Jonathan Lam, Min Cheng, Joshua Yoon
Prof. Shlayan
ECE 241
Electronics I
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Electric Car Charging Subsystem Project

Electronics Final Project

Introduction

The goal of this project was to design the charging circuitry for an electric vehicle modeled after the Gem Polaris e2. This charging subsystem would consist of a Li-ion battery, photovoltaic solar cells, and charging circuits to charge the battery from the solar cells or from a standard 120VAC 60Hz wall outlet. A circuit using basic power electronic concepts was built and components were chosen to fit design specifications outlined by the Gem Polaris characteristics, the solar cell chosen, and the wall outlets. Research was performed in order to better grasp the concepts behind the solar cell and the regulator technology, to gauge realistic and desirable specifications, and to properly simulate the different components of the circuit. The circuit was simulated in LTspice to provide insight into the battery charging rates and how the solar cell and the wall outlet representations interact with the voltage regulators.

Design and Analysis

Defining specifications

The following are tables of design specifications considered while designing the circuit:

Provided design requirements

Real-life model	Polaris Gem e2 electric vehicle
Motor	48V AC induction motor
Motor maximum power output	5.0kW (6.7hp)

Desired specifications

Maximum vehicle weight	907kg (2000lb) (1200lb dry weight + 800lb payload)
Maximum speed	11.2m/s (25mph)

Interface specifications

Solar panel	Count	4
	Maximum power rating	250W
	Maximum current rating	8.33A
	Open circuit voltage	37.4V
	Power efficiency	15.1%
	Dimensions	1652mm x 1000mm x 45mm
Battery	Voltage	48V
	Storage capacity	8.9kWHr
	Type	lithium-ion
Wall charger	Voltage	120V 60Hz AC
	Maximum power[1]	1.4kW

Circuit Design and Analysis

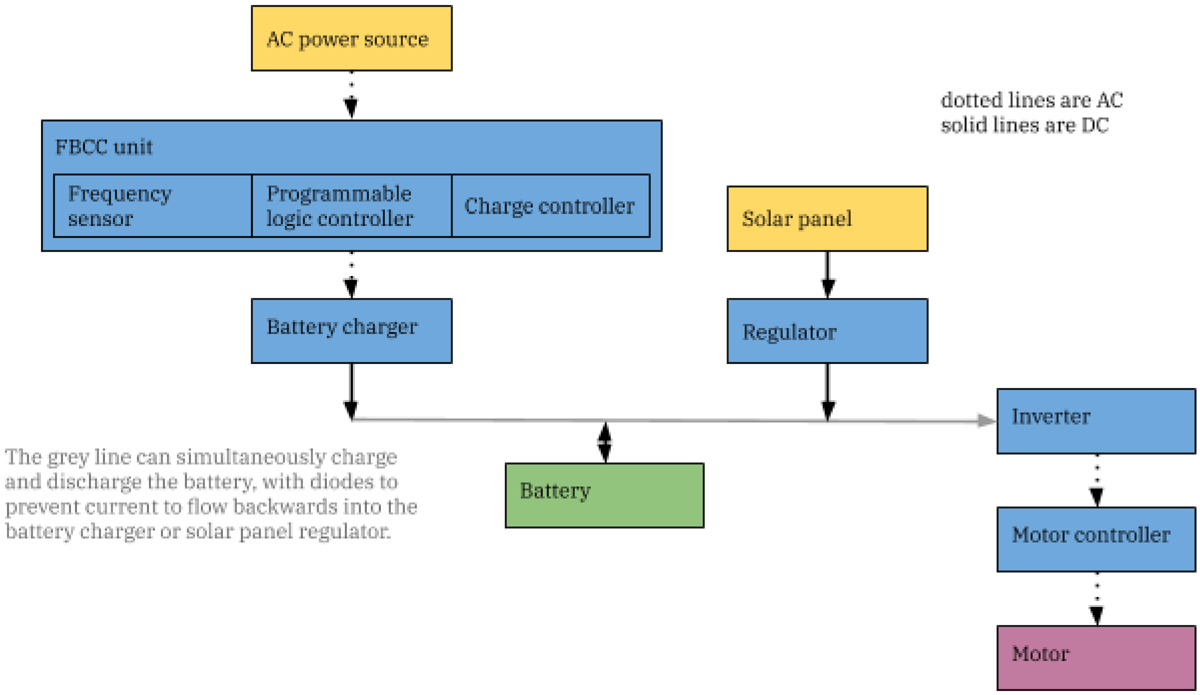
We aim to design the power system of an electric car similar to that of the Polaris Gem e2. Our design consists of three major components: a solar panel, an interface to connect with a standard 60Hz, 120V AC wall charger and the battery. There are various voltage regulators, transformers, diodes, and other devices to connect different parts of the circuit.

The below block diagram outlines a basic flow of our system. Each block will be further discussed. The above circuit outlines the basic circuitry of our system; note that the ATmega328-PU chip was used to facilitate the pins of the Arduino Uno.

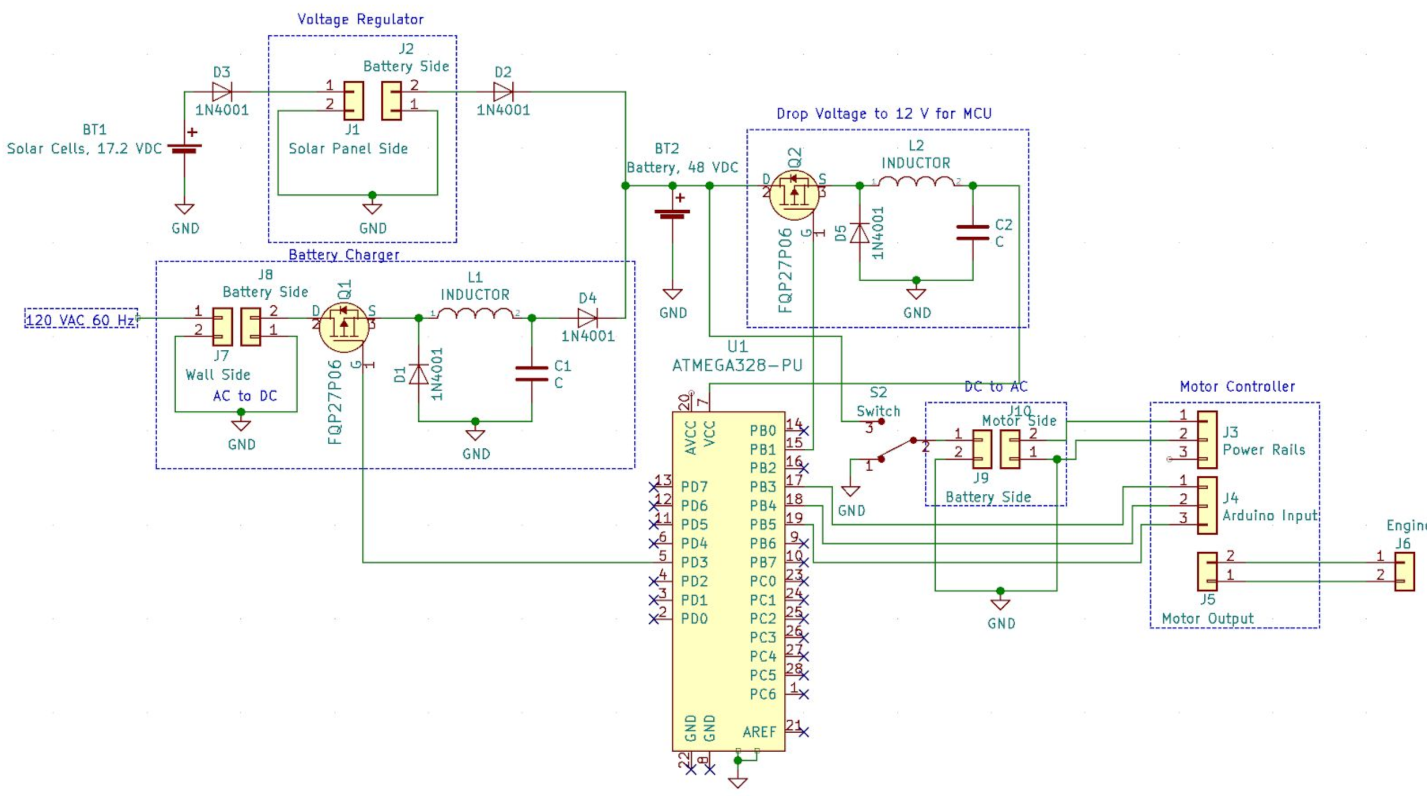
The flow of the system is as follows: the voltage from the solar panels will be fed into a voltage regulator to output a clean 50 V output, with diodes in place to protect the regulator and solar panel. Voltage from the wall will be fed into a transformer to step the AC voltage down to around 50 V, and then fed into a voltage regulator to produce a clean 50 V output. These voltage values were chosen specifically to be above the voltage value of the battery in order to facilitate charging. Also note that linear voltage regulators were chosen over switching regulators in order to better absorb changes to the input; solar panels produce notoriously noisy signals, and thus if switching regulators are used, while more power efficient with less I^2R loss, the circuit will require some kind of feedback loop to maintain a constant voltage value.

