JOURNAL OF
EMERGING INVESTIGATORS

Article

Differences in Reliability and Predictability of Harvested Energy from Battery-less Intermittently Powered Systems

Nithya Sampath[1], Bashima Islam[2], Shahriar Nirjon[2]

[1]North Carolina School of Science and Mathematics, Durham, North Carolina

[2]Department of Computer Science at the University of North Carolina at Chapel Hill, Chapel Hill, North Carolina

SUMMARY

Solar and radio frequency harvesters serve as a viable alternative energy source to batteries in many cases where the battery cannot be easily replaced. However, energy harvesters do not consistently produce enough energy to sustain an energy consumer; thus, both the energy availability and execution of the energy-consuming process are intermittent. By simulating intermittent systems with large-scale energy demands using specifically-designed circuit models, the harvested voltage and other parameters such as the voltages across the capacitor and the load were determined. We plotted these data, for both harvested solar and harvested radio frequency energy, to make probability plots depicting the likelihood that energy will be available now given that N number of energy events have occurred. Additionally, we designated a metric as the η-factor, which was calculated from these probability plots for the solar and radio frequency data to quantify the reliability of the power source. The η-factor for harvested solar energy was statistically significantly higher than the η-factor for harvested radio frequency energy, meaning harvested solar energy was more consistently available than harvested radio frequency energy. Finally, we collected data to determine the effects on the output voltage of various obstacles between the radio frequency transmitter and receiver. We found that obstacles like metal and people caused a more pronounced drop in the amount of energy harvested when compared to other obstacles like foam or wood. Quantifying the reliability of different harvested sources would help in identifying the most practical and efficient forms of renewable energy; determining which obstacles cause the most obstruction to a signal can aid in the strategic placement of harvesters for maximum energy efficiency.

INTRODUCTION

Battery-powered devices are not suitable in many systems because of the need to frequently replace the battery. One example of this problem would be an implantable device, such as a pacemaker, whose battery would need to be replaced through surgery. Harvested energy from solar radiation, radio frequency, or other sources, such as heat, are an attractive alternative to batteries in such systems. However, since energy is not consistently available from these sources (for example, when a cloud passes in front of the sun, the energy collection is interrupted), the power availability is characterized as intermittent. There are two components to these intermittently-powered systems: the energy harvester and the energy consumer. The energy consumer uses up the energy captured by the energy harvester, and requires a designated amount of power to turn on. There is often a discrepancy between the amount of energy required to power the consumer and the amount of energy supplied to the system by the energy harvester, so the device consuming energy goes through cycles of being turned on and off **(Figure 1)**. Thus, the sporadic energy harvesting pattern leads to an interrupted, or intermittent, execution of an energy-consuming software (1). Most renewable energy sources like solar and wind power plants have an intermittent power output (2).

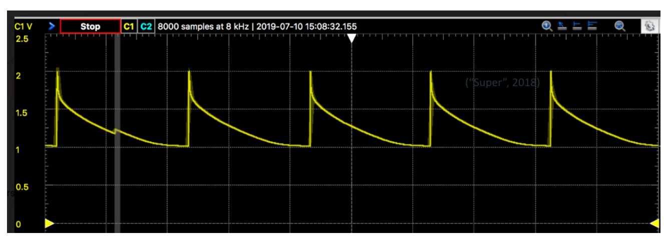

Figure 1: Graph of Voltage vs. Time for an energy consuming device. The device turns on when it reaches a threshold voltage — in this graph, the threshold voltage is approximately 2 Volts — and begins to consume power at a rate greater than the rate at which harvested energy is supplied to the circuit. When energy levels in the circuit drop enough — in this graph, when the voltage is approximately 1 Volt — the device shuts off, the energy is allowed to increase again from the harvested power supply, and the cycle repeats.

