SOLAR BEACH CHAIR

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Abstract
We designed and built a solar powered beach chair. The chair uses solar energy to provide power that will allow a user to run a built-in drink cooler and charge two Universal Serial Bus (USB) devices (cell phone, tablet, e-reader, etc.) off the chair. The chair itself is rugged enough to withstand any damage from water and sand. The chair also collapses into a backpack that makes it easy for transport.

Contents

1. Introduction

We successfully designed and built a solar beach chair. The chair harnesses power from the sun using a solar panel mounted on its canopy; and it uses a buck converter and control circuitry to convert the power from the panel into power that is accessible to Universal Serial Bus (USB) devices. Overall, the solar beach chair is of great convenience and novelty.

1.1. Purpose

The goal of this project was to design and build a beach chair that allows the user to safely and conveniently charge their USB devices while they are away from electrical outlets. This was accomplished by converting the energy from the sun into power that can be delivered via USB ports. The entire project is integrated on a canopy beach chair that is safe, portable, and durable. As an added convenience, a drink cooler is built into the chair to keep beverages chilled. The product brings the luxury of power to the serenity of the beach in a convenient and environmentally friendly way.

1.2. Functions and Features

1.2.1. Functions

The main idea of this project is to take something that is typically brought to the beach anyway and transform it into an all-in-one charging station for your USB devices. All you have to do is strap on your chair like a backpack and you are ready to go.

This product provides the user with benefits that include:

- Charge devices while soaking up the sun
- Solar canopy provides the user with shade
- Backpackable for easy transport
- Built-in electric drink cooler
- On/Off safety switch
- Environmentally friendly

1.2.2. Features

This device has many features that make it unique and functional. These features include:

- On/Off switch
- Three USB charging ports
- Drink Cooler
- 50 W Solar Panel
- Backpack Straps
- Durable, water resistant, and sandproof to ensure longevity

1.3. Block Diagrams

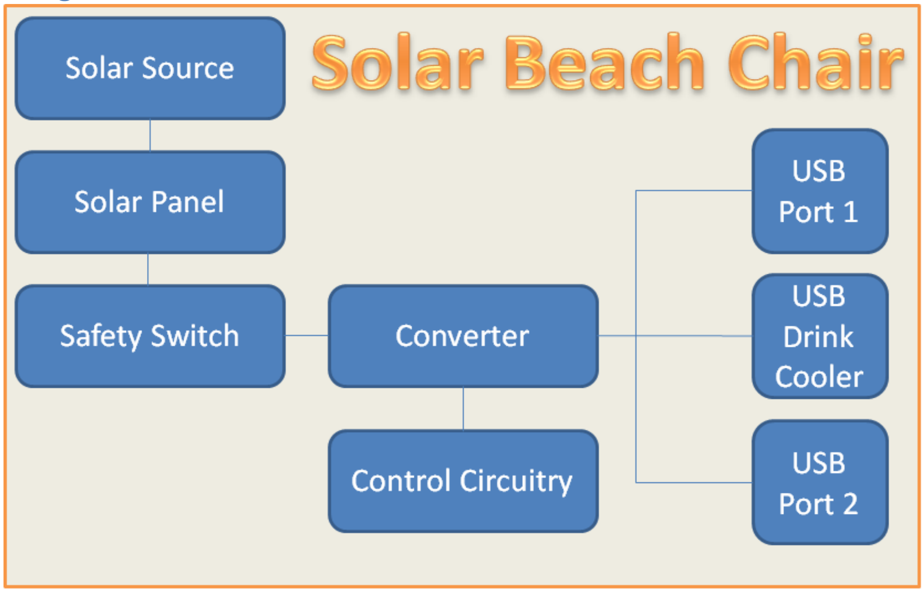


Figure 1: Top Level Block Diagram

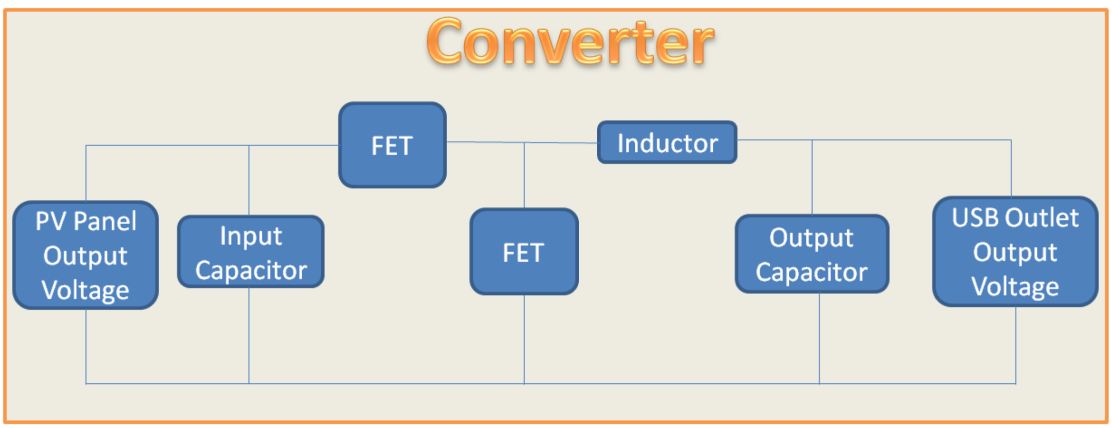


Figure 2: Converter Block Diagram

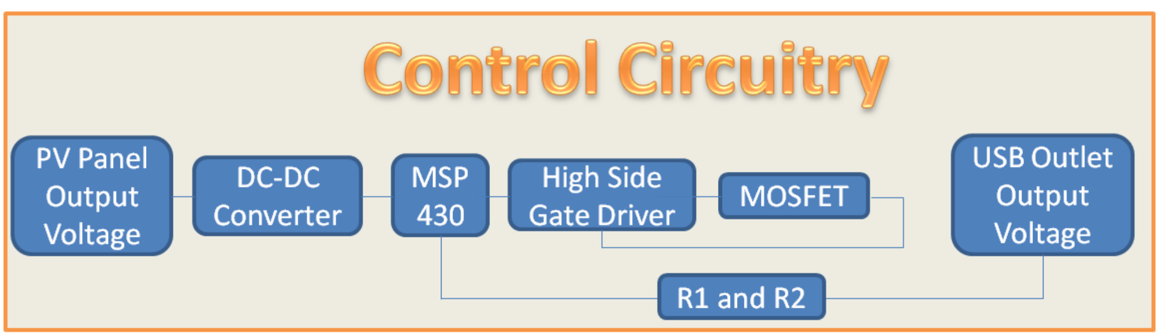


Figure 3: Control Block Diagram

1.4. Block Descriptions

1.4.1. Solar Source

This project gets its power from the sun. The sun shines down on the solar panel allowing it to produce a voltage and current. Halogen lamps can also be used to simulate the sun if necessary.

1.4.2. Solar Panel

A 50 W, 14% efficient, Monocrystalline Photovoltaic (PV) Module from Solarland is mounted on the beach chair's canopy and converts solar energy into a current and voltage output. The current and voltage is fed into a waterproof box through the safety switch. The panel is encased in glass to protect it from the elements.

1.4.3. Converter

The converter circuit takes the voltage and current from the solar panel, and converts it to meet the USB charging standards. According to USB.org [1], USB charging requires 5 V $\pm$ 5%. The voltage from the panel can range from 5 V to 21.6 V, so the converter will have to step this voltage down.

1.4.3.1. Input and Output Capacitors

A 470 µF capacitor is placed across the input from the solar panel in order to provide maximum power and prevent source damage. We used 1.41 mF of capacitance across the output to ensure that the voltage ripple did not exceed the specified $\pm$ 5%. The output capacitors do this by absorbing the ripple current so that a more steady current reaches the output.

1.4.3.2. MOSFETs

The Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) are the major switching component of the buck converter. Their gates are connected to the output from the control circuitry. Depending on the signal from the control, current will either flow through the Field Effect Transistor (FET) or the FET will act like an open circuit. We used a PSMN1R1-30PL Power MOSFET, IRF540PbF. According to its data sheet [2], these MOSFETs are able to handle high voltages and currents. They only have a resistance of 0.0013 Ω when they are on so the losses will be small.

1.4.3.3. Inductor

A 39 µH inductor acts as the energy storage element in the buck converter. It draws current from the FETs and either stores its energy or discharges its energy to the output.