These two outputs will be coupled together, with diodes to prevent current from flowing in the incorrect direction. This output will charge a battery, which will be connected via an ignition switch to a DC to AC converter, which will be fed to the motor of the car. A microcontroller, powered by the battery via a buck converter that steps the voltage down to 12 V, will control the various buck converters and feedback loops throughout the circuit. The microcontroller and motor portion of the circuit will not be simulated.

Block Diagram



Overall Circuit (KiCAD)



Functional Design

Solar panel

Solar panel converts sunlight into DC power with solar cells to charge the battery. We use four 100W monocrystalline flexible solar panels. They can maximize the area for solar energy absorption because of their bending property. They are lighter and cheaper than the rigid solar panels, and the monocrystalline design makes them more efficient than polycrystalline ones. Every solar panel's dimension is 40.9" x 26.8" x 0.1", based on the WindyNation 100W flexible panels.

Regulator

The regulator ensures the battery is charged properly; it is a 48 V 60 A 3000W DC Step Up Converter Voltage Regulator[2]. The regulator has an input voltage range of 18 - 35 VDC, which encompasses the voltage range of the solar panel. This portion of the circuit also includes a diode to ensure no current flows in the wrong direction. The Arduino Uno will monitor the battery to ensure that when it is filled, no more power is fed to the battery; one way to do this would be to step down the battery voltage with a buck converter so that it can be read from the Arduino Analog pins. As stated before, however, this part of the circuit will not be simulated.

Battery Charger

The battery charger is used to charge the battery by converting the power of AC grid electricity into DC power that goes into the battery. The battery charger we ended up using simply consisted of a transformer, AC to DC converter and a linear voltage regulator.

Battery

We use a lithium-ion battery for our solar car. We assume our battery is a simple two-terminal battery. We can provide simultaneous charging and discharging[3] by connecting the charging inputs (the battery charger for AC outlet charging and the regulator for solar panel charging, with diodes to prevent current backflow), the load (the inverter for the motor), and the battery in parallel. We chose a capacity of 8.9kWHr, one of the available choices for the Gem and which allows reasonable drive and charging times. Our battery would be a four-cell, 48V battery (12 4.2V Li-Ion cells in series), which is similar to the e2's battery pack. This would match the e2's 48V motor, so that we wouldn't need to have voltage conversion between the battery and the motor.

Charging the Battery While in Use

The battery will be charged by the solar panels from the solar cell system when the car runs. The driver will be able to monitor charge levels. The solar panels, battery, and engine will be in parallel so you can charge and discharge the battery at the same time. The car can also be charged from the wall outlet when it is not running.

Battery charging considerations:

- The charging current and voltage of Li-Ion batteries should be monitored to be close to the desired wall charger specifications.
- Li-Ion batteries should not be charged at excessively low or high temperatures (lower than 0ºC or higher than 45ºC).
- Li-Ion batteries should not be overcharged (over 4.2V per cell) or charged with the wrong polarity.
- Li-Ion batteries are usually charged in two stages: at constant voltage until it is nearly full, and then at constant voltage near saturation. For the sake of finishing this project, we are only going to focus on the constant-voltage charging.

Inverter

The inverter is used to convert DC power into 48V AC electricity. We assume our inverter outputs a pure sine wave, which ensures maximum conversion efficiency. This will be used to convert the battery DC voltage to AC voltage that will power the engine/motor. The design simply consists of four diodes connected in a way to create the inverter (more details will be shown in the simulation portion of this report).

Performance Metrics

Power efficiency

We have power transfer in the circuit charging the battery from the solar panels, the circuit charging the battery from the charging station, the DC/AC conversion circuit, and any voltage converter circuits. We may evaluate power efficiency by finding, for each one of these circuits, the ratio of output power to input power. A “good” power efficiency rating for charging would be over 80%, and an “excellent” power efficiency would be over 90%. (For reference, Tesla chargers have a maximum power efficiency of 92%)[5]. We might also expect similar losses in energy from the discharging battery to the engine.

Speed of charging

A typical 120V 60Hz household outlet (not specifically designed for an EV) can deliver roughly 1.4kW max[4]. With an 80% efficiency, we hope to fully charge our 8.9kWHr battery in roughly 8 hours (without any contribution from solar panels, e.g., if parked in a garage). With an “excellent” 90% efficiency, this would be roughly 7 hours.

Similarly, if roughly 80-90% of the battery's power is sent to the engine, then the car may drive for roughly 1.5 hours on a single charge (without any charging from the solar panels). Thus we would have roughly 5 hours of charging time per hour of driving time, which should be reasonable for the average short-distance commuter.

Regulator Calculations

A very simple calculation to determine what kind of voltage regulator to use is as follows: 4 solar panels x 100 W = 400 W, so we should have a voltage regulator that handles this kind of power[3].

Summary of Research

Solar Cell Physics

Solar panels are made from n and p type silicon, i.e. pn junctions[14]. A depletion layer forms between the two types of doped silicon. Photons from the sun excite electrons in the n-doped region and cause more electron-hole pairs to be formed, widening the depletion region and increasing the builtin voltage; the electrons are driven to the top of the n type silicon and holes are driven to the bottom of the p type silicon by the electric field generated by the depletion layer, creating a potential difference. If a load is connected across the solar cell, the potential difference drives electrons from the n type silicon, through the load, and back into the p type silicon, thus delivering electrical power to the load.

If a photovoltaic cell is not connected to a load, the absorption of photons creates more free (excited) electrons and holes (akin to increasing doped-ness of both sides), which causes the widening of the depletion region, and higher drift and diffusion currents (still in equilibrium) for both holes and electrons. If there is an external path connecting the n-doped and p-doped sides with some load (resistance), then the electrons can become un-excited as they travel down that path, and will recombine with holes on the p-doped side. In other words, when an external (Ohmic) path is connected to the photovoltaic cell, it acts as a voltage source with hole-current traveling from the p-doped side to the n-doped side, until all excited electrons return to their ground state (i.e., the photogenerated charge carriers generate a current along the external path).

