Electrical Engineering Department
California Polytechnic State University

Senior Project Report

PV Hybrid Inverter & BESS

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Abstract

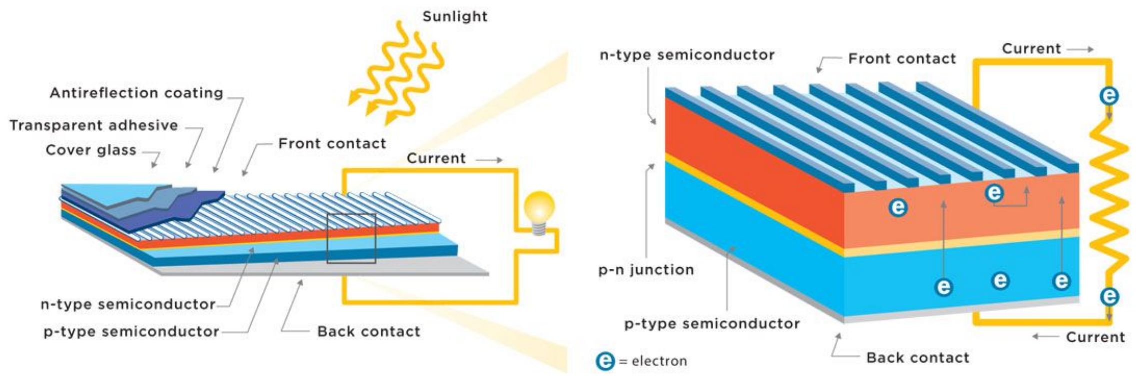
The storage of energy from renewable sources such as photovoltaic based systems is a growing market, with 36 MWh of storage installed in Q1 of 2018. A report from EnergySage earlier this year states that in 2017, 74% of residential solar owners were also interested in energy storage systems. Mainstream systems like Tesla's Powerwall are competing with other lithium-ion based storage systems from a wide number of providers on the market today. Short term and long term data collection on a system like this could be useful in designing future systems which perform better than the current market offerings.

This project seeks to install and operate the Tabuchi EIBS that the Cal Poly Electrical Engineering department currently owns. EIBS stands for Eco Intelligent Battery System, and it is meant to be used in conjunction with a photovoltaic array in a residence. This kind of system is a parallel to a source like a Tesla Powerwall, and uses two 10 kWh Li-Ion batteries. As of right now the system is being rolled between room 102 and room 146 of building 20, where it is assembled and ready to be energized. This team would like to assemble, mount, and integrate this system into the EE building micro-grid allowing for future students to test the storage and economical benefit of this system while connected to either the grid or a photovoltaic array. Our first priority was mounting the system on a mobile platform to enable flexible usage wherever its power would be most beneficial. After installation, time permitting, we wish to measure characteristics such as battery life, charge time, switching time, maximum throughput and how efficiently the batteries charge and discharge the energy to be stored.

1. General Introduction and Background:

Solar power is becoming more and more popular due to rising efficiencies and cost effectiveness. In fact, renewable energy generation grew by 167 GW in 2017, representing a stable growth rate of 8.3% according to the SDG Knowledge Hub, a site that documents sustainable development [8].

Solar panels are large panels that are made of many smaller units called photovoltaic cells. These cells use the photons irradiated by the sun to free electrons from the atoms in the photovoltaic cell which generates a current that can be used to charge batteries, power a house, or any other application that requires reasonable amounts of electrical energy.



Solar cells are composed of two layers of semiconductor material with opposite charges. Sunlight hitting the surface of a cell knocks electrons loose, which then travel through a circuit from one layer to the other, providing a flow of electricity.

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Figure 1: Photovoltaic Cells in a Solar Panel

When solar panels first came out around 1977 the price for the electricity they produced was about $76.67 per watt, but as of 2013 solar costs about $0.74 per watt (according to Clean Technica) which makes solar a much better investment today.

