Indoor solar panel energy harvesting for low power wireless devices

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Abstract

This bachelors thesis discusses different aspects of Low power indoor energy harvesting. Energy source, harvesting, management, storage, and consumption are covered to get a good insight into designing devices powered by harvested energy. A method for measuring energy consumption of low power devices by measuring energy transferred from a capacitor is proposed and presented in practise. In addition to this, indoor lighting is discussed from the perspective of energy harvesting by solar panels. Different solar panels are compared and their performance in indoor environment is evaluated. Finally, energy management and storage is breafly discussed to enclose the subject.

Keywords Energy harvesting, solar panel, low power, wireless devices

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Tekniikan kandidaatintyön tiivistelmä

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Tiivistelmä

Pienet elektroniikkalaitteet käyttävät virtalähteenään usein pattereita, ladattavia akkuja ja johdollisia virtalähteitä. Elektroniikkalaitteiden tehon kulutuksen pienentyessä voitaisiin kuitenkin siirtyä käyttämään laitteen ympäristöstä kerättyä energiaa. Aiemmin tätä on hyödynnetty lähinnä taskulaskimissa, eikä tekniikan liittämistä laajemmin muihin kaupallisiin tuotteisiin ole juuri hyödynnetty.

Tämä kandidaatintyö tutkii aurinkokennojen hyödyntämistä sisätiloissa matalaenergisten langattomien laitteiden energianlähteenä. Tarkoituksena on saada yleiskuva siitä, mitä asioita tulee ottaa huomioon, kun suunnitellaan matalaenergistä energiankeruujärjestelmää. Tavoitteena on kattaa energian keräämiseen, hallintaan, varastointiin ja kulutukseen liittyvät tekijät.

Kun mitataan pienitehoisien langattomien laitteiden tehonkulutusta, lyhyet ja voimakkaat virtapiikit ja vaihtelevat käyttöjännitteet tekevät tarkojen tulosten saamisesta haastavaa. Nopeiden ja suuriresoluutioisten mittalaitteiden sijaan mittauksissa voidaan hyödyntää kondensaattorin jännitteen suhdetta siihen varastoituneeseen energiaan. Kun sopivan suuruinen kondensaattori kytketään laitteen energianlähteeksi, voidaan tiettyyn toimintoon, kuten esimerkiksi radiolähetykseen, kulunut energia määrittää kondensaattorin jännitteen alenemasta. Näin matalampikin näytteistysnopeus saadaan riittämään, ja valitsemalla kondensaattori oikein, jännitteen muutoksesta saadaan helposti mitattavan suuruinen.

Sisävalaistuksen ja ulkona vallitsevien olosuhteiden erot tulee ottaa huomioon, kun suunnitellaan aurinkokennojen käyttöä sisäolosuhteissa. Ensinnäkin, valaistuksen voimakkuus on sisällä huomattavasti pienempi. Tämä ei pelkästään vähennä saatavilla olevan energian määrää, vaan alhaisempi säteilyvoimakkuus heikentää myös aurinkopaneelien suorituskykyä. Myös sisävalaistuksen spektri poikkeaa ulkovalaistuksesta, mikä valaistustyypistä riippuen saattaa sopia joko paremmin tai heikommin yhteen aurinkopaneelin spektrin kanssa.

Paremman toiminnallisuuden takaamiseksi, kerätty energia kannattaa säilöä jotenkin. Tähän sopivat esimerkiksi superkondensaattorit ja ladattavat akut. Akkujen etuna on niiden suurempi energian varastointikyky tilavuutta kohden. Ne kuitenkin menettävät osan kapasiteetistaan ajan myötä, toisin kun superkondensaattorit, jotka voivat kestää tuhansia uudelleenlatauskertoja. Molempien toiminta kuitenkin hyötyy ulkoisesta energianhallintapiiristä, joka suojelee laitteen osia yli- ja alijännitteeltä, ja ohjaa energian keruuta.

Avainsanat Energian keruu, matala teho, langaton

Preface

I want to thank my instructor Dr Petri kärhä and Scientific research project- course crew Tuomas Paloposki and Maurice Forget for their feedback and guidance.

Otaniemi, 22.12.2017

Eero J. Prittinen

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Symbols and abbreviations

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MPPT	Maximum power point tracking

1 Introduction

Generally, almost all small commercial electronics are powered by either wall adapters or batteries. This of course does not allow truely wireless and maintainance free operation. Wires make the locating of the device dependent of wall outlets, and having batteries requires changing them from time to time, so the device has to be accessible, and someone has to take the responsibility for the maintenance. In addition to this, it might be hard to tell, when the battery is going to run out, making the operation unreliable.

To eliminate the need of batteries and wires, the energy requirede by the device could instead be collected from the environment. This approach has been used in outdoor applications such as weather stations [1] and commercial outdoor and garden lamps [2], [3], [4]. The utilisation of same tecniques in indoor environment has not really broken trough yet, which can be seen just by counting all the solar powered devices in any regular office or public building. In addition to pocket calculators, only some marginal products have been developed, for example Logitec has developed a solar powered wireless keyboard[5].

