Ambient Energy Harvesting - a Feasibility Study and Design of Test Circuits

An electrical engineering bachelor thesis, examining the various methods of harvesting ambient energy for storage and usage.

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Abstract

This report investigates the various methods of harvesting and storing the ambient energies which surround us. The concept and interest of harvesting ambient energy has been prevalent for some time. Mainly seen as an alternative and smarter way of storing energy for instant or later usage for low power devices. Typically to avoid the excess use of pre-stored energy where energy already exists.

For this project, various energy harvesting methods will be examined in greater detail and to then be constructed together in a coherent way. Something which has yet to become more ubiquitous which therefore becomes a motivation for this thesis. To explore the possible outcomes of this implementation and if it will further the subject.

This device could have many applications in terms of charging other devices in remote or powerless locations. It can also serve as an alternative to traditional charging and by that showing that the charger could be just as good as any other socket charger could be.

Summary

The report will consist of some introducing concepts of ambient energy harvesting. Followed by examining the electrical components which will be used in the product development as well as discussing practical and theoretical concepts of how energy harvesting can be conducted. Thereafter implementing components into a proposed design to later present the results and discuss what could have been done better.

Acknowledgments

We want to thank Jacob Wikner for suggesting and providing this interesting thesis project and for helping us with ideas of how to make it even more interesting. We would also like to thank Martin Nielsen Lönn for helping us with equipment, providing components and his positive feedback.
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## Notations

In the report, several abbreviations and acronyms are to be used. Common notations and terms in the field of electronics is considered. To clarify this, a table has been compiled to state various definitions throughout the report.

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<th>Explanation</th>
<th>Context</th>
</tr>
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<tr>
<td>A, mA</td>
<td>ampere, milli ampere</td>
<td>The quantity of flowing electrons in a conductor. 1 A is considered to be 1 C (Coulomb) which is the amount of the electric charges per second.</td>
<td>When using the circuitry and designing the system, current drain as well as current consumption is of importance.</td>
</tr>
<tr>
<td>AC</td>
<td>alternating current</td>
<td>One of the two different ways current behaves. AC being an alternating current, oscillating in relation to a bias voltage.</td>
<td>AC is relevant when considering some of the input energy sources which provide alternating current.</td>
</tr>
<tr>
<td>Ah, mAh</td>
<td>ampere hours, milli ampere hours</td>
<td>Similar to ampere, A, but instead the time which the current is provided. I.e 1 Ah is thus 1 A for one hour.</td>
<td>The unit ampere hours, Ah, is very practical when assuming for how long a battery can provide power with a certain current.</td>
</tr>
<tr>
<td>AVR</td>
<td>Alf Egil Bogen and Vegard Wollan</td>
<td>A certain microcontroller with 8-bit, RISC architecture</td>
<td>The ATmega328 used is of AVR architecture.</td>
</tr>
<tr>
<td>DC</td>
<td>direct current</td>
<td>Current with consistent, steady flow of electrons. Non varying current.</td>
<td>Electronics primarily use DC as well as means of storage in batteries.</td>
</tr>
<tr>
<td>F</td>
<td>farad</td>
<td>A unit for measuring capacitance. Farads is the result of the amount of C (Coulombs) per amount of voltage.</td>
<td>Practical when choosing the right size of a capacitor.</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
<td>Additional Information</td>
<td></td>
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<td>---------</td>
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<td>------------------------</td>
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<tr>
<td>GSM</td>
<td>global system for mobile communications</td>
<td>Second generation mobile network. Sometimes called 2G. One of the most prevalent mobile networks around the world.</td>
<td></td>
</tr>
<tr>
<td>ISY</td>
<td>institutionen för systemteknik</td>
<td>A department of electronics at Linköping university. The department where this project was done.</td>
<td></td>
</tr>
<tr>
<td>LiPo</td>
<td>lithium-ion polymer</td>
<td>One of many lithium-ion battery technologies. The most commonly used battery type, used presently in everyday devices.</td>
<td></td>
</tr>
<tr>
<td>MCU</td>
<td>microcontroller unit</td>
<td>Programmable IC in different sizes and for all kinds of utilities. The controller unit was used in this project for easy electrical control.</td>
<td></td>
</tr>
<tr>
<td>MOSFET</td>
<td>metal oxide semiconductor field effect transistor</td>
<td>One type of several transistor types. The MOSFET is controlled by using voltage rather than current as means of controlling the saturation. The MOSFET is especially practical in this project since it works better with the digital voltage control from the MCU.</td>
<td></td>
</tr>
<tr>
<td>PCB</td>
<td>printed circuit board</td>
<td>A way of elaborately integrate electrical schematics to create compact constructions on a thin board of fiberglass laminated with one or more layers of copper. Useful in the case of compressing a circuit construction to a more compact design. Also preferable if a construction is to be used permanently.</td>
<td></td>
</tr>
<tr>
<td>PMOS</td>
<td>p-channel MOSFET</td>
<td>A MOSFET with a layout of PNP - the saturation between the gate- and source pins is decisive for voltage control. Additionally important for voltage control was the behavior of a PMOS because it can be digitally controlled directly without additional components.</td>
<td></td>
</tr>
<tr>
<td>RF</td>
<td>radio frequency</td>
<td>RF is the definition of radio waves in the span 3 kHz to 300 GHz. In this project - the means of using the energy from the received radio waves for energy harvesting.</td>
<td></td>
</tr>
<tr>
<td>SC</td>
<td>supercapacitor</td>
<td>Capacitor with a much larger storage capacity compared to regular (electrolyte)capacitor. Usually more convenient to use for much larger energy storage and with a lower voltage.</td>
<td></td>
</tr>
<tr>
<td>T, nT</td>
<td>tesla, nano tesla</td>
<td>A measurement of the strength of a magnetic field. The unit is used in the relation of a one meter in diameter sized conductor.</td>
<td></td>
</tr>
<tr>
<td><strong>USB</strong></td>
<td>universal serial bus</td>
<td>One standard for transferring data and power</td>
<td>Versatile connector type used as one of the input sources as well as the primary output power connector.</td>
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<td>---------</td>
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<td>---------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
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<tr>
<td><strong>W</strong></td>
<td>watts</td>
<td>A measurement of power. The product of ampere and voltage. ( P = U \cdot I )</td>
<td>More practical to express components and circuitry in terms of effect since voltage and current can differ in proportion to the other.</td>
</tr>
<tr>
<td><strong>Wh</strong></td>
<td>watt hours</td>
<td>A measurement of power over a period of time. Similar to Ah but the product of the voltage and the ampere hour.</td>
<td>As equally motivated for watts, W, the unit Wh says more in terms of total power storage than solely Ah.</td>
</tr>
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1

Introduction

1.1. Motivation

Smartphones and other battery dependent devices require electrical energy in order to work. They have to be recharged when their batteries are out of energy. There are various solutions for charging a smartphone on-the-go such as using a regular wall outlet charger or a portable powerbank. Both of which has their benefits and drawbacks. Using a wall outlet charger requires the user being in reach of a wall mounted outlet. This is not always the case and especially not when the user is on the move. By using a powerbank, the device can be recharged while being on the move. This works as long as the powerbank is charged, but when it is out of power both the device and the powerbank will be unusable.

This is where an alternative course of action comes in. By using a powerbank that is capable of recharging itself by converting different forms of ambient energy into electrical energy the needs for a wall outlet will be highly reduced. The idea is to use various current sources such as solar power, radio frequency signals, electromagnetic induction, Qi wireless charging technology and other external sources to charge the powerbank. This concept of collecting energy from the surroundings is also known as “ambient energy harvesting”.

![Diagram](image.png)

*Figure 1.1-1. The concept of the project where different sources are merged together.*
1.2. Purpose

The purpose of this project is to show that the ambient energy which surrounds us suffices for charging various devices. It can be combined in an elegant way by traditional charging and yet have the option to do it some other way, which in this case would be by harvesting the ambient energy.

By doing this combination of various methods for energy harvesting, the versatility entails the vast multi-utility purposes which can be accomplished. By looking at the benefits of extracting energy from where it is usually not thought of.

1.3. Problem statements

Generally during the project, several issues regarding the implementation of the different energy harvesting techniques as well as unpredictable or unwanted results have been encountered.

More detailed questions and problems which were considered are:

- Since some less effective energy harvesting methods will be used, can these generate enough power to make charging devices feasible within a reasonable amount of time?
- Is it possible to construct a pocket-sized device which contains all selected features in order to charge an internal battery with sufficient efficiency and within reasonable time?
- How can an effective electrical control be implemented considering that all sources are to be combined and collaborate adequately?
- How energy efficient can the control system be constructed?

There is an unfortunate possibility that some of the energy harvesting methods which are to be used cannot provide enough energy. This may prevent adequate charging of the battery in a reasonable time or even fail to charge the battery at all due to various reasons such as mere voltages or insufficient currents. For small voltages, this problem may be tackled by adding proper voltage transformation steps in order to consistently run the system. Too much voltage fluctuation may cause the system to fail. For currents however, the problem may persist as the amount of current is heavily dependent of the source output power.

The components needed, circuits and sources, have to be relatively small in order to fit inside a pocket-sized case. This may restrict the amount of recovered energy that could otherwise be utilized by using larger form factors. Each component has to be carefully selected with respect to efficiency and size. If suitable components are to be found and implemented, it probably will be possible to charge a battery within a reasonable time.
Assuming that multiple energy sources need to be connected, the problem whether there will be extensive leakage issues which may inflict disruptions in the system has to be considered. If there, upon testing, turns out to be problems when merging the sources’ currents together, some kind of control essentially needs to be implemented to address this issue. The system may be implemented with either something as simple as a manual switch or more elaborately, with a microcontroller.

The device may have several parts which could have the potential to make it a more energy efficient construction. It could be possible to look into how the circuitry is constructed in minor detail but the most reasonable approach at first is to implement the design with consideration of the major stages where most of the energy may be lost. Those major details could for instance be to not waste energy or to avoid currents to interfere with each other.

1.4. Project limitations

There are many different methods of extracting energy from various sources and at the start we had to decide which sources would be suitable to implement in order to limit the project. We realized that designing and constructing every little piece of circuit hardware needed for the project by ourselves would not only be tricky but simply burst our time schedule and thus seemed unreasonable. Therefore we accomplished the project by focusing more on the implementation as a whole, seeing how the different energy harvesting techniques could most elegantly be put together. Creating a system rather than staring blindly at small details.

While we did not design every piece of hardware such as integrated circuits, PCBs and so on, on our own, we still conducted several tests and carried out assessments of the hardware’s functionality. Assuring we acquainted ourselves well enough with it to know how to make the best out of it.
Background

2.1 Background

Mankind has always searched for various methods of extracting energy which has been at disposal in the environment to aid with various tasks which have been too heavy for manpower alone. The mill for example which uses wind power to refine grain or the water mill which provides energy for sawing. These are a few examples where energy was extracted at a certain place where it directly was used more or less at the same place. By that time, the definition of “ambient energy harvesting” was practically the only way to acquire energy.

When means of distributing electricity became a reality in the beginning and middle of the 20th century, the concept of “local electricity” faded away and in some sense became obsolete. However, during the last two decades or so, new ideas of how to think about how energy can alternatively be produced for smaller low powered devices has been brought back once again in a similar yet different way. Thus the idea to avoid excessive use of batteries and dependency of the power grid.

Until the early 20th century, electricity was obviously known and well justified to be the cornerstone for the future. Since then, the usage of devices which either are directly connected to the power grid or using a battery has become much more prevalent. And if the batteries are rechargeable, they are more or less dependent on charging from the power grid either way. As the quantity of such devices has exploded and became more or less the normalized state for most people, one could ask whether or not this state could be changed for the better. Preventing a too power grid dependant future of all devices and gadgets out there.

Gadgets and devices which are powered by the power grid or by batteries have therefore become so common, the concern for battery dependency has increased. The term of “ambient energy harvesting” came as an idea to deal with this problem by using alternative means of energy. The research area has grown rapidly for the past years, implementing new designs of everyday tools for the customer market. However, as for now, only one energy source is commonly used and advertised in these products which limits the versatility a lot. If multiple sources could be used simultaneously the versatility may improve significantly.
2.2 Conclusions

The principle idea of this project was to examine whether a multiple set of various current sources could collaborate to create a unit which charges itself efficiently and continuously with the available ambient energy. This while simultaneously being able to tap the device of energy for direct charging with any common electronic 5 V device. That could be anything from a mobile phone, GPS, camera etc.

We managed to construct a product of this basis but with a few discrepancies from the original ideas, however, with the finished product design still intact and well motivated for. Essentially in such a way that respective energy source discussed in chapter 4.2.3 were all combined except one, the RF. This source is described in chapter 6.1.1 and further explained why it was not successfully included like the other sources. Possible solutions and improvements of how RF could be implemented are also described.

We hope that our ambient energy harvesting construction with these characteristics which has been developed in this project will have a wide utility value in the future. We also hope that our efforts may open up further product development and theoretical aspects within the field of energy harvesting.
3

Theory

3.1 Introduction

In this chapter, all the components and circuitry are to be discussed and meticulously examined. The physical properties as well as the relevant and important aspects such as running characteristics, efficiency and theory versus practice are to be reviewed and examined. Whether or not some of the sources will not perform adequately or up to expectation is thought of and taken into consideration. Some of the harvesting techniques such as the electromagnet and RF are already approached with scepticism yet with anticipation. Hopefully showing that even these rather vague or controversial means of tapping the ambient energy will generate acceptable results upon testing and implementation.

