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On the comparison of energy sources: Feasibility of radio frequency and ambient light harvesting

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ABSTRACT

With growing interest in multi source energy harvesting including integrated microchips we propose a comparison of radio frequency (RF) and solar energy sources in a typical city. Harvesting devices for RF and solar energy will be competing for space of a compact micro or nano device as well as for orientation with respect to the energy source. This is why it is essential to investigate importance of every source of energy and make a decision whether it will be worthwhile to include such harvesters. We considered theoretically possible irradiance by RF signal in different situations, typical for the modern urban environment and compared it with ambient solar energy sources available through the night, including moonlight.

Our estimations show that solar light energy dominates by far margin practically all the time, even during the night, if there is a full moon in the absence of clouds. At the same time, in the closed compartments or at the new moon RF harvesting can be beneficial as a source of “free” energy.

1. Introduction

Consideration of alternative and “free” energy sources as a power source for different devices, including microelectronics, is an important and popular topic [1–3]. One of the most promising directions is energy harvesting – utilization of energy available as a background radiation noise: solar radiation, light from the lamps in the building, Wi-Fi or cell phone radio frequency (RF) radiation etc. Let us estimate the potential for energy harvesting from different sources. We shall not consider vibration or thermal sources, because they greatly depend on the environment and may be highly intermittent. We thus concentrate on solar energy, moonlight, ambient city light, and RF energy, because these types of energy are available in any modern city. For example, if we consider a photovoltaic (PV) panel augmented with RF-antennas and conversion microcircuit integrated into the horizontal surfaces of an automobile (roof, hood, tint film on windows etc.) to power different micro-sensors it is useful to know how much energy we can potentially harvest from different sources, in order to make a decision already on the design stage about the cost effectiveness of integrating of RF antennas and conversion microcircuits, which usually include Schottky diode, into the PV-devices. While for the usual micro-controllers (e.g. Ref. [1]) there is no strict limitation in space and addition of energy conversion circuit will not change the price of device significantly, for micro and nano scale devices the space limitation can be already crucial.

Our estimations show that in most of situations solar energy will be dominant by at least order of magnitude. Even during the night moon light can provide more energy than RF-radiation, if we do not consider cases when the Moon is absent. During dark nights or in environments with blocked solar radiation RF energy source can be valuable.

The plan of the paper is as follows: first we consider different types of energy sources and estimate irradiance generated by them – power per unit area. After that, taking into account conversion rate of available harvesting devices, we discuss feasibility of different sources in the conclusion.

2. Solar energy

As a reference point we used data about surface irradiance collected by the Photovoltaic Systems Evaluation Laboratory in

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Sandia National Laboratories for latitude 35.111 N, longitude 106.61 W (Albuquerque, New Mexico, USA) during a twenty four years period (from 1989 to 2012 year) [4]. Data for different locations can be found at NASA Surface meteorology and Solar Energy web-site [5]. Global horizontal irradiance (GHI, the total amount of shortwave radiation received from above by a horizontal surface) averaged over a twenty four years period yields the value

$$I_{Solar} = 1.1 \times 10^3 W\Big/m^2. \tag{1}$$

This value can vary due to different factors, like seasonal monsoon rains, volcanic eruptions (Mt. Pinatubo, Philippines, erupted 6/91, reduced solar resource in late 1991, 1992, early 1993; maximum decrease in GHI was about 10% and was observed in 1992 [4]). Nevertheless for order of magnitude estimation such fluctuations are definitely beyond the required accuracy.

Conversion efficiency also affects all sources of energy so we have to take it into account. For PV cells conversion rate depends on the material and type of the cell. Widely used cells based on crystalline silicon with single p–n junction have a theoretical limiting power efficiency of 33.7% (Shockley-Queisser limit [6]) and current crystalline silicon based PV cells are approaching this limit, while state-of-the-art multijunction samples with concentrators can yield up to 44.4% efficiency [7]. Taking into account the packing ratio (not the whole surface of the PVC panel is occupied by a converting element) of real PV devices conversion efficiencies between 17% and 20% are typical for commercially available Si-based solar cells.

3. Light from the full moon

3.1. Theoretical estimation

During the night the Moon can be a significant source of light depending on phase of the Moon cycle. It is useful to compare irradiance from this source of energy with other options. Let us estimate irradiance due to full moon in reasonably good conditions. We shall calculate an attenuation factor similar to one introduced in Ref. [8] (the factor was not calculated in the paper and proposed formula gave result several orders of magnitude lower even for wrong albedo value which was order of magnitude higher than the real one due to derivation error).

