

# **Economic Overnight Smart Outlet**

ECE 445 Project Design Document

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# 1. Introduction

## 1.1 Problem

Real-time pricing in ISOs, such as those in the Midwest, Texas, California, New England, and New York, provides frequent differentials in electricity prices throughout the day that can be taken advantage of. Currently, most electronic users will charge devices at economically inopportune times. Whether that be needlessly charging during the day to “top off” or companies charging devices at the end of a workday, many consumers miss out on periods of lower electricity prices. While the price differences may seem minor, the daily minimum price can be up to 70 percent lower than the peak price of electricity. Therefore, price agnostic charging often results in unnecessary costs.

While smart chargers that charge during nightly hours currently exist, these do not actively monitor electrical prices posted by ISOs. If a price spike were to occur, they would continue to charge regardless, thus incurring unnecessary costs. As the recent Texas winter price surge proved, these spikes can be dramatic and potentially expensive to unsuspecting consumers.

## 1.2 Solution

We will build a smart outlet for small EVs and commercial applications that utilize high capacity lithium batteries. Currently, these devices charge when they are plugged in and do not exploit maximum savings potentials from the real-time electricity market, nor do they have any way to quickly respond to dramatic price spikes. Our product will resolve this by charging overnight at the nightly minimums, ensuring that customers save the most possible money over a given charging period. The lowest price of a potential charging period will be determined by factoring in common utility rate distributions with the real-time prices. That is, typical real-time price curves reach their minimum rate at approximately 10:00 p.m. until 4:00 a.m. the next day. This period is generally preceded by a steep fall in electricity price, as local maximums occur at around 6:00 to 8:00 p.m. [1]. The viability of our solution rests on its ability to recognize when this period of minimum price points has been reached. Our charging algorithm will also avoid price spikes should they occur during the charging period. Extrapolated over the product's lifetime, the outlet will recuperate its cost, profiting the user in electricity savings.

While there are smart appliances that utility companies are trying to push for, these are not generic devices that can be applied to any application. Since ours will simply be a 120VAC outlet that enables charging during low cost times, this keeps the product robust and highly flexible in how users can use it. Essentially anything that charges overnight can benefit from this product.

### 1.3 Visual Aid

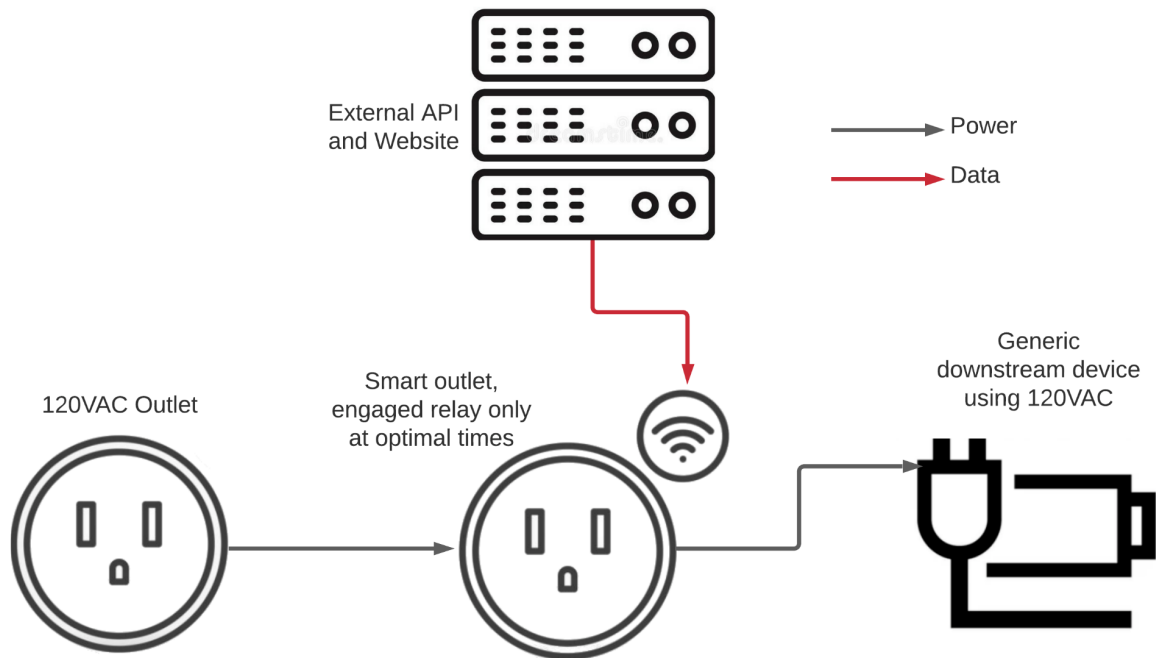


Figure 1: Visual Aid

### 1.4 High Level Requirements

- The state of charge (SoC) of the battery of the device being charged must be greater than 90 percent by the user-determined “charge by” time. This need supersedes price savings
- The user’s “profit” will be defined as the savings in electricity when comparing charging at the end of the day (5:00 p.m.) versus charging when night prices are at their minimum. From Figure 2, it can be seen that the price decrease from 5:00pm to 2:00 am is around 40 percent on average. Capturing at least half of this savings potential overnight will prove the viability of the economical benefit. Thus, if the profit is found to be greater than 20 percent over the device lifetime of about 3 years, we can deem that it makes economic sense to utilize the device.
- The outlet must be able to react to real-time energy cost data by pulling information from the ISO API. In ideal conditions, the outlet should be able to pull the cost data every five minutes and begin charging the device once price levels have plateaued to their minimums. Charging will halt if a price spike of greater than two times the average nightly cost is detected.