1.4.4. Control Circuitry

The control circuit regulates the converter so that it consistently outputs the desired 5 V $\pm$ 5%. The control takes a sample of the output voltage and adjusts the duty cycle for the MOSFETs in accordance with the algorithm in Figure 4.

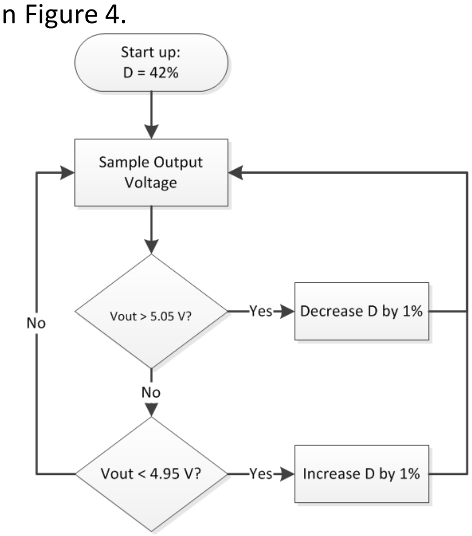


Figure 4: Control Circuitry Algorithm

1.4.4.1. DC-DC Converter

According to the MSP430's datasheet [3], the microcontroller requires a 3.3 V, 1.65 mW input to function. The BP5277-33-ND Direct Current to Direct Current (DC-DC) converter provides this input by converting the solar panel voltage.

1.4.4.2. R1 and R2

R1 and R2 act as a voltage divider. The MSP430 cannot accept sample voltages higher than 3.3 V, so the 5 V output needs to be stepped down before the MSP430 can sample it.

1.4.4.3. MSP430 Microcontroller

The MSP430 microcontroller is a programmable chip that dictates the duty cycle of the control waveforms delivered to the MOSFETs. It samples the output of the voltage divider and follows the algorithm from Figure 4 to determine how to adjust the duty cycle to ensure a 5 V ± 5% output.

1.4.4.4. Low and High Side Gate Driver

The low side gate driver is used to amplify the MSP430 signal so that the high side gate driver can function properly. The high side gate driver provides the synchronous switching signals for the two MOSFETs. The IR2111's datasheet [4] shows that the chip provides both the high side and low side gate signal needed for synchronous switching.

1.4.5. USB Ports

There are three USB charging ports: one designated for the drink cooler and two designated for charging. The 5 V output and ground from the buck converter connects to the 5 V and ground pins of the USB as specified by [1].The USB ports are located on the printed circuit board (PCB) and made available to the user through USB extension cords.

1.4.6. Drink Cooler

The drink cooler is a purchased Coolit USB Drink Cooler that has been modified so that it can keep 12 oz. of water with a starting temperature of 40°-60° F within 5° F of its starting temperature for fifteen minutes when the ambient temperature is 70° F.

1.4.7. Safety Switch

An on/off switch is placed between the solar panel and the rest of the circuit. This switch allows the user to turn off the chair when they are not using it. When the switch is off, the solar panel is open circuited and the circuitry will not receive power.

1.4.8. Beach Chair

The beach chair is the platform on which the entire project is built. The solar panel is mounted onto the canopy. The circuitry is protected from the elements and mounted onto the chair. The USB ports are run from the circuit box and made available to the user. The chair is backpackable for easier transport and light enough for safe transport. According to [5], a safe weight for a backpack for an average adult is 35 lbs. The final chair weighs 26.8 lbs.

2. Design

We designed our project in order to ensure that the requirements and verifications in Appendix A were met. The final circuit design and PCB layout can be seen in Figure 25 and Figure 26 found in Appendix B and C, respectively. The tests and calculations that led to this design are discussed below.

2.1. Solar Source

The sun is the source of energy for our project. We had to establish sun requirements to ensure that the panel had enough power to handle the given loads. We considered the panel area, the efficiency of the panel, the insolation of the sun, and the angle of the panel in relation to the direct sunlight.

The insolation of the sun is a measurement of the solar radiation energy received on a given surface and is given in W/m$^{2.}$ The datasheet for the solar panel [6] states that the efficiency for converting solar energy into electricity for our panel system is 11.26% (14.081% conversion efficiency and 80% PV module efficiency). So, the power produced by the panel in direct sunlight is

$$P = S * A * 0.1126 \text{ W} \tag{1}$$

where S is the insolation and A is the area of the solar panel measured to be 0.3551 m^2.

We can use Equation (1) to find the needed insolation for a given power demand as

$$S = \frac{P_{needed}}{A * 0.1126} \frac{\text{W}}{\text{m}^2} \tag{2}$$

We can account for indirect sunlight by defining an effective area of the panel

$$A_{effective} = A_{panel} * sin(\theta) \text{ m}^2 \tag{3}$$

where θ is defined as the angle between direct sunlight and the plane of the panel (θ=90° is direct sunlight). By replacing *A* in Equation (2) with $A_{effective}$, we can calculate the solar insolation requirement based on the load. We see that full load (two 10 W devices and the 5 W drink cooler) could require up to 625 W/m^2 of insolation in direct sunlight.

2.2. Solar Panel

The solar panel was chosen based on anticipated power need. We purchased Solarland's SLP050-12U High Efficiency Monocrystalline PV Module. This panel has the technical specifications shown in Table 18 in Appendix E. This panel is able to provide the necessary power as long as the amount of solar insolation is sufficient.

2.3. Safety Switch

According to Table 18, the short circuit current from the panel is 2.94 A, so we needed a switch rated to block this current. To be safe, we overrated the switch and chose a switch rated at 10 A, 28 V [7]. The switch is located in the overall circuit before the panel reaches the converter input. Figure 5 shows the final implementation of the switch. The green wires coming from the left of the picture are connected to the solar panel. They are fed through the switch which is encased in silicon to ensure dust, sand, and water cannot reach it. The connection then continues through the switch to the converter located in the box.

Figure 5: Safety Switch Implementation

2.4. Buck Converter Design

2.4.1. Design Theory

The converter must be designed to output 5 V ± 5% when any voltage from 5 V to 21.6 V is present at the input. The load will range from no load to 50 W. Such requirements suggest a buck DC-DC converter. For our buck converter we will use a switching frequency of 10 kHz, which represents a good trade-off between efficiency and converter size. With these specifications, we did the necessary calculations to determine inductor and capacitor sizes.

The inductor size is determined such that the converter stays in continuous conduction mode (CCM). This involves finding the critical inductance. From our ECE 464 textbook [8], we know the critical inductance L_{crit} is

$$L_{crit} = \frac{V_{in}(1-D)D}{2f_{sw}} * \frac{V_{out}}{P_{out}} \ \mu\text{H} \quad (4)$$

where D is the duty cycle of the switching signal, f_{sw} is the switching frequency, V_{in} is the input voltage, V_{out} is the output voltage and P_{out} is the output power. For the average input voltage and maximum power output, the critical inductance is 14.59 µH, so any inductor larger than that will ensure CCM operation.

The input and output capacitor values are determined by analyzing the current and voltage waveforms of the circuit. The input capacitance C_{in} and output capacitance C_{out} are defined as

$$C_{in} = \frac{\Delta Q}{\Delta V_{in_{p-p}}} \ \text{F} \quad (5)$$

and

$$C_{out} = \frac{\Delta Q}{\Delta V_{out_{p-p}}} \ \text{F} \quad (6)$$

where ΔQ is the change in charge on the capacitor and ΔV is the change in voltage. Using the procedure outlined in the design review, the minimum capacitance values are found to be 12.68 µF for C_{in} and 25 µF for C_{out}.

We initially designed the buck converter using a Schottky diode for high efficiency operation. A Schottky diode is desired because of its low reverse recovery time t_{rr} and thus a low reverse recovery loss Q_{rr}. Also Schottky diodes have a low forward voltage drop of about 0.2 V-0.3 V, which results in a higher switching speed and a higher efficiency.

The final step in this buck converter design is to determine what type of output capacitors to use. Because efficiency is the number one design consideration, we chose to use ceramic capacitors. The advantages of using ceramic capacitors are that they have excellent high frequency characteristics with low losses [10]. We will choose capacitors that have a working voltage higher than three times the expected voltage. Since our expected input voltage is 12 V, we will select a capacitor at a working voltage greater than or equal to 36 V. Since our expected output voltage is 5 V, we will select a capacitor that has a working voltage of at least 15 V. With all of these components selected, we will be able to meet the desired specifications.

The final proposed design in shown in Figure 6.

