International Conference CONSOLFOOD-2016
Advances in Solar Thermal Food Processing
Faro, Portugal, 22-23 January 2016

SOLAR COOKING WITH HEAT STORAGE: EXPERIMENTS USING PCM AND FIGURES OF MERITS FOR SOLAR COOKERS

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Contents

Introduction

- Cooking food is a human basic need

1. In a developed economy cost and impact of cooking is **minor** in:
    - Energy
    - Economy
    - Environment

    ~ 10% cost of the average dwelling is Spain (6-12 €/month per family)

2. In a developing economy this proportion grows.

"*Energy poverty exist when >10% of incomes are for energy*"

Brenda Boardman

(In Spain between 9 and 18% of families fulfil this criterion, in Europe 50 millions and in South America is generalized)

Asociación de Ciencias Ambientales y Economics for Energy

3. In a developing country cooking is the major energy consumption, in addition to indoor heating in temperate and cold climates.

"*one could speak about systemic energy poverty*" One example:

Introduction

Based on: *Nature. Sustainability: Clean cooking empowers women Laura S. Brown& William F. Lankford. 20 May 2015* *and others*

- *4 a.m. Eunice in Nicaragua, as every day, starts a wood fire for the breakfast and the smell animates the family to wake up. Eunice launches into a coughing fit. Her daily routine has started.*
- *The smoke reaches the wood beams at the ceiling, contributing to the tar that protect them from termites.*
- *Men go out for work.*
- *During the day Eunice will go downhill to come back loaded with firewood. Also she must bring water from the creek. She must take care of the children and the grandmother and prepare the dinner.*

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Introduction

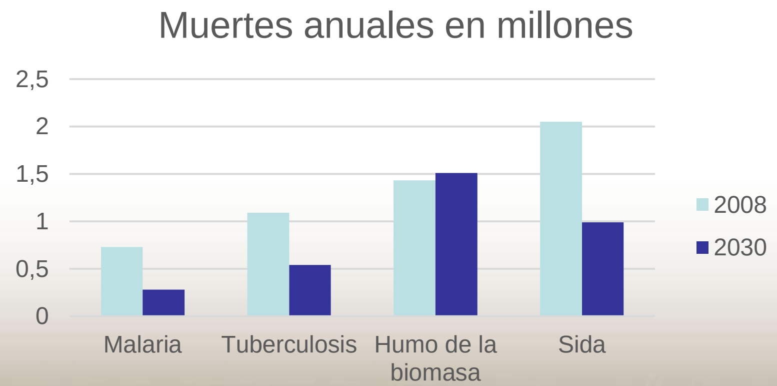
Smoke in the kitchen is a problem?

- 3 billion people:
  - Use firewood or dung (1kg/person per day) or coal for cooking.
  - Without effective ventilating fumes.
  - In open cookstoves (η ~ 5%).
- 0,9 billion suffer hunger.

➢ Causes > 4 million premature deaths per year. LIKE A WORLD WAR!.

➢ 3 million deaths/year children die by hunger.

➢ Others studies (IEA WEO 2013)



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Source: Nature New Feature. Global health: Deadly dinners. 28 May 2014.

Introduction

Are there any other problems with firewood?

1. Collecting firewood (from nature)

- Women and children spend several hours per day, having to walk long distances with heavy loads, up to 20 km.
- Risk of sexual attack and wild animal threats.
- Diminish opportunities for development.

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Source: Violencia sexual y recolección de leña en Darfur, VIOLENCIA SEXUAL RMF 27, pp 40-41, Erin Patrick.

Source: http://www.fsec.ucf.edu/En/research/solarthermal/solar_cooker/images/houtjuk1.jpg

Introduction

Are there any other problems with firewood? (cont.)

2. Deforestation

- 3.2 million m^3 of wood were collected in 1998, 50% were for burning.
- In many accessible regions firewood use is non-sustainable, specially near populated areas, causing deforestation.

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Deforestation in Myanmar
http://thewatchers.adorraeli.com/2011/11/28/deforestation-and-food-crisis-threatens-myanmar/

Deforestation in Syria
http://www.mennoworld.org/archived/2013/2/4/syrians-plight-war-winter/

Introduction

Are there any other problems with firewood? (cont.)

3. Atmospheric pollution

- Regional pollution by airborne particles
  - 60%-80% from total in some areas.
- Greenhouse effect by particles and CO_2.
  - Firewood amounts 10 % of the world energy consumption.

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Area contaminated by airborne particles. Source: Nature 509, 7502, Global health: Deadly dinners. Meera Subramanian 28 May 2014

Introduction

Are there any other problems with firewood? (cont.)

3. Firewood crisis

- ~ 10% of the world energy consumption is for the home, especially in the third world. In India is 36 %. In Africa is even larger.
- For ~ 1/3 of humankind the main energy consumption is for cooking (and heating).
- ~ 76% of the sub-Saharian Africa population cook with biomass, mainly firewood. 69% in India and 65 % for the remaining Asia. *(International Energy Agency, 2006) Chapter 15, p. 419*.
- Firewood is the fourth world energy source. Its world distribution is heterogeneous; 10% in developed countries and 80% in developing countries (*Garg, 1987*).

  - Distances for collecting firewood longer and longer. In some regios 150 km (with motoring help).
  - Firewood for cooking can cost more than food. http://www.thefortunecooker.com/the-firewood-crises .

Introduction

Solutions

1. Improved cookstoves

Source: [Nature New Feature. Global health: Deadly dinners. 28 May 2014].

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Source: Sol solidari Cameroon, with permission.

Image removed for author rights protection

Source: Sol solidari Lalibela, Etiopía. With permission

- ☹ The three stones cooker is very inefficient η ~ 5-15%.
- ☹ Low cost ~ 1 € or null.
- ☹ Are constructed in-situ immediately and in 3-5 days.

- Improved cookstove η ~ 15%- 35%. e. g. ↑
- Can be constructed in-situ or by a blacksmith → dependency.
- Main design: enclose the fire.
- Reduced smoke.

Introduction

Solutions (cont.)

