Wood pole vibration monitor – Power supply

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Abstract

The utility pole sensor would need a reliable source of energy to power its microcontroller and sensors. The device is designed to be low power thus not much energy is needed per wake up. However, this device wakes up many times during a day and must be able to continuously operate for 20 years. A choice needed to be made regarding a primary or secondary energy source. Current energy storage technology is not able to provide a primary battery that has enough energy or lifespan - at our cost limitations - to last the whole 20- year maintenance cycle. Solar energy harvesting with a secondary energy source was chosen as source of energy.

The Power supply design consists out of three main parts:

- Solar panel
- Power management device
- Energy storage

The system turned out to successfully work in real life as it did on paper. However the actual functioning of the power supply was limited to the fact that it could not be tested with the correct load conditions, the parameters of the power supply could also not be changed to calculated ones due to the use of an evaluation board. Due to limited time there was only 2 days to acquire results therefore they were enot so thorough.

Designing a device that has a 20 year lifespan turned out to be tricky but a big success due to supercapacitor technology.

Acknowledgements

As I write this acknowledgement there is 10min left before this project is due.
Many things change, but somethings always stay the same.

Studying engineering at UCT was so much more about the degree. It included learning about culture, identity, and the fact that all of us are just trying to carve our own path in this life. The experience has been hard, fun and incredibly rewarding. I've gained a fundamental understanding of how most things work and got armed with an ability to use those fundamentals to solve any problem. I also walk out with life-long friends and a better sense of who and what I want to be in this world.

Finishing a Mechatronics degree has definitely been the biggest challenge I've faced this far and I can happily say, I did it.

And for whoever reads this. You can do anything you put your mind to. Look, the proof is in the pudding

Thanks everyone.

Plagiarism declaration

1. I know that plagiarism is wrong. Plagiarism is to use another's work and pretend that it is one's own.
2. I have used the IEEE convention for citation and referencing. Each contribution to, and quotation in, this final year project report from the work(s) of other people, has been attributed and has been cited and referenced.
3. This final year project report is my own work.
4. I have not allowed, and will not allow, anyone to copy my work with the intention of passing it off as their own work or part thereof

Name:	**Michael Wetzel**		
Signature:	**M.Wetzel**	**Date:**	13 November 2021

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1. Introduction

This report details the research, design, implementation, and optimisation of a power supply subsystem of a utility pole sensor.

1.1 Background of Study

Is it a bird? is it a tree? No, it's a utility pole. Blending into walkways and lampposts, utility poles are all around us. They span millions of kilometres and provide a connection between consumers and electricity providers. To reduce losses during transmission, electricity is transmitted at high voltages. Failure of electricity poles comes at high risk to humans and the environment. If a power line comes into contact with a tree or a road sign it creates a ground connection to the earth and one can be electrocuted just by being in the vicinity. In addition, unexpected pole failure brings about maintenance costs and power outages. Which brings about the question; can one monitor the health of an electricity pole and predict failures before and when they happen?

The answer is yes. Electricity poles are predominately made from wood. Healthy poles vibrate at a different frequency than poles that are leaning or have been damaged. A combination of attitude and vibration measurements can give one an estimate of the health of a pole

There is also the case of sudden unexpected failure for example, a tree falling on the power line, a car crash or flooding. By monitoring the anomalous magnetic field created by the power lines, one can detect a sudden change and thus identify when a pole has failed.

The utility pole vibration sensor design and implementation are split up in subsystems between multiple final year Mechatronics students.

1.2 Utility Pole Sensor

The device should be low-cost, easy to install and continuously provide data regarding the health of a pole. The device should be able to supply the following information:

- Mechanical inclination of a pole
- The dc and ac magnetic field
- Temperature, vibration and shock
- Detect anomalous changes in magnetic field

The device must have some form of power supply, either by battery or energy harvesting. Device must be able to communicate with neighbouring sensor in a daisy chain manner. The maintenance cycle of the device is 20 years.

1.3 Power Supply Subsystem

The utility pole sensor would need a reliable source of energy to power its microcontroller and sensors. The device is designed to be low power thus not much energy is needed per wake up. However, this device wakes up many times during a day and must be able to continuously operate for 20 years. A choice needed to be made regarding a primary or secondary energy source. Current energy storage technology is not able to provide a primary battery that has enough energy or lifespan - at our cost limitations - to last the whole 20- year maintenance cycle. Solar energy harvesting with a secondary energy source was chosen as source of energy.
The Power supply design consists out of three main parts:

- Solar panel
- Power management device
- Energy storage

The energy storage was by far the most challenging part to design due to the long lifespan requirement of the device.

1.4 Objectives

The objective of this report is to design and implement a power supply for a utility pole sensor, able to power it for 20 years. The following were sub-objectives that were needed to accomplish the main objective:

- Estimate device power requirements. This step is crucial to determine the amount of energy needed from energy harvesting and the amount of energy needed to be stored.
- Conduct a study on climate conditions of South Africa and estimate energy available
- Research and choose suitable components
- Test components to check if they satisfy specifications given
- Assemble and collect data from component
- Assess results obtained

1.5 Thesis contributions

After a thorough literature review was conducted, devices with a long lifetime in the range fifteen or more was found to be limited. The use of supercapacitors has been studied with a focus of their quick charge and discharge rate and the application of this in modern day electronics. Although many websites and articles discuss the almost infinite lifetime of supercapacitors in respect to batteries, literature does not have many actual examples. This project aims to provide an example of the design of a wireless sensor that can last 20 years.

1.6 Scope and limitations

Limitations:

- Time was a big limitation in the project. Partly due to myself falling ill halfway through the project.
- The power management circuit’s evaluation board not having tuneable parameters

Scope:

The project involved designing and implementation of a power supply able to power a sensor for 20 years. Scope included:

- Thorough literature review of existing wireless sensors and their respecting power supply technology.
- Research on different energy harvesting techniques and energy storage devices.
- Hardware design and implementation of the power supply.
- An actual working system
- Results

1.7 Thesis outline

The remainder of the thesis is organized as follows:

Chapter 2: Literature review

Chapter 3: Methodology

Chapter 4: Energy requirement

Chapter 5: Energy availability in South Africa

2. Literature Review

2.1 Introduction and structure of Literature review

For a utility pole sensor to operate as intended it needs access to electrical energy. The device does not have access to AC mains and therefore needs an external power supply. In this literature review I explore various options and methods of providing energy to a device. First energy harvesting and its different methods are explored, after which an in-depth analysis of solar energy harvesting is done. Next, different energy storage technologies are explored with a focus on Li-ion batteries and Super Capacitor technology. Finally, I conclude highlighting gaps in literature. Figure 2.1 provides a flowchart of the literature review

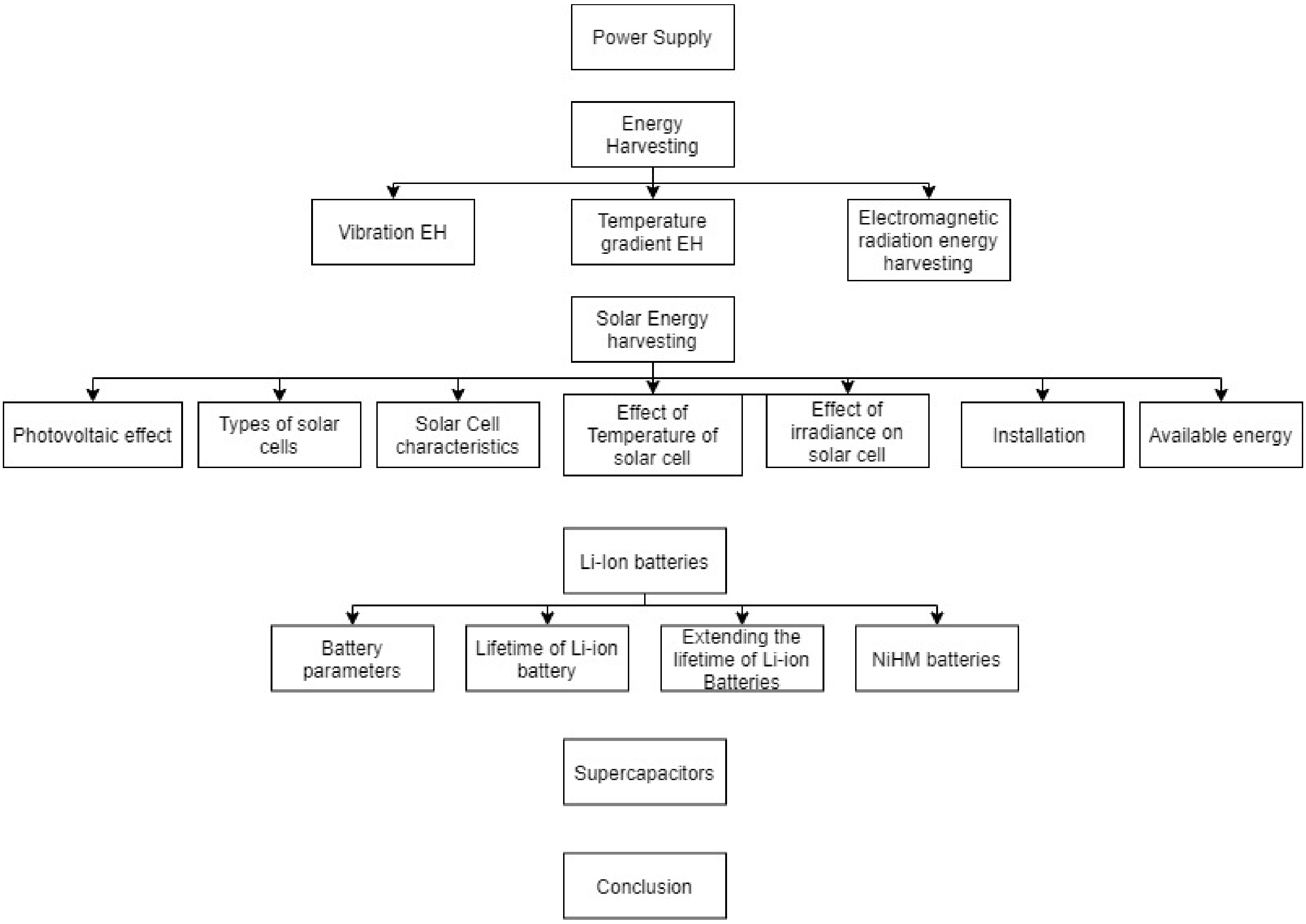


Figure 2.1: Flowchart indicating structure of Literature review

2.2 Power supply

One should not confuse a power supply with a power source. A power source is where and how the power is obtained, either through energy harvesting, a mains outlet, or a battery. A Power supply function is to convert the power coming from the source into the right format and quantity that is needed by the load. A power supply is responsible, but not limited to, the following tasks:

- Step up or down of Voltage
- Output Voltage regulation
- Over Voltage and over current protection
- AC-DC conversion and vice versa [1]

In this final year project when referring to a power supply, it is an all-encapsulating term for providing power to the device. It includes these three main parts:

1. Power source
2. Power management (Power Supply)
3. Power storage

Power source and power storage will be discussed, starting with the power source. The device does not have access to AC main and therefore this branch of power sources will not be discussed.

2.3 Energy harvesting

Wireless sensor networks, smart devices and wearable tech have conventionally been using electrochemical battery technology as a power source. However, the life of the battery is often insufficient to satisfy the demands of the device. The limited lifetime of battery technology and a global shift to clean/renewable energy has fuelled the way for energy harvesting research [2, p. 1].
Energy harvesting as defined in [3, p. 541], is the collection of locally available natural energy. Energy that would have otherwise been converted to heat. An energy harvesting device takes in one medium of energy and converts it into electrical energy through some mechanism. There are two main groups into which energy harvesting is divided:

- Macro-energy harvesting: In this technology energy is harvested in the kilowatt to megawatt range and is seen as an alternative to non-renewable energy sources.
- Micro-energy harvesting: in this technology energy harvested is tiny in the microwatt to milliwatt range. These harvesters are designed around collection of residual energy sources and is seen as a replacement for electro-chemical battery technology [4, p. 3]

In this literature review micro- energy harvesting will be considered since the utility pole sensor is a low power device using microwatts of power. There are different types of energy harvesting that can be used and each is applicable to the type of energy that is available and the energy requirement of the device. Different types of energy harvesting are shown in figure 2.1.

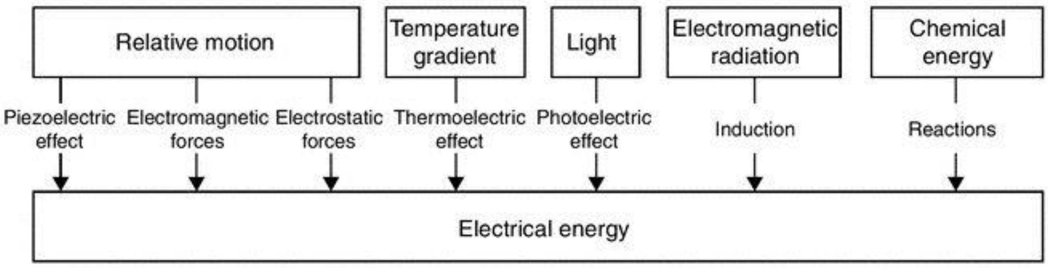


Figure 2.1: Categories of energy harvesting. Source: [3, p. 542]

2.3.1 Vibration energy harvesting

As mentioned earlier an energy harvesting device converts different energy sources into electrical energy. On railroads and bridges, one such type of energy is very abundant, namely vibration. Devices have been designed to use the piezoelectric-, electromagnetic- and electrostatic effects to collect the ambient vibrational energy around the device into electrical energy.
A piezoelectric transducer uses active material to convert mechanical strain into electrical charge by means of intrinsic polarization of the material [2, p. 2]. an electromagnetic device consists of a tiny magnet inside a coil as illustrated in Figure 2.3. When there is ambient vibration, the magnet moves in a relative translational motion with the coil and thus following Faraday's rule, produces an electrical current [5, p. 3]. An Electrostatic transducer make use of variation in area and separation of capacitance plates in response to mechanical vibration. This causes a change in voltage and thus a flow of current [6]. Examples of possible vibration harvesting circuits are given in [7] and [8] provides a design and study of a vibration powered sensor node.

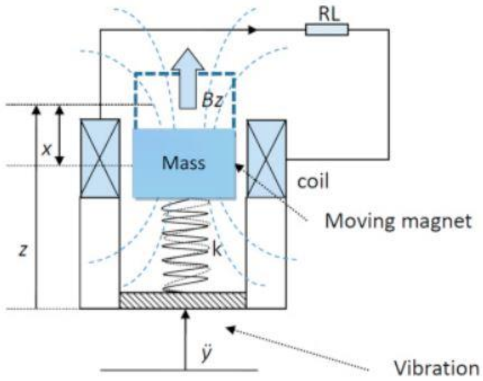


Figure 2.3: Model of an electromagnetic vibration energy harvester. Source: [5, p. 4]

2.3.2 Temperature gradient energy harvesting

Thermoelectric energy harvesters generate a current according to the Seebeck effect. One side of the transducer is exposed to heat while the other end is cold. This creates a temperature gradient in the material – metal and semiconductors - and charge carriers move like gas particles from the hot end to the cold end. This creates a net charge on the cold side resulting in an electrical potential difference. In this manner a current is produced [9]. This harvester is useful in environments which produce a temperature gradient like wrist watches, heat pipes, and motor engines. The efficiency and hence possible power output of the transducer is small, efficiency ranging from 5-15% and power output from hundreds of microwatts to a few milliwatts [10]. Examples of wearable thermoelectric energy devices are shown in [11] and discussed thoroughly in [12].