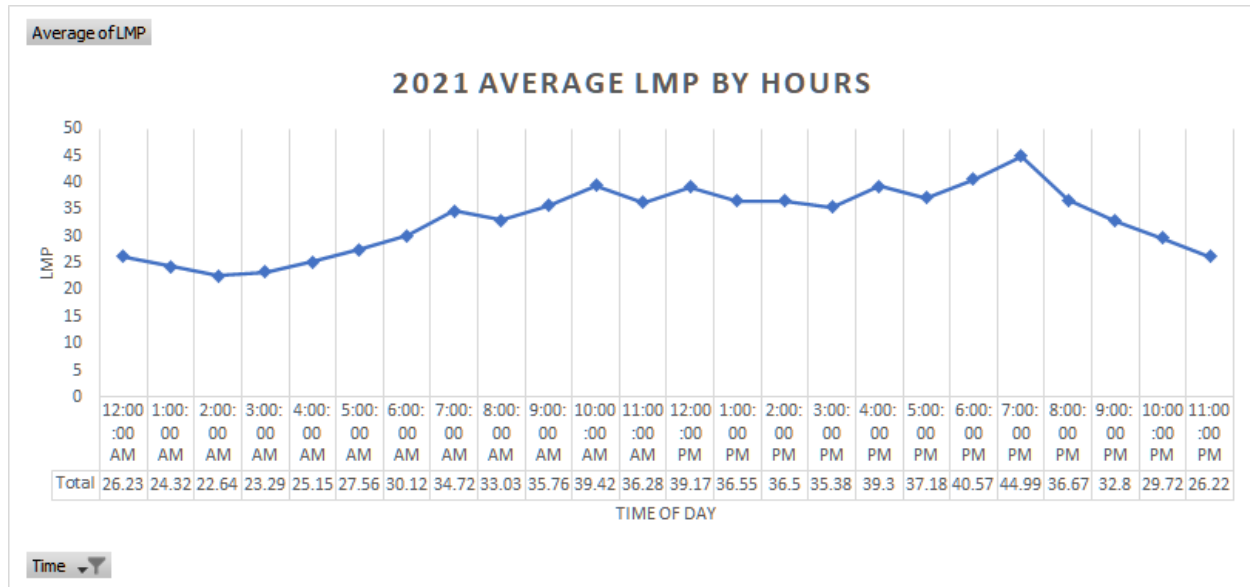


Figure 2: Average Illinois LMP prices in 2021 by hour

## 2. Design

### 2.1 Block Diagram

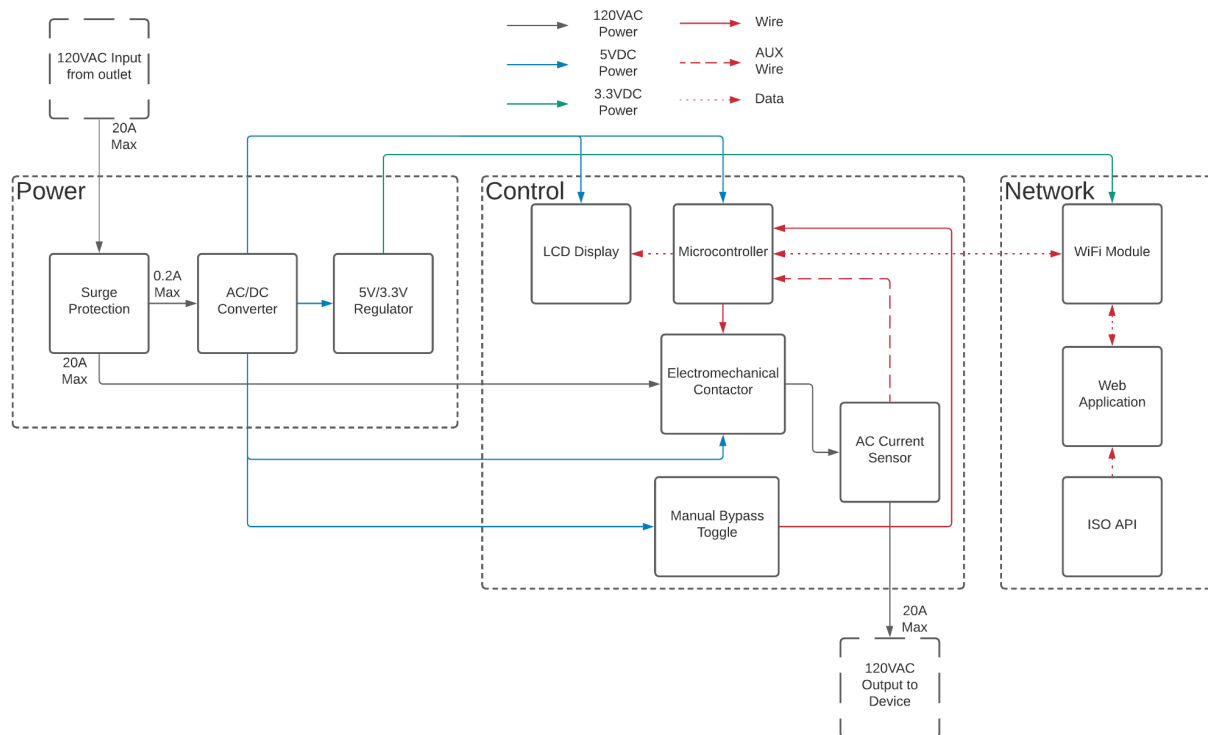


Figure 3: Block Diagram

## 2.2 Physical Design

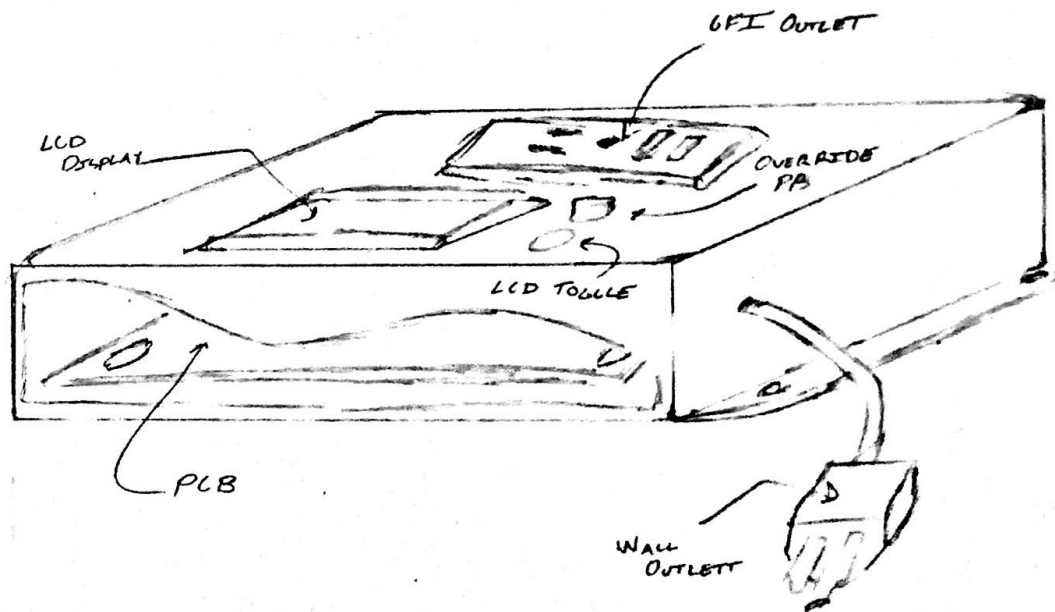


Figure 4: Physical Design

## 2.3 Power

The power components will allow all of the control components downstream to run off of the 120VAC outlet connection. This will be accomplished through a 120VAC/5VDC power inverter outputting up to 300mA. The 120VAC input will be accompanied by a surge protector, which will short out voltage spikes and dissipate inrush current.

### 2.3.1 Control Power Converter

The power converter will be a 10:1 step down transformer to bring the 120VAC input to 12VAC followed by a full bridge rectification. This rectified 12VDC is then passed into a linear regulator to bring it to a steady 5VDC.

