Insulated Solar Electric Cooking – Tomorrow's healthy affordable stoves?

T. Watkins[a], P. Arroyo[a], R. Perry[b], R. Wang[a], O. Arriaga[c], M. Fleming[d], C. O'Day[a], I. Stone[b], J. Sekerak[a], D. Mast[a], N. Hayes[c], P. Keller[e], P. Schwartz[b,*]

[a] Mechanical Engineering, California Polytechnic State University, San Luis Obispo, CA 93407 USA
[b] Physics, California Polytechnic State University, San Luis Obispo, CA 93407 USA
[c] Electrical Engineering, California Polytechnic State University, San Luis Obispo, CA 93407 USA
[d] Industrial Technology, California Polytechnic State University, San Luis Obispo, CA 93407 USA
[e] Aid Africa, a 501(c)(3) Corporation, 3916 Pennsylvania Ave., La Crescenta, CA 91214 USA

A B S T R A C T

We present a cooking technology consisting of a solar panel directly connected to an electric heater inside of a well-insulated chamber. Assuming continued decrease in solar panel prices, we anticipate that in a few decades Solar Electric Cooking (SEC) technologies will be the most common cooking technology for the poor. Appropriate use of insulation reduces the power demand making low-power **Insulated** Solar Electric Cooking (ISEC) systems **already** cost competitive. We present a $100 prototype and preliminary results of two implementations in Uganda.

1. Background

The World Health Organization estimates that three billion people cook with biomass and coal causing 4 million deaths per year from breathing the associated emissions (WHO, 2016). Besides the dangers of indoor air pollution (Lim, 2013; Subramanian, 2014), cooking over open fires also results in deforestation, and climate change emissions of CO_2 and soot (MacCarty et al., 2008). The negative effects of current cooking methods can be reduced but not eliminated by the use of fuel-efficient stoves (Wilson et al., 2016; Smith, 2011; Lambe et al., 2015). While solar cookers eliminate health and environmental impact, they are often not readily adopted for reasons including inconvenience, dissimilarity to traditional cooking methods, and lack of power. Natural gas cooking alleviates the health concerns of indoor air pollution (Smith and Dutta, 2011), but remains a costly option. Electrical cooking eliminates health concerns, although the environmental impact will depend on the method of electricity generation. Additionally, typical electrical cooking technologies require grid connection or some other powerful electrical supply that in many places is prohibitively expensive, unreliable, or nonexistent.

As the cost of photovoltaic (PV) solar panels continues to decrease, Solar Electric Cooking (SEC) will become increasingly cost competitive. We are developing Insulated Solar Electric Cookers (ISEC) in order to reduce required power and the associated costs while adapting and accommodating the technology to different community cooking practices. The goal is to develop the appropriate cooking technology by the

time the price of solar panels is low enough to make ISEC the best cooking option. We believe that for some places, or with the correct financing strategy, that day has already arrived.

The price of solar panels has decreased by about a factor of 200 over the last 40 years, corresponding to a ½ price cut every 5 years (Swanson, 2006). At well below $1/W, residential solar panels deliver electricity less expensively than most conventional generation technologies. Accordingly, we purchased a 120 W polycrystalline silicon panel in Uganda in July 2016 for $100.

It's well known that one can cook on an electric range powered by solar panels, but the 1000 Watts of required power, corresponds to about $800 today just for the panels. Limiting power to 100 W reduces the cost, but is insufficient to cook food by means of a stove top. However, if no heat is lost to the environment, 100 W brings one liter of water from 20 °C to boiling in 55 min. Thus, by insulating the cooker we can reduce heat losses enough to slow-cook between 4 kg and 8 kg of food over the course of the day. At a caloric density of about 1000 Calories/kg for rice and beans, this would be enough food for 5–10 people.

Compared to conventional solar cooking technologies that rely on direct thermal conversion of sunlight, ISEC first converts the sunlight to electricity, physically disconnecting the collection of solar energy from the cooking, resulting in:

a) reduction in conversion efficiency;
b) an increase in heating efficiency through use of opaque insulation; and
c) ability to build a stationary, indoor cooking facility.

