MECS Final Project Report (public)

Project Name: Thermal Storage with Phase Change Materials

Organization Name: California Polytechnic State University, San Luis Obispo

Produced by: Dr. Pete Schwartz and Katarina Brekalo

Date: April 2022

This material has been funded by UK Aid from the UK Government and is implemented by the Foreign and Commonwealth Development Office; however, the views expressed do not necessarily reflect those of the UK Government.

Document Control:

Issue Status	Author(s)	Reviewed By	Loughborough University Approved By	Issue Date
Draft version	Schwartz, Brekalo			
Final version				

Contact Details:

Pete Schwartz

Cal Poly Physics Department, San Luis Obispo, CA 93401

805-756-1220, pschwart@calpoly.edu

Executive summary Use of $70,000, MECS Stage II Grant Award:

1. **Improving Insulated Solar Electric Cooker** (ISEC) technology. Thermal storage strategies pursued include Phase Change Materials (PCM: erythritol, xylitol, potassium/sodium nitrate salts) and solid thermal storage (STS: aluminum). We are also testing a commercially-available SunBucket, collecting data on an ISEC with battery storage, and innovating many ISEC features to improve performance, construction, and cost.

- With proper heater placement and ISEC geometry, minimal heat is transferred to PCM storage as long as there is food being heated in the cookpot.
- erythritol (melting point = 118 ºC) is an ideal PCM, but degrades from thermal cycling over a few months. However even degraded, erythritol still functions as liquid thermal storage
- xylitol does not degrade, but is inferior to erythritol in cost, specific heat, heat of fusion and melting temperature (92 ºC, below the boiling point of water).
- The high temperatures of nitrate salts (melting above 200 ºC), used in SunBuckets and our ISECs, result in higher performance but require expensive materials and safety precautions.
- There is a considerable drop in temperature across a solid-solid interface such as transferring heat from a thermal storage vessel to a pot of food. The surface smoothness and flatness is crucially important.
- Resistive heaters benefit from voltage modulation to optimize power from the solar panel but are more thermally robust than diode heaters that don't need voltage modulation.
- Hot wires and wire junctions often corrode over the course of a few months.

2. **Distributed production in low income communities (LIC) via the Global Learning Community:** We continue our dissemination efforts with collaborators from Africa, India, Virginia, and Jamaica. Collaborators have made improvements in constructing, delivering, and training others about ISEC. We are improving ways to source inexpensive materials to collaborators, especially solar panels.

- ISEC deployment is inherently linked to rural electrification - a large selling point. People want electricity for many uses, especially revenue-generating solar electric irrigation.
- The superior performance of battery storage along with the continued decrease in battery prices will make batteries the future of energy storage.
- ~200 Cal Poly students have developed technology and/or interfaced with international collaborators.
- Diversity in both technology and dissemination strategies among collaborators stimulate learning - both locally and in the Global Learning Community.

Activities and progress are documented on our research website:
http://sharedcurriculum.peteschwartz.net/solar-electric-cooking/,
collaborator forum: https://www.isecforum.com/, and
service learning class student projects: http://appropriatetechnology.peteschwartz.net/about-us/

Table of Contents

1. Introduction

In 2015, we began developing Insulated Solar Electric Cooking (ISEC) whereby a solar panel is directly connected to an insulated, electrically heated cookpot.[1] In 2018, we explored diode heaters rather than resistive heaters because diode heaters more effectively couple power from a solar panel under a wide range of solar intensities.[2] Typically, we use a 100 W solar panel, capable of heating 5 kg of food to boiling during the course of the day. Answering the demand for more power and/or to cook in the evening after the sun has set, we developed phase-change thermal storage capability using Erythritol,[3] Nitrate Salts and Xylitol. These materials melt, storing thermal energy throughout the day, to be available to cook at night. The cookers can deposit much of this energy in a short period of time after external power has been disconnected, providing power much greater than 100 W. With the decreasing cost trends of solar panels, a 100 W panel can be purchased for as low as $25, making ISEC an affordable and attractive solution for modern clean cooking.

Aims of the Project

The aims of the project are to improve the design, share knowledge with LIC collaborators (Africa, India, Caribbean) where we anticipate dissemination, collaboratively disseminate the technology, and study the technology adoption process. Our dissemination model is to support local enterprises in constructing and innovating ISEC products for local sale. Our efforts and finances are leveraged by student participation in service-learning classes (http://appropriatetechnology.peteschwartz.net/about-us/) and in the laboratory as part of their education.

Objectives of the Project

- Improve design of ISEC with and without thermal storage; which includes testing a commercially-available immersion heater within the PCM.
- Test a combined ISEC / LTO (Lithium Titanate) battery system
- Arrange shipment of low-cost solar panels to collaborators
- Hold training sessions for local communities on ISEC education and construction
- Study community adoption of the technology
- Share ideas and brainstorm with the International Learning Community

[1] *Development Engineering* 2 (2017) 47–52, https://doi.org/10.1016/j.deveng.2017.01.001
[2] *Development Engineering*, 4 (2019) 100044, https://doi.org/10.1016/j.deveng.2019.100044
[3] *J. Solar Energy*, 220, 2021, 1065-1073, https://doi.org/10.1016/j.solener.2021.03.040

