Determining the Efficiency of a Typical Home Rooftop Photovoltaic System

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The number of communities in the United States working to stimulate interest in environmental sustainability has been increasing significantly over the past few years. One of the pieces of this sustainability puzzle is the use of home rooftop photovoltaic (PV) systems, which are far less polluting than the conventional fuel mixes of coal, oil, nuclear, and gas. A majority of these home PV systems are rated at less than 10 kW. Nevertheless, their production is high enough to significantly reduce the amount of electrical energy that a home would otherwise draw from the traditional electric grid. This reduction is particularly important considering the fact that appliances including air conditioners, refrigerators, clothes washers, and dryers are large users of electricity.

Manufacturers of PV systems are constantly working to improve the efficiency of these systems, and often compete on the basis of how efficient their systems are. Efficiency is defined as the ratio of the electrical energy produced by the PV system to the total electromagnetic energy incident on the solar panels making up the PV system. Home owners with solar PV systems can also use efficiency as a way to determine if their system is performing according to the manufacturer's claim. Lower than expected efficiency calculations may also indicate a problem with one or more solar panels. Finally, many manufacturers of solar panels warrant that their panels will see a degradation of a most 20% in efficiency after 25 years of operation. Home owners who monitor efficiency over time can check the validity of this claim.

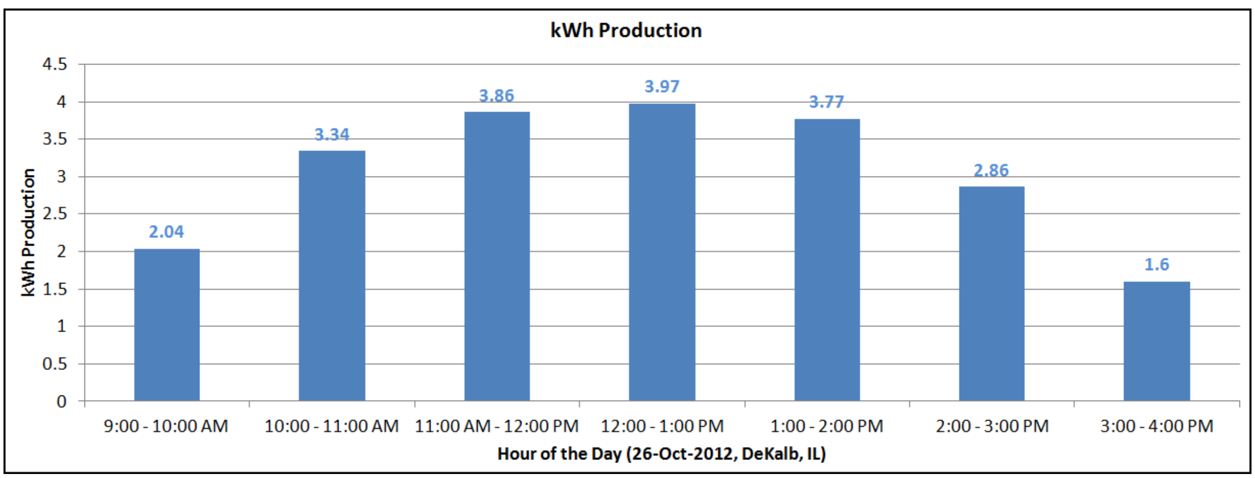
The number of students whose parents have installed home PV systems has no-doubt increased over the past several years. The Vernier Pyranometer provides these students with a convenient means for determining the efficiency of their home PV system, *without the need to measure current and voltage delivered by the PV system*. The reason that current and voltage measurements are not required is because most home PV systems include a web-based monitoring system that informs the home owner of the number of kWh generated during each hour of the day. The only other things the student needs are the Vernier Pyranometer, an appropriate interface such as LabQuest® 2, dimensions of the solar panels, and the number of panels on the roof. Panel dimensions can be obtained without the risk of injury from climbing on the roof by consulting the manufacturer's specifications on the web. Manufacturer specifications also include the efficiency rating of the panels, which the student can use to compare with his/her pyranometer-based calculations.