By assessing the various energy harvesting methods and by stating their relevance and usefulness in the construction, the sources can be managed properly since it will generate different results. And whatever the results may yield, they are to be analyzed and discussed throughout the report. Especially the lesser energy harvesting methods since these might need further consideration in the design and construction stage, for example due to low voltages and so forth.

When done reading this chapter all the background details and data regarding the energy sources and other building blocks of the project should have been acknowledged and understood. This in order to later understand how it is all meshed together and implemented.

3.2 Possible sources for ambient energy harvesting

As seen in figure 1.1-1, various sources are combined in order to capture energy and store it. A list of possible sources has been compiled in Table 3.2-1. Note that not all of these are to be implemented. In the table, a theoretical conclusion especially regarding efficiency has been attempted. Size, price and a short explanation have also been added.
### Table 3.2-1. Stating the various proposed and potential sources to use for energy harvesting.

<table>
<thead>
<tr>
<th>Source</th>
<th>Efficiency</th>
<th>Size</th>
<th>Price</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Induced current</td>
<td>High</td>
<td>Small</td>
<td>Low to medium</td>
<td>Using Qi wireless technology</td>
</tr>
<tr>
<td>Dynamo/alternator</td>
<td>High</td>
<td>Large</td>
<td>Medium</td>
<td>Some form of handle</td>
</tr>
<tr>
<td>Vibration</td>
<td>Low</td>
<td>Small to medium</td>
<td>Low</td>
<td>Converting kinetic energy to electrical energy</td>
</tr>
<tr>
<td>Wind (Micro turbine)</td>
<td>Medium</td>
<td>Medium</td>
<td>Low to medium</td>
<td>Electrical motor with a small turbine connected to it</td>
</tr>
<tr>
<td>Radio frequencies</td>
<td>Extremely low</td>
<td>Medium</td>
<td>Low to medium</td>
<td>Using the received energy from a set of antennas</td>
</tr>
<tr>
<td>Solar power</td>
<td>Medium to high</td>
<td>Large</td>
<td>Medium to high</td>
<td>Photovoltaic cells</td>
</tr>
<tr>
<td>Thermal</td>
<td>Very low</td>
<td>Small</td>
<td>Low</td>
<td>Potential temperature difference</td>
</tr>
<tr>
<td>Chemical</td>
<td>Low to high</td>
<td>Varying</td>
<td>Varying</td>
<td>Using chemical reactions to extract energy</td>
</tr>
</tbody>
</table>

3.3 General overview of voltage control

Further on, each and every source will be investigated, bringing up matters like previous research and implementation which are relevant to understanding each respective source. Doing so will cover more of the technical aspects as well as giving a more accurate prediction of what to expect upon testing.

All sources produce different voltages, whether that is AC or DC and whatever magnitude they produce, they have to properly be managed and controlled in order to achieve a good efficiency. The voltage control, described in figure 3.3-1 depicts the steps of how this is accomplished.

In the first step of figure 3.3-1, a voltage is applied. Since the voltages may have to be rectified, a full bridge regimentation of the voltage is at hand for that purpose. After the rectifier a boost-/buck converter which will be further explained in chapter 3.7.1 is cascaded. A clever yet simple concept of a circuit designed to handle different voltages, in this case between 3-12 VDC and adjust it to 5 VDC. The stable voltage is essential for maintaining an accurate charge for the battery. This described principle is used in the design later on and thus essentially important to bring up this early in order to see the whole picture later on.
Figure 3.3-1. Block diagram of how the voltage input is managed. Generally this method goes for most source inputs.

3.4 Sources and hierarchy

If there is a need, implementation of switching on and off to control whether a source should be able to contribute with charging or not is needed. The switches ought to be needed if the construction turns out to have leakage currents or if the system can not merge all sources together at once. Adding different sources of electricity together of different magnitudes and voltages is not the easiest thing. This has been taken into account and more or less seen as a predictable obstacle which has to be avoided.

By measuring the voltage from the output port of the boost-/buck converters whether it is 5 V or 0 V provides the system with useful information about if a source is active or not. This creates an easy design feature to control which of the current sources that should either be connected or disconnected.

PMOS transistors have the right characteristics to work in accordance with switching control seen in figure 3.4-1. To the gate pin, 5 V is applied respectively of each PMOS which leads to the potential difference of 0 V between the source pin and the gate pin, blocking any current to pass through either direction. Obviously this works the other way too, as 0 V would saturate the transistor which lets current easily through. Therefore it is an inverted control (active low) where 5 V entails that the transistor is off and 0 V entails that it on. In figure 3.3-1, the rightmost block called “MOSFET-Switches” corresponds to where the PMOS transistors should be placed of the control design.

Figure 3.4-1. P-channel MOSFET.
3.4.1 Qi wireless charging technology

Choosing to wirelessly charge the device gives an additional opportunity to improve the versatility. The receiver should be able to connect to all types of Qi-standard transmitters. The receiver has a built-in voltage regulator which limits the output voltage to 5 V. The magnetic field usually operates in the 100’s kHz region [1]. The Qi receiver used in this project is depicted in 3.4.1-1.

![Figure 3.4.1-1. Adafruit Qi receiver showing the receiver coil and the circuitry.](image)

The wireless charging unit is fairly simple in its design. It uses the principles of electromagnetism [2] which state that a resonant inductive coupling, illustrated in figure 3.4.1-1 gives

\[
Q = \frac{1}{R} \sqrt{\frac{L}{C}} \tag{Eq. 3.4.1-1}
\]

where \(Q\) is the quality factor which is a dimensionless parameter used to measure the dampening of a resonator or an oscillator, \(R\) the resistance of the coil, \(L\) the inductance and \(C\) is the capacitance. Using two coils with individual properties \(Q_1\) and \(Q_2\) the following efficiency relation \(U\) can be given as

\[
U = \frac{\omega M}{\sqrt{R_s R_d}} = k \sqrt{Q_1 Q_2} \tag{Eq. 3.4.1-2}
\]

\[
M = k \sqrt{L_s L_d} \tag{Eq. 3.4.1-3}
\]
where \( \omega \) is the induced angular frequency by the generator, \( M \) (equation 3.4.1-3) is the mutual inductance relation, the two \( R_{sd} \) are the primary and secondary resistances of the coils. \( U \) is the efficiency and \( k \) is the coupling coefficient. Preferably, the transmitter and the receiver coils should be as similar as possible in design to get maximum power transfer. Lastly, the maximum power transfer gives

\[
\eta_{opt} = \frac{U^2}{(1+\sqrt{1+U^2})^2}.
\]  
(Eq. 3.4.1-4)

According to Eq. 3.4.1-4 one can deduce that after a certain angular frequency the efficiency of the power transfer will be close to optimum. A frequency of 125 kHz has been mentioned previously, supposedly a frequency not picked randomly but for its relatively low frequency, within non-harmful levels yet high enough to not lose too much of the efficiency.

One of the issues with Qi wireless power transfer is that power transfer declines exponentially in relation to the distance. [1] This is a problem when efficiency is regarded as an important aspect. Following the discussions of the equations, particularly equation 3.4.1-4, the decline of efficiency is be depicted in figure 3.4.1-3.
3.4.1 The efficiency in relation to distance between Qi receiver and the transmitter.

In figure 3.4.1-4, [4] the charging station of the Qi circuit is illustrated which is the one used for this project. However as previously described the charging mechanism is not restricted to any specific product.

3.4.2 User’s choice (USB)

Another source is called the user’s input and connects via a USB-port. It is very flexible and can handle both AC and DC voltages with a range from 3 to 12 V. The user has the option of charging the battery with practically anything in this voltage range and it can still be used as a conventional portable battery.
In figure 3.3-1, an illustration in general terms shows the user’s input as it is made with a full bridge rectifier and a smoothing capacitor to maintain a continuous and even voltage without too much distortion. This rather simple, straight forward construction comes in handy for the various other energy sources as well. The step is crucial for handling the applied input as a “messy” source voltage would not perform well if connected directly to the boost-/buck converter.

3.4.3 Solar panel

Solar cells or photovoltaic cells convert solar energy to electrical energy. They consists of a semiconducting material, most commonly crystalline silicon [5], which creates a voltage difference as it absorbs sunlight. An arranged set of photovoltaic cells is called a “solar panel”. The panels are illustrated in figure 3.4.3-1.

Each solar cell has a measurement of roughly 10.5 mm by 28 mm and there are 16 cells in each solar panel which adds up to a total area of approximately 4700 mm$^2$ = 0.0047 m$^2$. When illuminated, it will deliver a power of 0.5 W. The intensity of the sun is about 1367 W/m$^2$. With these numbers the efficiency of the solar panel can be calculated

$$\eta = \frac{0.5 \text{W}}{0.0047 \text{m}^2 \times 1367 \text{W/m}^2} \approx 0.078 = 7.8\%.$$  \hspace{1cm} \text{(Eq 3.4.3-1)}

The efficiency proves to be approximately 7.8 % which shows that these solar panels are not the most optimal ones since the efficiency can reach as high as 20-30 % [6] but still these solar panels suffices for this project.
3.4.4 Electromagnetic induction “Shaker”

A moving (permanent) magnet inside a coil is a known way to induce current. When a magnet moves its magnetic field moves with it and when a magnet moves inside a coil, the result is an alternating magnetic field which affects the coil in such a way that a current is generated. The induced alternating current can be extracted from the coil and can be used to power an electronic device. According to Faraday’s law, the amount of current induced depends on the amount of windings in the coil, the velocity and magnetic flux of the magnet and the space between the magnet and the coil. The concept is shown in figure 3.4.4-1.
In order to induce any current at all the magnet has to move and for that some sort of kinetic energy is required. The principle of a magnet moving from side to side in a sealed tube with a coil on the outside is used in some flashlights called “Faraday flashlights” or “shake flashlights”. If the magnet slides inside the tube there will be some friction loss between the magnet and the tube itself. This can partially be prevented by attaching the magnet to the tube with a pair of springs according to figure 3.4.4-1. In an ideal world the magnet will swing from side to side without touching the tube. This ensures that even the smallest change in speed will make the magnet move and keep it moving for some time.

3.4.5 Radio frequency energy harvesting

There are two concepts of wirelessly transferring energy. One being the far-field and another being near-field. In chapter 3.4.5, the far-field is examined whilst in chapter 3.4.1 near-field is explained.

The question whether energy from the RF spectrum (300 kHz - 300 GHz) [7] can be harvested has since some time been of interest to investigate as an alternative way to the more commonly existing energy harvesting sources. Still the technique is merely in its early stages when it comes to implementing it to supply low powered devices or store energies for other purposes in commercial terms. The technique suggests that modest energies, of up to a couple of 10’s of μW/cm² [8] can be harvested, for instance to power microprocessors or other low energy demanding hardware or devices.

When choosing the right frequency to obtain the right energy harvesting methods, the energy of the actual signal may play a significant role in how much energy that can be obtained from particular frequencies. Usually there is a tradeoff with frequency and the emitted power which is transmitted from various sources due to regulations of radiation levels and its usability.

It is not uncommon to see transmitters of hundreds of kW of low frequency amplitude modulated radio (longwave and middlewave) in the kHz region to the low MHz region. These frequencies does not dissipate as easily over longer distances and thus chosen for the purpose of reaching out far away. [9] However, compared to cell towers which commonly operates in the GHz region, these may only have a fraction of that transmitted power. This is because higher frequencies weaken over distance and because of that, there is no need to transmit at high power for such signals seen in equation 3.4.5-2 where the so called “free path propagation loss” is greater. Therefore the choice of frequency and possible energy extraction of radio waves is highly dependent on location.

The energy of a photon is given by Planck’s relation which states that

\[ E = hf \]  
(Eq 3.4.5-1)
where $E$ is the energy of the photon per period, commonly expressed in eV (electron volt) or joules. $h$ is Planck’s constant and $f$ is the frequency of the photon. The expression is obviously linear which suggests that the higher the frequency, the higher the energy. Although, choosing to extract energy from the highest frequency possible may not always be the best choice since, as discussed above in equation 3.4.5-1, these frequencies may be transmitted with a lower power.

The relation between the transmitted power and the received power is given by Friis transmission equation which states that

$$P_r = \frac{P_tG_rG_s\lambda^2}{(4\pi r)^2}$$

(Eq 3.4.5-2)

where $P_r$ is the received power, $P_t$ is the transmitted power, both preferably expressed in $P_{dBm} = 20\log_{10}(P_{W})$. $G_t$ and $G_r$ are the transmitted and received mean effective gains respectively and $\lambda$ is the wavelength of the signal, also known as $\lambda = fc$, where $c$ is the speed of light. As seen in equation 3.4.5-2, the received signal declines squared with the distance $r$. It is also highly dependent on the wavelength. All assuming that an isotropic antenna is used (ideal spatial energy propagation in all directions equally) and that there are no attenuation factors present.

