WORCESTER POLYTECHNIC INSTITUTE

Department of Electrical and Computer Engineering

Solar Powered Wireless Charging Device

A Major Qualifying Project Report Submitted to the Faculty of WORCESTER POLYTECHNIC INSTITUTE In partial fulfillment of the requirements for the Degree of Bachelor of Science

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This report represents work of WPI undergraduate students submitted to the faculty as evidence of a degree requirement

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Abstract

In today's fast-paced society, everyone is in constant need of handheld technology. The most common problem facing consumers is power; where and how can we charge all our devices. To alleviate the anxiety and the need to slow down and plug in, wireless charging offers the possibility to provide power to all our devices without being tethered by cords, and potentially without even thinking about it.

This MQP involves the design and implementation of a versatile charging system that implements solar charging and wireless power transfer (WPT) in the form of inductive coupling. During this project the team designed and developed a fully-functioning product through a three-stage design plan. First, a proof of concept (POC) test bench validating the ability of the technologies we have chosen to function correctly in our specific application. Second, a prototype utilizing these concepts was developed for testing and exploration of possible future improvements. This prototype was designed and developed by our team based on product and performance criteria detailed in the methodology. Third, we finalized a version of our design with changes and upgrades from a suite of testing performed on our prototype.

Acknowledgments

Our team would like to acknowledge and thank our sole advisor Professor Reinhold Ludwig for his help and guidance through the MQP process and in the successful completion of this project.

1. Introduction

1.1. What is Wireless Power Transfer

Traditionally, our power grid supplies buildings with alternating current (AC), delivered through a massive network of high-voltage and low-voltage transmission lines and transformers. Simply put, power travels from the grid and into a commercial building, then through internal electrical wiring until reaching an electrical outlet. Typically, a device must be physically tethered to an electrical outlet in order to charge or power it. This is where Wireless Power Transfer (WPT) technology comes in. Wireless power transfer technology can supply power through the air from a distance, no wires required. This can be done through a multitude of different technologies such as Inductive Coupling, Laser Light, or Ultrasonic transmission. Recently, the concept of transferring power without wires has been gaining popularity and attention, however, this concept is by no means new. There have been efforts to transfer electricity wirelessly since the late 1890s [1].

During the 19th century, Nikola Tesla was able to light electric bulbs completely wirelessly using what he called electrodynamic induction, later referred to as inductive coupling. In one of his experiments, he lit 30 bulbs 60 feet from a power source, an extremely impressive feat at the time. During his tests, a power source was attached to a coil and a capacitor in the coil absorbs a charge. Then, the current flows out of the capacitor and creates a magnetic field. This energy induces an electric current in the secondary coil. The energy is then passed back and forth between the two coils and builds up in the secondary coil and capacitor. When the charge in the secondary capacitor gets high there is a burst of electric current. This results in high-frequency AC voltage which can power bulbs and lamps from up to 60 feet away [2]. Much of this groundwork paved the way for modern electronics making use of similar wireless power transfer technologies.

Today wireless charging products are becoming more prominent. Many cell phone manufacturers are listing wireless charging capabilities as a selling point for their phones, and some even marketing wireless chargers of their own design and brand. Even so, the market for WPT devices and products is still in its infancy, but it is quickly gaining traction with tech consumers.

Most companies creating inductive charging devices follow what is called the Qi Standard. This industry standard is a product certification for coils using inductive coupling for wireless power transfer. The Qi Standard was developed by the Wireless Power Consortium in 2008 with the goal of creating a universal standard to allow cross compatibility between different companies' wireless charging devices [3]. While this standard is a great thing for the industry moving forward, it has its limitations as well. For example, most Qi devices operate at a range of around 5mm, with a maximum distance of only 40mm.

1.2. Motivation

The main motivation behind our design is the creation of a product that makes the charging of mobile devices more convenient. In our current use of handheld devices, we are tethered by a cord to charge everything. Not only is a cord in hand required, but there is also a need to have a proper outlet nearby to supply power. Our product is an attempt at alleviating this pressure for the cord-outlet system by having its own internal power generation and a cordless charging system. If a product like ours were to become widespread, charging devices would become much less of a hassle by allowing devices to be charged in more convenient locations. On top of convenience, we were also motivated to make our product using a renewable source of energy, which is where solar power comes in.

Using only energy collected from the solar cells, our product can play an interesting role as an off-the-grid power source. Aiming for a product that could function entirely from collecting and storing solar energy, we sought to create a product that will be usable in all kinds of different environments. This includes schools and offices, outdoor events, and could potentially be adapted for use in developing countries where there is not a power grid set up. Harnessing solar energy to avoid a dependency on a wall outlet is not a brand-new idea, but we hoped to bring it down to a smaller scale in a user-friendly way.

1.2.1. Market Analysis

Wireless power is a topic of increasing popularity with many businesses, startup companies, and research groups trying to perfect the design of a device which could benefit people around the world. Much of this technology is still in research and/or development, as refining wireless transfer methods is difficult and time consuming. There are many challenges with wireless power due to low rates of efficiency, as well as safety when considering higher power transfer levels and longer range. Even so, some companies have begun sale of their own devices and others are very close to going to market with a finished product.

One company called Pi Inc. [4] has begun selling a wireless power device of their own design named Pi, shown in Figure 1. Their technology uses weak magnetic fields in order to charge devices in close proximity. Their claim is the ability for the device to change the angle of its magnetic field. Their product does this in order to charge multiple devices, each in a different direction. With their technology they can charge up to 4 devices, each receiving a claimed 10 watts of power, which is quite substantial. For reference, Apple's iPhone X supports a maximum of 7.5 watts [5]. However, nothing is mentioned about the efficiency of their design. The system also requires a special case to be placed on the device being charged, which currently only supports a few select smartphones. With the Pi device, the idea of charging multiple phones and electronics around the transmitter was an interesting idea that we would have liked to implement. While this was beyond the scope of our project in the end, inductive coupling itself is the industry standard, and was eventually the method we ended up using for our device.

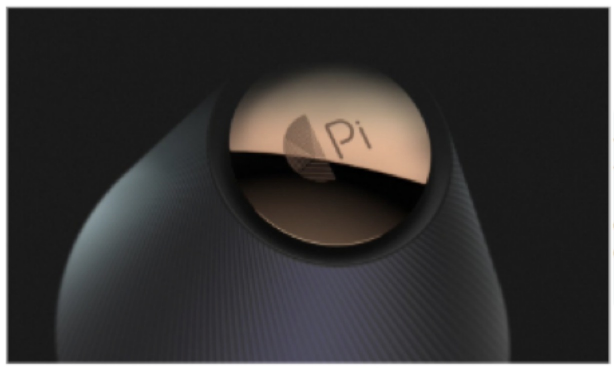

Figure 1: Pi Inductive Charging Device

Another product called uBeam [6], promises to transfer energy to a device using nothing more than the power of sound. Using ultrasound technology, uBeam has designed a system in which a transmitter, working like a speaker, emits a high-powered ultrasonic frequency. This frequency is well above the auditory threshold of humans and many common pets and animals. While the designers do not disclose the exact frequency or range, we can assume it is upwards of 80kHz, the upper hearing frequency limit of cats, who can hear the highest frequencies out of all common household pets [7]. The ultrasonic wave travels through the air until it is received from a device which functions similarly to a microphone, transforming acoustic energy into usable electrical energy. Like the Pi system, this would also require a relatively large receiver to be built into a case, dongle, or other peripheral to charge a device. While the idea of transferring energy using sound is intriguing, it is still a developing field. In order to implement an acoustic power transfer device, challenges would include design of the sound transmitter, building an effective and appropriately-sized receiver, and minimizing losses when transferring sound through the air.

Wi-Charge [8] is a company and product which uses light to charge a solar cell attached to a remote device. More specifically, they use infrared light to charge a custom-designed photovoltaic panel which again has been embedded into a smartphone case or into a dongle. This dongle can be seen in Figure 2. Their solution is market ready and a beta program for the device is well underway. Even though the specifications of the device are far from clear, they promise to deliver several watts from several meters away with their device mounted on a wall or ceiling of a room.

https://wi-charge.com/

Figure 2: Wi-Charge IR Receiver

A multitude of other devices are in various stages of development. In the case of most of the companies and research groups out there, many of the details, specifications, and information about their devices is either nonexistent or being kept confidential. This is understandable as much of this research is groundbreaking and sensitive, and a multitude of large companies would be interested in owning or developing it themselves.

2. Background

2.1. Near-field vs Far-field

Wireless power techniques fall into two main categories, non-radiative (near field) and radiative (far field). With near field techniques, power is transferred over shorter distances using magnetic or electric fields making use of inductive coupling and capacitive coupling, respectively. A British scientist, Michael Faraday, helped push the field of electromagnetism forward, creating Faraday's law of induction. This is important for determining how electromagnetic fields produce emf or electromagnetic induction. As shown in Equation (1), the so-called electromagnetic force (emf) voltage is simply the change in flux over the time interval, multiplied by the number of loops of the coil.

$$V_{emf} = -N\frac{d\phi_m}{dt} \quad (1)$$

Where: N = number of loops, ϕ_m= change in magnetic flux, and V_{emf} is the induced voltage [9].