2. Approach

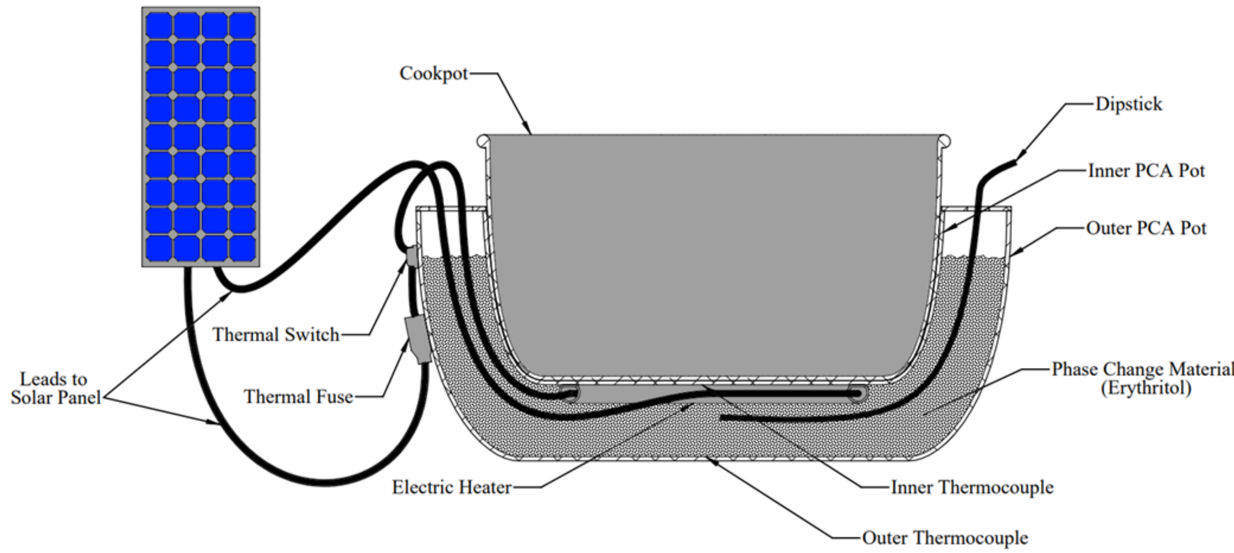

Fig. 1: Schematic of the ISEC with thermal storage made from a 24 cm outer pot and a 19 cm inner pot.[3]

Cal Poly research students worked on technical advancements in a variety of areas including: heater design, phase change materials, solid thermal storage, insulation, and overall design. We engage approximately six research students for 10 weeks in summer (2020, 2021, 2022) internally funded with $25,000 - $30,000 annually,[4] and 3-8 year-long capstone senior projects during each academic year. Additionally, our collaborators also make significant technical advancements. The International Learning Community meets for an hour every week (Thursday 10 AM, California time) to share ideas and lessons learned. We also provide information on our research website, the ISEC forum, and through Email and WhatsApp correspondence.

Concept

Using existing technologies, ISEC (Insulated Solar Electric Cooking) provides an inexpensive and simple way to cook with a solar panel at extremely high efficiency. Our MECS funding is to improve, refine, and disseminate thermal storage with a Phase Change Material (PCM), allowing the user to cook after electrical power is disconnected, and to have access to greater power by discharging the stored heat over a shorter period of time. Thermal Storage capacity could be used with grid electricity and other energy sources as well as with solar electricity. Electrical power itself is a high-demand feature for many of the global poor, to be used for a variety of purposes including lighting, cell phone charging, and pumping water.

[4] We acknowledge The William and Linda Frost Fund supporting Frost Research Fellows (Students), providing faculty summer salary, and funding some materials.

Rather than taking advantage of economies of scale in a large factory, we chose to support small enterprises in the same LIC targeted for distribution, providing the following benefits:

1) Supporting the local economies.
2) Providing motivation and means for local technological innovation.
3) Gaining a diversity of ideas and strategies from enterprises in a variety of cultures, with access to different technologies and materials.

3. Presentation of Results

Collaborators could be awarded three stages of funding by meeting each stage's requirements.

Stage I funding (US $1,000) was received by:

- Emmanuel Osei Amoafo from SolCook in Ghana, Africa
- Salma Bougoune from Togo, Africa
- Mark Manary from Project Peanut Butter, Sierra Leone, Africa
- Hawazin Khaleel from Karala, India
- Deepak Ghadia from Gujarat, India
- Chris Musasizi from Uganda, Africa
- Bidjanga Zach from Cameroon, Africa
- Andrew Mayanja and Alicwamu Moses from ASEI Uganda, Africa
- Alexis Zeigler,Living Energy Farms, Virginia, U.S. & Jamaica, Caribbean
- Crosby Menzies from Sunfire in South Africa

Stage II funding (US $4,000) was received by:

- Emmanuel Osei Amoafo from SolCook in Ghana, Africa
- Salma Bougoune from Togo, Africa
- Bidjanga Zach from Cameroon, Africa
- Andrew Mayanja and Alicwamu Moses from ASEI Uganda, Africa
- Alexis Zeigler from Living Energy Farm (LEF) in Virginia, U.S.

We have awarded Stage III funding (US$5,000) to one collaborator, Bidjanga Zach from Cameroon. He has made tremendous strides in ISEC dissemination and education, via weekly workshops among his local community and universities. More of his progress is described in the collaborator progress section below.

Collaborator Progress

Alexis Zeigler from LEF, Virginia, US

Living Energy Farm (LEF) is an off-grid community of about a dozen people relying solely on sustainable technologies and cooking mostly with ISEC. They have many different design variations of the ISEC, which they use year-around. They have finalized two designs: the Pearl Cooker (for perlite insulation) and the Roxy Oven (for rockwool insulation). Additionally, LEF is pioneering Direct DC Technologies, or "Daylight Drive" or "Direct Drive" where the majority of solar electricity is used during the day, requiring very small battery capacity for night time activities. LEF is teaching about and developing manufacturing capacity around Daylight Drive in nonindustrial communities where the reduction in cost is a game changer. Alexis and other LEF community members (as well as Pete Schwartz) have spent a considerable amount of time in Jamaica, at The Source Farm EcoVillage with corresponding nonprofit Living Energy Solutions (LES). Additionally, the Source Farm holds educational programs to educate people about the benefits of ISEC and Direct DC Solar technologies, especially for processing locally grown food. Similarly, LEF plans to collaborate with the Navajo and Hopi Nations in Arizona where they have previously established relations as well as with permaculture centers and activists in Puerto Rico. Unique ISEC designs from Alexis are documented in videos and a construction manual available on our research website.[5]

Fig. 2 Alex's Pearl design which uses perlite insulation and a resistive heater.

