# Flash Cooking: Phase Change Thermal Storage with Solar Salt


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## Abstract

After a few hours of sun, the solar salt Insulated Solar Electric Cooker (ISECooker) can deliver up to 0.7 kWh of energy to the contents of a cookpot. In the first 2 minutes of cooking, the ISECooker provides an average ~5000 W to the food, resulting in “flash cooking.” Molten solar salt holds solar electric energy in an insulated chamber, allowing a user to cook in the evening, hours after the sun has set. A global group of collaborators is working to optimize the construction, dissemination and designs of ISECookers.

## The Worldwide Cooking Problem

Approximately a third of the global population (~2.4 billion) cook by burning a harmful household air polluter. Coal, biomass, kerosene and open fires account for an estimated 3.2 million deaths annually (WHO, 2020). Solar electricity can be a healthy, inexpensive alternative.

In addition to health and environmental benefits, the adoption of solar-electric cooking can also provide economic benefits by reducing households' reliance on costly fuels. Developing these technologies can create opportunities for local businesses and entrepreneurs. We are supporting local manufacturing and dissemination as it helps address issues more directly, and encourages education of solar electrical systems. A Global Supergroup meets every Thursday to discuss latest ISECooker developments. See Dr. Peter Schwartz’s blog [5] for ISECooking around the world.


Fig. 1. Global Supergroup

As prices of solar panels, as well as batteries continue to plummet [2], solar-electric cooking becomes a much more viable option for low-income communities, and has become a promising option for the clean and modern energy cooking transition.

## Insulated Solar Electric Cookers (ISECookers)

In 2015, Insulated Solar Electric Cookers were introduced as a method to utilize solar electric energy to directly cook food [7]. The original design (shown in Fig. 2) includes an insulation chamber holding a cookpot and a resistive heating element, electrically connected to a 100W solar panel. A Direct Connect ISECooker (where the solar panel is directly connected to the resistive heater) has the capability to boil around 5 kg of food throughout the course of a day.

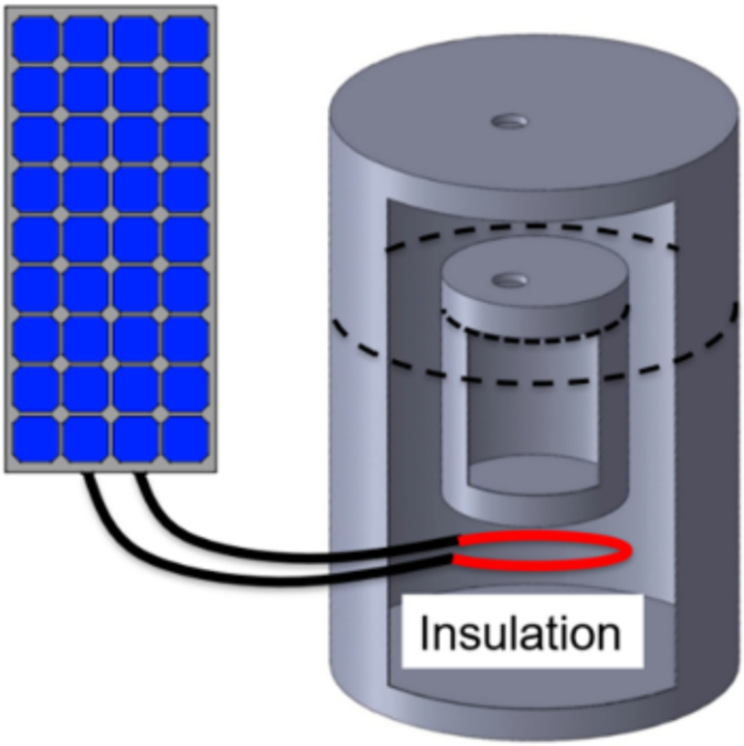


Fig. 2. The Original Direct Connect ISECooker

**Thermal Storage**

Phase change materials (PCM) are substances that release and absorb significant heat energy at a phase transition (most commonly solid to liquid and vice versa). In this case, a phase change material is beneficial because when it melts, there is latent heat stored in the ISECooker that is delivered to food when it solidifies. Feedback from early ISECooker users revealed that people desire to cook with more power, and after sundown. Thermal energy storage can fulfill both these requests: stored heat allows the user to rapidly draw energy from a PCM, and insulation will keep the phase change material hot overnight.  Previous ISECookers have implemented erythritol as a PCM [6].