Near field technology is used in many different "wireless" charging applications today. However, these applications are lacking both range and strength, mostly due to the limitations of the technology. Examples include devices such as phone charging mats, pacemaker devices, or electric toothbrushes. In far field techniques, power is transferred by a beam of energy using high frequency radio waves such as microwaves or lasers [10]. In using far field, a much longer distance can be achieved between the emitter and the receiver. Far field research into more advanced technology and devices is gaining traction in recent years with proposed applications in devices like solar powered satellites [11]. Far field technology is extremely important because it does not require a tether point, meaning it does not restrict a device to a very small range that it must stay within to charge.

2.2. Brief showcase of wireless power transfer methods

2.2.1. Wireless Power Transfer Through Light

Power transfer/conversion by means of light can be classified into three groups for our application. Our team primarily focused our research on ultraviolet (UV) light, visible light, and infrared (IR) light. We decided to stay away from gamma rays and x-rays due to the associated major safety concerns. In addition, higher frequency waves are mentioned in our research below on far-field radiative power transfer. While using solar photovoltaic (PV) cells to collect visible light is common, small amounts of energy can be collected by solar cells from the ultraviolet and infrared wavelengths present in sunlight.

Visible Light

Power transfer from visible light is the most common method of power transfer through light. This is the primary source for solar cells to collect the sun's energy [12]. A good example is a small solar cell found on calculators or a solar PV panel on top of a residential house. A conventional solar panel absorbs sunlight energy that reaches the ground, which consists of a small amount of ultraviolet light (around 10%) [13] with the rest of it being visible light and infrared light. Most modern-day solar panels convert the visible light that is received into electrical energy but can also convert some of the infrared energy received as well. In terms of efficiency, some ratings for solar panels can be as high as 22.5%, but most panels range from 15% to 17% efficiency [14].

The measurement of how much light is available at a given distance is called lux. There are many instruments and tools that can easily measure lux, which is essentially measuring light intensity at a given point. The factor of lux or irradiance (flux of radiant energy per unit area) would essentially be our only limiting factor. As long as our receiver can pick up the projected light, our device’s range would not be an issue and would work correctly.

Considering the safety of visible light, very few issues are present. At no point would we be using high powered lasers for our light transfer, and we would instead be using the light already available in a given environment. This way we introduce no new safety concerns, as people are already constantly exposed to the light that we are collecting. Only really in an outdoor setting does our product come with the risk of a sunburn. This is a difficult issue to address in the design of our product, so it would be more important for users to hold themselves responsible for controlling their exposure to sunlight.

Infrared Light

Power transfer from infrared light is another relatively common power transfer solution. Infrared light has a longer wavelength than visible light, and therefore is invisible to the human eye. This allows for a good method to transfer power wirelessly without being noticed, contrary to the use of a laser light. Currently, in terms of efficiency, solar panels can convert less than half of the infrared energy that reaches the elements [14]. This contrasts visible light, which is the main target of energy conversion using a typical solar panel. There are, however, new solar panel technologies being developed to make better use of the IR spectrum.

With respect to operating range, IR light can be detected at a similar range to that of visible light. In fact, for our application IR light would serve a slightly longer range due to the longer wavelength. This range, however, is also dependent on the capability of the transmitting source of light.

As stated previously, each type of light on the spectrum has its own safety concerns. Differing from visible light, IR waves can have harmful effects to both a person's eyes and skin [15]. The Food and Drug Administration (FDA) has set IR standards for manufacturers that accommodate for the hazards of IR light exposure [16]. Skin exposed to IR light provides a warning mechanism against thermal effect in the form of pain, but since the eye may not detect IR light, it is hard to prevent against the damage that can occur. Prolonged IR light exposure raises the internal temperature of the eye and can lead to lens, cornea and retina damage, including cataracts, corneal ulcers and retinal burns [13]. In part because of these complications we did not choose to use an IR transmitter in our design.

Ultraviolet Light

Using Ultraviolet (UV) light as a source for wireless power transfer is another technology that could have potentially been implemented. Unfortunately, the efficiency for collecting ultraviolet light is extremely poor. In terms of solar panels, as stated above, only up to four percent of energy from ultraviolet sources can be converted into electrical energy. Similarly to IR light, research is being done to use ultraviolet as an improved source for energy transfer, but with efficiency and practicality already so low, IR light will most likely be a better solution. Additionally, IR light already has a much greater efficiency and is arguably safer.

Out of the three types of light discussed, the obvious outlier in terms of safety would be Ultraviolet light. Exposure to UV light is a major risk factor for most skin cancers. This, along with its associated inefficiency, excluded it from our selection process. We decided to focus on visible light, as it has a much higher potential to accomplish our goals safely and effectively. The safety aspect of this is particularly important, as we did not want to design a product or use a technology that is unsafe to the consumer.

2.2.2. Near-Field, Non-Radiative Wireless Power Transfer Methods

Radio frequency (RF) wireless power transfer can largely be categorized into either capacitive or inductive coupling. While inductive methods of wireless power transfer are more common, both methods have their advantages and drawbacks.

Inductive Coupling

Inductive power transfer relies on the oscillating magnetic field created from alternating current flowing through a wire. When alternating current passes through a coil of wire, the magnetic field around the wire oscillates. In turn, a changing magnetic field can be used to induce a current in another coil of wire placed within the magnetic field, as is illustrated in Figure 3.

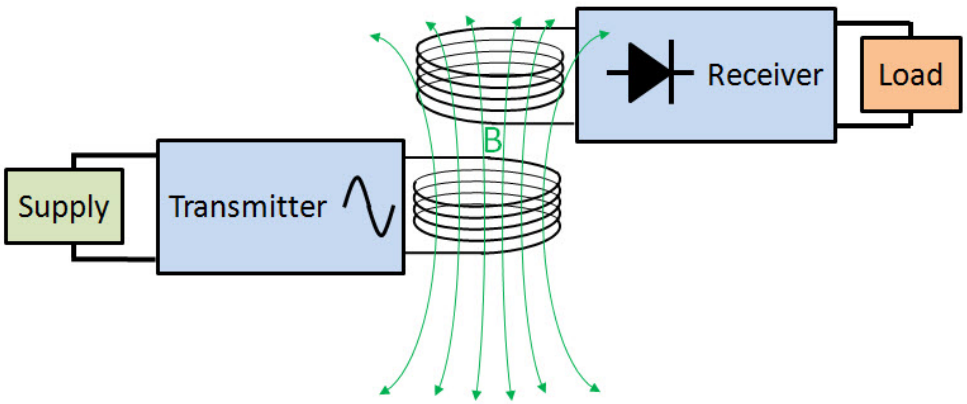

Figure 3: Inductive Coupling Diagram

This method of wirelessly inducing current forms the basis of most inductive power transfer systems, as well as the aforementioned Qi Standard for wireless power transfer. One interesting example of an application of inductive power transfer is the idea of localized charging. This works by arranging an array of coils and energizing only the individual coils as necessary, based on the position of the receiver. An example of this array of coils be seen in Figure 4.

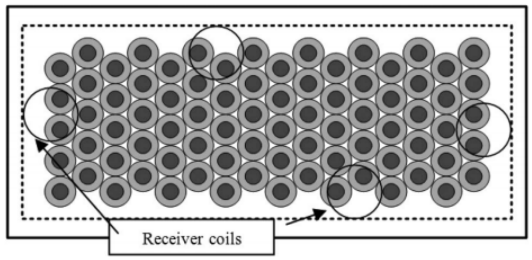

Figure 4: Array of Coils to form Localized Charging

While inductive power transfer is currently the standard for wireless power transfer with high efficiency levels, it is still considered a near-field power transfer technique, typically limited to well under 40mm in range [3]. It also becomes increasingly ineffective as the range is increased. Therefore, inductive coupling is mainly used in technologies such as wirelessly charging cell phones over short distances.

Capacitive Coupling

Capacitive power transfer is another method of power transfer that, compared to inductive coupling, has been much less popular in research and technology. Capacitive coupling works by feeding alternating current into an electrode that creates an electric field, which in turn transfers the energy into another electrode. This will induce an alternating current into the second electrode. Figure 5 shows how a capacitive coupling system would work taking a power source and then powering a load.

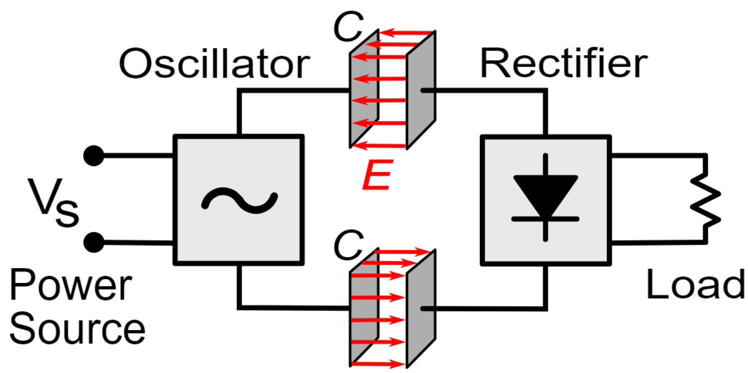

Figure 5: Capacitive Coupling Diagram

Unfortunately, like inductive, capacitive power transfer is also limited in range. In order to achieve significant power transfer at ranges over a foot, the electric field required would have to so strong that it would likely become dangerous. Being exposed to strong electromagnetic fields can be incredibly hazardous for humans [17]. While capacitive power transfer is feasible in low-power, short-ranged applications, it remains inferior to inductive coupling in both efficiency and in range.