* Corresponding author.
  E-mail address: pschwart@calpoly.edu (P. Schwartz).

A concise comparison of the two technologies is impossible because both technologies are very broad. ISEC should be able to achieve higher temperatures than conventional solar cooking, except for expensive concentrators that require tracking. ISEC is more expensive than many conventional solar cookers, but ISEC cost will continue to drop with decreased cost of solar panels. Hence, like with conventional solar cookers, the challenge for ISEC lies in how users can innovate the technology to their benefit.

(Joshi and Jani, 2013) studied heating of a moderately insulated chamber with electricity from a system of solar panels and batteries, but did not expand the study beyond the laboratory. To the best of our knowledge, we are the first to explore and implement ISEC in a way that is both operationally and financially compelling.

2. Design

Simply put: *ISEC = Solar Panel + Electric Heater + Insulation.*

We propose a low wattage solar panel directly connected to a heater inside of a well-insulated chamber such that the heat lost to the environment is small compared to that retained in either the food or some thermal storage medium. These design parameters leave specific implementations to be locally designed to suit local foods, cooking style, cooking architecture, and availability of resources using a range of enclosures and insulations (Table 1).

Table 1
Insulation materials.

Insulation Type	Thermal Conductivity W/m-K	Cost $/m^3	Maximum Temperature °C
Fiberglass (pink)	0.04	45.26	540
Polyurethane (chips)	0.03	52.44	120
Rice Hulls	0.05 – 0.07	–	440
Straw	0.04 – 0.08	1.63	220
Perlite	0.04 – 0.09	41.33	870

Below, we describe three distinct ISEC examples.

1) Barbeque

A 5-gallon steel drum cooking chamber is insulated from the surrounding 55-gallon plastic drum (Fig. 1). Electrical power heats a burner thermally connected to the lid of the cooking chamber.

2) Concrete Thermal Storage

We are presently exploring the possibility of using solar electricity to heat a thermal storage block (such as a block of concrete) to subsequently be used for frying, grilling, and baking. High temperatures would require specialized insulation (see Table 1).

3) Boil and Simmer

Boil and Simmer cooking is particularly inviting because no temperatures should rise substantially higher than 100 °C, reducing thermal requirements of insulation. Additionally, most of sub-Saharan Africa cooks via boil and simmer and also receives enough sunlight most days to adequately power ISEC. We built several prototypes at Cal Poly in San Luis Obispo, California during the past summer, and two prototypes in Uganda with local villagers and nonprofit Aid Africa using local materials.[1]

Fig. 1. Barbeque prototype. Some insulation has been removed to expose the inner cooking chamber.

3. Electric heater

We made our own heating element in order to minimize costs as well as to allow choice of electrical resistance and shape. We used 26 gauge Nickel-Chromium (NiCr) wire (with electrical resistance of 8.14 Ω/m) immersed in a concrete tile 1.3 cm thick. The left portion of Fig. 2 shows the 36-cm wire woven into the mold for a 2.9 Ω heater that rises to 3.2 Ω under operating temperatures. The right side of Fig. 2 shows two finished burners. Note, wires should be clamped together rather than soldered because the solder will melt during burner use.

4. Heater resistance

The heater is connected directly to the solar panel without additional circuitry. Therefore, the operating voltage, current, and power are determined by the match of the heater resistance to the solar panel. Fig. 3 illustrates a typical voltage/current (V-I) curve (solid black) for a solar panel under full solar exposure such as a solar panel directly facing the sun at noon. However, when the sunlight is not perpendicular to the panel, received solar intensity drops, resulting in a decrease of electrical current. The light blue curve illustrates the approximate power output for 8 AM or 4 PM for the same "noon facing" solar panel, corresponding to a 50% reduction in solar intensity.[2] V-I curves for the entire day between 8 AM and 4 PM fall between the two solid curves. Additionally, clouds, haze, and pollution similarly reduce current output. The delivered power (the area of the shaded inscribed rectangle) depends on the operating point on the curve, defined by the intersection of the curve with the I = V/R line of the heater resistance (straight lines[3] shown in black, brown, and blue in order of increasing resistances). Thus, the resistance of the heating element is crucial to maximize the delivered power. The resistance that maximizes noon sunlight is lower than the resistance that maximizes 8AM/4PM sunlight. A resistance that optimizes the delivered power throughout the day will strike a compromise between the 2 solid curves. Additionally, performance will improve if the solar panel can be rotated (even once a day) to better track the sun.