Requirements	Verification
1. The converter must be able to step down 120VAC +/-10% to 5.0VDC +/-5%. Note, utilities are expected to give 120VAC +/-5% [2], but we will overrate for +/-10% for safety. 2. Converter must be able to safely handle a continuous current load of 300mA from the 5V output.	1. <ul style="list-style-type: none"> <li>A. Use AC power supply to vary input from 108VAC to 132VAC over the course of 10 seconds. Use a multimeter to ensure output remains within desired bounds.</li> </ul> 2. <ul style="list-style-type: none"> <li>A. Use electronic load to simulate</li> </ul>

3. Maintain temperature below 80°C

current draw of 300mA. Leave for 15 minutes.

B. Verify with a multimeter that the output voltage remains within bounds.

3.

A. During test 2, use an IR thermometer to ensure devices stay below 80°C.

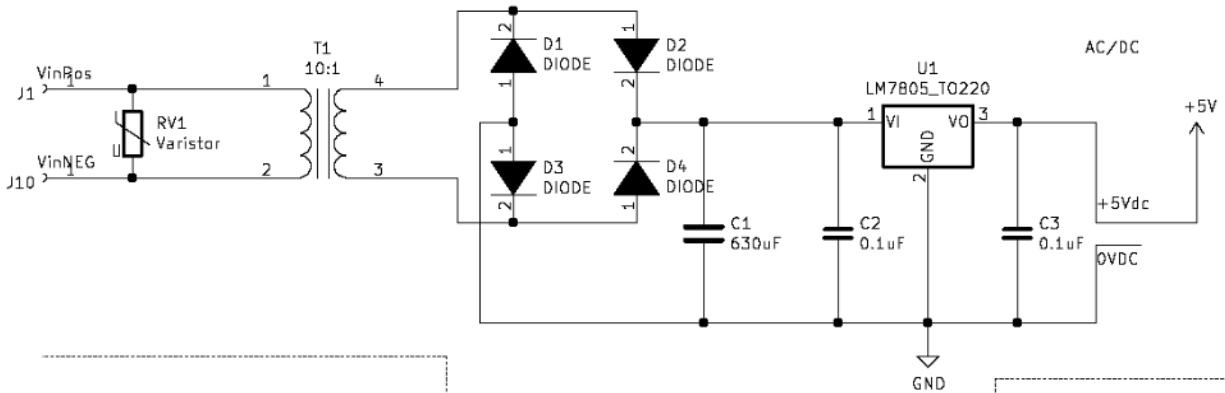


Figure 5: AC/DC Circuit Schematic

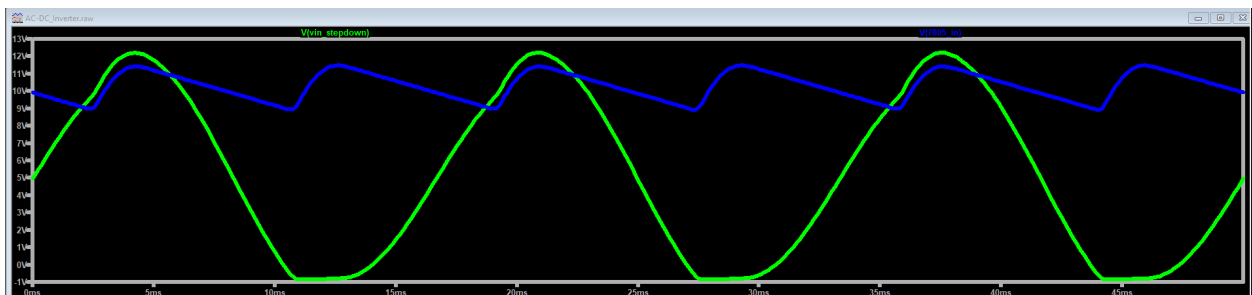


Figure 6: 12VAC stepped down (green) and full rectified and filtered 10VDC output (blue)

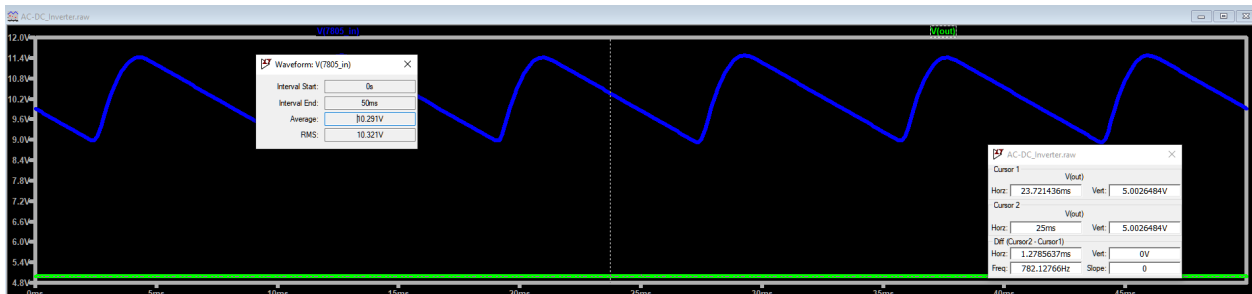


Figure 7: 10V DC input to 7805 regulator (blue) to steady 5VDC output (green)

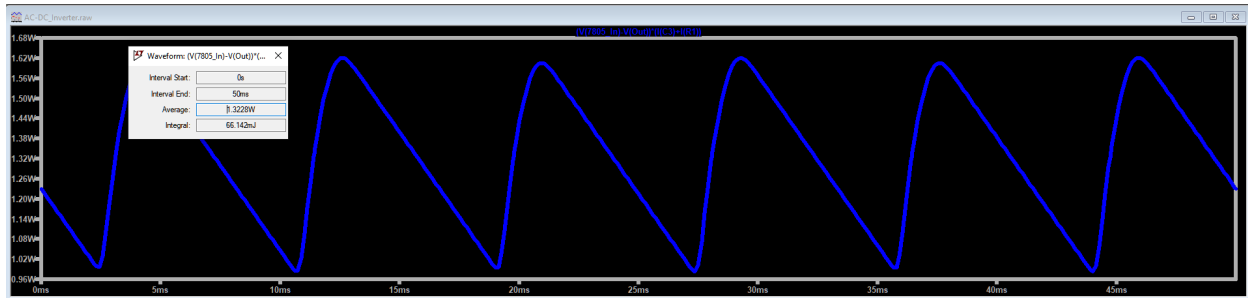


Figure 8: Power dissipated across 7805. Average is 1.3W.

### 2.3.2 Input Surge Protection

The input 120VAC will be protected via a MOV rated for 110% of 120VAC with protection shorting the input at approximately 340VAC. The current protection will be done by a 3A fuse after the voltage transformation.