The Shockley diode equation[15] describes the IV characteristic for a diode and can be used to model the current (I_D) across the photovoltaic cell (which is essentially a pn-junction, or diode):

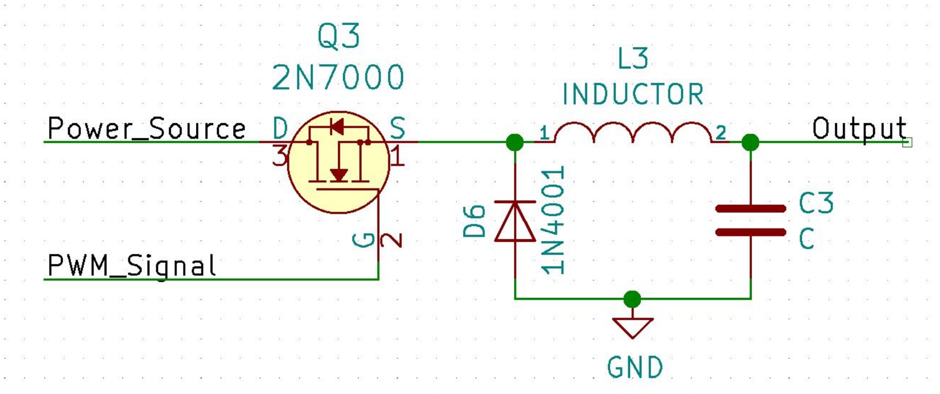
$$I_D = I_S\left(e^{V_D/V_T} - 1\right)$$

where I_s is the saturation current, V_D is the voltage across the diode, and V_T is the thermal voltage (and all assuming an ideal diode).

Power Electronics

Some basic important power electronics devices used in the circuit are buck, boost, and buck/boost converters. Transformers were also used in the circuit.

The buck converter is used to step down a DC voltage to a lower DC voltage. Below is a diagram of a standard buck converter.

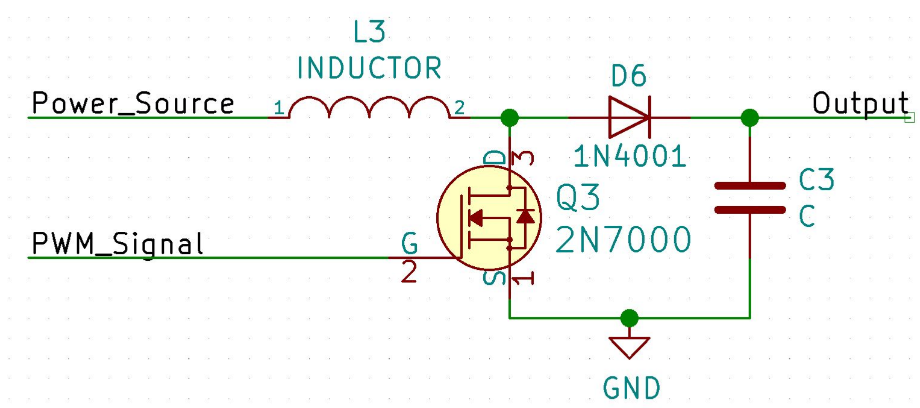


The output DC voltage value depends on the duty cycle of the signal that turns the transistor on and off, and is thus governed by the following equation:

$$V_{OUT} = V_{IN}\frac{t_{ON}}{T}$$

The buck converter is often used in favor of linear voltage regulators as it has less I2R loss. Note that the output does not depend on the values of the components in the circuit, but rather on the input signal. Because the diode needs to handle small voltages and large currents, a schottky diode is often favored for its smaller forward voltage drop[16].

The boost converter is used to step up a DC voltage to a higher DC voltage. Below is a diagram of a standard boost converter:

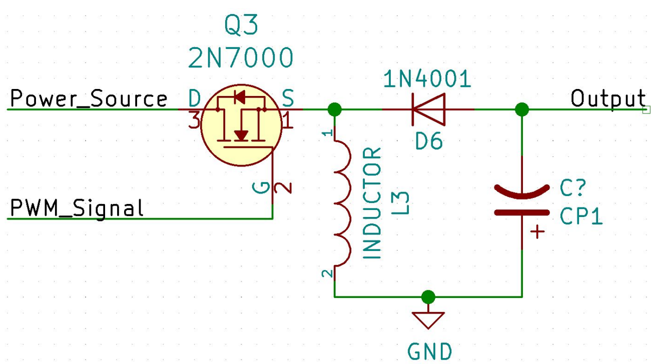


The output DC voltage, similarly to the buck converter, also depends on the duty cycle of the signal that turns the transistor on and off, and is governed by the following equation:

$$V_{OUT} = \frac{V_{IN}}{1 - D}, D = \frac{t_{ON}}{T}$$

The boost converter output voltage also does not depend on the component values. An example application of a boost converter is to maintain a certain voltage for a discharging battery. A boost converter is often controlled by a PWM feedback loop to maintain a target voltage[17]. Note that power is conversed, and thus less current can be sourced from the output.

The buck/boost converter combines the functionalities of the buck and boost converter and allows for fine voltage control. The following is a circuit diagram of a typical buck/boost converter (note that the capacitor is reverse polarized with respect to the input voltage!):



The output DC voltage depends on the duty cycle of the signal that turns the transistor on and off, and is governed by the following equation:

$$V_{OUT} = V_{IN}\frac{-D}{1 - D}, D = \frac{t_{ON}}{T}$$

When the transistor is on, the inductor charges and current is blocked from flowing into the capacitor by the diode; when the transistor is off, the inductor charges the capacitor, which discharges its load to the output. Like the boost and buck converters, this device has a high efficiency and is often used in PWM feedback loops to maintain a constant voltage. An example application would be if you had a battery at 15 V, and needed to power a sensitive circuit that only accepts 12 V. Initially, the voltage needs to be stepped down to 12 V, but once the battery is sufficiently discharged and its voltage falls below 12 V, the voltage must be stepped up. A buck/boost converter would be the ideal device to use due to its flexibility[18].

Batteries

There are numerous types of batteries used in industry; some examples include Lithium-ion, Lead-acid, and Nickel metal hydride batteries. The lithium-ion battery will be discussed in more detail, as it is the battery of choice for this project. The lithium-ion battery consists of an anode and cathode which store the lithium, a separator which allows flow of lithium ions but blocks electrons, electrolyte which acts as the medium through which the ions flow, and two current collectors (positive and negative)[6]. During a discharge cycle, lithium ions flow from the anode to the cathode, and the separated electrons flow through the load and recombine with the lithium ions arriving at the cathode. The ions and electrons both facilitate current, thus creating an electric circuit between the battery and load[7]. When an external power source is applied to the battery, it charges, reversing the previous process. After many charge and discharge cycles, imperfections in the metal that make up the anode and cathode lessen the capacity of the battery[8].

Table of Comparisons Between types of Batteries

Type	Pros	Cons
Lithium-Ion	• High energy density (thus useful in lightweight, small, and high-capacity applications). • Low maintenance (i.e. replenishing acid, periodic discharge, etc). • High cell voltage, requiring fewer cells per battery. • Good load characteristics provide relatively constant 3.6 V per cell until charge falls off[9].	• Requires protection circuitry to prevent being charged or discharged too far. • These batteries age, thus decreasing the number of charge-discharge cycles available. • Not safe for airline transportation. • Relatively expensive[9].
Lead-Acid	• Relatively cheap. • Easily rechargeable. • High power output capability[10]. Can withstand harsh conditions with little to no maintenance[11].	• Very heavy. • Batteries tend to be huge as power density is very low[10]. • Requires maintenance to remove lead sulfate buildup. • Have a limited lifespan. • Some types have risk of fire if shorted[11].

Nickel Metal Hydride	• High power density. • Often come in “standard” sizes. • Easy to recharge[12].	• Self-discharges quickly. • Relatively expensive[12]. • Cannot deliver high load. • Poor low temperature performance[13].