5. Earth wall prototype

We built a boil-and-simmer ISEC with earth walls, digging a hole and using the removed dirt to build up a surrounding square perimeter.

---

[1] Complete technical reports and Aid Africa's business plan are available at http://appropriatetechnology.wikispaces.com/PV+Cooking+in+Uganda

[2] This approximation is only correct for equinox and also overestimates intensity by neglecting the increased amount of atmosphere that sunlight passes through in morning and evening, although this is a reasonable simplification to illustrate the concept.

[3] Resistance increases slightly with increased temperature and therefore with increased power, so the lines will not be straight but have slight downward curvature. The straight-line approximation serves to illustrate the concept. Resistance should be measured under operating conditions.
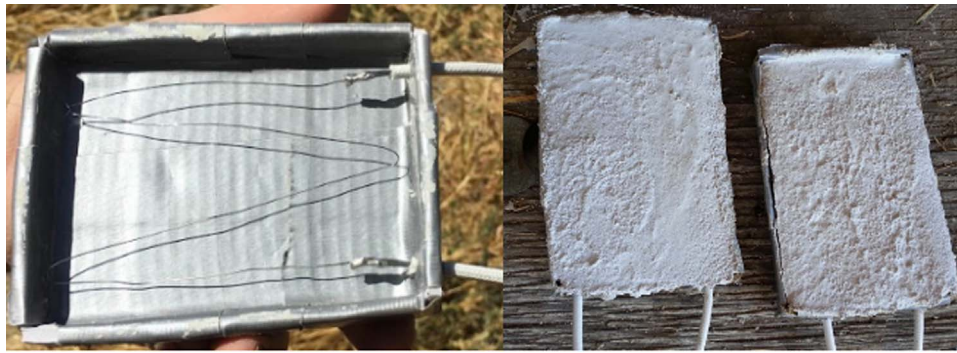
Fig. 2. Nickel chromium heating elements. Resistive nickel chromium wires are held into place in a mold (left). After concrete hardens, the finished heaters can be used (right).
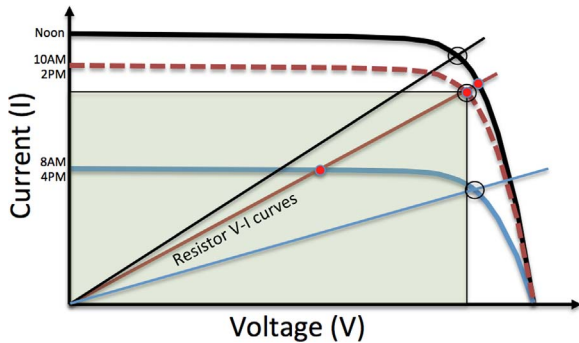

Fig. 3. Standard solar panel power curve. The operating points for each curve at its optimized resistance are indicated with black open circles while the operating points of each curve at a single chosen resistance are highlighted by red dots. Power is equal to the area of an inscribed rectangle defined by the operating point. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The square void was filled with straw for insulation, with a concrete enclosure to house the metal cooking pot (Fig. 4). The electric heater is placed between the concrete enclosure and the pot, and another layer of straw is added above the pot.