Requirements	Verification
<ol style="list-style-type: none"> <li>1. The surge protector must be able to sustain 3 voltage spikes lasting 1ms per year over 5 years with only a 10% increase in clamping voltage.</li> <li>2. The surge protector should have a rapid response time of less than 100ns.</li> <li>3. The fuse must not blow under normal current conditions but must blow at sustained current greater than 3A.</li> </ol>	<ol style="list-style-type: none"> <li>1. <ol style="list-style-type: none"> <li>A. Use a signal generator to create a 340VAC pulse lasting 1ms. Repeat this after MOV has cooled to within 10°C of room temperature as verified with an IR thermometer. Do this 5 times.</li> <li>B. After 1A, subject MOV to 1mA with current supply and ensure MOV voltage drop is within 185-225V with a multimeter.</li> </ol> </li> <li>2. <ol style="list-style-type: none"> <li>A. Use an oscilloscope during the first test of 1A to capture the current response of the MOV. Verify that once the voltage spike passes 340VAC, the MOV draws 63.2% (1/e) of maximum observed current.</li> </ol> </li> <li>3. <ol style="list-style-type: none"> <li>A. Flow 1A with the current supply through the fuse grounded for 5 minutes and ensure it does not blow.</li> <li>B. Use current supply to push 3A through the fuse for 10 seconds. The fuse should pop.</li> </ol> </li> </ol>

## 2.4 Control

The control subsystems will receive data from the network subsystems as well as probe the downstream devices for SoC status. It will be powered by tapping the wall outlet and converting

it down to 5VDC. Using API price data and estimations on battery state of charge, the control will determine when to turn the relay on or off to begin charging at the most economical times. It will also use the data to provide the user a display of savings over time to allow users to observe the performance of the device.

### 2.4.1 Power Contactor

This contactor will act as a NO on/off switch which allows the 120VAC, up to 20A, to pass through the outlet to any downstream connected devices. It will be an electromechanical relay where the coil will be energized from the microcontroller output signal, thus allowing the microcontroller to determine when to switch on or off.

Requirements	Verification
<ol style="list-style-type: none"> <li>1. The temperature at 20A draw must stay below 80°C</li> <li>2. The relay must switch on with at least 100mA coil current.</li> </ol>	<ol style="list-style-type: none"> <li>1. <ul style="list-style-type: none"> <li>A. Enable the coil with a 120mA current source. Verify the relay is engaged with a continuity test with a multimeter. Use a 6Ω power resistor with a 120VAC voltage source to push 20A through relay contact for 10 minutes, or until the temperature reaches steady state. Verify with an IR thermometer that the relay is below 80°C.</li> </ul> </li> <li>2. <ul style="list-style-type: none"> <li>A. Using a voltage source, activate the relay circuit using a 5V node. Test the coil current with a current probe. Ensure that the relay engages using a continuity test with a multimeter.</li> </ul> </li> </ol>

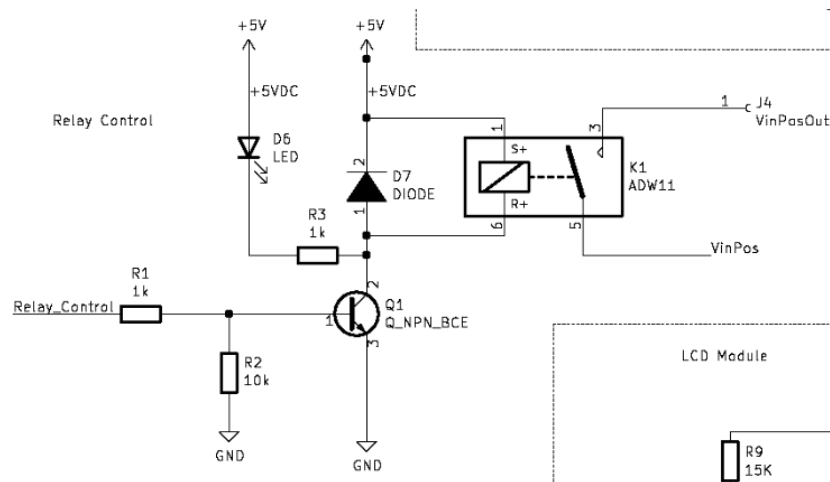


Figure 9: Relay Control Circuit Schematic



## 2.4.2 LCD Display

The LCD display will be used to highlight information about the current energy price (labeled “CurPrice” on the display, which will be taken from the ISO API, and the current day’s savings (labeled “Savings” on the display), which will be calculated using the prices at all times in which the device is charging subtracted from the price at the time of day when the device was plugged in for the same amount of charging time.

Requirement	Verification
1. The LCD display must receive and display data from the microcontroller.	A. Connect the LCD display to the programmed microcontroller using SPI. B. Verify that the LCD is capable of displaying exactly the following: “Savings \n \$XXX.XX”, and “CurPrice \n XX:XXx”.

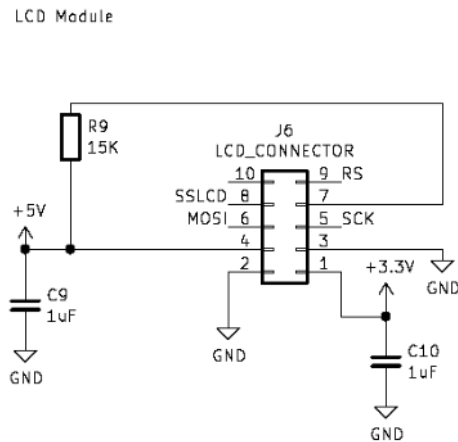


Figure 10: LCD Display Circuit Schematic

## 2.4.3 AC Current Sensor

The AC current sensor will provide information regarding the battery’s charging status. Namely, the AC current will be used by the microcontroller’s coded Kalman filter to create a linearized relationship between the internally modeled state, battery state of charge (SoC), and the measured output state, input AC current, measured as  $I_{rms}$ . Similarly, the sensor will be configured to recognize positive jumps in current, indicating that a battery has been plugged into the power converter and is ready to be charged (Figure 11). A toroidal, non-invasive current sensor that emits an analog voltage reading will be selected to avoid overcurrent damage to the device.

Requirements	Verification
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1. The AC current sensor must be able to interface with the microcontroller via an analog interface.
2. The sensor must be able to recognize AC current values of up to 20A.

1.
  - A. Provide DC bias for the -1 to 1V output voltage of the current sensor on a breadboard.
  - B. Connect the output to the analog input of the microcontroller.
  - C. Connect a voltmeter to the biased signal.
  - D. Verify that the output signal stays between 0V and  $V_{cc}$  of the microcontroller for a signal with 20A AC.
2.
  - A. Connect the non-invasive current probe to an AC current source (e.g. the model found in ECEB4024).
  - B. Test current peak-to-peak values of 10, 20, 30, 40, and 50A.