PROCEDURE

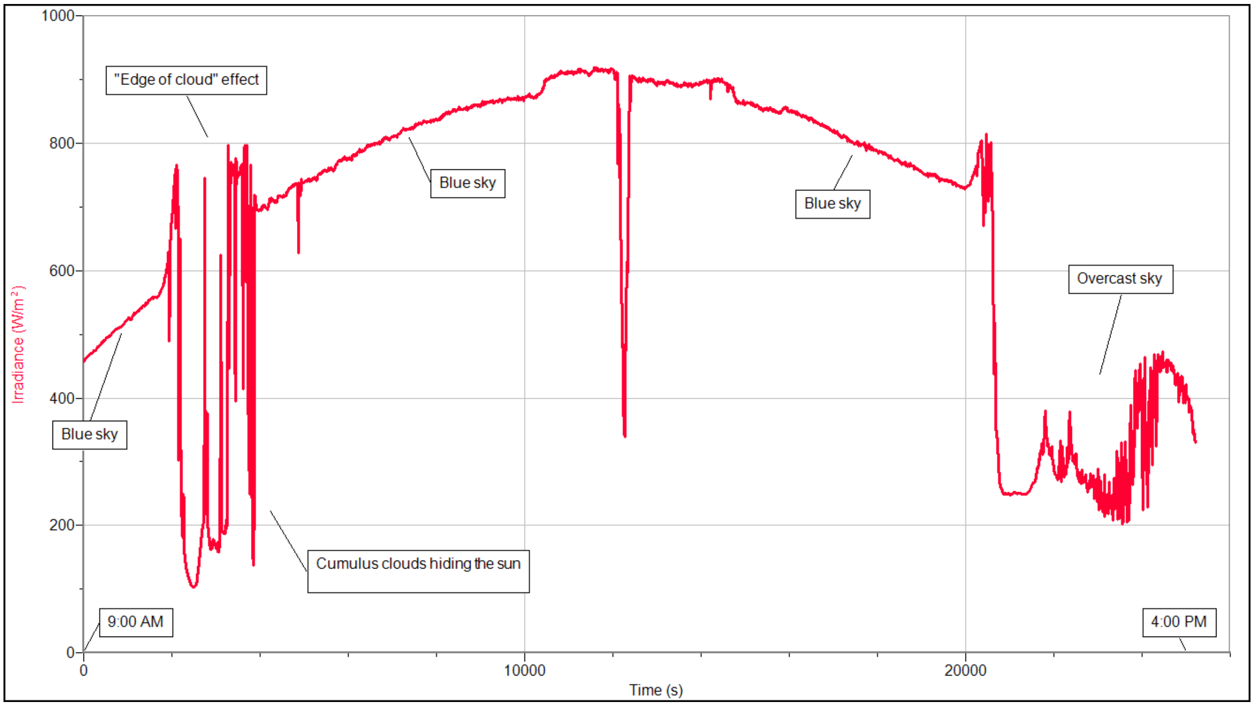
With the above discussion in mind, the efficiency of the PV system (total capacity of 5 kW) shown in the picture (home of Richard Born) was measured. The PV system consists of 16 solar panels facing south, each panel being 1.046 m wide by 1.559 m high. The area of each panel is, therefore, $1.046 \text{ m} \times 1.559 \text{ m} = 1.6307 \text{ m}^2$, giving a total area of $16 \times 1.6307 \text{ m}^2 = 26.09 \text{ m}^2$.