6. Immersion heater, single-wall boil and simmer ISEC

An immersion heater inside the cooking pot can heat food directly, eliminating concerns of the burner creating a dangerous hot spot in the insulation; thereby also eliminating the need for the inner concrete enclosure. These common heaters can be bought or made for about $2, and can be connected through the lid via the steam vent as shown at left in Fig. 5. The heater at right was made with NiCr wire (4.4 Ω while under power) inside of stainless steel tubing, insulated from the tubing with powdered magnesium oxide (MgO). We chose stainless steel for

hygienic reasons. Magnesium oxide is commonly used for heaters because it is both electrically resistive and thermally conductive. Only the bottom circular section of the immersion heater gets hot because the conducting leads extend well into the tubing and connect to the resistive NiCr wire at the bottom of immersion heater.

7. Numerical analysis – thermal modeling

Rigorous modeling requires a computer mesh analysis and iteration at all points in the insulation prescribed by the model. However, it may be more instrumental to use a simplified cylindrical model to get a rough estimate of the thermal behavior, even if some of our prototypes have slightly varying geometry. We use the thermal resistance equation (Eq. (1)) where P is the rate of heat loss; ΔT is the difference in temperature between the inner and outer surfaces; and R is the thermal resistance.

$$P = \frac{\Delta T}{R} \tag{1}$$

We model the heat flowing through the insulation in three sections: The hollow cylindrical middle housing the cooking chamber and the two disks above and below the cooking chamber (Fig. 6). The hollow cylinder is approximated as a section from an infinitely long cylinder yielding a resistance of:

$$R = \frac{Ln(r_2/r_1)}{2\pi\lambda L} \tag{2}$$

where r_1 is the inner radius of the insulation; r_2 is the outer radius; R is the total thermal resistance; λ is the thermal conductivity of insulation material, and L is the length of the cylinder.

Similarly, we can estimate the insulation end pieces as solid disks of radius r_2 and thickness l, which we set equal to the cylindrical wall thickness $(r_2 - r_1)$, yielding the resistance,

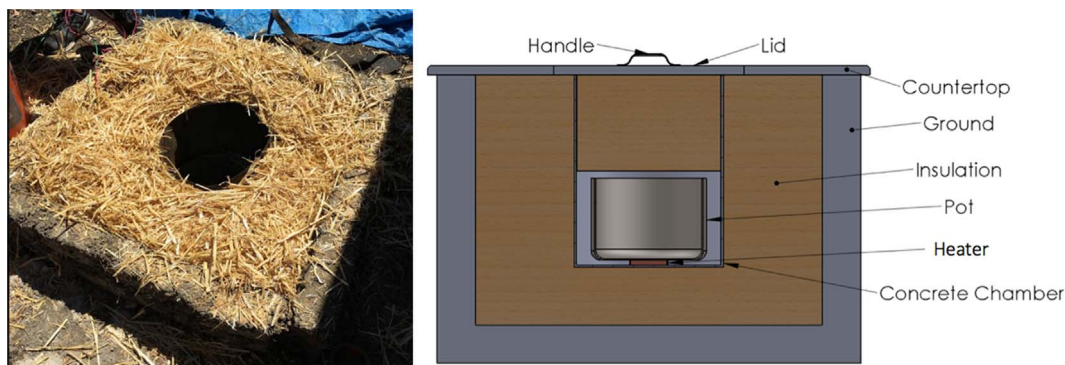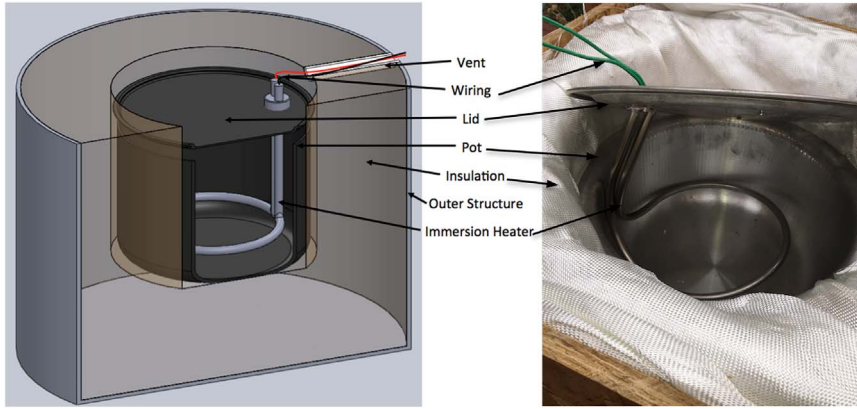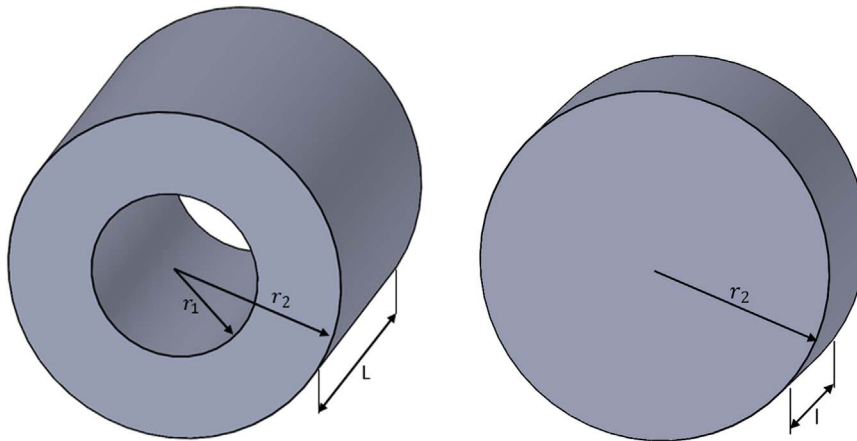$$R = \frac{r_2 - r_1}{\lambda\pi r_2^2} \tag{3}$$