[5] http://sharedcurriculum.peteschwartz.net/solar-electric-cooking/

Fig. 3 Alex's Roxy, similar to a well-insulated traditional oven

LEF has spent most of their funding on materials for Jamaica, in particular $5000 for a large shipment of solar panels that arrived in Kingston in December of 2021.

<u>Hawazin Khaleel from Karala, India</u>

Hawazin constructed and disseminated 5 ISECs to her community. She continues building the PCM model ISEC using erythritol. She has spent her portion of the funding on the equipment and materials and is continuing to build new designs suitable for her community. She is also seeking new collaborations to help with production and dissemination. She plans to collaborate with a student group at her local University.

Fig. 4 A pot with the resistive heater strung through ceramic beads.

Chris Musasizi from Uganda, Africa

Chris is our newest collaborator who has built and disseminated 4 working ISECs. They are testing local insulation, specifically vermiculite, which is readily available in Uganda. They plan to continue building and disseminating ISECs as well as make an informational brochure on the ISEC for distribution in local communities and schools.

Fig. 5 Chris meets with Peter and Irene Keller from AID Africa

Salma Bougoune from Togo, Africa

Salma has been working on two new ISEC designs; one using a small cook pot with 200W with 10A/12V-24V charge controller and another using a larger pot with 300W-400W with a 20A/12V-24V charge controller. 15 small pot ISECs and 5 larger pot ISECs were built and have been tested. He is waiting for a $5,000 shipment of 100 subsidized (200 W) solar panels brokered by Robert Van Buskirk (Kuyere!, Kachione LLC), to disseminate the ISEC systems and other DC solar electric technologies.

Fig. 6: Six constructed ISECs

Andrew Mayanja and Alicwamu Moses from ASEI Uganda, Africa

Andrew and Moses have made impressive progress in a short amount of time, receiving Stage I funding since Jan. 1, 2022. They are a part of African STEM Education Initiative (ASEI) which is a non-profit organization aimed to increase capacity for innovation in Uganda through STEM projects which help involve communities, especially the youth, in project-based learning. They have adopted ISEC as their newest project to develop and introduce to their community. They have already built and disseminated eight working ISECs. Takataka Plastics, Uganda, produces personalized products from recycled plastics. They have designed a new model/outer casting for the ISEC using recycled HDPE (High Density Polyethylene). ASEI will likely partner with NGO Aid Africa (Gulu, Uganda), who has connections to communities, marketing experience, and access to funds.

Fig. 7 The updated version of the ISEC using the recycled material for the outside of the ISEC

Fig. 8 A resistive heater casted in an aluminum plate

Emmanuel Osei Amoafo from SolCook in Ghana, Africa

Emmanuel has used his funding in materials and equipment to construct direct as well as erythritol PCM ISECs for distribution in local communities. He is working with Fred Akuffo, a professor emeritus at KNUST in Kumasi, who is now dedicated to a solar electric company and is conducting market research with the ISEC. Emmanuel is currently looking for additional partnerships in hopes of expanding manufacturing.

Fig. 9 Two ISECs with phase change material (erythritol) and wool insulation

Bidjanga Zach from Cameroon, Africa

Bidjanga has constructed and disseminated over 50 ISECs in his community. He has taken a step further from development to education. He has conducted a variety of ISEC training sessions, teaching high school and university students the technical background necessary to construct the ISEC and how to cook with them. He has held a total of ten ISEC training sessions, holiday ISEC cooking campaigns; and is planning to hold a large conference at the University with many students at the end of April.

Fig. 10 Bidjanga and four of his students at an ISEC conference

Fig. 11 Five university students attended Bidjanga's ISEC training conference

Fig. 12 Bidjanga leads an ISEC training session to four women in his community

Figure 13: Traditional Foods cooked with the ISEC

Fig. 14 Gnetum Africana (a tropical vegetable), Plantains, and Ndole (bitter leaves, palm oil, ground nuts, macabo)

Fig. 15 Easter ISEC Cooking Party

Project Peanut Butter from Sierra Leone, Africa

Project Peanut Butter has been working on building and testing an ISEC for some time. They have been having difficulties with sourcing materials and miscommunication among their team. They continue to stay in contact with us and give updates when they can, however the facility they planned for ISEC construction was repurposed for a food manufacturing facility. They hope to find a new space and continue to progress by this coming summer.

Robert Van Buskirk from California, U.S.; & Malawi

Robert is an additional collaborator who has recently partnered with us. He does not receive any collaborator funding from us but is also an MECS funding recipient. He does most of his work in Malawi, Africa where he founded NGO Kuyere!, dedicated to rural distributed solar electrification. He has introduced the Lithium-Titanate (LTO) Battery as a storage mechanism. LTO batteries have a longer life-span and can cycle close to ten times more than regular lithium ion batteries. He imports battery cells and has them assembled in Malawi. He is importing container shipments of low cost solar panels, allowing our collaborators to receive 200W solar panels with a maximum power voltage of 20V at a rate of $0.25 per Watt. Presently, only Salma (Togo) is set to receive a shipment.