2.3.3 Electromagnetic radiation energy harvesting (EMREH)

EMRH is concerned with the collection of energy from artificial radiofrequencies that are present all around us. Sources can include wi-fi routers, radio stations and mobile signal stations. One can either harvest from a specific radio frequency (RF) source or gather energy from ambient RF. The 2 most important design considerations of this type of energy harvesting is the receiving antenna and the rectifying circuit. Since the ambient radio frequency sources are weak, an antenna with a high gain must be used. A rectifying circuit with high efficiency should be chosen and is currently the biggest challenge faced with this technology, as this is where most power is lost [13]. [14] discusses energy harvesting from ambient radio frequencies and mentions on page 4, that energy harvested from solar power dominates radio frequency harvesting even on a full moon cloudless night. Figure 2.4 shows the energy available from different sources. One can see that cell phone towers and wi-fi transmit a fraction of the power sunlight does.

Interior lighting [W/m^2]	Moon [W/m^2]	Cell tower [W/m^2]	WiFi [W/m^2]
0.5	1.0×10^{-3}	0.1×10^{-3}	0.01×10^{-3}

Figure 2.4: Comparison of different sources of energy. Source: [14]

From [14] it can be concluded that the average power density that ambient radio frequency can provide is around 1 microwatt/cm^3 and thus inferior to what the sun can provide. Designing a EMRH system is challenging due to the need for very low loss components and the technology is still in its infancy.

2.4 Solar energy harvesting

Solar power needs its own section as the sensor will be solar powered.

Starting out as a niche power providing technology 30 years ago, solar energy is today the most widely used renewable energy source [15, p. 3]. This is due to it being a more predictable energy source relative to other renewable energy sources. One can estimate the available energy fairly well if provided with a location, solar cell type and positioning [4, p. 37]. Solar energy harvesting is usually used in conjunction with Maximum Power Point

Tracking (MPPT) methods to get the maximum efficiency out of the panel. [16] discussed different MPPT methods.

Another advantage of solar energy is that it is available in most areas of the world. Solar energy can be harvested in even cloudy areas although the available power is significantly reduced. Most solar cells are silicon based and different types will be discussed in this section. Photovoltaic technology is the most popular solar energy harvesting technique and makes use of the photovoltaic effect. [17], [18] and [19] discuss already implemented solar energy harvesting devices and how to improve them, while [20] is concerned with the design approach.

2.4.1 Photovoltaic effect

Solar cells makes use of the photovoltaic effect. When sunlight hits a solar cell it causes an increase in the electron hole pairs of the semiconductor, which causes an increased concentration of minority carriers in the depletion region. Minority carriers are holes in the n-type region and electrons in the p-type region. This has the effect of causing the minority carriers to flow from the depletion region into the quasineutral region. Thus, a current is generated [21]. Figure 2.5 provides the basic structure of a solar cell connected to a load.

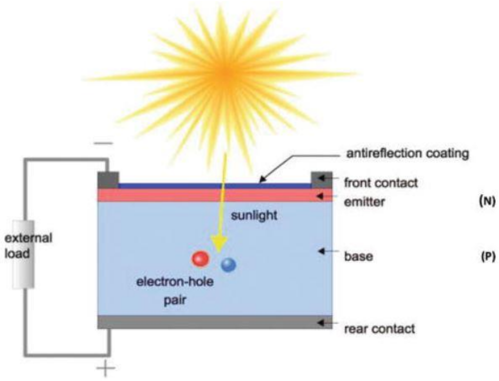


Figure 2.5: Incident light on a solar cell. Source: [21]

2.4.2 Types of Solar cells

Crystalline-silicon technology dominates as solar panel material with 80-90% of solar panels consisting of it [22]. A Solar panel is made up of different series connected solar cells. There are 3 different PV solar cell types:

- Mono-Crystalline Silicon; These cells are made out of single-crystalline silicon and has the highest efficiency of around 14%. The technology is however more expensive to produce than other types
- Multi-Crystalline Silicon; These cells are composed of multiple silicon crystals that are melted and poured into moulds. The efficiency is slightly lower at around 11%. These cells are however less expensive to produce than Mono-Crystalline cells and contributes to less waist.
- Amorphous Silicon; This type of cell suffers from a lower efficiency and life-span but is more cost effective. This type is used in smaller applications [23, p. 50], [24].

2.4.3 Solar Cell characteristics

Solar panels have specific characteristics and operation curves. The following are parameters and characteristics of a solar cell:

- Open circuit Voltage (V_{OC}): This is to total maximum voltage that the solar panel can produce
- Short circuit Current (I_{SC}): The current that flows from a solar cell when the cell is short circuited. This is the highest amount of current that the solar panel can provide.
- Maximum Power: This is the product of the maximum values of current and Voltage in the V-I curve of a solar cell.
- Efficiency: This is the ratio of the output energy of a solar cell compared to the input energy received.

A solar cell is normally rated by the peak amount of power it produces when illuminated by a 1000W/m^2 irradiance source at 25 degrees Celsius. This is defined as standard test conditions [25, pp. 144-143].
Manufacturers will commonly include a V-I power curve and as can be seen in figure 2.6 the maximum power is reached just before the knee of the current curve. Any increase in voltage will decrease the power.

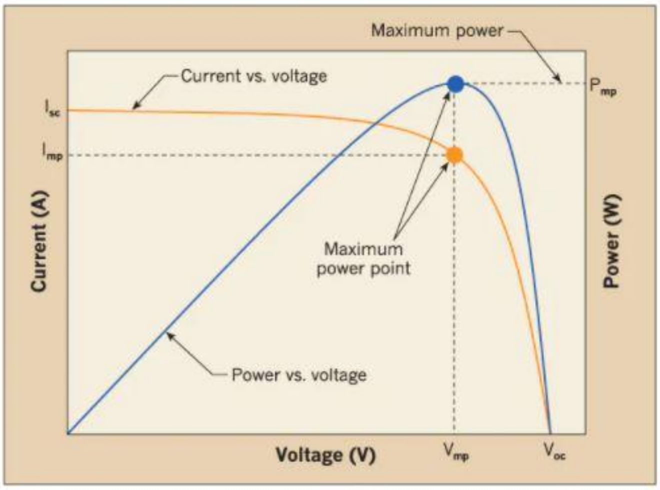


Figure 2.6: V-I curve of photovoltaic module. Source [26]

2.4.4 Effect of temperature on solar cell

The output power of the solar cell depends on the temperature of the cell. Open circuit voltage decreases as temperature increases. This is due to an increase in reverse saturation current. Solar panel data sheets can provide a temperature coefficient which will most often define the change in open circuit voltage with respect to degrees.

2.4.5 Effect of irradiance on solar cell

The prime source of energy driving a solar cell's output is sunshine. Irradiance is directly proportional to the current provided by the solar panel. Voltage, however, has a more logarithmic function to irradiance. Figure 2.7 shows the general current-voltage curve at different irradiances. It can be seen that if irradiance decreases, then the power output of the solar panel will decrease. [25, p. 144]. The voltage of a solar cell is much less sensitive to irradiance than current. One can assume that if there is ambient light, then the solar module can produce its rated voltage output [26].

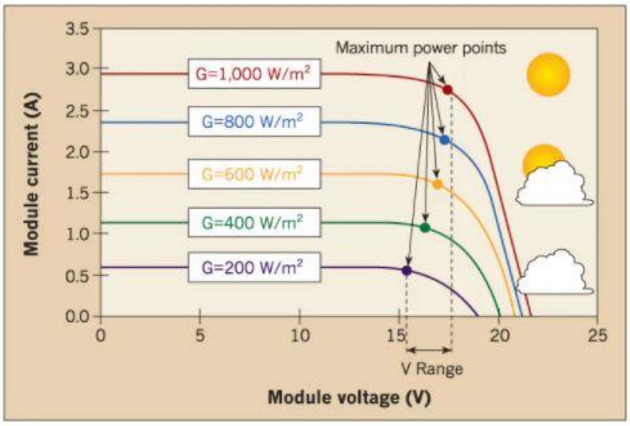


Figure 2.7: Voltage vs current curve with varying irradiance intensities. Source [26]

2.4.6 Installation

The amount of electrical power produced by a solar panel is directly proportional to the amount of solar radiation received. One can either have a sun-tracking or a fixed solar panel installation. When using the latter method, the panel is most effective at certain orientation and tilt angles. It is worth noting that a sun tracking system receives around 30% more irradiance than a fixed installation [27, p. 7].

The rule of thumb is that if the location is in the northern hemisphere the solar panel should be faced south and vice versa. The tilt of the panel should be roughly equal or a few degrees lower than the latitude of the location [23, p. 44], [28, p. 2]. For example: Cape Town, South Africa has a latitude of 33° and according to [29] the optimal tilt is 29 °. [28, p. 2] states that a panel is not that sensitive to minor deviations in tilt and North-South orientation. A panel installed in the northern hemisphere, 45 degrees east or west of south will only have a 6% reduction in power output. A panel installed at 0 degrees instead of at latitude tilt will only have about a 10% in power output reduction.

Solar panels should optimally not be installed in a position shaded of the sun as shading dramatically reduces the power output of a solar panel. To calculate the amount of irradiance hitting a shaded area is complicated and different in each situation. It depends on the weather conditions of the day and hugely on the position of the panel relative to the object shading it [30]. [31] suggests that solar panels in the shade produce roughly 50% less output power than in sunlight although testing will be done on the specific solar panel for this project to determine the power production in shade reduction.

2.4.7 Available energy

The sun is a hot energy dense star making up about 98.88% of the mass of our solar system. It emits a massive amount of energy and only a fraction is intercepted by the earth. However, this tiny fraction is still thousands of times more than the daily energy consumption rate. Being able to estimate how much energy is available at a location is imperative to the profitability and functionality of a solar powered system. Literature is rich with methods for calculating available energy based upon time, day, year, weather and panel orientation. [23] and [25] provides formulas and ways to calculate the theoretical energy availability at a given location. A script can be compiled to calculate these values and [32] provides a python script example. The use of these equations is out of scope of this project but in future iterations a database of available energy can be compiled.
As shown in figure 2.6, the solar energy hitting the surface of the earth comprises of two types:

- Direct normal irradiation (DNI): This energy hits the earth's surface directly without being blocked by any atmosphere
- Diffuse horizontal irradiation (DHI): The amount of energy that gets intercepted by clouds

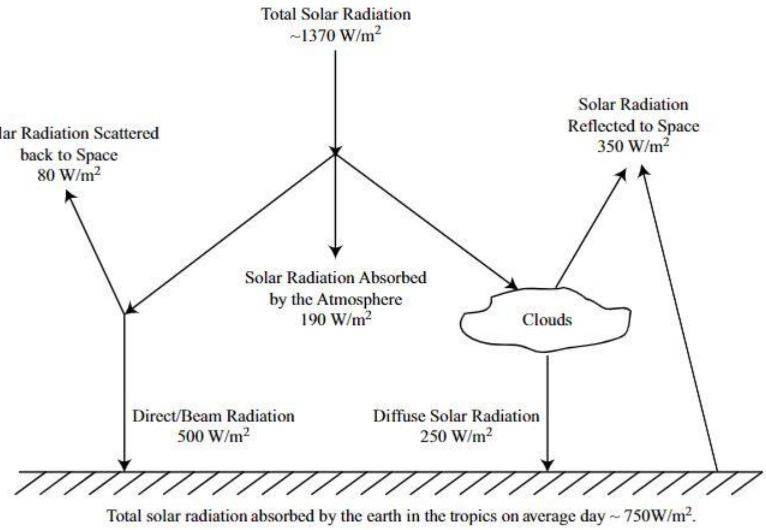


Figure 2.7: Simplified sketch of solar irradiance hitting the earth. Source: [23]
Global Horizontal Irradiation (GHI) is the sum of the diffuse horizontal irradiance and the direct normal irradiance based upon the formula:

$$GHI = DHI + DNIsin(\theta) \quad (2.1)$$

Where θ is the angle between the sun's rays and the vertical of the earth's surface (zenith angle) [28].

The amount of irradiance on a tilted surface vs a surface perpendicular to the sun's rays will vary. The amount of irradiance received on a tilted surface at a specific angle is coined Global Tilt Irradiance (GTI). GTI is of concern to a photovoltaic project since this is the amount or energy the solar panel will receive on it's surface. [27] is concerned about calculating GTI from DNI and GHI measurements. It stipulates that if your DNI measurements are accurate you can get an accurate GTI measurement. Solargis is an online tool providing weather data and software for solar power projects. More importantly it provides you with GHI, DNI and GTI data for a specific location.

2.5 Li-ion batteries

Batteries are the most mature, studied and widely used form of energy storage. The flow of current is made possible by chemical reactions with anode and cathode. A primary battery is a single use technology and once the capacity has been used the battery cannot be recharged. When choosing a primary battery to use for an application one should consider the capacity needed to satisfy the lifetime, size constraints and the operating conditions. Even for low power applications using 100 microwatt of power, primary batteries do not provide a long lifetime [33]. Thus, they will not be discussed.

A secondary battery can be reused and recharged once the capacity has been spent. Secondary batteries are seen as the most capable of handling the requirements - voltage and frequency regulation, time shifting, etc - of a renewable energy source [34, p. 6]. Lithium-ion batteries are the most popular form of wireless sensor batteries due to their high energy density. [33] provides application of sensors using batteries as energy sources. Examples like intelligent tyres, smart buildings and predictive maintenance is discussed. Figure 2.9 provides a comparison of Li-ion with respect to different battery chemistries. This study is however not concerned with thorough research of the chemical properties and construction of batteries, but more about the application the technology can provide. See [35] for thorough chemical composition and properties.

Li-ion batteries is a well-studied and mature battery technology. This battery is popular in mobile devises due to its high energy density. Li-Ion batteries operate by moving lithium ions between electrodes. There is a big number of possible electrodes to use for a Li-ion battery and this contributes to the big number of variances in operating voltages. Generally, Li-ion batteries are available with operating voltages between 3V and 3.9V. Main disadvantage of this battery technology is that it is sensitive to over and under charging and needs a dedicated protection circuitry [33].