An energy event is defined as the generation of a specific amount of energy in a given time interval. In this investigation, we defined an energy event as the generation of enough energy to turn on the energy consumer (a microcontroller board), which was 2.8 Volts, over a period of five minutes. To say that N energy events have occurred is the equivalent of saying it has been 5N minutes since the energy consumer last shut off. We chose the specific time designated for an energy event in this investigation to facilitate the testing of energy available in short bursts and to allow for the data to be more easily observed when the probability of an energy event decreased toward zero. Additionally, burstiness is the property of consistency over short periods of time, and it is a feature we will be looking for in the voltage data. Finally, energy neutrality involves the introduction of an intermediate stabilizing power supply in the circuit (3). In this investigation, the energy neutrality device was a capacitor, which is integral to the circuit. Without the capacitor, energy flowing directly from the harvester to the consumer would cause the execution of the software by the consumer to be shut off instantly in the absence of an energy event. The capacitor allowed for energy to be stored and slowly released into the consumer. This slow release through the capacitor highlights how intermittent energy sources do not provide consistent energy output to the consumer despite the stability of an energy neutrality device.

There were several goals for this investigation. The first was to model a large-scale energy harvesting system on a smaller scale using small solar harvester and radio frequency harvester units. The second goal was to test the burstiness of energy by constructing graphs of the likelihood of power availability at any given moment, given that N number of consecutive energy events had already occurred. This experiment was conducted with the hypothesis that all harvested energy will be available in short bursts, consistent over short periods of time. The third goal was to compare the reliability of different harvested sources in terms of their power availability using the η-factor. The η-factor is a calculated metric between 0 and 1 which uses the Wasserstein metric to compare the experimental energy harvesters to a random energy harvester, for which energy events are independent – this is not the case for real energy harvesters, for which energy events are conditional and dependent upon each other. We expected this experiment to show that no source will be as reliable as wall power, which has an η-factor of 1.0 but that solar energy will have a higher η-factor than radio frequency (RF) energy and thus be more reliable. The final goal was to determine how different obstacles between an RF transmitter and receiver affect the amounts of harvested energy at various distances, with the hypothesis that obstacles such as people would allow for less energy to be harvested than obstacles such as foam or wood, which were the least dense of our set of obstacles. We considered obstacles only for harvested RF energy, not for harvested solar energy; in the real world, solar energy is typically harvested without obstruction as the solar panels are placed in such a way to maximize the amount of sunlight received. In contrast, RF harvesters, which use cell towers and WiFi routers as sources, face much more obstruction, including from people, cars, or even objects around a house. These questions have great relevance at this time as the world begins to look towards renewable energy sources, such as solar, to replace fossil fuels. Investigating the patterns of energy availability and consumption allows us to predict when energy will become available or unavailable and allows for the successful scheduling of tasks or execution of processes.

RESULTS

One goal of the investigation was to test the hypothesis that harvested energy has a high amount of burstiness by constructing and analyzing graphs of the likelihood of energy availability. The idea that energy was only available in short bursts was suggested by earlier data collected in our lab, but the data collection did not occur for long enough to draw supported conclusions. To determine whether or not the energy-consuming device was turned on and how much energy was being supplied to the circuit, we recorded voltage data at various locations in the circuit, including the input, the capacitor, and the load. The data gathered for solar **(Figure 2)** and radio frequency **(Figure 3)** supported the hypothesis of the burstiness of the harvested energy, since the voltage does not increase and decrease rapidly over the majority of the graph. The correlation between probability and the number of energy events started decreasing around N = 70 **(Figure 2)**. This is consistent with the definition of an energy event designated by our lab, since 70 energy events, using the designation of 5 minutes per energy event, would be about 5.83 hours, approximately the length of time for which there was enough light outside facing the energy consumer to power it at the location this experiment was conducted. This feature is not seen in RF energy **(Figure 3)**, as the amount of harvested radio frequency energy was not dependent upon the time of day. The horizontal axes of the solar and RF probability plots contain both positive and negative values for the number of previous energy events (**Figures 2 & 3**). Negative numbers of energy events correspond to a continuous absence of energy events. For example, when N = -40, an energy event has not occurred in the last 40 time intervals, or the last 200 minutes.

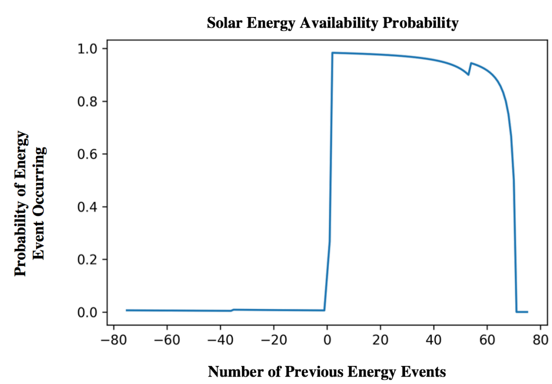

Figure 2: Probability plot for harvested solar energy. This plot displays energy occurring in short bursts. The mean η-factor is 0.8595 (n = 6). The data collection for this experiment spanned three days.