Fig. 16 shows Robert (on left) and a team from Kuyere! Malawi (on right)

Student Progress

Several student groups work on independent research as well as year-long senior projects. We also have a group of five to six students conduct full-time research over summer through the funded Frost program at Cal Poly representing $25,000 - $30,000 per summer in 2020, 2021, and projected 2022. The projects are described below.

Frost Summer Research:

During the summer of 2021, a group of five Cal Poly Students and Martin Osei, a Ghanaian graduate student from Illinois University worked on the technical development of the ISEC. They were the first group to work with the phase change material consisting of 70% of Sodium Nitrate and 30% of Potassium Nitrate (by mass); we refer to this combination as the Nitrate Salts PCM. The group also built 12 Direct ISECs (without thermal storage) with available USB charging. The presentation of the group's results is in the appendix of this document.

Fig. 17 shows 7 ISECs which were built over the summer (left)

Two Mechanical Engineering groups with four members in each, develop thermal storage Sept 2021 - June 2022.

(1) Solid Thermal Storage: The group designed engageable thermal storage in an otherwise direct-drive ISEC. The thermal storage is a resistively heated aluminum puck for storing thermal energy. The design allows people to choose whether they want to heat and store energy into the puck for later or they can also cook directly. The group has designed a model to allow both options for the user.

(2) Phase Change Thermal Storage: The group is working with nitrate salts PCM. Nitrate Salts reach temperatures exceeding 300ºC, presenting safety and materials challenges. Because of the corrosive salt environment, a commercially available immersion heater (rather than a homemade heater) will be inside the salt mixture.

Physics Senior Projects: We have six physics senior projects this year.

Katarina Brekalo & Andrew Shepherd: PTC Heaters and LTO battery testing

This pair of students is focusing on using a PTC thermistor heater as the heating element. The PTC heater is a self-regulating heater where the resistance of the heater increases with temperature by nearly a factor of 1000 at a defined temperature (we are choosing 220 ºC). Therefore, the heater will not exceed 220 ºC, as a safety precaution. In order to record and track how the PTC operates, a microprocessor-controlled arduino was built to record the PTC's activity.

Separate from the senior project, in collaboration with Robert Van Buskirk, the Lithium-Titanate (LTO) battery has been introduced as another energy storage option. The LTO battery has proven to have a decade-long life-span, fast charging performance, and high resistance to a wide range of temperatures. It is currently being tested using two 100 W solar panels on an ISEC otherwise engaged for direct cooking. It is being directly compared to the quality of cooking done using a direct ISEC and 200W, but with no battery storage, testing whether the additional battery storage is monetarily worth its investment.

Fig. 18 The LTO battery and direct cooking comparison with four 100W panels on the shed: two for each ISEC

<u>Andrew Perez & Jordan Liam: Power optimization and electronic control</u>

As described in our "Hot Diodes" publication,[2] a solar panel cannot optimally transfer electrical power to a directly-connected resistive heater under varying solar intensities. Our microprocessor-controlled buck convertor modulates the voltage to the ISEC, optimizing the power delivered under all solar intensities. The solar panel voltage output is modulated by a buck convertor that is controlled by a microprocessor monitoring the voltage on the ISEC electrical load.

<u>Michael Fernandez: Simulating ISEC heat-flow transfer with solid thermal storage</u>

A computer simulation of heat flows and transfers throughout the ISEC with an aluminum puck for solid thermal storage was tested against the actual ISEC. The goal is to make fair predictions on the ISEC's performance if materials or certain properties are changed, allowing us to test different options for the ISEC without building it. The simulation agreed with experiment within acceptable uncertainty.

Sid Gamoj: Cycling Erythritol

We are testing the durability of erythritol over a five-month period of thermal cycling. Four separate beakers of erythritol were thermally cycled at four different temperatures to determine how erythritol degrades. A few hours of data are shown below.