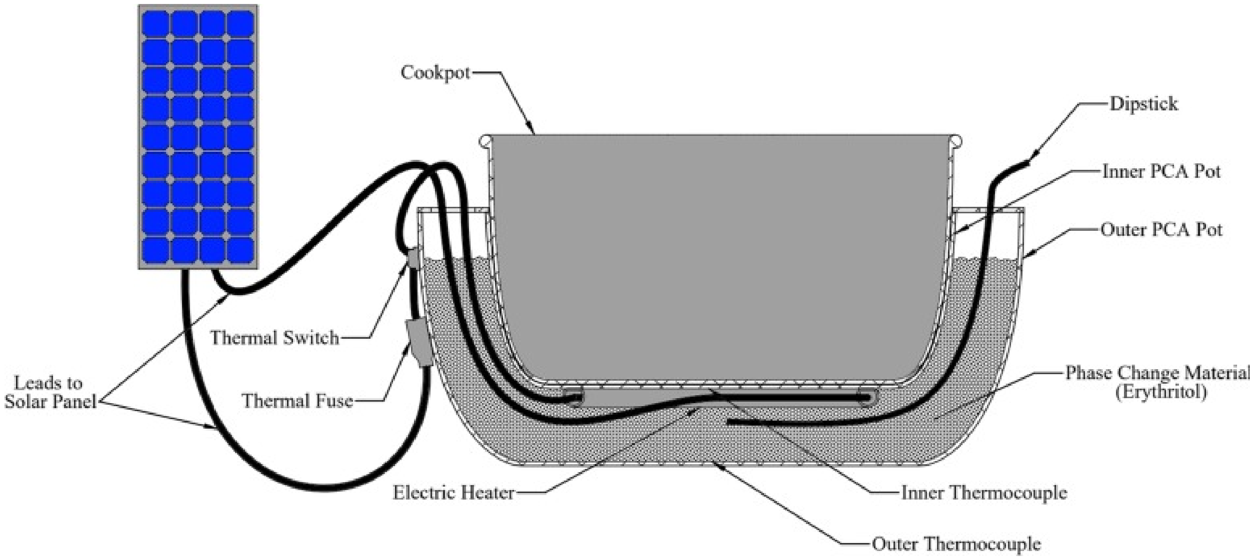


Fig. 3. ISECooker with thermal storage (erythritol)

Looking for methods to reach higher temperatures and energy outputs, this paper explores Solar Salts as a PCM in ISECookers.

It is important to note that with a battery system, users are able to use an ISECooker after dark. However, these systems are much more expensive than the ISECooker itself. As the cost of batteries continues to drop, they likely will become an inexpensive option, but battery systems are not currently viable for many communities in developing countries. Additionally, batteries have their disadvantages. They die after a period of time, and there is an increased complexity with voltage matching and charge controlling. ISECookers are a more simple solution, easier to use for the average person.

**Solar Salt**

The solution of Sodium and Potassium Nitrate (60% $NaNO_3$, 40% $KNO_3$) has been utilized for years as a method of storing thermal energy in renewable systems. Often this mixture of molten salt is found in solar power plants, retaining solar heat to reliably generate grid electricity [4]. We explore the usage of solar salts as a phase change material in an ISECooker. The high heat capacity in Solar Salt makes it an excellent option as a medium for thermal storage [3]. Additionally, the melting point allows the user to cook with increased power at higher temperatures.

Physical Properties of Solar Salt (60% $NaNO_3$, 40% $KNO_3$)

Table 1

| Property | Value |
|---|---|
| Melting Point | $223_{\circ}C$-$275_{\circ}C$ |
| Liquid Heat Capacity | 1.596 J/g·K |
| Solid Heat Capacity | 1.74 J/g·K |
| Density ($300_{\circ}C$) | 1902 $kg/m^3$ |
| Heat of fusion | 170.1 kJ/L |

[3]

Note that this heat of fusion is in the non-standard units of kJ/L, rather than kJ/kg. This is intentional due to the fact that we are limited by volume in the phase change assembly. Water has a solid and liquid heat capacity of 2.093 J/g·K and 4.184 J/g·K, respectively. It has a density of 997 $kg/m^3$ and a heat of fusion of 333 kJ/L. With higher values of heat capacities and fusion, water appears to be a more effective option as a PCM. However, a higher density of solar salt makes up for some of this disparity, as we can fit more material into the same volume. Additionally, water is not viable as a PCM since the temperature of vaporization is not high enough to cook.