Even though the indoor energy harvesting is not widely applied technique in commercial products, a lot of studies have analyzed the different aspects of it. One of the main concerns has been the functionality of solar cells under indoor environment to reveal the actual potential and limitations of obtainable energy [6], [7], [8]. Other important aspect has been to develope state of the art energy harvesting controllers to get the highest possible efficiency [9] and to apply this to an actual system [10].

This thesis investigates different aspects of applying solar cell energy harvesting in indoor environment. A method of measuring energy consumption of micro power devices is proposed and tested using Nordic semiconductors nRF51 development kit as an example. Indoor lighting is evaluated from the perspective of energy harvesting and performance of solar panels is discussed in this environment. Some aspects of possible energy storage and management methods are discussed to enclose the power system of energy harvesting device. The goal of this thesis is to help to evaluate, if energy harvesting in certain application and environment is reasonable, and to raise awarenes of what things should be considered, when designing such systems.

2 Power measurement of low power devices

In design of low power energy harvesting systems, the energy consumption of the end device is a good starting point. This way the power scale of the device can be determined and the requirements for other components of the system can be approximated.

The energy consumption can be resolved using various methods. Most electronics producers give some approximations of their products consumption in the component datasheets. These tend sometimes to be a bit optimistic and describe the optimal situation. The other way is to actually measure the used energy in the end device with all the sensors and other components aboard. This way different use case scenarios can be tested, and the actual performance of the device in the end product can be determined. By comparing the energy consumption with the amount of harvested energy, the device operation on different use loads can be simulated with computer. This way, the limitations and optimisations can be tested without time-consuming real life logging.

Measuring low power energy systems can be challenging. Usually the current drawn is far from constant and can vary from microamperes to several milliameres. In addition, the source voltage can vary as well. Measuring power by multiplying current and voltage would in this application require high sampling rate and high resolution.

To measure the energy consumption with less precise equipment we can take advantage of the energy voltage relation of a capacitor. By utilising a charged capacitor as a voltage source to the device, the voltage drop can be measured and the amount of transferred energy can be calculated. After all, the interest is not really about the momentary power consumption, but rather the overall energy loss of one action, for exaple a transmission or a measurement.

The energy E of a capacitor is polynomially related to its voltage U,

$$E = 1/2 \times C \times U^2, \tag{1}$$

where C is the capacitance of the capacitor. The energy loss ΔE during an action can thus be calculated as

$$E = 1/2 \times C \times (U_1^2 - U_2^2), \tag{2}$$

where U_1 is the voltage before the action and U_2 is the voltage after the action. The source voltage level might affect the amount of current drawn, and thus on the consumed energy. To minimize this effect, a capacitor is chosen so, that the voltage change is kept small, but still accurately measureable.

A nRF51 bluetooth module development board was used to test this measuring method in practice. Measurements included measuring the characteristics of the current drawn by the module, when performing transmissions, measuring the energy consumed by those transmissions with different source voltages, and measuring the sleep mode energy consumption. The current profile was obtained with an oscilloscope tracking the voltage over a 10 Ohm shunt resistor located in series with the development board.

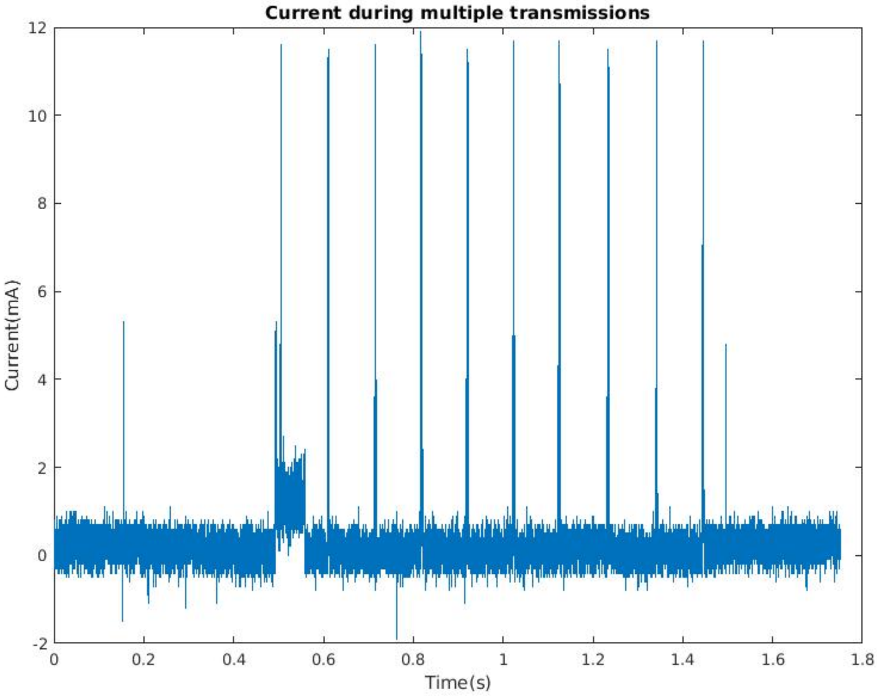

Figure 1: Current form during transmission sequence.