RESULTS

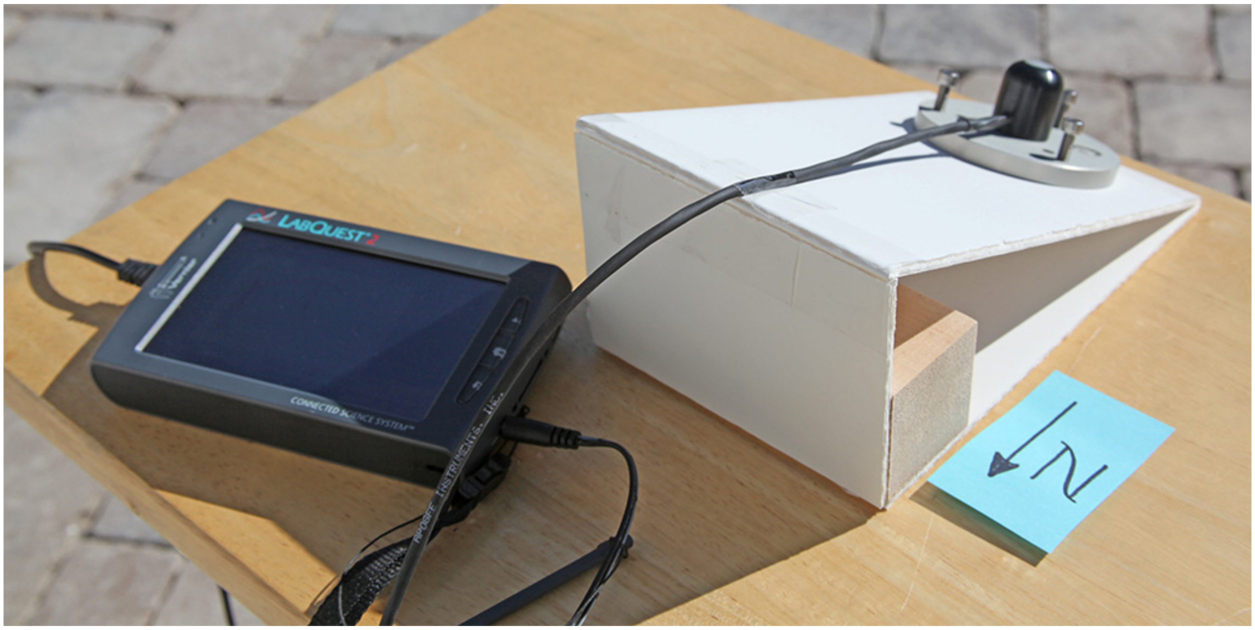
The Microsoft® Excel® chart shown below (representing data from 26-October-2012) is similar to that produced by the web-monitoring system, which is provided by the PV system manufacturer. The actual chart from the web is not provided here to keep the manufacturer anonymous. Data prior to 9:00 a.m. was not used as there was a shadow on the panels due to the higher roof portion to the east of the panels—this shadow was not on the Pyranometer that was on the ground. Data after 4:00 p.m. was not used as there was a shadow on the panels from some distant trees in the west—this shadow was not initially on the Pyranometer. Therefore, the PV system's efficiency was calculated for each of seven hours of the day from 9:00 a.m. until 4:00 p.m. The day was a cool, late October day in DeKalb, IL, with temperatures ranging from 39°F at 9 a.m. to 49°F at 4 p.m., and with wind speeds in the single digits. When solar panel manufacturers compute panel efficiency, it is done at 1000 W/m^2, and a cell temperature of 25°C, which happens when the ambient air temperature is approximately 10°C (50°F). So the air temperature the day of the experiment was reasonably close to the desired value.