There are in fact many factors which correlate with the reduction of the received signal strength. Not just according to the distance but other important aspects too such as when considering attenuation factors. Propagation medium (in most cases air), the reflection coefficients of the transmitter/receiver and the quality of the receiver and so on. There are other factors which also have to be considered.

To simplify the concept of loss of power in correlation with frequency, the free space path loss (FSPL) which correlates with the Friis transmission equation states that

$$FSPL = \left(\frac{4\pi rf}{c}\right)^2$$

(Eq 3.4.5-3)

where $FSPL$ entails the free path propagation loss and $r$ is the distance from the transmission. In figure 3.4.5-1, a couple of typical frequencies are illustrated and how the loss corresponds to distance.

In figure 3.4.5-1, the total signal loss is viewed on the y-axis, expressed in decibels in relation to the distance on the x-axis. As seen in the figure, the signal strength decreases depending on distance. In an ideal environment (line-of-sight), without reflection or additional attenuation factors the loss in signal strength will only be due to the distance.
A misinterpretation of FSPL is that the frequency corresponds to the signal strength. However that is not the case because the different plots correspond to a relative state of frequency and distance, not in absolute measures. Since the frequency is somewhat dependent on whichever antenna is used the aperture is dependent of the gains and the powers of transmitter and receiver. The FSPL is commonly used in correlation with these conditions when a certain frequency is taken into consideration. The following relation derived from the Friis transmission equation 3.4.5-2, gives that
\[
FSPL = \frac{P_t}{P_r} G_r G_t.
\]
(Eq 3.4.5-4)

Typically the gains \( G_r \) and \( G_t \neq 1 \) but for the sake of simplicity, isotropic conditions are assumed. FSPL is supposedly a powerful tool to measure when several factors have a critical role in deciding what RF power intensity that could be harvested. It is also considered to be the global standard for antennas [10].

To conclude the reasoning, antenna aperture should as well be mentioned which is the definition of how efficiently an antenna can receive radio waves. The expression of an antenna’s effective aperture is stated as
\[ e_a = \frac{A_{\text{eff}}}{A_{\text{phys}}} \]  
(Eq 3.4.5-5)

where \( e_a \) is the dimensionless factor ranging from 0 to 1 which states that an aperture factor of 1 would be an antenna which used all the energy it received and 0 would imply that it does not use any of the energy it receives. \( A_{\text{phys}} \) is the physical aperture and \( A_{\text{eff}} \) is the effective aperture calculated. The effective aperture can be expressed as

\[ A_{\text{eff}} = \frac{\lambda^2}{4\pi}. \]  
(Eq 3.4.5-6)

As seen in the equation 3.4.5-6, the aperture becomes smaller the shorter the wavelength of the received radio wave or the higher the frequency. Thus saying that the higher the frequency, the smaller antenna area is needed if the same energy is thought to be received. If also as previously considering gains of respective antenna to be equal to one and no significant attenuation has been assumed.

Antenna design is important as it typically filters out other frequencies. Therefore choice of antenna equals operation range in frequency and thus the most common and prevalent frequency bands should implicate the best energy harvesting potentials.

The commonly used frequency bands found to be used everywhere around the globe are within the upper 100’s of MHz to lower 1-10 GHz region [11]. Other frequency bands which may be of interest is the GSM (Global system network commonly operating in the 900 MHz region [12]. 3G and 4G as well as wifi in the lower GHz ranges are also of relevance.

In figure 3.4.5-2, the general idea of how an antenna receives a signal, how the signal gets rectified and thereafter transformed is illustrated. The received energy is, preferably for practical utilisation, to be stored in a capacitor. Essentially a capacitor is a good choice of storage because of its low discharge time, low internal resistance and practicality for voltage convenience and measurement.
3.5 Micro controller

A microcontroller unit (MCU) is a small programmable processing unit with a built-in memory for storing a small program. The program is written by the user and instructs the MCU what to do in certain situations. MCUs come in many different sizes and configurations to meet the demands by the user. Implementing MCUs can be done with very low expenses and with whatever purpose imaginable they might serve given with a user friendly programming contemporary environment.

The ATmega328 model is an up to date microcontroller with a low energy consumption of 0.2 mA in active mode at 1 MHz clock frequency. It is essential because of its amount of ports which cohere with the design. The microcontroller can be programmed with a STK500 debugger, a programmer/debugger for all available AVR devices. [13]

3.6 Other components

The design will be implemented with various hardware and circuitry. These will be discussed and analysed in this chapter.

3.6.1 Battery

LiPo (lithium-ion polymer) batteries are almost exclusively used in small electrical devices and gadgets such as smartphones, tablets etc. They are very versatile and can hold a large capacity in a relatively small form factor because of their high energy density. When treated correctly LiPos are both user friendly and safe. However, if they get damaged, that is crushed, pierced or being used incorrectly (overcharge, over-discharge, short circuit or over-heat) they are likely to fail. If that happens they may leak electrolyte, expand or spontaneously catch on fire. To prevent LiPos from being overcharged, over-discharged and short circuited they are normally fitted with a protection circuit. This circuit regulates the charge- and cut-off voltage. Common voltage values for LiPos are listed in Table 3.6.1-1 [14].

<table>
<thead>
<tr>
<th>Lithium-ion polymer</th>
<th>Charge voltage</th>
<th>Cut-off voltage</th>
<th>Nominal voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value per cell</td>
<td>4.2 V</td>
<td>3.0 V</td>
<td>3.7 V</td>
</tr>
</tbody>
</table>

*Table 3.6.1-1. Lithium-ion polymer battery cell data.*

One general way of describing the charge and discharge capability of a battery is to use a common notation that works for all LiPos, regardless of their capacities. This notation is called *C-rating* (continuous discharge rating) and denotes the relation between storage capacity and charge/discharge capability. This is a way to explain to the user what maximum drain and maximum charge current that is allowed for a particular battery without damaging it. The battery illustrated in figure 3.6.1-1 is stated to have a capacity of 6600 mAh. Its
**C-rating** for discharge is 1 C. That means it can deliver a continuous current of 6600 mA without damaging the battery. The **C-rating** for charging the battery is 0.5 C, i.e. 6600/2 = 3300 mA. That means that the battery can be charged with a continuous current of 3300 mA without getting damaged. [15]

![Battery pack](image1)

**Figure 3.6.1-1. Battery pack.**

### 3.6.2 7-Segment display

7-segment displays are widespread and commonly used in all sorts of applications and devices. They consists of seven LED segments arranged in a figure of an “8” and one additional segment for the decimal point. This allows for the user to be able to display any number from 0 to 9 and some letters, commonly A to F.

![7-segment display](image2)

**Figure 3.6.2-1. 7-segment display segment layout. To the left is a photo of the actual display and to the right, an illustration of the segment arrangement.**

Even the most simple 7-segment display requires at least seven individual LED segments in order to be able to show all numbers from 0 to 9 and one additional segment for the decimal point. These normally share a common anode or cathode, depending on if the display LED segments are active high or active low. In order to save pins and space another way to reduce the amount of pins is to use a display with a built-in encoder. This allows for reducing the
number of pins roughly by half but restricts the user from the ability to control each segment individually. The decimal point can not be controlled either and needs a separate bit in order to work. One benefit is that instead of writing 8 bits to the display, one for each segment, only 4 bits are required. This is explained in Table 3.6.2-1.

<table>
<thead>
<tr>
<th>Char</th>
<th>4-bit</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
<th>(DP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0000</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0001</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0010</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0011</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0100</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0101</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
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<td>6</td>
<td>0110</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>0111</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<td>1000</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>1001</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>A</td>
<td>1010</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>b</td>
<td>1011</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>c</td>
<td>1100</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>d</td>
<td>1101</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<td>0</td>
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<tr>
<td>E</td>
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<td>0</td>
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<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>F</td>
<td>1111</td>
<td>1</td>
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<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3.6.2-1. Encoder working principles. In a to DP, 1 means that the segment is on and 0 means that it's off.

3.7 Circuits

In section 3.7, other components of more physical essence are reviewed. That is the PCB embedded circuits used for voltage conversions. These circuits are crucial as they provide the relevant properties that is needed for the system to function properly. They act as a middle step between the sources and the system voltage output.

3.7.1 Boost-/buck converter

This particular circuit is fairly simple and straight-forward in its design and running properties. Figure 3.7.1-1, displays the appearance of the boost-/buck converter where $V_{in}$ (to the left in the figure) is where the assumed DC voltage is intended to be applied in the range of 3-12 V. Whereas the right part of the figure is where the output of 5 V is found. Hence
giving a circuit which either transforms the voltage down or up within an arbitrarily range to a specific voltage level. Boost-/buck converters come in all forms, sizes and ranges.

![Adafruit VERTER boost-/buck converter.](image)

The range of 3-12 V generally works good for many applications but not for all. For voltage levels either below 3 V or above 12 V a different boost-/buck converter will have to be used.

For sources that are not capable of delivering high voltage levels another boost-/buck converter may have to be used. The range of 3-12 V generally works good for many applications but not for all. For voltage levels below 3 V a different converter will have to be used, such as the Sparkfun LiPower boost converter shown in figure 3.7.1-2. The principles are exactly the same as for the VERTER boost-/buck converter, but its input voltage range is different. The LiPower boost converter can handle input voltages in a range of 0.3-5.5 V and provides a constant 3.3 or 5 V at the output depending on the user’s needs. This is selected by resoldering the boxed-in pads at the top-left in the picture in the desired configuration. When shipped, the LiPower boost converter is preset to 5 V. The input is at the connector to the right and the solder pads near the middle in the picture. The output is to the left.
Figure 3.7.1-2. Sparfun LiPower boost converter.

The importance of adding a step like a boost-/buck converter is to avoid eventual messy voltages, which might occasionally occur since most of the implemented sources are of a too unpredictable nature to just assume a neat input voltage. The source voltages may vary a lot which is not suitable for powering devices that requires a steady input voltage. The boost-/buck converters serve the purpose of being able to handle a positive varying DC-voltage at the input and providing a smooth regulated DC-voltage at the output.

The principles of boost-/buck converters are a few. Essentially it has two different running modes, depending on which voltage conversion that is supposed to be accomplished. That is increasing or decreasing the voltage as mentioned. To achieve and understand that, certain circuitry for up or down conversion respectively has to be illustrated.

The boost circuit or step-up converter seen in figure 3.7.1-3, acquires an increased voltage by continuously switching in between two stages. First, when the switch is closed, the current will start rushing due to the short circuit. It is somewhat held back due to the inertia of the inductor. Secondly, something to pay attention to here is that when the switch opens up, the inductor will for a short time act as a current source and force current through the diode and the load at a higher rate than it would with only the voltage source connected. This is also due to the inertia of the inductor and thus for a short time the voltage level over the capacitor and the load is higher than the source voltage.

For this to work properly, the switching has to be done frequently at a high pace, commonly in the kilohertz range [16]. It could also be done in the megahertz range in order to reduce the size of the inductor and the capacitor slightly. The benefits of doing that is the overall size of the circuit would shrink and that an even smoother output voltage can be obtained. However,
the drawback is that the power losses in the switch which commonly consists of a MOSFET will be much greater [16].

\[ D = 1 - \frac{V_{in}}{V_{out}} \]  
(Eq. 3.7.1-1)

where \( V_{in} \) is the applied voltage and \( V_{out} \) is the resulting output voltage. This suggest that choosing a certain duty cycle will result in a certain voltage conversion ratio. In the case of the converter used in this project, a feedback has to be present in order to constantly adjust for an uneven \( V_{in} \).

A similar relation corresponds to the buck converter. The principle is the same as for the boost converter but the component setup is somewhat different. When the switch is closed current will start to flow through the inductor and through the load. The voltage over the load will not instantly be the same as the source due to the inertia of the inductor. When the switch opens up, the inductor acts as a current source and will maintain the current flow through the load while pulling current through the diode in order to maintain a closed circuit. Yet, to achieve a voltage somewhat free of ripples, the inductor needs to be large enough in order to remain a constant current long enough to prevent large drops for the resulting voltage. This goes as well for the inductor in the boost converter. The capacitors in both cases works along with the inductor and smoothes out the voltage. For the buck converter the duty cycle state is similar to the boost converter

\[ D = \frac{V_{out}}{V_{in}} . \]  
(Eq. 3.7.1-2)

Figure 3.7.1-4 below illustrates the general overview of a buck converter.
These instances take no consideration into account whether the load is draining the circuit faster than what it is supposed to handle. Hence under smooth running conditions, the load drains the circuit modestly and enough for the inductor to continuously push current forward. This good condition is called *continuous mode*.

In cases when the drain is too large for the inductor to keep up through the whole time of the switch being open, the inductor is completely drained even before the cycle is completed. This instance is called *discontinuous mode* and is undesirable in most cases since it is disrupting smooth output voltage.

### 3.7.2 Battery charger

The battery charger circuit plays the central role for the whole device as it is the main junction for the battery, source input and charge output voltage. The circuit elegantly merges all these features together creating the opportunity to charge the battery, measure its current voltage while simultaneously draining the battery. Illustrated in figure 3.7.2-1.
Figure 3.7.2-1. Flow diagram of principle schematics of the battery charging module.

In figure 3.7.2-2 the battery charger circuit can be viewed. The input is to the left and connects via a micro USB-connector. The black connector to the low left is the battery connector and the output is to the right.