As can be seen in figure 1, the current draw of the device consists mostly of short pulses that can rise up to 10 mA. When in sleep mode, the current is relatively low, and possible changes in it are lost in the static noise. By inspecting the spikes closer in figure 2, we can see, that there are actually a couple of separate spikes.

The energy consumption was measured using a charged capacitor as a power source, 22 000 µF for the transmission measurements and 1 000 µF for the sleep power measurements. The measurements were made with an oscilloscope by measuring the voltage between the capacitor terminals. This measurement was conducted with different starting voltages to find out the effect on the energy consumed. The resolution of the oscilloscope was 10 mV.

The Voltage drop of the capacitor during one transmission cycle is presented in figure 3. By calculating the energy lost in the action (equation 2) we can conclude a value of around 4.7mJ. We can estimate the length of one transmission sequnece with figure 1 to be 1000ms. Since current I depends on the Power P and Voltage U,

$$I = P/U, \tag{3}$$

and P is defined to be energy E over time t,

$$P = E/t, \tag{4}$$

we can express I as

$$I = \Delta E/(\Delta U \times t). \tag{5}$$

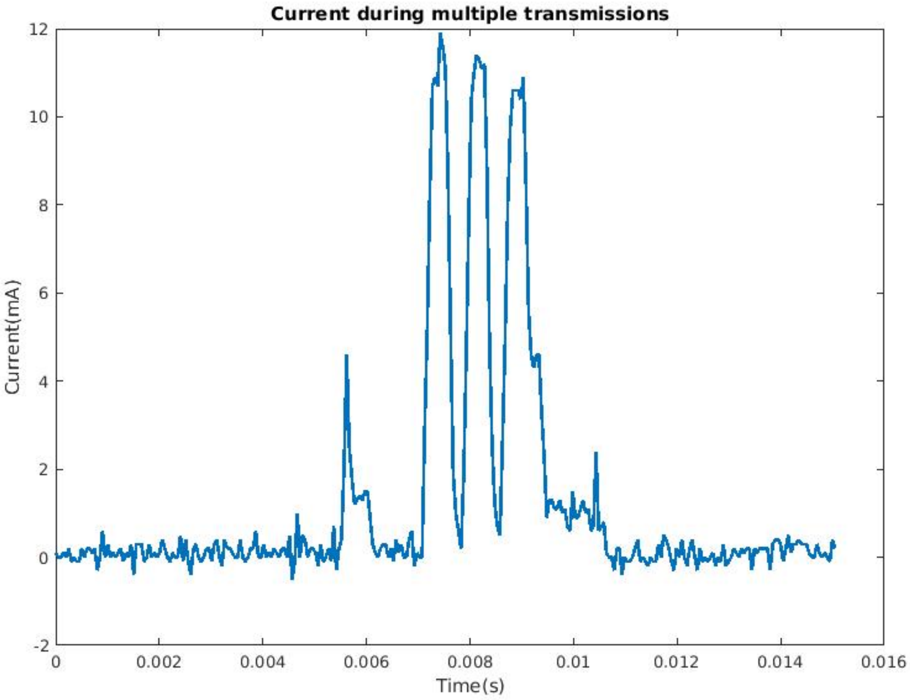

Figure 2: Current spike form of single transmission.

Thus we can calculate the median current to be 1.4mA.

By calculating the energy drop values for different starting voltages and plotting them together, a trend can be seen. In figure 4, it seems that with higher voltage values, the circuit seems to waste more energy.

The sleep current measurements were conducted with quite big time division in order to capture the full range of supply voltages. In figure 5, the voltage level drops almost linearly over time, which further suggests that the device consumes less power when operating at lower voltage. When calculating the median power flow on different time divisions, we can plot the current consumption to be around 13 µA. In the very end we can see the voltage drastically drop, when the device brownouts.