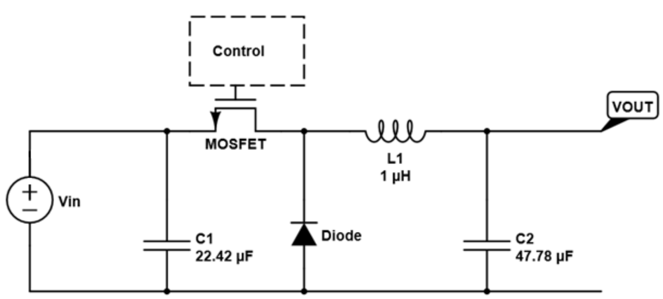


Figure 6: Proposed Buck Converter

2.4.2. Final Design/Actual Implementation

We started off with the circuit in Figure 6 and made modifications necessary for optimal operation. During the mock design review, Ryan May mentioned that we should use synchronous rectification in our design in order to improve efficiency, so we investigated this as an alternative. We ran comparison tests that are summarized in Table 1 and Table 2. These results confirmed that synchronous switching would be the best choice for our project.

Making the change to synchronous switching required changing the design in several ways. First, we replaced the low side diode in our circuit with a low side MOSFET. We then replaced our IR2117 high side gate driver chip with an IR2111 high side gate driver chip in order to have both a high side output (HO) and a low side output (LO). HO and LO are complementary signals, so when HO is on, LO is off. Dead time is incorporated in order to ensure that both switches are not on simultaneously.

Although the previous design was to use the smallest inductance possible to operate on the boundary of discontinuous conduction mode and CCM, we decided to increase the size of our inductor in order to handle more current. We purchased a 39 µH inductor rated for 21 A.

Table 1: Efficiency Measurements for Diode Configuration

Traditional Rectification with Diode							
V_{in} [V]	I_{in} [A]	P_{in} [W]	D	V_{out} [V]	I_{out} [A]	P_{out} [W]	Efficiency [%]
10.01	1.67	16.72	0.54	4.57	3.01	13.75	82.25%
10.00	1.99	19.90	0.59	5.01	3.30	16.53	83.07%
17.02	0.85	14.47	0.30	4.22	2.79	11.78	81.43%
17.02	1.17	19.91	0.35	4.98	3.29	16.33	82.01%
17.01	1.44	24.49	0.35	4.81	4.11	19.60	80.02%
10.10	2.47	24.95	0.59	4.88	4.12	20.00	80.17%

Table 2: Efficiency Measurements for Synchronous Rectification

Synchronous Rectification							
V_{in} [V]	I_{in} [A]	P_{in} [W]	D	V_{out} [V]	I_{out} [A]	P_{out} [W]	Efficiency [%]
10.10	1.08	10.91	0.40	5.47	1.79	9.70	89%
10.09	0.91	9.18	0.42	5.01	1.64	8.20	89%
12.02	0.73	8.77	0.42	4.89	1.59	7.70	88%
17.03	1.65	28.10	0.33	5.28	1.72	9.00	32%
17.02	0.60	10.21	0.33	5.26	1.72	9.00	88%
12.76	0.97	12.38	0.49	5.70	1.86	10.51	85%
10.01	0.73	7.31	0.49	4.42	1.44	6.34	87%
10.01	0.89	8.91	0.54	4.89	1.60	7.77	87%

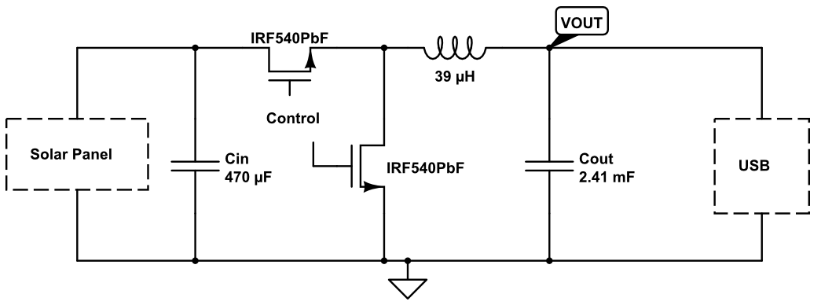


Figure 7: Final Buck Converter with Synchronous Rectification

Another aspect of the circuit that was improved upon was the reduction in ringing of the switching signal. This was accomplished by adding a snubber circuit to each of the MOSFETs, which significantly reduced the ringing and thus improved efficiency. The final implemented circuit is shown in Figure 7.

2.5. Controller Design

2.5.1. Design Theory

The role of the control circuitry is to generate a Pulse Width Modulation (PWM) switching signal that will drive the MOSFET switch. As the input voltage to the circuit increases, the duty cycle must decrease to keep the output voltage in the desired range of 4.75 V–5.25 V.

A Texas Instruments MSP430 is the heart of our control circuitry. This microcontroller was chosen for its ultra-low power consumption, which is around 506 µW. Low power consumption is critical for our project as power must be budgeted carefully. One downside of this low power consumption is that the output logic level for the microcontroller is only 3.3 V. This means that when the PWM signal is 'high', the 3.3 V output is not enough to switch the MOSFETs on and off. The IR2111, a high side gate driver, was chosen to amplify the switching signal from the microcontroller.

The initial control design is shown in Figure 8. The MSP430 requires a voltage input of up to 3.6 V. A DC-DC converter was chosen to provide a regulated 3.3 V output. Both the DC-DC converter and the IR2111 accept a varying input VCC range, so only one regulated power supply was required.

The logic algorithm for the microcontroller is shown in Figure 4. The output voltage is sampled once per cycle, and the duty ratio is adjusted accordingly if it is not within the specifications.

2.5.2. Final Design/Actual Implementation

The final design of the control circuitry varied quite a bit from the initial design. It was discovered that the 3.3 V logic signal output of the microcontroller was not enough to trigger the high

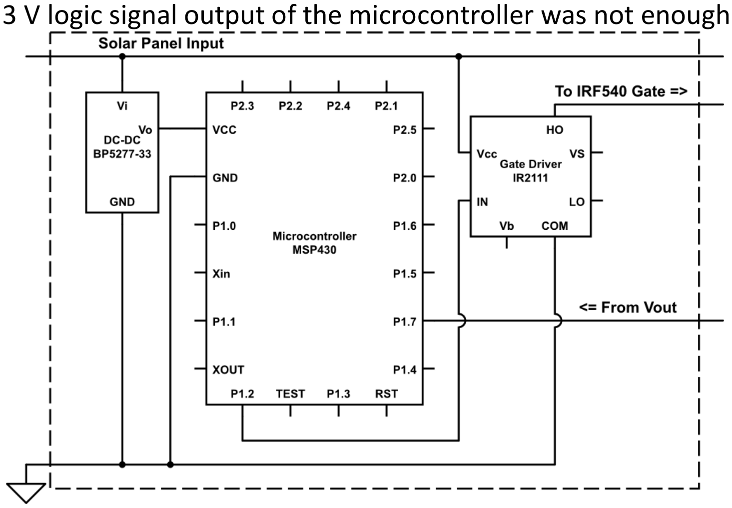


Figure 8: Initial Control Design

side gate driver. In order for the IR2111 chip to function it needed a switching signal with an amplitude greater than 9.5 $V_{p\text{-}p}$. A low side gate driver, a MIC4420, was added to the circuit to amplify the PWM signal. This technique was used in ECE 445 Project 7 from Spring 2007 [11]. The chip increased the amplitude of the switching signal coming from the MSP430 up from 6.52 $V_{p\text{-}p}$ to 22.8 $V_{p\text{-}p}$.

In addition to amplifying the switching signal, synchronous rectification was implemented in the circuit. Synchronous rectification increases circuit efficiency since the losses in a MOSFET are lower than the losses in a diode. The high side gate driver that was originally chosen also had the ability to synchronously drive a low side gate, so this was a natural progression of our design.

The microcontroller logic was also modified in the final implementation. A copy of the final code used can be found in Appendix D. Instead of changing the duty cycle directly from the sampled output voltage, a rolling average of 8 samples was calculated and used as the value that determined if the duty cycle should be modified. The rolling average helped to smooth out noise from the feedback circuit. The range of acceptable output voltages was also narrowed. While the USB specification allows 5 V $\pm$ 0.25 V, our design allows 5 V $\pm$ 0.05 V. This change was made to produce a higher quality and more stable output voltage.