2. **Biogas cookers (China), Combustion is cleaner, needs community action and some investment. Residues are not always available.**
3. **Introduction of modern forms of energy**

- **Mainly as a failure of the improved cookstoves, because:**
  - Expensive 10-80 €.
  - Spare parts and repair are sometimes not available.
  - Not able to roast or grill.
  - Heterogeneity of firewood.
  - They require constant care and attention.
  - Firewood not available…
- **Possibilities:**
  - GLP y micro-grids of electricity and biogas.
  - Solar cooking …

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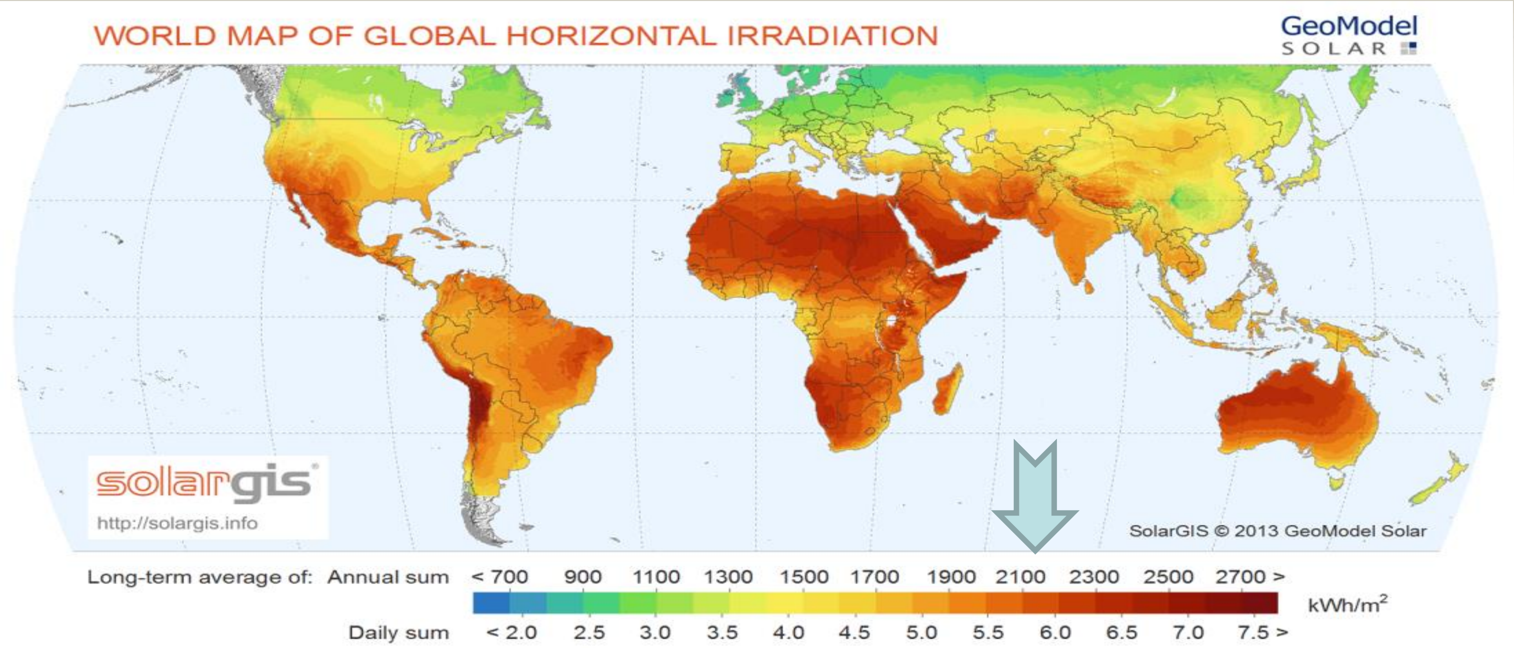
Source: Nature 509, 7502, Global health: Deadly dinners. Meera Subramanian 28 May 2014

Introduction

Is sun enough for cooking?



http://geosun.co.za/wp-content/uploads/2014/10/GHI-Solar-map-World.png

The average daily consumption for a family is ~ 4 kWh/day. Assuming twice the efficiency of firewood cookstoves (30%) means on average 2 kWh/day. This makes necessary 2 m² of solar aperture area if we fix on 5 kWh/m² horizontal irradiance with a daily exposure of 4,8 h sun/day = $2\ \mathrm{m}^2 \times \frac{2\frac{\mathrm{kWh}}{\mathrm{day}}}{5\frac{\mathrm{kWh}}{\mathrm{m}^2}} \frac{24\ \mathrm{h}}{8\ \mathrm{h\ sun}} \frac{1}{50\%\ \mathrm{solar\ effi.}}$

Solar cookers

What a solar cooker is?

- No fuel, only sun rays.
- Can also sterilize water.
- Are also used among us as a help and a hobby.
- There is no risk of catching in fire.

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http://solarcooking.wikia.com/wiki/%22Minimum%22_Solar_Box_Cooker

http://www.terra.org/html/s/sol/encuentro/solar2008/foto.html

http://www.fundaciontierra.es/es/actividades/economia-solar/recursos-sobre-la-cocina-solar

Solar cookers

Characteristics:

- ☺ Around ~ 1million deployed, moderate success.
- ☺ Can be constructed by local materials.
- ☹ Cooking outdoors is normally required.
- ☹ Slow cooking.
- ☹ Heating capacity is moderate.
- ☹ Sensitive to wind and dust.
- ☹ Sun is necessary: ¿dinner?, ¿breakfast?
- ☹ Sun must be tracked (15 min-2 hours)

- **Working principles**
  - **Accumulation** (greenhouse effect) for reducing heat losses.
  - **Concentration** of solar radiation to reduce the surface of heat losses.

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Women in Guatemala cooking in a solar oven built by their selves. Source: NATURE. Sustainability: Clean cooking empowers women. Laura S. Brown& William F. Lankford 20 May 2015 CASEP project. - *Tom Cogill*

Types of solar cookers

- Direct and indirect

2 examples of the family/community Scheffler cooker

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The world biggest solar cooker 38.500 lunches.
http://inhabitat.com/world%E2%80%99s-largest-solar-kitchen-in-india-can-cook-upto-38500-meals-per-day/

Shallow concentrator of the Scheffler type built with mirror facets in Fundación Tierra in Terrassa, Barcelona. Foto: Romain Boussaud., Source: http://en.wikipedia.org/wiki/File:Parabole_de_cuisson_solaire_Scheffler_coccion_solar_cooking.jpg.