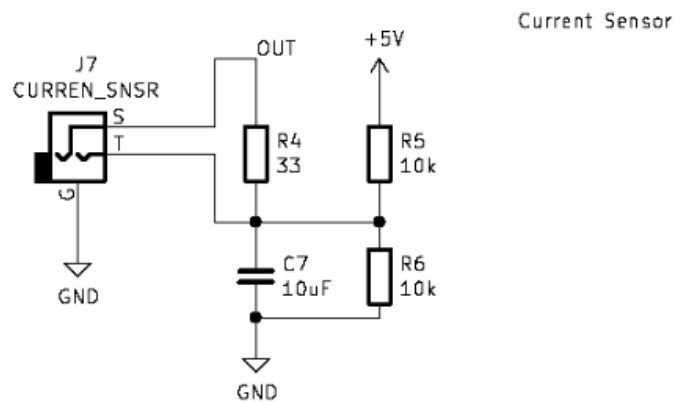


Figure 11: Current Sensor Circuit Schematic

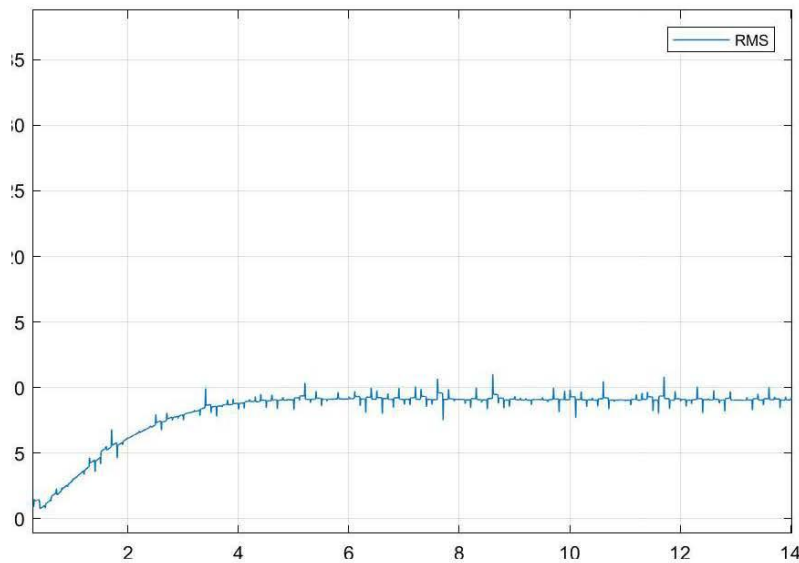


Figure 12: Transient Current Indicating Plugged-In Battery ( $I_{rms}$  (A) vs. Time (s))

#### 2.4.4 Microcontroller

The microcontroller will perform on-board computations and communication with peripherals and sensors. Once a control scheme is fully matured and required computational power has been determined, a processor will be chosen. High-level computation and communication requirements are detailed below.

Computational Requirements	Verification
<ol style="list-style-type: none"> <li>1. The controller must be able to perform an SoC estimation algorithm ("Coulomb counting" or "Kalman filter").</li> <li>2. The controller must be able to perform approximations for charge finish time with +/- 1 hour accuracy.</li> </ol>	<ol style="list-style-type: none"> <li>1. <ol style="list-style-type: none"> <li>A. Load the Kalman filter C code to the microcontroller.</li> <li>B. Verify using the terminal monitor of the Arduino software that the Kalman filter is updating its discrete time steps and storing modeled parameters to device memory without overloading the microcontroller storage space.</li> </ol> </li> <li>2. <ol style="list-style-type: none"> <li>A. Run Simulink Simscape™ simulations with parameters representing a 20V 4.5A laptop charger [3], 36V 20A golf cart charger [4], and 24V 18A electric forklift charger [5] using a Kalman filter block with 1 second discrete time steps.</li> <li>B. Verify that within 0.5 hours of plug in time, the Kalman filter</li> </ol> </li> </ol>

	approximation was accurate to within 1 hour of the final charge completion time, found at the end of the simulation.
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Communication Requirements	Verification
<p>3. The controller must be able to send charger usage data to the LCD display.</p> <p>4. The controller must be able to send and receive data to the peripheral WiFi module.</p> <p>5. The controller must be able to read 0-1V analog readings from the current probe.</p>	<p>3.</p> <p>A. Connect the LCD display to the microcontroller using SPI.</p> <p>B. Verify that the LCD is capable of displaying exactly the following: "SAVINGS \n \$XXX.XX", and "PlanStrt \n XX:XXx".</p> <p>4.</p> <p>A. Connect the Wifi module to the microcontroller using I2C.</p> <p>B. Verify on the Arduino software print screen using a test program that WiFi connection has been achieved.</p> <p>5.</p> <p>A. Connect the non-invasive current probe to an AC current source (e.g. the model found in ECEB4024) and to the DC biasing circuit breadboard.</p> <p>B. Test current peak-to-peak values of 40A on current source and verify on the Arduino software print screen that sensor voltage output values are being read by the microcontroller.</p>

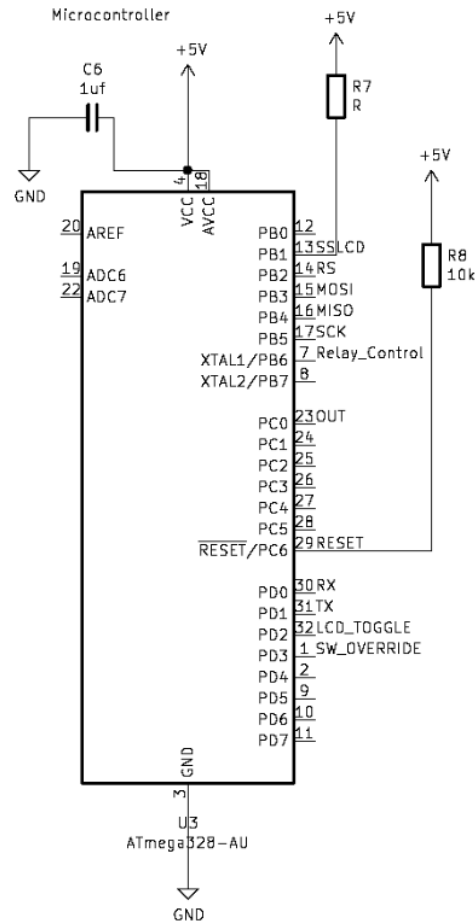


Figure 13: Microcontroller Circuit Schematic

## 2.5 Network

The network subsystems will connect the device to a web application and the ISO API using a WiFi module. These subsystems will transmit data among each other, with the WiFi module serving as a link to the microcontroller.

### 2.5.1 WiFi Module

The WiFi module will be used to transmit data regarding times in which the device is charging to the web application, which will showcase visualizations of cost savings over time.