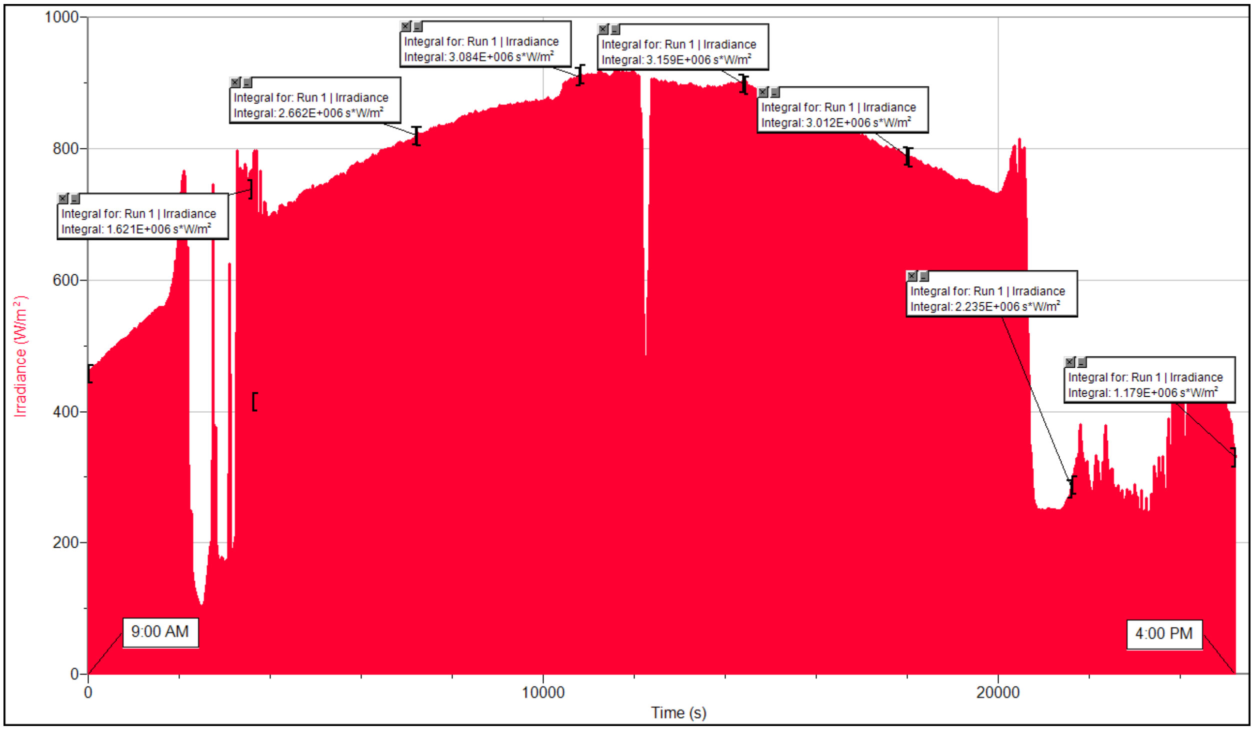
The Logger *Pro* chart below shows irradiance in W/m^2, as was obtained from the Vernier Pyranometer, with readings recorded every 10 seconds. Of particular interest is the region labeled “Edge of cloud effect” during the first hour, shortly after 9:00 a.m. During this time frame, some fair-weather cumulus clouds occasionally hid the sun. The interesting thing is what happens when the cloud is just starting to hide the sun and again when it is leaving the sun. The irradiance actually increases above that of the normal, sunny, blue sky! This is caused by the refraction of light on the edge of the cloud, concentrating sunlight while the edge of the cloud passes by. The combination of direct sunlight and refracted light boosts the irradiance above the normal blue sky value.



The picture on the next page shows the Pyranometer, with the cord pointing north as required. A leveling plate is used, in this case, not to level the Pyranometer, but rather to provide a solid object on which to mount the Pyranometer with the screw provided by Vernier. When manufacturers determine the efficiency of their panels, they mount a Pyranometer so that its axis is perpendicular to the plane of the panels. That is why the picture shows the Pyranometer resting on an incline constructed to be at the same angle as the panels on the roof. Ideally, the Pyranometer should be mounted *on the roof* with the panels (with neither item shading the other) so that it experiences nearly the same light conditions as the solar panels. However, as a safety measure and as a convenience for student experimentation, the Pyranometer is placed on a nearby table on the ground. (Note that there are some nice iPhone® apps that turn your iPhone into a tilt-meter, so you can easily measure the angle of the panels on the roof by resting the iPhone on the surface of a panel—but be careful if you climb a ladder to do this!)