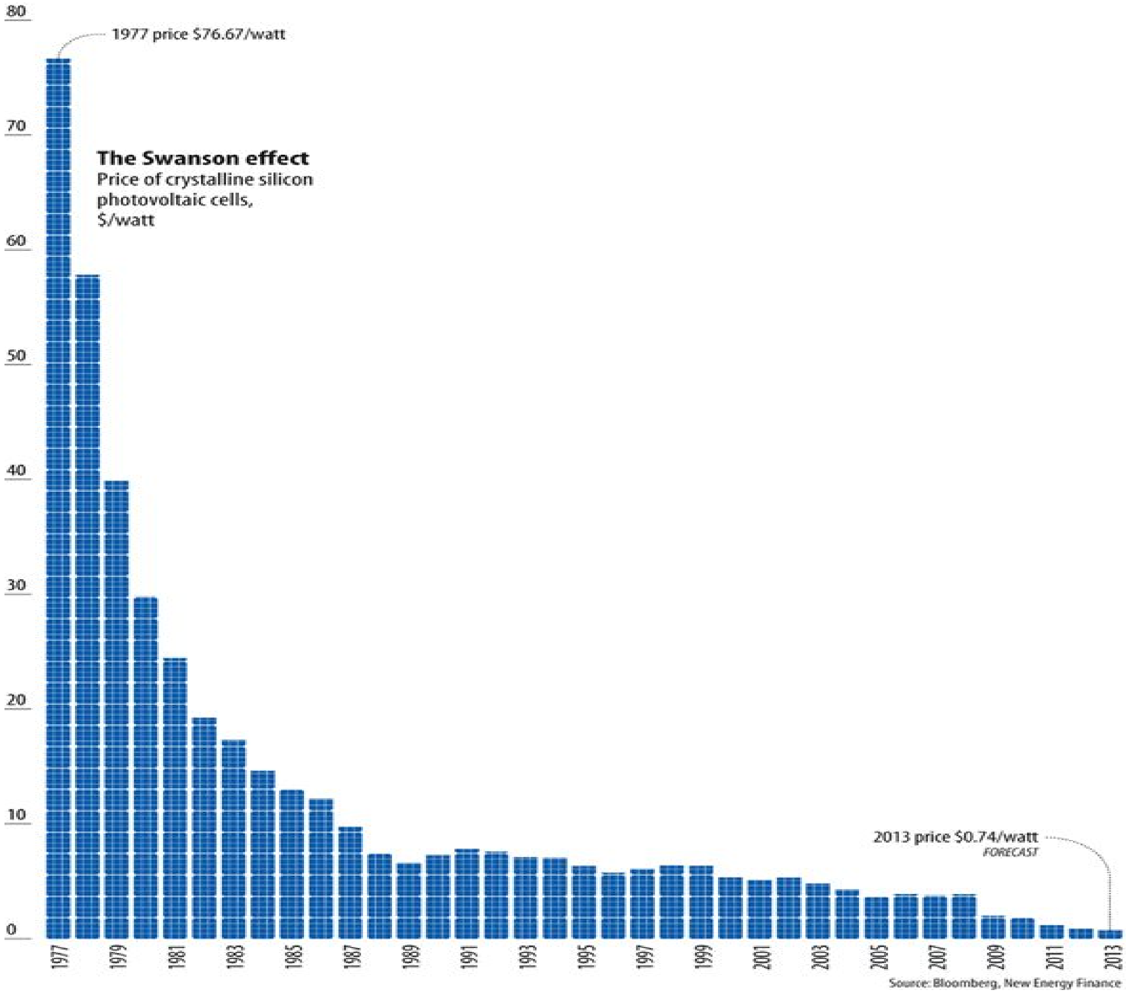


Figure 2: Cost Trend of Solar Power

To really get the most out of a photovoltaic system, an energy storage system can be used to capture the energy that is generated by the photovoltaics. By doing this, the energy can then be stored and either sold back to the electric company if it is not used, or the energy can be used during peak hours and be replenished the following day. The benefit of using the energy during peak periods of electricity usage is that the customer can typically pay less for electricity than they normally would be if they were taking power from the grid. In both cases the resident or business saves money compared to the usual practice of relying entirely on the grid for power consumption.

Our project is a system that integrates both photovoltaic and grid-based power. The product will have an inverter and high-capacity batteries mounted on a mobile platform so that the energy can be used in different locations, or to power systems that cannot be turned off. EIBS in general will allow customers to save money by running off of battery power during peak electricity hours, but in our case we hope to use the system primarily as an education and research tool.

2. Overview of Customer Need:

With the usage of renewable energy becoming more and more prevalent, a method for storing excess power generated via renewable sources is an obvious next step. Without a storage system, customers with solar panels are forced to rely on grid power during the evening, or when weather restricts daylight hours. A storage platform enables the user to save money and stay self-reliant under a variety of adverse conditions. In addition, our system focuses on portability, with the inverter and batteries able to be transported separately and easily for testing in multiple locations. This allows users the ability to transport a power source directly to the electronics to be powered without having to attach the system to the building's internal wiring and the grid.

3. Project Description:

Our system will consist of the Tabuchi Electric EIBS Hybrid Inverter and Storage Batteries mounted to a portable skeleton and it will be wired for use in pulling from a DC or AC power source, such as a solar array or the grid. Our system will take a DC input of 70-550V or an AC input directly off the grid, store the power in two 9.89kWh batteries, and return the power at the standard 120/240V, 60Hz. Via the control panels, power can be inputed or distributed on command, either in on-grid operation or running as a stand alone system. Finally, if setup and installation goes smoothly, we plan to measure capacity, charge and discharge rates, and storage efficiency. However, after reaching the final step of testing the system we found that it had to be plugged into both a DC power source and the AC grid for the batteries and inverter to function. Due to running out of time we were unable to test the system fully but we were able to confirm that it was wired correctly and that the inverter and batteries turn on.