Types of solar cookers

- Individual o communitarian
- Portable or stationary

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Panel cooker CooKit

Indirect solar cooker Solar Bowl in Auroville, India

Types of solar cookers

- No heat storage
- With heat storage (above 80 ºC cooking starts):
  - With additional mass for heat storage (more in advancing)
  - By heat retention in the food itself (heat retention) .

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Source: Solar Cookers International

Source: Fundación Tierra and Fundación Terra

Source: Fundación Terra. Photo Virginia Bauso, Puna, Argentina.

Types of solar cookers

Heat accumulation

(Portuguese solar oven)

Pot is enclosed in a heat insulated greenhouse.

Slow. Cheap. Stirring is difficult. 10-100 €

http://en.wikipedia.org/wiki/File:Solar_oven_Portugal_2007.jpg

Concentrating.

(Parabolic mirror, Spanish)

Can fry.

Need frequent sun tracking.

Higher cost 100- 300 €

http://en.wikipedia.org/wiki/File:ALSOL.jpg

Mixt

(panel type, Mexican) Slow.

Foldable.

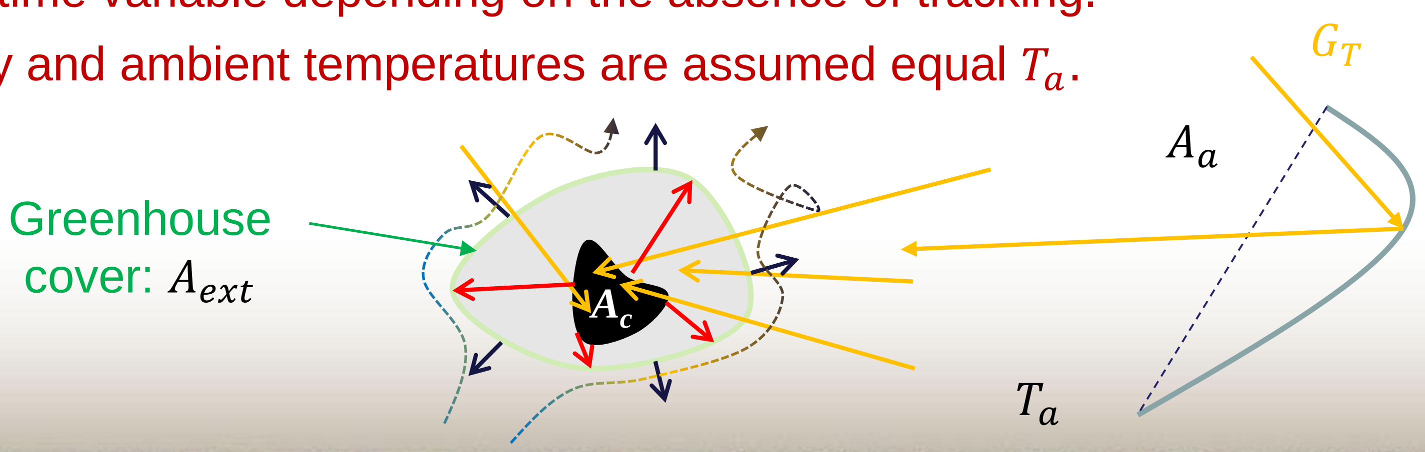
Short lived if with cardboard (this is not the case).

Cheap 1-10 €. (100 € this case)

Cooker with foldable panel mirrors and bot with cover as greenhouse, 5 liters, Source: http://en.wikipedia.org/wiki/File:HotPot_d.PNG by Paul Arveson, June 27, 2011. Origen: http://www.she-inc.org/hotpot-1.php.

Modelling solar cookers

- For homogenizing results water is used instead of food.
- Net heating is usual considering only the water heating capacity C.
- $$\eta = \frac{\text{Thermal energy in water}}{\text{energy uses (solar)}}$$
- Convective motion and stirring allows considering Biot number $Bi = \frac{hL^*}{k} \ll 1 \rightarrow T = const.$ for food and sauce.
- Depending on design the external area ($_{ext}$) is pot ($_c$) cover ($_{co}$) or retention ($_{re}$).
- A sky model yields the tilted solar irradiance G_T over the aperture area A_a.
- A_a can be time variable depending on the absence of tracking.
- Usually sky and ambient temperatures are assumed equal T_a.



Modelling solar cookers

- Formulation is similar of a solar thermal collector (0D model):

$$C\frac{dT}{dt} = \dot{Q} = F'\left[A_a G_T \eta_o - AU\left(\underbrace{T}_{\substack{\text{Food}\\ \text{+sauce}}} - T_a\right)\right]$$

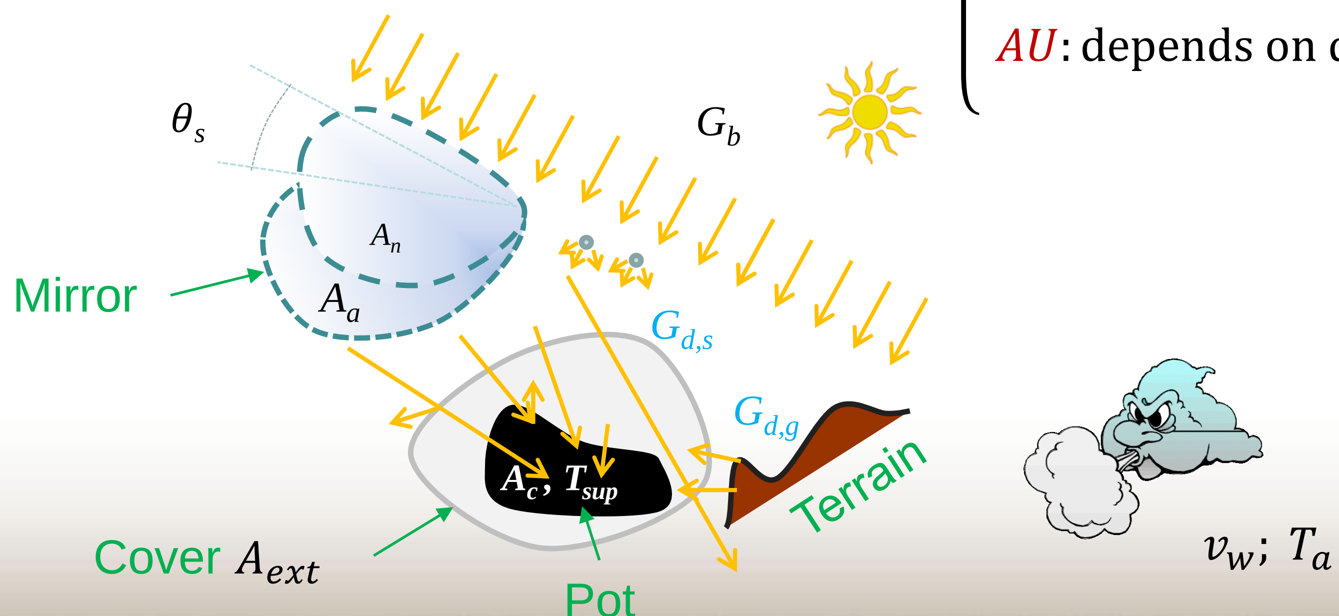
Heat capacity: $C = \underbrace{C_{fl}}_{c_{fl}m} + C_c + C_{co}$