In addition to averaging 8 samples from the microcontroller's analog to digital converter (ADC), a voltage divider was added to the feedback input. The MSP430 is unable to accept voltage samples in the 5 V range. In order to properly measure and regulate the output voltage of our converter with the MSP430, we needed to use a voltage divider circuit with resistors that are approximately 100 kΩ and 680 kΩ to step the voltage down from about 5 V to about 0.63 V. This is a readable voltage level for the MSP430. Another issue that arose when we were sampling our output voltage was that the noise of the output voltage was tainting the samples. In order to reduce the noise and solve the problem a large 1 mF capacitor was placed physically near the voltage divider between 5 V and ground. The final control circuit is shown in Figure 9.

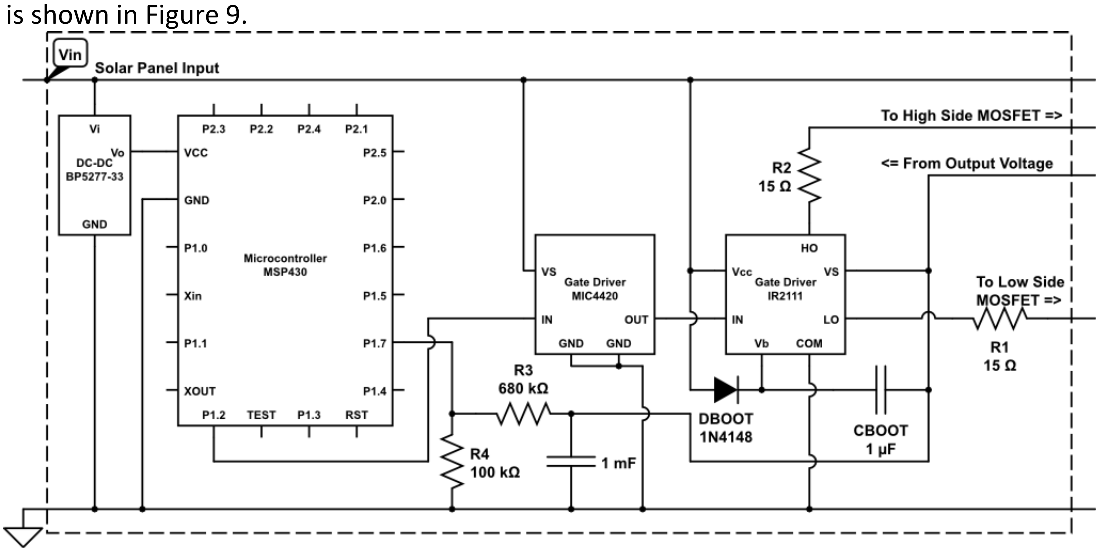


Figure 9: Final Control Design

2.6. USB Port Design

2.6.1. Design Theory

Universal Serial Bus (USB) is an industry standard. Figure 10 shows the pin configurations for USB. For charging purposes, there needs to be 5 V $\pm$ 5% between the V_{BUS} and GND pins (Pin 1 and Pin 4). Since data is not being transferred, the data pins can be grounded and charging will still occur.

2.6.2. Final Design/Actual Implementation

We found that the initial design could not charge apple devices. Upon some research, we found that charging apple devices requires a special circuit setup. According to pinout.com [12], setting up the pins as shown in Figure 11 allows for the charging of apple devices.

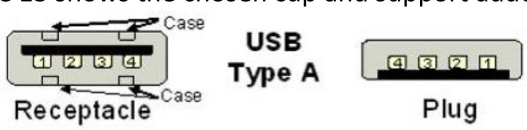
2.7. Drink Cooler Design

2.7.1. Design Theory

For this project, we purchased a Coolit USB Drink Cooler. The drink cooler works in accordance with the Peltier Effect. According to [13, 14], the Peltier Effect can draw heat from water by applying a voltage to a special p-n junction set-up. Figure 12 shows the heat flow in the drink cooler. A voltage is placed across p-type and n-type semiconductors that are sandwiched between two ceramic plates. The voltage will cause current to flow. The current carries heat from one plate to the other. This results in a net flux of heat out of the top plate. When a cup of water is set on the ceramic cold plate, heat from the water will flow into the cup and then the heat from the cup will be transferred to the cooling plate and ultimately to the heat sink.

2.7.2. Final Design/Actual Implementation

Based on the knowledge of the Peltier Effect, the cooler is standardized with a flat bottom copper cup because we wanted to maximize the contact area. Copper has one of the highest thermal conductivities at an average of 400 W/m*K [13], which allows the heat to quickly flow out of the cup. Figure 13 shows the chosen cup and support added to the cooler to hold the cup.



Pin		Description
1	VBUS	Red
2	D-	White
3	D+	Green
4	GND	Black
Shell	Shield	Drain

Figure 10: USB pins identified according to [1]

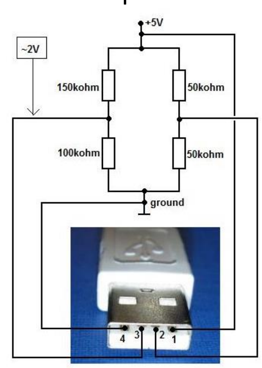


Figure 11: Apple Resistor Configuration [12]

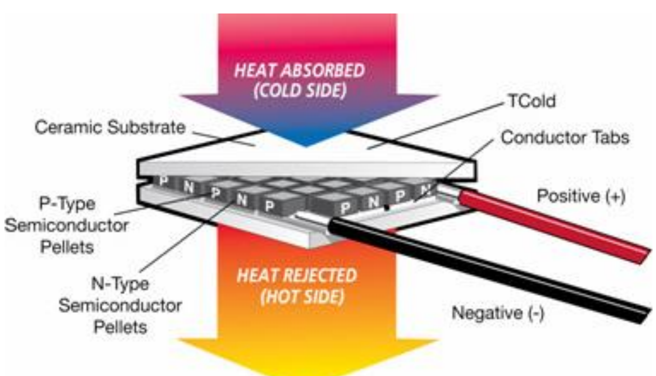


Figure 12: Peltier Effect Heat Flow [14]

Figure 13: Drink Cooler

Figure 14: Kelsyus Wave Beach Canopy Chair [15]

Figure 15: Final Beach Chair Implementation

2.8. Beach Chair Design

The entire project came together on the beach chair. We used a Kelsyus Wave Beach Canopy Chair, Figure 14, as the base for the project and made modifications to accommodate the different parts of the projects. Figure 15 shows the final beach chair with all the modifications made. The modifications included: mounting the solar panel, mounting the circuit box, mounting the drink cooler, and adding backpack straps. The chair as a whole was also made to be rugged enough to withstand sand and water damage. Finally, the chair was required to weigh less than 35 lbs, so we had to ensure we did not add unnecessary weight.

2.8.1. Mounting the Solar Panel

We were able to use the existing canopy on the chair to mount our solar panel. We worked with the Machine Shop and they were able to use a steel support beam, as shown in Figure 16, to mount the panel on the canopy.

The chair was equipped with a plastic gear that enabled the canopy to be adjustable. Unfortunately, the plastic gear could not support the added weight of the canopy so a steel stopper was also needed as shown in Figure 17.

2.8.2. Mounting the Circuit Box

The waterproof enclosure that housed the electrical circuitry was also mounted on the chair. For debugging and demo purposes, the box was not permanently mounted to the chair but was instead temporarily mounted to the support bar of the solar panel with Velcro as shown in Figure 16.

2.8.3. Mounting the Drink Cooler

The drink cooler is mounted to the right arm rest of the chair. We again worked with the machine shop to mount the cooler. We opened the cooler base and found an empty space where screws could be drilled through and bolted the cooler to the arm rest in two places as shown in Figure 18.

Figure 16: Solar Panel and Circuit Box Mounting

Figure 17: Steel Stopper Added for Canopy Support

Figure 18: Drink Cooler Mounting

Figure 19: Backpack Implementation

2.8.4. Adding Backpack Straps

An important feature of the beach chair is that it is backpackable. The chair came with backpack straps, however, the straps were located on the canopy and had to be moved to the bottom of the chair so that the solar panel could go on the canopy. Figure 19 shows the final backpack implementation. Even with all the parts mounted on the chair, it was still able to fold and be carried like a backpack.