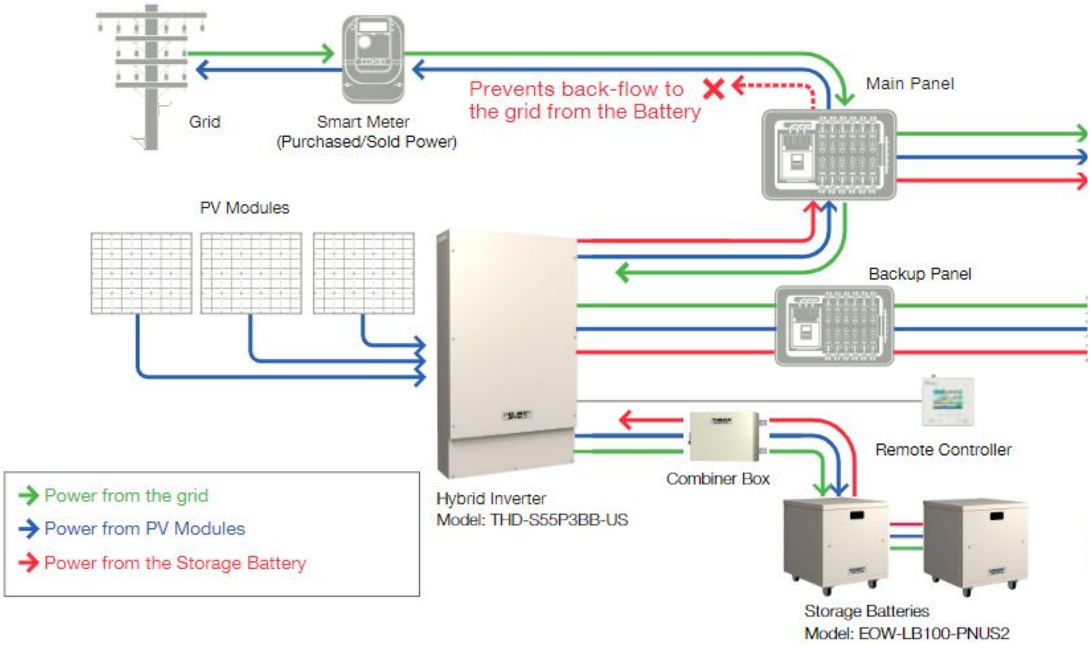


Figure 3: Tabuchi Diagram of EIBS16GU2 Energy Flow

The project is mobile, with the batteries and inverter mounted separately. With this setup, they can be transported to any accessible site and allowed to charge, then moved to a secondary location for usage. This is accomplished with quick attach-detach cables that interconnect the separate parts. The important thing to note about the Tabuchi system is that when attached the grid, power will not be allowed to flow back to the grid. If power were able to flow back to the grid then we would have to get certified technicians to set the system up for us, but luckily this is no problem and we can hook to the system to the grid without having to worry about sending power back.

4. Market Research:

The Tabuchi system available for use is approximately 20 kWh in energy capacity and includes an inverter, battery connection box, remote controller, and a ten year warranty. The invoice accompanying this product lists the sale price to Cal Poly as $12,000. The Tesla Powerwall is the direct competition of Tabuchi Electric's EIBS, with a prominent presence in North America. Looking at the current iteration of Tesla's website, a single powerwall unit has a capacity of 13.5 kWh, includes an inverter, has a 10 year warranty, and can be expanded using multiple connected units. Tesla only sells the powerwall as a set of two for $13,400 with $1,100 of supporting hardware required for a total cost of $14,500. Costs of $12,000/20 kWh and $7,200/13.5 kWh for Tabuchi EIBS16GU2 and Tesla Powerwall, respectively, equate to $600/1 kWh for Tabuchi and $533.33/1 kWh for Tesla. In the North American market there is no competition in name recognition between the two, other companies with name recognition like LG are releasing similar systems in 2018/2019. Tabuchi might have less name recognition with an everyday consumer such as a resident, but for the purposes of this project the EIBS will provide useful information on how these systems operate. We learned later in the project that

Tabuchi USA was ceasing operations but the company still works and we were able to contact them with any questions we had while wiring and powering up the system.

5. Customer Archetype:

This P.V. hybrid inverter system that we are assembling has many competitors that have similar products making the market a lot harder to enter. However, our idea of making it a mobile power system is an idea that has not previously been marketed by other companies. The customers that may be interested in this include: Residential Housing, Small Businesses, and Educational Facilities.

Table 1: Customer Archetype

	Description	Reason	Product Use
Residential Housing	This will be a large archetype target. Solar is growing in popularity and many people are investing.	Due to the falling cost of alternative energy solar is more popular than ever and with the additional backup battery system our option may be even more enticing to the average person.	Our system will be used by the average person at their house. The solar panels will save them money on electricity while the battery backup will keep essential things powered in the case of a power outage.
Small Businesses	These are businesses that don't have a lot of infrastructure but have essential systems that need to be on for their business to operate.	By having a battery storage system that will give power in the event of a power outage, small businesses will be able to continue operations and make money instead of being forced to close and missing out on potential revenue.	The system will power the small business at any time the power goes out. Saving them money by charging with solar and keeping the business operational when other competitors may have to close.
Educational Facilities	School campuses need power to operate on a day to day basis. In this day and age technology is often needed to teach effectively.	Schools have many tools to educate students effectively. When these systems go down unexpectedly often times the students will not actually learn everything that was planned for the day and fall behind.	The solar will charge the batteries without having to tend to them, so when the power goes out all of the computers, projectors, and internet will stay active and available so the students can learn effectively.

It is important to note that after testing the system the end user will have to have the system hooked to both a DC source and an AC source for the system to function properly. Further testing may reveal that once set up we will be able to move the system and discharge the batteries somewhere else.