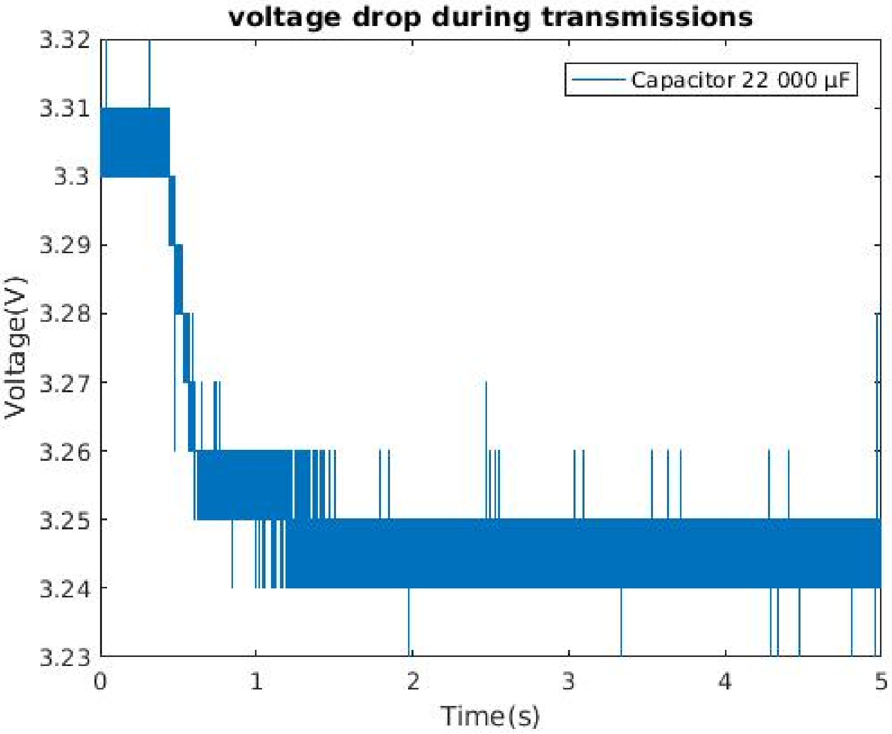

Figure 3: Capacitor voltage during one transmission.

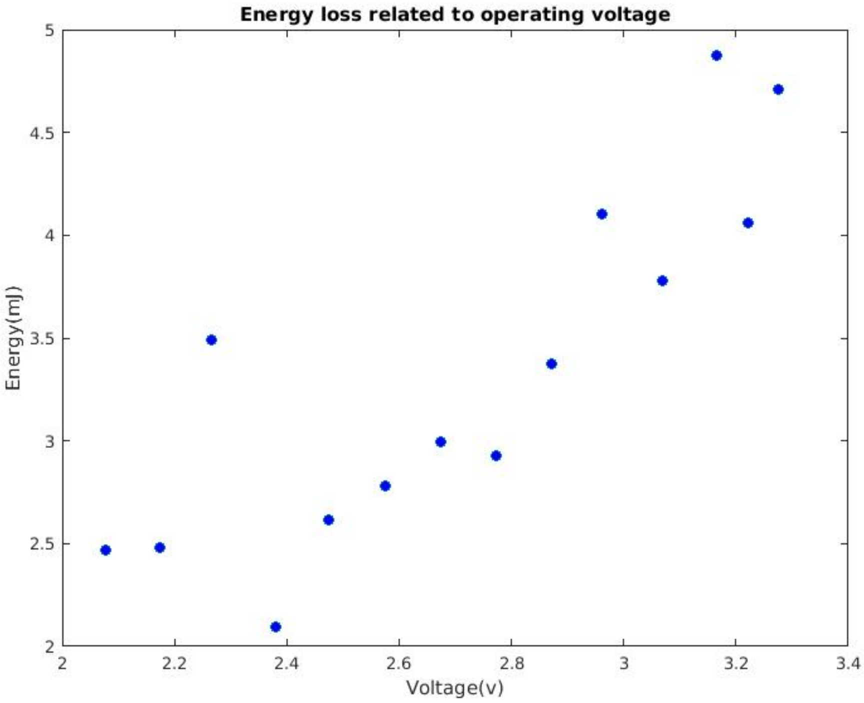

Figure 4: Energy consumption compared to source voltage.

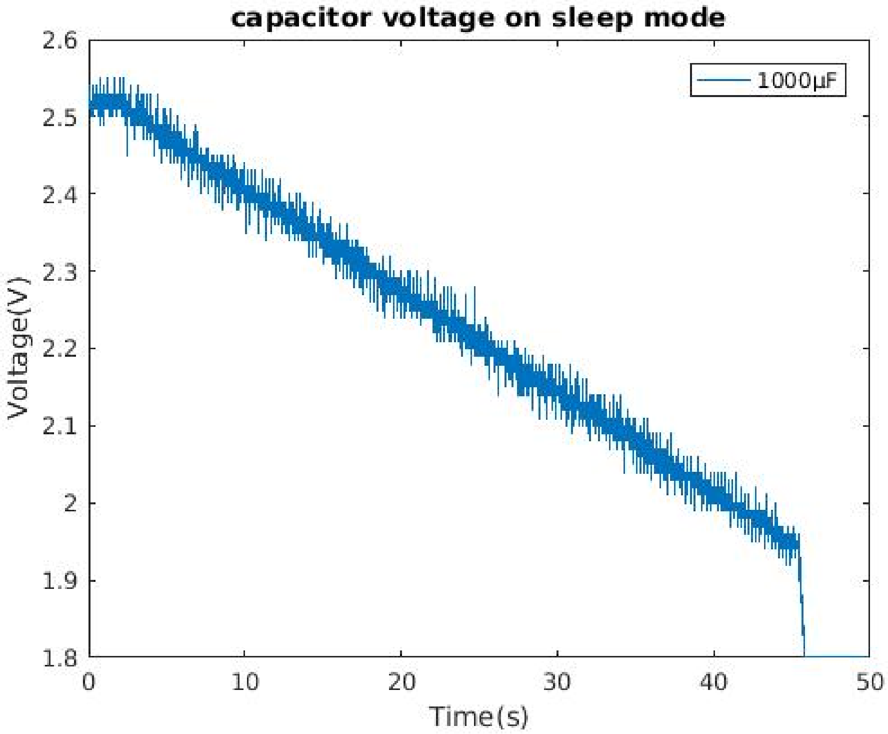

Figure 5: Capacitor voltage during sleep mode operation.