2.8.5. Weatherproofing

To ensure that the circuit was protected from sand and water damage, we took a Pelican 1050 waterproof case and modified it to fit our needs without sacrificing the integrity of the box. The project required that wires be run in and out of the box. To do this we used a combination of silicone and polyvinyl chloride (PVC) pipe. The machine shop drilled ½'' holes in each side of the box and we used ½'' PVC couplings to act as a window to the box. The necessary wires were run into and out of the box through the PVC pipe, and the pipe was filled with silicone to seal the openings. Figure 20 shows the final design. The black wires on the left are USB extension cords that run from the USBs on the PCB to the user, and the green wires on the right are the input from the solar panel. The PVC on the right also houses the safety switch as shown in Figure 5. Here, the connections are also filled with silicone so that the switch is safe from sand and water.

Figure 20: Waterproof Box with PVC Alterations

3. Design Verification

Overall the entire project worked as expected. For our demo, we only had 201 $\frac{W}{m^2}$ and it still individually charged a drink cooler, an Apple IPhone and a Samsung Galaxy S2. Additionally, a USB powered speaker system was plugged in, and a song was played. After electronic checks were completed, the mechanical tests were performed. In order to test the weight of the chair, Damen stepped onto the scale without the chair and then with the chair. Taking the difference of the two scale readings showed that the final chair weighs 28.6 lbs. which is under the 35 lbs requirement. The chair was able to be folded, backpacked, and unfolded very easily. Finally, we were able to confirm sand and water resistance. The box that housed the circuitry was placed on the ground and water and sand was poured onto the box. The converter was then turned back on and a Samsung Galaxy S2 was plugged back into the chair to confirm that charging still occurred and thus that the circuit is both water and sandproof. Even though all the portions of the project worked as whole integrated system, we also confirmed that each sub-block of the project worked.

3.1. Solar Source

In order to verify how much solar insolation was received from the sun, the Illinois State Water Survey website was used [16]. Figure 21 shows a screenshot from the Illinois State Water Survey website, highlighting the Solar Radiation field used.

3.2. Solar Panel

To ensure the solar panel was working properly, we took the solar panel outside along with various resistors and a multimeter. We then recorded the description of the weather conditions and recorded the output voltage for the various resistances. Table 3 shows the results obtained. Output powers of up to 48.79 W were achieved, thus ensuring that the panel would be able to output the necessary power.

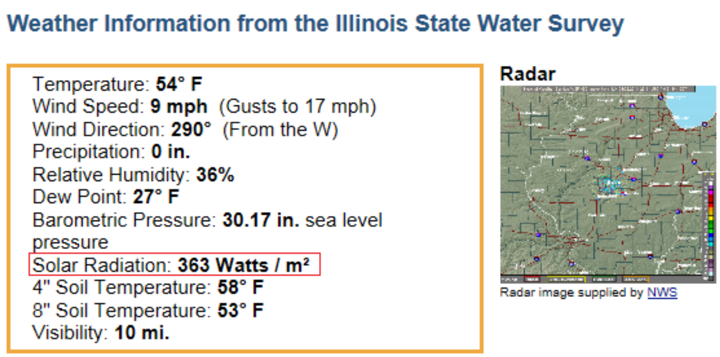


Figure 21: Illinois State Water Survey Screenshot [16]

Table 3: Solar Panel Measured Data

Light Source Description	Load [Ω]	Voltage [V]	Power [W]
"Mostly Cloudy Day" 2-21-14	512.6	20.3	0.80
"Mostly Cloudy Day" 2-21-16	51.23	17.4	5.91
"Mostly Cloudy Day" 2-21-17	26.76	10.45	4.08
"Mostly Cloudy Day" 2-21-18	5.55	2.2	0.87
"Mostly Sunny Day" 3-12-13	5.6	16.53	48.79
"Mostly Sunny Day" 3-12-14	39	22.2	12.64
"Mostly Sunny Day" 3-12-15	28	22	17.29
"Mostly Sunny Day" 3-12-16	18	21.4	25.44
"Mostly Sunny Day" 3-12-17	16	21.3	28.36

3.3. Safety Switch

The safety switch was verified by creating a circuit consisting of an input voltage (from the power supply) of 12 V, and a 5.78 Ω resistor. Between the input voltage and the resistor, a safety switch was hooked up. Then, a current probe was hooked up to measure the current through the circuit and the current waveform was viewed on an oscilloscope. When the safety switch was on, current flowed through the load, and when the switch was off, the current was zero.

3.4. Converter

In order to ensure that the buck converter was working properly, a FET box was used. The input voltage was varied from 10 V-21.6 V and load resistances were varied to simulate different output powers. Table 4 shows the results obtained. As can be seen, the output voltage always remains between 4.75 V and 5.25 V.

3.5. Control

To verify that the control circuit was operating correctly, the PWM signal at the microcontroller output was viewed with the oscilloscope. The amplified signals for the high and low side gate drivers were also viewed with the oscilloscope. The output voltage was observed with a Fluke meter. Using a power supply, the input voltage was swept from 10-20V. The duty cycle was automatically adjusted as necessary, and the output voltage remained within the design range.

Figure 22 shows the switching signals in the circuit. Ch1 is the PWM switching signal from the microcontroller output, Ch2 is the amplified high side switching signal, Ch3 is the amplified low side switching signal, and Ch4 is the inductor current waveform.

Table 4: Buck Converter Measured Results

Vin [V]	Iin [A]	Pin [W]	Vout [V]	Iout [A]	Pout [W]	Rout [Ω]	Duty Ratio
10.00	0.54	5.40	4.99	0.90	4.50	5.60	55.05
12.00	0.45	5.40	5.00	0.90	4.50	5.60	44.46
15.00	0.36	5.40	5.00	0.90	4.49	5.60	34.06
17.00	0.32	5.44	5.00	0.90	4.51	5.60	29.45
20.00	0.27	5.40	5.00	0.90	4.47	5.60	23.59
21.60	0.26	5.62	5.00	0.91	4.51	5.60	21.45
10.00	1.22	12.20	5.00	1.80	9.00	2.73	64.56
12.00	1.02	12.24	5.00	1.80	9.04	2.73	52.80
15.00	0.82	12.30	5.00	1.81	9.04	2.73	40.65
17.00	0.73	12.41	5.00	1.80	9.03	2.73	35.03
20.00	0.61	12.20	4.99	1.80	8.98	2.73	28.13
21.60	0.57	12.31	5.01	1.79	8.93	2.73	25.70
10.00	1.86	18.60	5.00	2.61	13.08	1.87	72.00
12.00	1.56	18.72	4.99	2.60	13.01	1.87	58.83
15.00	1.26	18.90	5.00	2.62	13.10	1.87	45.70
17.00	1.10	18.70	5.00	2.61	13.02	1.87	39.30
20.00	0.93	18.60	4.99	2.59	12.95	1.87	31.90
21.60	0.86	18.58	5.00	2.59	12.92	1.87	29.02
10.00	2.38	23.80	4.98	3.16	15.76	1.57	76.61
12.00	2.02	24.24	5.01	3.17	15.90	1.57	63.69
15.00	1.61	24.15	5.00	3.16	15.81	1.57	49.28
17.00	1.43	24.31	5.01	3.18	15.95	1.57	42.70
20.00	1.20	24.00	4.99	3.16	15.74	1.57	34.66
21.60	1.13	24.41	5.00	3.17	15.82	1.57	31.78

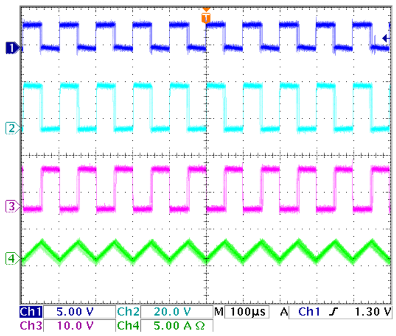


Figure 22: PWM Switching Signals

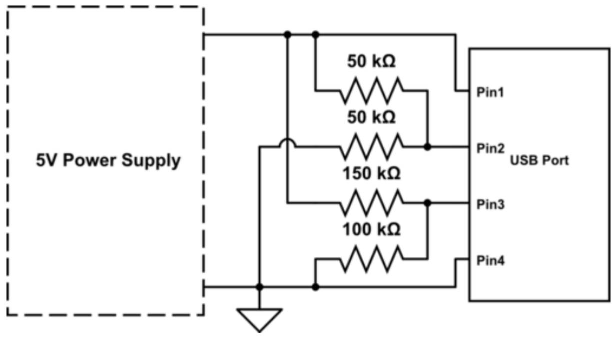


Figure 23: Apple Charging Test Circuit

3.6. USB Ports

The USB ports must be able to charge Apple devices, such as an iPad or iPhone, in addition to charging other USB devices. To test the charging circuit, the circuit shown in Figure 23 was set up on a breadboard with a female USB plug. A lab power supply was used to supply the 5 V signal. The test circuit successfully charged an iPad, iPhone, iPod, and a HTC smartphone.