Parameter	Units/conditions	Sealed lead acid	NiCd	NiMH	Li-Ion	Li-polymer	Li-iron phosphate	Rechargeable alkaline
Average cell voltage	V	2.0	1.2	1.2	3.6	1.8-3.0	3.2-3.3	1.5
Relative cost	NiCd = 1	0.6	1	1.5-2.0				0.5
Internal resistance		Low	Very low	Moderate	High	High	High	
Self-discharge	%/month	2-4%	15-25%	20-25%	6-10%	18-20%		0.3%
Cycle life	Cycles to reach 80% of rated capacity	500-2000	500-1000	500-800	1000-1200		1500-2000	<25
Overcharge tolerance		High	Med	Low	Very low			Med
Internal resistance		Low	Very low	Moderate	High (coke electrode) Highest (graphite electrode)			
Energy by volume (volumetric energy density)	watt-hour/liter	70-110	100-150	200-350	200-330	230-410	200	220
Energy by weight (gravimetric energy density)	watt-hour/kg	30-45	40-60	60-80	120-160	120-210	100	80

Figure 2.9: General characteristics of dfferent battery chemistries. Source [36]

2.5.1 Battery parameters

There are a few important parameters pertaining to this project and will be briefly discussed, see [36] for in-depth information. It is important to note that these parameters will vary per manufacturer and datasheets should be reviewed:

- Capacity: The battery capacity is the integral of current over time and is an estimate of the amount of, capacity – measured in mAh – a battery can charge or be discharged. There are many different terms of capacity including actual capacity, available capacity, rated capacity and retained capacity. Capacity of a battery decreases as it ages.

- Energy density: Energy density of a battery is the division of the energy its able to provide and its weight or volume. This parameter is critical if you have size or weight constraint
- Cycle life: The cycle life is the amount of deep discharging and recharging cycles a battery can withstand before it is unusable in the application.
- Shelf life: The amount of time a battery can be stored at STC and still retain a significant portion of its capacity
- Self-discharge: This is the amount of Capacity internally discharged and thus lost over time.

2.5.2 Lifetime of Li-ion batteries

Capacity loss and internal resistance increase is the ageing metric used to track battery aging. Literature is full of methods to predict battery lifetime. [37] provides a method for analysing calendar aging of a Li-ion battery, while [38] provides a cycle ageing method and [39] provides a method of analysis including both calendar and cyclic aging. Calendar-aging is a function of the state of charge of the battery, the temperature it is stored at and the amount of time it is stored for. Cyclic -ageing is a function of repetitive depth of discharge (DoD), C-rate – measure of the rate at which a battery is discharged or charged - and the Ampere hour throughput. [40] however, states that no matter which method of lifetime prediction you use, the real-life lifetime still differs quite a bit from the theoretical given. Ultimately their lifetime is dependent on the manufacturer, construction, and most of all working conditions. It is challenging to find literature with confident numbers indicating calendar life and cycle life. [41] is a website based on the information from [42] and has provided the most useable information. This source will be used as reference for the remainder of this section 2.6.

2.5.3 Extending the lifetime of Li-ion batteries

DoD is considered the main contributor to battery aging. When a battery is at 0% or 100% capacity one side of the cell is full of ions and the battery experiences strenuous forces that adds to its deterioration. By keeping a battery's capacity between 20% and 80%, one can double the life of a battery. Table 1 shows how the cycle lifetime increases with a low DoD.

Depth of discharge	Discharge cycles	
	NMC	LiPO4
100% Dod	~300	~600
80% Dod	~400	~900
60% Dod	~600	~1500
40% Dod	~1000	~3000
20% Dod	~2000	~9000
10% Dod	~6000	~15000

Table 1: Cycle life as a function of Dod. Source: [41]

Li-ion batteries are sensitive to temperature and storing a battery at elevated temperature (>30 degrees) can have worse effects on its lifetime than cycling. Table 2 shows how much a battery retains its capacity after being stored at different temperatures.

Temperature	40% Charge	100% Charge
0 degrees	98%	94%
25 degrees	96%	80%
40 degrees	85%	65%
60 degrees	75%	60% (after 3 months)

Table 2: Capacity Li-ion is able to recover after time period. Source [41]

The Voltage at which a Li-ion battery operates also has a big effect on its lifetime. In general Li-ion batteries charge to 4.2V. In the "How to Prolong Lithium-based Batteries" section of [41] more tables with numbers can be found but the take-out is that for every 0.1mV decrease in operating voltage, the battery lifetime doubles. However a decrease in Voltage constitutes in a lowered capacity. Decreasing the voltage below 3.9V counteractsthe increased lifetime so it is recomemded to keep operating voltage above that. Figure 2.12 shows how lifetime varies with charge voltage.

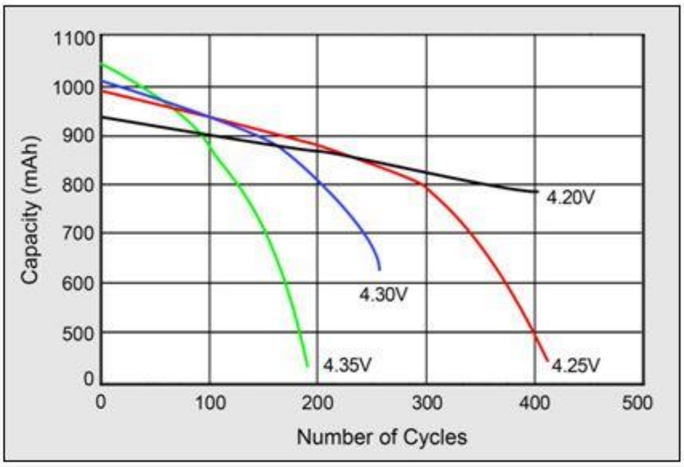


Figure 2.12: Variences in cycle life at different charging voltages. Source: [41]

Thus to prolong the battery life as long as possible, use a lower operating voltage, limit the DoD t as much as possible and keep the operating temperature as low as possible (not below 0 degrees though).

2.5.4 NiMH batteries

Nickel metal hydrate is another type of battery chemistry that are applicable to wireless technology. NIHM batteries have an advantage over Li-ion batteries due to them being generally safe. If these batteries are over charged a chemical reaction will turn the hydrogen and accumulating oxygen to water and no pressure build up will occur. The disadvantages of this battery technology over Li-ion is that the useable temperature (0-45 degrees, while Li-ion is typically 0-60 degrees) and energy density are lower. Another aspect to consider is that NiMH suffers from considerably more self-discharge [33].

2.6 Supercapacitors

Energy harvesting is an applicable power source for wireless sensors. Energy harvesting techniques often provide tiny power values but with innovation in low power devices, that is all that's needed. However, most energy harvesting techniques suffer from not being a continues source of energy. Sensors often work on a continues basis and the device needs an alternative source of energy when the energy harvester is not operational. Batteries have offered great applicability in this case due to their high energy density, however, their cycle life is limited. For devices that need to last a long time this poses a problem.

Supercapacitors, in comparison, have a cycle lifetime from half a million to over a million cycles, infinite in terms of battery lifetimes. Supercapacitors are similar to normal capacitors in the sense that they store energy in an electric field according to equation 2.

$$E = \frac{1}{2}CV^2 \quad (2.2)$$

Where E is the energy in Joules, C is the capacitance in Farads and V is the Voltage over the Capacitor. One can see the energy increases exponentially with an increase in voltage. If a supercapacitor is disconnected from a circuit, it will keep its charge.

The big difference between a capacitorand supercapacitor is a much higher capacitance and slightly different composition [36, pp. 150-164]. Supercapacitors have the following advantageous characteristics as a power supply:

- Relatively infinite cycle life.
- Able to withstand shock, vibration, and temperature changes.
- Predictable remaining energy based upon current voltage level
- High charge and discharge rates [43]

Research on the application of supercapacitors is widely focused around the high discharge and charge rates [44], [45], [46] and the application it has in electric vehicles. Fast charging, regenerative breaking and hybrid battery-supercapacitor systems are being considered. [47] showcases a sensor device with a supercapacitor power source with a 20-year life-time and [48] discussed supercapacitor power management techniques. [49] was found to be the most similar project making use of a small supercapacitor to power small sport sensors, however the project did not make use of energy harvesting and did not have a long device lifetime.

The big disadvantage of supercapacitors is that they have a high leakage rate [50] and research like [43] is focused on providing methods to combat this. Datasheets should be referenced when looking for individual supercapacitor characteristics.

2.7 Conclusion

Research on wireless sensors with a lifetime of 20+ years are scarce and I believe this is because most of the sensors are designed to be battery powered, either by Li-ion or NiHM technologies. The lifetime of the batteries limits the lifetime of the device. Energy harvesting research is thorough and much information can be found. Research on supercapacitors as a power supply for wireless sensors is limited but increasing steadily. The usefulness of supercapacitors as a power supply is recognised but it seems a novel purpose. I believe with a bit more research, supercapacitors in combination with low power devices can satisfy the requirements of the modern-day wireless sensor.

3. Methodology

The following section details the unfolding of the project. Not all is in chronological order as one discovery often led to going back or changing the course of the development plan. For example, while waiting for feedback from my supervisor about device energy requirements I would do research on energy harvesting or realising the possibility of a different energy source led to changing the power management etc. [20] provided a design approach. I did however not assume a load requirement but calculated it and did not make use of MPPT techniques.

3.1 Understanding of basic principles and literature review

The beginning phases of the project is all about understanding what exactly the project entails. A literature review was conducted to find out how others have done it in the past. It was discovered that designing a device with a 20+ year lifetime is rare or maybe novel and literature does not have many examples. This is mainly due to the dominant power supply being electrochemical batteries. A request was sent to my supervisor to confirm the lifetime and he replied with:" Try design for a 20+ year service life, if this is not possible then consider a 10 year life." The challenge was embraced.

From literature and books [25], [13], [20], basic components needed were identified:

- Energy source: either a battery or energy harvesting
- Energy storage: either a battery or supercapacitor
- Energy/Power management: Energy Source first needed to be established before further research towards a power management device

General types of components were scoped based upon certain parameters but before further progress was possible, the device energy requirement needed to be determined.

3.2 Device energy requirement

To determine how much energy the device requires and thus how much the power supply must provide, the functional requirements of the utility sensor needed to be clarified. With the help of my supervisor and a device description document it was established what basic functions the device must be able to provide. Some time was spent trying to calculate exactly how long it will take to run certain scripts or take measurements but, in the end, rough estimates were used (with good reason). Datasheets of each component was studied and an excel spreadsheet created to calculate current consumption of each component during different functions and standby mode. Energy consumption per wake-up was calculated based on supply voltages and time on.

3.3 Power supply possibilities

With the energy requirement per wake-up known, the total amount of energy over the lifespan of the device was calculated. The possibility of having a primary battery as power source proved not applicable as the amount of energy needed was too large for the budget or weight. It was established that the power supply would have to make use of energy harvesting from the surrounding environment and dependant on the availability of the energy harvesting method would need an energy storage device.

3.4 Energy harvesting technology

Although solar energy harvesting was provided as an option in the description of the final year topic, my supervisor made it clear that it was not limited to this type of energy harvesting. Additional form of energy harvesting was researched for example, vibration energy harvesting and temperature gradient energy harvesting, and their applicability assessed. It was determined that solar energy harvesting is the most simple and reliable.

3.5 Climate data

A study of the environment is needed if solar energy harvesting is to be used. Energy generation is dependant on irradiance from the sun and overcast weather reduces the energy output of a solar panel significantly. Cape Town South Africa was chosen as location where the sensor is to be implemented first and an analysis of the climate was done to see if enough energy is available for solar energy harvesting. Average hourly Irradiance data was gathered from [29], temperature from [51] and [52] provided cloud coverage information.

3.6 Energy Storage technology

Batteries are the most mature energy storage technology [33] and an in-depth study of secondary electrochemical batteries was conducted, with a focus on Li-ion technology. Literature did not contain any examples of battery powered sensors with lifetime of 20+ years. Datasheets of different batteries and literature was studied [39], [41] but the general lifetime expectation of electrochemical batteries was found to be non-sufficient, however more research was done to see how one can prolong the cycle lifetime to the maximum.

A study on supercapacitors was conducted and [49] consulted as it has the most similar approach. Improper understanding of the basics of capacitors led to not immediately choose to use this technology and more research on batteries were conducted. It was thought that if a capacitor is connected to a circuit, it will discharge itself according to its time constant in any situation. Consultation with my supervisor concluded that if no current is drawn the capacitor will retain its energy. Thus, supercapacitors were deemed fit for the device.

3.7 Power management device

Search for a power management device on electronic component stores was initiated. The device needed to support solar energy harvesting, supercapacitors and characteristics that matched that of the utility sensor. The cypress S6AE102A PMIC looked promising, and a careful study was made of its datasheet [53]. A flow of operation, voltage and current considerations and applicability to supercapacitor technology (also the possibility of it working with an Li-ion battery) were made and the component was deemed fit.

It was realised that the PMIC has a 24-QFN surface mount packaging and thus soldering would not be possible. Alternative components were considered however they either lacked in some regard or also had surface mount packaging. After consultation with my supervisor the Cypress S6E102A evaluation kit was decided on, which featured the component on a PCB and thus one can test and gather data from it.

3.8 Component value selection and System design

The cypress S6AE102A PMIC has certain voltage, current and operational characteristics that the components need to abide by. A flow of operation was refined, and an idea of possible component values was determined. Energy requirements and datasheets in conjunction with energy calculations led to the choosing of components and component values.

Additional resistor values needed for PMIC settings were calculated and a wiring diagram with all components was created on KiCad. Everything was double checked and components ordered.

3.9 Assembly and data collection

Components were received and assembled. Tests were conducted to verify component parameters. Data was gathered.

4. Energy requirement

An excel spreadsheet was created with relevant electrical characteristics to calculate energy requirements. The following two equations were used to calculate power and then energy.

$$P = IV \quad (4.1)$$

Where power is in watts And

$$E = \int P \, dt \ (4.2)$$

Where energy is in Joules

4.1 Utility pole vibration sensor

The utility pole vibration sensor consists of four main components that draw current namely the microcontroller, magnetometer, power management device and accelerometer. To calculate the total energy requirement needed by the system, all the individual components consumption needed to be calculated and added. This was done by referencing the data sheets of each component. Component suggestions were given in the brief and the energy requirement calculations are only relevant to them. If different components were to be used, the energy requirement would have to be recalculated.

4.2 Device Component electrical characteristics

4.2.1 Microcontroller – CC265R1

The CC265R1 processor is a 32-bit wireless low power microprocessor with Bluetooth and Zigbee functionality. The microprocessor has a dedicated sensor controller engine that controls sensors. Thus, when a measurement is being taken the processor is in idle mode and the sensor control engine is active. Peripherals cannot be used if device is in standby mode. Recommended Operating Voltage is 1.8 – 3.8 V. See appendix A or [54]

Description	Supply current (uA)
Standby with Cache	3,3
Idle	675
Active	3390
Peripheral Current consumption	
Peripheral Power domain	97,7
Timers	81
I2C	10,1
UART	167,5
RFcore	210,9
Sensor Controller Engine	
Active @ 24MHz	808,5
LP @ 2MHz	30,1
Radio Modes	
Radio RX	6900
Radio TX @ +0 dB	7300
Radio TX @ +5 dB	9600

Table 3: Relevant power consumption of CC265R1. Source [54]

4.2.2 Sensors – LIS2D12 & MMC5983MA

The accelerometer has different power modes and low power @ 100Hz will be selected as it is the highest frequency available for low power while still consuming a small current. The magnetometer's supply current is dependant on the output resolution mode. This mode can be set by changing the bits in the inter control register 1. Chosen mode is BW11 as it has the lowest current consumption. See appendix B & C or [55], [56]

Description	Part Name	Supply Voltage (V)	Mode	Supply current (uA)
Accelerometer	LIS2DS12	1.62 - 1.98 V	LP @ 100Hz	12,5
Magnetometer	MMC5983MA	2.8 - 3.6 V	BW11	32

Table 4: Relevant electrical characteristics of sensors. Source [55], [56]

4.2.3 Power management integrated circuit

The PMIC used has a very small current consumption. The LDO has two modes onboard - a normal operation and standby. This mode can be changed via pins and can be managed by the micro controller. More on the PMIC can be found in the design section.