Earth and Moon are on average at approximately the same distance from the Sun, so for our rough estimation we can consider the irradiance from the Sun as the same one. This estimation is confirmed by measurements [9], if we shall take into account albedo of Earth atmosphere which is approximately 30%. Moon's mean radius is $R_M \simeq 1738\ km$ [10], which is significantly smaller than Earth's mean radius $R_E \simeq 6371\ km$ [11] resulting in smaller amount of energy obtained by Moon from Sun, which is proportional to the surface area. This means that the reduction coefficient for energy obtained by Moon from Sun will be $R_M^2/R_E^2 \simeq 0.074$. Moon albedo is $\alpha \simeq 0.12$ [9] (here we neglect the fact that Moon albedo depends on the light incident angle, resulting in stronger reflection if the source of light is behind the observer [12], which is typical for the full Moon), which means that only 12% of incoming radiation is scattered in all directions over the surface (i.e. in upper hemisphere). In order to figure out what fraction of this energy reach the Earth we need to compare the solid angle of the whole hemisphere of scattering (which is 2π Sr) and solid angle of the Earth from Moon. Average distance from Earth to Moon is $L_{EM} \simeq 384400\ km$ [10], which give us the solid angle $\Omega = 2\pi(1 - L_{EM}/\sqrt{R_E^2 + L_{EM}^2}) \simeq 0.86 \times 10^{-3}$ Sr. The resulting attenuation coefficient for the Sun radiation can be estimated as follows:

$$C_{Moon} = \left(\frac{R_M^2}{R_E^2}\right)\alpha\left(\frac{\Omega}{2\pi}\right) \simeq 1.2 \times 10^{-6}. \tag{2}$$

Taking into account this attenuation coefficient one can get the following estimation for the irradiance from the Moon light

$$I_{Moon}^{Theory} = C_{Moon} I_{Solar} \simeq 1.3 \times 10^{-3} W\Big/m^2. \tag{3}$$

Here we supposed that moonlight attenuation in the Earth atmosphere is approximately the same as for the sunlight.

It should be noted that this number decrease significantly with different phases of the Moon, resulting in its complete extinction when there is a new Moon or if Moon is under horizon. Some estimations of the availability of this source of power is given in Conclusion. It follows from these calculations that Moon is present at dark times only 25% of the time.

Because we consider the conversion of the moonlight by PV cells we shall use the same conversion rate about 20% as for the sunlight conversion. For our rough analysis we can neglect difference in the spectra.

3.2. Measurements

Following [13], illumination from the full moon (at 60° elevation angle) can achieve 0.7 *lux* which roughly corresponds to

$$I_{Moon} = 1.0 \times 10^{-3} W\Big/m^2. \tag{4}$$

This value is in good correspondence with our estimation (3). For convenience and in order to be on the safe side when comparing with different sources later in the article we shall use this value for the irradiance from the Moon.

We have performed a measurement of harvested moonlight power at full moon conditions at the same location (Albuquerque, NM, USA). No visible clouds were present during the measurement night. Two of standard 6-inch mono-crystalline Si solar cells, each of surface area of $0.0235 m^2$. Both cells were connected in series, forming a miniature PV panel of total area of $0.047 m^2$. Each of these solar cells had nominal STC (Standard Test conditions) conversion efficiency of 21%, as reported by the cell manufacturer (Schott Solar). Under a full moon conditions, and at normal incidence to moonlight, a total current of $1.5 \times 10^{-5} A$ at voltage $1.2 V$ was measured from this miniature panel, which gives $1.8 \times 10^{-5} Watt$. This measurement translates into $\simeq 3.8 \times 10^{-4} W/m^2$ produced by the panel, or, taking into account 21% conversion efficiency, $1.8 \times 10^{-3} W/m^2$ of moon power available for harvesting under realistic conditions. This number is slightly higher compare to the value estimated above – but this is a realistic expectation due to relatively high elevation of the measuring site (Albuquerque, NM is situated at the approximately 1.6 *km* above the sea level), good atmosphere transparency, and relatively low air pollution.

4. Interior lighting

Interior lighting can also be a source of energy inside the building. In order to evaluate possibility of using interior lighting for energy harvesting, we performed a similar measurement of a harvested interior lighting energy with the same miniature Si PV panel. In a typical US office environment with fluorescent lighting, a total of 4.5 *mWatt* was measured. This measurement translates into approximately 0.1 W/m^2 produced by the panel, or, taking into account 20% conversion efficiency, 0.5 W/m^2 of interior lighting available for energy harvesting purposes. Of course, the actual amount of interior light will vary greatly from building to building,