Circuit Implementation

Part Considerations

Overall Considerations

The starting cost of the Gem e2 vehicle is listed as $10,299 on their website. We aimed for an upper limit of roughly $15,000 for our cost, on the basis that we were buying parts individually (as opposed to in bulk).

Desired Battery Properties

There are a number of technical and non-technical aspects to consider when choosing a battery.

Cost	<$8000
Ease of implementation / simplicity of design	made for electric vehicles
Reliability	made for electric vehicles
Capacity	>8kWh
Voltage & current (both charging and discharging) specs	48V DC, 100A discharge current (to saturate motor maximum power output)
Efficiency	>95%
Warranty	A few years, if possible

Some of the choices we found when choosing the battery were:

Cost	Main features	Benefits	Order Link
$8200	8.9 kWh, Li-ion, 44 V	Use a proven electric car battery. Meets specifications we need	https://gem.polaris.com/en-us/shop/accessories/batteries-and-charging/4017366/
$7352	10 kWh, Li-ion (LiFePO4), 48V, 2500 charge cycles, 2 year	Cheaper and higher capacity than e2 8.9kWh battery pack,	https://www.amazon.com/4

	warranty	meets specifications, warranty, made for electric vehicles, internal BMS	8-VDC-Kwh-Battery-Pack/dp/B079348MM1
$3800	10 kWh, Li-ion, 51.2V, 25.6"x18.9"x7.5", 216lb, 4000 charge cycles, 10 year factory warranty, small self-discharge, high temperature range, charge voltage 58.4v, max discharge current 100A, max charge current 50A, LiPO4 cell technology 98% efficiency, operation temperature 32-122 deg. F, storage temperature -4-140 deg F	Cheap, high capacity and charge/discharge speeds, lists golf carts as one of its potential uses, long warranty, internal BMS (battery management system), much more detailed specs	https://www.electriccarpartscompany.com/10KWh-48V-200Ah-LiFePO4-Lithium-Battery-Solar-Energy-Storage-System

Of these three, we decided to go with the latter. Not only was it the cheapest, but it had many of the desired requirements, had the most useful information, and lists electric vehicles as one of its potential uses. We were unsure why this one, which seems so much cheaper than the others, is this cheap when it boasts many similar characteristics, but were unable to find any reasons for this.

Desired Solar Panel Properties

We changed and specified some of our requirements for the solar cars' roof-top panels. Instead of using rigid solar panels, we will use flexible solar panels. They can maximize the area for solar energy absorption because of its flexible bending property. They are lighter and cheaper than the rigid solar panels. The disadvantages are that they are less efficient than the rigid ones, and most of them only have about 100W output. We pick monocrystalline solar panels instead of polycrystalline ones because they are more efficient.

The number of solar panels are determined by the size of the solar panels and the roof area of our 2-passengers eVehicle. We plan to embed the solar panels in the windshield and the roof of the car to maximize the area of radiation absorption, so we can fit approximately four solar panels on the roof based on a 126" x 40" roof and windshield size of a golf car.

We will pick up solar panels based on the following criterias: work output, cost, solar cell efficiency, size, power ratings, power tolerance, and temperature coefficients (in the sequence from the most important to the least important). Solar cell efficiency decides how much electricity can be generated in a certain size of the solar panel. It is one of the most important criteria when we pick up solar panels. The efficiency for monocrystalline is normally between 18% and 25%. Power rating is the amount of power in DC form that can be produced under ideal lab conditions. Power tolerance, which is the difference between the power produced by the solar panels in reality and its nameplate rating. For example, a 250-watt panel with a +/= 5% power tolerance has the power output range from 237.5W to 262.5W. The more concentrate of the range, the better because it means more certainty for the output. Temperature coefficient quantifies how a panel's power capacity decreases as the temperature is higher than the standard temperature (77°F) the tests are performed. Panels with less temperature coefficients perform better in the long run.

Cost	<$500
Solar cell efficiency	between 18% and 25% (but higher is better)
Power tolerance	+-5%

The choices we encountered are shown below. We ended up choosing the WindyNation 100W flexible panels. We would order four of them, for a total of $434.

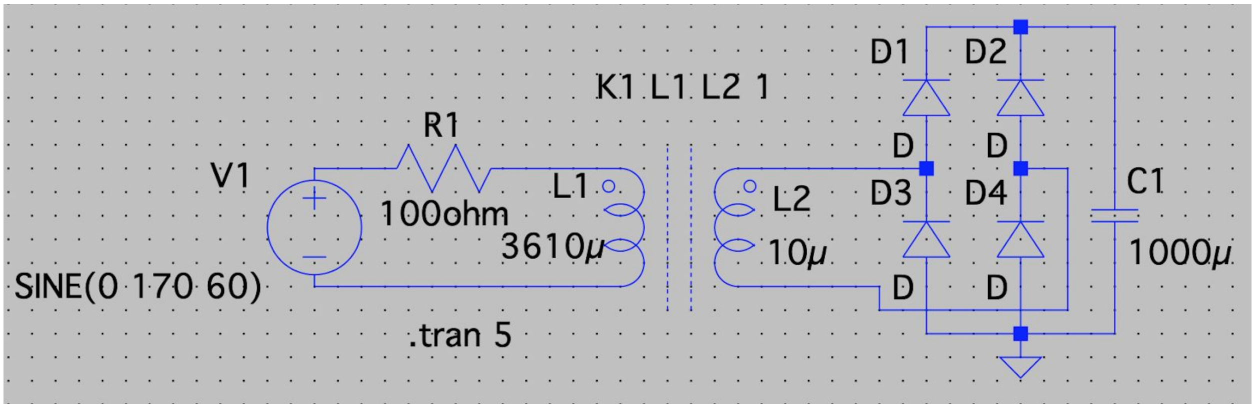
Solar Panels	Cost/panel	Reasons for choosing/ not choosing
WindyNation 100W flexible panels	$108.5	It's cheaper than other 100W flexible panels, and it is weatherproof
Giaride 100W flexible panels	$123	More expensive than the WindyNation 100W one
RichSolar 80W flexible panels	$106	Although its price is lower than the WindyNation one, it can produce less work output, which may drag the charging rate down too much.

Battery charger (Voltage rectifier)

We decided to design a simple smoothing voltage rectifier as part of the battery charger circuit. This features a transformer (AC voltage step-down), a bridge rectifier, and a smoothing capacitor to transform the 120VAC wall plug current to roughly 50VDC current to charge the battery. As mentioned before, we hoped to be able to harness the full 1.4kW maximum power output of a standard wall plug, so we had to look for high-power components when looking for components, which was slightly problematic sometimes (it was difficult to find such high power components, a problem that would come up again when designing the circuit on LTSpice).

Battery charger schematic

The schematic did not change from the first part of the project.



Battery charger component list

(Everything in the following table has quantity 1.)

Component	Cost	Specifications	Justification	Order Link
Step-down transformer	$310	115VAC to 56VAC (tapped for additional voltages as well), 1400VA (kW) power rating, 38 lb, 162x181mm	High power rating allows us to use full wall outlet wattage (1.4kW)	https://www.digikey.com/product-detail/en/signal-transformer/56-25/56-25-ND/1984771
Bridge rectifier	$42	400V, 60A, 4-pin	High power ratings and current ratings, should be safe (PIV should be accounted for)	https://www.sager.com/m5060sb400-4157601.html
Smoothing capacitor	$1.52	1000uF, 160VDC, aluminum electrolytic	Common capacity for smoothing capacitors, is rated for battery's voltage	https://www.mouser.com/ProductDetail/EPCOS-TDK/B43254D1108M000?qs=sGAEpiMZZMsh%252B1woXyUXj4oSl%252BFvVmKmmKDMFjfMzUE%3D

Other components

(Everything in the following table has quantity 1.)

