that inspired this project, Wine to Water, started out working in communities in Nepal. The amount of energy needed to boil

750 mL of water from 20°C to 100°C has been calculated, and the mass needed of wood to achieve this energy requirement was determined. The price per kg of this material in U.S. dollars will be used and the cost will be determined by the total amount of mass needed to boil the recommended 2 L of drinking water for each person, each day for a whole year. The temperature range was chosen because most countries heat their water to a rolling boil, which would occur at 100°C. The price for wood will vary in every region, so to do the cost analysis of actual implementation, these calculations would need to be done for the specific community that this system would be implemented. This cost analysis is brief and does not give a full picture of how feasible either system would be due to varying fuel prices, and the fact that some people choose to cut their own firewood due to cost, but is included to give an idea of the cost barrier from implementing the Fresnel lens and parabolic reflector systems.

Cost of Boiling Water with Wood in Nepal

The cost of firewood in Nepal is roughly \$0.22 USD/ kg.[10]The specific heat of firewood is 2300 $J/kg \cdot C$; this value will be used in Equation 1 to determine how many kilograms of wood is needed to heat 0.75 kg of water from 20°C to 100°C. Using Equation 1 and the specified temperature range, water mass, and specific heat of water, the heat needed to boil 0.75 kg of water is 251,160 Joules. This amount of energy will be plugged into Equation 1 with the specific heat of firewood in order to determine what mass of wood is needed to produce enough energy to boil water. For firewood, one would need 1.4 kg to boil 0.75 kg of water. It is recommended that a person drinks 2 L of water each day to remain healthy, so the cost per day of heating 2 L of water uses Equation 2, where *m* is the mass of firewood and \$ *USD/kg* is the cost per kg of firewood.

$$\$\,USD/day = (2\,L/750\,mL) \cdot m \cdot \$\,USD/kg \qquad (2)$$

From Equation 2 it is determined that it would cost $0.80 USD per person each day to heat 2 L of water with firewood in Nepal. For this analysis, this cost will be multiplied by 4 to attempt to display how much water a family would need, and how much they would spend each year. After this adjustment it costs $3.20 USD per day, which equates to $1,170 USD each year for a family of four, if each person was drinking 2 L of clean water each day.

Cost of Parabolic Reflector System

The parabolic reflector apparatus is commonly sold as a package deal on most of the solar cooking websites. The closest package to the apparatus used in this study is the GoSun Sport Stove. It consists of the reflector used in this study and an evacuated tube of a similar size. It also comes with a cooking tray for filling the tube with vegetables or any other food. GoSun prices this set-up at $249.00 USD, but it is also available at $140.00 USD during specific sale periods.[14] I believe it would also be beneficial to have a SunFinder for the reflector apparatus as well, which would add $30 USD to this cost if the same one as the lens apparatus had was used. This gives a total system cost of $170-$279 USD, depending on if the reflector-tube package is bought on sale or not.

Cost of Fresnel Lens Solar Water Pasteurizer

The cost of the evacuated tube used in this system was $80 USD and the lens price could vary. There are Fresnel lenses on the market ranging from $3-$100 that could feasibly be used in this study. To encompass this range, the lenses will be priced at $50 USD, since the actual lenses used were already available and not purchased specifically for this purpose, so there is not a specified price. Three lenses had to be purchased to cover the top of the evacuated tube. $60 USD was used for the pieces of particle board and the wood screws purchased to build the box. The SunFinder was available for use, but a similar model is priced at $30 USD. These estimates price the system at $350 USD. This design is half of what it would cost using firewood for a year.

Limitations and Implications of Cost Analysis

It should be noted that likely not all people in Nepal are drinking 2 L of purified water each day, so these cost estimates are likely on the high side. The price of firewood per day is cheap, but many families may not be financially able to make this purchase each day. This leads to families cutting their own firewood, or not bothering to boil their water. Rogue firewood cutting can be extremely detrimental to the forests surrounding these communities when multiple families may be making that choice. In the 1990's in China, forest plantations were rendered useless due to deforestation for use in cooking and boiling water.[15] Deforestation can result in greater effects due to climate change as these communities, and the world will lose the carbon sink that forests provide until there is enough regrowth. If families cannot afford to purchase firewood or do not have the time and ability to cut their own, people simply do not boil their water. This results in illness in these communities that could have been avoided if there was a better, reusable system in place to pasteurize water.

Both the Fresnel lens system and the parabolic reflector system are cheaper than the cost of purchasing firewood for a year. Both of these systems could also be manufactured at much cheaper rates if cheap materials were found to make reflectors and if research was conducted determining whether cheaper Fresnel lens worked just as well. If cheaper lenses were able to be used, that would cut the cost of the system nearly in half. Although the upfront cost may be daunting, once a solar water pasteurizer is purchased, there does not need to be any additional cost of adding fuel or other materials, so any expense difference could be offset in a year. Not only is it cheaper in the long run to use this evacuated tube system, it also has health and environmental impacts from limiting the burning of firewood. Many women in Southeast Asia and parts of Africa suffer more respiratory illness, likely due to the use of indoor fires to cook and boil drinking water.[13] This system would eliminate most of the need for firewood, as it can be used to boil water and cook food; which could result in improved health of the affected people in these regions. The Fresnel lens in particular also has the capability to be used as a solar box oven. If the evacuated tube was removed, a pan or pot could be placed in the enclosure and be heated by the lens.

IMPROVEMENTS AND FUTURE IMPLICATIONS

The Fresnel lens heated water more quickly than the parabolic reflector system in the same amount of time when there were sunny or mostly sunny conditions. On the cloudy day, the reflector performed better, but with a much smaller gap between the two systems. The large gap between the systems' efficiencies on sunny days may make up for the less efficient Fresnel lens on cloudy days. More data needs to be collected comparing the two systems to investigate how different irradiance conditions affect each system in order to make a full, quantitative comparison of which solar concentrator is more efficient. A more in depth cost analysis needs to be conducted, but with the analysis used in this paper, the price for each system is more expensive upfront when compared to how much one might spend on firewood each day, but is offset within a year when the annual cost of firewood is examined. The price of this Fresnel lens system would likely decrease with commercialization as well. A mesh filter should be added to both evacuated tube systems to filter water for particulates before pasteurizing. The next step for studying how the lens system could be applied is to conduct an experiment investigating the practicality of using the Fresnel lens enclosure as a solar box oven. While the evacuated tubes can be used to cook food, there is typically a low adoption rate in developing communities because it is an unfamiliar way to cook. If traditional pots and pans could be used, or designed to be compatible, with the lens system then it would have the appeal or serving two purposes: water pasteurization and cooking.

The current data collected and analyzed for this thesis suggests that a Fresnel lens is a very viable solution for a solar concentrator that can be used with evacuated tubes. Not many Fresnel lenses are currently used with evacuated tubes outside of generating steam for power plants or a few smaller scale experiments developed for research. The standard right now for solar cookers on the market is to use parabolic reflectors. The results of this study suggest Fresnel lens are a more efficient alternative, and with some design modifications, this system could potentially be produced commercially for use with solar cookers. This study also proves the point that evacuated tubes have much more practical uses than simply hobby cooking. With more studies investigating how efficient they are at pasteurizing water, there is a possibility to change the market and use these systems to serve the very real need of providing clean water around the world.

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