3.7. Drink Cooler

The drink cooler was required to take 12 oz. of water at 40° F-60° F and keep it within 5° F of that temperature for fifteen minutes. The functionality of the drink cooler was confirmed by running tests over the specified range of starting temperatures. We used a waterproof thermometer kept at the same location in the cup to measure temperature changes. The results of our tests are shown in Table 5.

3.8. Beach Chair

3.8.1. Mechanical

In order to verify the weight of the chair was less than 35 lbs., Damen stepped onto the scale without the chair and then with the chair. Taking the difference of the two weight readings gave a beach chair weight of 28.6 lbs., which is under the 35 pound requirement. The circuit was in a weatherproof containment and Velcro was used to connect the circuit to the chair. Metal support bars and rods allow the solar panel to sit on the canopy without causing the canopy to collapse on itself. Finally the drink cooler was mounted to the right armrest with screws. This entire system is able to fold, unfold and be backpacked with great ease.

3.8.2. Weatherproofing

The chair was setup, and the converter box was placed on the ground, and water and sand was poured onto the box. After this, the converter was turned back on and a Samsung Galaxy S2 was plugged in and charging was obtained thus confirming that the circuit is both water and sandproof. In addition to that, the box was dried and reopened to show that not water or dust got into the box.

Table 5: Drink Cooler Measured Results

T_{amb}=74°F		
T_{START} (°F)	T_{15}(°F)	ΔT (°F)
40.1	44.6	4.5
45.0	48.2	3.2
50.9	53.2	2.3
55.0	56.4	1.4
56.4	57.6	1.2
57.6	58.5	0.9
58.5	59.3	0.8
59.9	60.4	0.5

4. Costs

4.1. Parts

Table 6: Total Cost of Parts

Description	Part Number	Quantity	Unit Price	Total Cost
Canopy Beach Chair	Kelsyus Canopy Beach Chair	1	$46.88	$46.88
Solar Panel (50 W)	SLP050-12U	1	$151.00	$151.00
Waterproof Enclosure	Pelican 1050	1	$23.19	$23.19
USB Receipt Port	A31726-ND	3	$1.44	$4.32
High Side Gate Driver	IR2111PBF-ND	1	$3.07	$3.07
Power MOSFET	568-6719-5-ND	2	$3.25	$6.50
USB Extension Cord	AE9934-ND	3	$3.33	$9.99
Rocker Switch	CW102-ND	1	$2.08	$2.08
3.3V DC-DC Converter	BP5277-33-ND	1	$7.50	$7.50
Drink Cooler Base	Coolit USB	1	$34.95	$34.95
Copper Cup	-	1	$7.00	$7.00
Inductor	1140-390K-RC-NC	1	$7.17	$7.17
Resistors	-	18	$0.04	$0.72
Ceramic Capacitor	-	1	$0.10	$0.10
Metal Film Capacitor	-	2	$0.10	$0.20
Electrolytic Capacitor	-	5	$3.00	$15.00
MSP430 Microcontroller	MSP430	1	$5.68	$5.68
PCB	-	1	$0.00	$0.00
Diode	MUR120	3	$0.25	$0.75
Low Side Gate Driver	MIC4420CT	1	$1.00	$1.00
PVC Pipe	1/2"	2	$0.10	$0.20
Silicone Sealant	GE Outdoor Sealer	1	$5.00	$5.00
Total Cost				**$332.30**

4.2. Wholesale Parts Cost

Table 7: Wholesale Parts Cost Based on 1000 Chairs Purchased

Description	Quantity	Unit Price	Total Cost
Beach Chair	1	$15.00	$15.00
Solar Panel	1	$41.59	$41.59
Waterproof Case	1	$7.80	$7.80
Resistors	18	$0.04	$0.70
Ceramic Capacitor	1	$0.00	$0.00
Metal Film Capacitor	2	$0.05	$0.11
Electrolytic Capacitor	5	$0.20	$1.02
Mosfet	2	$1.48	$2.97
Inductor	1	$5.65	$5.65
USB Connectors	3	$0.71	$2.12
High Side Gate Driver	1	$1.37	$1.37
USB Extention Cord	3	$1.80	$5.39
3.3 V DC/DC	1	$3.75	$3.75
MSP430 Launchpad	1	$4.30	$4.30
MSP430 Chip	1	$0.25	$0.25
Diode	3	$0.08	$0.25
Lowside Gate Driver	1	$0.55	$0.55
PCB	12	$0.10	$1.16
Rocker Switch	1	$0.05	$0.05
Total Cost			**$ 94.03**

4.3. Labor

Table 8: Labor Cost

Name	Hourly Rate	Number of Weeks	Hours Per Week	Total Hours	Total = Hourly Rate x 2.5 x Total Hours
Damen Toomey	$30.00	12	12	144	$10,800
Andrew Gazdziak	$30.00	12	12	144	$10,800
Emily Mazzola	$30.00	12	12	144	$10,800
Total	**$90.00**	**36**	**36**	**432**	**$32,400**

4.4. Grand Total

Table 9: Total Cost

Labor	Parts	Grand Total
$32,400.00	$332.30	**$32,732.30**

5. Conclusion

5.1. Accomplishments

Throughout the semester, we have had many great accomplishments. Once we completed our request for approval, we hit the ground running and started to design our circuit. The first step was to get a simple buck converter working on a FET box. After this was completed, a MOSFET was placed into our circuit and only the switching signal from the FET box was used. The next major accomplishment was getting the control from the MSP430 to work. After this was complete, the FET box was no longer necessary. In order to use the switching signal from the MSP430 to switch the MOSFET, we implemented a low side gate driver MIC4420CT to amplify the switching signal, and then used a high side gate driver IR2117 to switch the high side gate.

This was a working configuration, but to ensure that efficiency requirements were met, we changed the design to utilize synchronous rectification. This was done by replacing the low side diode with a MOSFET and replacing the IR2117 high side gate driver with an IR2111 high side gate driver with both a high and low side output. Snubber circuits were also used to reduce ringing and increase efficiency.

The first revision of the PCB was created, and after components were soldered on, it was determined that a few more minor changes needed to be made. One change was to add a voltage divider circuit as well as a large output capacitor in order to reduce noise in the output voltage waveforms. An output resistance of 1 MΩ was used to ensure the circuit was never open circuited, and thus ensured a self-starting behavior. Apple USB charging compatibility was achieved in each of the three USB ports, and finally a second PCB was created. The components again were soldered on and the whole circuit worked as expected.

After accomplishing a working buck converter and control scheme, several mechanical aspects were added. The panel was mounted on the canopy, the drink cooler was mounted on the right armrest, and the canopy was ensured to not collapse on itself by adding metal rods. The circuit was placed in a waterproof containment, and a safety switch was added. By using General Electric Silicon and PVC, the input and outputs for the converter were water and sand sealed. After realization that the DC-DC converter to power the chips was defective, a series combination of two AA batteries was added, and became the new 3.3 V and ground for the MSP430. In order to ensure that the batteries were not always on, an on/off switch for the battery bank was added.

Overall, all of the debugging paid off, and much was learned along the way. If 1000 of each of the components used are purchased, the price of the solar beach chair can be near $150.00. Doing a market study on the quad, customers said they would be willing to pay $150.00 - $175.00 for the chair, so our group not only accomplished a functional design, but also a very marketable design.

5.2. Uncertainties

Although our group has a great overall knowledge of the final design, there are still a few uncertainties with regard to our beach chair. One of the uncertainties is in terms of marketability. Is this product highly marketable and would we be able to sell at least 1000 units per year? Although market research was done with regards to a potential $150.00 price tag, no surveys were conducted with regard to who would actually buy the chair. Another uncertainty with our beach chair is the lifetime. How long will the circuit last under normal operating conditions? In conjunction with this, another uncertainty is the temperature ranges that our beach chair will operate. Will the beach chair operate properly at subzero temperatures, and if so, for how long? If the product were to be sold to the market, this type of information would be required.