Requirements	Verification
<ol style="list-style-type: none"> <li>The module must be able to interface with the microcontroller and web application and receive and send data.</li> <li>The module should send charging time data to the web application at a minimum of</li> </ol>	<ol style="list-style-type: none"> <li> <ol style="list-style-type: none"> <li>Send any number of hours (e.g. 1 hour) from the microcontroller to the WiFi module and send this signal from the WiFi module to the web</li> </ol> </li> </ol>

<p>once per day, after the connected device has finished charging and has been disconnected.</p>	<p>application. Check that the number appears on the web application page.</p> <p>B. Send any time of day (e.g. 9:00 a.m.) from the web application to the WiFi module and send this signal from the WiFi module to the microcontroller. Check that the signal has been received by the microcontroller using its output pins.</p> <p>2.</p> <p>A. After a charged device has been disconnected, check the visualizations on the web application and ensure that the current day's charging price comparison has been added.</p>
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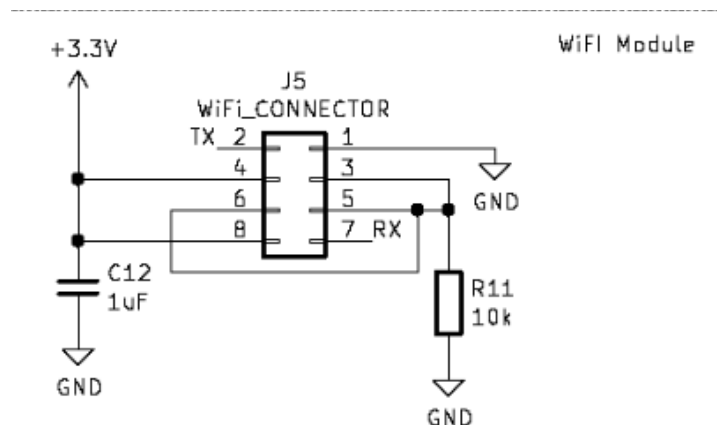


Figure 14: WiFi Module Circuit Schematic

## 2.5.2 Web Application

The web application will allow the user to input preferences, such as the time of day they need their device to be charged by. It will also display visualizations of cost savings over time, which will utilize the ISO API and data from the WiFi module to show actual costs compared to maximum costs of charging for each day.

Requirements	Verification
<p>1. The web application should allow for a user to set preferences regarding the device's charging patterns and should send these preferences and any updates to the device upon entry.</p> <p>2. The application should display visualizations of the amount saved each day</p>	<p>1.</p> <p>A. Set the charge by time to a time within an hour of the current time and connect the device to be charged. The device should start charging instantly if its battery is low, regardless of the current price.</p> <p>2.</p>

over time. The charging time data needed for this will be received from the WiFi module.

A. After a charged device has been disconnected, check the visualizations on the web application and ensure that the current day's charging price comparison has been added.

