The Availability and Statistical Properties of Ambient Light for Energy-Harvesting for Wearable Sensor Nodes

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***Abstract*—Data for the availability of ambient light for a wrist-attached senor node was gathered. The average energy harvest totaled 0.074 J/cm^2/day when using a 1.8% efficiency, 0.6V DSSC (dye-sensitized solar cell) and 0.48 J/cm^2/day when using a standard 16% efficiency, 0.65V mono-crystalline Si cell. The irradiance averaged for both indoor and outdoor activity of office employees was found to be equivalent to 0.78 W/m^2 of solar spectrum light. At lower irradiation, the DSSC produced a higher open-circuit voltage but harvested less power than the Si solar cell.**

Keywords - solar cell; sensor network; sensor node; wearable; energy harvesting

I. INTRODUCTION

Solar power may be a viable solution for powering wearable sensor nodes. However, there is a scarcity of data on the actual harvestable power for wearable sensor nodes using photovoltaic cells. The actual power depends on the following factors:

Primary (light-related) factors:

- The total irradiance (W/m^2)
- The angular distribution of light from light sources
- The spectrum of the light sources
- The daily variability of the light sources
- The seasonal variability of light sources

Secondary (harvester-related) factors:

- Type of solar cell
- Lifestyle of wearer
- Harvesting location on body

Because of the many unknowns, solar cells have been considered too unpredictable to serve as a power source for wearable sensor nodes without using additional power management methods [1] [2]. Even for the total irradiance metric, wide and conflicting ranges have been reported, as summarized in Table 1. Therefore, experimental data on solar energy harvesting for wearable sensor nodes attached to the users' wrists is provided in this paper. The reason irradiation data for wearable nodes has not been gathered before is because of the obtrusiveness and unreliability of past wearable sensor nodes. Previous sensor nodes required frequent maintenance, charging, and data downloading, thus affecting behavioral patterns of the person wearing a node. Because the behavioral patterns affect the irradiation measurements, a smaller, more autonomous sensor node was necessary for unbiased measurements.

Recently, there have been several attempted implementations [3][4][5] of a wearable sensor node system utilizing solar cells. Therefore, a detailed assessment of the properties of ambient light is necessary for the proper selection of solar cell type – either high-efficiency at high irradiation level (Si cell) or more stable at lower irradiation and lower efficiency (DSSC).

TABLE I. PREVIOUSLY REPORTED IRRADIANCE LEVELS

Parameters		
Sensor node type	***Indoor irradiance, W/m^2***	***Outdoor irradiance, W/m^2***
Building management [6]	6.7	500
Wearable [7][8]	0.4-38	10-100
Building management[9]	1-5	-
Wearable[10]	1	1000

In this paper, Section II describes measurement conditions and algorithms used for data processing. Section III presents the irradiance measurement results and calculations of the harvestable energy for the DSSC and Si solar cells. Section IV concludes that although the Si solar cell was more effective in overall energy harvesting, the DSSC cell provides more reliable energy harvesting.

II. MEASUREMENT PROCEDURE

The measurement of light levels was done using the Indy2050 DSSC [11] attached to the wearable sensor node prototype LM03 provided by the University of Hyogo. The location of the experiment was Himeji, Japan. A photograph of the sensor node with solar cell is provided in Figure 1. The solar cell was connected directly to the voltage input of the ADC of the sensor node. To convert photocurrent (and hence the irradiance) to a voltage signal, a resistor was connected in parallel with the solar cell.

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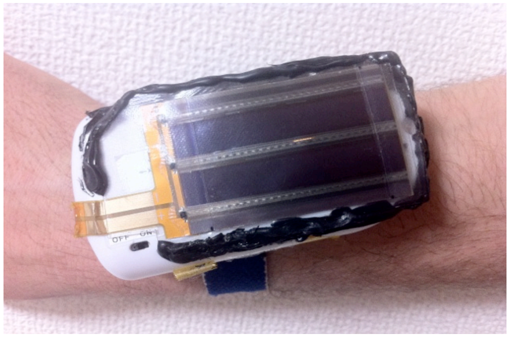

Figure 1. Photo of the measurement setup.