Fig. 4. An insulated Solar Electric Cooker (ISEC) is made from earth with straw insulation (left). A concrete inner chamber separates the insulation from the heater (right).

Fig. 5. An insulated pot with immersion heater. The insulation above the pot is not shown in the figures. The pot has a 25.5 cm diameter and is 15 cm deep. The box is 43 cm wide and 38 cm deep.

Fig. 6. Cylindrical Geometry for Heat Loss Analysis.

Thermal resistances are added by taking the inverse of the sum of the inverses. The three sections of insulation combine to give a total thermal resistance of 0.213 K/W, with an inner radius of 18 cm, an outer radius of 29 cm, a length (*L*) of 20 cm, and thermal conductivity of 0.06 W/m-K for straw. These equations are used to calculate the rate of heat loss (Eq. (1)).

8. Heating

Our computer model calculates the temperature of the chamber every minute, assuming uniform temperature of the contents of the pot and outer surface of the insulation.

The amount of energy present in the system is used to find the difference in temperature between the inside and outside of the insulation. By subtracting the rate of heat loss (Eq. (1)) from the input power provided by the solar panel, the amount of energy is updated to the next time increment:

$$E_n = E_{n-1} + (P_{in} - P_{loss})*t_{step} \tag{4}$$

Where E_n represents the energy in the chamber at a certain moment in time; E_{n-1} represents the energy at the previous timestep; P_{in} is the power received from the solar panel; P_{loss} is the heat loss rate (Eq. (1)); and t_{step} is the time between calculations. The increase in temperature of the contents, ΔT is found from Eq. (5).

$$E_n = mC\Delta T \tag{5}$$

In Eq. 1, ΔT represents the temperature difference across the insulation and in Eq. 5, ΔT represents the increase in temperature of the cooking pot. However, these can be assumed to be the same ΔT if the experiment begins with both sides of the insulation at the same temperature ($\Delta T=0$) and if the temperature of the outer wall remains constant over time. From Eq. (5) we can solve for the temperature change:

$$\Delta T = \frac{E_n}{(mC)_{h2O} + (mC)_{mass}}, \tag{6}$$

where E_n is the total energy from Eq. (4); *m* is the mass; and *C* is the specific heat. The denominator is separated into 2 parts, one for the water that is being heated, and another for various other masses that are present in the system. These include potential thermal storage (or a concrete enclosure) and the pot.