F': Correcting coeff. because $T \neq T_{sup}$

η_o: Optical efficiency

$G_T = G_{b,T} + \underbrace{G_{d,s} + G_{d,g}}_{\text{If } C_S \approx 1}$

AU: depends on design $\begin{cases} A_{ext}U_{ext} \text{ or} \\ A_c U_c \end{cases}$

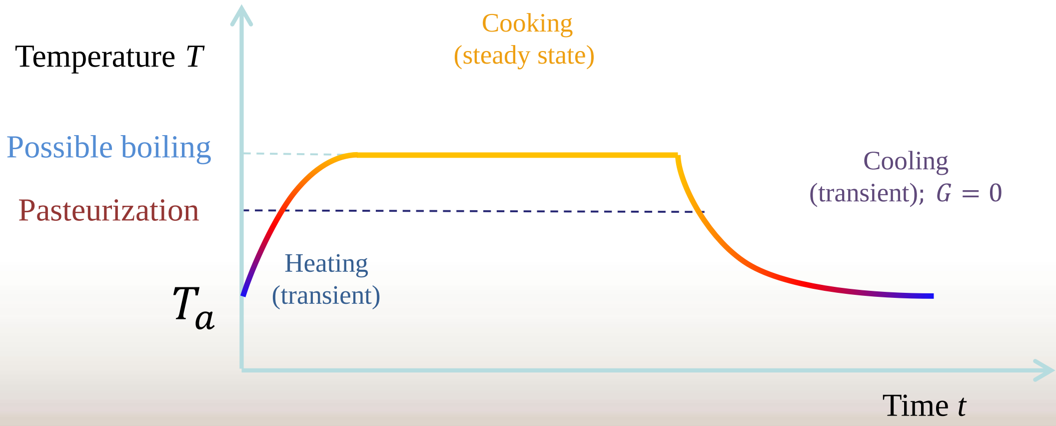


$$C_S = \frac{A_a}{A_c}$$

Modelling solar cookers

- Result in a schematic way:
  - At high temperatures water evaporation has to be included $\dot{m}L_w$.
  - The heating power $\dot{Q}$ diminish because of losses.
  - During temperature keeping (cooking) $\dot{Q} = 0$, limited by boiling or evaporation
  - During cooling sun is not operating.

$$\underbrace{C}_{\text{Heat capacity}} \frac{\mathrm{d}T}{\mathrm{d}t} = \dot{Q} = F' \left[\underbrace{A_a G_T \eta_o}_{\text{Solar}} - \underbrace{AU(T - T_a)}_{\text{Losses}} \right] - \underbrace{\dot{m}L_w}_{\text{Evap.}}$$



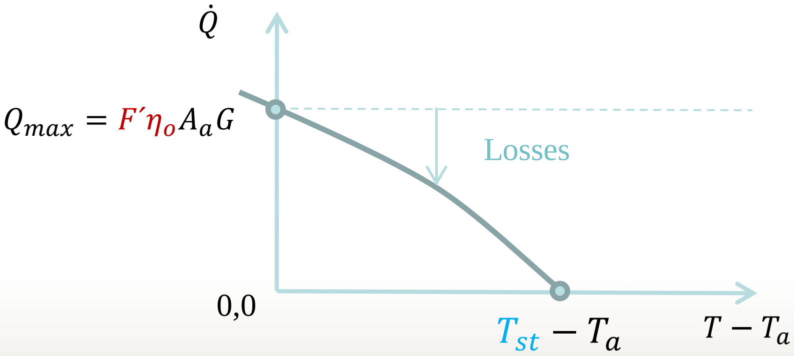
Testing solar cookers

Oriented towards:

- Offering the user/planner a few figures of merit
- Measure optical and thermal parameters that are theoretically difficult to calculate: $F'\eta_o, F'UA, C, \dot{m}$.

For that:

- Controlled test are performed measuring with simple instrumentation. E. g. **heating test under the sun up to stagnation temperature** T_{st} (measurable):



$$0 = C\frac{dT}{dt} = F'\left[\underbrace{A_a G_T \eta_o}_{\text{Solar}} - \underbrace{AU(T_{st} - T_a)}_{\text{Pérdidas}}\right] \rightarrow$$

$$AU_{st} = \frac{A_a G_T \eta_o}{T_{st} - T_a}$$

- F' cannot be determined, but fortunately $F' \approx 1$.
- Is necessary $\dot{m} = 0 \rightarrow$ no water.
- AU_{st} is not meaningful for the user, but T_{st} yes.