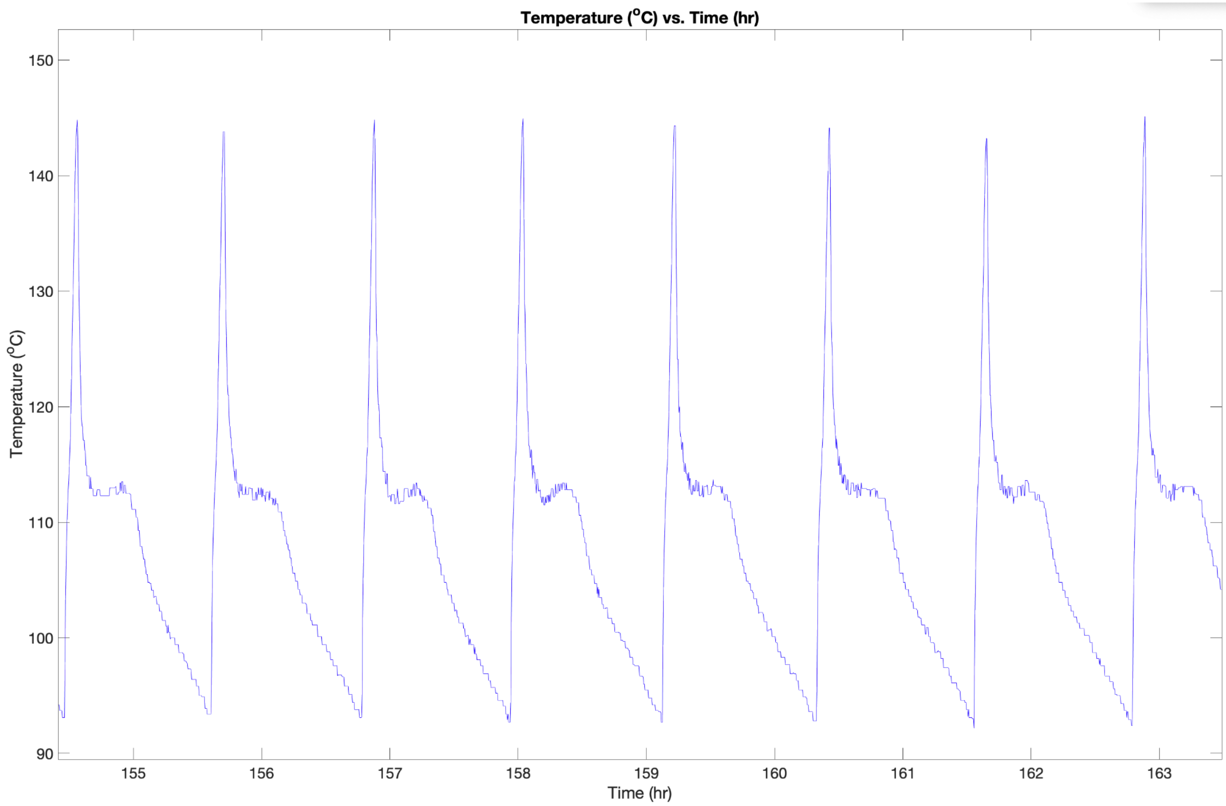

Fig. 19 Erythritol was thermally cycled over a week-long period. Nine hours are shown.

Independent Research: Students from different majors conduct ISEC experiments.

Martin Osei: Master's Thesis

Development of Phase Change Thermal Storage Medium: Cooking with More Power and Versatility, Martin Osei, Spring 2022, https://thekeep.eiu.edu/cgi/viewcontent.cgi?article=5932&context=theses

Elsa Micklin & Daniel Nagy: Testing PCM durability and degradation

To quantify the energy being absorbed and released during the phase change material's transitions, pure and degraded samples of erythritol and xylitol were run through a differential scanning calorimeter (DSC). The DSC subjects the sample to a given routine heating and cooling at specified temperatures, generating graphs of the heat flow [W/g] versus time or temperature.

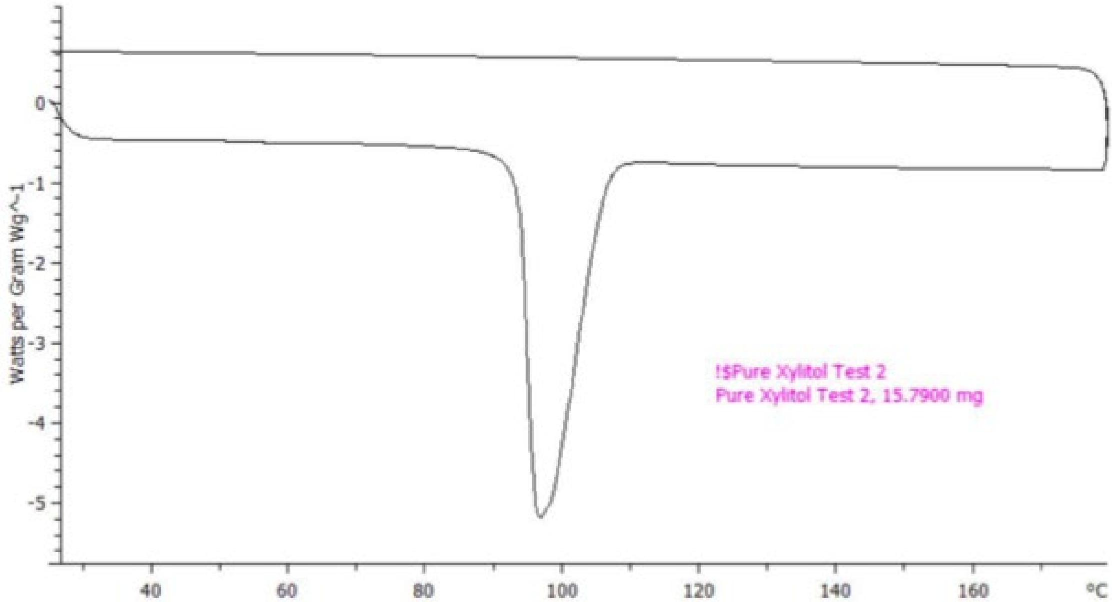

Fig. 20 shows the DSC graph of Xylitol

The DSC graph of xylitol shows the substance melting. However, it does not recrystallize to complete its phase transition. This is due to the PCM exhibiting supercooling, which means the sample cools past its fusion temperature while remaining in the liquid state. The DSC graph for erythritol shows the sample also experiences some supercooling, however crystallization still occurs. The DSC data imply xylitol should not replace erythritol as a good PCM.