6. Market Description:

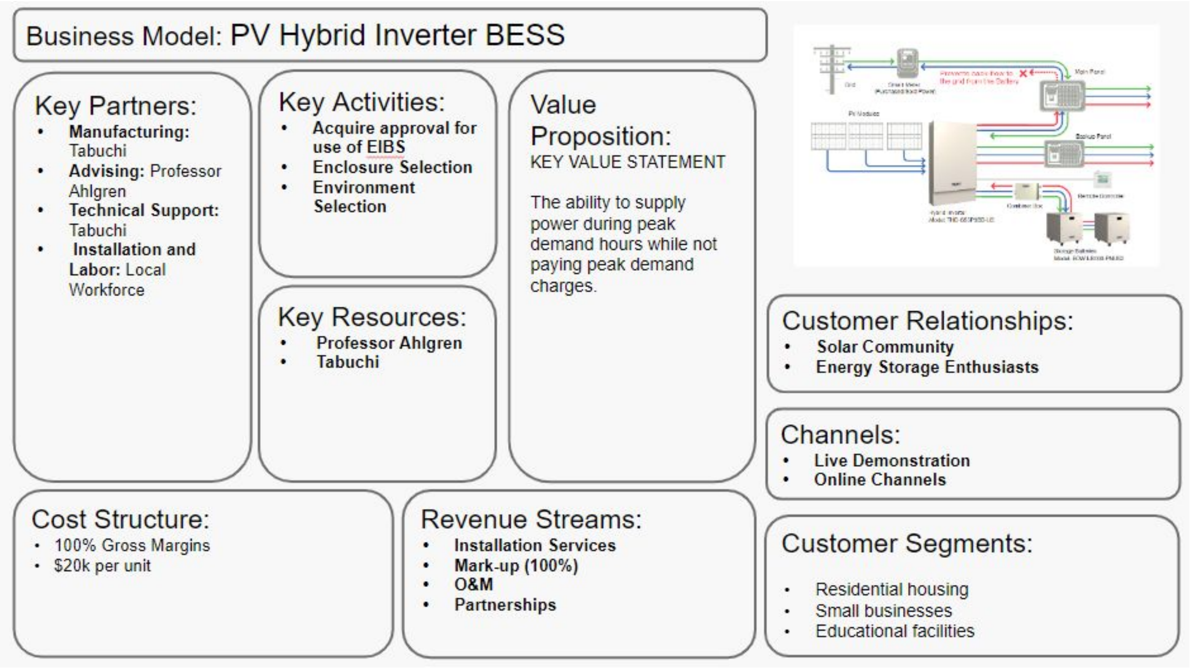
The energy storage market is beginning to emerge in parallel with the economizing of residential-scale solar arrays and the increasing portability of battery-based storage. Companies like Tesla are thrusting themselves into to the public lens of progress. Energy storage technology has thus spent its fair share of time in the recent limelight. In the wake of Hurricane Maria, Elon Musk and Tesla associates oversaw installation of backup power reserves in Puerto Rico. This is one of the first large-scale implementations of residential-level battery storage, and demonstrated the utility of these systems when residents equipped with Tesla Powerwalls were able to retain power through a recent island-wide blackout according to Electrek.com. At Cal Poly there is also large PV panels on 18.5 acre piece of land west of the Cal Poly campus. The PV panels on this land generate 4.5 megawatts of power which is 25% of Cal Poly's needs. This PV system also has environmental benefits and has saved Cal Poly about $10 billion on utility bills over the last 20 years. It is important to also mention that in 2020 every new home that is built in the state of California will be required to be built with solar panels, making our system more viable than ever before.

From this and other examples, we can glean how energy storage will eke its way into the market in the coming years. As it stands, an ever increasing number of people are looking to add storage capabilities to their homes. This is caused by a multitude of trends; the willingness to reduce carbon footprints, the desire to reduce energy expenditure costs, and for sustainability in case of disaster. As an emerging field of technology, this can be capitalized as such. A feasible and very practical business model can be formed around the energy storage market.

In new studies, methods of utilizing quick-response energy storage are being developed and economized. Until recently, the only viable and established way to sell back energy to the grid was to gather and immediately sell energy during the day, if not being used. Similarly, as large-scale (ie, city-wide supply) renewable energy sources become ubiquitous, so too do the problems they introduce. Solar and wind power in particular are vulnerable to inclement weather. If a given day has lower than expected wind velocity, or is unexpectedly cloudy, the power for an entire region may be compromised. It is in this regard that the nature of the daily energy producing, buying, and selling market is changing; unfettered access to surplus energy in the form of distributed storage has proven to be a solution to a power grid that has low inertia.

The market for commercial and residential energy storage is large, and rapidly growing. According to Mordor Intelligence, in 2017 about 1,315 energy storage projects were operational with a global installed energy storage of around 176 GW. This figure has continued to climb at an astounding rate in the US, with a 46% year-on-year growth rate for energy storage systems from 2016 to 2017. This means that demand is high for our product and others like it.

7. Business Model Canvas Graphic:



Business Model: PV Hybrid Inverter BESS

Key Partners:
- **Manufacturing:** Tabuchi
- **Advising:** Professor Ahlgren
- **Technical Support:** Tabuchi
- **Installation and Labor:** Local Workforce

Key Activities:
- **Acquire approval for use of EIBS**
- **Enclosure Selection**
- **Environment Selection**

Key Resources:
- **Professor Ahlgren**
- **Tabuchi**

Value Proposition:
KEY VALUE STATEMENT

The ability to supply power during peak demand hours while not paying peak demand charges.

Customer Relationships:
- **Solar Community**
- **Energy Storage Enthusiasts**

Channels:
- **Live Demonstration**
- **Online Channels**

Cost Structure:
- 100% Gross Margins
- $20k per unit

Revenue Streams:
- **Installation Services**
- **Mark-up (100%)**
- **O&M**
- **Partnerships**

Customer Segments:
- Residential housing
- Small businesses
- Educational facilities

Figure 4: Business Model Canvas

8. Marketing Requirements:

One benefit in the development of energy storage is that is is almost entirely modular, and near infinitely scalable due to the ability to continue adding batteries for additional storage. The same principles apply at either a residential, industrial, or national level. Each stage requires satisfaction of the same standards: interaction with the power grid, interaction with other electrical products, and interaction with a Photovoltaic system. With this mindset in place, we can begin to start small with our model, a portable and interchangeable merging of inverter and batteries. Designing a simple, residential-scale, proof of concept product will allow us to expand into either a market of larger scale technology, or wider distribution.

This begs two of the most critical questions when engineering a product- how big is it? And how much will it cost? Luckily for us, here at Cal Poly we have a large surplus of unused PV supplies on-site. Each Sunpower 435 panel is four feet wide, by six feet long, and ideally we could gain access to these resources at a low cost. Access to these supplies would bolster the resilience of the system, in addition to reducing up-front developmental costs. To start, we will try to spec an approximate size of the panel array, and compare that to the time it would take to charge the Tabuchi energy storage system using N number of panels.