Thermocouple and solar meter required

Testing solar cookers

Figures of merit for heating:

- Standard ASAE S580: Normalized heating power:

$$\dot{Q}_{norm} = \underbrace{\left(\dot{Q}\Big|_{T-T_a=50^\circ C}\right)}_{C_w\,\Delta T/\Delta t}\left(\frac{\overset{700\frac{W}{m^2}}{G_{norm}}}{\underset{\text{Average. during heating}}{\bar{G}}}\right)$$

- Time Δt for boiling a nominal water load ($_w$) m:

$$\underset{C}{mc_w}\left(\overset{95^\circ C}{T_2} - \overset{40^\circ C}{T_1}\right) = \bar{Q} = A_a \overset{900\frac{W}{m^2}}{\bar{G}_T}\ \bar{\eta}\underbrace{(t_2 - t_1)}_{\Delta t} \rightarrow \bar{\eta} = \frac{mc_w(T_2 - T_1)}{A_a \bar{G}_T \Delta t} = \text{Average efficiency}$$

- Parameter F_1 of the Indian standard. Ratio (dimensional) between solar capture and losses:

$$\left.\begin{aligned} F_1 &= \frac{\eta_o}{U_{st}} \\ T_{st} &= T_a + \frac{A_a}{A}\eta_o \frac{G}{U_{st}} \end{aligned}\right\} \rightarrow F_1 = \frac{A}{A_a}\frac{(T_{st} - T_a)}{\bar{G}}$$

- In this standard η_o is determined in the heating test: $F'\eta_o = \frac{C(\Delta T/\Delta t)_{T=T_a}}{A_a G_T}$

Bureau of Indian Standards (BIS). (2000). *Indian standards IS 13429: solar cooker box type, first revision.* BIS, Manak Bhawan, New Delhi.

Testing solar cookers

Cooling test ($_{coo}$): $G_T = 0;\ \dot{m} = 0$

- $C\frac{\mathrm{d}T}{\mathrm{d}t} = F'_{coo}AU(T - T_a) \rightarrow$ losses can be determined: $F'_{coo}AU\langle T\rangle = \frac{C\frac{\mathrm{d}T}{\mathrm{d}t}}{T-T_a}$
- Assuming $F'_{en}AU, T_a$ and $C = \text{cte}$. The cooling process follows an exponential decay with characteristic time t^*_{coo} that can be experimentally determined by curve fitting:

$$\frac{T - T_a}{T_0 - T_a} = \exp\left(-\frac{t}{t^*_{coo}}\right) \ ; \ \ t^*_{coo} = \frac{C}{\overline{AF'U}_{coo}} = \text{const.}$$

- This allows predicting the heating evolution starting at (t_i, T_i):

$$T = T_a + \underbrace{\frac{A_a}{A}}_{C_S}\frac{\eta_o G_T}{U_c}\left\{1 - \left[1 - \frac{A}{A_a}\frac{U_c}{\eta_o G}(T_\mathrm{i} - T_a)\right]\exp\left(-\frac{t - t_\mathrm{i}}{t^{*\prime}_{coo}}\right)\right\} \ ; t^{*\prime}_{coo} = t^*_{coo}\frac{(F'U)_{coo}}{(F'U)_c} < t_0$$

Testing solar cookers

Results by ITEA-UC3M on commercial cooker HOT-POT (Bachelor Thesis by David Fernández Juárez):

Average aperture [m^2]	Water mass [kg]	Characteristic cooling time t^*_{coo} [s]	Losses coef. $F'AU_c$ [W K^{-1}]; $w = 0$	Optical efficiency η_o [-]
0,436	1,53	6.509	1,18	0,425

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$G_{n,max}$ [$W\ m^{-2}$]	T_a [ºC]	Max. heating power $\dot{Q}_{máx}$ [W]	Net heating char. Power $\dot{Q}_{T-T_a=50\ ºC}$ [W]	$T_{st} - T_a$ [K]
1.020	31	157	77	160



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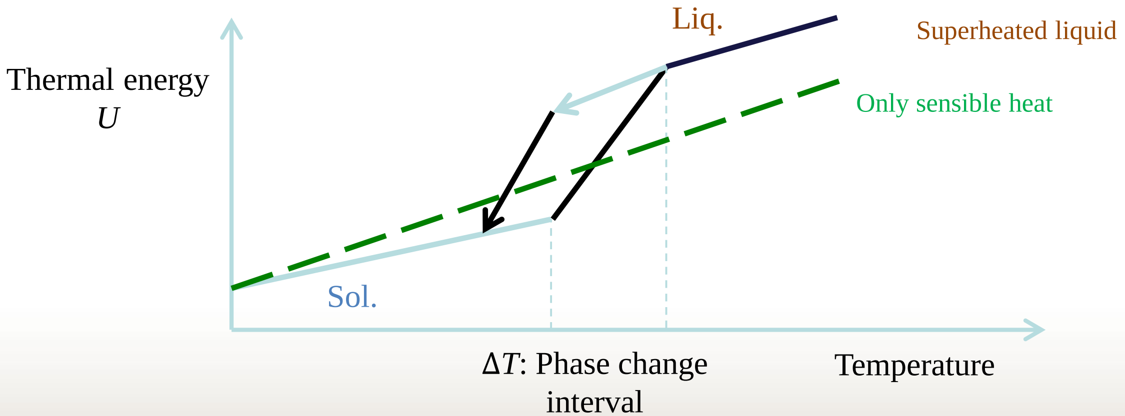
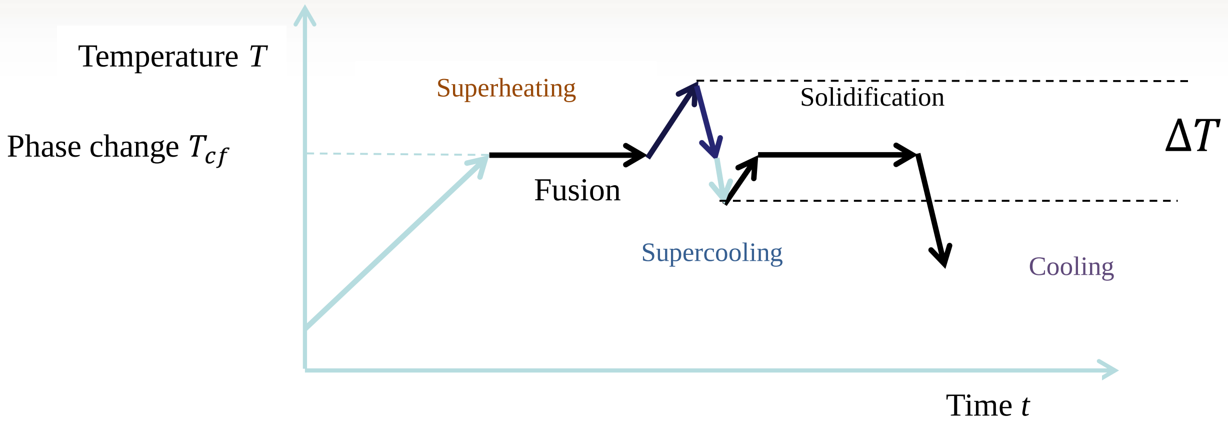
Heat storage solar cookers