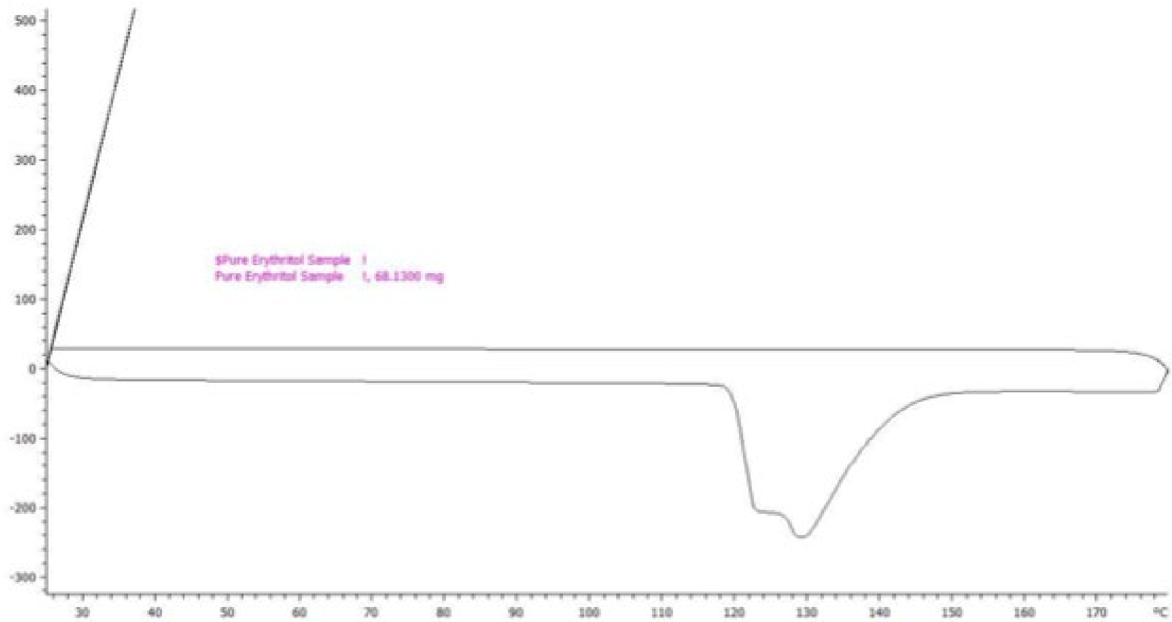

Fig. 21 shows the DSC graph of erythritol

<u>Michael Dalsin: Testing thermal conductivity of different Insulation material</u>

We designed and built an inexpensive thermal conductivity meter (<$2000, comparable to $30,000 for a purchased instrument) to investigate insulation materials. The instrument uses a positive thermal coefficient (PTC) thermistor, an ice water bath, and two custom-made heat flux sensors. Insulation samples measured include pyrolyzed bread (carbon foam) as well as fire bricks. Fire bricks are made from a combination of clay and organic material such as sawdust. When the bricks are fired, the organic material burns away, leaving pores behind.

<u>Bre Evans: SunBucket ISEC</u>

We have made an ISEC whereby a 425W solar panel heats a SunBucket in an insulated chamber. The SunBucket's composition (70% sodium nitrate and 30% potassium nitrate) is the same as the PCM ISEC we are developing, mentioned above.

PSC392 Appropriate Technology, https://canvas.calpoly.edu/courses/74277: Pete Schwartz's project-based class this spring has two student groups of interdisciplinary majors, each supporting an ISEC collaborator.

(1) ISEC in Uganda
A group of four students are working with two different collaborators, Peter Keller from Aid Africa and Andrew Mayanja from ASEI. This group is working on creating an attractive design for the ISEC to appear as a market-ready product for Aid Africa. For ASEI, they are building and testing prototype designs.

(2) ISEC in Cameroon
A group of two students are working with Bidjanga from Cameroon, supporting his efforts in ISEC education. The group is preparing an ISEC course for Bidjanga's university students, where students pay a fee to attend classes, learn how to build an ISEC, and take home the ISEC they build. This group is also filming a step by step instructional video for the course and providing other resources.

4. Analysis of the results

Two important challenges are: (1) the transfer of thermal energy from the energy storage to the food, and (2) disengaging the thermal storage when none is wanted, for instance when the thermal storage is cold and the user wants to cook food directly. Our phase change model (Figure 1) accomplishes both needs elegantly. The PCM is a thermal insulator in the solid state, but readily convects heat in the liquid state. Also, the heater is at the bottom of the cookpot, but is in the *middle* of the PCM. If the bottom of the cookpot was at the top of the PCM (as it is with the SunBucket), the PCM would become disconnected from the cooking surface. If the bottom of the cookpot were at the bottom of the PCM, the PCM may not convect heat as effectively. Thus, when the ISEC is cold and the sun comes up, energy from the heater will not be transferred to the PCM until it melts, allowing food to be cooked at temperatures approaching 120 ^{o}C. After the food is cooked, the PCM will first melt around the heater, and convect the heat to uniformly warm the PCM. Later, when food is introduced into the hot ISEC, the cookpot will be the coldest part of the ISEC and be quickly heated by the convecting PCM. Once the PCM is solid, the heat will transfer slowly to the food, allowing food to stay hot for many hours at a low boil.[3] When we added shredded aluminum to the PCM, the power at hot temperatures decreased (the shredded aluminum impeded convection) and the power at low temperatures increased (the shredded aluminum increased the thermal conductivity). We regard both of these changes as undesirable and do not recommend adding conductive metals to the PCM in this geometry.[3]

It is not so easy for solid thermal storage to be as dispatchable as the above PCM because disengaging the thermal storage requires that the user move something to prevent conduction. Additionally, heat does not readily conduct from one metal surface to another unless the surfaces are exceedingly flat and smooth. With less than perfect surfaces (i.e. in all the cases we tested) heat transfer between an aluminum thermal storage puck and an aluminum cookpot was increased with the insertion of a silicone thermal pad such as that produced by Aiunni, with a thermal conductivity of 6 W/mK.

The most reliable and inexpensive ISEC is “direct connect” without any storage capacity, requiring people to change the way they cook: filling the ISEC in the morning with lunch, and at noon with dinner to be cooked over a longer period of time. Robert Van Buskirk has been prototyping a hybrid model: during the day the ISEC heats water and charges a small LTO battery. In the evening, a small electric pressure cooker is filled with beans and hot water. The battery provides a small amount of extra energy to bring the beans to a boil. We have been testing this prototype. We anticipate that in a short time, batteries, and likely LTO batteries will be the dominant energy storage medium.