Table 2: Number of Panels in Configuration and Relevant Metrics

Number of Panels	Output Voltage (V)	Output Current (A)	Power (W)	Charge Time (Hrs)
2	72.9	10	729	27.43484225
4	145.8	10	1458	13.71742112
6	218.7	10	2187	9.144947417
8	291.6	10	2916	6.858710562
10	364.5	10	3645	5.48696845

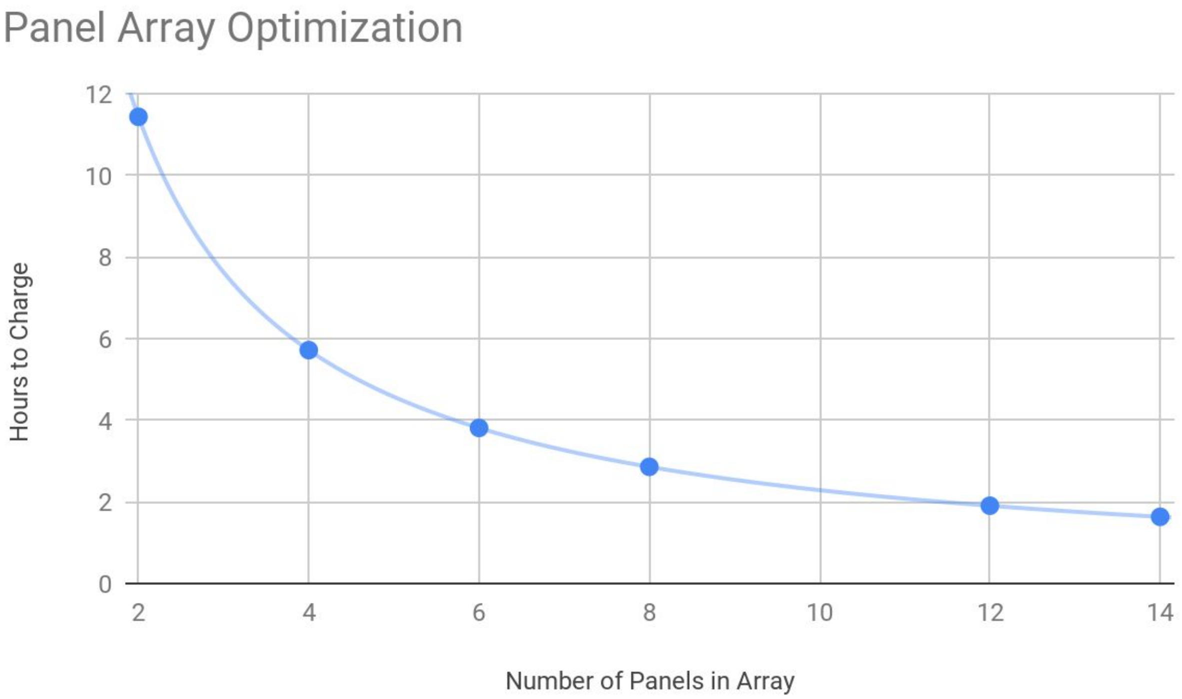


Figure 5: Graphical Representation of the Number of Panels in PV Array vs Charge Time

Minimum viability is reached around four panels if we want to meet the full charge cycle per day threshold. Ideally, six or eight panels should be implemented into this project, to account for inclement weather, and allow for rapid power cycling of the system.

9. Block Diagram:

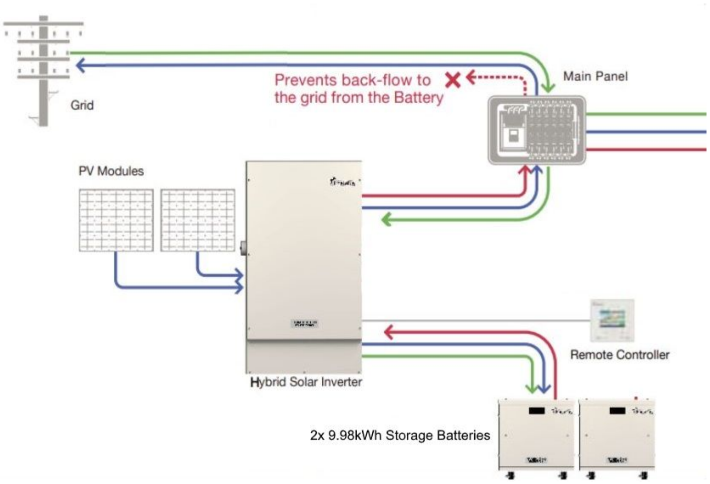


Figure 6: Block Diagram of How the Tabuchi System will be Implemented

Our project centers on the Tabuchi Hybrid Inverter (Seen center). This can be input either AC grid power, or DC power from a PV array. From the inverter, the power will be transferred to the storage batteries, mounted separately for ease of mobility. The batteries can then be transported to wherever the power is needed.

10. Requirements:

Table 3: Requirements

Requirements	**Method**	**Justification**
Portability	The Inverter and Batteries will be mounted on seperate mobile rigs	Mobility will allow power to be delivered to wherever it is most needed
Charge/Discharge Rate	An array of 8-12 PV panels will allow for a charge/discharge cycle in the course of one day	The system must be able to charge and discharge in a day to be useful in future applications
Flexibility	The system will be able to draw power from either grid or solar sources	With a choice of sources, the system will provide a variety of testing options
Capacity	Two Lithium-ion batteries will provide 19.96kWh of storage	High capacity storage is needed in order to perform future tests with the system