Because the ADC embedded in the sensor node had insufficient dynamic range, two setups were prepared: first with a 100 Ohm resistor, giving a measurement range of 1 to 400 W/m^2, and second with a 10 kOhm resistor, giving a measurement range 0.01 to 4 W/m^2. The two setups were worn by different users (both working in the same lab), and were swapped between users twice per week. A larger number of experimental setups was prepared, but severe hardware problems of the highly-experimental LM03 sensor node resulted in only two setups being operational. The ADC was sampled 20 times per second, and data was stored on a MicroSD card inside the sensor node. Ten days of recorded data (from April 1 to April 11) were downloaded to the PC on April 12, 2012 and processed. Processing included the removal of anomalous data (whenever time stamp showed discontinuity due sensor node being shut down) and simple averaging of samples down to a data rate of 1 sample per second. Also, the data from both setups was merged into a single dataset using the measured photocurrent-to-voltage gain and the ADC's offset voltages. The solar cell efficiency versus irradiance for the Indy2050 DSSC solar cell and typical Si cell was measured before starting energy harvesting measurements. The data on the efficiency of the Indy2050 solar cell and typical Si cell (extracted from [1]) is shown in Figure 2.

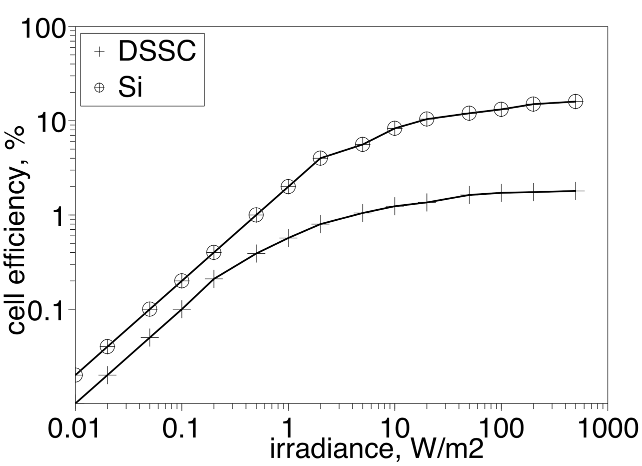

Figure 2. Efficiency of the DSSC and Si cells versus irradiance.

Power efficiency of the solar cell is not the only important property for energy harvesting. The open circuit voltage is also important. Since dark current is the dominant cause of efficiency loss, the open-circuit voltage drops to half of the nominal value at a corresponding power efficiency of 25% of nominal. At low irradiation levels, the DSSC cell [11] produces higher open-circuit voltages (0.6V), enabling the use of less demanding power converters in the sensor node. Below that point, energy harvesting for the solar cells becomes complicated because the supplied voltage becomes insufficient to drive CMOS low-leakage transistors above their threshold voltage. For the DSSC, the voltage-limited harvesting threshold was found to be 0.7 W/m^2 compared to 2.0 W/m^2 for the mono-crystalline Si cell.

III. MEASUREMENT RESULTS

The raw irradiance data averaged over 10 days was normalized for 1-day intervals (86,400 seconds) with a sampling rate of 1 sample/s (see Figure 3) and binned using thresholds listed in Table 2. The data from Table 2 is plotted on Figure 3. The probability peak at 0.2-0.5 W/m^2 most likely corresponds to indoor conditions, while the smaller peak at 2-5 W/m^2 may be attributed to outdoor light. The averaged time series of the irradiance can be seen in Figure 4. The peak at about 9am corresponds to transit to the workplace. The broad peak about midday corresponds to daylight leaking through the office windows and to lunchtime activity, and the peak around 5pm corresponds to the transit from the workplace to home.