For the next objective, comparing the reliability of different harvested sources in terms of their power availability using the η-factor, we used the constructed graphs to calculate the η-factor. In regards to the hypothesis that one harvested energy source will be more reliable than another due to the fact that different energy sources are likely to have different patterns of availability over time, our findings could suggest that a certain energy source should be favored over another to allow for the most reliable execution of processes. The mean η-factor for harvested solar power was 0.8595 and the mean η-factor for harvested radio frequency power was 0.3657, with a standard deviation of 0.0018 for the solar data and 0.0762 for the radio frequency data. We performed a student's t-test using calculations for six trials each of the solar and radio frequency experiments; the test yielded a two-tailed p-value of less than 0.0001, meaning that the difference between the η-factor for harvested solar and harvested radio frequency energy was statistically significant. The η-factors for both harvested solar and harvested radio frequency energy fall below the ideal standard of 1.0 as the η-factor for wall or battery power. For wall and battery sources, the probability of energy being available now given that any number of energy events have occurred is 1.0 **(Figure 4)** (5). The higher η-factor for solar power suggests that harvested solar energy is more reliable than harvested radio frequency.

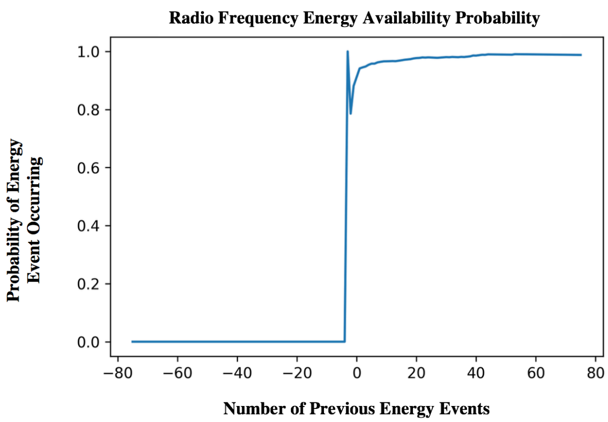

Figure 3: Probability plot for harvested radio frequency energy. This plot displays energy occurring in short bursts. The mean η-factor is 0.3657 (n = 6). The data collection for this experiment spanned two weeks.

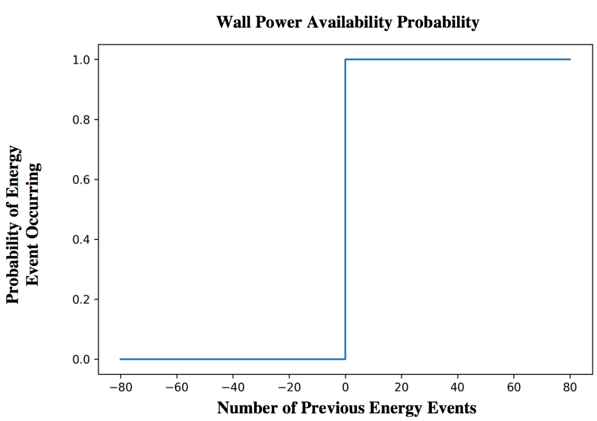

Figure 4: Theoretical probability plot for wall power. Wall power has an η-factor of 1.0 since it is not intermittent.

Finally, we placed different obstacles between a radio frequency transmitter and receiver to determine how they would affect the amounts of harvested energy; the experiments were also replicated with various distances between the transmitter and the receiver. Different obstacles are likely to have different effects on the amount of energy able to be harvested, due to density of the object, thickness, and other factors. Metal and people were the obstacles which most affected the ability of the receiver to harvest energy from the transmitter, with wood and foam having a less pronounced effect on the harvested energy **(Figure 5)**. Foam had a slightly higher voltage input value than the absence of an obstacle at a distance of 1 meter, but this difference was too small to be significant and was likely caused by random variation. Additionally, as distance increased, the received signal input decreased across all obstacles; fewer signals were received from farther away and converted into electrical energy.