9. Testing

Fig. 7 shows the temperature of 1 kg of water (1 liter) heated with 3.5 kg of concrete in an ISEC similar to that shown in Fig. 4.[4] The red points of the figure are actual data points, and the black line is the model defined above. The experimental temperature gain in the beginning is less than that predicted by the model. This may be due to the initial temperature of the concrete enclosure being lower than the initial temperature of the water. The model used an input power of 75 W, which was the average measured power in the experiment.[5]

---

[4] The cylindrical model slightly underestimates the resistivity of the square experiment because the outer radius of the model's insulation corresponds to a circle inscribed in the square of the experimental box.

[5] The solar panel has a registered output of 100 W with a working voltage of 18.0 V and working current of 5.56 A. We suspect that the solar panel itself and the sunlight that day were less than optimal. Accordingly, we recorded higher power output with a heater of increased resistance.
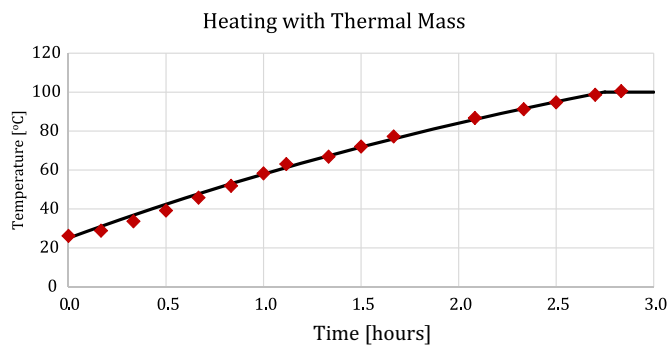
Heating with Thermal Mass

Fig. 7. Temperature of water in ISEC similar to that in Fig. 4 (red diamonds), compared to the thermal model (black line).
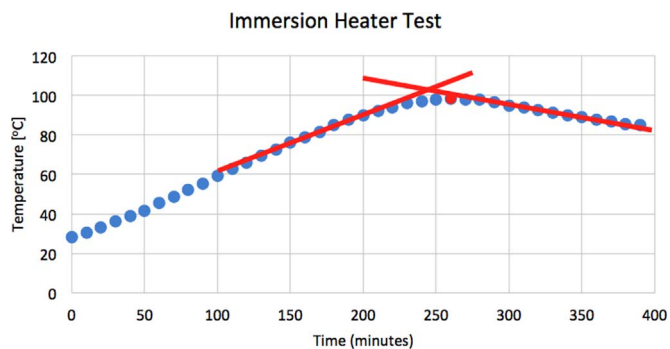
Immersion Heater Test

Fig. 8. Temperature of 2.7 kg of stew in immersion heater ISEC similar to that in Fig. 5. The heater was turned off at 260 min represented by the red data point. Data after this point shows the cooling of the system.

We ended these experiments at boiling, but we can calculate the maximum temperature that this ISEC could achieve if water is not present. To find this equilibration temperature we allow the model to calculate the temperature necessary to lose 100% of the input power through the insulation, yielding 185 °C or 365 °F for a 75 W heater. This maximum temperature increases with increased power, and thickness and quality of insulation indicating potential risk of combustion if no water is present. The same equilibrium calculation yields a maximum temperature of 502 °C (935 °F) for the 5-gallon drum insulated with fiberglass of Fig. 1 heated with 100 W.

Fig. 8 displays the temperature of about 2.7 kg of a stew (meat, beans, and vegetables) brought to a boil and allowed to cool. The food was cooked with the immersion heater ISEC (Fig. 5) using the same solar panel of Fig. 7. We can find the absorbed energy by using Eq. (5), where E_n is the energy, and ΔT is the temperature increase. Taking the slope of the cooling curve (red line) at 90 °C yields a temperature loss rate of 6.67 °C/h, corresponding to thermal loss rate of 20.7 W, if we estimate the specific heat of the stew to be that of water. Similarly, the 19.2 °C/h of thermal gain at 90 °C corresponds to 59.6 W of net power, for a total power input of 80.3 W. This corresponds to a thermal heating efficiency of 74% (for 90 °C at 80.3 W input power) and is consistent with our readings of the solar panel output.