## 2.6 Circuit Schematics

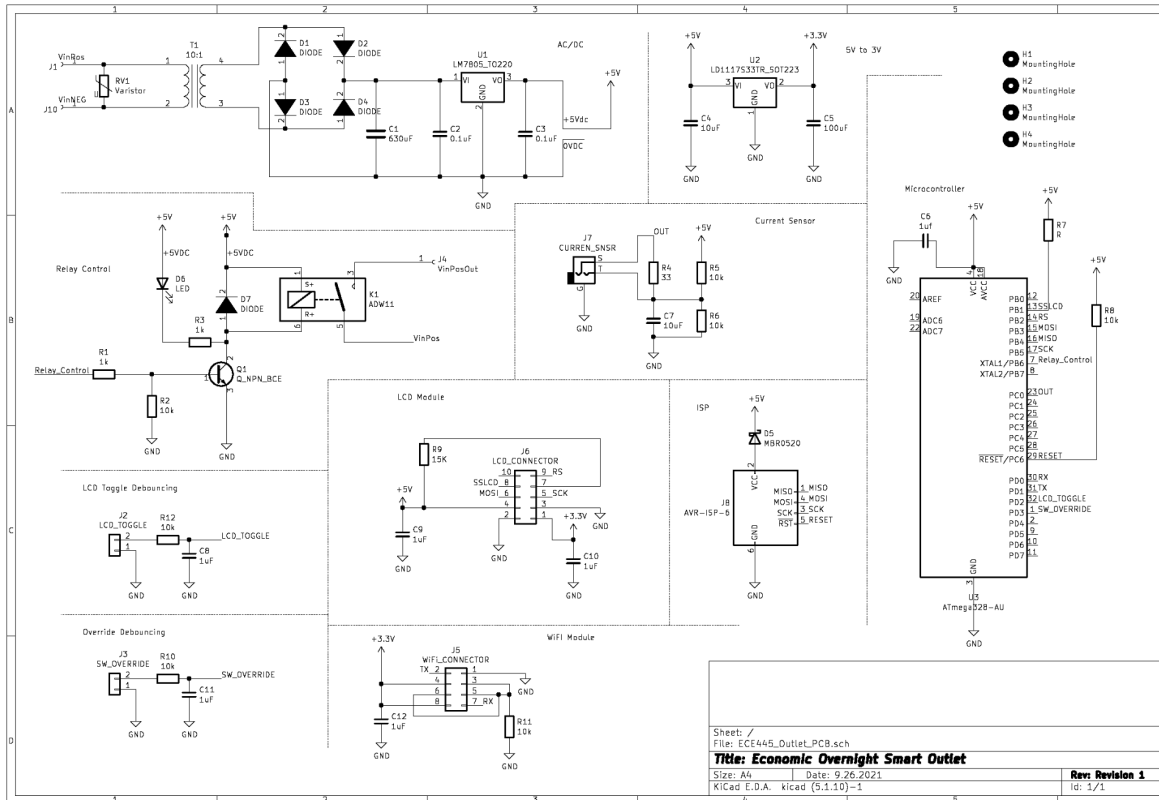


Figure 15: Circuit Schematic Overview

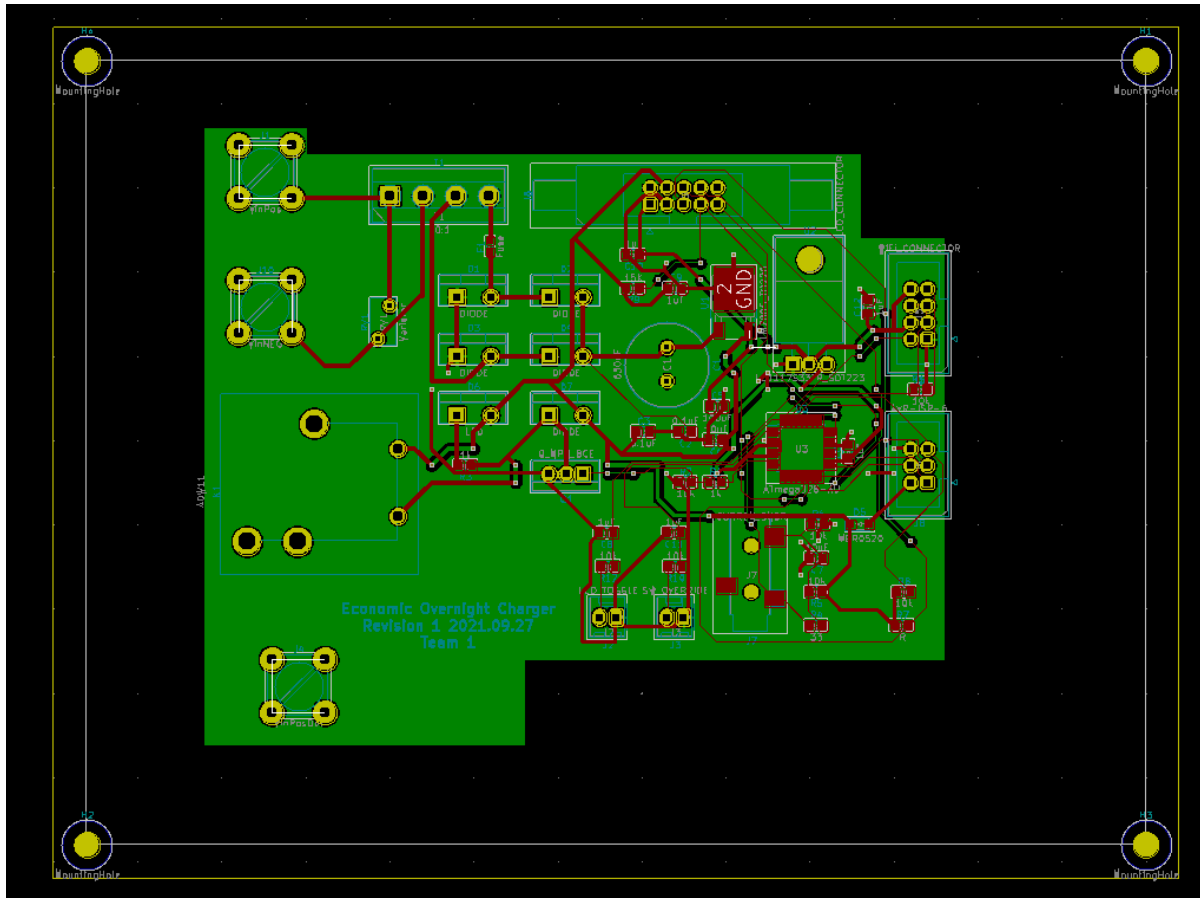


Figure 16: PCB Design

## 2.7 Device Charging Control Algorithm

### High-Level Relay Control Algorithm

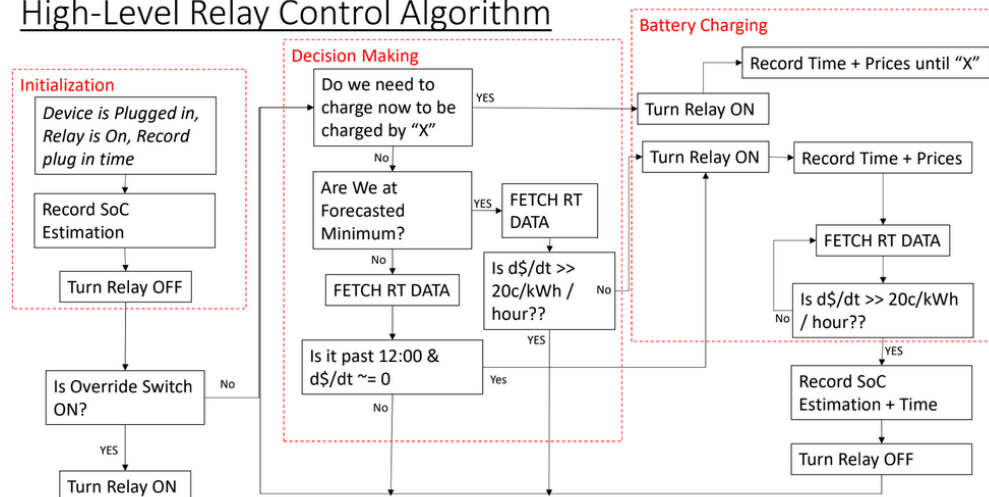


Figure 17: High level control diagram for price analysis algorithm



## 2.8 Tolerance Analysis

Since our device will be handling downstream devices, we must ensure that we can safely and effectively handle voltage surges in the line. For this, we refer to NEC code 230.67, which requires a type 3 SPD. To meet this, we will use a permanent MOV installed immediately across the outlet input terminals. To find a well rated MOV, we will assume we are providing 120VAC at full load 20A when an additional 300VAC surge appears lasting at least 1ms. The MOV must keep the current to the devices below 500% of 20A, or 100A. The justification for this is that for short spikes such as these, devices are rated for several multiples of their full load due to the surge not lasting a significant amount of time. See the below simulation results.

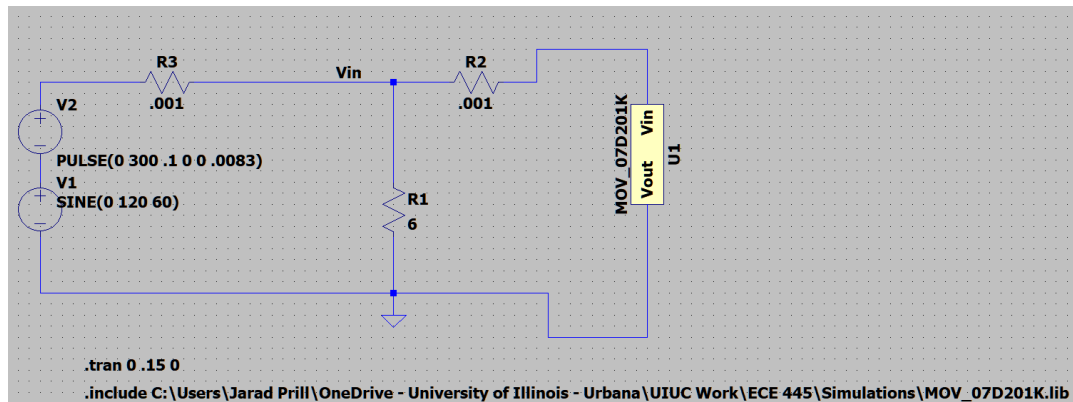


Figure 18: Simulation circuit using Spice model of MOV 07D201K provided by Bourns Inc.

This simulation has V1 as a normal 120VAC 60Hz source. Then, V2 creates a 300VAC surge that lasts for 0.0083ms. Note that the 8.3ms was chosen so we could see the MOV over a half period.