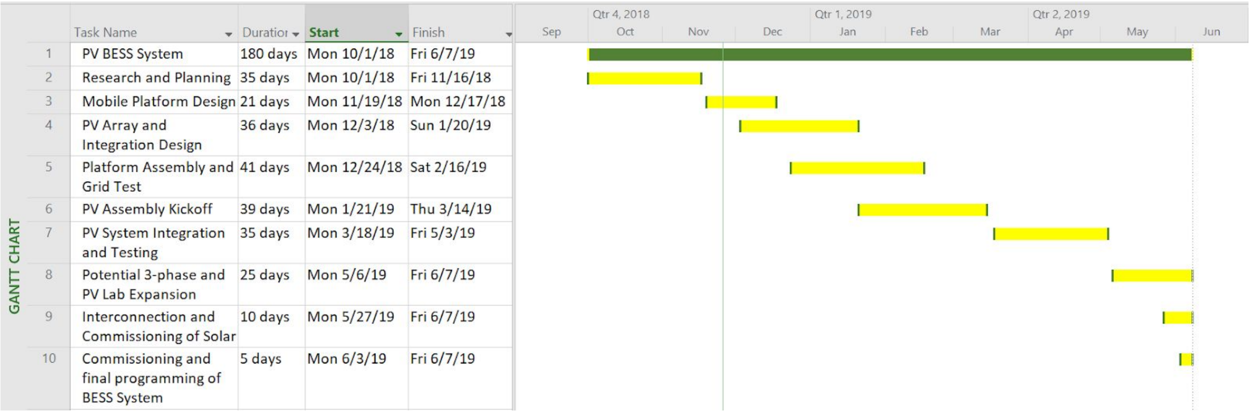
11. Cost Analysis:

Table 4: Bill of Materials

Senior Project: PV Hybrid Inverter BESS
TEAM: Will Dresser, Owen McKenzie, Derek Seaman, Jacob Sussex, Jonathan Wharton
DATE/REV: DEC 7, 2018 VERSION V1.0

Sub	Sub	Sub	Sub	Description	Qty	P/N	Document	MFG	MFG P/N	USA 1pcs Price (USD)	Foreign 1pcs Price (convert)
Box Build - Model XYZ - Retail Configuration							Custom	Custom	--		
1	Final Assy - Unit PV Hybrid Inverter BESS					1000	Custom	Custom	--		
	1	Main Mobile Storage Assy				1100	Custom	Custom	--		
		1	Tobuchi EIBS		1	1110	Spec	Tobuch	EIBS	14500	16900
			1	Battery Units, 10 k	2	1111	--	--	--		
			2	Hybrid Inverter Un	1	1112	--	--	--		
			3	Control Panel	1	1113	--	--	--		
			4	Polymer Mounting	4	1114	--	--	--		
		2	80/20 Framework Set		1	1120	Spec	80/20	TBD	250	300
			1	Linear Railing, 4"x	50 ft	1121	--	--	--		
			2	90 Degree Interior	20	1122	--	--	--		
			3	Rivetting Connecto	75	1123	--	--	--		
			4	Linear End Caps	10	1124	--	--	--		
		3	Castor Wheels, 6" DIA			1130	Spec	TBD	--		
	4	Rooftop PV System				2100	Custom	Custom	--		
		1	SunPower 4'x6' Solar Panels		10-Jan	2110	Spec	SunPower	435	300	450
		2	80/20 Framework Set		1	2120	Spec	80/20	TBD	250	300
		3	3 AWG Wire		50 ft	2130	Spec	TBD	TBD	0.1	0.11
										17555	20655.5
								If made in USA	0.5hrs x $40/hr	20	2.5
								If made in Foreign	0.5hrs x $5/hr		
								Product Shipping leadtime		1	8
										17576	20666

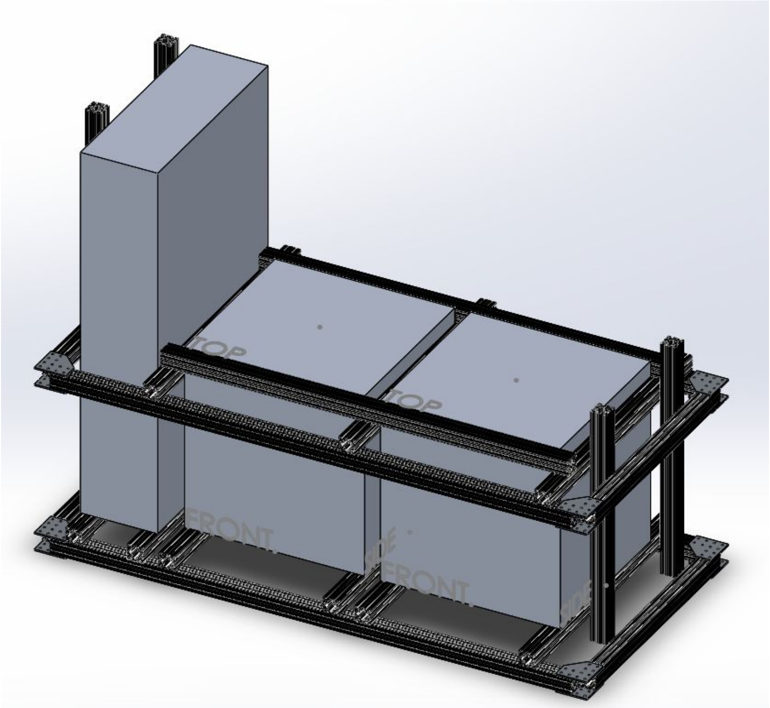
12. Team Coordination:



	Task Name	Duration	Start	Finish
1	PV BESS System	180 days	Mon 10/1/18	Fri 6/7/19
2	Research and Planning	35 days	Mon 10/1/18	Fri 11/16/18
3	Mobile Platform Design	21 days	Mon 11/19/18	Mon 12/17/18
4	PV Array and Integration Design	36 days	Mon 12/3/18	Sun 1/20/19
5	Platform Assembly and Grid Test	41 days	Mon 12/24/18	Sat 2/16/19
6	PV Assembly Kickoff	39 days	Mon 1/21/19	Thu 3/14/19
7	PV System Integration and Testing	35 days	Mon 3/18/19	Fri 5/3/19
8	Potential 3-phase and PV Lab Expansion	25 days	Mon 5/6/19	Fri 6/7/19
9	Interconnection and Commissioning of Solar	10 days	Mon 5/27/19	Fri 6/7/19
10	Commissioning and final programming of BESS System	5 days	Mon 6/3/19	Fri 6/7/19