Figure 3.7.2-2. Adafruit Power Boost 500 appearance.
The controller IC unit of the Adafruit Power Boost 500 incorporates the integrated circuit TPS6 1090. It is capable of delivering 5 V and up to 500 mA at the output when the voltage supply is within a range of 1.8 V - 5.5 V. Its efficiency is about 85 - 95 % during that condition. The specifications also suggests a ripple of 20 mV when running continuously at an input voltage of 3.3 V and a load resistance of 10 Ω. Such ripples, if necessary could be fixed by a smoothing capacitor. [17]

3.7.3 Radio frequency unit

This circuit inputs the signal from radio waves which have been received by antenna(s). These signals will be converted by the circuit into voltages up to 40 V implying that a fair magnitude of antenna signal strength can be managed giving that the maximum current is restricted to 18 mA. According to the specifications given, the circuit can handle RFs from 60 Hz - 6 GHz and at 915 MHz supply 0 dBm.

The term dBm (decibel milliwatts) is useful when working with received and transmitted power. Technically, the power can be explained regularly in terms of watts but the magnitude may occasionally be of a very small magnitude. Therefore expressing it in decibels of milli is much more convenient. Since dBm implies decades of milli, 1.0 mW equals 0 dBm.

According to the given specifications of 40 V and 18 mA, the maximum output power would be 0.72 W. This corresponds to a magnitude of 28-29 dBm. However, this suggest a large and very efficient antenna design which could be feasible. [18]

In figure 3.7.3-1, the antenna input to the right is connected to the integrated circuit. The circuit itself rectifies the signal and provides an output DC voltage.

![RF Diagnostics RF to DC converter module](image)

*Figure 3.7.3-1. RF Diagnostics RF to DC converter module.*
3.8 Theoretical charging time

To understand how the different chosen sources constitute for the charging time, table 3.8-1 has been generated to show the time it theoretically would take to charge a battery per individual source. The charging time takes a whole battery charging cycle into account, meaning the time it would take to fully charge a battery that is completely empty.

The battery time has conveniently been chosen to be expressed in Wh (Watt hours). Thus the battery time is about 3.7 V • 6.6 Ah = 24.42 Wh. All values are rounded up.

<table>
<thead>
<tr>
<th>Source</th>
<th>Output power, Watts</th>
<th>Time, hours (from 0 to 100 %)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qi wireless</td>
<td>2.5</td>
<td>10 h</td>
<td>Received maximum current of 0.5 A</td>
</tr>
<tr>
<td>User (USB-port)</td>
<td>2.5</td>
<td>10 h</td>
<td>The user input may vary. Here the maximum allowance of 0.5 A input is used</td>
</tr>
<tr>
<td>Solar panels</td>
<td>1.0</td>
<td>25 h</td>
<td>Current of about 0.15 A under optimal conditions</td>
</tr>
<tr>
<td>Shaker</td>
<td>~60 mW</td>
<td>~400 h</td>
<td>Continuously shaking</td>
</tr>
<tr>
<td>RF</td>
<td>1 mW</td>
<td>~3 years</td>
<td>Using a good, large antenna setup. (Battery)</td>
</tr>
<tr>
<td>RF</td>
<td>1 mW</td>
<td>~1 day</td>
<td>(Supercapacitor at 1 F)</td>
</tr>
</tbody>
</table>

Table 3.8-1. Estimated charging time for respective source.

When doing calculations regarding the RF, rather optimistic values has been used. Supposedly 1 mW is quite large when dealing with RF. However, a good set of antennas in close proximity to a transmitting tower could generate a power of such magnitude. Also, preferably the charging could preferably be combined with a capacitor of some kind for better energy storage. Thus direct storage in a battery may not be optimal but rather a combination of a capacitor, a voltage transformation circuit and lastly a battery.

3.9 Hypothetical sources

So far the various methods of more conventional and perhaps of more familiar essence have been described in a sense which states how the energy can be obtained. However there are several other methods worth paying attention to which might, but most certainly will not, generate significant energies. Some of them will be described below. For instance, advocates hastily tend to point out the extraordinary capabilities in these energy harvesting methods to charge everyday devices. Although, which very often tends to be faulty and unreasonable claims but in reality turns out to be flaws or even hoaxes.
3.9.1 Organic

One way of extracting energy is from the chemical reaction which occurs in plants as they exert photosynthesis by absorbing and give off ions and other electrical particles. By using these constant chemical reactions as a source for draining electrons, energy can be obtained. In a study [19], a plant was chemically stimulated and illuminated with 250 W/m² to perform reactions. Electrons were stucked into a plant to measure the differential voltage, particularly the redox reactions as these dispose of excess electrons. The conducted tests generated results of 0.4 V and a total of 9 µW/cm².

According to several inventors, some of their products can allegedly charge several devices a day by using the energy solely from one small plant. Whether or not that is feasible can be discussed. What is reasonable to believe is that there are great potential in this energy harvesting technique but still at present does not generate any significant energies for charging everyday devices. [20]

3.9.2 Earth’s magnetic field

Another possibility would theoretically be to use the magnetic fluctuations in the Earth’s own magnetosphere. Yet again, there are certain claims whether it is a possibility to harvest marginal energies from these fluctuations. The surface fluctuation of Earth is about 1 nT per second and square meter which means that a total of 1 nV could theoretically be harvested if a one square meter loop where to be constructed. Whether or not that could be utilised for anything whatsoever is debatable. [21]
4

Method

4.1 Introduction

In chapter four, the reader will be able to understand how the design is implemented, how all components are interlinked and how they cooperate to create a complete charging system. To be able to do just that, conclusions regarding the essential choices of why certain components were chosen and why some were not will give a wider comprehension. This will be discussed in the chapter 4.2. For the sake of replicability, the implementation chapter in 4.3 will essentially be brought in chronological order. Beginning with stating the various steps of the microcontroller’s tasks followed by a more detailed description of those tasks.

The microcontroller (MCU) has a core position in both controlling the currents as well as indicating battery percentage. Generally it has something to do with everything in the design one way or the other. Therefore the implementation stage will be described with the MCU as a starting point as well as returning point when bringing up a new aspects at hand. However, despite the fact that the MCU has a depending role upon the system’s functionality, the main purpose of this project is not meant to give the impression that the MCU is the main cornerstone but rather as described, using its convenient role in the system as a tool to a more straightforward description and design.

4.2 Prestudy

In section 4.2, planning, thoughts and discussions of every part of the product will be mentioned and described.

4.2.1 Planning

The concept of how the design should be constructed was known from the start in some sense. What it was going to be was a gadget that is capable of converting various forms of ambient energy into electrical energy and with that, charge an internal battery. The stored energy will then be used to power some kind of USB-device such as a smartphone. Further on the steps will be discussed in greater detail.
4.2.2 Storage unit

The original idea was to use a set of supercapacitors (SC) to store the extracted electrical energy. The idea is not bad but, in our case, not practical because more than 1000 SCs would have to be used in order to be able to store any significant amount of energy. If MCUs were the only thing that would be powered, then it would be enough with just a few SCs. However, this project was aimed to construct a portable power bank capable of charging various USB-devices and for that, SCs are not suitable. The storage capacity is too small in proportion to price and size compared to a regular battery, but theoretically it is possible to use.

In order to calculate how many SCs that are needed in order to store enough energy for charging a 1000 mAh battery, some assumptions have been made. A typical SC can store voltages up to 5.5 V and has a capacitance of 1 F. The drain current is assumed to be 1 A, duration 1 hour (3600 s) and the voltage over the SC is 5.4 V. The DC-DC conversion circuits (VERTER) are capable of transforming anything within 3-12 V at the input to 5 V at the output. The lower voltage limit is thus 3 V. The difference between 5.4 V and 3.0 V is 2.4 V. That is the space in which the capacitors will work. This means that most of the energy stored in the SCs can not be used. In equation 4.2.2-1 is a short calculation example that shows why capacitors are inconvenient for this type of use.

\[ i(t) = C \cdot \frac{\delta v(t)}{\delta t} \Leftrightarrow C = i(t) \cdot \frac{\delta t}{\delta v(t)} = 1 \cdot \frac{3600}{2.4} = 1500 \text{ F} \quad \text{(Eq. 4.2.2-1)} \]

In order to charge a device that has a battery of 1000 mAh using the SCs mentioned above, an amount of about 1500 caps are needed. This package would not only be much bigger than a conventional battery, but also much more expensive and it would be harder to implement. Because of this, a battery was chosen to be used for storage instead. Batteries are better suited for this large capacity long-term storage and that is why they are the most common way of storing electricity. However, in many ambient energy harvesting system, direct or little storage would be desirable and thus making a battery not suitable.

The next issue was how to make sure that the design could charge its own internal battery and charge a connected device, both at the same time. At first we planned to solve this problem by using two battery setups and charge one while the other was drained, charging some consumer device. When the drained battery is empty, an automatic switch will rearrange the battery setup so the drained battery will recharge and the charged battery will drain, which makes the consumer device charge. This should happen automatically without user interaction. In the search for suitable components and battery chargers, the Power Boost 500 battery charger (see 3.7.2) was found and considered to be the most suitable. It requires only one battery and still has the ability to charge and drain it at the same time, depending on the output power. This circuit is the one that was decided to be used.
4.2.3 Source selection

Before the start a numerous of various possible sources were mentioned in chapter 3.2 and discussed whether to implement or not. Their efficiencies, ease of use and physical dimensions were evaluated and from the results a selection of five was chosen to be implemented. Sources #1 to #4 are fairly straightforward and known principles of charging methods. Source #5 is more of a scientific experiment, a test to see whether it is possible or not to extract energy from radio frequency signals.

Source #1 is the Qi wireless technology. It consists of one transmitter and one receiver (see section 3.4.1, figures 3.4.1-(1,4)), both of which were ready to be used right out of the box.

Source #2 is the user's input. This is the most versatile source as it can handle both AC and DC voltage in a range of 3-12 V (see figure 3.3-1). It consists of a full-bridge rectifier at the input, a smoothing capacitor and a DC-DC converter (see 3.7.1) which regulates the voltage to a steady 5 V at the output.

Source #3 is the solar panels. They provide electricity when exposed to light, preferably direct sunlight. The solar panels used in this project delivers up to 0.5 W each and two of them are used which means a combined output power of 1 W (see figure 3.4.3-1). The output voltage from each panel is up to 4.7 V and they are connected in series which means a combined output voltage of up to 9.4 V. This is transformed down to 5 V using a DC-DC converter (see 3.7.1).

Source #4 is the “shaker” or electromagnetic induction. It is named “shaker” because it basically is what one has to do in order to generate any current from it. Is consists of a magnet inside a tube, surrounded by a copper coil (see figure 3.4.4-1). When one shakes it, a current is induced in the coil and can be used to power different devices.

Source #5 is radio frequencies. This is a test to see whether it is possible to charge a battery or SC using something as common as RF. Theoretically, it is possible to use RF to power devices rather than just transmit signals since a measurable amount of power can be extracted. The problem is that the signal intensity diminishes by the square of the distance. This means that the received power gets very low when the transmitter is far away. This can been seen in chapter 3.7.3 in figure 3.7.3-1.

Using multiple sources implies some issues. They are all different in terms of power delivery which means that there is a risk that current from a stronger source may sneak through a weaker source instead of into the battery. To prevent this from happening a ranking system was developed that allows for only one source to be active at a time. All five sources were ranked with respect to their power delivery capabilities and user friendliness. The ranking
order corresponds to the source numbers above. By using switches (MOSFETs), controlled by
the MCU, the source with the highest rank that is capable of delivering power will be
selected. The MCU checks every source to determine whether the source is active or not. This
will be further described in section 4.3.

4.2.4 Voltage control

Because of the uneven voltages from each source, some sort of control must be implemented.
Therefore, each source was given its own DC-DC converter which transforms the input
voltage within a range of 3-12 V to 5 VDC at the output. There were two circuits to chose
from: VERTER by Adafruit and LiPower by Sparkfun. Three VERTER circuits were
supposed to be used, one for the user’s input, one for the solar panels and one for the shaker.
LiPower was supposed to take care of the RF because the RF signal strength is generally very
low and LiPower is supposed to be able to transform voltages within a range of 0.3-5.5 V at
the input to 5 V at the output. However, as the circuits were tested, they did not perform as
advertised as shown in table 4.2.4-1 where \( V_{\text{in}} \) is the applied input voltage to respective circuit
and where \( V_{\text{out, VERTER}} \) and \( V_{\text{out, LiPower}} \) is the corresponding output voltages of the circuits.