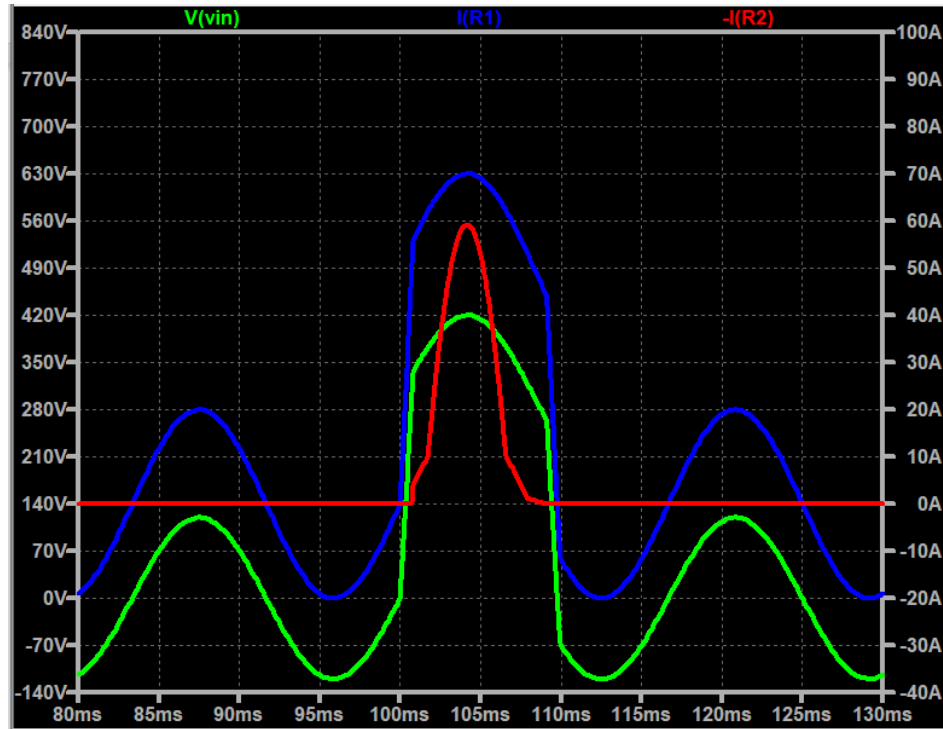


Figure 19: Simulation waveform. MOV current (red), input voltage (green), load current (blue)

We can see that during the spike, the MOV resistance drops as it reaches its clamping voltage (340V) and will allow significant current to flow through itself, thus allowing the load current to remain below 70A. This means that the MOV can successfully prevent extreme current spikes being pushed through downstream devices. Due to the nature of the MOV taking large amounts of current, the lifetime of the surge protection is limited.

## 3. Cost and Schedule

### 3.1 Cost Analysis

#### 3.1.1 Labor

With an hourly rate of \$40/hr and assuming we will work on average 15 hours a week over the full semester of 15 weeks, total labor costs for our group of three comes out to \$67.5k.

$$\$40/\text{hour} \times 2.5 \times 15 \text{ hours/week} \times 15 \text{ weeks} \times 3 \text{ team members} = \$67,500.$$

#### 3.1.2 Parts

Part	Prototype Cost (\$)	Bulk Cost (\$)
Microcontroller (Mouser; ATMEGA328AU)	\$2.05	\$1.97

Wifi IC (Sparkfun; ESP8266)	\$6.95	\$6.95
LCD Display (Digikey; AMC0802BR-B-B6WTDW-SPI/Orient Display)	\$8.94	\$4.83
Current Sensor (Mouser; 713-101990061/Seeed Studio)	\$6.90	\$6.90
Relay (Digikey; T9GV1L14-5/Potter & Brumfield)	\$4.44	\$2.46
10:1 Transformer (Digikey; TCT40-03E07K/Triad Magnetics)	\$16.19	\$10.79
PCB Enclosure (Polycase; SG-14 Weatherproof NEMA/Spelsberg)	\$31.62	\$21.58
Assorted Resistors, Capacitors, Connectors, Relays (Digikey, Mouser)	\$18.50	\$7.92
PCB (PCBway)	\$4.80	1.91
<b>Total</b>	<b>\$100.39</b>	<b>\$65.31</b>

### 3.1.3 Sum of Costs

With the design and implementation of one prototype, we estimate a total development cost of \$67,600. Our prototype device costs \$100.39, though taking advantage of bulk pricing we anticipate that a commercially available device would cost \$65.31 in parts to produce.

## 3.2 Schedule

<b>Week</b>	<b>Chester Hall</b>	<b>Sabrina Moheydeen</b>	<b>Jarad Prill</b>
10/4	Kalman Filter Program + K Filter Validation	Run simulation of device charging algorithm	LCD Display programming
10/11	Assist with programming as needed	Program microcontroller with charging algorithm	Assist with programming as needed
10/18 [PCB and parts arrival]	Current Sensor Validation, Solder PCB	Create and integrate web application	Power contactor, converter, and surge protection validation. Breadboard test the power electronics
10/25 [PCB 2nd order due]	PCB adjustments, as needed	Debug charging control and web	PCB adjustments and efficiency testing

		application integration	
11/1	Weather Test Assembly under operating conditions	Simulate final algorithm with 2021 historical data to prepare for demo	Temperature stress test device under full load. Implement air flow if too heat dense
11/8	Field Testing. Charge Motorcycle battery	Field testing, enhance algorithm as time permits	Field testing. Charge motorcycle battery.
11/15	Mock demo	Mock demo	Mock demo
11/22	Fall Break	Fall Break	Fall Break
11/29	Demonstration	Demonstration	Demonstration
12/6	Presentation and Final Paper	Presentation and Final Paper	Presentation and Final Paper

## 4. Discussion of Ethics and Safety

The team will ensure customer data privacy in accordance with the ACM Code of Ethics principle 1.6, "Respect privacy," by enabling collecting only relevant and necessary data and limiting access to this information [6]. The information to be collected will be user-inputted data about the time of day their device needs to be fully charged by and information about the user's ISO location and their device's charging times and energy costs at these times.

Similarly, the team will strive to ensure that the safety and wealthfare of the device's user is held paramount, as stated in the 7.8 IEEE Code of Ethics [7]. Given the nature of the device, poor power system conversion and excessive battery charging could present potential electrical and heat hazards, respectively. If the testing or simulation of the device reveals that it exacerbates these hazards, changes to the design will be made to curtail the potential danger.

Another consideration of note is OSHA 1926.44(b)(1), which specifies that "battery charging installations shall be located in areas designated for that purpose" [8]. As the device is intended for commercial and industrial applications, the team will strive to ensure that users of the device will not be encouraged to relocate their charging infrastructure to a non-charging-specific location in order to accommodate the device. This will be accomplished by providing a device that is capable of withstanding industrial and warehouse conditions as defined by the Whole Building Design Guide (WBDG) [9], as well as outdoor environments consistent with NEMA protection standards 4X and 12 [10].

Following NEC code 210.8 [10], since our 120VAC outlet will potentially be installed in outdoor environments as mentioned, the product will require a GFCI outlet for the user. This will prevent ground faults from potentially harming personal operating a device connected to the outlet.

## 5. Citations

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