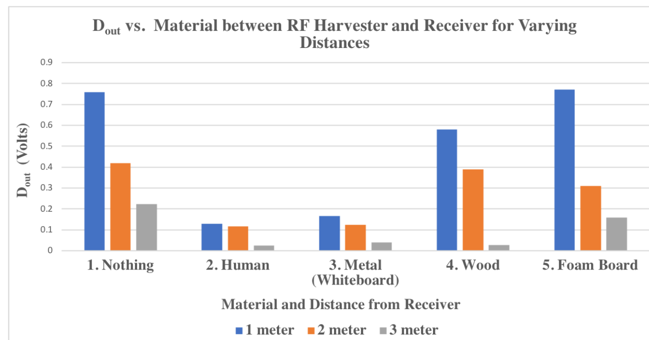

Figure 5: Graph depicting D_{out} for various obstacles and distances in the RF obstacle experiment. The D_{out} value is correlated with the radio frequency input, so higher D_{out} values correspond to higher radio frequency input.

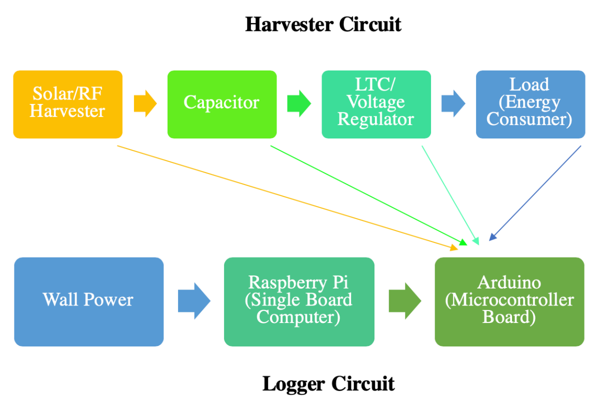

Figure 6: Diagram of circuit setups for solar and radio frequency harvesting experiments. Output voltages from each component in the harvester circuit — the harvester unit, the capacitor, the LTC, and the load — were connected to the Arduino and recorded.

DISCUSSION

The major objectives for this investigation included investigating the burstiness of energy, comparing the reliability of harvested solar and harvested radio frequency energy, and exploring the effects of various obstacles and distances on the amount of radio frequency energy able to be harvested. We constructed and analyzed graphs of the probability of energy availability given that a certain number of energy events had occurred **(Figures 2 & 3)**, from which η-factors were calculated, addressing the first two objectives. We also plotted the average D_{out} values for different obstacles and distances in a bar graph **(Figure 5)** against a control group to compare which obstacles had the greatest effect on D_{out} values.

The solar and RF probability plots support the hypothesis of the high levels of burstiness for both harvested solar and radio frequency energy **(Figures 2 & 3)**, as the probability of an energy event occurring is relatively high after many energy events occur until the correlation stops in the case of harvested solar energy; this was due to the limited time during which there was daylight. Factors that could have influenced the display of the data include increasing the time interval t, which defines an energy event. Choosing a larger value of t may show parts of the graph well after the correlation ends for solar energy, causing probabilities in the middle to appear closer to 1 than they truly are. Choosing a smaller value of t may not show where the correlation ends, which may incorrectly suggest that the correlation does not, in fact, end. In the RF probability plot, there is a spike in probability around N = -1 **(Figure 3)**, meaning that if in the previous time interval there was no energy event, then the probability of an energy event occurring now is extremely high. This suggests that when a person walks in front of the sensor, they cause the absence of a single energy event, but they are not likely to cause the absence of a second energy event; in other words, most people walk by the sensor rather than standing in front of it. Thus, when considering human interference in real-world RF-harvesting situations, we believe they do not tend to stand in place and obstruct the signal for extended periods of time. Factors that may have influenced the data collection include the sensor recording the presence of a person when there was not a person, or failing to record the presence of a person when there was one. Finally, the Arduino could only record voltages to two decimal places, restricting the precision of the data analysis. These results are significant as the burstiness of energy will allow for more ease in the process of scheduling tasks to be executed.