<table>
<thead>
<tr>
<th>( V_{\text{in}} )</th>
<th>( V_{\text{out, VERTER}} )</th>
<th>( V_{\text{in}} )</th>
<th>( V_{\text{out, LiPower}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 - 2.2</td>
<td>0.0</td>
<td>0.0 - 3.4 (2.5)</td>
<td>0.0</td>
</tr>
<tr>
<td>2.3 - 2.6</td>
<td>5.2</td>
<td>3.5 (2.6) - 5.5</td>
<td>5.0</td>
</tr>
<tr>
<td>2.7 - 12.0</td>
<td>5.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 4.2.4-1. VERTER and LiPower output voltage behaviour depending on input voltage. Values within the parentheses illustrate a voltage step applied at the input.*

Using a variable power supply and a 100 Ω resistor as a load, both circuits were tested for
conductivity. Two multimeters were used to measure the voltage, one at the power supply and
the other over the load. During the test it became obvious that the LiPower was the worst
performer of the two. Not only because it did not perform according to the specifications, but
also because the point of turn-on depends on whether the input voltage is slowly rising or
applied as a step. This makes LiPower worse than VERTER in the area where it was
supposed to be superior (at very low input voltages) and more unreliable due to the turn-on
difference depending on the “type” of voltage applied. VERTER performed consistently
regardless of the type of voltage applied. The thresholds were the same for both slowly rising
input voltages and voltage steps and it is also lower than the measured threshold voltage of
LiPower.

As a result of this, only VERTER circuits will be used. This means that source #5 (RF) will
be turned off almost all of the time since it lacks the power of turning on the VERTER circuit,
unless a very large and efficient antenna is used and if the user is right next to a powerful RF
transmitter of some sort.
4.2.5 Battery charge indicator

In the planning stage there was a discussion whether to implement a battery charge indicator or not. It was decided that it should be implemented and the next question was how to do that. Since a battery does not have a linear voltage drop per time unit when being charged or discharged, a simple voltage measurement will not show an accurate result of the actual battery charge status. This is illustrated in figure 4.2.5-1.

*Figure 4.2.5-1. Battery charge curve. The black curve is the actual look of the battery voltage behaviour in relation to the charge and the red line is the preferred look for easier voltage measurement.*

When the battery is fully charged and then drained at a constant rate, the voltage drops rapidly at first before it stabilises at approx 3.8 V. From there the voltage/charge ratio is almost linear down to about 3.6 V where the voltage starts to drop rapidly again. This makes it quite difficult to measure the actual battery charge status at any given moment.

One way to solve this problem would be to make a function that corresponds to the charge curve and somehow compare the measured voltage with that function in order to check the charge status of the battery. Another way of measuring a more linear condition would be to measure the amount of current which has been drained from the battery assuming that the start point is known. Several methods of measuring can be combined to attain a more accurate result. [22]
4.3 Implementation

In chapter 4.3, the full implementation will be explained step by step. Starting with the microcontroller’s overview as a block diagram in figure 4.3-1 followed by a more detailed picture of each and every step of this diagram where all white blocks in the loop are functions. The literate names of these block are explained chronologically in greater detail in table 4.3.1-1.

![Flow diagram for the microcontroller.](image-url)
4.3.1 Microcontroller installment

As previously mentioned, the AVR microcontroller ATmega328 is used for the purpose of controlling the system as well as give a visual feedback indication of the charging process in terms of percentage on the two 7-segment displays.

In order to also give it an advantageous autonomous feature and improving the performance, undesirable current paths, according the hierarchical order, are to be turned off in order to improve the efficiency and thereby the charging capability. In table 4.3.1, the different tasks of the microcontroller is listed.

<table>
<thead>
<tr>
<th>Function</th>
<th>Executing</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Button pressed?”</td>
<td>Checking if the external button is pressed or not.</td>
<td>To inform the MCU that certain things should be done when pressed.</td>
</tr>
<tr>
<td>“Battery voltage check”</td>
<td>A routine to check the voltage of the battery.</td>
<td>To inform what the 7-seg should display.</td>
</tr>
<tr>
<td>“7-seg display (Voltage in percent)”</td>
<td>Displaying the percentage of the battery.</td>
<td>A feature to easily acknowledge the amount of ampere hours remaining.</td>
</tr>
<tr>
<td>Source check (“Qi on?”, “User on”, “Solar”..)</td>
<td>Checking a digital 1 or 0 at 5 V stage at boost-/buck converter for respective source.</td>
<td>To confirm presence of sources for the control routine.</td>
</tr>
<tr>
<td>“MOSFET-control”</td>
<td>The control routine is used to choose which of the current sources that is included.</td>
<td>Adding various sources implies that they all should have the same voltage to not risk backwards current flow. Since used components obviously are not ideal, this is not an option. Thus the need of isolating one current source at a time.</td>
</tr>
</tbody>
</table>

Table 4.3.1-1. The various tasks of the microcontroller executed in chronological order with respect to 4.3-1.

4.3.2 Control layout

Sources control

Making sure that the right sources and their respective currents are let through when a voltage is recognised or otherwise turned off is crucial in order to achieve a good performance. To accomplish that, PMOS-transistors have been suggested as a mean to acquire this rather straightforward behaviour.
When voltages are applied from various sources, they are initially prioritised as previously discussed where the Qi goes as priority one seen in chapter 4.2.3, followed by the user’s input, the solar panels, the shaker and lastly the RF. Thus always only letting through one single source at a time, that is the highest prioritised source which indicates its presence in terms of applied voltage.

In order to see whether the source is connected and available to provide a current or not, the last end of the transformation stage will be checked. Because the boost-/buck converter provides 5 V at its output, a connection to a digital I/O pin has been arranged to indicate a ‘1’ or ‘0’ corresponding to a 5 V or 0 V. Every source has its own assigned pin to recognise if it is capable of delivering enough power.

The source chosen for power delivery is applied by an assigned digital output pin which each and every source is also provided with. These pins gets to control the PMOS-transistors. A digital ‘1’ at respective transistor will be the default mode, implicating that it is closed and a ‘0’ will let through current. Thus making it easy to decide which current that should be let through and prevent it to leak backwards.

All of the above mentioned control input and output I/O-pins are distributed on PORT D and partially PORT C and can be fetched from the PORT-tables (see tables 4.3.4-(2-4)).

**Power control**

To save as much energy as possible, some kind of energy switch should be outlined. After all, the battery package can only store so much. Hence the energy would much rather be used in the charging process as well as providing energy for the device the user may wish to charge.

Therefore the idea that the various energy draining components only thought to be on whenever these actually are to be used and turn off when they are not used. Consequently, the issue can similarly be applied in the manner as for the control pins whereas a PMOS-transistor comes in handy once again to distribute, whether it should be turned on or off with a simple digital solution.

### 4.3.3 External button

The external button became relevant as to the above mentioned need for power control. The snippet below which has been slightly simplified to only show the relevant parts which is associated with the power control is illustrated in *Code 1*. The version of the can be found in appendix 1.
if(External_button() == 1) //Button pressed?
{
    /*Turn ON power supply for the two 7-seg displays.
    So to say, drop the voltage for the PMOS*/
    PORTD &= ~0b10000000; //Power on
    turn_on_ADC();
}
else
{
    PORTD |= 0b10000000; //Power off
    turn_off_ADC();
}

Code 1. Showing that the power toggles corresponding to the condition of the button.

As the code depicts, the power control is dependent on the condition of the button where it is simply pressed or not which corresponds to a digital signal.

Upon testing the power consumption when the battery status indicator was off versus on, showed a significant drain in “on-mode”, many times that when the battery status indicator was off. During “on-mode” the power consumption was 824 mW and when the indicator was off, only 12.26 mW. Suggesting that a large power consumption can be saved by doing this rather simple task.

It might seem strange to let a microcontroller execute code all the time in the background and drain the battery of energy. However since the battery can deliver a total of 24.42 Wh if fully charged and the drain is only 12.26 mW at a given moment, the discharge time would be 24.42 Wh / 12.26 mW = 1991.84 hours ⇒ 83 days. Which may in this case be considered negligible.
Figure 4.3.3-1 displays the percentage of the battery when the button is pressed, whereas it is in this case 65 % remaining. The ADC pin has been connected to the battery management circuit to read the battery level.

4.3.4 ADC configuration

Up until now, the two 7-segment displays have been mentioned several times as an indicator feature for checking the battery status. However the process behind it has not yet been sorted out and will therefore be explained. Another point is to show how the problems was confronted by code design rather than, for example initialise data status registers and so forth. Although the complete code can for the sake of replicability be viewed in appendix 1.

To be able to view the percentage of what is left in the battery, presumably some kind of voltage measurement has to be conducted every time the external button is pressed. However rather promptly an issue arise when assuming that measuring the battery voltage can be done as it is simultaneously charging. It would not be possible as the charging voltage would dominate the measurement. Fortunately the Adafruit Power Boost 500 is featured with a battery pin which solves the problem statement above and this is also where the pin for battery status is connected to.
ADC stands for Analog to Digital Conversion, which means that an analog signal from 0 V up to the supply voltage (V\text{cc}) of 5 V can be represented digitally. As for the ATmega328, the options of 8-bits or 10-bits can be selected for different resolution specifications. In this project the 8-bit choice was not just more convenient in coding and quick to setup but more than enough to acquire adequate resolution for what was needed.

To first understand how the analog to digital conversion operates a few steps have to be explained in order to see the whole picture.

The exact voltage value of V\text{cc} has for the sake of simplicity been considered to be 5.0 V as of now and has worked well for explanations. However upon testing, the supply voltage from the Power Boost 500 circuit is steadily supplying the circuit with 5.15 V and thus important to take into account now as the supply voltage will be the actual reference voltage V\text{ref}.

The V\text{ref} is the voltage which determines what the maximum register representation 255 (decimal), 0b11111111 (binary) or 0xFF (hex) should be. V\text{ref} is a physical pin on the ATmega328 and could be applied with whatever voltage desired giving that the correct settings have been done for the ADC seen in table 4.3.4-1.

<table>
<thead>
<tr>
<th>REFS1</th>
<th>REFS0</th>
<th>Voltage reference selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>AREF, Internal Vref turned off</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>AV\text{cc} with external capacitor at AREF pin</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>Reserved</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Internal 1.1V Voltage Reference with external capacitor at AREF pin</td>
</tr>
</tbody>
</table>

Table 4.3.4-1. ADMUX – Data register for reference voltage, V\text{cc}

Though the only available and stable voltage source reference which can be found is by the output supply voltage of the power boost circuit, thus giving no other suitable choices than that. Therefore choosing to write ‘1’ to REFS0 and ‘0’ to REFS1 results that the V\text{ref} pin will obtain supply voltage internally, thus removing the need for V\text{ref} to be connected to anything. A full list of all pins are found in tables 4.3.4-(2-4).

Specification of the voltage reference selection suggests a capacitor to the V\text{ref} pin however this is only needed for very fast measures and since only one measure per push is conducted for this case, a capacitor would turn out to be excessive.

Presume that the ADC register called ADCH is ready for usage since it has been loaded with a number ranging from 0 to 255 assuming that the right initialization step has been done. Then the input voltage at PC0 can take the values between 0 V and 5.15 V but the battery only range from 3.0 V to 4.2 V which is the relevant values, thus 0.0 V up to 3.0 and from 4.2 to 5.15 V should therefore be ignored. Since the highest value is 5.15 V and there are 256
steps in total, the resolution is $5.15 \, \text{V} / 256 = 20 \, \text{mV/step}$. The voltage may fluctuate fairly much and considering that the operating range is quite narrow. Therefore every percentage step come to be steps of 5 % in order to avoid too much fluctuation.

To isolate the relevant values which may be loaded in the ADCH register, the limits of the specified voltages have to be found. The lower limit 3.0 V would be $3/5.15 = 0.5825 \rightarrow 255 \times 0.582 \approx 148$ and the upper limit 4.2 V corresponds to $4.2/5.15 = 0.8155 \rightarrow 255 \times 0.815 \approx 208$. Hence these are the values [148 - 208] of interest.

Since percentage from 0 - 100 % is desired but the range is only 60 seen in code 2 some scaling has to be done. Leading to scale factor $100/60 = 1.667$. Resulting in a resolution of $20 \, \text{mV} \cdot 1.667 \approx 33 \, \text{mV}$.

```c
if(ADC_data >= 148 & ADC_data <= 208)
{
    correction = (60-(208-ADC_data))*1.6667;
    // Scaling factor! Lowest = 1 * 1.6667 Highest = 60 * 1.6667 = 100 %
}
return correction;
```

*Code 2. Stating scaling factor.*

Although there is a problem. The value which is scaled can be anything ranging between 0 - 100 in steps of 1 percentage units. Therefore the value has to be truncated in steps of 5 percentage units. For instance, the value 63 is truncated to 60 or the value 14 is truncated to 15. The resulting steps can be seen in appendix 1.