2.2.3. Far-Field, Radiative Wireless Power Transfer through Microwaves

Microwave power transfer is a radiative method of transmitting power over long distances by directing high frequency radiation to a receiver. This method of power transfer can be used to send high levels of power over much further distances than the near-field power transfer techniques discussed above. It relies on a transmitting antenna directing microwave radiation towards a receiving rectenna that converts the waves into electrical energy. A basic diagram displaying microwave power transfer is shown in Figure 6.

Figure 6: Microwave Power Transfer Block Diagram

The main drawbacks of microwave power transfer are the potential health impacts microwave radiation could have, as well inconveniences associated with the fact that the radiation must be directed towards the receiver. While no definitive conclusions have been drawn, exposure to microwaves or similar radiation has been linked with higher rates of developing cancer [18]. Traditionally being a directed method of power transfer, building a compact rectenna is also a challenge. This is because in general, large, finely tuned antennas are needed for the operation of microwave transfer.

2.3. Technology Performance Matrix and Comparisons

In order to make the best choice for the technology we wanted to utilize, we performed a value analysis. The first step was to choose the criteria that are important in the design, and weigh the importance of each against all others. We used the number 1 to signify one criterion was more important than the other, 0.5 to signify equal importance of the two criteria, and 0 to signify that the first criterion is less important than the second. The sum of all these numbers gives us the total importance of that criterion, which we then weighted to a 100-point scale for better readability, seen in Appendix A, Table A1.

With our weight factors of each criterion created, we then set out to compare and rate each of the technologies for each category using a decision matrix. By multiplying the ratings of each technology's criterion by the weight factor determined in the table above, we were able to score and rank each of the proposed technologies based on these criteria. Adding all these scores together gives the decision factor for each technology, which should be a direct mapping of how closely each technology meets the criteria we most desire to complete this project. This was performed for each technology, which gave way to Inductive Coupling and Visible light standing out from the others. The table itself can be seen in Appendix A, Table A2.

The value analysis clearly showed that visible light best fits our criteria and our requirements for this project. Careful examination and discussion of the many possible technologies mentioned in the background section along with this analysis, have yielded two technologies. With this in mind, we planned to integrate a solar panel solution to collect visible light into a desk, table or pad. This light source is typically found in overhead lights in a classroom or office setting, making it readily available with no modification required. Collecting energy from visible light will not accomplish our goal alone. Additionally, we plan to implement an inductive coupling system. This would take the power generated and stored by the solar panel and storage system, from the panel, and send that power to devices on or near the table. This will allow us to provide a truly wireless experience for the end-user. Ideally, the user could place their phone or device anywhere on the table's charging zone for it to be powered.

3.Objective

Our team developed explicit technical specifications and requirements to drive our prototype product designs. These requirements were followed during the design and construction process.

1.) Product charges 1 phone placed on top of the tabletop surface with 5V at 1A.
2.) Product collects and stores energy via solar cells and battery when placed in an environment with light. It should be able to generate at least 5W in both indoor and outdoor environments
3.) Product transfers energy from a battery to an inductive coupling circuit.
4.) Product integrates matching networks to optimize power transfer between coils and minimize losses across the entire system.
5.) Product is aesthetically pleasing and complete, resembling a finished, polished product.
6.) Product makes use of a modular design wherever possible
7.) System supports Micro-USB and Lightning connection type devices with stretch goal to support other connectors like USB-C.
8.) Product should pose no safety or health concerns to the user.
9.) Product should be environmentally friendly, creating no negative byproducts.

Developing and working with these nine objectives helped us to focus our design process and set our priorities for our product. We did have stretch goals and extra ideas, such as multiple-device charging, larger battery capacity, or other aesthetic or structural improvements, but meeting our objectives with a functional product was our first priority.

The expected outcome for our project was a demonstration-ready product that would ideally meet all our product and performance specifications. We planned to create a wireless charging device using both visible light and inductive coupling technologies. Our team planned to build a table/tabletop which would harness light energy via preexisting lighting fixtures in a building, then store it in a battery and distribute it to a smart cellphone device at a wattage of 5 watts using inductive coupling and a small device attached to the phone acting as a receiver.

4. Methodology & Approach

4.1. Addressing safety concerns

Since the main application of our design makes use of ambient lighting indoors for the solar panels and inductive power transfer for charging, safety concerns were significantly minimized. We no longer had to worry about the health concerns associated with far field, radiative methods of power transfer. Additionally, different wavelengths and intensities of light can cause skin damage or other health issues, but since we are relying mainly on indoor lighting, we are not adding any light source that people would not normally be exposed to. This concern increases if our product were to be adapted for the outdoors, but only because the sun already produces UV light and causes sunburns. Our product does not contribute to an increase exposure to the sun. As for the inductive coupling, especially on such a small scale, the magnitude of the slowly changing electromagnetic fields involved in charging a device poses no significant dangers even when operated continuously.

Another safety concern that arises comes with working with solar cells. Most solar cells contain a small amount of inorganic compounds including Cadmium and Arsenic, which can pose a health risk to exposed individuals. One study shows that people who work with or are heavily involved in solar cell production may be at risk for significant levels of exposure to these compounds [19]. On the smaller scale of our product, we can safely assume that users would be safe from exposure to the aforementioned compounds, especially since consumers would not be expected to be working directly with the solar cells. Additionally, the cells we use are coated in epoxy gel, which offers another layer in protection from these chemicals. In addition to this, mass production and consumption of solar panels can lead to environmental and waste issues later in the future [20]. Our cells can, however, be expected to have a lifespan of about 20 years before the need for replacement. The National Renewable Energy Laboratory (NREL) did a study that collected data to show the degradation rate of solar cells each year. These results demonstrate an average loss of about 0.8% efficiency each year, as shown in Figure 7 below [21].

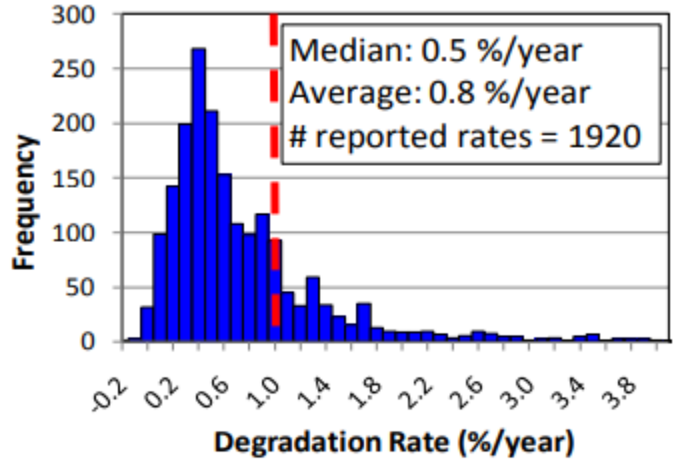

Figure 7: NREL's Solar Cell Degradation Rate Data

4.2. Matching Networks/Coil Matching

From our background research, one very important aspect of inductive coupling is the need for creating a matching network for the transmitting and receiving coils in order to properly "tune" the system. The reason for creating these matching networks can be seen by looking at the Maximum Power Transfer Theorem [22]. The theorem states that in order to achieve the maximum power transfer between two circuit elements, the two elements must have impedances that are a complex conjugate pair. When the two elements are tuned correctly, they both resonant at the same frequency, allowing for the peak power amplitude.

Matching networks become particularly important when using homemade coils, which leave a lot of room for errors and differences between the transmitting and receiving coils. Our team found that designing and winding our own coils was a bigger challenge than first anticipated, so we decided to make use of pre-designed coils. Despite ordering the same coils with the same specifications, we found that there were minor differences between the impedance on some of the coils. Because of this, when it came to our circuit design, we left space intentionally so that tuning capacitors could be added on both the transmitting and receiving circuits to more accurately tune the two coils so that we could obtain the maximum power transfer between them. This will also be helpful for those who use our design and decide to make their own coils, as there will be a place where tuning capacitors can be added.

4.2.1. Coil Frequency

After many considerations for the coil we intended to use for our circuits, we decided on a coil offered from Digikey [23]. In the beginning, we wanted to design and use our own coil, but this proved to be a challenging and time-consuming task within itself. When designing our own coil, especially a pancake coil, which is the coil type our system uses, you must have an effective way to wind the coil tightly.

Originally, we attempted to design a tool that could help us with wrapping our own coils and would allow us to make coils of various sizes for testing with our system. This is shown in Figure 8, where you would 3D print two of these circles, then put a screw with several washers in between them. Then, because of the shape of the 3D printed wheels and the pressure created between them, this would allow for a tightly wrapped coil.

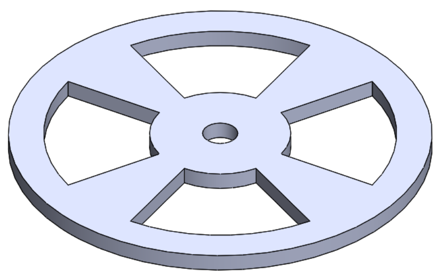

Figure 8: Custom Coil Wrapping Tool

The purpose of the holes cut out in the design, was so that you would be able to glue the coil when finished so that it would hold its shape. Despite spending time designing this, as stated before, we ended up using a premade coil that we ordered. We found that some of the coils sold, could be both Transmitters (Tx's) and Receivers (Rx's) which would work out well for our coil matching. The coil we chose to use was 53mm x 53mm and was mounted to a square plate. This plate made it easy for us to mount the coil to a flat surface, and also helped to make sure the coil stayed flat when designing and working with both the Tx and Rx circuits. We choose a coil with a resonant frequency of 1.8MHz, which we thought would be a good match for our circuit. This frequency was towards the lower middle range of the premade coils offered, but we thought that this would work fine for the power that we planned to transfer. We also had to consider the circuit we were building to make sure that we could produce a signal at the 1.8MHz range so that we could match the ideal resonant frequency of the coils.