The calculations of the η-factors and the results of the student's t-test suggest that harvested solar power is more reliable than harvested radio frequency power, supporting our hypothesis. One potential reason for the higher standard deviation for the radio frequency η-factor could be the increased variance among trials in the patterns of people passing in front of a sensor over a given time, compared to the more stable pattern of light reaching a solar panel. We performed calculations for harvested radio frequency energy using data which spanned a longer period of time than the solar data collection – a difference of about two weeks for RF energy versus three days for solar energy. The rationale behind this was that the absence of radio frequency energy events is less frequent than the absence of solar energy events, so more data needed to be analyzed to get a good overall picture for radio frequency energy. The same factors which could have caused error in the first experiment apply here – the reliability of the sensor and the accuracy of the Arduino. These results are significant as harvested solar energy may be a more suitable alternative to harvested radio frequency energy in terms of reliability and predictability.

Our data also suggests that people and metal most obstruct the radio frequency signal from being received and converted into electrical energy **(Figure 5)**. Thus, people were used to obstruct the signal in the radio frequency experiment in order to induce the absence of an energy event. Factors that could have influenced these results include the presence of multiple objects between the transmitter and receiver, such as a hand holding the foam board, and again, the accuracy of the Arduino for recording voltages. These results are relevant to the real-world application of harvested radio frequency energy – from WiFi routers, cell towers, and more – by suggesting which obstacles are more likely to cause the absence of an energy event and should be considered and avoided when choosing a location for a potential radio frequency energy harvester.

In regards to the goal of accurately modeling large-scale solar and radio frequency energy harvesting systems, there are some aspects of the models which translate better to the real world than others. For example, the placement of the solar panels in a location which maximizes the amount of sunlight received and the fact that a solar panel can only face towards a single direction are two characteristics of the model that reflect practical circumstances. However, for the radio frequency experiment, the model fails to account for the real-life conditions of multiple obstacles or static obstacles, which could decrease the likelihood of energy events by allowing for less energy to be successfully harvested.

Future experiments may involve conducting the same experiment for different forms of harvested energy, including piezoelectric energy which is the generation of electrical energy in response to mechanical pressure. Piezoelectric energy can be harvested in many forms, and another possible avenue of exploration would be the differences in amounts and reliability of harvested energy between different types of piezoelectric energy, including energy harvested from mechanical stress inside a person's shoe or from mechanical stress on a sidewalk or tile. Additionally, the solar experiment could be replicated under different weather conditions; if there were less sunlight available, it would be expected that energy events would occur less frequently, and if there were more sunlight available, energy events would occur more frequently. One interesting avenue of exploration with obstacles is including them for harvested solar energy in addition to harvested radio frequency energy. If obstruction were considered for harvested solar energy, the effect on voltage would likely be correlated with the opacity of the object obstructing the sunlight. Also, different densities and thicknesses of the obstacles could be tested. Finally, these experiments could be replicated using a different frequency for the radio frequency transmitted and the results could be compared to those of this experiment.

As we look to replacements for fossil fuels in this era of climate crisis, we should keep in mind the reliability of harvested energy sources. Harvested solar energy was found to be more reliable than harvested radio frequency energy, and we should consider this when deciding which types of renewable energy we want to invest in and implement on a large scale. When placing these harvesters, particularly radio frequency harvesters, we should attempt to place them in a way that minimizes obstruction from different objects, especially people and metal. In this way, we can maximize energy efficiency. Through harvesting energy from common and everyday sources like the sun and radio frequency signals, we take the first steps towards ensuring a more sustainable and energy-efficient future.