<table>
<thead>
<tr>
<th>PORTB</th>
<th>I/O</th>
<th>Function/Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>PB0</td>
<td>Out</td>
<td>7-Segment display (Low case, LSB)</td>
</tr>
<tr>
<td>PB1</td>
<td>Out</td>
<td>7-Segment display (Low case)</td>
</tr>
<tr>
<td>PB2</td>
<td>Out</td>
<td>7-Segment display (Low case)</td>
</tr>
<tr>
<td>PB3</td>
<td>Out</td>
<td>7-Segment display (Low case, MSB)</td>
</tr>
<tr>
<td>PB4</td>
<td>Out</td>
<td>7-Segment display (High case, LSB)</td>
</tr>
<tr>
<td>PB5</td>
<td>Out</td>
<td>7-Segment display (High case)</td>
</tr>
<tr>
<td>PB6</td>
<td>Out</td>
<td>7-Segment display (High case)</td>
</tr>
<tr>
<td>PB7</td>
<td>Out</td>
<td>7-Segment display (High case, MSB)</td>
</tr>
</tbody>
</table>

*Table 4.3.4-2. Pin planning of port B. Port B is a collection of eight pins which is coherent with the internal bit register of the MCU.*
<table>
<thead>
<tr>
<th><strong>PORTC</strong></th>
<th><strong>I/O</strong></th>
<th><strong>Function/Application</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>PC0</td>
<td>In</td>
<td>Analog input</td>
</tr>
<tr>
<td>PC1</td>
<td>In</td>
<td>Source #4 check (Shaker)</td>
</tr>
<tr>
<td>PC2</td>
<td>In</td>
<td>Source #5 check (RF)</td>
</tr>
<tr>
<td>PC3</td>
<td>Out</td>
<td>PMOS Source #4</td>
</tr>
<tr>
<td>PC4</td>
<td>Out</td>
<td>PMOS Source #5</td>
</tr>
<tr>
<td>PC5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PC6</td>
<td>In</td>
<td>(Reset pin)</td>
</tr>
<tr>
<td>PC7</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Table 4.3.4-3. Pin planning of port C. Port C is a collection of eight pins which is coherent with the internal bit register of the MCU.*

<table>
<thead>
<tr>
<th><strong>PORTD</strong></th>
<th><strong>I/O</strong></th>
<th><strong>Function/Application</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>PD0</td>
<td>In</td>
<td>External button</td>
</tr>
<tr>
<td>PD1</td>
<td>In</td>
<td>Source #1 check (Qi)</td>
</tr>
<tr>
<td>PD2</td>
<td>In</td>
<td>Source #2 check (User)</td>
</tr>
<tr>
<td>PD3</td>
<td>In</td>
<td>Source #3 check (Solar)</td>
</tr>
<tr>
<td>PD4</td>
<td>Out</td>
<td>PMOS Source #1</td>
</tr>
<tr>
<td>PD5</td>
<td>Out</td>
<td>PMOS Source #2</td>
</tr>
<tr>
<td>PD6</td>
<td>Out</td>
<td>PMOS Source #3</td>
</tr>
<tr>
<td>PD7</td>
<td>Out</td>
<td>PMOS Power control</td>
</tr>
</tbody>
</table>

*Table 4.3.4-4. Pin planning of port D. Port D is a collection of eight pins which is coherent with the internal bit register of the MCU.*

### 4.3.5 Source testing

In section 4.3.5 testing of the sources will be described.

**Qi**
Both the Qi transmitter a receiver were ready to be used right out of the box. Two cables, positive and ground, were soldered on to the receiver for easier connectivity. The transmitter was connected to a USB port capable of delivering 5 V and 500 mA. The receiver was placed on top of the transmitter and was connected to the battery charger circuit. The transmitter indicated that it was connected to a receiver and the battery charger indicated that the battery was charging.
User’s input
A bridge rectifier consisting of four schottky diodes was implemented. Connected to this is a USB cable (but any cable would work since it should be able to connect to anything) and a VERTER DC-DC converter which transforms the voltage to 5 VDC. This was connected to the battery charger which indicated that the battery was charging, thus the system worked.

Solar panels
When the solar panels arrived they were tested in order to make sure that they met the stated specifications. Upon testing the solar panels were brought outside and were tested for idle voltage (no load) and short circuit current. The test was conducted using one multimeter and one solar panel at a time to see whether they performed the same or not which they did. The results can be seen in table 5.3.1-1.

Shaker
Testing the shaker required a bit of handy work. It started out as a “Faraday flashlight” which means that it was used to power a LED. That circuit was removed and instead, extension cables were soldered on to the coils (there are two identical coils on the plastic tube). A multimeter was connected to the extension cables of one of the coils and both the idle voltage and short circuit current were measured. From one coil roughly 30 mW could be extracted. When both coils are used roughly 60 mW could be extracted.

RF
An antenna was constructed and used for testing the RF-circuit. The antenna was placed in a position to obtain a stable voltage of 50 mV. The antenna was connected to the RF-circuit and the output was connected to a capacitor of 1 mF. The test setup can be seen in figure 4.3.5-1. The results of the test can be seen in table 5.3.2-(1-2) and in figure 5.3.2-1.
Figure 4.3.5-1. Conducted RF outdoor test. Measuring the idle voltage. (GSM antenna with far off proximity). The measured voltage in the figure is not consistent with further measurements.

4.3.6 Source implementation

In section 4.3.6 the implementation of the sources will be described.

Qi

The Qi consists of one transmitter and one receiver. Both of them were practically ready to be used at arrival. Two wires had to be soldered to the receiver circuit, one for the positive terminal and one for ground, in order to make it more user friendly. Other than that, they
worked perfectly. No voltage control circuit needed to be added to this source since the receiver has a built-in circuit that delivers a steady 5 VDC at the output. The Qi chain is illustrated in figure 4.3.6-1.

![Qi chain schematic](image)

*Figure 4.3.6-1. Part of the system schematic, Qi chain.*

The positive wire from the receiver is connected to the source-pin of SW1 and to the MCU port D pin 1 (PD1). The MCU then detects if this source is active or not and sends a digital ‘0’ (0 V) or ‘1’ (5 V) to PD4 which is connected to the gate of SW1. A digital ‘0’ will allow current to flow through SW1 and a digital ‘1’ will block the current. The drain-pin of SW1 is connected to the drain-pins of SW2-SW5 (see fig. 4.3.6-6) and to the positive input of the Power Boost 500 charger circuit.

**User’s input**

At the user’s input any kind of electrical power source can be connected as long as the voltage is within 3-12 V, AC or DC. The user’s input chain is illustrated in figure 4.3.6-2.

![User’s input chain schematic](image)

*Figure 4.3.6-2. Part of the system schematic, user’s input chain.*

At the start of the chain is a full-bridge diode rectifier, which turns AC into DC, followed by a smoothing capacitor (not displayed in the schematic). DC will also pass through the rectifier with a slight voltage drop because of the two diodes that the current has to go through. After this stage the voltage is controlled by the VERTER converter to a steady 5 VDC before it reaches the source-pin of SW2 and pin PD2 at the MCU. A digital ‘0’ or ‘1’ at the gate of SW2 allows the current to pass through or block it.

**Solar panels**

The solar panels delivers a DC voltage and thus there is no need for a rectifier. Two of them are used and they are connected in series which implies that the voltage at the input is
between 9 and 9.5 V when they are illuminated. The solar panel chain is illustrated in figure 4.3.6-3.

![Solar panel chain diagram](image)

Figure 4.3.6-3. Part of the system schematic, solar panel chain.

The voltage is transformed in the VERTER circuit to 5 VDC and then measured by the MCU, through PD3, to check whether there is any voltage and if SW3 should be opened or closed. This is controlled by the MCU which sends a digital ‘0’ or ‘1’ to the gate of SW3.

**Shaker**

The shaker consists of a plastic tube with a moving magnet inside and a copper coil wound around it on the outside. As the magnet moves, a current is induced within the coil which can be used to power things. The shaker chain is illustrated in figure 4.3.6-4.

![Shaker chain diagram](image)

Figure 4.3.6-4. Part of the system schematic, shaker chain.

The chain for the shaker is exactly the same setup as for the user’s input. It starts with rectifying the voltage and then smoothes it out with a capacitor (not displayed in the schematic). The voltage is then transformed to 5 VDC before reaching SW4 which is controlled in the same way as previously mentioned for SW1 to SW3.

**RF**

The RF chain differs from the others in the way that it has its own little RF to DC circuit (see 3.7.3) which converts RF into a DC voltage. The amplitude of the voltage depends on the amplitude of the received RF signals, which depends on the size of the antenna that is being used. The antenna characteristics can be seen in chapter 3.4.5 regarding aperture and frequency. The RF chain is illustrated in figure 4.3.6-5.
Figure 4.3.6-5. Part of the system schematic, RF chain.

Other than the RF to DC circuit, the chain is the same as for the other sources. The voltage is controlled by the VERTER circuit. The current will pass through SW5, if the MCU allows it, and forward into the battery charger.

All sources combined
In figure 4.3.6-6 the whole system from sources and how they are connected to the consumer’s device is illustrated.

Figure 4.3.6-6. Part of the system schematic - the complete chain from sources, rectifiers, DC-DC converters, switches, battery, battery charger to the consumer.

4.3.7 7-segment displays and encoders
In section 4.3.7 the implementation of the displays will be described and illustrated. The displays require seven channels for controlling all necessary segments (decimal point is not included). This implies that seven pins on the MCU is required for controlling all necessary segments on one display unless an encoder is used. In this case an encoder is used which brings the amount of required pins at the MCU down to four per display. One port has eight pins which means that two displays can be controlled from one port as seen in figure 4.3.7-1.
The port in question is PORT B. PB0 to PB3 controls the lower case display and PB4 to PB7 controls the higher case display. The power supply for the displays are controlled by the user via a button placed on the device. This button sends a digital ‘0’ or ‘1’ to pin PD0 which tells the MCU to turn on or off the power for the displays, by allowing current to pass through SW6, and also starts the function which reads the current battery voltage value. The value information is sent to the encoders, through PORT D, where it is converted into the regular 7-segment display pin configuration.

The displays consumes quite a lot of power compared to the rest of the system which makes this option of being able to turn them on only when are supposed to be used a handy feature.

The complete system schematic can be see in figure 4.3.7-2.
Figure 4.3.7-2. System schematic.
5

Results

5.1 Introduction

In the beginning of the project, several aspects of the design’s layout was discussed to improve the results. Both in terms of choice of circuitry, implementation of components and what microcontroller tasks which may come to be important. In chapter 5 the results of the design will be presented.

5.2 Prestudy

The thought whether the battery was a better choice of storage unit was set and decided as a better approach to the finished project. Therefore the battery was implemented with the adherent battery control unit as described in chapter 4.2.2.

Since the beginning, all of the sources where decided to work one at a time in order to avoid inflicting currents and other issues when currents are combined. Therefore only one source at a time is allowed to provide current according to the hierarchy described in both chapters 3.4 and 4.3, regardless if the case is that all sources are connected simultaneously.

Instead of using two different versions of DC-DC converters, test results showed that only one of them was working according to the given specifications.

5.3 Implementation

For the microcontroller, the design specifications presented in chapter 4.3.1 were all implemented and completed. The MCU controls as discussed in chapter 4.3.2 constantly checks for which sources that might be connected and then rearrange the pin transistor for every source control in accordance to which one that should have precedence over the other sources.

It fetches the voltage status of the battery one time from the ADC when the external button is being pushed down. This for the sake of clearness regarding the visuality of the two 7-segment displays, the status is not constantly updated and printed out because it would
make the screens blurry due to that fact that the ADC has a ±5 percentage units uncertainty. The two 7-segment displays will hold the fetched value as long as the button is being pushed down.

When the Qi inductive charger is connected, it receives the transferred energy from the charger pad described in chapter 3.4.1. When placed correctly on the pad, it will provide a maximum power output. The user input is made to provide the option of inputting any source which could be DC or AC and reach to a minimum of 3 V and a maximum of 12 V. The user input will not activate unless the Qi charger is connected. The photovoltaic panels works in a similar way like the user’s input, however since the input is already DC, there is no need for a diode bridge. The shaker unit has two diode bridges since it is equipped with two coils. After that it works in a similar manner. RF is not connected as it will not be able to contribute anything to the overall charging unit. However it has other possibilities which have been described in chapter 3.4.5 and also when discussing the outcome in chapter 6.

5.3.1 Solar panels test results

The results from the test described in section 4.3.5, solar panels, are listed in table 5.3.1-1.

<table>
<thead>
<tr>
<th>Performance</th>
<th>Voltage (idle, no load)</th>
<th>Current (short circuit)</th>
<th>Power (load)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoors (fluorescent light)</td>
<td>~1.9 V</td>
<td>~0.25 mA</td>
<td>No load</td>
</tr>
<tr>
<td>Outdoors (direct sunlight)</td>
<td>4.7 V</td>
<td>~160 mA</td>
<td>No load</td>
</tr>
<tr>
<td>Stated specifications</td>
<td>4.6 V</td>
<td>160 mA</td>
<td>0.5 W</td>
</tr>
</tbody>
</table>

Table 5.3.1-1. Solar panels test results. The different test conditions have a direct effect on the output power.

As shown in the table, using a solar panel indoors will not generate sufficient power for charging the battery. Using them in direct sunlight however will.

5.3.2 RF test results

The results from the test described in section 4.3.5, RF, are listed in table 5.3.2-1.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Voltage output</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoors</td>
<td>0.05 mV</td>
<td>A steady voltage all over, implying radio shadow</td>
</tr>
<tr>
<td>Outdoors</td>
<td>10-100 mV</td>
<td>Certain areas may give peak voltage, thus the rather strong variations</td>
</tr>
</tbody>
</table>

Table 5.3.2-1. RF signal strength measurement.

A test was conducted seen in figure 5.3.2-1 to measure the charging time of a 1 mF capacitor using the rectenna circuit described in chapter 3.7.3. A spot outdoors was found to provide a
stable voltage reference of approximately 50 mV as idle voltage, (the voltage varied between everything from 1 mV - 150 mV). Then a series of voltage measurements with the capacitor connected was noted which can be seen in in table 5.3.2-2.