4.3. Shielded cables

Because of the nature of coils (wire wound in order to propagate an electric field), it is important to take into account interference. One easy way to combat aspects of interference is to make use of shielded cables in connecting the solar cells to the charge controller, charge controller to the battery, battery to the inductive charging circuit and finally the charging circuit to the transmission coil. The wires connecting the transmission coil and the transmitting circuit are by far the most important for shielding because these carry a lot of voltage and current and are very close in proximity to the coil.

In addition to this, it is important to consider losses in this situation. Fortunately, the prebuilt coil we purchased had a fairly durable construction as well as came with high permeability shielding. This shielding runs the length of the coil, but stops at the ends of it, which leaves the connections exposed to both losses and interference. After research into possible connector types to use, we decided to go with an MMCX (Micro-miniature coaxial) connector type. These connectors have a snap-like locking system which still allowed for 360 degrees of rotation; they are capable of transmitting up to 6 GHz signals [24]. Our goals for selecting a cable/connector type were that we wanted it to be small enough for the circuit, ruling out standard coaxial cables, but also maintain durability. Durability starts to become a problem when using very small connectors, and we wanted to make sure that the connector we choose had enough lifetime to be removed and reconnected if need be, to follow our modular design goal. MMXC was a happy medium for this, meeting our size, durability and transmission goals. Moving forward beyond our initial prototype, this would be the ideal connector for a more polished product.

4.4. Signal Generation

One of the primary components that our transmitting circuit is based on is the 555 timer[25]. When researching and designing our circuit, we investigated several designs for the transmitter, but decided to go with the 555 timer for its simplicity, low cost, and that it was an ideal oscillator for putting out a steady, low noise, filterable waveform. In the beginning, we started out using a conventional 555 timer, which was the NE555 timer. This timer is a Bipolar IC 555 timer, which we eventually found could not operate at the high frequency of 1.8 MHz that we needed for our coil. The solution to this was to use a fairly new Texas Instruments chip called the LMC555. This chip was a LinCMOS style IC which allowed for a maximum frequency of 3 MHz, more than enough for what we needed in our design. This 555 timer, along with the correct filtering would be ideal for the signal we needed to drive our transmitting coil.

4.5. Solar Charging

Looking at the challenge of solar charging, the main objective was to collect light, convert it to electrical energy, then subsequently store this energy before it is sent to the inductive charging component of our product. During our research on solar cells, it was important to consider the power output capabilities of the cells, the lifespan of the cells, as well as the sturdiness of the cells. The latter concern was particularly troubling in the initial stage as we quickly learned how brittle solar cells can be. To solve this, research was conducted into coating techniques, in particular, enamel and epoxy coating. Both substances, when applied to the fragile solar cells both do not inhibit the function of the cells and reasonably protects the cells from damage. The wiring for each solar panel and the system as a whole was designed mathematically, considering parallel and series configurations to best output the necessary 12V required to activate the charge controller. The charge controller was a necessary component so that our battery would not overcharge or discharge energy as levels of light fluctuated.

5. Design and Development

5.1. Full Table Design Block Diagram

At the start of the physical design process we created and made use of many diagrams and schematics. This is an integral part of assemble as these figures and documents can act as explicit assembly instructions. The first to be developed was our system top-level block diagram, showing the basic connectivity and power levels of every component in the system, seen in Figure 9. This was helpful to put together as it allowed us to visualize and outline all the different pieces of the system and make sure that they were all going to work together.

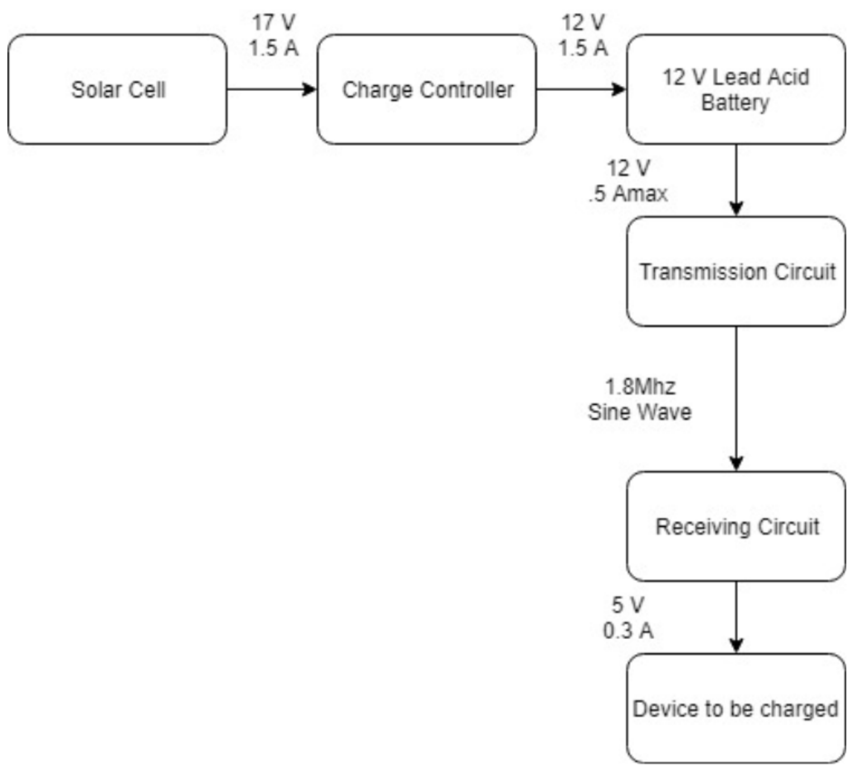

Figure 9: Top-level System Block Diagram

5.2. Circuit Schematics and Explanation

5.2.1. Transmission

As stated before, for the transmitting circuit, we used a 555 timer at the core of the circuit to generate the waveform we needed to drive the two coils. We went through many iterations of the transmitting circuit trying primarily to maximize our output current. This was one of the most challenging pieces of the project. Starting out, we were using the standard NE555 timer to generate the sine wave to drive our coils. While testing this design, we ran into a hardware limitation with the timer, as we realized that even with changing the resistor and capacitor values, the timer we were using could not support the high frequency we wanted our circuit to operate at. We remedied this quickly by looking into our options for 555 timers and deciding to go with a fairly new timer offered by Texas Instruments. The new LMC555 timer is a CMOS IC, whereas the original NE555 timer used a bipolar design. The LMC555 timer can support frequencies up to 3 MHz, which would be more than enough for our coils that have a resonant frequency of 1.8 MHz [25]. After switching to this timer, we used Equation 2, show below, to calculate what components we needed. Using this setup, we were able to generate an ideal waveform at 1.79 MHz to 1.8 MHz. After making the switch to the new 555 timer, we went through more iterations of modeling, designing, and testing different transistors and MOSFETs to achieve our goals of increasing the liftoff distance between the two coils as well as having a power output of at least 5W. This proved very difficult, as in the beginning we were able to have voltage levels that were high enough to charge a phone, but our current was very low. Our final design made use of the BD139 NPN power transistor [26], which gave us a boost in the power transmitted to the receiving circuit, and still kept a clean 1.8 MHz sine wave.

$$f = \frac{1.44}{(R_1 + 2R_2)\, C_1} \tag{2}$$

Where: R_1, R_2, and C_1 are resistor and capacitor tuning components to achieve the desired output frequency.

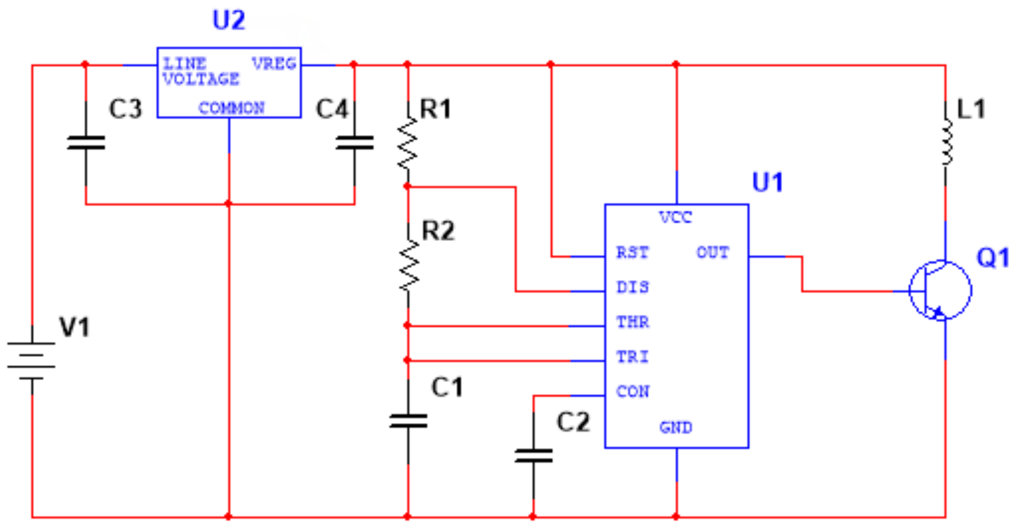

Figure 10: Transmission Circuit without Coil Matching

5.2.2. Receiving

For our receiving circuit, one of our primary goals was to keep it as simple and small in size as possible. The idea was that this was something that needed to fit in either a cell phone case, or on the back of a cell phone. We started out using a very simple design with the coil, a tuning capacitor, the diode bridge rectifier, and then a voltage regulator so that our cell phone only ever received 5V. The diodes we used were the 1N4003 [27], which were more than enough for the power that we were transferring from the transmission circuit. This was the design we used for most of the duration of our project, before changing the design slightly getting rid of the voltage regulator and replacing it with a buck converter. We decided to use a buck converter based around the LM2596 [28] DC to DC IC. Using the buck converter had more upsides than the voltage regulator. The first was that we were able to “tune” the buck converter so that we could have an output not just at 5V, but at other voltage levels to support bigger devices as well as support the 9V fast charging standard. In addition to this, it also gave us a slight increase in current output which allowed us to have enough current to charge a standard cell phone. This circuit was also small enough that it could easily be mounted/inlaid into a standard cell phone case, as shown in Figure 12.