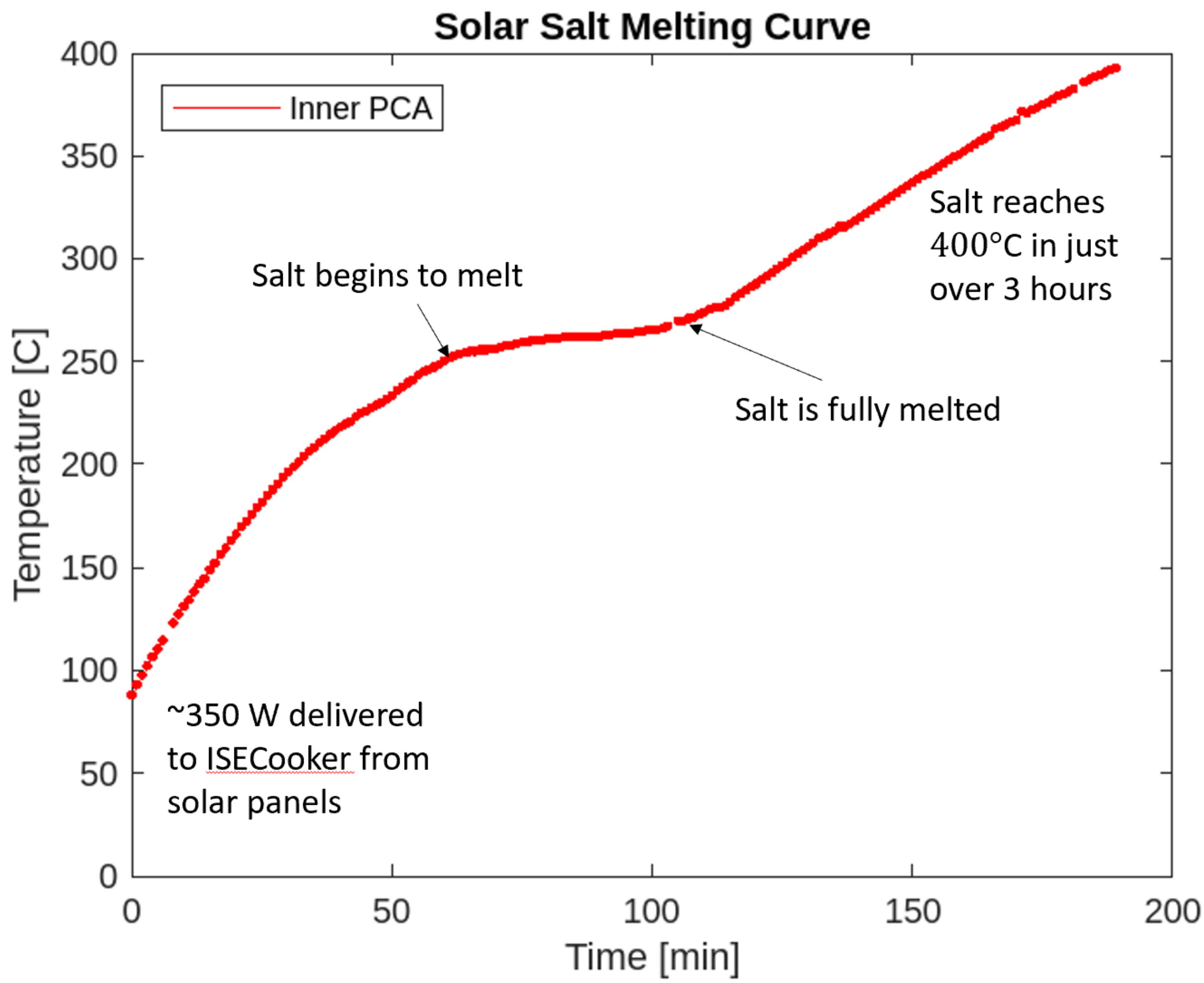


Fig. 4. Melting Curve of Solar Salt

**Insulation**

Insulating the ISECooker is critical, especially when thermal storage is incorporated. ISECookers are commonly insulated inside a large vessel, with the cookpot surrounded by rock wool, fiberglass or both. An issue with these insulators is the lack of structural integrity. An alternative is vermiculite concrete. A mixture of 5 parts vermiculite, 1 part Portland cement creates a sturdy, insulating material. The thermal conductivity of 5:1 vermiculite concrete was measured to be 0.13 ± 0.01 W/m/C∘. [Heat Flow Meter] While this is a larger value of thermal conductivity than fiberglass or rock wool (around 0.04 W/m/C∘), the structural aspect is beneficial, although heavier and less convenient.