<table>
<thead>
<tr>
<th>Time, seconds</th>
<th>Voltage in capacitor, mV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>30.0</td>
</tr>
<tr>
<td>10</td>
<td>34.8</td>
</tr>
<tr>
<td>20</td>
<td>38.7</td>
</tr>
<tr>
<td>30</td>
<td>40.1</td>
</tr>
<tr>
<td>40</td>
<td>41.5</td>
</tr>
<tr>
<td>50</td>
<td>42.8</td>
</tr>
<tr>
<td>60</td>
<td>43.8</td>
</tr>
<tr>
<td>70</td>
<td>45.0</td>
</tr>
<tr>
<td>80</td>
<td>46.2</td>
</tr>
<tr>
<td>90</td>
<td>47.0</td>
</tr>
<tr>
<td>100</td>
<td>47.8</td>
</tr>
</tbody>
</table>

Table 5.3.2-2. A list of the charge time for a capacitor using RF.

The current was noted to be stable around 1-2 µA at about 50 mV. As seen in figure 5.3.2-1, the voltage increased with about 17.8 mV in 100 seconds, suggesting that as long as the rectified voltage is high enough, then the charging will reach to that point, which is the voltage specifications of the capacitor used, until it will stop charging.

The expression and correlation between the size of the capacitor and the time it will take to charge it fully gives

\[ i(t) = C \cdot \frac{dx(t)}{dt} \]  

(Eq 5.3.2-1)

which states that the time it takes to charge a capacitor fully of a particular size \( C \) with a the voltage \( v \) and the current \( i \) is

\[ dt = C \cdot \frac{dv(t)}{di(t)}. \]  

(Eq 5.3.2-2)

In figure 5.3.2-1 a graphical view of the charging cycle of the capacitor using RF can be viewed.
5.3.3 Final product

The final product ended up looking like figure 5.3.3-1. In the middle right section, the circuitry can be seen where the corresponding ICs, LED-displays, voltage indicator and voltage control circuits are positioned. Furthermore the battery is connected to the battery charger circuit (Power Boost 500) with the belonging sources. From upper left: solar panels, Qi charger, user’s input (USB) and shaker. The RF-circuitry with the antenna that we used was incompatible with the system and was thus left behind.

Figure 5.3.2-1. Charging cycle of the capacitor where the voltage has increased from the initial 30 mV to 50 mV over a time span of 100 seconds.
5.4 Conclusions

With respect to the results, one can utilise the ambient energy for charging batteries or powering low powered devices. In the end, the results turned out to be fine with what was initially planned which was to construct a product which would combine energy harvesting sources to one unit. All of the different energy sources turned out one way or the other to contribute with sufficient energies to make up for a charging unit. The sources were also successfully combined in an electrical arrangement, implying that a functional system could be constructed with the presumptions provided. As seen in all of chapter four and five, the results of respective source have been presented, supposedly suggesting that adequate results and research were able to be obtained.
6

Discussion

6.1 Results

First of all, beginning to mention that the extension of the project could have been expended to large proportions and cover the fields in much greater detail by making the whole system more complex and focus in greater extent for each and every energy harvesting source. However, due to the project limits, several decisions were made in order to get everything down and running before the time was up.

The project’s nature was to demonstrate an implementation design which in contemporary aspects are not really thought of which brought a large motivation point to the project as a whole. Another important aspect was to assess whether RF could be used as an energy source in whatsoever scale, which was also proven to be right.

Although despite the limits of the project, many concrete points were made. Essentially completing what was planned in the design and proved that each individual component and circuitry in theory can work well in the implemented state.

When looking at what was presented in the theory chapter and comparing it with the results, we found the results to be somewhat predictable, partially because we tested essentially every piece of component and circuitry the second we got our hands on them to know which limitations they would have on the construction of the overall design.

6.1.1 Radio frequency

Even though several volts can be achieved by the rectenna circuit, it often happens to be quite small. Since the voltages seen in 5.3.2-2 are fairly small, no efficient charging can be accomplished due to the voltage restriction in capacitors. This means that the supply voltage is the limit and it will not increase after it reached that point. However, this can be improved by adding additional voltage multipliers or by other means increase the voltage, thus the capacitor can be fully charged over a reasonable time and be utilised thereafter. Supposedly powering an MCU for a short time etc.
Despite that the energies are very low and because of this, the power is so low that it essentially becomes very difficult to make anything out of it, still something to bear in mind is if the antenna area is not an issue then a large enough assembly of antenna(s) could generate more significant energies.

Conceptually, the principle of receiving an electromagnetic signal of a certain frequency is fairly straightforward. However, the simplicity can be somewhat ostensible and equally mind boggling in terms of actually managing such immensely weak signals for the purpose of power storage and not “reading” the signal as information as it is commonly done and supposedly in first hand meant for.

6.2 Method

The implementation stage has several aspects to discuss since everything may not have performed as desired even though tests of every component was accounted for. For the consistency, the different parts will be discussed in greater detail henceforth.

6.2.1 Microcontroller

The MCU was since the beginning thought to be an essential part of the complete construction and a necessary part to provide desirable functions such as the battery indicator and the control switches. Although, whether or not the microcontroller could have been used for greater purposes, such as providing more profound functionality and complexity has not really been taken any steps further.

One interesting function would have been to use the PWM (pulse width modulation) function of the MCU. This could have lead to avoiding using the additional circuits for management of the voltage input it obtains and adjustments it make to maintain the measured 5.15 V it provides as output. The battery management unit (Adafruit Power Boost 500) also controls the critical feature to charge, tap and store the energy seen in chapter 3.7.2. Whether that could have been controlled completely by the MCU with a few additional transistors is also a point of view.

The sleep mode was never used in the complete construction of the design implementation. The measured idle power consumption of the MCU never exceeded large enough powers to be considered as a crucial concern to be fixed in this version. Therefore we let go for the time being of initializing the sleep mode partially since it did not seem necessary. However, other version of the design, using the built-in sleep mode could have been used.

6.2.2 Code structure and design

The code was in first hand written to achieve functionality and secondly in terms of optimization. Therefore the construct of the code may not be as great as it could have been,
however it accomplishes what it is supposed to do despite that it may have many parts of it which could be improved.

The function for checking the voltage level has an error rate of ±5 percentage units at the level indication, partially because of ripple and voltage drop when the external button is pressed down. This issue was attempted by adding a smoothing capacitor but without success. Preferably, this could have been compensated for by doing adjustments to the code if attempted. If the voltage drop was due to the displays being lit up, then the 7-segment displays could have been lit up some time later.

6.2.3 Pin planning

When we first started to construct the coupling and planned the arrangement of the pins for the various parts, we did not doubt that there might be serious complications when not considering structure. So when parts of the code got too messy, the whole pin planning was rearranged so it achieved more consistency. There was also concern whether the amount of pins would suffice, however it could have been solved by implementing a suitable de-multiplexer or choosing another MCU.

6.2.4 Storage unit

As previously mentioned, at the very start of the design specifications we were quite ambiguous about what the design should evolve around. We were not sure whether to use a battery or a set of supercapacitors since the application field, so to speak what devices the project should charge, was also vaguely stated at the time. Whether the project should involve power distribution to low energy consuming devices such as microprocessors, microcontrollers, ICs etc or as it turned out to be - consumer held products of greater energy consumption such as phones etc was somewhat confused.

It obviously turned out to be the latter one. But despite the fact that the supercapacitor came to lose some of its significance in the project, it later grew to eventually do good as a good substitute or complement if needed.

6.2.4 Boost converter

At implementation, two different types of boost converters were tested. The VERTER circuits and the LiPower circuit. Quickly we realised that the other one did not even perform close to as well as what specifications would suggest. Leaving us with the VERTER converters as the obvious choice to use for the construction.

6.2.5 MOSFETs

The system seen in section 4.3.7, figure 4.3.7-2, was believed to work just fine but there was a catch. The MOSFETs used for switches have a built-in safety diode which allows current to travel through it from the drain to the source when the voltage at the drain is larger than the voltage at the source. This type of MOSFET is called power MOSFET. The type of MOSFET
that was thought to be used was signal MOSFETs. The difference between them is illustrated in figure 6.2.5-1.

*Figure 6.2.5-1. Signal MOSFET (to the left) and power MOSFET (to the right).*

Using a power MOSFET instead of a signal MOSFET resulted in that when one source was active, that particular switch opened up which led to that the voltage at the drain pins was 5 V. Because of the built-in safety diodes, the voltage at the source pins for all sources was close to 5 V which led to that all switches opened up. Since only one source was active, the voltage quickly dropped since all other sources did not contribute with any additional voltage. This led to all switches being closed. In short, the system failed completely.

To solve this issue, diodes were implemented after the MOSFETs to prevent current from going backwards. In figure 6.2.5-1, these diodes are represented by D1 to D5. After implementing these diodes the system worked as it should. The final schematic can be seen in figure 6.2.5-1.
6.3 The work in a wider perspective

The idea is that this project should lead to think differently about how energy is used and stored. We first promoted a project without a battery and yet we used one, mostly because it was convenient for the project specifications. However, the initial idea was to suggest a design without a battery, thus not storing the extracted energy but rather using it instantly, leastwise for the more energy efficient sources and perhaps using a supercapacitor for RF and the shaker etc.

Because a battery was included in the design, it is easy to believe that this is the only proposed method of constructing such a product. However, what was hopefully conveyed was that the concept of this implementation has a wide variety of incidences and thereby hardly constructed in just one peculiar way depending on the area of usage.

6.4 Conclusion

The project has been educational and interesting to work with. We finally managed to produce a functional energy harvesting system that we hope can be used as a base for further investigation in this area.
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Appendix

Appendix 1

Appendix 1 consists of the complete code used in the project for the microcontroller unit (ATmega328). The code was written in C using the platform ATmel Studios 7. The code has not been edited in hindsight.

/*
 * proj.c
 *
 * Created: 2016-04-29 10:08:15
 * Author: Gustav & Gustav
 */
#include <avr/io.h>
#include <util/delay.h>
#include <avr/sfr_defs.h>
#include <stdlib.h>
#include <avr/interrupt.h>
#include <string.h>

//8 MHz
int battery_level(int percentage_input_converted);
int converts_ADC_into_stages(int ADC_data);

int Qi_Connect();
int Users_Connect();
int Solar_Connect();
int Shaker_Connect();
int RF_Connect();
int External_button();
void pin_control(int primary_source);
void Seg7_Displays(int battery_percent);
void turn_on_ADC();
void turn_off_ADC();
//Global variables
int battery, correction, temp1, one_read = 0;
int primary_source, knapp = 0;
int percentge_input_converted = 0;
int ADC_data = 0x00;

void main(void)
{
    DDRB = 0b11111111;  //OUT //The rightmost number is the 0th pin. 1 = output 0 = input
    DDRD = 0b11110000;
    DDRC |= 0b00011000;  //OBSERVE! The last bit (Pin7) can't be managed, it's always zero and thus worthless. (Check DDRC for more information)

    ADCSRA |= (1 << ADPS2) | (1 << ADPS1);  //Prescaler 64
    ADMUX |= (1 << ADLAR); //8 bit
    ADMUX |= (1 << REFS0);  //Aref = AVcc 255 = 5 volt
    ADCSRA |= (1 << ADEN); //Turn on ADC

    //100 nF between AVcc and GND might be needed for the ADC
    //A voltage source should NOT be connected to the AVref if Aref = AVcc has been chosen
    turn_on_ADC();

    while (1)
    {

    //-------------------------------

    primary_source = Qi_Connect();  //primary_source = 1 if Qi is connected

    if(primary_source != 1)
    {
        primary_source = Users_Connect();  // = 2 if user
    }
    if(primary_source != 1 && primary_source != 2)
    {
        primary_source = Solar_Connect();  // = 3 if Solar
    }
    if(primary_source != 1 && primary_source != 2 && primary_source != 3)
    {
        primary_source = Shaker_Connect();  // = 4 if Shaker
    }
    if(primary_source != 1 && primary_source != 2 && primary_source != 3 && primary_source != 4)
    {
        primary_source = RF_Connect();  // = 5 if RF
    }
}
pin_control(primary_source);  //.... if primary_source == 0 then no sources are connected....
knapp = External_button();

if(knapp == 1)  //Button pressed?
{
    ADCSRA |= (1 << ADSC);  //START A CONVERSION!

    while(ADCSRA & (1<<ADSC)) {}  //WAIT FOR THE CONVERSION TO COMPLETE
    PORTD &= ~0b10000000;  //Turn ON power supply for the two 7-seg displays.