5.3. Ethical Considerations

The purpose of this project is to provide a user with a way to better enjoy the outdoors by providing a charging station in otherwise powerless places. Since it is a product that will be used by people, it is important that it be safe for their use, which correlates to the first code of the IEEE Code of Ethics [17]:

1. to accept responsibility in making decisions consistent with the safety, health and welfare of the public, and to disclose promptly factors that might endanger the public or the environment;

The product is also marketable and therefore must do what it claims to be able to do. No data was fabricated to make it seem like the product does something it does not. Whatever, the product claims to be able to do, it does on the spot. This correlates to the second code of the IEEE Code of Ethics:

2. to be honest and realistic in stating claims or estimates based on available data;

5.4. Future Work

5.4.1. Solar Panel

To improve the design of this chair a different solar panel can be used. A flexible solar panel, such as one intended for outdoor or marine applications, would be ideal for this beach chair. This would greatly reduce the weight since a 40W flexible panel, such as the one pictured below, weighs around 3.3 lbs. [26]. For comparison, the panel in our original design weighs over 12 lbs. In addition to reducing weight, the flexible panel would not have sharp metal corners that are present on the existing panel, which will improve safety.

5.4.2. USB Bus Unit

A great idea brought up by Professor Carney is to have a bus of USB outlets where one can just plug a device into a port on a bus instead of having extension cords getting in the way. This would provide for a more sleek design as well as be more user-friendly.

5.4.3. Fan and Speaker

When a person goes to the beach, they want their electronics powered and their drink cooled, but they also want some music playing and to keep cool with a fan. A future improvement would be to implement a Bluetooth USB speaker system into the chair. This speaker system can be controlled with any smart phone. In order to stay cool on the beach, a fan can be built into the chair. The ideal location for the fan would be near the headrest, as to keep your neck cool. All of these features could be included in a more robust and premium version of the solar powered beach chair.

5.4.4. Adjustable Canopy

We lost the adjustability of the canopy because the panel was too heavy and required extra support. If we were to use the lighter flexible solar panel, we would be able to bring back the adjustable canopy. Having an adjustable canopy would allow the user to change the angel of the panel for optimal power as well as optimal shade.

5.4.5. Heat Sinks

We would also like to add larger heat sinks to improve efficiency even more. Our PCB and box design only allowed for small heat sinks. If we were to do a redesign, we would incorporate a bigger heat sink on the MOSFETs so they stay cooler longer and have lower losses.

Figure 24: Flexible Solar Panel [18]

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Appendix A: Requirement and Verification Tables

Table 10: Converter Requirement and Verification Procedure

Requirement	Verification
Output voltage must be between 4.75 V-5.25 V	Use a voltage probe on the output capacitor and use an oscilloscope to verify that the voltage ripple is within 4.75 V-5.25 V

Table 11: Controller Requirement and Verification Procedure

Requirement	Verification
Control circuit produces the desired PWM switching signal with the correct duty ratio	Connect a differential probe between pin 1 and 3 of the IRF540 MOSFET. Connect the probe to an oscilloscope. Vary the input voltage from the solar source from 10-20V and observe the operation of the MOSFET. As the input voltage changes, the output voltage should change. The control circuitry should then adjust the duty cycle of signal fed into the MOSFET to bring the output voltage into the range of 4.75-5.25 V.

Table 12: USB Ports Requirement and Verification Procedure

Requirement	Verification
Referring to Figure 10, when Pin 1 has a voltage of 4.75 V - 5.25 V, and Pin 4 is connected to GND it is able to successfully charge an iPod and iPad.	Use the power supply to generate a voltage of 4.75 V, and connect this voltage to pin 1 of USB ports 1 and 2. Next connect ground to pin 4 of USB ports 1 and 2. Plug in an iPod into USB port 1, and plug in an iPad into USB port 2. Verify if the charging status bar shows up, which indicates the device is charging. Repeat procedure with voltages of 5.00 V and 5.25 V.

Table 13: Drink Cooler Requirement and Verification Procedure

Requirement	Verification
Keep 12 oz. of water with a starting temperature of 40°-60° F within 5° F of its starting temperature for fifteen minutes when the ambient temperature is 70° F.	Set the ambient temperature of the room to 70° F. Use a waterproof digital food thermometer to measure the starting and final temperature of the water in the middle of the copper cup. Verify that the change in temperature is within 5° F after fifteen minutes.

Table 14: Beach Chair Requirements and Verification Procedure

Requirement	Verification
Can support the weight of the panel, does not exceed 35 lbs, and is at rated water resistance and sandproofing of IP62 [19].	Perform tests to verify that the IP62 rating is achieved. Weigh the chair to confirm its weight does not exceed 35 lbs.

Table 15: Solar Source Requirement and Verification Procedure

Requirement	Verification
To ensure maximum power from the solar panel, there must be $\frac{1kw}{m^2}$ of insolation available from a solar source	Use a solar insolation meter to ensure that the insolation present is at least $\frac{1kw}{m^2}$.

Table 16: Solar Panel Requirement and Verification Procedure

Requirement	Verification
Solar Panel must produce an output voltage of 5 V - 21.6 V and an output power of at least 50W.	Disconnect the solar panel from the circuit, and hook it up to a 5.78 Ω resistor. Use a Fluke meter to measure the output power and output voltage. Confirm whether the voltage is 5 V - 21.6 V and confirm if the output power is at or above 50W.

Table 17: Safety Switch Requirement and Verification Procedure

Requirement	Verification
When switch is off, no current reaches the load, and when switch is on, current reaches the load.	Create a circuit consisting of an input voltage (from the power supply) of 12V, and a 5.78 Ω resistor. Between the input voltage and the resistor, hook up a safety switch. Hook up a current probe to measure the current through the circuit and view the current waveform on an oscilloscope. Verify that when the safety switch is on, that current flows through the load, and when the switch is off, the current is zero.