**Experimental Setup**

In order to safely and effectively cook food, solar salt must be contained inside a vessel in close proximity to the cookpot.

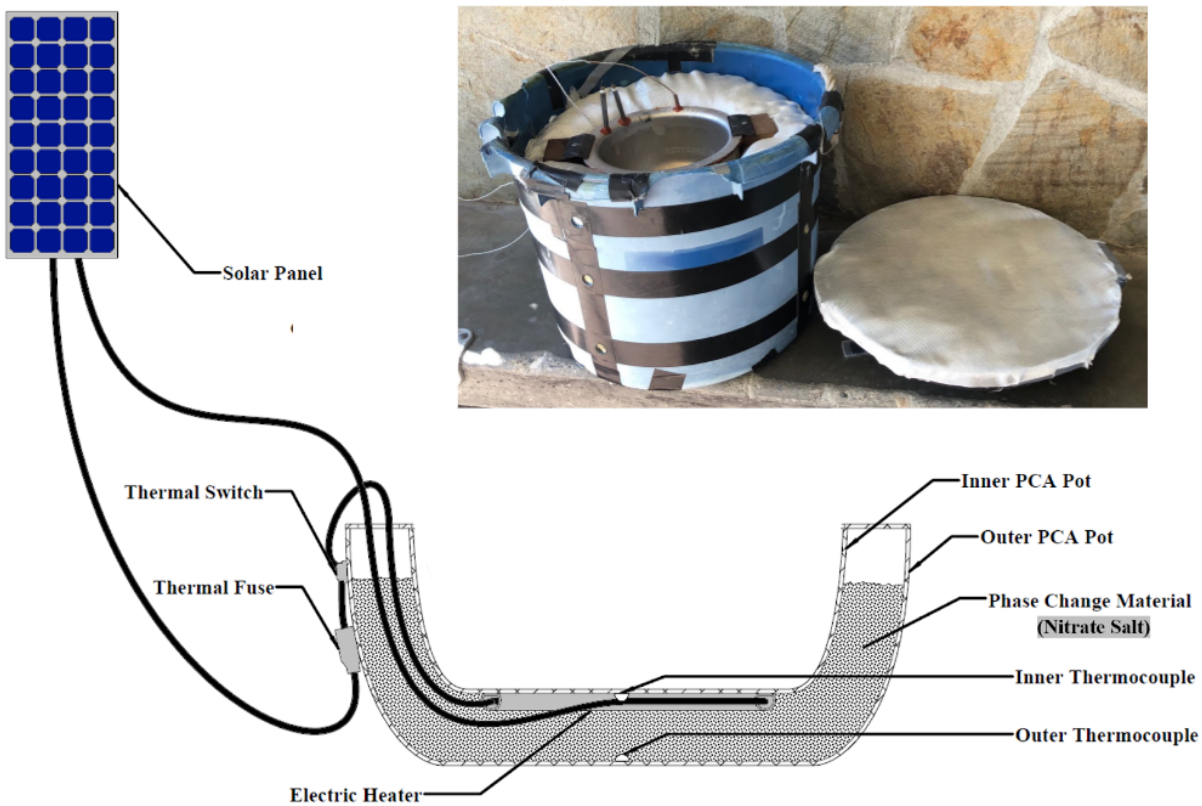


Fig. 4. Schematic of Phase Change assembly

This is achieved with a phase change assembly (PCA, Fig. 4), similar to the PCA used for the erythritol ISECooker [6]. First, an immersion heater of nichrome wire coated with steel is bound to the inner PCA pot (Fig. 5). The steel coating the immersion heater does not react with molten solar salt, and the leads to the NiCr heater are threaded through holes in the inner PCA pot. The immersion heater has a resistance of 3.2 Ω.

Fig. 5. Nichrome wire immersion heater bound to inner PCA pot.

The outer PCA pot has corner brackets attached at four points on the pot (Fig. 6). We explored adhesives to bind the inner PCA pot to the outer PCA pot, however there are no inexpensive adhesives that can withstand target temperatures for the ISECooker (350$_{\circ}$C-400$_{\circ}$C). The rim of the inner PCA pot is drilled with holes to connect the brackets, and the pot is connected with 3g of solar salt inside the PCA (1.8g $NaNO_{3,}$ 1.2g $NaNO_3$). Thermal couples are attached to the bottom of both the inner and outer PCA pots to record temperatures.

