

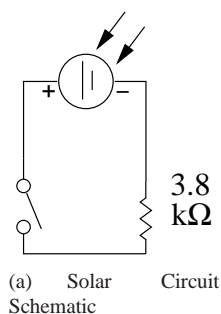
Calculating the Relative Efficiency of Solar Ovens

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Introduction

During the 2005 summer CDE II workshops, one of the activities was building solar ovens. As part of a more quantitative analysis, I built a small solar circuit that we could use to measure the relative efficiency of the solar ovens. A number of teachers requested a solar circuit for their classroom, this is the documentation for these circuits.



Switch	Measurement
ON/CLOSED	Voltage Across Resistor
OFF/OPEN	Resistance of Resistor

(b) Switch Positions for Measurements

Figure 1: The solar cell circuit

Circuit Design

The solar circuit consists of the simple design in Figure 1(a). The circuit generates about 215mV across the 3.8kΩ resistor in room lighting. The circuit has an ON/OFF switch, and it is important to have the switch in the correct position when making voltage or resistance measurements. **You cannot measure resistance in a live circuit, doing so will break most digital multimeters.** Consult Figure 1(b) for the correct switch position for measurements.

Store the solar circuit with the switch in the OFF position.

Using the Circuit

This is an example of using the solar circuit to measure the *relative* efficiency of a solar oven. Take the solar oven, a measured amount of water, a thermometer, the solar circuit, and a multimeter with clips to a sunny location. Configure the solar oven with a hanger or cradle to hold a container of water and place the thermometer into the water.¹ Set the multimeter to measure volts and clip the leads to the exposed wire on either side of the resistor. You should measure more than 0.250mV in direct sunlight. Record the time, the current voltage, and the current water temperature. Record these measurements every 1 or 2 minutes for at least 15 to 20 minutes or until the water temperature has gone up by 10°C.

¹Consult the CDE II activity write-up for all the details about constructing solar ovens and warming water with them. A digital thermometer with a submersible probe works nicely for this activity.

When your done recording your date, you should have a table like Figure 2. The steps involved for the efficiency calculations are:

1. calculate the solar power absorbed by the water
2. calculate the power per square centimeter absorbed by the solar circuit
3. calculate the normalizd power absorbed by each instrument
4. compare the solar power delivered to the water to the solar power a solar oven sized solar circuit

Time	Temperature °C	Voltage (V)
1:44	28.1	1.021
1:46	30.6	1.000
1:48	32.6	0.989
1:51	34.7	1.014
1:59	36.9	1.025
2:02	37.4	1.003
2:05	37.7	1.006

Figure 2: Example Data for 53 grams of Water

Power Absorbed by Water

Recall that power is a ratio:

$$Power = \frac{Energy}{Time}$$

The energy absorbed by the water raised it from 28.1 to 37.7 °C over a total of 21 minutes (1:44 to 2:05) or 1260 seconds.

It takes 1 calorie of heat to raise 1g of water 1°C;² there are 4.185 Joules of energy in 1 calorie. This turns out to be one big *dimensional analysis*:

$$\begin{aligned} \text{Energy for 1g Water} &= \frac{37.7 - 28.1^{\circ}\text{C}}{1} \cdot \frac{1\text{calorie}}{1^{\circ}\text{C}} \cdot \frac{4.185\text{Joule}}{1\text{calories}} \\ &= 40.2\text{J} \\ \text{Energy for 53g Water} &= 53 \cdot 40.2\text{J} \\ &= 2129\text{J} \end{aligned}$$

If we really pay attention to significant digits, this would be 2130J. This energy was absorbed over 1260 seconds, so the solar power absorbed by the water (in *Watts* = $\frac{\text{Joule}}{\text{second}}$):

$$\begin{aligned} \text{Solar Power absorbed by Water} &= \frac{2129\text{J}}{1260\text{s}} \\ &= 1.69\text{W} \end{aligned}$$

Power Absorbed by Circuit

To calculate the power absorbed by the solar circuit, we use the equation:³

$$Electrical\ Power = \frac{V^2}{R}$$

The resistor used in the solar circuit for the workshop was 22Ω, and the average voltage across the resistor (during the time the water was heating) was 1.005V. So, the solar power absorbed by the circuit was

$$\text{Solar Power absorbed by Circuit} = \frac{1.005^2}{22\Omega} = 0.04591\text{W}$$

Scale Circuit Size to Oven Size

But it is unfair to compare absorbed power of the solar oven to the circuit without accounting for the difference in the size of the two instruments. The solar panel (used during the workshop) was only 4cm x 4cm; while the solar oven had a projected area of nearly 40cm x 30cm. It stands to reason that the solar oven would absorb

²technically, at 15°C

³derived from $P = VI$; $I = \frac{V}{R} \rightarrow P = V \frac{V}{R} = \frac{V^2}{R}$

more energy, more rays of sunlight enter the solar oven than the solar panel. We need to scale or *normalize* the power absorbed by each instrument. We will calculate the ratio:

$$Efficiency = \frac{\text{Power}}{\text{cm}^2}$$

The efficiency of the solar circuit was therefore:

$$\begin{aligned} Efficiency_{circuit} &= \frac{0.04591\text{W}}{4 \cdot 4 \text{ cm}^2} \\ &= 0.002870\text{W}/\text{cm}^2 \end{aligned}$$

Measuring the exposed area of the oven is not as easy. First, the area we want to measure *is not* the area of the aluminum foil on the inside of the oven – this would overestimate the exposed area of the oven. We want to measure the area through which the sun's rays passed *into* the solar oven. One way to do this is to simply *overestimate* and use the area of a rectangle that bounds the solar oven top. Better than this would be to draw the outline of solar oven's top directly onto cm x cm grid paper and count the total area. Yet another technique would be to trace the outline of the solar oven's top and begin adding up the areas of non-intersecting rectangles (see Figure 3). During the workshop, we measured a 40cm x 30cm bounding rectangle and then estimated that the projected area was about 80% of this rectangle's area.

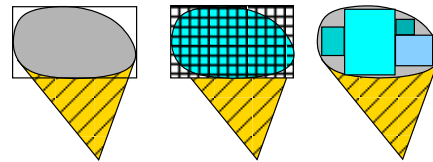


Figure 3: Measuring the Oven Area

$$\begin{aligned} Efficiency_{oven} &= \frac{1.69\text{W}}{40 \cdot 30 \cdot 0.80 \text{ cm}^2} \\ &= 0.00176\text{W}/\text{cm}^2 \end{aligned}$$

Comparison

The solar oven, by these calculations, was therefore $\frac{0.00176}{0.00287} = 61\%$ as efficient as the solar panel.

Final Words

The solar circuits provided to the teachers have different solar panels and different sized resistors than the circuit used during the workshop. The switch on the circuit is provided so that students can simply measure the resistance of the circuit you have and they will definitely want to measure the size of the solar panel on their own. Different solar panels were used primarily due to cost, I found them online as 'recycled' from some previous use, so you may end up in the classroom with drastically different values for power absorbed (the solar panels I used for the workshop circuit were probably higher quality). Don't be surprised if solar ovens built by the students show a *better* power absorption than the circuit. Be sure the students measure the correct values and perform the correct dimensional analysis, and the values you get should be reasonably valid.