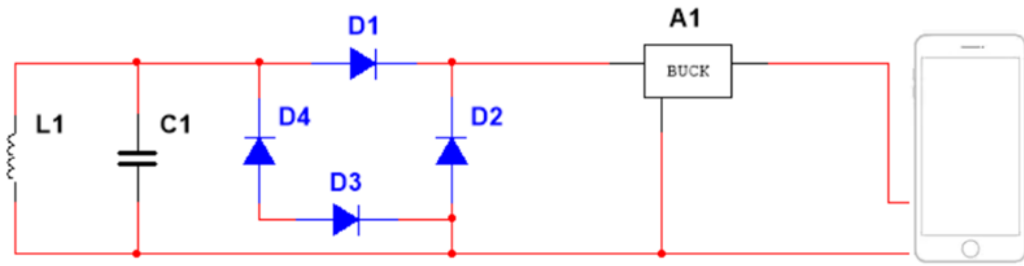

Figure 11: Receiving Circuit with Tuning Capacitor

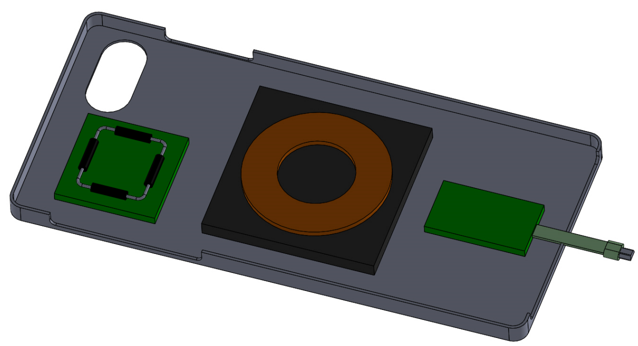

Figure 12: Example Receiving Circuit Layout in Phone Case

5.3. Table Construction

All the systems we designed needed a mechanical structure to be attached to and contained within. In our first rendition of the tabletop we had measured and cut a black IKEA table. This material proved suitable for an early prototype as it was easy to work with and was already shaped in the design we needed, a flat rectangular prism. However, it was soon clear that our tabletop would need to be completely custom designed in shape and material. We decided our primary material would be a PVC board. PVC board is lighter than wood, strong, waterproof, and most importantly does not burn or melt when laser cut. The idea for the table was that one solid 2′ x 3′ sheet of PVB board would serve as the bottom base layer. Another piece of PVC board would serve as the top of the table and would have holes cut in it so that the solar cell array and the circuitry and coils could be placed in it. Then, using spacers along with some bolts, washers, and nuts, the top and bottom would be matted together. Our first design was hand cut and served as a 2^{nd} prototype housing for our components while the circuit and cells were tested and tuned. However, as we quickly approached the end of the project, we needed a polished design for demonstration purposes and to satisfy all our design criteria.

5.3.1. CAD Drawings of the Table and Components

Our team designed and produced CAD drawings with exact dimensions for the final version of the tabletop, an example of one of the produced drawings can be seen in Figure 13. In working on the design, we also contacted a local machine shop in order to cut our PVC board precisely to our chosen specifications. These cuts met our expectations, making the tabletop look professional and aesthetically pleasing.

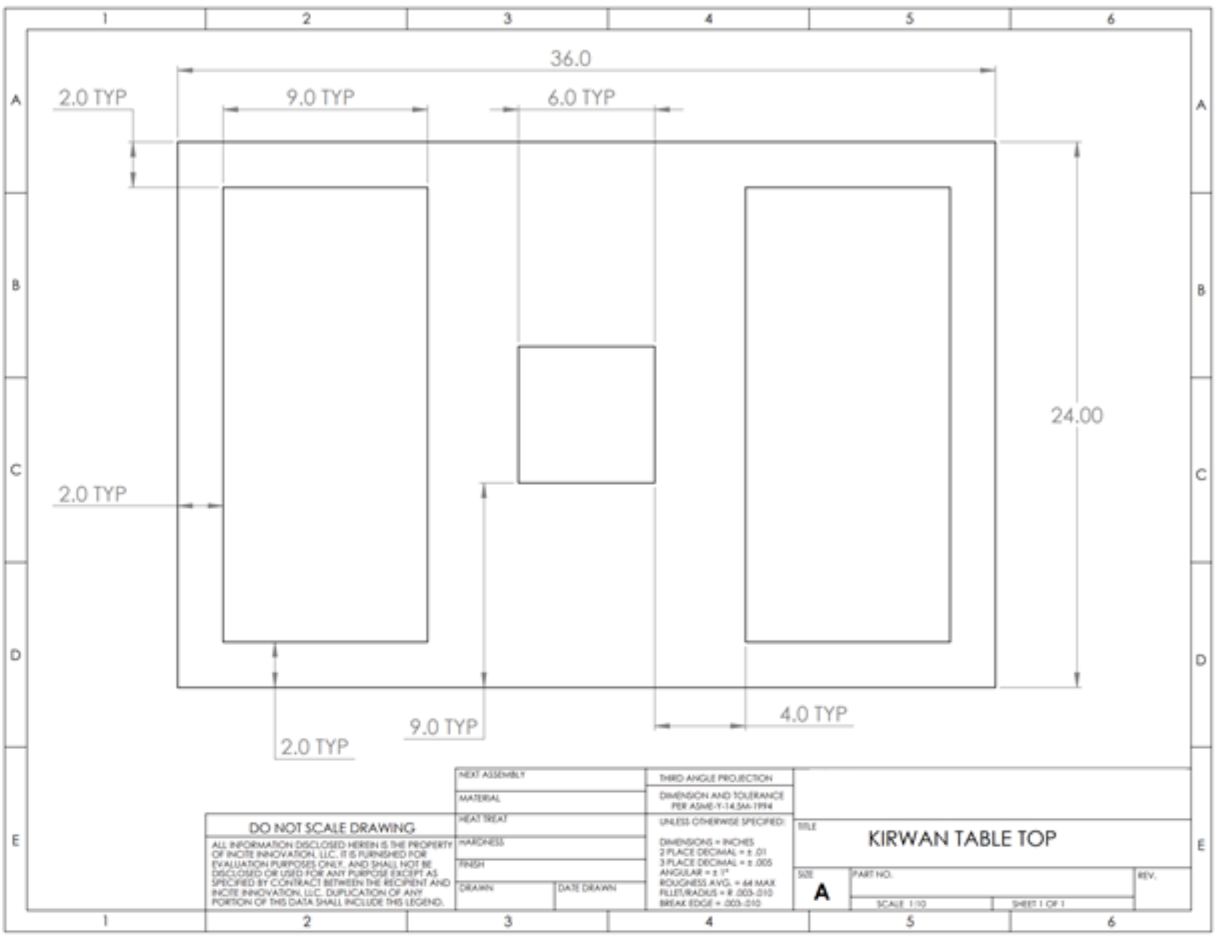

Figure 13: CAD Drawing of Cut PVC Board

5.4. Design and Assembly

The main objectives in the table design were to have a set of solar panels for gathering energy, and an area for a phone to charge. After several mockups and some calculations into what size of the solar panels would provide enough power to our system, we realized that most of the tabletop surface would need to be covered in solar cells. We decided on putting the charging area in the center of the table, displaying the charging capabilities front and center, while the solar panels were put off to the sides taking up most of the space on the table. Moving forward, we viewed the table as two different modules; the first module consists of the solar panels and the second includes the transmitter circuit and coil. The battery acted as the mediator between these two modules.

5.4.1. Solar Cell & Table Design

The array of solar cells that comprises each panel went through many iterations to best optimize them for our design. The first iteration to be physically assembled utilized solar cells that were 2 inches by 2 inches, and each generated an average of 0.5V at 0.4A. The space allotted allowed for 8 rows of 9 cells, or a total of 72 cells. To best achieve the 12V minimum voltage required for the activation of the charge controller, we soldered the cells together in two parallel circuits of 36 cells. Figure 14 shows how these cells were aligned and wired. This way, the cells would be able to achieve the 12V minimum for the charge controller in most lighting settings. The cells did consistently hit that mark in our testing, but the cells themselves were very delicate, and because of the assembly that was required, were very difficult to replace. We decided that moving forward we would need a more durable and more professional cell design that would be easier to work with.