So to say, drop the voltage for the PMOS
    ADC_data = ADCH;
    percetage_input_converted = converts_ADC_into_stages(ADC_data);
    battery = battery_level(percetage_input_converted);
    if(ADC_data > 208 && ADC_data < 148 && one_read == 1) PORTB = 0xEE;
    //"Error"
    else if(ADC_data <= 208 && ADC_data >= 148 && one_read == 1)
        Seg7_Displays(battery);
    one_read = 0;
}

// ----------------------------------------
if(knapp == 0)
{

    one_read = 1;
    PORTD |= 0b10000000;
//Turn OFF power supply for the two 7-seg displays and the two encoders
//turn_off_ADC();
//Sleep behövs inte. uCen drar bara 2-3 mA i running mode
}

void turn_on_ADC()
{
    //Initiate
    ADCSRA |= (1 << ADEN);  //Turn on ADC
}
void turn_off_ADC()
{
    ADCSRA &=(1 << ADEN);  //Turn off ADC
int battery_level(int percentage_input_converted)
{
    int battery_percentage, temp = 0;

    int range[] = {0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100};

    for(int index = 0; index < sizeof(range)-1; index++)
    {
        if((range[index] <= percentage_input_converted) && (percentage_input_converted <= range[index+1]))
        {
            temp = percentage_input_converted % 5;
            if (temp <= 2)
            {
                battery_percentage = range[index];
            }
            else
            {
                battery_percentage = range[index+1];
            }
        }
        break;
    }

    /*Will return the value which is closest. For instance - 72 is bigger than 70 but smaller than 75. Since 72 is closer to 70 than 75, it will return 70. */
    return battery_percentage;
}

int converts_ADC_into_stages(int ADC_data)
{
    // MIN 148 - 0x94 - 0b10010100 - (3.0 Volts) ||| MAX 198 - 4.2 V - 0xC6 - 0b11000110
    // [148,198] - Should I do something particular if the voltage happens to be out of this range? correction = 0;

    if(ADC_data >= 148 && ADC_data <= 208)
    {
        correction = (60-(208-ADC_data))*1.6667;    // Scaling factor! Low(est) = 1 * 1.6667 High(est) = 60 * 1.6667 = 100 %
    }
}
int Qi_Connect()
{
    //Is the Qi connected or not?
    if(bit_is_set(PIND, 1)) return 1;  //Yes it is
    else return 0;  //Nope
}

int Users_Connect()
{
    //Is the user connected or not?
    if(bit_is_set(PIND, 2)) return 2;  //Yes it is
    else return 0;  //Nope
}

int Solar_Connect()
{
    //Is the solar connected or not?
    if(bit_is_set(PIND, 3)) return 3;  //Yes it is
    else return 0;  //Nope
}

int Shaker_Connect()
{
    //Is the shaker connected or not?
    if(bit_is_set(PINC, 1)) return 4;  //Yes it is
    else return 0;  //Nope
}

int RF_Connect()
{
    //Is the rf connected or not?
    if(bit_is_set(PINC, 2)) return 5;  //Yes it is
    else return 0;  //Nope
}

int External_button()
{
    if(bit_is_set(PIND, 0)) return 1;
    else return 0;
void pin_control(int primary_source)
{
    //Do regulations according to flow diagram

    if(primary_source == 1) //Qi on!
    {
        //When PIND1 is '1', PORTD4 should open ('0')
        PORTD &= ~0b00010000;
        PORTD |= 0b00100000; //Cut current for User!
        PORTD |= 0b01000000; //Cuts current for SOLAR!
        PORTC |= 0b00001000;
        PORTC |= 0b00010000;
    }
    else if(primary_source == 2) //Users on!
    {
        //When PIND2 is '1', PORTD5 should open ('0')
        PORTD |= 0b00010000;
        PORTD &= ~0b00100000; //Cuts current for Qi!
        PORTD &= ~0b01000000; //Cuts current for Users
        PORTC |= 0b00001000;
        PORTC |= 0b00010000;
        PORTC |= 0b00010000;
    }
    else if(primary_source == 3) //Solar on!
    {
        //When PIND3 is '1', PORTD6 should open ('0')
        PORTD |= 0b00010000;
        PORTD |= 0b01000000; //Cuts current for Qi!
        PORTD &= ~0b01000000; //Cuts current for Users
        PORTC |= 0b00001000;
        PORTC |= 0b00010000;
    }
    else if(primary_source == 4) //Shaker on!
    {
        //When PINC1 is '1', PORTC3 should open ('0')
        //PORTC !!!!!!!!!!!!!! ---------
        PORTD |= 0b00010000;
        PORTD |= 0b00100000; //Cuts current for Qi!
        PORTD |= 0b01000000; //Cuts current for Users
        PORTD |= 0b00010000;
    }
    else if(primary_source == 5) //RF on!
    {

// When PINC1 is '1', PORTC4 should open ('0')

PORTD |= 0b00010000;  // Cuts current for Qi!
PORTD |= 0b00100000;  // Cuts current for Users
PORTD |= 0b01000000;
PORTC |= 0b00001000;
PORTC &|= ~0b00010000;

else
{
    PORTD |= 0b01110000;
    PORTC |= 0b00011000;

    // Cuts current for everything since nothing is connected (Shaker or RF)
}

void Seg7_Displays(int battery)
{
    // The lower screen (PB0 - PB3) The higher screen (PB4 - PB7)
    // Voltages between 3,0 -> 4,2 Volts

    if(battery > 0 && battery <=5) PORTB = 0x00;
    else if(battery > 5 && battery <=10) PORTB = 0x05;
    else if(battery > 10 && battery <=15) PORTB = 0x10;
    else if(battery > 15 && battery <=20) PORTB = 0x15;
    else if(battery > 20 && battery <=25) PORTB = 0x20;
    else if(battery > 25 && battery <=30) PORTB = 0x25;
    else if(battery > 30 && battery <=35) PORTB = 0x30;
    else if(battery > 35 && battery <=40) PORTB = 0x35;
    else if(battery > 40 && battery <=45) PORTB = 0x40;
    else if(battery > 45 && battery <=50) PORTB = 0x45;
    else if(battery > 50 && battery <=55) PORTB = 0x50;
    else if(battery > 55 && battery <=60) PORTB = 0x55;
    else if(battery > 60 && battery <=65) PORTB = 0x60;
    else if(battery > 65 && battery <=70) PORTB = 0x65;
    else if(battery > 70 && battery <=75) PORTB = 0x70;
    else if(battery > 75 && battery <=80) PORTB = 0x75;
    else if(battery > 80 && battery <=85) PORTB = 0x80;
    else if(battery > 85 && battery <=90) PORTB = 0x85;
    else if(battery > 90 && battery <=95) PORTB = 0x90;
    else if(battery > 95 && battery <=100) PORTB=0xFC;
}
Appendix 2

Appendix 2 consists of the datasheet used for the solar panels in the project. The datasheet was used in the theory chapter when the panels were described and was helpful when comparing the given specifications with the conducted tests.

### Appendix 2

#### Solarx MEGA * Series Module Products

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Wire Length</th>
<th>Vd</th>
<th>Iid(min.)</th>
<th>Iid(typ.)</th>
<th>Length*</th>
<th>Width*</th>
<th>Thickness*</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-25</td>
<td>MEGA module with wires</td>
<td>6.0&quot;(152.4mm)</td>
<td>7.5V</td>
<td>135mA</td>
<td>150mA</td>
<td>5.00&quot;(127.0mm)</td>
<td>5.00&quot;(127.0mm)</td>
<td>.125&quot;(3.0mm)</td>
</tr>
<tr>
<td>M-01</td>
<td>MEGA module with wires</td>
<td>6.0&quot;(152.4mm)</td>
<td>7.5V</td>
<td>135mA</td>
<td>150mA</td>
<td>5.00&quot;(127.0mm)</td>
<td>5.00&quot;(127.0mm)</td>
<td>.125&quot;(3.0mm)</td>
</tr>
</tbody>
</table>

#### Solarx SA-Series Plate Products [multiple components on 12" by 13" plates]

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Components/Plate</th>
<th>Vd</th>
<th>Iid(min.)</th>
<th>Iid(typ.)</th>
<th>Length*</th>
<th>Width*</th>
<th>Thickness*</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA-0250P</td>
<td>Finished 4X Plate</td>
<td>4</td>
<td>3.6V</td>
<td>300mA</td>
<td>320mA</td>
<td>13.00&quot;(330.2mm)</td>
<td>3.00&quot;(76.2mm)</td>
<td>.090&quot;(2.3mm)</td>
</tr>
<tr>
<td>SA-0610P</td>
<td>Standard 4X Plate</td>
<td>4</td>
<td>7.5V</td>
<td>110mA</td>
<td>125mA</td>
<td>6.00&quot;(152.4mm)</td>
<td>6.00&quot;(152.4mm)</td>
<td>.090&quot;(2.3mm)</td>
</tr>
<tr>
<td>SA-0610P</td>
<td>Coated 4X Plate</td>
<td>4</td>
<td>7.5V</td>
<td>110mA</td>
<td>125mA</td>
<td>6.00&quot;(152.4mm)</td>
<td>6.00&quot;(152.4mm)</td>
<td>.090&quot;(2.3mm)</td>
</tr>
</tbody>
</table>

#### SA-Series Components [individual components ready to use]

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Vd</th>
<th>Iid(min.)</th>
<th>Iid(typ.)</th>
<th>Length*</th>
<th>Width*</th>
<th>Thickness*</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA-0550</td>
<td>Finished 5X Component</td>
<td>3.6V</td>
<td>200mA</td>
<td>326mA</td>
<td>12.00&quot;(330.2mm)</td>
<td>3.00&quot;(76.2mm)</td>
<td>.090&quot;(2.3mm)</td>
</tr>
<tr>
<td>SA-0510</td>
<td>Standard 5X Component</td>
<td>7.5V</td>
<td>30mA</td>
<td>45mA</td>
<td>6.00&quot;(152.4mm)</td>
<td>2.17&quot;(55.0mm)</td>
<td>.090&quot;(2.3mm)</td>
</tr>
<tr>
<td>SA-0550</td>
<td>Standard 5X Component</td>
<td>7.5V</td>
<td>30mA</td>
<td>45mA</td>
<td>6.00&quot;(152.4mm)</td>
<td>2.17&quot;(55.0mm)</td>
<td>.090&quot;(2.3mm)</td>
</tr>
<tr>
<td>SA-1</td>
<td>Wired Component</td>
<td>17.5V</td>
<td>10mA</td>
<td>106mA</td>
<td>12.00&quot;(304.8mm)</td>
<td>4.33&quot;(110.0mm)</td>
<td>.090&quot;(2.3mm)</td>
</tr>
<tr>
<td>SA-2</td>
<td>Wired Component</td>
<td>17.5V</td>
<td>200mA</td>
<td>325mA</td>
<td>13.00&quot;(330.2mm)</td>
<td>6.00&quot;(152.4mm)</td>
<td>.090&quot;(2.3mm)</td>
</tr>
<tr>
<td>SA-5</td>
<td>Wired Component</td>
<td>17.5V</td>
<td>200mA</td>
<td>325mA</td>
<td>13.00&quot;(330.2mm)</td>
<td>12.00&quot;(304.8mm)</td>
<td>.090&quot;(2.3mm)</td>
</tr>
</tbody>
</table>

### Notes:
- Vd - Voltage under load
- Iid(min.) - Minimum initial current output measured at Vd under STC (Standard Test Conditions).
- Iid(typ.) - Typical initial current output measured at Vd under STC
- “Standard” SA-Series plates and components are provided with a protective back coating and solder pads.
- “Coated” SA-Series plates and components are provided with a protective back coating.
- “Finished” SA-Series plates and components are provided with a protective back coating and solder pads.
- STC - Standard Test Conditions are illumination of 1kW/m2 (1 sun) at spectral distribution 1.5 and a solar cell temperature of 25°C.

---

| All plate products | 12" x 13" x 0.09" | 364.8 mm x 330.2 mm x 2.3 mm |
## Electrical Specifications

<table>
<thead>
<tr>
<th>Model #</th>
<th>MSX-005</th>
<th>MSX-01</th>
<th>SA-03300</th>
<th>SA-0640</th>
<th>SA-0680</th>
<th>SA-06110</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specified Load Voltage (VLD)</td>
<td>3.3V</td>
<td>7.5V</td>
<td>3.6V</td>
<td>7.5V</td>
<td>7.5V</td>
<td>7.5V</td>
</tr>
<tr>
<td>Typical Current at Vld (Id)</td>
<td>150mA</td>
<td>150mA</td>
<td>320mA</td>
<td>35mA</td>
<td>90mA</td>
<td>125mA</td>
</tr>
<tr>
<td>Open Circuit Voltage (Ioc)</td>
<td>4.6V</td>
<td>10.3V</td>
<td>5.0V</td>
<td>12.0V</td>
<td>12.0V</td>
<td>12.0V</td>
</tr>
<tr>
<td>Short Circuit Current (Isc)</td>
<td>160mA</td>
<td>160mA</td>
<td>380mA</td>
<td>35mA</td>
<td>110mA</td>
<td>150mA</td>
</tr>
<tr>
<td>Temperature Coefficient of Voltage per °C</td>
<td>-16mV</td>
<td>-37mV</td>
<td>-15mV</td>
<td>-30mV</td>
<td>-30mV</td>
<td>-30mV</td>
</tr>
<tr>
<td>Temperature Coefficient of Current per °C</td>
<td>0.15 mA</td>
<td>0.15 mA</td>
<td>0.30 mA</td>
<td>0.05 mA</td>
<td>0.10 mA</td>
<td>0.15 mA</td>
</tr>
</tbody>
</table>

*Notes: Data based on measurement at STC. For full electrical data on the SA-1, SA-2, and SA-5, please consult the Solarax Data Sheets for these products.*