- Properly use an additional mass of heat storage effect that after heating it is stored in a heat insulating cover, acting as a heat losses retention ($_{re}$).
- Its use (heat delivery) is produced establishing contact with the food.
- It is common to use PCMs (Phase Change Materials) for their higher capacity. E. g. paraffins, sugar alcohols, acid fats …
- Thermal conduction of PCMs is limiting so that enhancers are needed, e. g. metal powder, fins, ...
- They need to be of:
  - Low cost
  - Non toxic
  - Durable
  - Low supercooling.
  - Non corrosive.
  - High c and L.



Heat storage solar cookers

- Supercooling is a meta-stable process that reduces solidification temperature.



- Modeling. Owing to the difficulty of the Stefan problem a temperature interval is assumed for phase change in the PCM (1D model):

$$C = cm : \begin{cases} T < T_{cf} - \Delta T/2 \rightarrow c = c_{sol} \\ T_{cf} - \Delta T/2 \leq T \leq T_{cf} + \Delta T/2 \rightarrow c = \dfrac{c_{sol} + c_{liq}}{2} + \dfrac{L}{\Delta T} \\ T > T_{cf} + \Delta T/2 \rightarrow c = c_{liq} \end{cases}$$

- $c \approx 2\ \mathrm{J\,g^{-1}\,K^{-1}}$
- $L \approx 100$ to $\underbrace{350}_{\sim \text{ice}}\ \mathrm{J\,g^{-1}}$
- $T_{cf} > 100$ ºC

Heat storage solar cookers

- Suitable PCM T_{cf}>100 ºC:
  - **Paraffins**: $T_{cf} < 110$ ºC low $L \approx 100 \text{ J g}^{-1}$ and $k \approx 0{,}2/0{,}2 \text{ W m}^{-1}\text{k}^{-1}$
  - **Erythritol**: $T_{cf} = 118$ ºC high $L \approx 350 \text{ J g}^{-1}$ and $k \approx 0{,}7/0{,}3 \text{ W m}^{-1}\text{k}^{-1}$ possible supercooling.
  - **D-Mannitol**: $T_{cf} = 164 - 169$ ºC high $L \approx 316 \text{ J g}^{-1}$ and $k \approx 0{,}3/0{,}3 \text{ W m}^{-1}\text{k}^{-1}$ shows different solid phases.

Heat storage solar cookers

Prototype of storage solar cooker, developed by ITEA group at Universidad Carlos III de Madrid.
After storing heat it is kept insulated with a prototype cover, 6 kg weight.

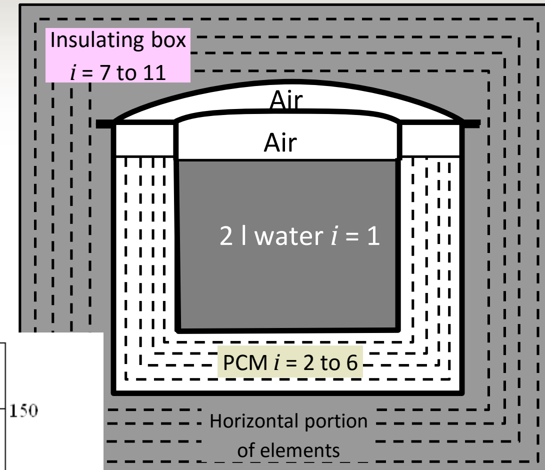
↑ Storing heat with a Chinese concentrating solar cooker.
Cover for heat retention→

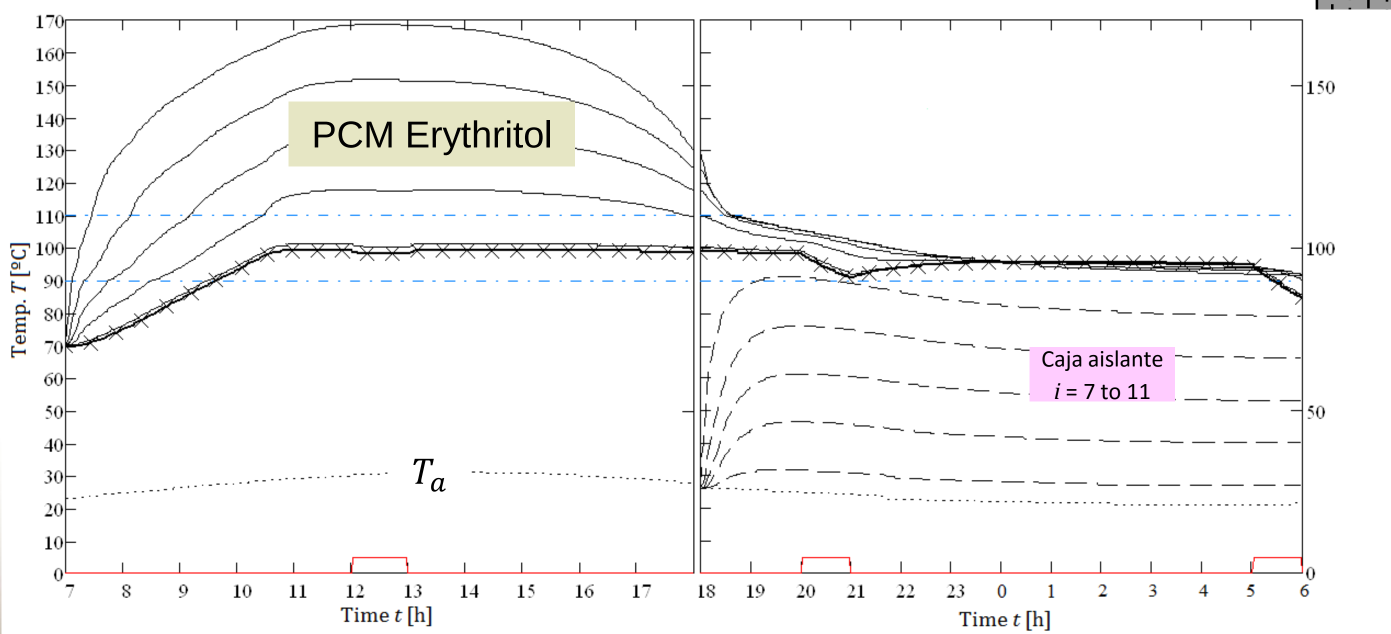
← Inner pot with flanges for joining with the outer pot.