13. Design Iterations and SolidWorks

Our first thoughts on designing a cart can be found in appendix B of this report. In this appendix we mention that we wanted to design two separate carts, one for the batteries and one for the inverter, due to better mobility and cheaper cost. However, looking further into this design we decided to resort back to the single cart design because the design would be cheaper and the batteries and inverter could remain hooked together making it easier to use. The first designs of this cart were constructed using 8020 as the building material. The designs for the first iteration cart are shown in Figure 7 and Figure 8. The two batteries are located in the front of the cart while the inverter is attached to the rear of the cart. The second layer of the cart is used to keep the batteries and the inverter stationary while the cart is in motion.



Figure; 7: First Iteration of 8020 Cart in SolidWorks

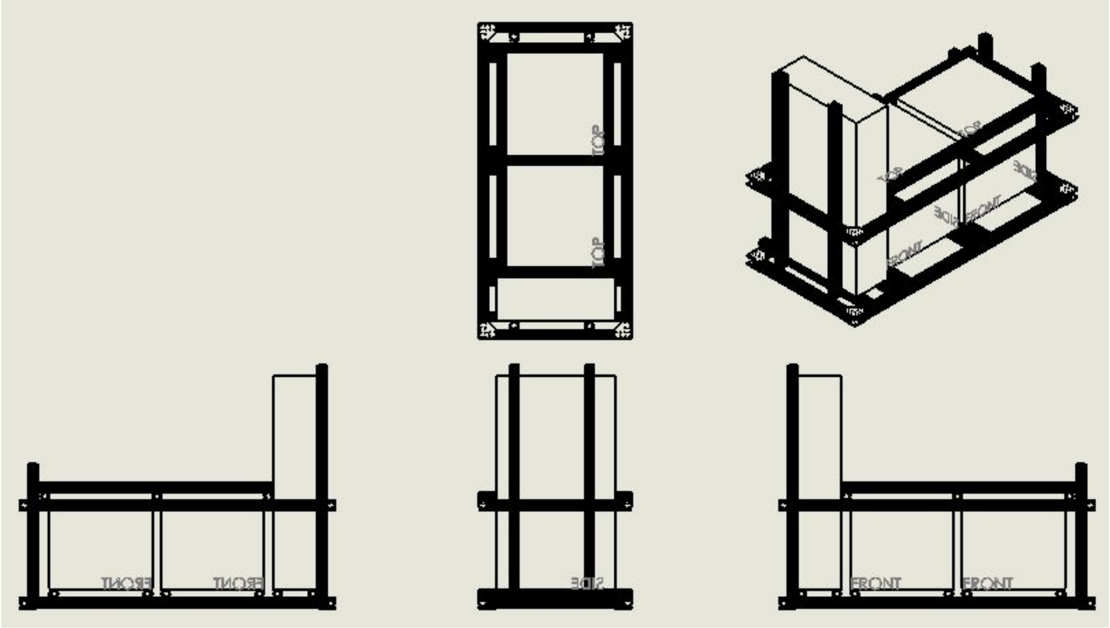


Figure 8: 2D CAD View of First 8020 Cart Design

After looking at our available budget to build the first iteration cart made of 8020 we decided that it would be too costly and looked to different building material options. After talking with Professor Alhgren about what materials might be useful he suggested Unistrut. Unistrut is a similar like beam construction material like 8020 but it is made of steel instead of aluminum. Looking at the cost of Unistrut it seemed like it would be within our budget to build the cart with Unistrut but in order to make the cart lighter we would have to use the thinner version of the Unistrut. To ensure that the thinner beams could withstand the heavy batteries and inverter, synthetic stress tests were performed on the material in SolidWorks. These stress tests showed us that the thinner Unistrut beams would in fact be able to withstand the weight of the batteries. In light of this we decided to rebuild our cart design in SolidWorks using the Unistrut material. The second iteration cart design made of Unistrut is shown below in Figure 9. It has the same general design as the first iteration but utilizes the new material.

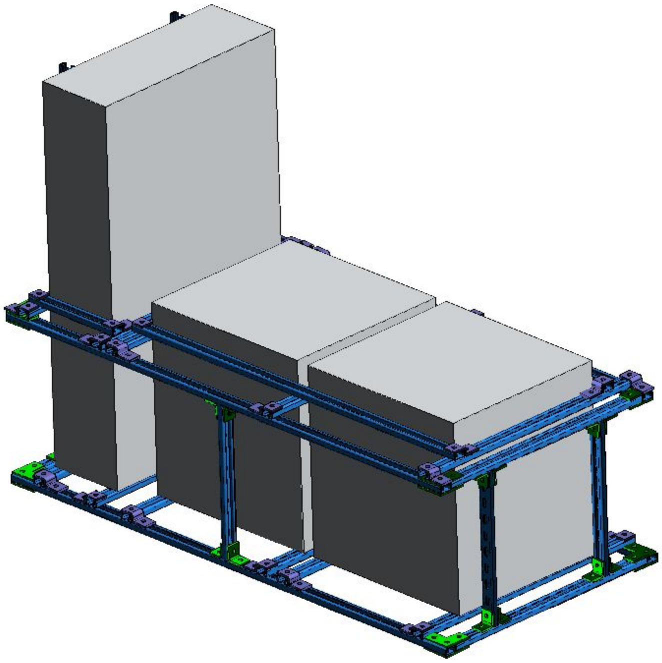


Figure 9: 2nd Iteration of Cart with Unistrut

Our first concern when designing the cart with the Unistrut was that we feared it would not work out as nicely as the 8020. The Unistrut only has two faces in which fasteners can be used to attach it while all four faces of the 8020 could be used to fasten to. However, we were able to make a design that required no drilling into the side of the Unistrut which alleviated these concerns. Our next concern was how easy it was going to be to access the inverter if need be. To fix this problem, we considered how the inverter was designed to be mounted to a wall, so to fit it onto the cart and make it accessible we needed to mount it to our own pseudo wall on the cart. The third and final iteration of our cart design is shown below in Figure 10.