3 Evaluating indoor lighting

In order to compare different solutions for indoor photovoltaic energy harvesting, the environment in use must be analysed. Usually in indoor lighting design, focus is on the appearance of the illumination from human perspective. This is because the purpose of the lighting is to help people see better in the room or given space. To evaluate the indoor lighting from the perspective of a solar panel, a different perspective has to be taken, since the thing that matters in energy harvesting, is the power available in the sensitive spectral area of the solar cells.

Usually, value in Lux is used describe illuminance when working with artificial light sources. Lux is an SI unit describing the amount of luminance per surface area. Luminance is described as lumens and corresponds to the amount of irradiation per steradian. Candela is the unit describing the irradiational power of the source, and one of the seven base units of the SI system. Candela has been specified in the "News from the BIPM, volume 16(1)"[11] as follows:

> "The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540 * 10^{12}$ hertz and that has a radiant intensity in that direction of (1/683) watt per steradian." [11, pp.56]

The conversion ratio is 1/683 Watt per Lumen and so 1/683 W/m^2 per Lux. In addition to this, when transforming from W/m^2 to lux, the different wavelengths of light have to be weighted with standard luminosity function. Because of this, the spectral properties of the source have to be taken into account as well.

To calculate example conversion factor between W/m^2 and Lux, two LED spectrums were used as an example 6. The process of achieving the conversion values from the luminance spectra begins with getting the absolute values of the spectral weighting from the relative spectra:

$$L_a(\lambda) = \frac{L(\lambda)}{\int_{380nm}^{760nm} L(\lambda) d\lambda} \times \frac{P}{A}, \tag{6}$$

where $L_a(\lambda)$ is the absolute spectra as W/(m^2 × nm), $L(\lambda)$ is the relative specrta as 1/nm and P/A is the irradiance power as W/m^2. Then this is weighted with the standard luminosity function to match it into Lux definition,

$$L_w(\lambda) = L_a(\lambda) \times V(\lambda), \tag{7}$$

where $L_w(\lambda)$ is the weighted spectra as W/(m^2 × nm). In the end, a conversion rate of 1/683 is applied, and the radiation power is integrated from the wavelength relative values.

$$L_l = \frac{\int_{380nm}^{760nm} L_w(\lambda) d\lambda}{1/683}. \tag{8}$$

So, we can get the conversion rate CR as Lx/(W/m^2) by dividing the value in Lux by the original power:

$$CR = \frac{L_l}{\int_{380nm}^{760nm} L(\lambda)d\lambda \times \frac{P}{A}}. \tag{9}$$

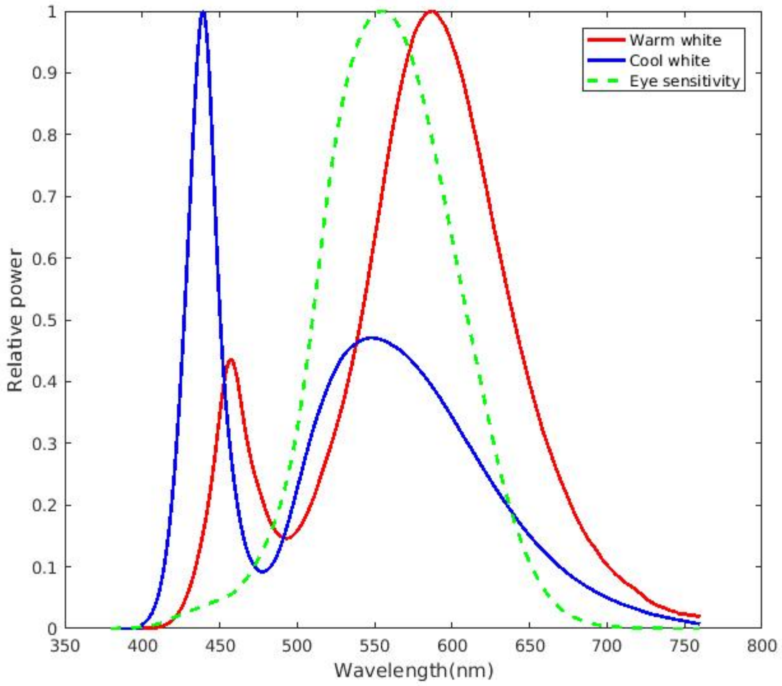

Figure 6: Cool- and warm white led spectra [12] and standard luminosity function $V(\lambda)$. [13]

If calculations are applied to the warm and cool white Led spectrums, conversion rates of 365.23 lx/(W/m^2) for warm white, and 307.99 lx/(W/m^2) for cool white are acquired. From here we can see, that it takes more powerful cool white LED to get the same illuminance level than with warm white.

Since indoor illuminance values can vary from 50 lx to over 5000 lx depending on the given space, it is hard to determine the exact guideline value for further calculations. But having for example a space illuminated with warm white LED to 400 lx, it would give us around 1.1 W/m^2.