Paraffin pure PCM with the outer pot removed, showing thermocouples ↓

Heat storage solar cookers

Element: $c_i M_i \frac{dT_i}{dt} = \underbrace{Q_s - Q_r}_{\text{Only for the external element}} + Q_c + Nu \times A_i \frac{k_i}{l_i}(T_{i-1} + T_{i+1} - 2T_i) - \underbrace{(Q_{co} + Q_v)}_{\text{Only for the inner pot element}}$.





1D modeled temperature 15/07:

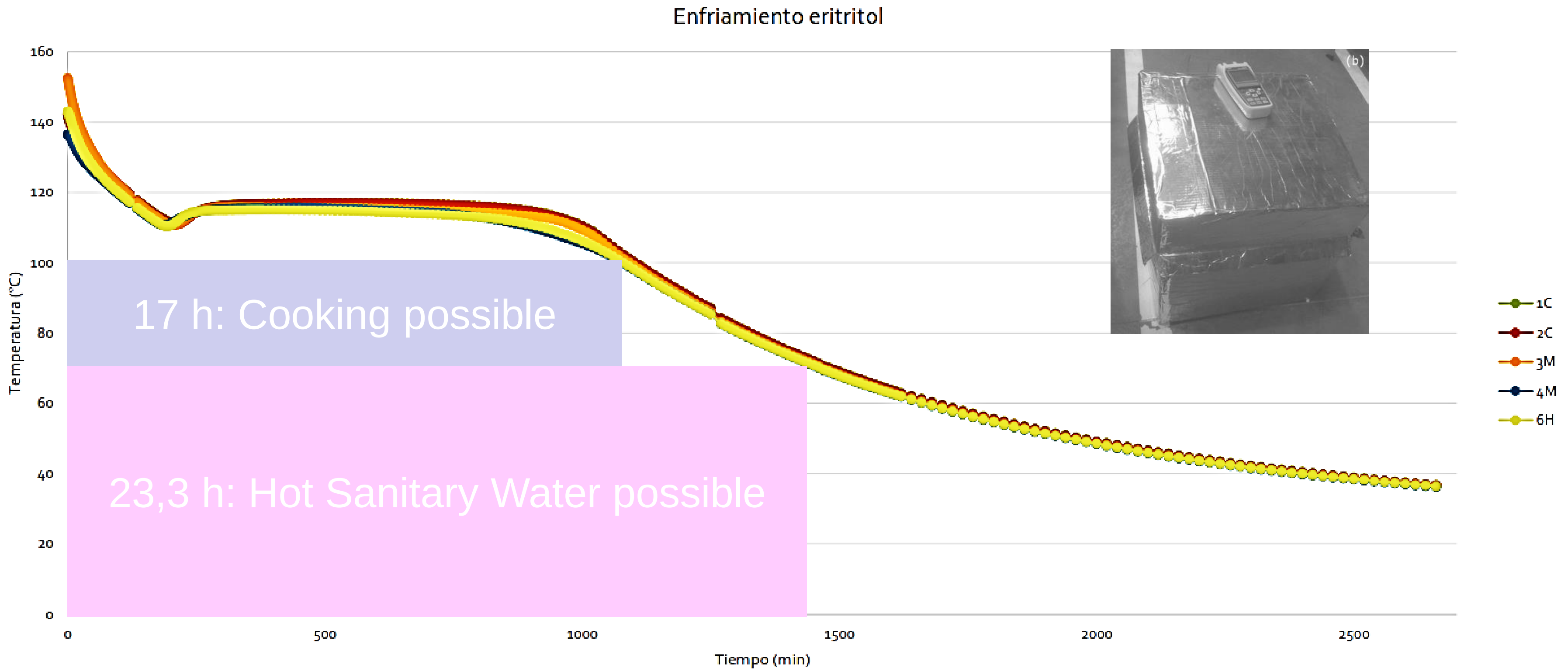
- Storage (with cooking 12-13h) and
- Delivery (dinner 20-21h and breakfast 05-06h next day).