Description	Current consumption (uA)
S6AE102A	0,28
S6AE102A LDO normal	6
S6AE102A LDO standby	0,4

4.3 Functional requirements of device per wake

The device operates in a daisy chain fashion sending data from one sensor to the next. The following is the flow of operation per wake up that was catered for.

- Device must be able to wake up periodically once every minute
- Measure magnetic field (200ms)
- Measure attitude (200ms)
- Make vibration measurement (10s once a week)
- Calculations (50ms):
    - Magnetic field ellipse
    - Attitude from dc magnetic field and gravity vector
    - Vibration measurement FFT
- Listen to three devices upstream and three devices downstream (60ms)
- Transmit data (10ms)

4.4 Current consumption per device function

4.4.1 *Magnetic field measurement*

The MMC5983MA is being used with a UART port. The sensor controller is being used

	Magnetic Field Measurement		
	Description	Current (uA)	Current (mA)
	MMC5983MA	32	
	S6AE102A	0,28	
	S6AE102A LDO	6	
Micro	Idle	675	
	Pheripheral Power domain	97,7	
	UART	167,5	
	Sensor Controll Unit LP	30,1	
	Total	1008,58	1,00858

Table 6: Total magnetic field measurement current consumption

4.4.2 *Attitude & Vibration measurement*

The LIS2DS12 is being used via I2C and the sensor controller is active

	Vibration & Attitude Measurement		
	Description	Current (uA)	Current (mA)
	LIS2DS12	12,5	
	S6AE102A	0,28	
	S6AE102A LDO	6	
Micro	Idle	675	
	Pheripheral Power domain	81	
	Sensor controll active LP	30,1	
	I2C	10,1	
	Total	814,98	0,81498

Table 7: Total attitude & vibration measurement current consumption

4.4.3 *Calculations*

The CPU is in Active mode

	Calculations		
	Description	Current (uA)	Current (mA)
	S6AE102A	0,28	
	S6AE102A LDO	6	
Micro	Active	3390	
	Total	3396,28	3,39628

Table 8: Total current being consumed when doing calculations

4.4.4 *Receive and Transmit*

The MCU is in idle mode and the RFcore peripheral is in use.

	Receive		
	Description	Current (uA)	Current (mA)
	S6AE102A	0,28	
	S6AE102A LDO	6	
Micro	Idle	675	
	Rfcore	210,9	
	Receive	6900	
	Total	7792,18	7,79218

	Transmit		
	Description	Current (uA)	Current (mA)
	S6AE102A	0,28	
	S6AE102A LDO	6	
Micro	Idle	675	
	Rfcore	210,9	
	Transmit	7300	
	Total	8192,18	8,19218

Table 9 & 10: Total receive and transmit current consumption

4.4.5 *Standby*

This is the current consumed by the device when it is in sleep mode. The lDO goes into sleep mode and the MCU is on standby.

	Standby		
	Description	Current (uA)	Current (mA)
	S6AE102A	0,28	
	S6AE102A LDO standby	0,4	
mircro	Standby with cache	3,3	
	Total	3,98	0,00398

Table 11: Total standby current

4.5 Energy calculations

4.5.1 Energy consumption per wake up

A microcontroller operating voltage of 2,3V is chosen. This allows for accurate operation but still low power.

Vibration & Attitude Measurement							
		Current (mA)	Voltage (V)	Power (mW)		t-on (ms)	Energy (uJ)
	LIS2DS12	0,0125	1,8	0,0225			
	S6AE102A	0,00628	2,3	0,014444			
	Micro	0,7962	2,3	1,83126			
	Total			1,868204		200	373,6408
Magnetic field measurement							
		Current (mA)	Voltage (V)	Power (mW)		t-on (ms)	Energy (uJ)
	MMC	0,032	3	0,096			
	S6AE102A	0,00628	2,3	0,014444			
	Micro	0,9703	2,3	2,23169			
	Total			2,342134		200	468,4268
Receive							
		Current (mA)	Voltage (V)	Power (mW)		t-on (ms)	Energy (uJ)
	S6AE102A	0,00628	2,3	0,014444			
	Micro	7,7859	2,3	17,90757			
	Total			17,922014		60	1075,321
Transmit							
		Current (mA)	Voltage (V)	Power (mW)		t-on (ms)	Energy (uJ)
	S6AE102A	0,00628	2,3	0,014444			
	Micro	8,1859	2,3	18,82757			
	Total			18,842014		10	188,4201
Calculations							
		Current (mA)	Voltage (V)	Power (mW)		t-on (ms)	Energy (uJ)
	S6AE102A	0,00628	2,3	0,014444			
	Micro	3,39	2,3	7,797			
	Total			7,811444		50	390,5722
						Total Energy/wake up	2105,809 (uJ)

Table 12: Power and energy consumptions of functions

Note:

Once a week a vibration measurement will be taken for 1 second and the total energy/wake up will be 3974,013 uJ

A 10% overhead will be added to calculations to cover unexpected clock cycles

4.5.2 Energy consumption per day

If device wakes up once every minute, then energy used in an hour is equal to (4.3).

$$\frac{Energy}{hour} = 60 * \frac{energy}{wake\ up} * overhead \quad (4.3)$$

$$\frac{Energy}{hour} = 60 * 2105{,}809\ uJ * 1{,}1$$

$$\frac{Energy}{hour} = 0.139\ (4.4)$$

$$\frac{Energy}{day} = 3.335\ J\ (4.5)$$

The assuming every year has 365 days and 12 months, the amount of energy needed in a 20 year maintenance cycle is: 438219J. Due to this calculation primary batteries will not be used as the size and cost of a battery needed is not feasible.

5. Energy availability in South Africa

This chapter is a study of South African climate parameters that are relevant to the utility pole sensors operation. Temperature, irradiance and cloud cover will be analysed and energy availability assessed. The aim is to get an understanding of how much energy is available for solar energy harvesting and what conditions the components will be subjected to.

5.1 Irradiance data

As said in the literature review, there are many formulas to calculate the theoretical irradiance and energy values for any location at any time. However, for this project real world data from Solargis [29] was used. Solargis [29] provides hourly GHI and DNI data but not hourly Global Tilt irradiance at optimum angle data. GHI values will be used in the cases that the solar panel is not installed at the optimum tilt angle. [28] suggest that a panel installed at 0 degrees will output only 10% less than one installed at optimum tilt angle. This is shown to be accurate by revering to data from Solargis [29], see appendix F. The GTI yearly value is 10.17% more than the yearly GHI value.

Global horizontal irradiation Wh/m^2

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1	-	-	-	-	-	-	-	-	-	-	-	-
1 - 2	-	-	-	-	-	-	-	-	-	-	-	-
2 - 3	-	-	-	-	-	-	-	-	-	-	-	-
3 - 4	-	-	-	-	-	-	-	-	-	-	-	-
4 - 5	-	-	-	-	-	-	-	-	-	-	-	-
5 - 6	-	-	-	-	-	-	-	-	-	-	1	4
6 - 7	56	8	-	-	-	-	-	-	0	28	94	110
7 - 8	243	162	74	28	1	-	-	6	77	198	267	285
8 - 9	439	355	264	177	95	51	57	119	238	377	450	476
9 - 10	633	551	444	333	224	179	195	262	392	547	634	661
10 - 11	800	725	606	468	337	285	310	376	529	693	791	820
11 - 12	924	854	720	562	406	352	386	455	608	796	896	930
12 - 13	992	930	787	613	449	386	424	504	665	845	942	977
13 - 14	998	943	800	610	441	377	423	512	666	835	921	972
14 - 15	937	884	746	555	384	329	374	463	602	744	835	895
15 - 16	809	753	612	429	285	238	284	356	471	596	688	762
16 - 17	636	580	442	275	156	123	161	222	312	417	509	594
17 - 18	439	382	254	90	13	7	13	74	135	230	316	399
18 - 19	231	163	43	0	-	-	-	-	3	35	103	202
19 - 20	20	3	-	-	-	-	-	-	-	-	0	15
20 - 21	-	-	-	-	-	-	-	-	-	-	-	-
21 - 22	-	-	-	-	-	-	-	-	-	-	-	-
22 - 23	-	-	-	-	-	-	-	-	-	-	-	-
23 - 24	-	-	-	-	-	-	-	-	-	-	-	-
Sum	8157	7293	5793	4139	2792	2329	2628	3349	4698	6341	7448	8102

Figure 5.1: Hourly GHI irradiance data for Cape Town South Africa. Source: [29]

From this data it is clear that irradiance is high between November to March and low from May to August. It would be best practise to design a device to have enough power even in the low months.

5.2 Consecutive overcast days

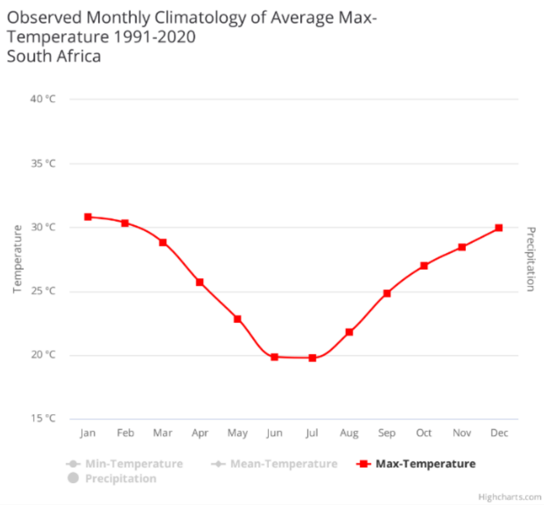
[52] was a study made to determine the effect of irradiance on photovoltaic panels in south Africa. Included in the study was research regarding the number of consecutive days one would have sunny, variable or overcast weather. The data is shown in table 5.2. This is of concern to this project because it gives an estimate of how long the power supply should be able to sustain itself without a solar energy harvesting method to charge it up. The number of days varies from one to nine so I will take five days as an average

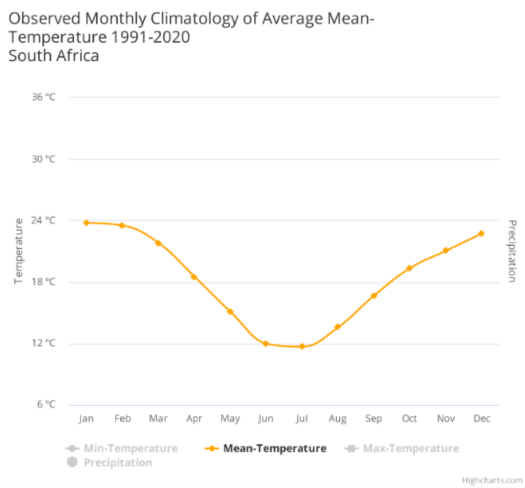
Aggregation level	Square size [km]	No. of power plants	Sunny weather *High production*	Variable cloudiness *Intermediate production*	Overcast weather *Low production*
			[Maximum number of consecutive days per year]		
0	5	1	10 to 58	3 to 20	1 to 9

Table 5.2: Consecutive days of a certain weather. Source: [52]

5.3 Average temperature

Below are three graphs indicated average temperature values according to the database of (move the bracket ref to sentence on top it now sits below the graph





A) b) above, C) belowe

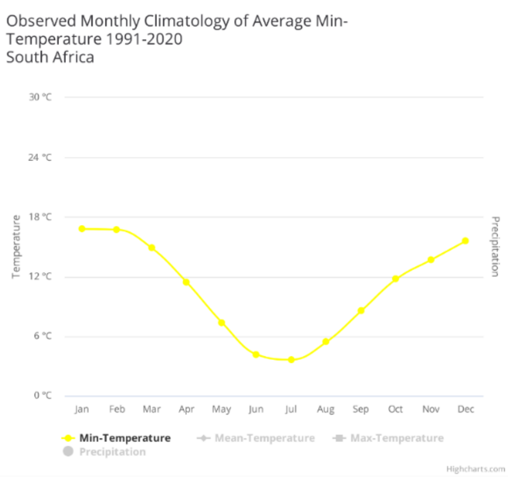


Figure 2.8: Charts showing average temperatures since 1990-2020; a) Average maximum temperatures, b) Average minimum temperatures, c) Average mean temperatures
Source: [51]

From this data it can be seen that the lowest average temperature is in June/July and doesn't go below 4 degrees. The highest average temperature is around 32 degrees happening in January. This dictates the operating temperatures that the power supply components should be able to withstand.

6. System design

The 3 main components in the design are the PMIC, solar panel and the supercapacitor. The flow of this section starts with the chosen components, a short description and why they were chosen. Next will be an integration section where the PMIC parameters will be calculated, and the supercapacitor operation discussed. Lastly the flow of operation of the device will be described accompanied by wiring diagrams and extra component values.

6.1 Component characteristics

6.1.1 Power management circuit - S6AE102A

This component is a PMIC designed for solar energy harvesting. The device can be used in conjunction with a primary battery and has the functionality of using a supercapacitor as energy storage. Output Voltage increases and decreases within limits set by the user. The variable ouput will be the input for the onboard Low dropout regulator (LDO) to provide a stable output voltage. The super-low power operation in conjunction with all the features makes this a good choice for the device. The following are recommended parameters that were considered

- Input Voltage from Solar cell: 2.0V – 5.5V
- Output voltage range: 1.1V – 5.2V
- Operating temperature: -40 °C - +85 °C
- Vout setting resistance: 10MΩ - 50 MΩ

The LDO has the following recommended important parameters:

- Input Voltage: 2V – 5.3V
- Output Voltage: 1.3V– 5V
- Maximum Output current: 50mA
- LDO output setting resistance: Max – 100MΩ

The packaging is QFN-20. See [57] for datasheet.