TABLE II. TABULATED IRRADIANCE DATA

Bin #	**Parameters**		
	Min. irradiance, W/m^2	***Max. irradiance, W/m^2***	***Seconds/day***
1	0	0.01	36776
2	0.01	0.02	54
3	0.02	0.05	113
4	0.05	0.1	286
5	0.1	0.2	5011
6	0.2	0.5	28681
7	0.5	1	6039
8	1	2	3002
9	2	5	3344
10	5	10	1916
11	10	20	819
12	20	50	323
13	50	100	35
14	100	200	0
15	200	500	0

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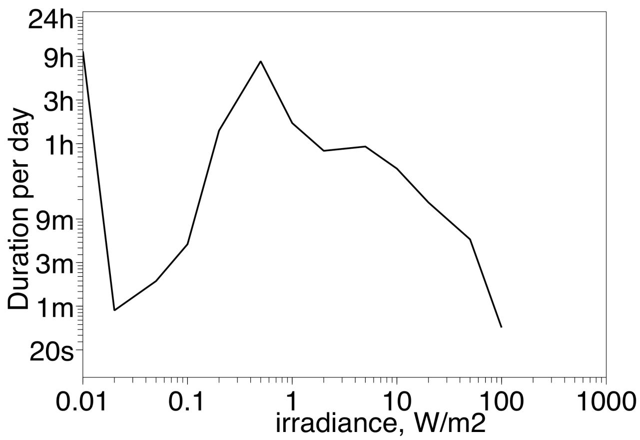

Figure 3. The probability distribuiton of irradiance.

Multiplying the probability distribution from Figure 3 with the geometric average of the power flux (irradiance) in a given bin results in a new metric: the harvestable energy per irradiance bin. Integrating the harvestable energy per irradiance bin results in the cumulative harvestable energy metric. This metric is useful if it is necessary to decide at which irradiance level the solar battery should start harvesting and to determine what losses are expected from not harvesting at lower irradiance levels. The harvestable energy and cumulative harvestable energy plots are shown in Figure 5. From Figure 5 it is shown that 99% of the harvestable radiant flux occurs at irradiances above 0.2 W/m^2 and 50% occurs at irradiancies above 5 W/m^2.

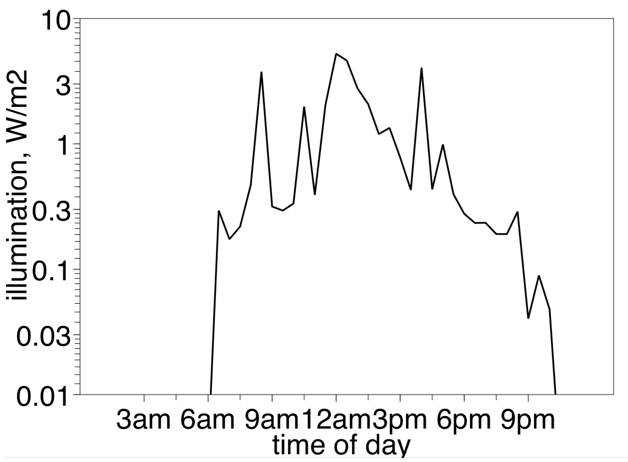

Figure 4. Daily variation of the irradiance.

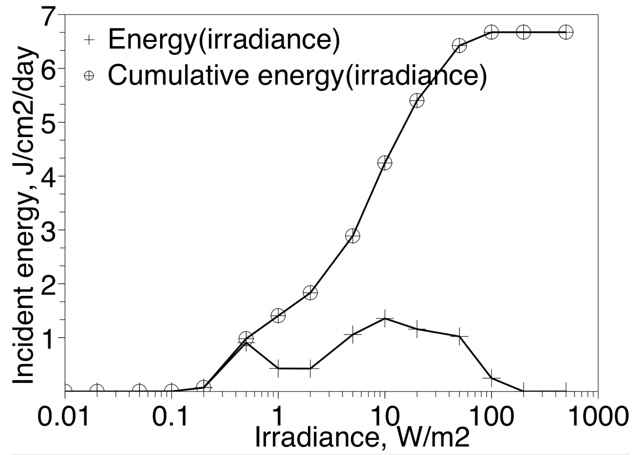

Figure 5. Harvestable energy and cumulative harvestable energy.