MATERIALS AND METHODS

The setup for both the solar and the radio frequency experiments for which the probability plots were constructed involved two main circuits **(Figure 6)**. The first, designated as the harvested circuit, captured either sunlight or a transmitted signal and converted it into energy. There were four main components to this circuit: the solar or radio frequency harvester unit, the capacitor to store energy and provide the circuit with more stability, the Load Tap Changer (LTC) , and the load, or the consumer. In this experiment, the load was an MSP-430 device (Texas Instruments) which was constantly running an energy-consuming software and required 2.8 Volts to turn on. The purpose of the LTC in the circuit was to ensure that given a certain amount of energy input, the amount of energy output would be 3.3 Volts; this simply amplified the input voltages so that the absence of sufficient energy would be more pronounced in the voltage recordings. We recorded voltage data at various locations in this circuit, including across the energy harvester, which captured the energy from the sun or from the radio frequency transmitter, and across the energy consumer. The voltages were recorded and printed out using a Python 3 program, an Arduino Uno (SparkFun Electronics), and a Raspberry Pi 3 (Raspberry Pi Foundation). The weather on the days the experiment was conducted is important to consider when dealing with solar data, so a light sensor was also used to record the full-spectrum, infrared, and visible light levels; part of the Python program retrieved real-time weather data from weather.com, including temperature and UV index. The weather on all three days during which the experiment was conducted was sunny with minimal clouds. The harvester was placed directly across from a window facing west, so that the system tended to reach peak energy in the afternoon, when the most sunlight was available to it.

For the radio frequency experiment, we used an infrared sensor to record the presence or absence of people; a person walking in front of the sensor, and thus blocking the signal, was considered as the absence of an energy event. The second main circuit, the logger circuit, was constructed to record voltages at each point in the harvester circuit. It included wall power connected to a Raspberry Pi 3 and an Arduino Uno. We wrote an Arduino program and a Python program to print out and save the recorded voltages into a .csv file. We then analyzed the data, calculated the η-factors, and constructed probability plots using a different Python program in Jupyter Notebook.

The setup for the obstacle experiment using a radio frequency harvester involved the same circuit setup as the other radio frequency experiment, but without the use of the infrared sensor. A Python and an Arduino program were used to record the voltages at various points in the circuit. Data were collected over a span of two minutes each for four different obstacles – metal, wood, person, and foam – over three different distances – 1 meter, 2 meters, and 3 meters. Note that the person used in this particular experiment was instructed to stand between the transmitter and harvester for two minutes; this experiment was conducted to establish that when a person is between the RF transmitter and receiver, they cause the absence of an energy event. We then used this fact in the radio frequency event, where we recorded when people walked in front of the sensor and considered it as the absence of an energy event. The voltages for this obstacle experiment were recorded from the D_{out} pin on the MSP-430, which is directly related to the amount of radio frequency input received. The absence of an obstacle between the transmitter and the receiver served as a control to which the other voltage values could be compared. We saved these data in a .csv file using a Python and Arduino program and further analyzed and graphed the data using Microsoft Excel. The approximate densities and thicknesses of the obstacles used were recorded **(Table 1)**. We approximated the density of a human at 1.01 grams per cubic centimeter (4).

Approximate Thickness and Density of Obstacles		
	Thickness (cm)	Density (g/cm³)
Human	25	1.01
Metal Whiteboard	2.0	0.85
Wood	2.0	0.70
Foam	0.3	0.13

Table 1: Approximate thicknesses and densities of obstacles used in experiment. The thicknesses were measured and densities were calculated using measurements of mass and volume. The thickness measurement for a human is very approximate as it is harder to measure with precision.

Received: September 18, 2018
Accepted: January 9, 2020
Published: April 29, 2020

REFERENCES

1. Lucia, Brandon, et al. "Intermittent Computing: Challenges and Opportunities." Summit on Advances in Programming Languages, May 2017. *SNAPL*, 10.4230/LIPIcs.SNAPL.2017.8.

2. Masoum, Mohammad A. S., & Fuchs, Ewald F. *Power Quality in Power Systems and Electrical Machines*. 2nd ed., Academic Press, 2015.
3. Islam, Bashima, et al. "On-Device Training from Sensor Data on Battery-less Platforms." *Information Processing in Sensor Networks Conference*, May 2019. ACM-IEEE, 10.1145/3302506.3312611.
4. "Density of Human Body in 285 Units and Reference Information." *Human Body, AVCalc*, www.aqua-calcn . com/page/density-table/substance/human-blank-body.
5. Islam, Bashima, et al. "Zygarde: Time-Sensitive On-Device Deep Intelligence on Intermittently-Powered Systems." May 2019. *ArXiv*, 1905.03854.

ACKNOWLEDGEMENTS

Thanks to Dr. Sarah Shoemaker, Ms. Shoshana Segal, and Mr. Chris Thomas for advice and assistance throughout my research process.