6.1.2 Solar panel

I was limited to what solar panels I could get in the small range of power I require. I chose the smallest solar panel I could find that has a reasonable price. The following are its important parameters:

- Rated Power: 0.52W
  - Power output at 1000 Wh/m^2
- Open circuit Voltage: 4V
  - This fits in with the PMIC input voltage
- Short circuit current: 130mA
- Diameter: 73mm
  - Panel Area = $\pi(\frac{0.072}{2})^2$= 0.004185 m^2
- Efficiency:
  - If Solar panel output $\frac{0.52W}{Panel\ area}$ @ $\frac{1000W}{m^2}$
  - Then Solar panel output $\frac{124.24W}{m^2}$ @ $\frac{1000W}{m^2}$
  - Efficiency = $\frac{Ouput}{Input} = \frac{124.24}{1000} = 12.4\%$

The most important is that the solar panel can provide enough power to run the device and charge up the Energy storage device. Using the data from section 5, the irradiance values of January and June are analysed. January is the month with the highest overall irradiance and June the lowest, this represents the best- and worst-case scenarios for energy production respectably. The GHI values of irradiance

(Wh/m^2) will be used since this is the worst-case scenario where the solar panel is not installed at the optimal tilt. Note that this device did not come with a solar panel

The values in table 6.1 was calculated using equations 6.2 – 6.4.

$$\frac{Wh}{m^2} = irradiance\ values\ from\ Solargis\ (6.1)$$

$$\frac{Wh}{solar\ panel\ area} = \frac{wh}{m^2} * \frac{0.004185m^2}{solar\ panel\ area}\ (6.2)$$

$$Wh\ output = \frac{wh}{solar\ panel\ area} * efficiency\ (6.3)$$

$$Electrical\ energy\ produced = Wh\ output * 3600\ (6.4)$$

Power calculations for solar panel				
January				
Time	Wh/m^2	Wh/solar panel area	Wh output	Electrical energy produced
0-6	0	0	0	0
6-7	56	0,234	0,029	104,4
7-8	243	1,017	0,126	453,6
8-9	439	1,837	0,228	820,8
9-10	633	2,649	0,328	1180,8
10-11	800	3,348	0,415	1494
11-12	924	3,867	0,48	1728
12-13	992	4,152	0,515	1854
13-14	998	4,177	0,518	1864,8
14-15	937	3,922	0,486	1749,6
15-16	809	3,386	0,42	1512
16-17	636	2,662	0,33	1188
17-18	439	1,837	0,228	820,8
18-19	231	0,967	0,12	432
19-20	20	0,084	0,01	36
20-24	0	0	0	0

June				
Time	Wh/m^2	Wh/solar panel area	Wh output	Electrical energy produced
0-6	0	0	0	0
6-7	0	0	0	0
7-8	0	0	0	0
8-9	51	0,213	0,026412	95,0832
9-10	179	0,749	0,092876	334,354
10-11	285	1,193	0,147932	532,555
11-12	352	1,473	0,182652	657,547
12-13	386	1,616	0,200384	721,382
13-14	377	1,578	0,195672	704,419
14-15	329	1,377	0,170748	614,693
15-16	238	0,996	0,123504	444,614
16-17	123	0,515	0,06386	229,896
17-18	7	0,029	0,003596	12,9456
18-19	0	0	0	0
19-20	0	0	0	0
20-24	0	0	0	0

Table 6.1: Energy and Power output of 0.52W solar panel using GHI irradiance values from Solargis

From this it is easy to see that the solar panel output much more energy than is needed by the device – which only needs 0.139 J/hour, equation (4.3) – and therefore will provide enough power to run Device from first light.

6.1.3 Supercapacitor

a 10F supercapacitor from AVX is used. This capacitor has a 2.7 V rated Voltage with a 10 year lifetime. However according to the datasheet and figure 6.1, the lifetime can be extended to 15 years by using the capacitor at 90% rated voltage and 20 years using 80%. A Trade of was made between lifetime and available – The higher the operating voltage, The more Energy is available but the lower the lifetime and vica versa. See [58] for datasheet.

- Maximum Voltage – Fully Charged: 2.45V as this this gives the supercapacitor a 15 year estimated lifetime. However, the supercapacitor will be discharging from its maximum to its minimum throughout its lifecycle and will not at the max voltage at all time. Therefore I estimate that at this max voltage the supercap can reach a 20 years lifetime.
- Minimum Voltage – Fully Discharged: 1.46V, This number will be better explained in the Integration section but it is the minimum voltage the PMIC can provide it + the forward voltage of a connecting diode
- Available Energy: using equation (2.2) the fully charged energy is equal to 30J and the fully discharged energy is 10.66J. Thus, the available energy is the difference being: 19.34J

- If the device uses 3.35J per day it is enough to power the device for roughly 6 days

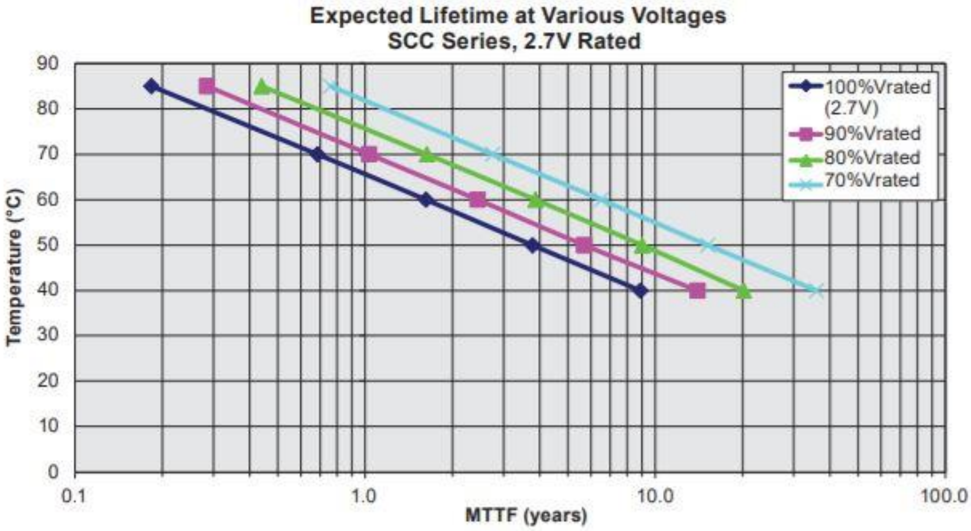


Figure 6.1: Supercapacitor lifetime prediction at different operating voltages. Source [58]

6.2 Hardware Integration

6.2.1 PMIC system Voltages

- Vout upper limit (VoutH): 2.45V
  - According to the PMIC datasheet the Max volage on the supercapacitor is equal to the VoutH. As discussed in section 6.1.3 this voltage is chosen to satisfy the lifetime requirement while still providing as much as possible energy
  - Vout was set by changing the resistors connected to the pins shows in figure 6.2. The formula to calculate resistor values is given in the datasheet:

$$VoutH = \frac{57.5 * (R2 + R3)}{11.1 * (R1 + R2 + R3)} \tag{6.1}$$

  - Setting VoutH = 2.45V and R1 = 10MΩ, an equation with R2 in respect to R3 was calculated
- Vout lower limit (VoutL): 1.1V
  - According to the PMIC datasheet the Lowest voltage on the supercapacitor is VoutL + the forward voltage drop of the diode separating Cap1 and supercapacitor. See figure 6.1, the yellow highlighted section on the Vstore2 Voltage chart shows operation. The lowest possible voltage was chosen to get the maximum amount of energy from the Capacitor
  - Similar to VoutH, VoutL was set using the formula given in datasheet:

$$VoutL = \frac{57.5 * R3}{11.1 * (R1 + R2 + R3)} \tag{6.2}$$

  - Setting VoutL = 1.1 and using parametric equation calculated in VoutH formula. R2 and R3 was calculated to be 5.697MΩ and 3.33MkΩ respectfully. These can be made up of a combination of standard resistor to get as close as possible

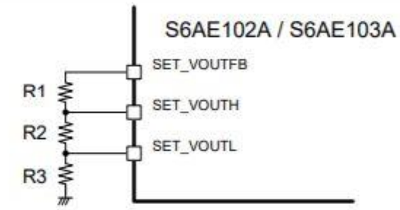


Figure 6.2: Setting of output voltage with R1,R2 and R3. Source: [57]

- LDO output voltage (VoutLD): 2.3V
    - This value is low to reduce power consumption but enough to get accurate operation form the microcontroller
    - LDO output voltage is set by changing the resistor connected to the pins showed in figure 6.3. The formula for calculating the resistor values are given in formula 6.3 and R4 and R5 were calculated to be

Note: It was only later found out that the onboard LDO can only support a minimum of 2V input voltage. Therefore for a future project an LDO with a lower input voltage range should be considered. Design here was just assumed to continue however the onboard LDO would be damaged if operation continued for a long time.

6.3 Power supply operation

The operation of the device can best be described by referring to figure 6.2 on the next page. The section numbers are at the bottom of the figure in blue, red and green.

- Section 1:
    - Solar panel is providing power via VDD and power in is higher than power out. Capacitor 1 (Cap1) charges up.
    - When Cap1 reaches VoutH, SW1 closes, and power is provided to Outputs via Cap1.
    - SW2 opens and SW5 closes, VDD charges Supercapacitor until Cap1 voltage falls below VoutM (VoutM = VoutH * 0.95).
    - SW5 opens, SW2 closes and VDD charges Cap1 up to VoutH.
- Note: If Supercapacitor voltage reaches VoutH it is fully charged and extra power will be discharged.
- Section 2:
    - Power input from VDD is lower than power output to load.
    - SW5 is open and power flows from supercapacitor to Cap1 by overcoming the forward voltage of the connecting diode.
    - When supercapacitor voltage drops to VoutL + VF2 the supercapacitor is fully discharged and SW1 opens.
- Note: If there is not sufficient light, i.e.. Power from the solar panel through VDD and supercapacitor is fully discharged then the device does not have enough power to function and is off.
- Section 3:
    - An increase in power from the solar panel causes Cap1 voltage to rise and device resumes operation described in section 1 and 2.

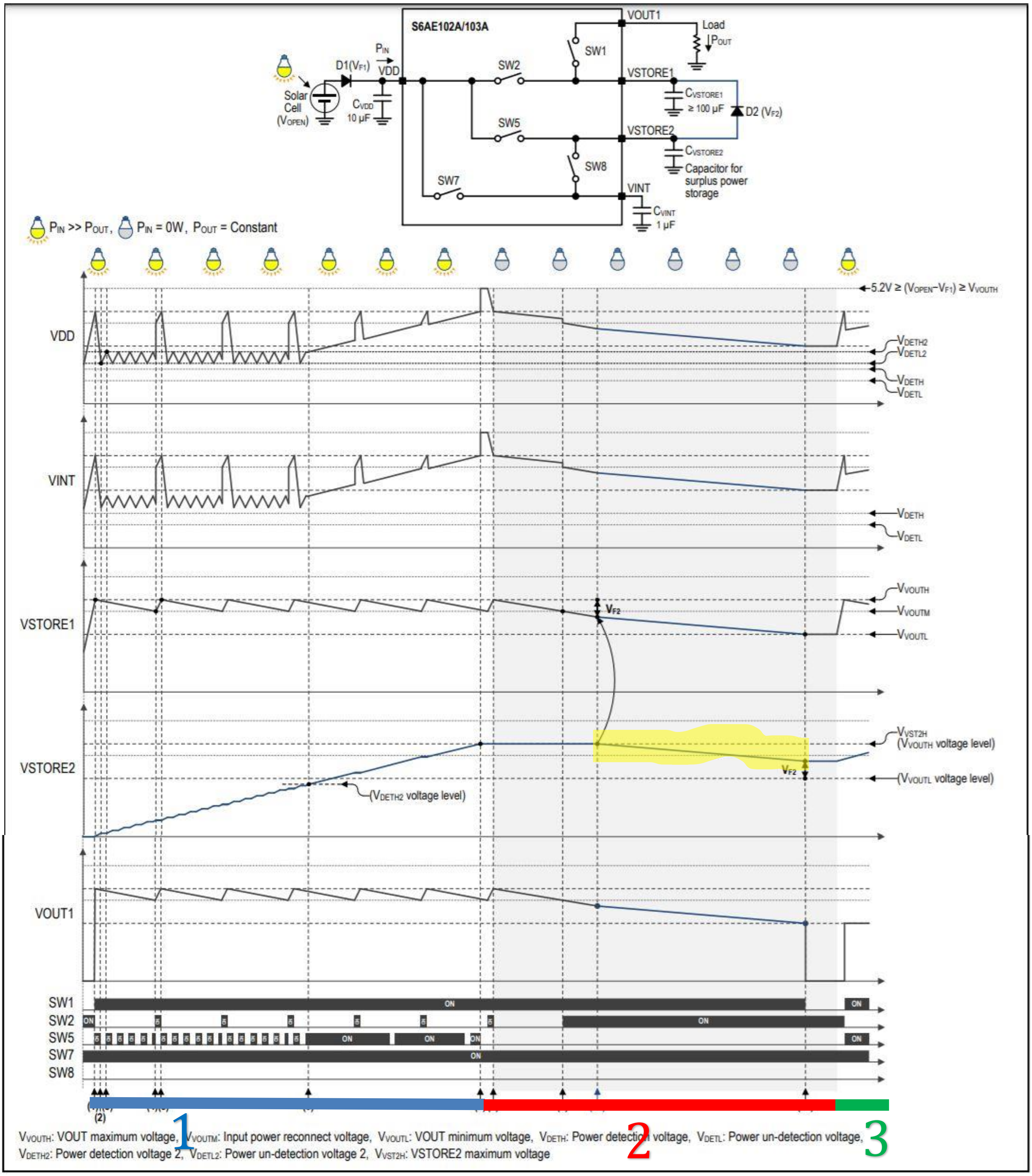


Figure 6.2: Operation of PMIC. Source: [59]

6.4 Wiring diagram

a Wiring diagram of the complete system was created using Kicad. There are 3 extra capacitors included as suggested by the PMIC datasheet. The diodes used are 1SS417 shottkey diodes with a forward voltage of 0.36V at 10mA suggested in its data sheet, see [60].