We have had difficulty with some heaters and power wires connected to the heaters. When we directly connect nichrome wire to copper power leads, the junction creates a hotspot, presumably due to increased resistance at the junction point. The resistance of the junction increases and eventually fails. Additionally, flexible finely braided copper wires that stay hot corrode over a period of months. Hence, the inner wires that do not need to routinely bend should be made of solid copper wire of reasonably large diameter (14 gauge or less). Alexis does not report these difficulties, so we will learn from him. Pete Schwartz plans to join a workshop at Living Energy Farm in June, 2022.

We have learned from collaborators, students, and everyone who has engaged in this project, and the project has taken turns we would have never predicted. We continue our distributed dissemination model. Our collaborators prefer constructing the ISECs themselves and having ownership over their work. Having the knowledge of how the technology works allows them to fix and repair the cooker when it is broken, and allows them to teach others.

Bidjanga has been conducting ISEC training sessions on a weekly basis for his community. He has taken ISEC education to a new level by teaching students from his community as well as university students. Salma has also held an ISEC demonstration and plans to follow this path of community education. Other collaborators have also taken steps further in search of partnerships or other collaborations within their own country.

We tested three different phase change materials: erythritol, nitrate salts and xylitol.

Data Table 1: PCM Properties

PCM	Melting Temperature [ºC]
Erythritol	122
Nitrate Salts	240-260
Xylitol	92

We cycled erythritol hundreds of times to distinguish when and how it degrades. We have tested xylitol as a secondary option, by using it to cook and test its similarities with erythritol. We are still exploring nitrate salts as a PCM. We have not recommended nitrate salts to collaborators yet due to safety concerns while we continue further testing.

Xylitol is an option for slow or low-power cooking due to its lower melting temperature. We find it to behave similarly to degraded erythritol. In a domestic trial (Pete Schwartz's house) three months of cooking, and about 100 day-long cycles between 180 ºC and 80 ºC, the melting point of erythritol decreases by 20 ºC, which is identical to that of xylitol. Therefore, we still see erythritol as the best option of the three phase change materials. Degraded erythritol means that the melting temperature has decreased, and it can no longer phase change completely. However, it can still heat to 180 ºC and release sensible heat while cooling.

Solid thermal storage is also appealing because it will not degrade, and it allows the user to independently engage the thermal storage by physically disengaging it from the heater.

5. Changing the narrative on modern energy cooking services

Appliance performance and acceptance

Each collaborator had different challenges. Insulation is necessary with direct (low power) cooking or thermal losses will prevent the food from getting hot enough to cook. Therefore, having enough insulation from the bottom, sides and on the top of the cooker is required. Many use the ISEC for hot water, teas, rice and beans; others use it to cook traditional meals they otherwise would have cooked using the fire.

Our collaborators with technical backgrounds were able to build and test the cookers quickly as well as show others how to use them. Collaborators without technical background were still able to build ISECs. They needed additional help and support, which our team was willing to provide, although we encouraged them to acquire a technically accomplished partner.

Market Surveys

Market surveys indicate that traditionally women will be using our product. In general, people who answered our surveys want more power and ability to cook when they please, which is why having an option for thermal storage is beneficial. Our surveys also indicate the size of standard households in that region and how the ISEC can be adopted into their daily routine.

Supply chains

Our goal is to source as many materials as we can locally. However, not all materials are made in the intended country. We have a collaboration with Robert Van Buskirk to assist in sourcing low-cost solar panels to our collaborators. We have some test trials happening presently, and hope to continue this collaboration. Importing goods into different countries sometimes presents challenges with taxes and paying duties, so Robert is careful to first import a smaller test quantity before committing to an entire shipping container.

Monitoring electricity supply and use

Users prefer more power when cooking, comparing their cooking experience with the ease and power of fire or gas stoves. However, a 100W solar panel powering a direct ISEC can boil water at a rate of one kilogram per hour. This is suitable for many of the cooking practices we see among our collaborators. Using a phase change material, aluminum puck or the lithium titanate battery greatly improved power output. Using the storage also removes the “day time only” cooking constraint. It allows users to cook at dawn as well as after sunset.

We are monitoring our tests with a thermocouple data logger, recording temperature in several places, while an arduino records voltage and current. A cooking log is being kept to compare cooking with and without battery storage.

Finance and affordability

A direct ISEC system would cost $50-$100 including the solar panel. Our collaborators claim that aesthetics is important and complained that our ISEC is ugly. We invited each collaborator to creatively improve the appearance of their ISEC. In the future, we will emulate the best aesthetic ideas from collaborators to be shared with other collaborators. The ISEC allows great versatility in the outer appearance, if the technical components are similar and work.
We strive for a sustainable dissemination model with local assembly, using as much local material as possible and importing only what is not locally available.

Stakeholder interactions

Important stakeholders are collaborators, funders, and students (at Cal Poly and in Africa). Our collaborators continue to work hard in their construction and dissemination. We meet every week sharing ideas. An important collaborator we highlight again is Robert Van Buskirk who has taken on the role of distributing low-cost solar panels to our collaborators in large shipments.

Scaling up electric cooking

The transition to clean energy cooking will continue to grow, buoyed by the continued decrease in solar panel cost. More families are willing to make that initial investment if they see it paying off. Robert Van Buskirk notices in Malawi that people are willing to buy the entire solar cooker system because of their strong desire to own a large solar panel.