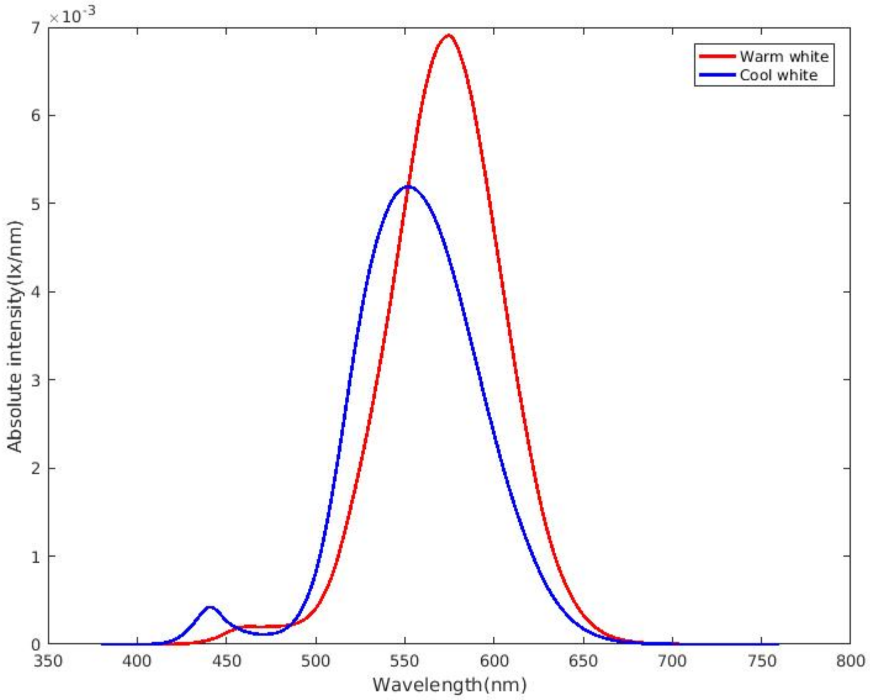

Figure 7: LEDs spectra for 1 W/m^2 weighted with standard luminosity function.

4 Solar cell performance under indoor environment

Most of the small, commercially available solar panels are made out of silicon in a form of either monocrystalline, polycrystalline or amorphous silicon. Some other panel technologies have been developed and new types of panel materials are being researched, but they are not so easily available commercially, and might be way more expensive due to the lack of large scale mass production.

When comparing different types of panels to each other, it is important to clarify in what kind of environment the panels will be used. Usually the manufacturers give the efficiency measured with the standard testing condition, 1000 W/m^2, AM1.5 spectrum [7]. For indoor applications, this is not suitable measure, since the light intensity can be just fractions of the intensity outdoors. Also the spectral properties of the light are different from outdoors since various kinds of lamp types can be used. Usually we can talk about having a mixed light with some irradiance coming through the windows and some generated from artificial sources.[6, pp.71-72, 74-76]

Monocrystalline silicon solar cells have the best efficiency (25.6%) of the easily available and affordable panel types under the standard test condition. Polycrystalline (multicrystalline) solar cells perform also quite well (20.8%) and are a bit more affordable. Amorphous cells do not quite reach the same levels(10.2%) but have advantage when utilised under lower light.[14] When the light intensity drops, the monocrystalline and polycrystalline cells start to loose their efficiency. Amorphous silicon cells on the other hand maintain their efficiency levels quite well.[8, pp.2 Figure 3, pp.4 Table 2] For extremely low light applications the amorphous cells seem as the best choice, but in the figure 8 we can see that still even under 10 W/m^2 the monocrystalline silicon cells can have over 50% of their efficiency left and thus have a better efficiency than amorphous cells [8, Figure 2].

In indoor environment, not only the light intensity can be lower from the one on outdoors, but also the spectral properties have differences as well. In figure 6 we can see the power distribution of the spectra. If this information is compared with the solar cell spectral sensitivities [8, Figure4, 5 and 6], it can be seen, that the crystalline silicon cells have just slight advantage in efficiency around 650 nm and shorter, where most of the power of LEDs are.

To obtain the power output of a solar cell under certain illuminance level we can first calculate the efficiency $\mu_a(P_w)$ of the cell:

$$\mu_a(P_w) = \mu(P_w) \times \mu_c, \tag{10}$$

where P_w is the illuminance power as W/m^2, $\mu(P_w)$ is the efficiency factor respect to the illuminance level and μ_c is the original cell efficiency. To approximate the harvesting capabilities of a solar cell, an example environment calculated previously can be used (400 lx, 1.1 W/m^2). In this light intensity, the amorphous silicon solar cell seems like a good option. With values of 10.2% for regular efficiency [14] and 85% for efficiency under around 1 W/m^2, which can bee seen in figure 8, we can calculate the approximated efficiency to be 8.67%.