Finally, the effect of the reduced efficiency of solar cells at lower irradiance levels should be taken into account. Multiplying solar cell efficiency from Figure 1 by the harvestable energy from Figure 5 results in harvested energy as a function of irradiance. Figure 6 shows that because of the low performance of existing solar cells in low light conditions, most energy is harvested at irradiance 10-50 W/m^2. The DSSC cell used (designated by maker as an indoor energy harvester) performs more consistently at various light levels compared to Si cell, but it still fails to harvest energy efficiently at irradiation range 0.2-0.5 W/m^2 corresponding to typical indoor lighting conditions.

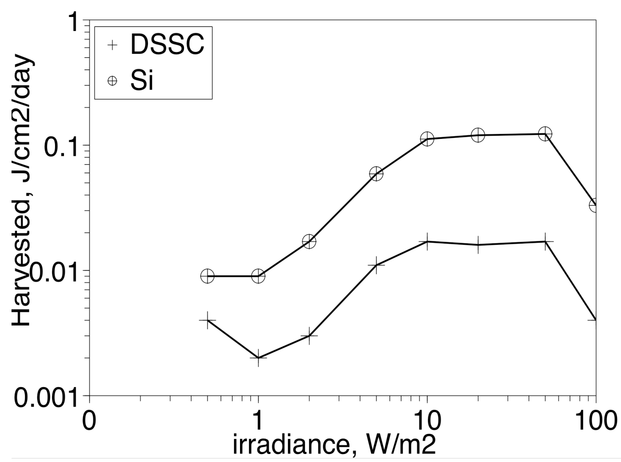

Figure 6. Harvested energy as function of irradiance.

IV. CONCLUSION

The parameters of harvestable light for wearable sensor nodes worn on the wrist of a typical office worker were measured. Harvestable solar energy for the DSSC and mono-crystalline silicon solar cell was estimated. The results are written in Table 3.

TABLE III. SUMMARY OF THE AMBIENT LIGHT ENERGY HARVESTING FOR THE WEARABLE SENSOR NODE

Parameters	Values
Indoor irradiance, W/m^2	0.2-0.5
Outdoor irradiance, W/m^2	2-5
Average irradiance on wrist, W/m^2	0.78
Energy harvested with DSSC [11], $J/day/cm^2$	0.074
Energy harvested with 16% efficient Si cell, [1] $J/day/cm^2$	0.48

For the tested DSSC solar cell, average power available at the solar cell terminals was 7.7uW (for cell area of 9 cm^2). Because the LM03 sensor node does not have any facility for power conversion, estimation of the conversion efficiency and storage efficiency was not attempted. Typical conversion and storage efficiency reported in literature was 11-18% [12].

The authors are continuing to gather data in order to reduce random errors and ultimately to acquire the dependence of the harvested energy on the season of year.

The authors believe that DSSC is more promising for indoor light energy harvesting. The important property of DSSC is the ability to deliver high voltages at low irradiation levels. Harvesting energy at low levels of irradiation reduces the probability of sensor node brownout, because low-light conditions (0.2-0.5 W/m^2) are very common for a typical office employee lifestyle (see Figure 2). Therefore, DSSC-based sensor node may have a smaller, cheaper battery subsystem. To more fully utilize energy from indoor lighting, further effort is necessary to reduce the dark current by 65% to 75% and simultaneously increase the efficiency of the commercially available DSSC to at least 8%.

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