6. Social inclusion and Impacts

Bidjanga offers free ISEC trainings to his community, open to all ages but geared towards the youth. He provides equipment and technical training to educate many individuals from his community on ISEC technology. The impact his trainings have are felt amongst the community. Many of the younger members of the community attend the training sessions on a weekly basis. Bidjanga provides these informational sessions on the weekends when the majority of people have the most free time. A recent, multi-week course costing money allows for students to construct an ISEC and take it home.

Gender

The majority of the students attending Bidjanga's workshops are girls and women. In his region it is most common for women to be using the technology, therefore they are the target audience in learning how to build and use ISECs. Not only are they receiving education on this specific technology, but it also saves them time that would otherwise be spent away from home in search of wood as well as keeps them safe from both assault and indoor air pollution.

Fig. 20, ISEC workshop in Cameroon

7. Next steps

We will continue to guide ISEC technology via weekly meetings and correspondence. We will also continue to facilitate sourcing materials and solar panels. We will continue full time summer research with 5 research students at Cal Poly. We will seek further funding for collaborators. We appreciate guidance from the larger solar electric cooking community.

Pete Schwartz will spend the next academic year on sabbatical (actually "difference in pay leave") visiting collaborators teaching about ISEC, promoting rural electrification, food production, and permaculture while learning about local culture and challenges.

8. Conclusions

We have improved ISEC technology to include a variety of storage strategies to cook with more power and to cook after sundown.

The most affordable and reliable ISEC is still the “direct-connect” with no energy storage. While this technology works beautifully, it will only slow cook, requiring at least some change in cooking routine.

ISEC implementation inherently involves rural electrification, and the scaling challenges are mostly the sourcing of parts not manufactured in Africa.

Likely the greatest achievement is the formation of the global learning community - the “SuperGroup” that meets every Thursday. We have a network of creative, curious change agents with considerable technical knowledge and insights to share.

What began as a technological challenge may shift to one of business and sociology as we consider how to empower and support small local enterprises to bring value to their communities.

9. Appendix

Progress Reports from Collaborators

Alexis Zeigler https://docs.google.com/document/d/1AC9s2nXVmbBNfLNvADw-TtUVJq-T4mb59M2leL89MsY/edit?usp=sharing

Andrew Mayanja and Alicwamu Moses
https://docs.google.com/document/d/1FmyMzTAH_FAAsMRz0sWTFyGRxAfewZyNEF9nXyyA3PU/edit?usp=sharing

Chris Musasizi
https://docs.google.com/document/d/1wIxjSDY5snzk84y90IeYrRsA1KpF2oCiSQU1IPyLE8o/edit?usp=sharing

Hawazin Khaleel
https://docs.google.com/document/d/1_pTcVdDU0oW6qIvQVktYzxdRVnCj2tKzbb5S1lImf5E/edit?usp=sharing

Bidjanga Zach
https://docs.google.com/document/d/1EIV6bzw3w2abHI5v6GkgF8wivSctepfO4PZzgpr7oNA/edit?usp=sharing

Mark Manary
https://docs.google.com/document/d/17a6eG8PEEkTc_FidmKmNc7hJdbxwlc6Q/edit?usp=sharing&ouid=106906045117624018280&rtpof=true&sd=true

Salma Bougoune
https://docs.google.com/document/d/1tAHu20MEyIg68D66JJSWEdO-rpZuGy3yB42bIoCKt0Q/edit?usp=sharing

Presentations

ISEC Research team from FROST summer research (June 2021-August 2021) presented their results which begins at time 45 minutes, 41 seconds
https://calpoly.zoom.us/rec/play/yban5SNJFO_XQy0WW5y1X6MBPbxWeSEJwyyVGn1VR9xgLEZt9dvkl9MwkcIyl41LBjJAH1G9-fCa0o6L.1aAPdf9sdc0hG2w0?startTime=1628886765000&_x_zm_rtaid=JNPBkWmLQRy33hCW7eI6Bg.1633110860571.a42538096cfe371294b80d352c625965&_x_zm_rhtaid=813

Dr. Pete Schwartz presented at a conference for Engineers Without Borders (EWB)
https://www.youtube.com/watch?v=hkosRwstw9M

Katarina Brekalo presented at the ETHOS conference in January 2022
https://www.youtube.com/watch?v=gxMzO8bvM5E

Questionnaires

Cooking Method
https://docs.google.com/document/d/1nLRoVA1UlGon6mtPG-ufMenho_zbZ1PYLC7eSAUhjGA/edit?usp=sharing

ISEC
https://docs.google.com/document/d/1VSg8QtOGeiF2vieWBG1fiZh8y02EMBzw/edit?usp=sharing&ouid=106906045117624018280&rtpof=true&sd=true

Acknowledgements

We are grateful to MECS for the funding as well as consistent guidance (especially Jane Spencer and Simon Batchelor) and partnership that reminds us we are working together as a community. This gratitude extends to the collaborators that have joined this community as well as the ~200 students and supportive faculty who have engaged in research and service learning projects in the past 3 years. Robert Van Buskirk (Kuyere!, Kachione LLC, also a MECS grant recipient - look for his final report) supports inexpensive sourcing from China. We acknowledge the generous support from the William and Linda Frost Fund.

References

Our three peer-reviewed scientific papers:

1. *Development Engineering* 2 (2017) 47–52, https://doi.org/10.1016/j.deveng.2017.01.001
2. *Development Engineering*, 4 (2019) 100044, https://doi.org/10.1016/j.deveng.2019.100044
3. *J. Solar Energy*, 220, 2021, 1065-1073, https://doi.org/10.1016/j.solener.2021.03.040
4. Our research website with videos, construction manuals, and more project resources: http://sharedcurriculum.peteschwartz.net/solar-electric-cooking/