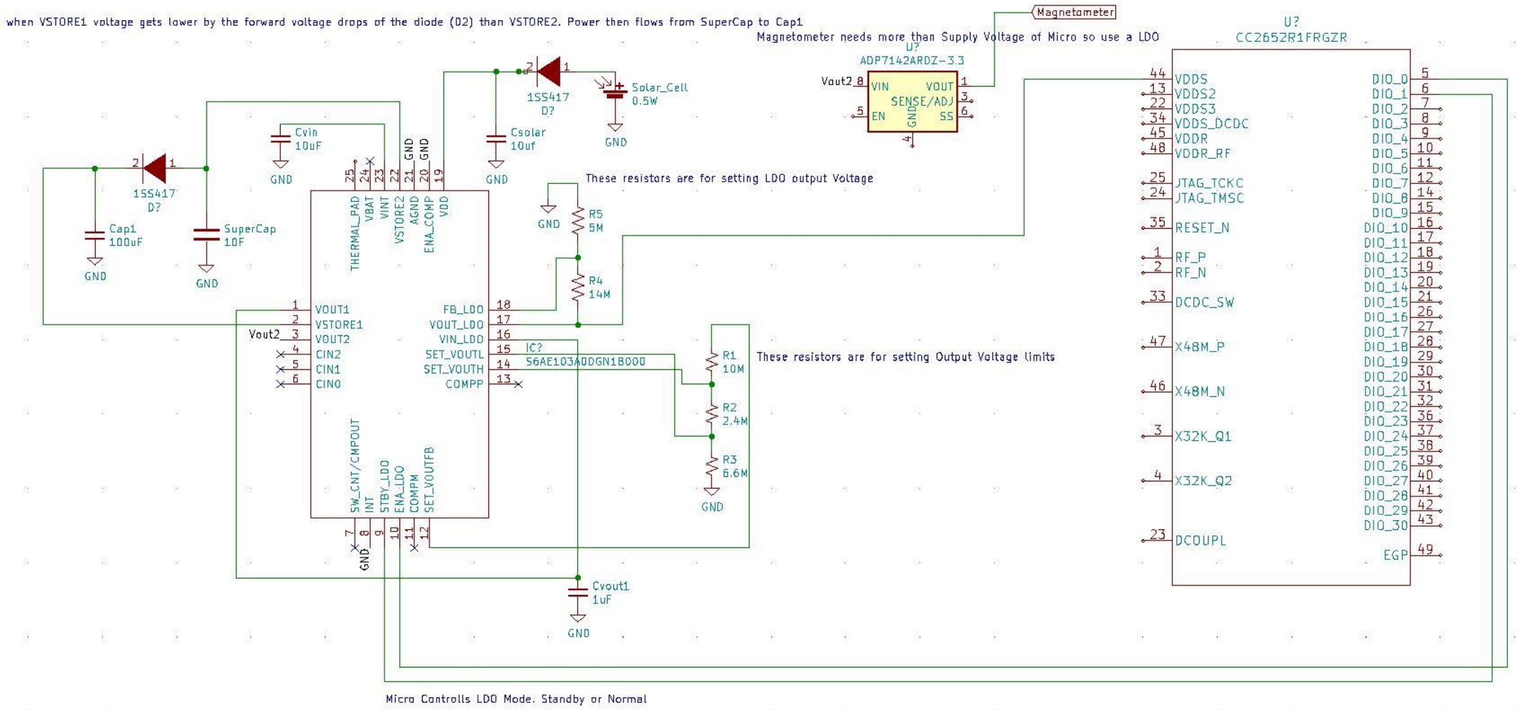


Figure 6.3: Wiring diagram of system created with KyCad. Source: [61]

6.5 System Cost in 10000's of units:

PMIC: R39.82
SuperCapacitor: R42.8
Solar Panel: R25
Total Cost: R107.6

This cost can be cut by contacting manufacteres and providing the big amount of components to order.

7. Results

Unfortunately there was only 2 days available to obtain results. Thus this section is not so thorough but the best was made of the time.

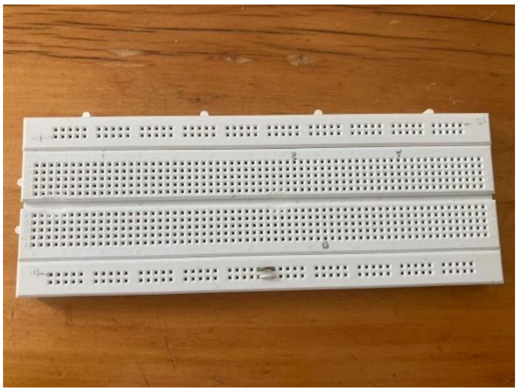
7.1 Experimental setup

The cypress S6AE102A evaluation kit was used to test the system. Reason for this is because of the S6AE102A QFN packaging one cannot solder it using basic equipment. The evaluation kit comes with the component already soldered into a PCB. Due to it being an evaluation kit some parameters were already set and I was not able to change them. Mainly the resistors for setting VoutH, VoutL and Vout LDO were already set and one could not change them.

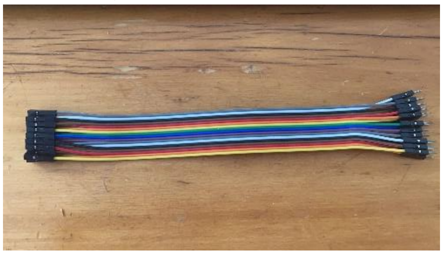
- VoutH = 3.39V
- VoutL = 2.15
- Vout LDO = 1.8V

Testing Components include:

Breadboard



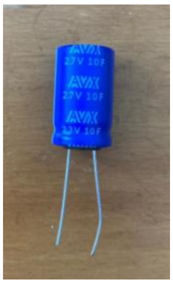
Rainbow jumper wire



S6AE102A evaluation kit

10 ohm Resistor

10F AVX Supercapacitor



0.5W solar panel

Figure 7.1-7.6: Components used in testing

7.2 Experiment description

7.2.1 System in full sunlight

The solar panel was put in full sunlight at 12pm and voltage and current measurements were regularly taken. The supercapacitor started with a 0.32V over it as indicated in figure 7.7. The experimental setup was then left in full sunlight.
The aim of this experiment:

- Test Solar panel parameters
- Test the 3 components together
- Test if the power from the solar panel is sufficient to power the system
- Test whether the power from the solar panel charges the supercapacitor
- See how long it takes to charge the solar capacitor

Solar panel parameters:
In full sunlight @12pm the solar panel had the following parameters:

- Open circuit voltage: 4.5V
- Short circuit current: 40 mA

The three components were connected using a breadboard and rainbow jumpers according to the wiring diagram in section 6.4. a 10 ohm resistor was connected to act as a load and connected between the LDO output pin and ground as shown in figure 7. .

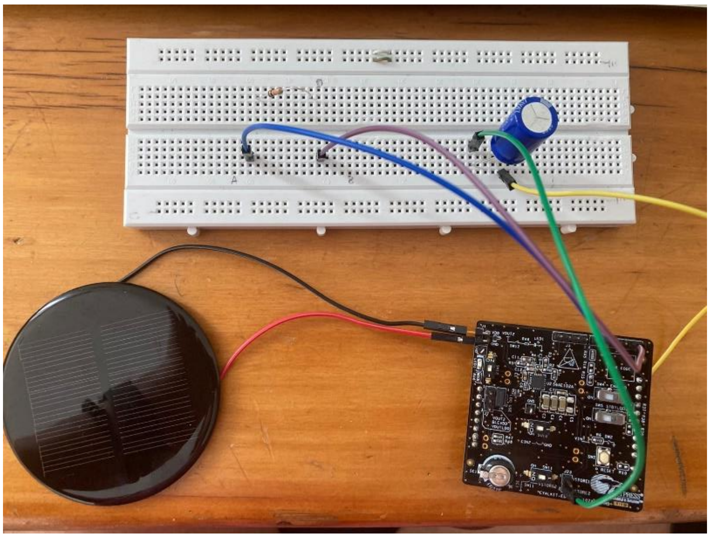


Figure 7.7: Power supply components assembled. Experimental setup. Photo taken with camera

Supercapacitor charging:
Regular measurements were taken over the supercapacitor to monitor its voltage. Time was taken to see how long it takes to charge the capacitor to full

7.2.2 Supercapacitor solemnly powering system

When the supercapacitor was fully charge the solar panel was disconnected. The aim of this experiment was to see if the supercapacitor can power the system when there is no power from the solar panel

7.2.3 System in shade

The system was placed in the shade around 2pm. The solar panel was thus not in direct sunlight.
The aim of this experiment:

- Test solar panel parameters in the shade
- See if system can be powered if device is in shade
- See if supercapacitor can be charged in the shade

7.2.4 Supercapacitor leakage throughout night

The supercapacitor voltage was taken at 7pm and then again 9am the next day. This is to establish how much voltage is lost throughout a night or 12 hours.

7.3 Experimental results

7.3.1 System in Full sunlight

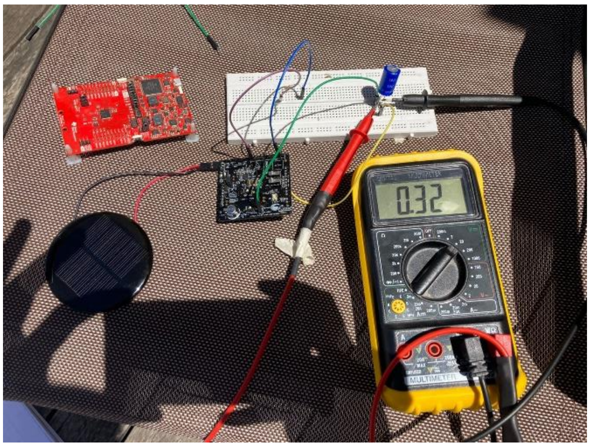
Solar panel parameters In full sunlight at 12pm:

- Open circuit voltage: 4.5V
- Short circuit current: 40 mA
- Power: 180 mW

The components were connected, and placed in full sunlight. Voltage measurements were taken over the Resistor.

- Voltage measurement over resistor: 1.8V

Supercapacitor charging:
In full sunlight the supercapacitor charged from partially discharged - 0.32V, to 3.3V in roughly an hour. See figure 7.8 and 7.9. Energy stored: 54J



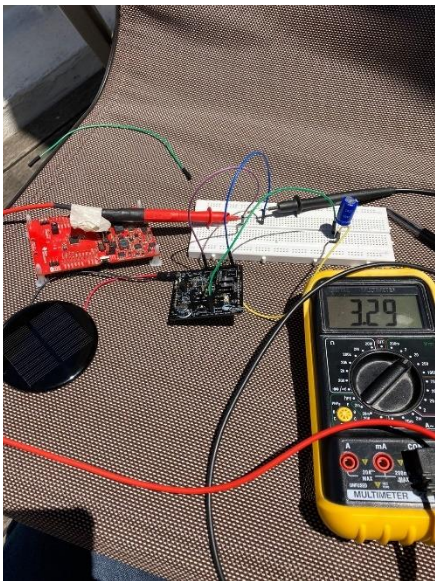


Figure 7.8 and 7.9: Voltages of capacitor before and after 1 hour of charging in full sunlight

7.3.2 Supercapacitor solemnly powering system

Voltage over resistor: 1.8V

7.3.3 System in shade

Solar panel parameters with concrete wall 10m away shading panel:

- Open circuit voltage: 4.1V
- Short circuit current: 7.6 mA
- Power: 31.16 mW

Supercapacitor Voltage at start: 0.11V
Supercapacitor voltage after 1 hour: 0.39V
Energy stored: 0.45J

Solar panel parameters with book 20cm away shading panel:

- Open circuit voltage: 2.3 V
- Short circuit current: 3.2 mA
- Power: 7.36mW

Voltage was measured over resistor was 1.8V in both cases

7.3.4 Supercapacitor leakage throughout night

Voltage at 7pm: 2.56V
Energy at 7pm: 32.76J
Voltage at 9am next morning: 2.38V
Energy at 9am next morning: 28.32J
Voltage loss: 0.18V
Energy loss: 4.43J

7.4 Result discussion

Although the power supply wasn't powering an actual utility sensor. It still showed promising results. The solar panel provides more than enough power in full sunlight to power the system and charge the supercapacitor. The supercapacitor only needs an hour of full sunlight to charge itself full in the experiment. In the actual operation of the device the voltage parameters will be much less and I estimate the supercapacitor can charge fully in half an hour.

If the solar panel is shaded it still produces enough power to power the device. It does charge the supercapacitor at a much much slower rate, almost 100 times slower. The distance that the shading object is from the solar panel has a big effect on how much power it produces. For example if the solar panel is shaded by a big tree 5m away, it will produce 3 times more power than a solar panel shaded by a lead close by. Although in both cases the system can still be powered and the supercapacitor charged.

A troubling find was the voltage leakage of the supercapacitor. In 12 hours it lost 4.43J which accounts to a little more than a day of power. By this logic in 24 hours the supercapacitor would've lost 2 days of operation voltage. One thing to note is that the voltages that were recorded is higher than would be in actual operation. The energy loss is therefore estimated to be much less as energy is the square of voltage.

The solar panel characteristics were lower than described in the data sheets. However, it maintained a suitable input voltage to the PMIC that could power it if shaded and if not.

These results were conducted with a resistor load that had the following parameters:

- Voltage: 1.8V
- Resistance: 10kohm
- Current: 0.18 mA
- Power: 0.32 mW

The resister was continuously discharging so in 1 hour the energy discharged is 1.16J. Which is roughly 10 times more than the Utility pole sensor at around 0.139J – see Section 4, however, the instantaneous power that the utility pole sensor would need is much higher. The solar panel in full sunlight can provide 180mW of power and shaded by a close object roughly 10mW. Which according to the energy requirement of the device is sufficient.

8. Conclusion

8.1 Conclusions

The problem that had to be solved in this project was to design a power supply able to power a wireless sensor for 20 years. This was accomplished by doing a study of the sensor components and calculating the required energy. Research was conducted on energy harvesting and energy storage methods. The system was designed and components ordered. Components was assembled and result obtained from tests.

The system turned out to successfully work in real life as it did on paper. However the actual functioning of the power supply was limited to the fact that it could not be tested with the correct load conditions, the parameters of the power supply could also not be changed to calculated ones due to the use of an evaluation board. Due to limited time there was only 2 days to acquire results therefore they wer enot so thorough.

Designing a device that has a 20 year lifespan turned out to be tricky but a big success due to supercapacitor technology.

8.2 Future iterations

Future iterations of the power supply could include:

- Optimization of cost, efficiency and size of components
    - Especially the solar panel, as much less energy is needed than the one used in this project
- Testing applicability in other climates and providing components that would work
- PCB design
- Better test results with real load used for results
- MPPT techniques introduced into solar harvesting

8.3 What could've been done better

- Not spending so much time on energy requirement calculations which were not that important
- Double checking packaging of components to check if it can be used

References

[1] ACT power, “What Is a Power Supply, and How Does It Work?,” Advanced Conversion Technology, 2001. [Online]. Available: https://www.actpower.com/educational/what-is-a-power-supply-and-how-does-it-work/.

[2] M. K. N. Sezer, “A comprehensive review on the state-of-the-art of piezoelectric energy harvesting,” *Nano Energy,* vol. 80, 2021.

[3] M. K. a. M. Yeatman, “Materials and techniques for energy harvesting,” in *Functional Materials for Sustainable Energy Applications*, Cambridge, Woodhead, 2012, p. 541.

[4] O. Kanoun, “Part 1: Fundamentals and methods,” in *Energy Harvesting for Wireless Sensor Networks*, Berlin, Walter de Gruyter GmbH, 2018, p. 3.

[5] X. J. C. Wei, “A comprehensive review on vibration energy harvesting: Modelling and realization,” *Renewable and Sustainable Energy Reviews,* vol. 74, 2017.

[6] G. D. a. S. S. Boisseau, “Electrostatic conversion for vibration energy harvesting,” in *Small-Scale Energy Harvesting*, 2012.

[7] A. G. C. Covaci, “Piezoelectric Energy Harvesting Solutions: A Review,” *Sensors,* vol. 20, pp. 21-26, 2020.

[8] V. N. J. P. J. C. Rodriguez, “A Vibration Energy Harvester and Power Management Solution for Battery-Free Operation of Wireless Sensor Nodes,” *Sensors,* vol. 19, 2019.