10. Implementation

While the technology is effective at cooking substantial amounts of food, it is not clear that people will use ISEC. The long cook times required by the low power require people to change their way of cooking. However, people who boil and simmer may find ISEC convenient for soups, stews, rice, and beans, which can be left unattended in the morning and the food will be ready to eat at the end of the day. The crucial issue is to find people who would either

Fig. 9. Photo of ISEC built in Uganda. A reed mat was used as the outer structure. The heater rests inside of a lager pot as shown. A smaller pot holding the food rests on top of the heater and a ceramic tile under the larger pot insulates the rice hulls from the hot spot beneath the heater.

already like this technology or readily adapt to it.

We implemented two ISEC units in Gulu, Northern Uganda with local families. Working with Aid Africa, four students studied village life and cooking protocol before suggesting an ISEC design while addressing basic principles, possible uses, and maintenance. All necessary materials were purchased in Gulu, something we prioritize for long-term project sustainability. Although we brought NiCr wire with us, it is available in Gulu. Working alongside the villagers, we arrived at a design that villagers felt best fit their needs. Many of the villagers disliked the appearance of our original model and decided on a reed-mat outer structure, shown in Fig. 9. The rice hull insulation is nearly free. All of the materials, including a 120 W solar panel were bought for $110.

Aid Africa has introduced about 60,000 high efficiency combustion cook stoves, and follows a "build-your-own" policy with the understanding that personal investment will increase pride in new technologies, resulting in more use. Accordingly, we jointly constructed the stoves with the women who are using them; mounting the solar panels and laying rebar supports and rice hulls. Lastly, the women using the ISEC were encouraged to further adapt the design as they see fit.

Through periodic visits over the following five weeks to the two families who received ISEC's, we know that both ISEC units are consistently being used and the families continue to innovate. While one family claims there is insufficient power to cook in the evening after returning from the farm, the ISEC is being used to cook vegetables for short periods of time, or larger meals such as beans over the course of the day. After the last meal, surplus electricity is used to heat bath water – something that these families have found to be too extravagant for firewood.

11. Efficiency and combustion-hybridization

While the solar electric stove can completely cook a raw meal, the cooker could also be used to keep food warm after being heated from a fire. This reduces the use of firewood and greatly reduces indoor air pollution because low intensity fires are often higher emitters than hot fires (Rein, 2009).

12. Future considerations

Future additions may include battery-LED light systems and cell phone charging. A microcomputer may be important to control the cooking, manage electrical power, and record performance data, such as temperature and power output. Future challenges are electronic control of cooking, logging use for carbon market verification, and development of remote financing methods whereby users pay daily for the use of electronic products via mobile phone such as M-Pesa, currently used throughout most of Africa (Jack and Suri, 2011).

13. Financing

At $100 per stove, ISEC is presently one of the more expensive cooking options. While we expect solar panel price to continue to decrease to make the technology competitive in the next 5 - 10 years, other financing mechanisms can be invoked now and developed for the future. One funding possibility is through Mobile Money in Uganda, a mobile-phone-based money transferring system currently used throughout most of Africa (Jack and Suri 2011). Another is to receive funding from the Carbon Market (Hogarth, 2012) (Smith, 2010) for the reduction of CO_2 emissions by displacing biomass combustion.