Fig. 6. Corner brackets attached to Outer PCA pot, solid solar salt shown inside

**Simulation: Cooking after dark**

To simulate cooking after dark in the solar salt ISECooker, we heated the pot with 350W (four 100W panels) for 3.5 hours, then let it be without power for 1 hour.

Fig. 7. Solar Salt ISECooker powered by four 100 W solar panels.

To measure the power delivered to the contents of the pot, we pour 2 kg of $25^{\circ}$C water directly into the inner PCA pot to boil. Temperature data is recorded with a Gain Express 4-channel K-type thermocouple data logger, with $0.1^{\circ}$C precision and $1^{\circ}$C accuracy. After a few hours, we can weigh the remaining water to measure the weight of water that has evaporated due to the stored thermal energy.

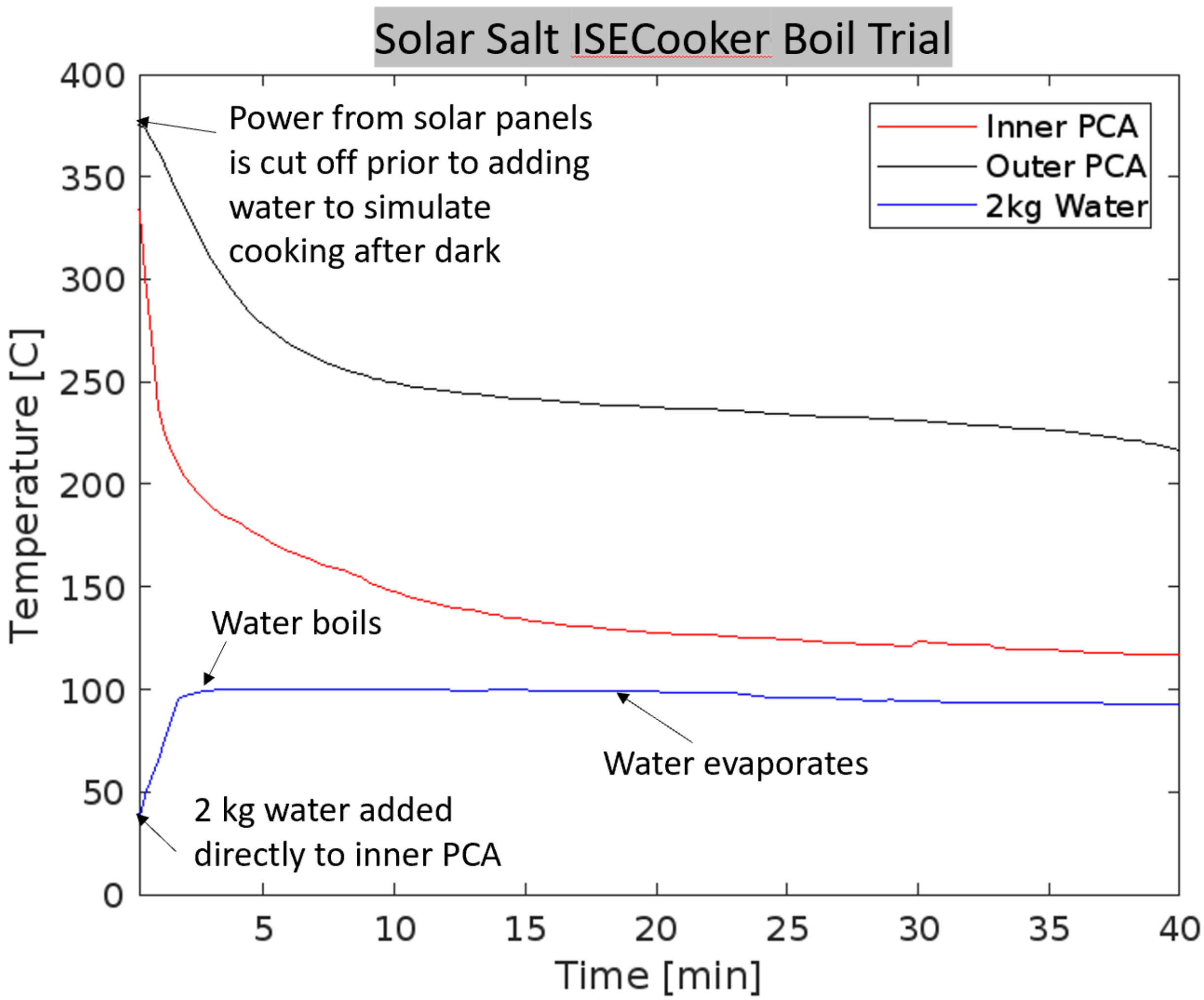


Fig. 7. 2 kg water is boiled directly in the inner PCA.