Source: A. Lecuona et al. *Applied Energy 111, 2013, 1136–1146.*

Heat storage solar cookers

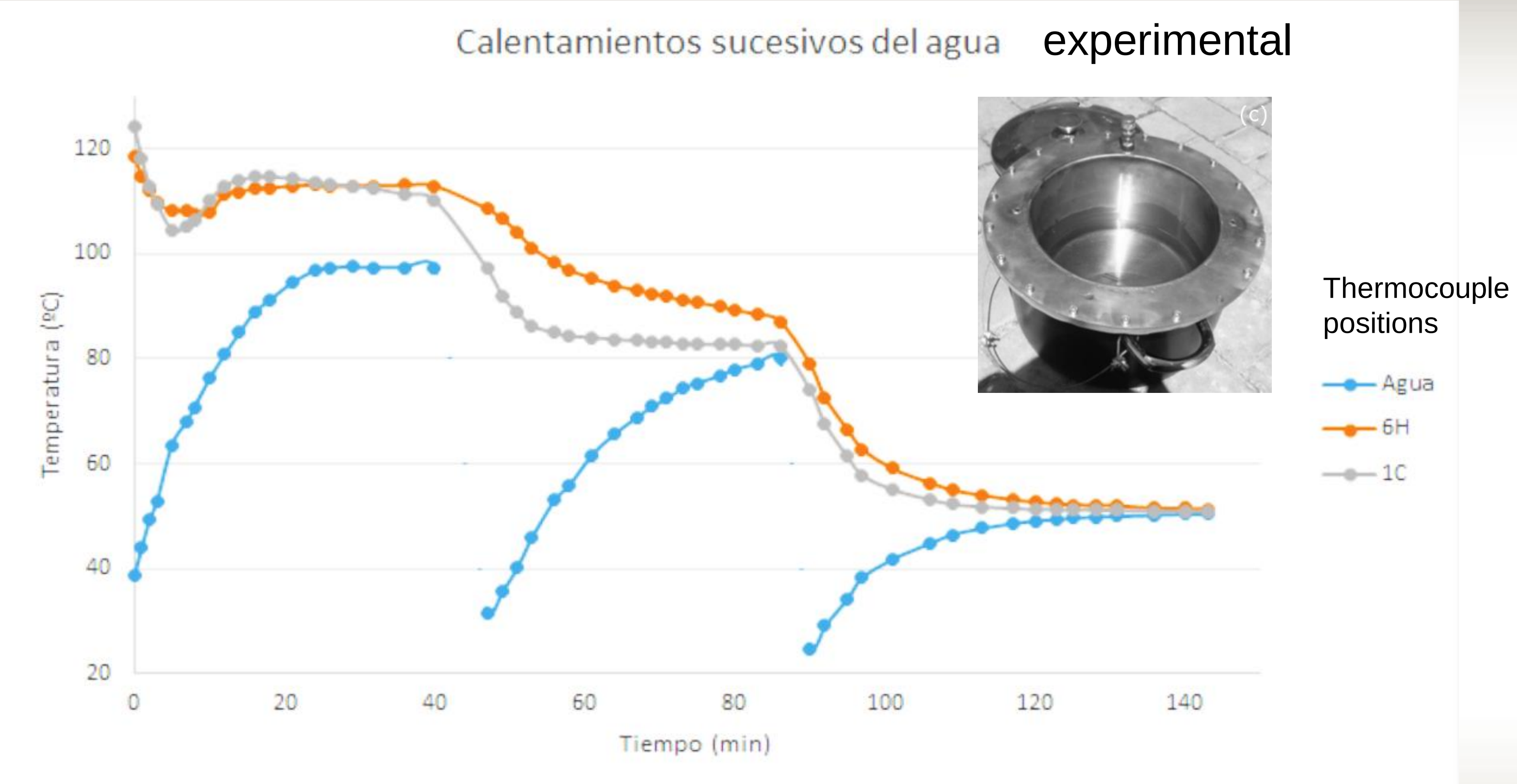
Prototype developed at Universidad Carlos III de Madrid, ITEA research group.
Result: PCM temperature during heat retention with PCM initially completely melted.
Testing result in the Master Thesis of Miriam Cabañas Martín (graduated with honors).

Curva de enfriamiento experimental



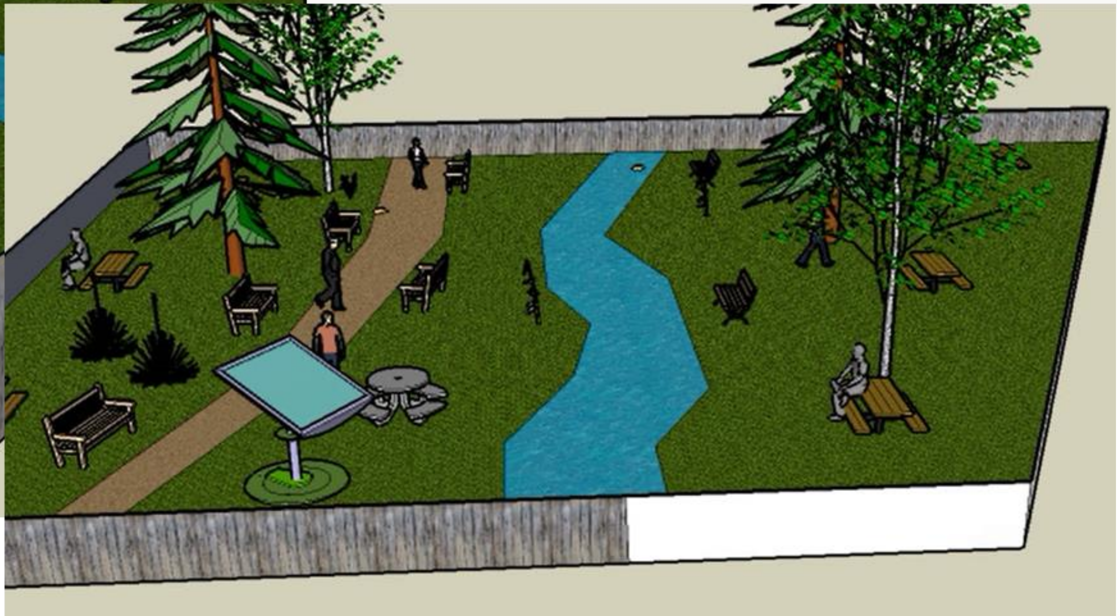
Heat storage solar cookers

Prototype developed at Universidad Carlos III de Madrid, ITEA research group.
Result: After storage, the utensil heats3 times 2 l of cold water (blue line), while the PCM cools down (grey and orange lines).



It is possible: cook lunch, dinner and breakfast next day for a family in a sunny day.
PCM used, erythritol (non-caloric sweetener).

Heat storage solar cookers



Proposal of a storing solar cooking permanently. Solar oven below the collector with additional capability of delivering hot water for cleaning. Suitable for camping, parks, beaches, communities, schools and corporations. Created by ITEA group at Universidad Carlos III de Madrid. Patent pending.

Conclusions

- Solar cooking offers some new gastronomic possibilities:
  - Cooking *Sous Vide and Slow cooking*

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Source: www.fusionchef.de

  - *Thermal cooking*

Image removed for author rights protection

Image removed for author rights protection

Source: www.thethermalcook.com

Conclusions

- Solar cookers are the most clean.
- They offer new sustainable possibilities for society.
- Energy poverty can be fought.
- New developments and applications are needed.

Thanks for your attention

Panel cooker of the funnel type using laundry scrap eyes as cover. Photo with permission: Prof. Celestino Rodrigues-Ruivo, Universidade do Algarve. Thanks for him to inspire my dedication to solar cooking, Antonio Lecuona.