Component	Price	Purpose	Features	Justification	Order Link
Voltage Regulator	$500	Regulate voltage from Solar Panel to power the battery	Input range from 18 to 35 V, rated for 0 - 60A, 3000W rating, efficiency up to 95%, over current and voltage protections	Need this part to regulate unstable output from solar panels, choose over buck converter to avoid a feedback loop, this part has the specs we need.	https://www.daygreen.com/products/24v-36v-to-48v-60a-3000w-dc-dc-step-up-converter-voltage-regulator
Arduino nano	$22	Control buck converters and motor controller via PWM, create feedback loops to properly maintain constant voltage	32 KB Flash, 16 Mhz, 8 Analog IN, 22 Digital IO, 6 PWM pins, input 7-12 V	Easy to use and integrate into design, need microcontroller to control voltage levels of buck converter output and for feedback control. Also use for motor controller.	https://www.digikey.com/products/en?mpart=A000005&v=1050
Voltage regulator	$34	Regulate voltage from smoothed rectifier circuit	Input 10-60VDC, output 12-90V (adjustable), 1500W maximum power rating, 130x52x85mm, conversion efficiency 92-97%, over current protection, low voltage protection, input	High power rating, voltage adjustable and in range, high efficiency, low cost, good built-in protection	https://www.amazon.com/Voltage-Converter-DROK-Regulator-Transformer/dp/B076TTBKFG

			reverse polarity detection		
DC-DC Converter	$12	Step down voltage of the battery to power the arduino	Voltage input range of 43.2 V - 52.8 V, Voltage output of 9 V, 2 W power capability, 82% efficiency	Need to step down voltage to Arduino for a reasonable price and reasonable efficiency, the Arduino won't need much power so this simple DC to DC converter will suffice. Meets specifications necessary.	https://www.digikey.com/product-detail/en/xp-power/IL4809S/1470-2442-5-ND/4785548

Overall design cost

Component(s)	Cost
Battery	$3800
Solar panels	$434
Voltage regulator	$354
Other components	$545
Total	$5163

This is much lower than the $15,000 original upper limit on cost, but there is still a large possible error in this estimate, given that we have no way to test these components to see if they are a good fit. For example, this cheap battery may have some unknown disadvantage as compared to the OEM e2 battery (which cost $4400 more) that we cannot know without further testing or inquiry. However, this cost estimate is reasonable given that the total e2's base configuration's cost is $10,299 and the charging subsystem is only one of various systems in the car (the engine and chassis are likely to contribute to another large portion of the car's cost).

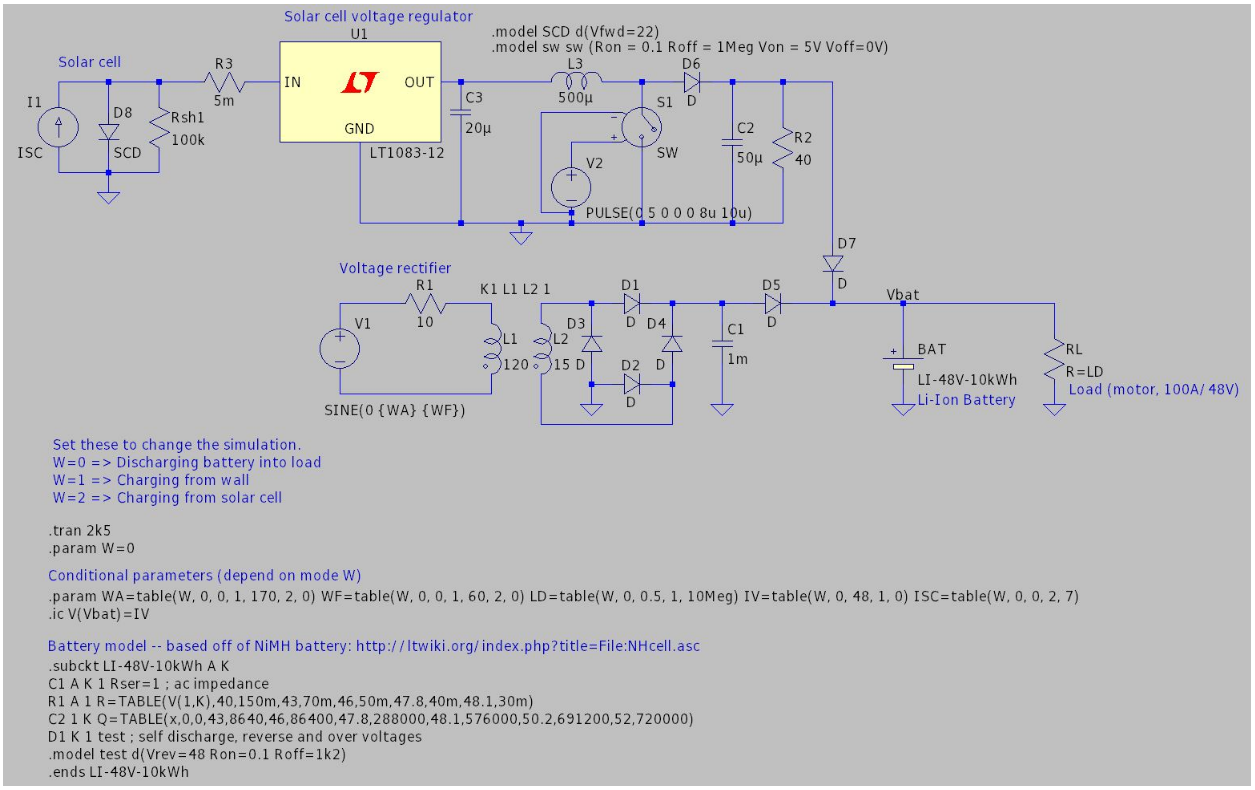
Simulations

We simulated the following blocks:

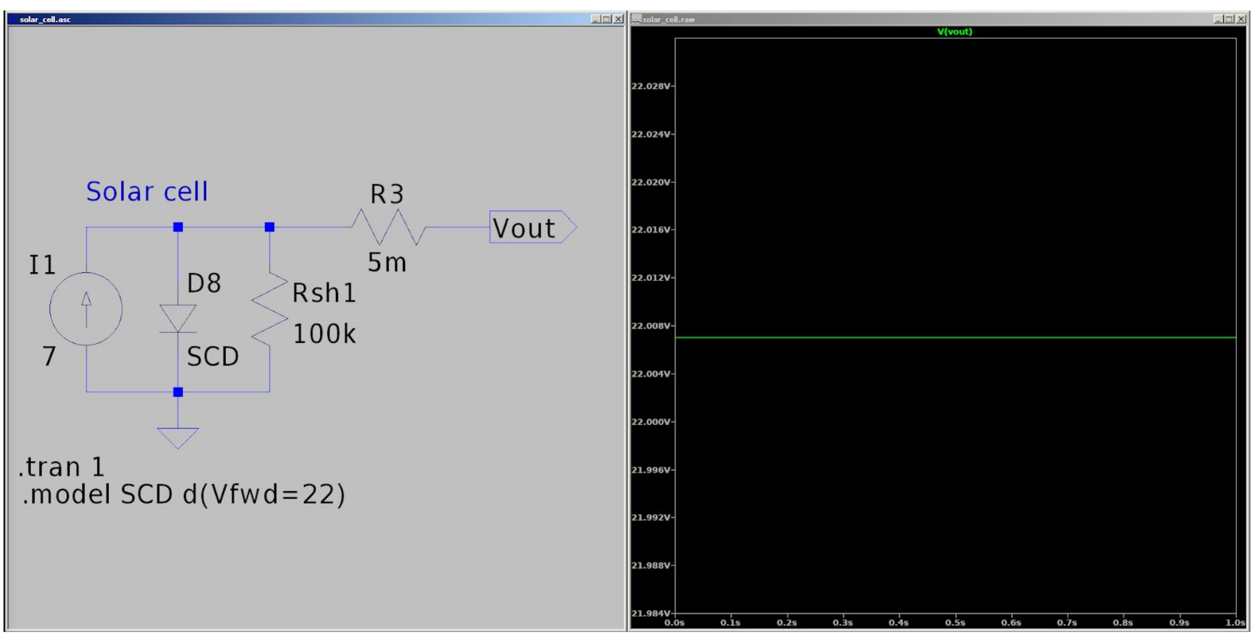
- The solar cell
- A 12V solar cell voltage regulator (IC model from LTSpice)
- A 12V to 48V boost converter from the solar cell voltage regulator
- The AC-DC voltage step-down/rectifier circuit
- A 48V 10kWh Li-Ion battery