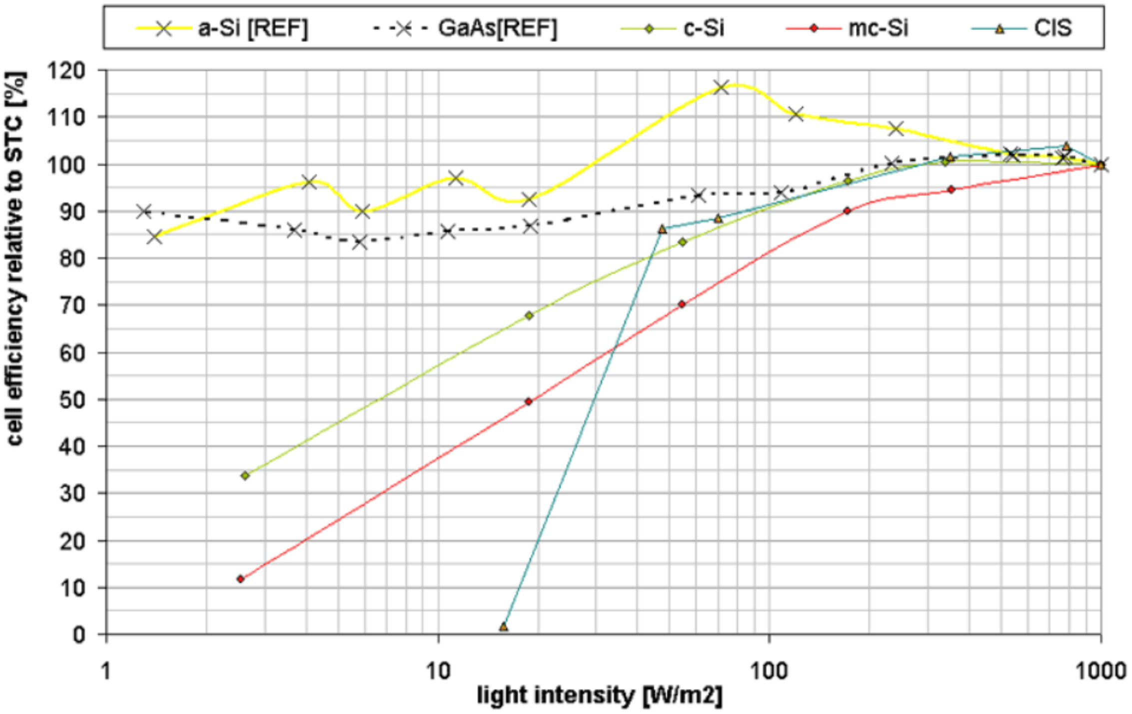

Figure 8: Efficiencies of different solar cell types relatively to standard test condition. [8, Figure 3]

When the efficiency is known, we can calculate the actual power P_c respect to the surface area A of the cell:

$$P_c = P_w \times \mu_a(P_w) \times A. \tag{11}$$

With our example values and a solar cell size of 5 cm x 5 cm (0.0025 m^2), we can get power of 237 µW. If this value is compared with the sleep mode current, we can see, that the device would be able to stay operational, and even have some excess energy to sore for later use. When we know the amount of power being stored, we can get the recovery time t of energy loss δE of one transmission as

$$t = \frac{\delta E}{P} \tag{12}$$

With the input power of 93 µW and energy loss of 4.7 mJ, it would take around 22.6 s to recover from the energy loss of one transmission sequence.

5 Energy storage and management

5.1 Super capacitors and rechargeable batteries

When harvesting energy for a device, the excess energy can be strored for later use. The stored energy can be utilised to keep the device on after the energy source, in this case solar cell, stops delivering power, or it can be used when the power consumption of the device exceeds temporarily the power delivery capability of the energy harvesting module. The energy storage solution in this case should be relatively small and suitable for low power applications. Most common ways to store electrical energy these days are rechargeable batteries and supercapacitors.

Lithium-Polymer(Li-Po) batteries are the most commonly used rechargeable batteries in consumer electronics where small size and low weight are valued. They can be made slim and shaped to fit the size of the device easily. The wide range of applications from smartphones to RC-models has increased the mass production volume and made the price of these cells to drop. They overall fit well for light consumer devices.

Supercapacitors are a special type of capacitors that can have a capacitance of multiple farads. Their voltage ratings are usually lower than the other types of capacitors. When for example electrolytic- and ceramic capacitors can withstand voltages from tens of volts to hundreds of volts, a supercapacitor usually has a voltage limit lower than six volts. They are usually utilised as a small backup power to enable small devices shut down properly in case of a power outage.

The use loads and energy flow expectations should be taken into account, when trying to make a choise between rechargeable batteries and supercapacitors. Rechargeable batteries usually offer higher energy storage per volume, as the energy E stored in a battery can be calculated as

$$E = \frac{C_b t}{1000} \times 3600 \times U, \tag{13}$$

where $C_b t$ is the capacity of the battery in mAh, which is transformed into Ah by dividing by 1000. U is the median voltage of the battery, and the 3600 is to transform from hours to seconds. With this, we can calculate that even the smalles Li-Po batteries with storage capacity of 20 mAh and nominal voltage of 3.7 V can store up to 266.4 J, while if we refer to equation 1, a super capacitor with capacitance of 5 F and voltage rate of 5 V can store just 62.5 J.