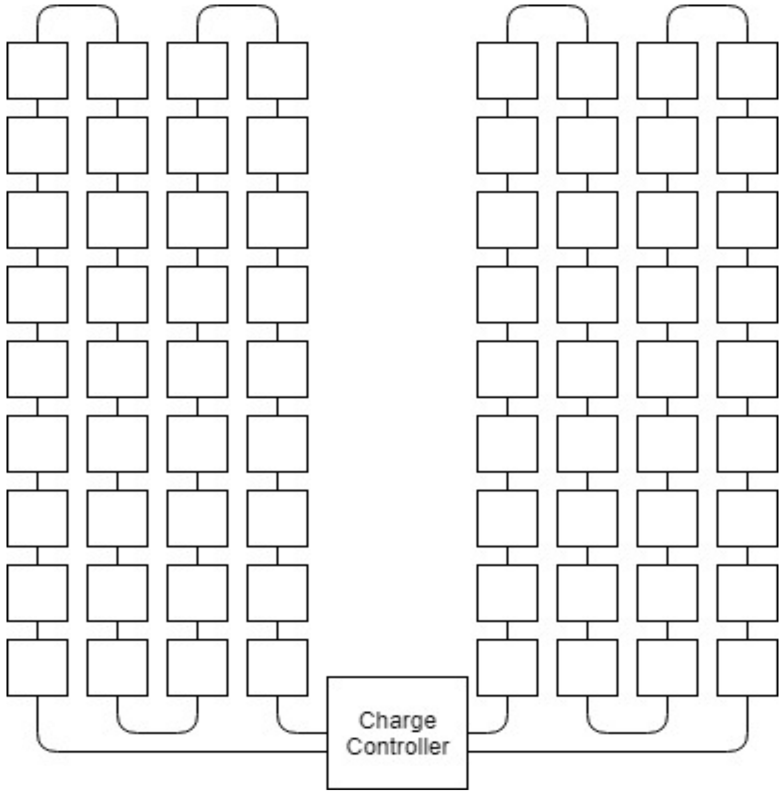

Figure 14: First iteration of solar cell design

In the second iteration, we eliminated the first design and decided on a new solar cell type and configuration. Additionally, we needed a protection method to keep the cells safe and secure. After researching different options, we decided on one method making use of epoxy sealant. The design also included soldered wire connectors to positive and negative terminals, instead of tab wire running over and under each cell. This meant that the cells were much more durable, and in the event that they did break, we could simply pull one cell out of the array for easy replacement. The new cells are 2.67 inches by 1.45 inches, meaning that 6 rows of 12 cells would fit into the allotted space. The cells are aligned in groups of 12, using parallel and series circuits, as shown in Figure 15, in order to produce a calculated combined output of about 17V at a current of 1.5A. The cells are individually capable of creating 60mA of current based on a voltage of 5V.

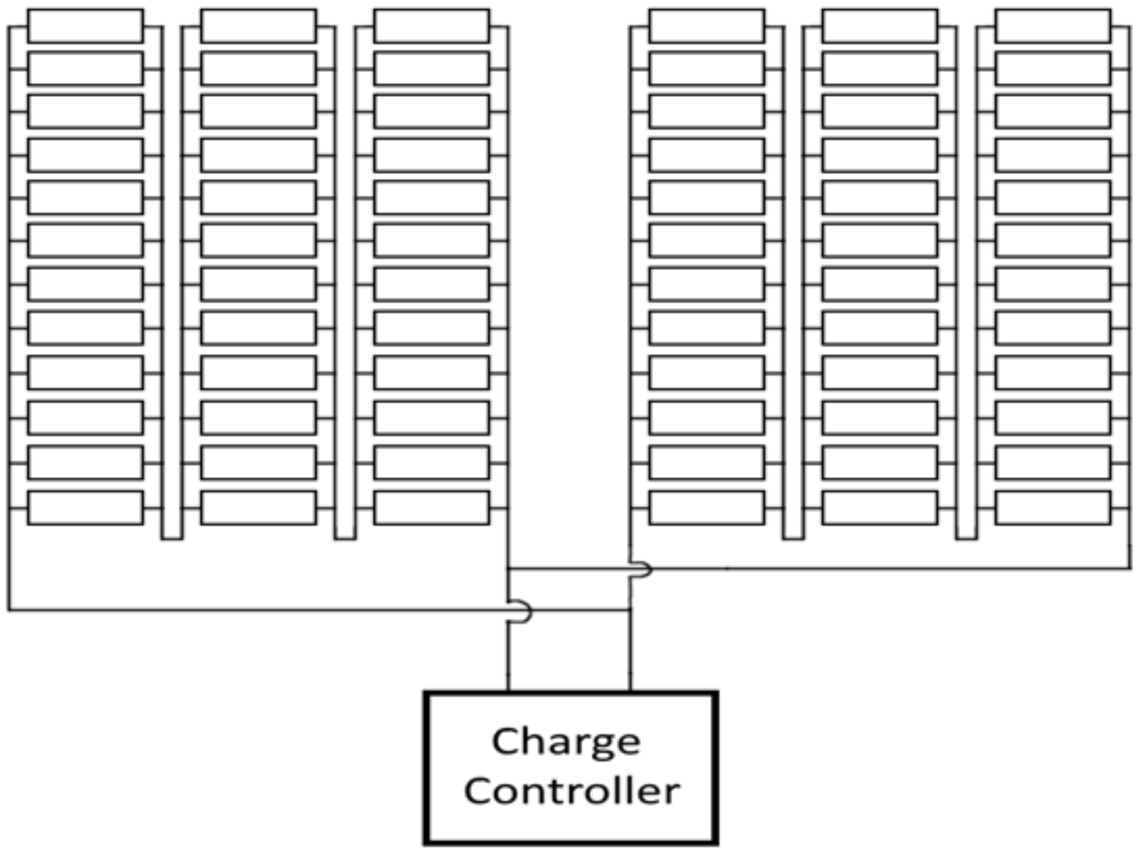

Figure 15: Second Iteration of Solar Cell Design

5.4.2. PCB Design

Once the receiver and transmitter circuits were designed and their functionality verified through physical tests, it was decided to use a printed circuit board (PCB) for a cleaner final product. We decided to use the software Eagle [29] because it is free to use, as well as because of its simple interface. Our circuits were relatively simple and not many components were needed, so the basic functionality of Eagle fit our needs quite well. Important design considerations for this aspect of the project included making sure the components on the board were spaced far enough apart, as well as ensuring the circuit boards fit mounted on the table. The tables were cut to allow a six inch-by-six-inch area to house the transmitter circuit, so the PCB layout was designed accordingly to fit within this area. Figures 16 and 17 depict Eagle screenshots of the schematics and board layouts for both circuits.

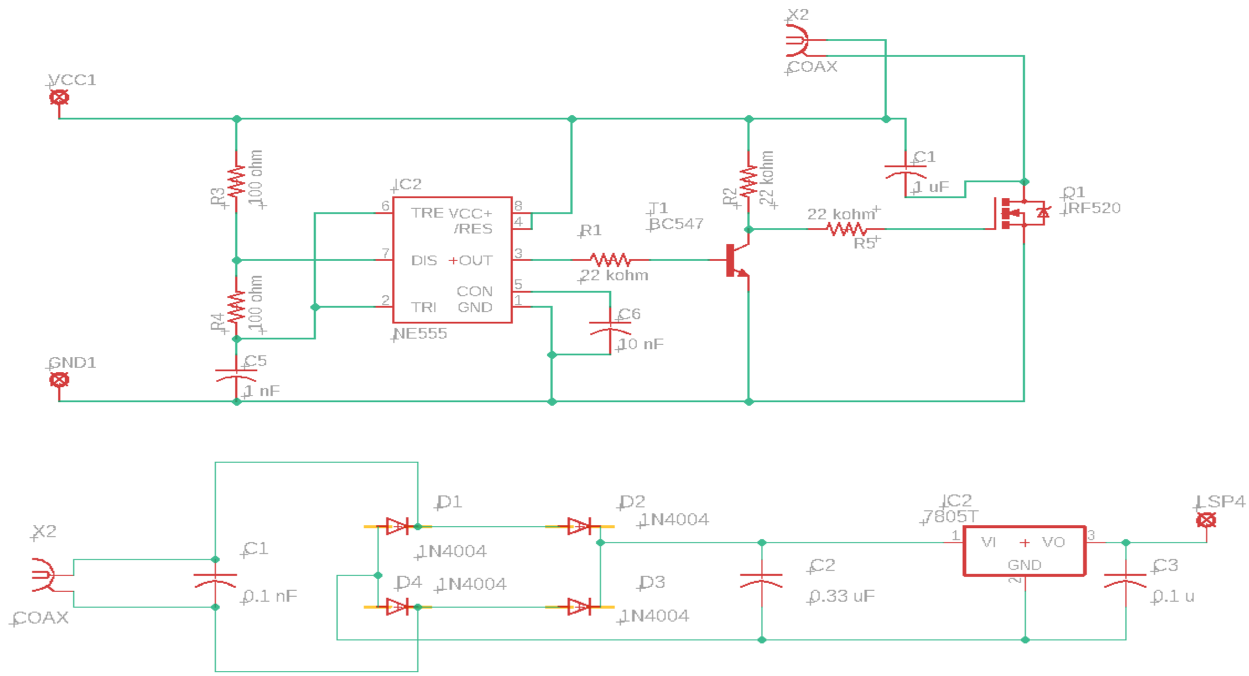

Figure 16: Transmitter Circuit Schematic (top), Receiving Circuit (bottom)