The total energy delivered can be found with a sum of two equations. First, the energy put out to bring the water to the boiling point:

$$E_{\Delta T} = mc\Delta T \quad (1)$$

(where c is the specific heat of water (4182 J/kg·K), m is the mass of water (2 kg), and $\Delta T$ is the change in temperature (100∘C-$T_{initial}$))

Second, the energy put out to boil the water:

$$E_{\nu} = m_{\nu}H_{\nu} \quad (2)$$

(where $m_{\nu}$ is the mass of water that was evaporated and $H_{\nu}$ is the heat of vaporization of water, 2260 J/g)

Inserting numbers, we get:

$$E_{\Delta T} = (2kg)(4182J/kg \cdot K)(75K) = 627\ kJ$$

$$E_{\nu} = (807g)(2260J/g) = 1824\ kJ$$

$$E_{tot} = 1824 + 627 = 2451kJ = 0.68kWh$$

It was found that in the first two minutes, the ISECooker was able to deliver extremely high power to the contents of the pot. With a starting inner PCA temperature of 375∘C, the ISECooker delivered an average of 5200W ($\frac{627{,}300\ J}{120\ s}$) over the first two minutes. Over a span of 90 minutes, the ISECooker was able to send 0.68 kWh of energy to the contents of the pot, corresponding to an average power of 453 W. Other trials were consistent, evaporating an average of 803 g of water per trial over 5 trials.

## Efficiency

Efficiency can be defined as the percentage of energy delivered to the contents over the total electrical energy captured by the solar panel. A low efficiency indicates that a significant amount of heat is being lost to the environment, and the insulation needs work. In the simulation, we powered the ISECooker at 360 W for 3 hours, corresponding to (350 W)(3 hrs) = 1.05 kWh. This gives a 65% efficiency. As storage times increase, more energy is lost into the environment, especially at high temperatures.

## Discussion

The ETHOS clean cooking conference in January 2023 displayed the general goal of clean cooking to be reducing emissions of combustion cooking. This is sensible since households are reluctant to give up the familiar cooking methods (whether it be coal, biomass, kerosene…). However, the fans and filters of improved combustion cooking do not eliminate all fumes, especially when they are inconvenient for the cook and subsequently used incorrectly (or not at all). ISECookers are 100% clean, and also can have positive impacts on communities through local manufacturing and learning basic electricity principles. Although solar panels are a considerable capital cost, the systems are cost effective in the long run, so a funding mechanism is helpful. The Global Supergroup works to educate and fund people to build ISECookers around the world, sharing design ideas and strategies every week.

The Solar Salt ISECooker uses materials that are readily available in most communities. The salt solution is a fertilizer that can be found in most towns. Although access to materials does not pose too much of a problem, there are concerns with safety. Molten salt at the target temperatures is dangerous, doing significant damage to skin, as well as being a fire hazard. Without a fully sealed phase change assembly, the solar salt ISECooker is not the safest. A solid alternative is the Solid Thermal Storage ISECooker, where heat energy is stored in a solid aluminum puck. This does not make use of the latent heat storage that a PCM does, but it eliminates many of the safety concerns.

Cooking with the Solar Salt ISEC is quick and flashy. I found around 325$_{\circ}$C to be an ideal temperature to "flash cook," cooking a full 2 portions of chicken and vegetables in under 5 minutes (with a lot of oil). Though I did not use it for this purpose, it would also be useful in the mornings/overnight to cook/warm up soups or stews, due to the latent heat of fusion.

## Conclusion

We increased the versatility and power of ISECookers with thermal storage via molten salt. We are able to raise the ISECooker to temperatures up to 400$_{\circ}$C, providing a peak power output of 5200 W, an average power over 90 minutes of 453 W, and an overall efficiency of 65%. ISECookers are environmentally-friendly alternatives to harmful pollutants often used in the kitchen.

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