Appendix B: Final Circuit Schematic

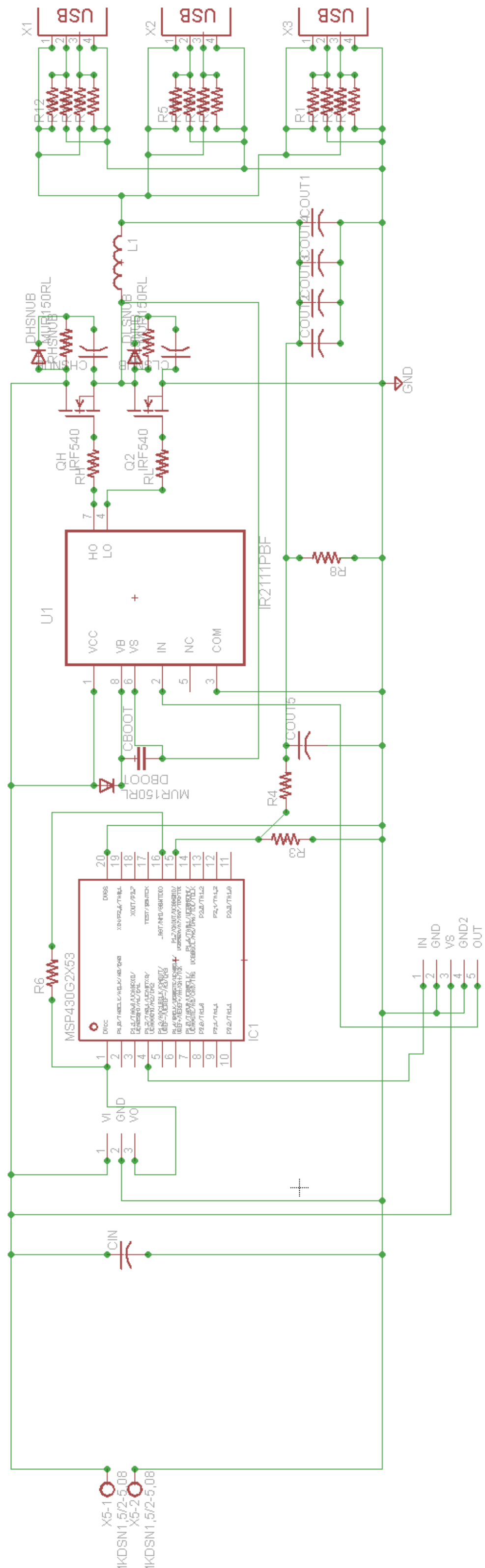

Figure 25: Final Circuit Schematics

Appendix C: PCB Design

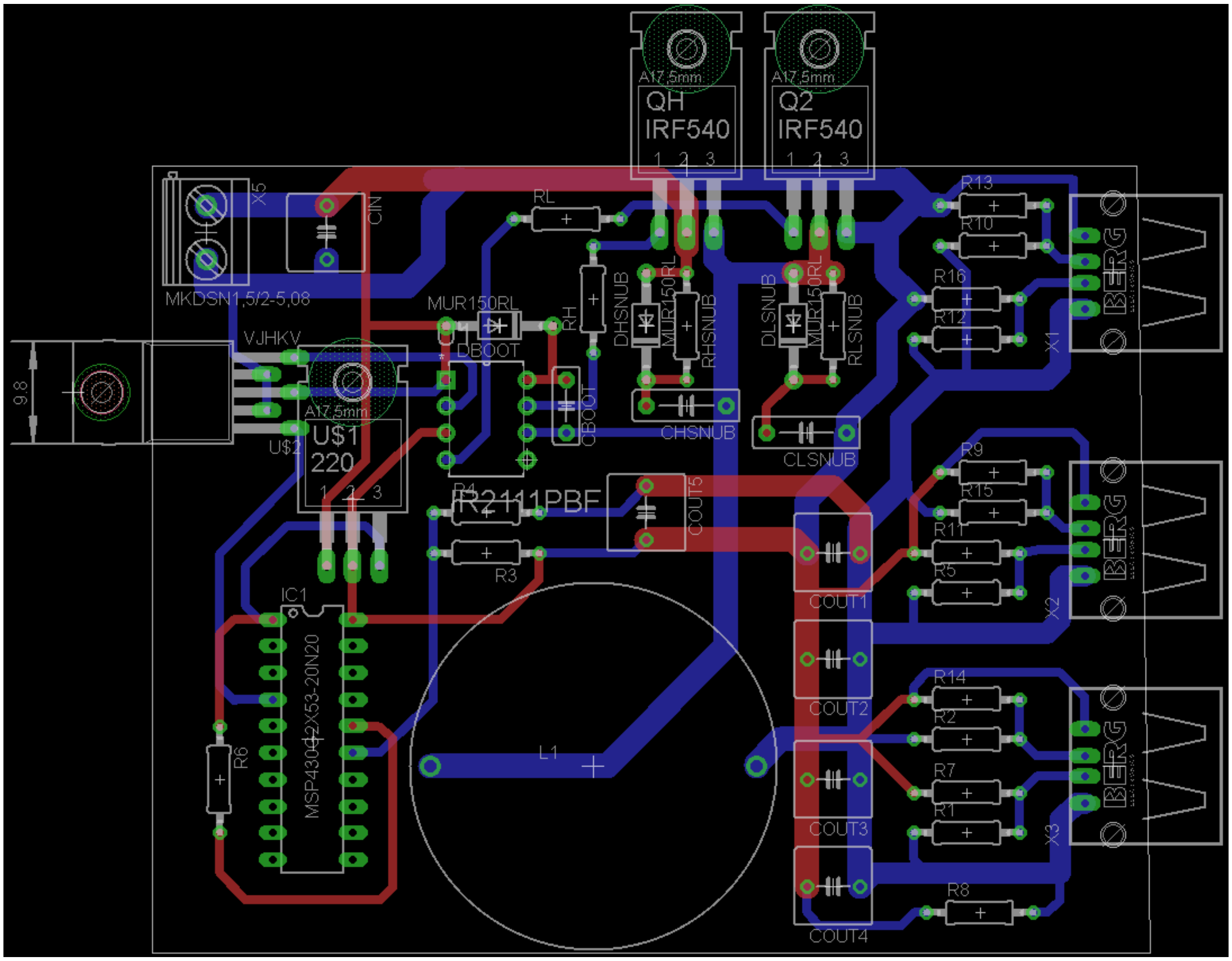

Figure 26: Final PCB Layout

Appendix D: MSP430 Microcontroller Source Code

```
//***************************************************
// MSP430G2452 Control Code
// For University of Illinois ECE 445
// Senior Design Project - Solar Beach Chair
//
// Description: This code will generate a PWM signal to control a buck
// converter. The ADC will sample the output voltage and if the value
// is too low or too high the duty ratio will be increased or decreased
// if necessary.
//
// This code was based on some of the the MSP430G2231 demos from
//  various websites, specifically these:
//  http://www.msp430launchpad.com/2010/09/simple-adc-example-on-launchpad.html
//  http://www.msp430launchpad.com/2010/07/timers-and-clocks-and-pwm-oh-my.html
//  http://myweb.wit.edu/johnsont/Classes/462/ADC%20for%202%20sensors.htm
//
// Last modified by Andrew Gazdziak on 4/13/2013
//****************************************************
#include "msp430G2452.h"
#include "stdbool.h"
#define LED0 BIT0      //For ADC
#define LED1 BIT6      //For ADC
//Declare some variables.
long sample;
long sampleMeasured[8];
long sampleAvg;
unsigned char samplePos;
unsigned int countDown;
void main(void)
{
  unsigned char i;
  WDTCTL = WDTPW + WDTHOLD;            //disable watchdog timer
  BCSCTL1 = CALBC1_1MHZ;               // Set range
  DCOCTL = CALDCO_1MHZ;                // SMCLK = DCO = 1MHz
  BCSCTL2 |= SELM_0 + DIVM_0 + DIVS_0;   // MCLK = DCO/0
  P1DIR |= BIT2;           //P1.2 to output
  P1SEL |= BIT2;           //P1.2 to TA0.1
  P1DIR |= LED0 + LED1;      //for LED's
  P1OUT &= ~(LED0 + LED1);    //for LED's
  //Configure ADC
  ADC10CTL0 = SREF_1 + ADC10SHT_3 + REFON + REF2_5V + ADC10ON;    //Vref = 2.5V, Turns on ADC,
enables interrupts
  ADC10CTL1 = INCH_7 + CONSEQ_2;                          // Channel 7, P1.7.
  for (countDown = 240; countDown > 0; countDown--);           //delay to allow references to settle
  ADC10AE0 = 0x02;          //Enable the analog input for CH1. Eventually change to CH7. Needed?
  //Start Timers: ~10 kHz signal
```

```c
CCR0 = 100-1;           // PWM Period.
CCR1 = 43;              // CCR1 PWM duty cycle. Modify this in the while to change duty
CCTL1 = OUTMOD_7;       // CCR1 reset/set
TACTL = TASSEL_2 + MC_1;  // SMCLK, up mode

 while(1)
 {
    //Start sampling and conversion.
    ADC10CTL0 |= ENC + ADC10SC;        // Sampling and conversion start
    while (!(ADC10CTL0 & ADC10IFG))    //wait for ADC to complete
   sampleMeasured[samplePos++] = ADC10MEM; //sample and stick in array

   //Shut off conversion & lower flag to save power.
    while (ADC10CTL1 & ADC10BUSY)
    ADC10CTL0 &= ~ENC;
    ADC10CTL0 &= ~ADC10IFG;
    //average 8 cycles together to get an average
    if(samplePos == 8)                    //reset position if at end
       samplePos = 0;
    sampleAvg = 0;
   for(i=0; i<8; i++)                 //loop through and sum samples
      sampleAvg += sampleMeasured[i];
   sampleAvg >>= 3;       //Divide by 8 to get avg (bit shift)
//Check if sample is above a range, and if so, turn on corresponding LED
    if(sampleAvg < 260)
    {
       P1OUT &= ~(LED0 + LED1);
       P1OUT |= LED0;          //red LED
       if(CCR1 >= 90)          //set max range of the duty cycle
          CCR1 = 90;
       else
          CCR1++;
    }
    else if(sampleAvg > 271)
    {
       P1OUT &= ~(LED0 + LED1);
       P1OUT |= LED0;
       if(CCR1 <= 10)          //set max range of the duty cycle
          CCR1 = 10;
       else
          CCR1--;
    }
    else
    {
       //Do nothing: In proper range
       P1OUT &= ~(LED0 + LED1);
       P1OUT |= LED1;          //green LED
    } }//end while loop}
```

Appendix E: Solar Panel Technical Specifications

Table 18: Solar Panel Technical Specifications

Power (W)	50 Watts
Open Circuit Voltage (V)	21.30 Voc
Short Circuit Current (A)	2.94 Isc
Maximum Power Voltage (V)	18.20 Vmp
Maximum Power Current (A)	2.75 Imp
Cell Type	Mono-Crystalline
Length	24.80" (629.92) mm
Width	21.30" (541.02) mm
Depth	1.38" (35.05) mm
Weight	11.02 lb (5.00) Kg