While Aid Africa presently distributes their low-emission, fuel efficient cookstoves free of charge, they are poised to collect $30 per stove per year through the U.N. sponsored Gold Standard voluntary carbon market. While similar funding for ISEC stoves would reduce the time before ISEC would also be free or even cost competitive, there are considerable barriers to be eligible for this funding.[1] The stoves must be vetted and certified, and the distribution must be documented in a process that costs $20,000 for the application and $25,000 for auditor fees, $8000 to the Uganda Carbon Bureau, and about $5000 in sales fees. Additionally, receipt of carbon market funding requires the end user to sign away their rights to the displaced carbon dioxide and have annual inspections. The process may take more than two years. Additional costs not related to the carbon market are transportation and labor associated with education as well as the distribution and registry of each stove. Thus, while Aid Africa estimates $9 for the cost of production of its fuel efficient cookstove, total costs come to $25 per cookstove. Consequently, it would not be reasonable to even consider carbon market funding until we are sure that we can successfully distribute at least 10,000 ISEC stoves to people who will consistently use them for the majority of their cooking. Our goal for summer 2017 is to collaboratively design and implement 100 ISEC stoves with villagers and Aid Africa in a single community to support ongoing collaborative learning.

The determination of a payback time would depend on many factors including what people presently pay for cooking fuel. In Uganda, many of the recipients have a money-free economy and can't pay for any technology. Additionally, one might consider that part of the payback is decreased global carbon emissions, decreased mortality (especially for children) and decreased deforestation. If we consider only the value of carbon market funding, the ISEC installment would be paid for in about 4 years. With a stable carbon market and continued solar panel price decrease, this payback time will likely be cut in half every five years. Lastly, surplus electricity from ISEC systems could provide electricity for electronics such as lighting, radios, and cell phone chargers. We therefore speculate that by supporting ISEC installation, carbon market funding would also support the building of a resilient infrastructure of distributed photovoltaic electricity.

14. Conclusion

Insulated solar electric cooking (ISEC) represents a possible convenient cooking technology that is safer for the users, as well as for the local and global environment. Use of insulation significantly reduces power demand and therefore cost. Additional benefit will come from making use of the available solar electricity to power other appliances such as lights and cell phones. The broad, flexible technology allows local users to design specific implementation contextual with local needs and resources as demonstrated with two preliminary stoves in Uganda.

Acknowledgements

References

Hogarth, J.R., 2012. Promotion of diffusion of solar lanterns through microfinance and carbon finance: a case study of FINCA Uganda's solar loan programme. Energy Sustain. Dev. 16, 430438.

Jack, W., Suri, T., "Mobile Money: The Economics of M-Pesa." Working Paper 16721, National Bureau of Economic Research (2011), http://www.nber.org/papers/w16721.pdf

Joshi, S.B., Jani, A.R., 2013. "A new design of solar cooker for optimum utilization", conference paper, solar asia, In: Proceedings of the 2nd International Conference on Solar Energy Materials, Solar Cells & Solar Energy Applications, Kulal Lumpur, Malysia, Aug, pp. 22–24.

Lambe, F., Jurisoo, M., Wanjiru, H., Senyagwa, J., 2015. "Bringing Clean, Safe, Affordable Cooking Energy to Households across Africa: An Agenda for Action." The New Climate Economy. Stockholm Environmental Institute

Lim, S.S., et al., 2013. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. (9859)lancet 380, 2224–2260.

MacCarty, N., Ogle, D., Still, D., 2008. A laboratory comparison of the global warming impact of five major types of biomass cooking stoves. Energy Sustain. Dev. 12.2, 56–65.

Rein, G., 2009. Smouldering combustion phenomena in science and technology. Int. Rev. Chem. Eng..

Smith, K.R., 2010. What's cooking? A brief update. Energy Sustain. Dev. 14.4, 251–252.

Smith, K.R., Dutta, K., 2011. Cooking with gas. Energy Sustain. Dev. 15.2, 115–116.

Subramanian, M., 2014. Global health: deadly dinners. Nature 509, 548–551. http://dx.doi.org/10.1038/509548a, (28 May.

Swanson, R.M., 2006. A Vision for Crystalline Silicon Photovoltaics. Wiley. SunPower Corp.http://onlinelibrary.wiley.com/.

WHO, 2016. "Household Air Pollution and Health." World Health Organization. Updated February.

Wilson, D.L., Talancon, D.R., Winslow, R.L., Linares, X., Gadgil, A.J., 2016. Avoided emissions of a fuel-efficient biomass cookstove dwarf embodied emissions. (June) Dev. Eng. 1, 45–52.