Other advantages of Li-Po batteries is that they are usually quite flat and can come in different shapes. They also hold their output voltage quite stable when discharging [15, Figure 1], at least if compared to the supercapacitors, whose voltage is related to the energy stored 1. Also due to the wide use of rechargeable batteries in existing products in the market, their price per obtained capacity can be significantly lower.

Supercapacitors on the other hand can withstand more recharge cycles than batteries [16]. This might be useful if the purpose of the energy storage is just to filter out current draw peaks or support the device operation for short periods of time when there is no energy available. If the device needs to be operational for longer periods of time without access to energy, the bigger capacity of a Li-Po battery could be beneficial. One example of this kind of situation would be periodical operations, like measurements, in an environment, where the device can recharge during daytime day and make measurements during nighttime.

One drawback especially for power sensitive designs when dealing with Li-Po batteries is that they should always be equipped with a companion circuit that monitors the voltage of the cell, and makes sure it stays on appropriate levels. Unlike super capacitor, whose voltage drops to zero when discharged, lithium batteries should never be discharged under a certain voltage. Over discharging them might cause internal damage to the cell and render it unusable. Also the maximum voltage given to a cell should not be exceeded, since this may cause swelling and bursting of the cell. [17]

When it comes to managing the electricity flow from the solar panel to the energy storage unit and the load device, both supercapacitor and lithium polymer batteries benefit from having a device to control the energy flow. For Lithium polymer batteries the protection from under- and overvoltages is mandatory to keep the battery operable. Super capacitors can on the other hand be fully discharged without a problem, but should not be overcharged as it might damage them. Still, referring to figure 5, if the capacitor voltage falls under usable voltage levels of the end device, it will brown out, and drain the capacitor empty, which wastes some precious power.

5.2 Maximum power point tracking

Not only the energy storage devices benefit from external power flow control. To get the maximum power output from solar panels requires some control as well. Solar cells as a power source are quite interesting as their impedance is nonlinear and depends on the current drawn from the cell. With small enough currents the voltage of the cell stays quite stable, but after a certain point it start's to drop drastically.[18, Fig. 1] So to achieve the best power output from the cell, maximum power point tracking(MPPT) could be utilised. MPPT is a method, that with one way or another, tries to convert the electricity from the solar cell so, that the output voltage and current would be possibly close to the ones on the maximum power point.[18, pp.1-2]

Different techniques of MPPT have been developed, but they are mostly focusing on higher power solar systems, where increase of performance has bigger advantages in increased produced power. MPPT is performed using a controlling circuitry which controls the electricity flow from the cell to achieve the maximum power point. There are multiple ways to perform this. Some methods utilise active measurements and search for the maximum power point and some others are preset to approximate the maximum power point from cell voltage. Obviously the more complicated tracking methods require more processing power and thus consume more electricity. They are usually more expensive too. On the other hand they are better at finding the maximum power point and so increase the performance of the solar system. So the bigger the overall system is, the more it pays off to use more sophisticated methods.

For low power applications though, the ratio between the power the MPPT device uses, and the power that is being harvested will decrease. So using a separate processor to take measurements and to calculate the maximum power point might use too much power. Luckily there are microchips available that have been designed to perform in low energy harvesting purposes.

6 Conclusions

To start evaluating the suitability of energy harvesting in certain use and environment, it is good to start from approximation of the end devices possible energy consumption. To achieve that, a measurement method was proposed and demoed in this thesis. Instead of classically tracking current and voltage of the device, the energy consumption was determined by measuring the energy transferred from a capacitor, to obtain more precise values. By determining the energy consumption of different operational modes this way, the energy budged for different workloads can be calculated and the amount of energy storage needed can be determined. For example, the recovery times after more power consuming actions can be calculated if the consumption and estimated amount of harvested power are known, like in equation 12.

The environment and the energy harvesting techology, in this case solar panels, have to be analysed to determine the energy that is harvestable. Indoor lighting was studied from the perspective of power available for solar panels to use. This was done by calculating conversion rates from lux to W/m^2 for two LED light spectras, warmwhite and coolwhite. With this, approximated values for indoor energy density could be calculated under typical indoor illuminance levels. This is not only crucial to uncover the energy available, but also to help determinine the solar cell type to be used, since different solar cell types have different responses to lower light levels. Cells made out of amorphous silicon can preserve their efficiency better in low illuminance, unlike cells made out of crystalline silicon, the efficiency of which tend to experience a major drop when utilised under lower light levels.

For low power energy storage, supercapacitors and Lithium polymer batteries were compared. While rechargeable batteries have a higher energy dencity and lower price, supercapacitors can handle multiple recharge cycles better in the long run. So, it depends on the use and requrements, which is more suitable for which situation. For example, if the device is longer times without possibility to recharge, the larger storage capability of lithium battery might be beneficial, unlike in the situation, where the device just needs to stay operational while it is also capable of harvesting energy.

This thesis has covered the main aspects of energy harvesting and what to take into consideration when applying it to real life products. Approaching energy harvesting in an analytive manner is crucial to get a working solution in highly challenging environment. Having realistic approximations of the requirements and capabilitiesof the system, as well as the challences and limitations of the environment, helps to build reliable and operational systems.

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