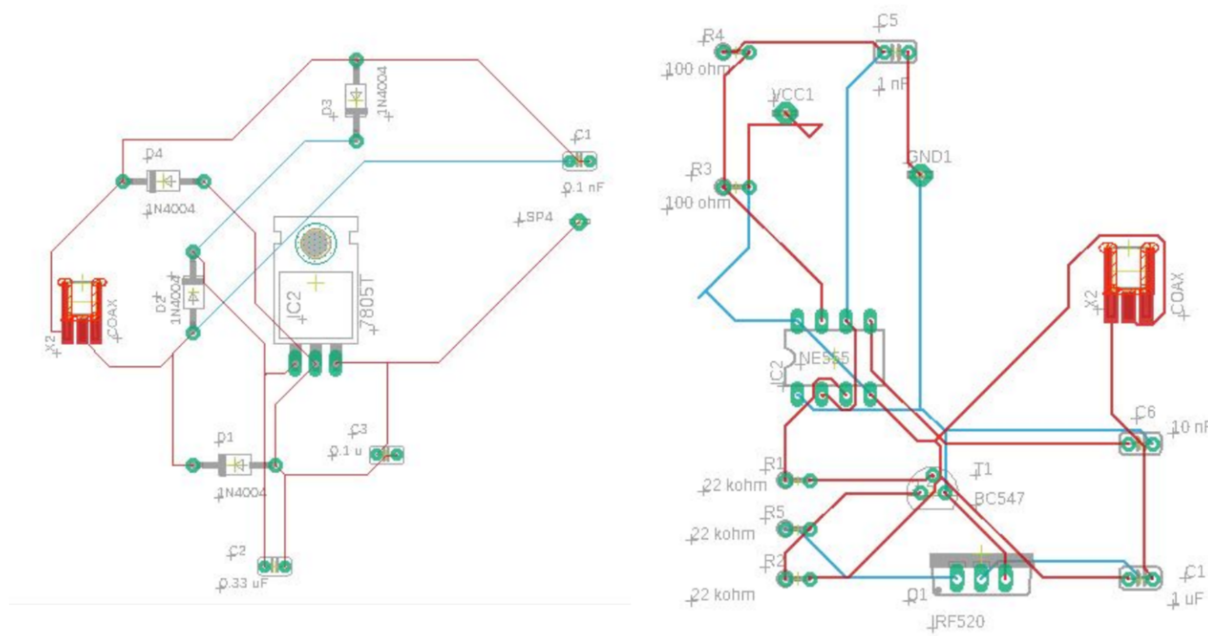

Figure 17: Receiver PCB Layout (left) and Transmitter PCB Layout (right)

We designed these circuits while still finalizing our end design for both the transmitting and receiving systems. We did this before we finished our design because of the lead time and manufacturing time required for designing, testing, and receiving our PCB. In-between this, we went through many circuit redesigns, thinking that we would at least use the PCB for the receiving circuit, as it was unlikely for it to change. We ended up not using either design, and decided to use a perfboard style PCB that would let us just solder our own components onto the board. An example of the perfboard used in our design can be seen below in Figure 18. This would also allow us to minimize the size of the board and make it as small as possible, whereas the PCB that we ordered was a lot bigger in size than what we wanted. In addition to this, using this method allowed us to still work on the circuit, and then after finalizing our design, made it easy to transfer our components over.

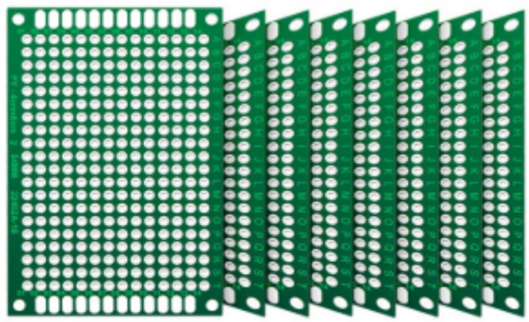

Figure 18: Perfboard Electric Circuit Board

6. Results

6.1. Testing

After completing the assembly of the table, we began running a suite of testing to ensure we met our design goals and specifications. We divided the testing into two big sections, the output capacity of the solar cells and the charge rate of the battery, and the power transferred through the coils and the final output power reaching the device being charged.

6.1.1. Solar Cells Output capacity, battery charge rate

First, we began our testing with exposing the solar cells to different lighting environments. We identified four primary light sources to test, as these would be the most likely to be encountered with our table, Sunlight, Incandescent, Fluorescent, and LED light. The results of this testing can be seen in Table 1 below. It is important to note that these numbers are the observed output values under the specific light bulbs we tested and in future testing considering small manufacturing errors and completing tests comparing different brands would provide more insight into changes in output power between bulb type. Simply put, in our testing, Incandescent came out on top, followed by LEDs, then Fluorescent, but this does not mean that in other tests with different shaped bulbs and or different brands, the result would be the same. It is also important to point out that Outdoor lighting levels are hard to quantify, we describe two levels, Direct Sun and Cloudy. For our purposes, Cloudy describes a day where the sun did not visibly shine through the clouds.

Table 1: Solar Cell Testing Results

Light Source/Environment	Voltage per row	Amps per row	Total
Outdoor (Cloudy)	3.6v	.70A	10.8v, 1.4A
Outdoor (Direct Sun)	5.9v	.95A	17.7v, 1.9A
Indoor (Incandescent) distance of ~15 feet	4.1v	.75A	12.3v, 1.5A
Indoor (Fluorescent) distance of ~15 feet	3.9v	.70A	11.7v, 1.4A
Indoor (LED) distance of ~15 feet	4.0v	.70A	12.0v, 1.4A

* Our target output was 15V, 1.5A in direct sunlight or close artificial light

*All totals are enough to begin charging the battery

In testing, we found that direct sunlight was the most effective and had the highest output power. This was expected as solar cells are most effective and typically used in outdoor sunlight than indoor lighting conditions. In testing, we found that in each environment we tested in, the charge controller showed active and the battery was successfully being charged. Additionally, we found that in direct outdoor sunlight, our cells would charge the 12V 5 Ahr lead acid battery in about 4 hours. In indoor lighting conditions the battery is charged from fully depleted to full in about 10-12 hours.

6.1.2. Coil power transferred, final output power to device(s)

In our final design, using a buck converter instead of a voltage regulator at the end of the receiving circuit, we were able to obtain an output voltage of 5V and a current of approximately 297mA when the coils were perfectly aligned. When testing this, we found that when the coils were aligned, we were able to get around 24V with the receiving coil placed directly on the transmitting coil. This worked in our favor, as it allowed us to have the increased liftoff distance between the coils. Even at a distance of two inches away, we are still able to get the 5V needed to charge a phone. Of course, at this range, the current starts to drop off, increasing the time it takes for the device to charge. This is one of the places that could use improvement, as if we increase the current in the transmitting circuit, drawing more current from the battery, we would be able to charge devices at a much faster rate and then support charging at those farther distances.

6.2. Efficiency

6.2.1. Solar Cells Output capacity, battery charge rate

In using solar power as an energy source for charging our battery and our wireless charging circuits, we are already using a method of renewable energy. The table will never net a negative energy usage. This means that because the table does not plug into any outlets or interface at all with the power grid, it creates its own energy using photovoltaics. So already we are talking about a high efficiency rating when comparing power used or lost in the charging process and power consumed to charge the battery and power the circuit. In the solar cells and battery system, it is important to ensure that the charge controller is properly setup. The power produced by the solar cells should reach the battery to charge it without major losses in between. Our team monitored both voltage and current levels produced by the solar cells and the charge rate of the lead acid battery. From this data we were able to conclude that losses in this system were minimized.

6.2.2. Coil power transferred, final output power to device(s)

In terms of inductive charging our wireless charging circuit is just as efficient when at close range to the standard Qi wireless charger. A Qi charger operating at the 5W low-power level has between 75-80 percent efficiency rating. [30] Looking at Figure 19, the graph shows our device’s charging efficiency vs the range at which the receiving coil is positioned away from the transmitting coil. As you can see, the farther away from the transmitting coil, the less efficient the circuit becomes, as it is essentially wasting power that cannot be picked up by the receiving coil. At close range our charging is between 70-75 percent efficiency, coming close to the Qi standard. For the Qi standard, in addition to our device, the farther you get from the transmitter, the less efficient. This will vary slightly between Qi chargers, but as we saw when testing, the majority of Qi chargers only support between 5-15mm of liftoff and do not support distances as far as our charger. This makes it hard to compare our results directly. For our charger, you can see that the efficiency begins to start to drop off drastically at the 25mm mark.