We put everything into one schematic and tried to simulate it, but it turned out terribly slow to simulate (<1/1,000,000 simulation/real time ratio). The overall schematic is shown first, followed by the individual components.

Overall Schematic

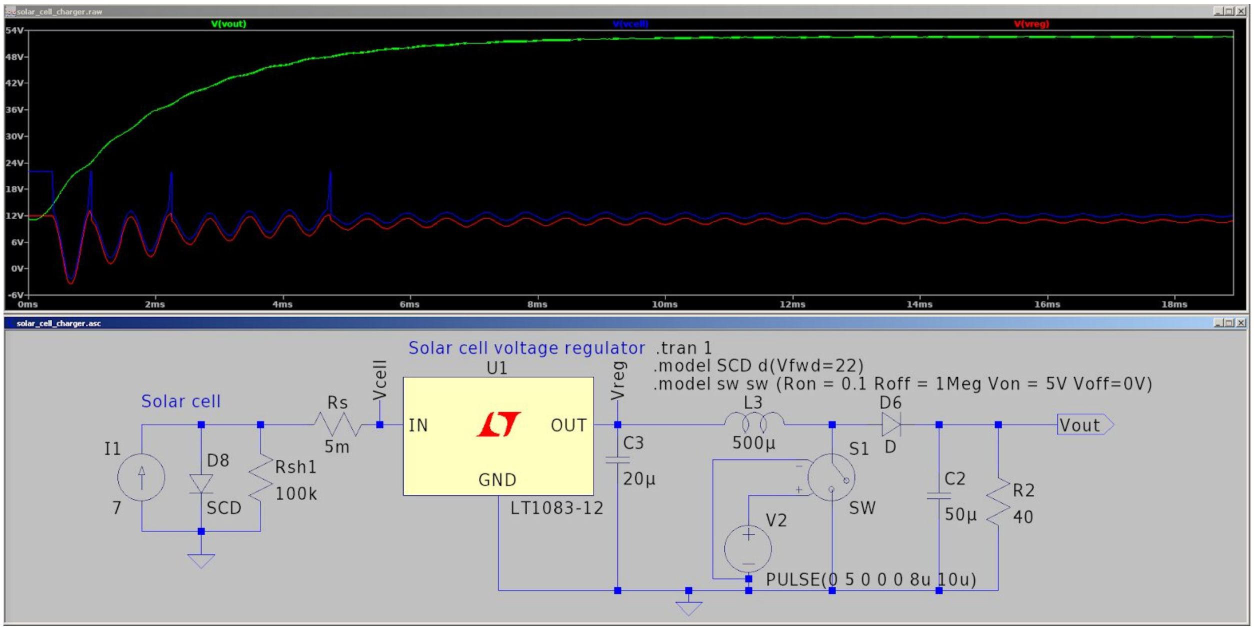


Solar Cell



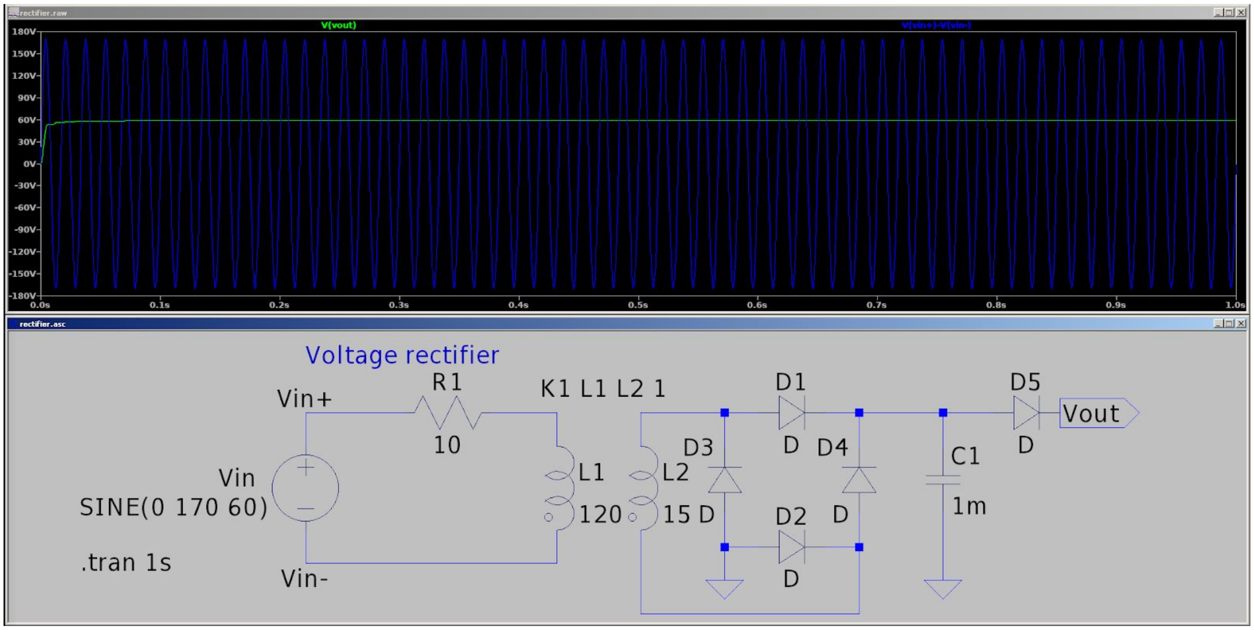
This solar cell was supposed to roughly match a 6V, 22Voc, 12Vout, 100W solar cell. While many sources online suggested this model of a solar cell (and this was the same solar cell schematic we found in the research stage of this project), we were unable to find good sources on how to calculate reasonable values for the resistors and characteristics of the diode for this circuit, so this is largely based on trial and error. By making the forward voltage of the diode 22V, this made the open-circuit voltage Voc=22V.