[9] G. Snder, “Thermoelectric Energy Harvesting,” in *Energy Harvesting Technologies. Springer*, Boston, 2009.

[10] D. Enescu, “Thermoelectric Energy Harvesting: Basic Principles and Applications,” in *Green Energy Advances*, IntechOpen.

[11] L. L. Y. Z. e. a. H. Lv, “A flexible spring-shaped architecture with optimized thermal design for wearable thermoelectric energy harvesting,” *Nano energy,* vol. 88, 2021.

[12] H. C. K. D. e. a. A. Nozariasbmarz, “Review of wearable thermoelectric energy harvesting: From body temperature to electronic systems,” *Applied energy,* vol. 258, 2020.

[13] X. B. W. H. e. a. J Zhang, “The design of radio frequencyenergy harvesting and radio frequency-based wirelesspower transfer system for battery-less self-sustainingapplications.,” *Int J RF Microw Comput Aided Eng.,* vol. 29, pp. 1-2, 2019.

[14] A. Q. U. B. S. Mekid, “Energy Harvesting from Ambient Radio Frequency: Is it Worth it?,” *Arab J Sci Eng,* vol. 42, 2017.

[15] S. J. S. S. J. C. I. J. A. Kilner, “Silicon-Based Photovoltaic Solar Cells,” in *Functional Materials for Sustainable Energy Applications*, 2012.

[16] V. G. M. A. J. J. A. A. M. J. M. M. J. Mnati, “Review Different Types of MPPT Techniques for Photovoltaic Systems,” in *International Conference on Sustainable Energy and Environment Sensing* , Cambridge city, 2018.

[17] R. s. Y Li, “An intelligent solar energy-harvesting system for wireless sensor networks,” *EURASIP Journal on Wireless Communications and Networking,* vol. 179, 2015.

[18] A. H. Z. A. J. H. Sharma, “Maximization of wireless sensor network lifetime using solar energy harvesting for smart agriculture monitoring,” *Ad Hoc networks,* vol. 94, 2019.

[19] A. H. Z. D. J. H. Sharma, “Modeling and Optimisation of a Solar Energy Harvesting System for Wireless Sensor Network Nodes,” *Journal of Sensor and Actuator networks,* vol. 7, no. 3, 2019.

[20] B. T. K. R. S. B. J. W. Kimball, “A System Design Approach for Unattended Solar,” *TRANSACTIONS ON POWER ELECTRONICS,* vol. 24, no. 4, 2009.

[21] B. Zaidi, “Introductory Chapter: Introduction to Photovoltaic Effect,” in *Solar Panels and Photovoltaic Materials*, 2018.

[22] R. J.-A. D. F. M. Woodhouse, “On the Path to SunShot: The Role of Advancements in Solar Photovoltaic Efficiency, Reliability, and Costs,” Golden, United States of America, 2016.

[23] S. C. Capareda, “Solar Energy,” in *Introduction to Renewable Energy Conversions*, Florida, Introduction to Renewable Energy Conversions, 2020.

[24] T. R. e. hub, “WHAT ARE SILICON SOLAR CELLS,” The Renewable energy hub, 2020. [Online]. Available: https://www.renewableenergyhub.co.uk/main/solar-panels/silicon-solar-cells/. [Accessed 29 10 2021].

[25] S. Deambi, in *Photovoltaic System Design: Procedures, Tools and Applications*, Florida, Taylor Francis Group, 2016.

[26] R. Mayfield, “EC&M,” 23 7 2012. [Online]. Available: https://www.ecmweb.com/renewables/article/20896643/the-highs-and-lows-of-photovoltaic-system-calculations. [Accessed 30 10 2021].

[27] C. A. Gueymard, “Direct and indirect uncertainties in the prediction of tilted irradiance,” *Solar Energy,* vol. 83, 2009.

[28] M. S. M. M.Akter, “A Novel Model to Calculate Global Tilted Irradiation (GTI) from Solar Variables Using Netcdf and Rstudio,” *International Journal of Scientific & Engineering Research,* vol. 6, 2015.

[29] SolarGIs, “SolarGis Prospect,” SolarGis, 2021. [Online]. Available: https://apps.solargis.com/prospect/detail/8neP2fVwFOM0Mc1r/overview. [Accessed 29 10 2021].

[30] V. Q. R. Hanitsch, “Irradiance calculation on shaded surfaces,” *Solar Energy,* vol. 62, 1998.

[31] J. Marsh, “Do solar panels work in shade?,” EnergySage, 20 6 2018. [Online]. Available: https://news.energysage.com/solar-panels-work-shade/. [Accessed 29 10 2021].

[32] p. python, “pvlib python,” [Online]. Available: https://pvlib-python.readthedocs.io/en/stable/_modules/pvlib/irradiance.html. [Accessed 31 10 2021].

[33] R. J. M. V. R. v. S. J. F. M. Oudenhoven, “A review of the present situation and future developments of micro-batteries for wireless autonomous sensor systems,” *International journal of energy research,* vol. 36, no. 12, 2012.

[34] N. N. E. O. M. H. Balali, “An overview of the environmental, economic, andmaterial development s of the solar and wind sourcescoupled with the energy storage systems,” *INTERNATIONAL JOURNAL OF ENERGY RESEARCH,* vol. 41, 2017.

[35] D. A. J. R. P. C. R. M. Dell, Understanding batteries, France: Royal Society of Chemistry, 2001.

[36] N. Kularatna, in *Energy Storage Devices for electronic systems - Rechargable Batteries and Supercapacitors*, Hamilton, Elsevier, 2015.

[37] I. G. L. R.-M. e. a. E. Sarasketa-Zabala, “Calendar ageing analysis of a LiFePO4/graphite cell with dynamic model validations: towards realistic lifetime predictions,” *Power Sources,* vol. 272, 2014.

[38] I. G. E. M.-L. e. a. E. Sarasketa-Zabala, “Cycle ageing analysis of a LiFePO4/graphite cell with dynamic model validations: towards realistic lifetime predictions,” *Power Sources,* vol. 275, 2015.

[39] E. M.-L. M. B. e. a. E. Sarasketa-Zabala, “Realistic lifetime prediction approach for Li-ion batteries,” *Applied Energy,* vol. 162, 2016.

[40] J. M. L.-R. J. L. B.-A. R.Dufo-Lupez, “Comparison of different lead–acid battery lifetime prediction models for use in simulation of stand-alone photovoltaic systems,” *Applied Energy,* vol. 115, 2014.

[41] Battery Universe, “Learn about batteries,” Cadex, 2021. [Online]. Available: https://batteryuniversity.com/articles. [Accessed 01 11 2021].

[42] Batteries in a Portable World: A Handbook on Rechargeable Batteries for Non-Engineers, Fourth Edition, USA: Cadex Electronics Inc., 2017.

[43] Z. Z. Y. G. e. a. T. Zhu, “Leakage-Aware Energy Synchronization,” in *Mobysis*, Krakow, 2019.

[44] N. B. D. Rezzak, “Management and control strategy of a hybrid energy source fuel cell/supercapacitor in electric vehicles: Hybrid energy source Fuel Cell/Super-Capacitor in electric vehicles,” *International transactions on electrical energy systems,* vol. 27, 2017.

[45] R. A. D. S. P. R. Meyer, “Hybrid Model Predictive Power Management of a Battery-Supercapacitor Electric Vehicle,” *Aian journal of control,* vol. 18, 2016.

[46] D. I. A. J. Partridge, “The Role of Supercapacitors in Regenerative,” *Energies,* vol. 12, 2019.

[47] P. H. C. F. Simjee, “Everlast: Long-life, Supercapacitor-operated,” *ISLPED,* vol. 06, 2006.

[48] H. Y. a. Y. Zhang, “Power Management in Supercapacitor-Based Wireless Sensor Nodes,” in *Supercapacitor Design and Applications*, 2016.

[49] W Hans, “Supercapacitors Serving as Power Supply in Tiny Sport Sensors - Field Testing Through Heart Rate Monitoring in Endurance Trail Runs.,” *Proceedings of the 5th International Congress on Sport Sciences Research and Technology Support (icSPORTS 2017),* pp. 1-2, 2017.

[50] F. M. A. M. M. A. M. H. A. Malek, “Mohammad Hadin A. Malek, Farahiyah Mustafa, Anis Maisarah Mohd Asry,” *International Journal of Power Electronics and Drive System,* vol. 10, 2019.

[51] Climate Change Knoledge Portal, “Current Climate: Climatology,” World Bank Group, [Online]. Available: https://climateknowledgeportal.worldbank.org/country/south-africa/climate-data-historical. [Accessed 31 10 2021].

[52] “CLOUD COVER IMPACT ON PHOTOVOLTAIC POWER PRODUCTION IN SOUTH AFRICA,” *Southern African Solar Energy Conference SASEC2014,* vol. 1, no. 2, 2014.

[53] Infineon + Cypress, *Energy Harvesting PMIC,* July 2015: Revised: May 2017, S6AE102A / S6AE103A Datasheet.

[54] Texas instruments, *CC2652R SimpleLink™ Multiprotocol 2.4 GHz Wireless MCU,* Jan 2018: Last revised: March 2021, CC2652R datasheet.

[55] STMicroelectronics, *MEMS digital output motion sensor: ultra-low-power, high-performance 3-axis "pico" accelerometer,* 2017, LIS2DS12 Datasheet.

[56] MEMSIC, *±8 Gauss, High Performance 3-axis Magnetic Sensor,* 2019: Rev A, MMC5983MA Datasheet.

[57] Cypress, *Energy Harvesting PMIC,* July 2015: Revised: May 2017, S6AE102A / S6AE103A Datasheet.

[58] AVX, *High Capacitance Cylindrical SuperCapacitors,* SCCS30B106PRB Datasheet.

[59] Cypress, *Basic Concepts for Energy Delivery with S6AE101A, S6AE102A, and S6AE103A,* July 2016: Latest review: June 2021.

[60] Toshiba, *Silicon Epitaxial Schottky Barrier Type,* Novemeber 2007, 1SS417 Datasheet.

[61] KyCad.

[62] R. Manyala, “Introductory Chapter: Trends in Research on Energy Harvesting Technology,” in *Energy Harvesting*, IntechOpen, 2018.

[63] B. D. S. G. e. a. A. Barré, “Realistic lifetime prediction approach for Li-ion batteries,” *Journal of Power sources,* vol. 241, 2013.

Appendices

Appendix A: Microcontroller datasheet snippet

8.5 Power Consumption - Power Modes

When measured on the CC26x2REM-7ID reference design with T_c = 25 °C, V_{DDS} = 3.0 V with DC/DC enabled unless otherwise noted.

PARAMETER		TEST CONDITIONS	TYP	UNIT
Core Current Consumption				
I_{core}	Reset and Shutdown	Reset. RESET_N pin asserted or VDDS below power-on-reset threshold	150	nA
		Shutdown. No clocks running, no retention	150	
	Standby without cache retention	RTC running, CPU, 80KB RAM and (partial) register retention. RCOSC_LF	0.94	µA
		RTC running, CPU, 80KB RAM and (partial) register retention XOSC_LF	1.09	µA
	Standby with cache retention	RTC running, CPU, 80KB RAM and (partial) register retention. RCOSC_LF	3.2	µA
		RTC running, CPU, 80KB RAM and (partial) register retention. XOSC_LF	3.3	µA
	Idle	Supply Systems and RAM powered RCOSC_HF	675	µA
	Active	MCU running CoreMark at 48 MHz RCOSC_HF	3.39	mA
Peripheral Current Consumption(1) (2)				
I_{peri}	Peripheral power domain	Delta current with domain enabled	97.7	µA
	Serial power domain	Delta current with domain enabled	7.2	
	RF Core	Delta current with power domain enabled, clock enabled, RF core idle	210.9	
	µDMA	Delta current with clock enabled, module is idle	63.9	
	Timers	Delta current with clock enabled, module is idle(5)	81.0	
	I2C	Delta current with clock enabled, module is idle	10.1	
	I2S	Delta current with clock enabled, module is idle	26.3	
	SSI	Delta current with clock enabled, module is idle	82.9	
	UART	Delta current with clock enabled, module is idle(3)	167.5	
	CRYPTO (AES)	Delta current with clock enabled, module is idle(4)	25.6	
	PKA	Delta current with clock enabled, module is idle	84.7	
	TRNG	Delta current with clock enabled, module is idle	35.6	
Sensor Controller Engine Consumption				
I_{SCE}	Active mode	24 MHz, infinite loop	808.5	µA
	Low-power mode	2 MHz, infinite loop	30.1	

8.6 Power Consumption - Radio Modes

When measured on the CC26x2REM-7ID reference design with T_c = 25 °C, V_{DDS} = 3.0 V with DC/DC enabled unless otherwise noted.

PARAMETER		TEST CONDITIONS	TYP	UNIT
	Radio receive current	2440 MHz	6.9	mA
	Radio transmit current 2.4 GHz PA (BLE)	0 dBm output power setting 2440 MHz	7.3	mA
		+5 dBm output power setting 2440 MHz	9.6	mA

8.3 Recommended Operating Conditions

over operating free-air temperature range (unless otherwise noted)

	MIN	MAX	UNIT
Operating junction temperature	–40	105	°C
Operating supply voltage (VDDS)	1.8	3.8	V
Rising supply voltage slew rate	0	100	mV/µs
Falling supply voltage slew rate(1)	0	20	mV/µs

Appendix B: Accelerometer datasheet snippet

Symbol	Parameter	Test conditions	Min.	Typ.(2)	Max.	Unit
Vdd	Supply voltage		1.62	1.8	1.98	V
Vdd_IO	I/O pins supply voltage(3)		1.62		Vdd+0.1	V
IddHR	Current consumption in high-resolution mode	@ ODR range 12.5 Hz - 6400 Hz, 12-14 bit		150		µA
IddLP	Current consumption in low-power mode	ODR 100 Hz		12.5		µA
		ODR 50 Hz		8		
		ODR 12.5 Hz		4		
		ODR 1 Hz		2.5		
Idd_PD	Current consumption in power-down			0.7		µA
V_{IH}	Digital high-level input voltage		0.8*Vdd_IO			V
V_{IL}	Digital low-level input voltage				0.2*Vdd_IO	V
V_{OH}	Digital high-level output voltage	I_{OH} = 4 mA(4)	VDD_IO - 0.2 V			
V_{OL}	Digital low-level output voltage	I_{OL} = 4 mA(4)			0.2 V	

Appendix C: Magnetometer datasheet snippet

SPECIFICATIONS (Measurements @ 25°C, unless otherwise noted; V_{DD}=3.0V unless otherwise specified)