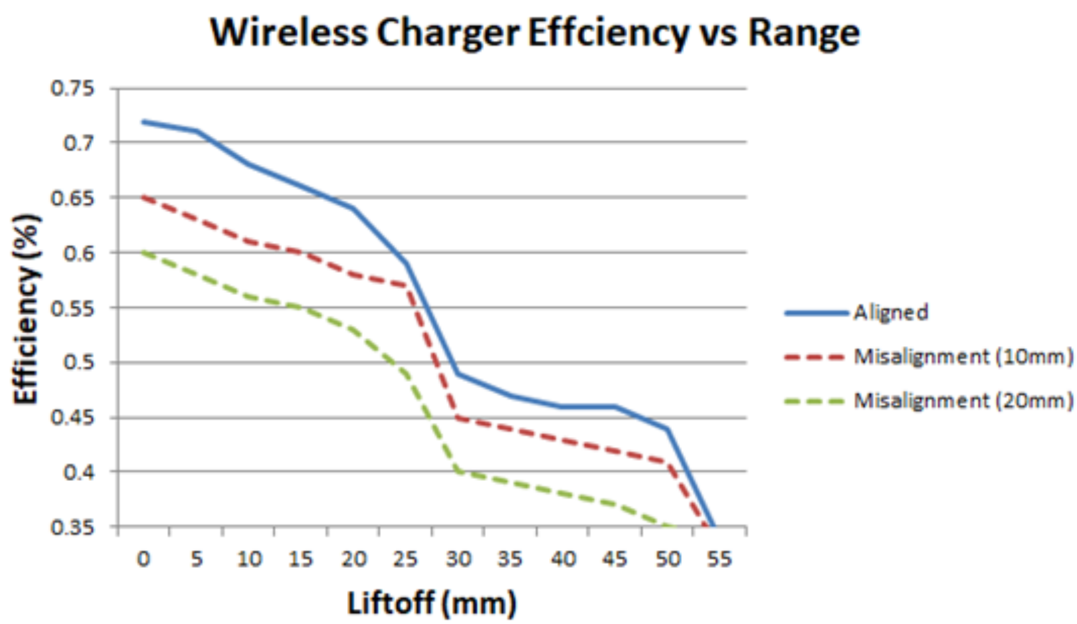

Figure 19: Wireless Charger Efficiency vs. Range.

6.3. Longevity of the System

When designing a product, one of the most important design aspects is how long your device will last, how you will service and repair it, and how you or the consumer will handle disposal. In our entire design, the limiting factor is the solar cells. The cells used are gallium arsenide-based cells and as described above in the safety section, our cells, like many others, contain toxic inorganic compounds, arsenic in our case. As such, care will have to be taken in the disposal of the cells. In Europe, the solar energy market is much more prevalent and developed than in the United States, because of this, more recycling and recollection options exist for solar cells. [31] While many U.S. companies are working towards developing disposal plans, currently the best option is making use of electronic recycling events.

6.4. Cost Analysis

Cost was a key factor throughout the project and during much of the development as well as assembly processes. In the case of this project, a device of similar functionality or size has never been created, as such it is very hard to know how well total cost was minimized and how well this product lines up with the market. Our device fits into a tough spot as charging cables are $10 or less and Qi wireless chargers typically go for less than $50. Because our product is fundamentally different than the devices available now on the market, we have some grey area to set our pricing. Additionally, typical buyers of this system would be wireless charging enthusiasts or an organization buying in bulk for a school or office building. Table 3 shows the breakdown of costs for the development model we assembled.

Table 2: Cost Breakdown of Development Model

Item No.	Part Description	Qty.	Price
1	PVC Board	1	$35
2	Clear Lexan	1	$35
3	Bolt	6	$0.30
4	Nut	6	$0.20
5	Washer	6	$0.20
6	Coil	2	$8.00
7	Solar Cells	72	$1.75
8	Folding Legs	4	$5
9	1/2 Inch Spacer	6	$0.50
10	Charge Controller	1	$10
11	Misc. Wire and Connectors	N/A	$10
12	Battery Level Display LCD	1	$10.00
13	USB Type-B Female Port Circuit	2	$6.00
14	LM7505 Voltage Reg	1	$0.50
15	LMC555	1	$1.75
16	BD139 Transistor	1	$0.50
17	1N4003	4	$0.15
18	LM2596 Buck Convertor	1	$1.75
19	Resisitors	2	$1
20	Capacitors	6	$1
21	PCB Board	10	$1.00
Total:			**$298.30**

In this design, the most expensive components are the PVC board, clear lexan plastic, and solar cells. Out of those three, the solar cells are by far the most expensive. At almost $2 per cell, the cost climbs very quickly and accounts for almost half of the total design cost. This is the biggest item to be reduced in cost in the future. Additionally, designing a custom cell would cut down on this cost drastically. However, clearly delineating between the cost of a working development model and cost of a marketable product is important. Many, if not all the components used in our design get drastically cheaper when ordered in bulk, especially when quantities reach close to 1,000 pieces. In this project we would never need amounts even close to that for design and development, but if this product went to market and needed to be mass produced, the price would go down sharply.

7. Conclusions

7.1. Summary

Recapping the work we accomplished during this project, we set out with several design goals which we strived to meet. Our product collects and stores light energy via solar cells and can generate more than 5W in both an indoor and outdoor setting. The design moves power from the battery, through both a transmission and receiving inductive coupling circuit using matching networks to optimize power transfer, tune coils, and minimum losses. The system supports any charging standard through the use of a female USB Type-B port located on the receiving circuit. Additionally, through the modular design of the table itself, we were able to create an aesthetically pleasing, polished looking final product which was easy to service, repair, and assemble. Finally, in the development of our wireless charging system and our product design, we ensure that our device would pose no safety or health concerns to the users. Also, we worked to minimize the effort and environmental impact of disposal once the device reaches the end of it is projected lifetime.

The only design goal we did not meet completely was charging a device at a rate of 5 V at 1 A. The final output our receiving circuit reached was approximately 297mA. This proved to be sufficient to charge a device at 5V, ~0.3A. However, we were able to improve upon the Qi standards charging range. For our device, we were able to charge a phone at a range of greater than 50 millimeters. This was a significant accomplishment as the Qi standard lists it is maximum charge distance at 40mm, whereas in the real world from our testing, most Qi chargers stop charging at distances as low as 20mm. In conclusion, we were able to reach all our design goals and objectives besides falling short on one single goal. This project was a success and our team was able to achieve the design, assembly, and testing of our wireless charging table.

7.2. Future Improvements

Although we met most of our goals, there are several aspects of our design that could be improved. The biggest improvement to our design is increasing the current output from our wireless charging circuit. Our goal was to have a power output of 5W, which is 5V at 1A. This would allow us to cut down on the charging time it takes to charge a phone with our system drastically. In addition to being able to charge a phone faster, it would also allow us the ability to support multiple devices charging at once, which is something Apple had troubles with when designing their multi-device charger known as the AirPower [32] working on the Qi standard. Even as our circuit stands now, the possibility to charge multiple devices at once exists, but with the low current that our circuit produces, having another phone that is slightly misaligned would have the correct voltage to charge, but would not have enough current. So, increasing the power output so that the transmitting circuit draws more current from the battery and transmits more current to the receiver would be a huge improvement for our design.

In addition to this, having a custom designed transmitting and receiving coil would also be a good improvement for our design. In the beginning, this is something that we really wanted to accomplish, but quickly realized that this would be challenging to accomplish in the time constraints of our project. Designing a custom coil would allow us to increase the wireless charging range, as well as allow us to configure the resonant frequency for the system. Doing this would also help increase liftoff, increase the distance the phone could be misaligned from the coil, and could also eliminate more losses between the two coils.

A large part of the cost of this system comes from the cost of the solar cells that we used for the custom cell setup for the two solar panels. If we had solar cells that had the same or better performance as well as the same durability with a lower cost per unit, we could drastically lower the cost of our system. One way this could be achieved would be by looking at new technologies emerging on the market, or even by working with another team who are designing their own solar cells. Superior solar cells could also allow for an increased charging rate as well as decrease the number of cells required to provide an optimal charge to the battery.

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Appendix A

Table A1: Value Analysis for Design Criteria

	Range	Power Level	Safety	Efficiency	Ease of Use	Profitability	Cost	Maintenance	Total	Weight from Total	Weight Factor
Range		1	.5	1	1	1	.5	.5	5.5	91.7	90
Power Level	0		.5	.5	1	.5	1	1	4.5	75	75
Safety	.5	.5		1	1	1	1	1	6	100	100
Speed	0	.5	0		1	1	.5	.5	3.5	58.3	60
Ease of Use	0	0	0	0		.5	0	0	.5	8.3	10
Portability	0	.5	0	0	.5		.5	.5	2	33.3	30
Cost	.5	0	0	.5	1	.5		.5	3	50	50
Maintenance	.5	0	0	.5	1	.5	.5		3	50	50

Table A2: Decision Matrix for Wireless Energy & Power Transmission Types

Criteria	Range		Power Level		Safety		Efficiency		Ease of Use		Portability		Cost		Maintenance		Decision factor
Weight Factor	90		75		100		60		10		30		50		50		
	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	
Energy Harvesting	3	270	2	150	10	100	2	120	6	60	1	30	8	400	7	350	1480
Microwaves	10	900	10	750	3	30	6	360	3	30	2	60	4	200	4	200	1720
Capacitive Coupling	1	90	4	300	5	50	4	240	3	30	2	60	4’	200	6	300	1270
Inductive Coupling	4	360	8	600	8	80	8	480	5	50	5	150	5	250	6	300	2270
Ultrasonic	5	450	6	450	8	80	6	360	8	80	6	180	7	350	8	400	2350
Laser Light	7	630	6	450	8	80	6	360	8	80	7	210	3	150	7	350	2310
Visible Light	9	810	7	525	10	100	6	360	9	90	9	270	4	200	8	400	2755
UV Light	7	630	6	450	4	40	5	300	6	60	7	210	3	150	7	350	2190
IR Light	6	540	6	450	5	50	5	300	6	60	7	210	3	150	7	350	2110