Solar Cell Battery Charger



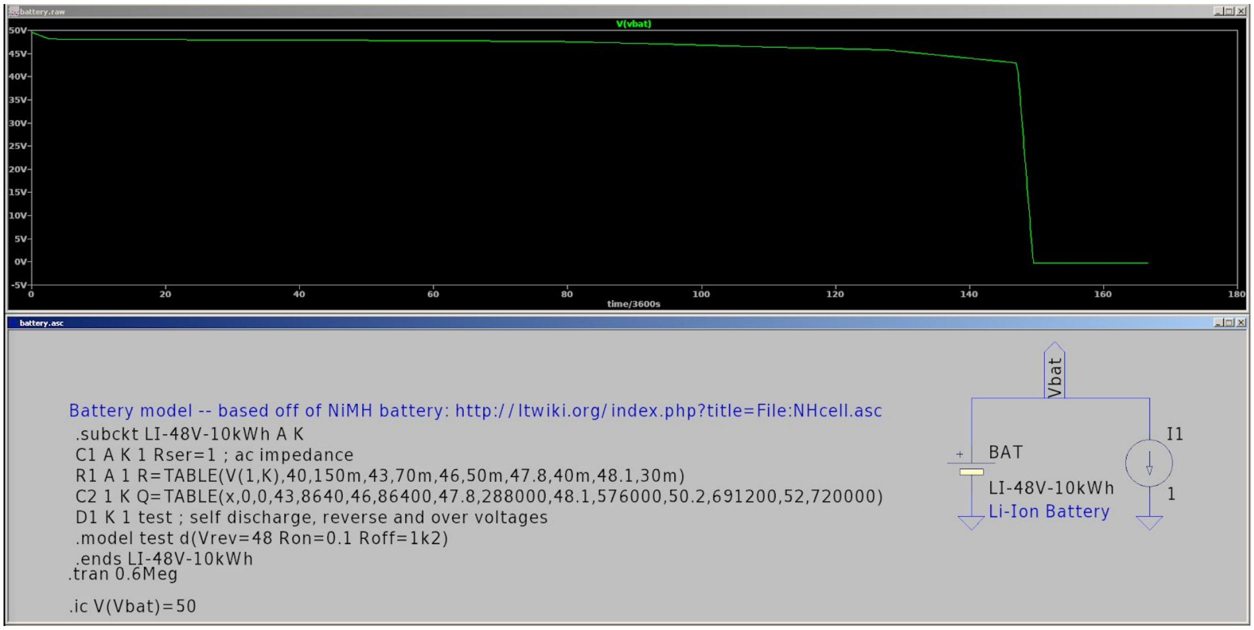
The voltage regulator after the solar panel is a 12 V linear voltage regulator and a 1:4 boost converter (75% duty cycle) to boost the voltage up to 48 V. We looked for spice models that fit the specifications of the model we found (10 - 60 V input range, 1500 W power rating) but were unsuccessful, so we had to use this combination of voltage regulator and boost converter. You can see the voltage regulator and boost converter cause the voltage at Vcell and Vreg to oscillate, but the oscillations decrease over time and the output voltage steadies around 50V, as desired.

Wall Charger Voltage Stepdown/Rectifier

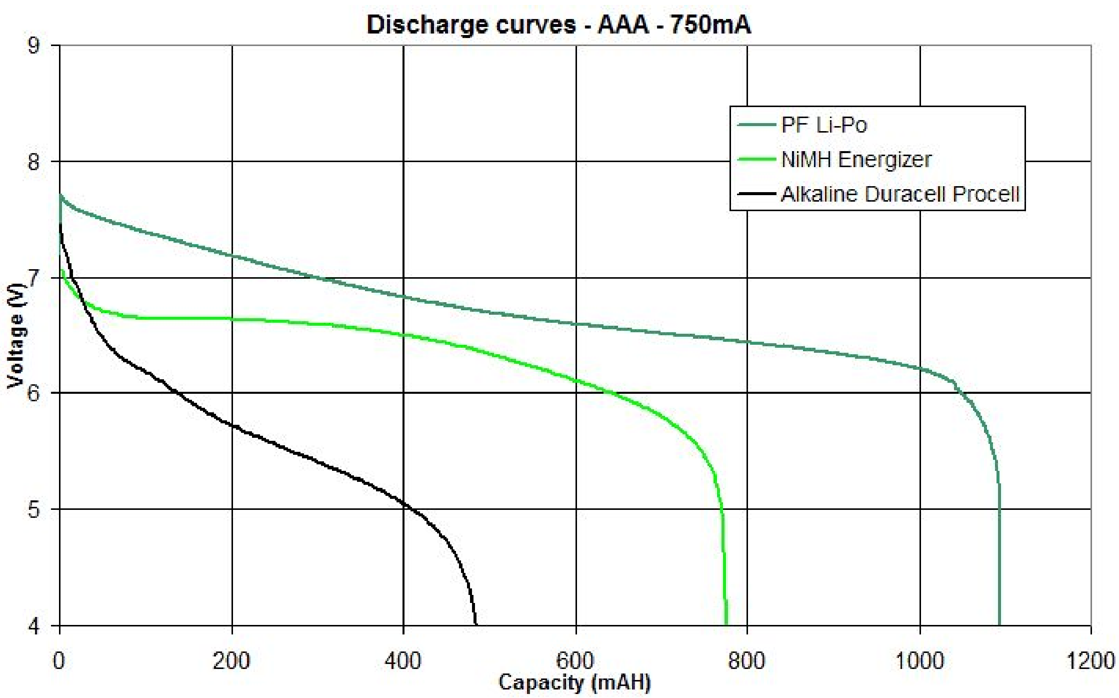


The principles behind this circuit are very similar to the bridge rectifier from class, and it works nicely to step down and rectify the wall current to the correct voltage. The diodes are left to the default model, and the capacitor and the “transformer” (modeled using inductors) have values chosen somewhat by trials and errors to get the expected result.

Li-Ion Battery

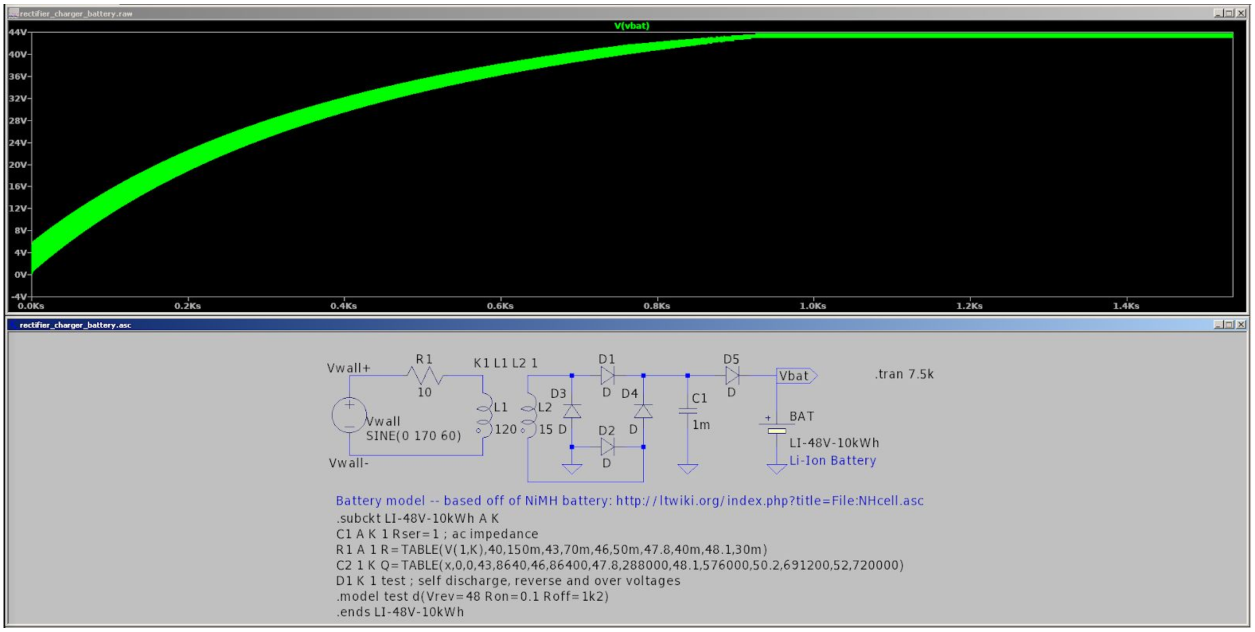


This was adapted from a 1.5V, 2.5Ah NiMH (nickel-metal hydride) battery model (from http://ltwiki.org/index.php?title=File:NHcell.asc). The model essentially hardcodes the charge based on the cell voltage. Looking at the voltage vs. charge graph for li-ion batteries vs. NiMH batteries, we see that the curve is not too different.