Parameter	Conditions	Min	Typ	Max	Units
Field Range (Each Axis)	Total applied field		±8		G
Supply Voltage	VDD	2.8	3.0	3.6	V
	VDDIO(I^2Cinterface and INT)	2.8	3.0	3.6	V
Supply Voltage Rise Time				5.0	ms
Supply Current[1,2] (7 measurements/second)	BW=00		450		μA
	BW=01		225		μA
	BW=10		112.5		μA
	BW=11		32		μA
Power Down Current[2]			1.0		μA
Operating Temperature		-40		105	°C
Storage Temperature		-55		125	°C
Linearity Error[2] (Best fit straight line)	FS=±8G $H_{applied}$=±4G		0.1		%FS
Hysteresis[2]	3 sweeps across ±8G		0.01		%FS
Repeatability Error[2]	3 sweeps across ±8G		0.1		%FS
Alignment Error			±1.0	±3.0	Degrees
Transverse Sensitivity			±0.8		%
Total RMS Noise[2]	BW=00		0.4		mG
	BW=01		0.6		mG
	BW=10		0.8		mG
	BW=11		1.2		mG
Output Resolution			18		Bits
Max Output data rate[2]	BW=00		50		Hz
	BW=01		100		Hz
	BW=10		225		Hz
	BW=11		580		Hz
	BW=11(CM_Freq=111)		1000		Hz
Heading Accuracy[3]			±1.0		Degrees
Sensitivity Accuracy[4,5]	±8 G		±5		%
	With16bits operation		4096		Counts/G
	With18bits operation		16384		Counts/G
Sensitivity Change Over Temperature	-40~105 °C Delta from 25 °C, ±8 G		±5		%
Null Field Output[5]			±0.5		G
	With16bits operation		32768		Counts
	With18bits operation		131072		Counts
Null Field Output Change Over Temperature using SET/RESET	-40~105 °C Delta from 25 °C		±3		mG
Temperature Sensor Output			0.8		°C/Count
Disturbing Field[6]			10		G
Maximum Exposed Field				10,000	G
SET/RESET Repeatability			±1		mG

Internal Control 1

Control Register 1	7	6	5	4	3	2	1	0
Addr: 0AH	SW_ RST	Reserved		YZ-inhibit		X-inhibit	BW1	BW0
Reset Value	0	0	0	0	0	0	0	0
Mode	W	W	W	W	W	W	W	W

<table>
<tr><th>Bit Name</th><th>Description</th></tr>
<tr><td>BW0& BW1</td><td>Output resolution<table><tr><td>BW1</td><td>BW0</td><td>Measurement Time</td><td>Bandwidth</td></tr><tr><td>0</td><td>0</td><td>8ms</td><td>100Hz</td></tr><tr><td>0</td><td>1</td><td>4ms</td><td>200Hz</td></tr><tr><td>1</td><td>0</td><td>2ms</td><td>400Hz</td></tr><tr><td>1</td><td>1</td><td>0.5ms</td><td>800Hz</td></tr></table>Note: X/Y/Z channel measurements are taken in parallel.
These bandwidth selection bits adjust the length of the decimation filter. They control the duration of each measurement.</td></tr>
<tr><td>X-inhibit</td><td>Writing “1” will disable X channel.</td></tr>
<tr><td>Y/Z-inhibit</td><td>Writing “1” to the two bits will disable Y and Z channel.</td></tr>
<tr><td>SW_RST</td><td>Writing “1”will cause the part to reset, similar to power-up. It will clear all registers and also re-read OTP as part of its startup routine. The power on time is 10mS.</td></tr>
</table>

Appendix D: C6AE102A datasheet snippet

Table 8-1 Electrical Characteristics (System Overall)

(Unless specified otherwise, these are the electrical characteristics under the recommended operating environment.)

Parameter	Symbol	Condition		Value Min	Typ	Max	Unit
Minimum Input power in start-up	W_{START}	VDD pin, Ta = +25°C, V_{VOUTH} setting = 3V, By applying 0.45 μA to VDD, when VOUT1 reaches 2.67V×95% after the point when VDD reaches 2.67V.		–	–	1.2	μW
Power detection voltage	V_{DETH}	VDD, VBAT ,VINT, VSTORE2 pins		1.0	1.4	2.0	V
Power undetection voltage	V_{DETL}			0.9	1.3	1.9	V
Power detection hysteresis	V_{DETHYS}			–	0.1	–	V
Power detection voltage 2	V_{DETH2}	VDD pin, When connecting a capacitor to VSTORE2 pin		2.0	2.1	2.2	V
Power undetection voltage 2	V_{DETL2}			1.9	2.0	2.1	V
Power detection hysteresis 2	$V_{DETHYS2}$			–	0.1	–	V
VOUT upper limit voltage	V_{VOUTH}	VSTORE1 pin, VOUT1 Load = 0 mA, VOUT2 Load = 0 mA	$V_{SYSH} \geq 2V$	V_{SYSH}×0.95	V_{SYSH}	V_{SYSH}×1.05	V
			$V_{SYSH} < 2V$	V_{SYSH}×0.935	V_{SYSH}	V_{SYSH}×1.065	V
Input power reconnect voltage	V_{VOUTM}	VSTORE1 pin, VOUT1 Load = 0 mA, VOUT2 Load = 0 mA	$V_{SYSH} \geq 2V$	V_{VOUTH} ×0.9025	V_{VOUTH} ×0.95	V_{VOUTH} ×0.9975	V
			$V_{SYSH} < 2V$	V_{VOUTH} ×0.88825	V_{VOUTH} ×0.95	V_{VOUTH} ×1.01175	V
VOUT lower limit voltage	V_{VOUTL}	VSTORE1 pin, VOUT1 Load = 0 mA, VOUT2 Load = 0 mA	$V_{SYSL} \geq 2V$	V_{SYSL}×0.95	V_{SYSL}	V_{SYSL}×1.05	V
			$V_{SYSL} < 2V$	V_{SYSL}×0.935	V_{SYSL}	V_{SYSL}×1.065	V
VSTORET2 storage upper limit voltage	V_{VST2H}	VSTORE2 pin		–	V_{VOUTH}	–	V
OVP detection voltage	V_{OVPH}	VDD pin		5.2	5.4	5.5	V
OVP release voltage	V_{OVPL}			5.1	5.3	5.4	V
OVP detection hysteresis	V_{OVPHYS}			–	0.1	–	V
OVP protection current	I_{OVP}	VDD pin input current		6	–	–	mA
Input voltage	V_{IH}	INT, ENA_LDO, STBY_LDO, ENA_COMP pins		1.1	–	VINT pin voltage (*1)	V
	V_{IL}	INT, ENA_LDO, STBY_LDO, ENA_COMP pins		0	–	0.3	V
Output voltage	V_{OH}	SW_CNT/COMPOUT, SW_CNT pins, Load = 2 μA		VINT pin voltage ×0.7 (*1)	–	VINT pin voltage (*1)	V
	V_{OL}	SW_CNT/COMPOUT, SW_CNT pins, Load = 2 μA		0	–	VINT pin voltage × 0.3 (*1)	V

Table 8-2 Electrical Characteristics (Consumption Current)

(Unless specified otherwise, these are the electrical characteristics under the recommended operating environment.)

Parameter	Symbol	Condition	Value Min	Typ	Max	Unit
Consumption current 1	I_{QIN1}	VDD pin input current, Energy driven mode (*2), SW2 = OFF, VDD = 3V, open VBAT pin, open VSTORE2 pin, VIN_LDO = GND, INT = GND, ENA_COMP = GND, ENA_LDO = GND, STBY_LDO = GND, Ta = +25°C, SET_VOUTFB resistance=50MΩ, VOUT1 Load = 0 mA, VOUT2 Load = 0 mA	–	280	440	nA
Consumption current 2	I_{QIN2}	Sum of I_{QIN1} and I_{INLD2} (LDO operation current) ENA_LDO = VINT (*1)	–	680	1140	nA
Consumption current 3	I_{QIN3}	Sum of I_{QIN1} and comparator operation current, ENA_COMP = VINT (*1)	–	300	470	nA

Appendix E: S6AE102A LDO datasheet snippet

Table 8-4 Electrical Characteristics (LDO)

(Unless specified otherwise, these are the electrical characteristics under the recommended operating environment.)

Parameter	Symbol	Condition	Value Min	Value Typ	Value Max	Unit
Output voltage	V_{OUTLD}	VOUT_LDO pin, VOUT_LDO resistance=20MΩ, Load = 0.01 mA	V_{SETLD} ×0.945	–	V_{SETLD} ×1.055	V
		VOUT_LDO pin, Ta = +25°C, VIN_LDO = V_{OUTLD}+1V, STBY_LDO = VINT (*1), VOUT_LDO resistance=20MΩ, Load = 0.01 mA	V_{SETLD} ×0.97	–	V_{SETLD} ×1.03	V
Input/output voltage difference (Normal mode)	V_{DELLD1}	Between VIN_LDO and VOUT_LDO pins, STBY_LDO = VINT (*1), Load ≤ 1 mA	0.3	–	–	V
Input/output voltage difference (Standby mode)	V_{DELLD2}	Between VIN_LDO and VOUT_LDO pins, STBY_LDO = AGND, Load ≤ 0.001 mA	0.3	–	–	V
Maximum output current (Normal mode)	I_{OUTLD1}	VOUT_LDO pin, (VIN_LDO−V_{OUTLD}×1.05) > 0.7V STBY_LDO = VINT (*1)	10	–	–	mA
Maximum output current (Standby mode)	I_{OUTLD2}	VOUT_LDO pin, (VIN_LDO−V_{OUTLD}×1.05) > 0.7V, STBY_LDO = AGND	0.1	–	–	mA
Line regulation	L_{INELD}	VOUT_LDO pin, VIN_LDO = (V_{OUTLD}×1.05+0.7V) to 5.3V	–	–	50	mV
Load regulation (Normal mode)	L_{OADLD1}	VOUT_LDO pin, STBY_LDO = VINT (*1) , Load = 1 mA to 10 mA	–	–	50	mV
Load regulation (Standby mode)	L_{OADLD2}	VOUT_LDO pin, STBY_LDO = AGND, Load = 0.001 mA to 0.1 mA	–	–	50	mV
Output current limit	I_{LIMLD}	VOUT_LDO pin, STBY_LDO = VINT (*1)	–	50	100	mA
LDO consumption current (Normal mode)	I_{INLD1}	Sum of VINT and VIN_LDO input current, Ta = +25°C, STBY_LDO = VINT (*1), Load = 0 mA	–	6	9	µA
LDO consumption current 2 (Standby mode)	I_{INLD2}	VIN_LDO input current, Ta = +25°C, STBY_LDO = AGND, Load = 0 mA, VOUT_LDO resistance=20MΩ, V_{OUTLD} setting = 1.3V	–	400	700	nA
OFF current	I_{OFFLD}	VIN_LDO pin, Ta = +25°C, ENA_LDO = AGND	–	60	120	nA
Discharge resistance	R_{DISLD}	VOUT_LDO pin, 1.35 ≤ V_{OUTLD} ≤ 5.0V	–	1	2	kΩ

Appendix F: Data for Solargis

Solar radiation and meteorological parameters

	GHI kWh/m2	DNI kWh/m2	DIF kWh/m2	D2G	GTI opta kWh/m2	ALB	TEMP °C	WS m/s	RH %	PWAT kg/m2	PREC mm	CDD degree days	HDD degree days
Jan	252.9	274.1	56.4	0.223	235.9	0.14	18.8	6.3	77	20	24	28	2
Feb	204.2	229.5	45.7	0.224	208.7	0.15	19.0	6.1	77	20	26	30	2
Mar	179.6	211.4	46.4	0.258	208.1	0.14	17.9	5.4	78	20	30	11	14
Apr	124.2	158.7	38.1	0.306	163.4	0.14	16.4	4.8	80	18	73	0	49
May	86.5	113.7	34.1	0.395	124.7	0.14	15.4	4.4	82	17	119	0	82
Jun	69.9	101.0	28.1	0.402	107.2	0.14	14.4	4.7	80	14	147	0	108
Jul	81.5	117.1	30.4	0.373	122.4	0.14	13.9	4.7	80	13	131	0	128
Aug	103.8	125.4	40.0	0.385	139.9	0.14	13.8	4.9	80	14	124	0	131
Sep	140.9	150.6	50.3	0.357	169.0	0.14	14.4	5.1	78	14	74	0	109
Oct	196.6	203.8	58.9	0.300	209.4	0.15	15.5	5.5	76	15	52	0	78
Nov	223.4	228.1	59.9	0.268	214.7	0.14	16.6	5.9	75	16	32	0	43
Dec	251.2	260.6	63.5	0.253	228.1	0.14	18.0	6.0	75	19	31	12	11
Yearly	**1914.7**	**2174.0**	**551.9**	**0.288**	**2131.4**	**0.14**	**16.2**	**5.3**	**78**	**17**	**863**	**82**	**756**

EBE Faculty: Assessment of Ethics in Research Projects

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to complete this form before collecting or analysing data. When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department. If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee: submit to Ms Zulpha Geyer (Zulpha.Geyer@uct.ac.za; Chem Eng Building, Ph 021 650 4791).Students must include a copy of the completed form with the final year project when it is submitted for examination.

Name of Principal Researcher/Student: Micheal Wetzel **Department:** ELECTRICAL ENGINEERING

If a Student: YES **Degree:** B. Eng Mechatronics **Supervisor:** Edward Boje

If a Research Contract indicate source of funding/sponsorship:

Research Project Title: Wood pole vibration monitor – Power supply

Overview of ethics issues in your research project:

Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a person not involved in your project)?	YES	NO
Question 2: Is your research making use of human subjects as sources of data? If your answer is YES, please complete Addendum 2.	YES	NO
Question 3: Does your research involve the participation of or provision of services to communities? If your answer is YES, please complete Addendum 3.	YES	NO
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If your answer is YES, please complete Addendum 4.	YES	NO

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as any interview schedules or questionnaires (Addendum 1) and please complete further addenda as appropriate.

I hereby undertake to carry out my research in such a way that

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

Signed by:

	Full name and signature	**Date**
Principal Researcher/Student:	**Michael Wetzel**	13 November 2021

This application is approved by:

Supervisor (if applicable):	**Edward Boje**	13 November 2021
HOD (or delegated nominee): Final authority for all assessments with NO to all questions and for all undergraduate research.	**Janine Buxey**	13 November 2021
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above		

ADDENDUM 1:

Student proposed?	*Y/N*	*If Y, student name*
ID:	**EB03**	
SUPERVISOR:	Prof. E Boje	
TITLE:	Wood pole vibration monitor – power supply	
DESCRIPTION:	A wireless sensor for wooden poles is being developed in a parallel project. Design, build and test a solar cell-based power supply, with microcontroller-based power management features. Design life is 10 years so battery-based technologies are probably not feasible.	
DELIVERABLES:	Careful problem analysis, design and a working system.	
SKILLS/REQUIREMENTS:	Control and Embedded systems	
GA 1: Problem solving: *Identify, formulate, analyse and solve complex* engineering problems creatively and innovatively*	The student must analyse the problem, formulate a solution and develop hardware towards this solution. Multiple design options must be considered.	
GA 4**: Investigations, experiments and analysis: *Demonstrate competence to design and conduct investigations and experiments.*	A proper technical investigation is required with laboratory measurements to support the theoretical work.	
EXTRA INFORMATION:		
BROAD Research Area:	Mechatronics/Embedded systems/IoT	
Project suitable for ME/ ECE/EE/ALL?		