Logger *Pro* was then used to compute the total electromagnetic energy delivered by the sun to the panels for each of the seven hours under investigation. The chart below shows this in watts-seconds per square meter for each of the seven hours (9:00 a.m. through 4:00 p.m.), obtained as the area under the Irradiance *vs*. Time chart from the Pyranometer.



Finally, the table shown below summarizes the results of this investigation.

Time of Day	W*s/m^2	kWh/m^2	Solar Energy Incident on the Panels (kWh)	kWh Production from the Web Monitoring System	kWh Production BEFORE AC/DC Wiring and Inverter Losses	PV System Efficiency (%)
9 - 10 AM	1,621,000	0.4503	11.75	2.04	2.22	18.88
10-11 AM	2,662,000	0.7394	19.29	3.34	3.63	18.82
11 AM - 12 PM	3,084,000	0.8567	22.35	3.86	4.20	18.77
12 - 1 PM	3,159,000	0.8775	22.89	3.97	4.32	18.85
1 - 2 PM	3,012,000	0.8367	21.83	3.77	4.10	18.77
2 - 3 PM	2,235,000	0.6208	16.20	2.86	3.11	19.19
3 - 4 PM	1,179,000	0.3275	8.54	1.60	1.74	20.35
					Average Efficiency→	**19.09**

W*s/m^2 = Integrals from the Logger *Pro* Irradiance *vs.* Time chart

kWh/m^2 = Previous column but with seconds converted to hours and watts converted to kW

Solar Energy Incident on Panels (kWh) = Previous column multiplied by the total area of the solar panels (26.09 m^2)

kWh Production from the Web Monitoring System = Data from the solar panel manufacturer web-monitoring system. This represents kWh's that are usable by the homeowner, either to power the home or send to the grid.

kWh Production BEFORE AC/DC Wiring and Inverter Losses = Previous column divided by 0.92. Inverter losses are typically about 5%. AC wiring loss is about 1%, while DC wiring loss is about 2%.

PV System Efficiency (%) = Ratio of kWh Production before AC/DC wiring and inverter losses to solar energy incident on panels, expressed as a percent.

CONCLUSION

The average of the seven hourly efficiency values is about 19.1%, which compares favorably to the manufacturer's rating of 19.5%. This investigation has assumed that the spectral range and response of the Vernier Pyranometer is the same as that of the solar panels.

As a check on repeatability, the investigation was performed again the next day (27-October-2012). This day was a blue-sky day (temperatures similar to the previous day), except for a little haziness the last hour of the investigation. The table shown below summarizes the results of this second investigation. The hourly PV system efficiency values are quite similar to those of the previous day, all between 18% and 19%. The only exception was that the efficiency was noticeably higher during the last hour of the investigation on the first day, when the sky was overcast. As a result, it is recommended that investigations on PV system efficiency using the Vernier Pyranometer not be done on overcast days. Occasional cumulus clouds resulting in edge-of-cloud effect incidents, however, do not seem to cause large deviations in hourly efficiency calculations.

Time of Day	W*s/m^2	kWh/m^2	Solar Energy Incident on the Panels (kWh)	kWh Production from the Web Monitoring System	kWh Production BEFORE AC/DC Wiring and Inverter Losses	PV System Efficiency (%)
9 - 10 AM	1,966,000	0.5461	14.25	2.48	2.70	18.92
10-11 AM	2,662,000	0.7394	19.29	3.33	3.62	18.76
11 AM - 12 PM	3,056,000	0.8489	22.15	3.79	4.12	18.60
12 - 1 PM	3,175,000	0.8819	23.01	3.91	4.25	18.47
1 - 2 PM	3,044,000	0.8456	22.06	3.74	4.07	18.43
2 - 3 PM	2,622,000	0.7283	19.00	3.23	3.51	18.48
3 - 4 PM	1,542,000	0.4283	11.18	1.91	2.08	18.58
					Average Efficiency→	**18.60**

ACKNOWLEDGEMENT

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