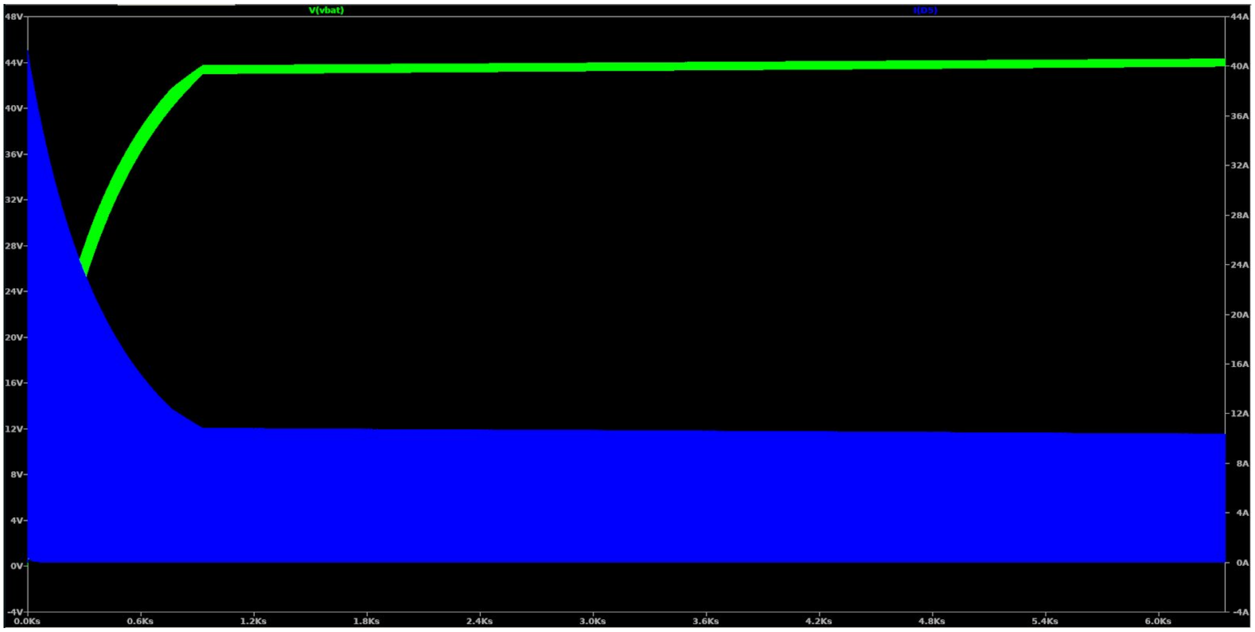


By tweaking the discharge rate (changing the resistor value) and diode voltage, we were able to make this act like a 10kWh (or roughly 200Ah), 48V battery. (This was verified by integrating the area under the current vs. time curve.) This was very much done empirically, and comments on how to improve this model would be welcome. The simulation shows that this battery, discharged at a rate of 1A, keeps its charge for roughly 150 hours, so it is actually around 150Ah (instead of the desired 200Ah), so this should require some tweaking to fix. Also, when charging (next section), it doesn't seem to reach exactly 48V, but is a little lower (~44V).

Charging the Battery with the Wall Charger



Once the battery is connected to the charger, there is a lot of oscillation in the output (battery voltage). You can clearly see the battery charging up slowly (as the battery's voltage is monotonic increasing w.r.t. its charge), and it reaches roughly its intended voltage around 900s. (This is the "plateau" of the battery's voltage-charge curve, so it still has a long way to charge.) Simulating for a longer time and also viewing the current through D5 (in blue):



You can see that there is a huge oscillation in the current through D5 (from 0-10A), which is probably not very efficient. Also, if we say that the average charging current after the voltage reaches the plateau is 5V, then this is only charging at roughly 44V*5A=220W, which wouldn't take into account the full 1400W of the wall voltage. We might need to add an additional regulator or find some other way to reduce oscillations.

Because of the higher modeling complexity of the solar cell charger (with the voltage regulator IC and boost converter), we were unable to get any useful simulation because the simulation was too slow to run.

Conclusions

Overall, the project was a useful exercise in thinking about what desired specifications (technical and nontechnical) should be met to fulfill a project, how to pick the components intended to fit the said specifications (as best as possible), how to design the basic circuitry for a photovoltaic system, and how to run proper simulation for various parts of the circuit. Finding the components that fit our specifications was aided by the filters available on different sites, but a deeper analysis into the datasheet information should be done before ordering parts. In addition, a more thorough cost analysis should be done before finalizing the bill of materials, as sometimes our group simply chose the first component that fit the set specifications. LTspice was a useful tool to use, but some problems hindered our progress, such as its slow simulation rates and its inability to simulate ICs. Finding the exact models for the components chosen in the LTspice libraries or some other online sources was almost impossible, and we were forced to create the components from the existing models or to tweak some properties from the online examples. The circuitry also required high voltage and high current rated products, and this hindered our search for the proper models to simulate.

Future Work

One aspect of this project that was frustrating was the lack of real simulations. While it would be infeasible to simulate power specifications on the power levels as those for a real electric car, even a small-scale simulation might dramatically help our understanding of the matter, even if not entirely accurate. This would aid mostly with simulations (as real life doesn't lag like LTSpice does in a simulation) and learning how some of the theorized parts might be better or worse than expected. Additionally, this could help us test how well our simplistic solar cell model works by comparing its output to that of a real solar cell.

Another aspect of this project that was left mostly unfinished was efficiency calculations. Because of the inability to satisfactorily simulate the entire circuitry in LTSpice, we could not obtain much useful information from the simulation. Nor were we able to calculate efficiency of the system manually due to the complexity of the system and the unknown properties of the battery and other blackbox components used such as voltage regulators.

If this project were to be continued in the future, a more robust circuit design would have to be created; one that optimized cost and included specifications for connections and properly accounted for input fluctuations. Designs for a potential custom printed circuit board or wiring diagram would be required to properly interface the different off the shelf components together. In addition, a more thorough size analysis would be required to gauge how the circuit would be mounted on the electric car.

Another way to expand the project would be to interface the battery charging circuit with the motor and microcontroller part of the car, as was originally intended for this project. Extensive testing on each component ordered and the circuitry built would be required to ensure safety and to better gauge how the different components interact with each other. Of course, funding would also have to be secured to purchase the off the shelf components and to prototype the circuitry and mechanical elements of the design.

Personal Takeaways

Josh - I enjoyed working with a team to do research and find components for a project that deals with a growing and important technology. I appreciated the chance to delve deeper into LTspice simulations and the intricacies of solar cells and power electronics, and feel that I can better search for parts and design circuitry. I hope to apply these skills to future projects, even if they don't involve solar cells.

Jon - Throughout most of this project I felt really lost. I don't have much experience with hardware or choosing components or knowing what to look for in components, and diving into it headfirst with a team and guidance from the TAs is very valuable. I remember last year in Motorsports when we were supposed to look for components and I was completely lost — now I feel (slightly) more confident in knowing what to look for.

Min - I feel a lot motivated working in a team, and I really enjoy our teamwork. Although this is just a simulation project, I figured out some research methods and testing steps that I was confused about before in some other projects. I didn't really understand the reason for spending time comparing different versions of components to finish the budget list previously, but after this project I found it critically related to the designing and testing standards we set and the realization of our design. I also learnt a lot from my teammates in time management and the habit of always doing an objective final check. I think I will approach all my future projects with all these skills confidently.

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