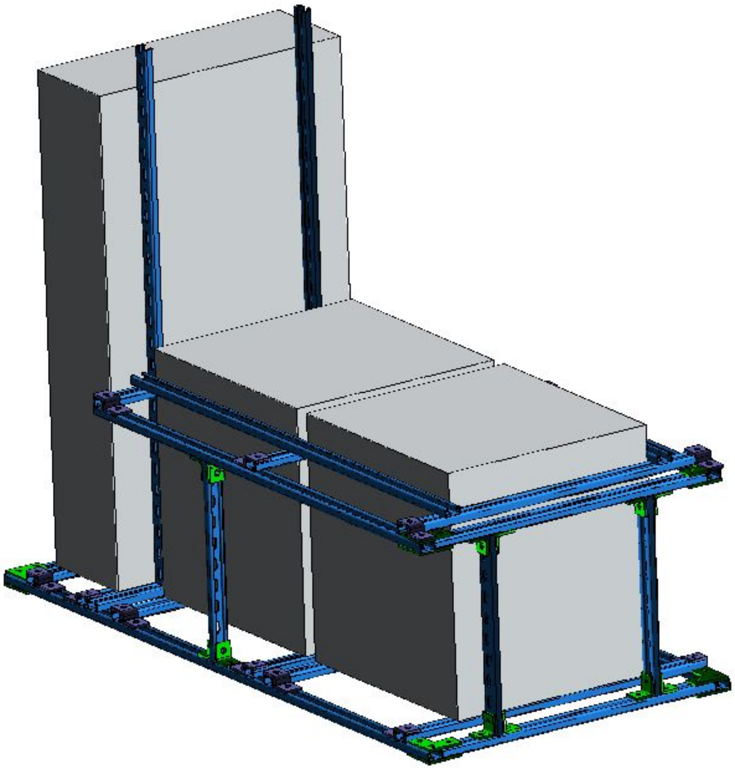


Figure 10: Final Cart Design

All of our cart designs were created using a program called SolidWorks that is readily used in industry and is also available for free to Cal Poly students who can download the software through the Technical Service Request tab of the Cal Poly Portal. The first step when designing the carts was going to the 8020 and Unistrut websites where 3D CAD files can be found for each part that we desired. All of the part files were found relatively easily in the technical section of each part. Each part was then loaded into SolidWorks and cut down to the appropriate size that we needed in each design. Next, an assembly had to be built in SolidWorks. An assembly in SolidWorks is a file that consists of different part files that have been assembled and mated together in a certain way. It is also important to note that when opening an assembly file, the computer used must have all the individual part files downloaded as well. Once the assembly file had been created, the part files that were modified to be the correct lengths are then added to the assembly. To join the parts in the correct orientation that is desired the mate tool is used. The mate tool connects faces and edges of adjacent parts together so that they may become fully defined in the assembly. This process of loading in parts and mating them is then repeated until the final design is created.

For the materials we used we also used the stress testing tool in SolidWorks to ensure the material we were using could withstand the weight of the batteries and the inverter. This is done by loading a part into SolidWorks and choosing points to fix in space. These points will be on the end of the part in our case because this is where the Unistrut beams will be attached to the rest of the cart. Finally, The stress must be added to the system and for our project the stress of the batteries would be in the middle of the beams. The stress that was added was equivalent to the weight of the batteries plus a little bit more just in case somebody wants to sit on the cart or something like that. The stress test showed us that the material may flex a little bit with the weight of the battery but would ultimately be able to withstand the force.

Table 5: Budget for Unistrut Cart Design

Item Name	Part Number	Manufacturer	Description	Cost per Unit	# Units	Total Cost	Purchase Link
Unistrut Based Cart							
HHXN - Hex Nut	HHXN050	Unistrut	Hex Nut		150		https://www.unistrut.us/product-details/hhxn
P1026 - 2 Hole, 90 degree Fitting	P1026 (Cheapest Material)	Unistrut	2 Hole "L" Bracket		20		https://www.unistrut.us/product-details/p1026
P3045 - 2 Hole, "Z" Shape Fitting	P3045	Unistrut	2 Hole "Z" Bracket		18		https://www.unistrut.us/product-details/p3045
P1036 - 3 Hole, Flat Plate Fitting	P1036	Unistrut	3 Hole, Flat Plat Fitting		16		https://www.unistrut.us/product-details/p1036
P3300T - 1-5/8" X 7/8", 12 Gage, Slotted	P3300T (Cheapest Material)	Unistrut	1-5/8" X 7/8", 12 Gage, Slotted (20')		4		https://www.unistrut.us/product-details/p3300t
HHCS - Hex Head Screw	HHCS05009415/16EG	Unistrut	Hex Head Screw		150		https://www.unistrut.us/product-details/hhcs
P3006 Channel Nut	P3006	Unistrut	Inter-channel bracer		125		https://www.unistrut.us/product-details/p3006-thru-p3013
Spacer Bracket	P1062	Unistrut	.25" Spacer		2		https://www.unistrut.us/product-details/p1062-thru-p2490

Table 6: Budget for 8020 Cart Design

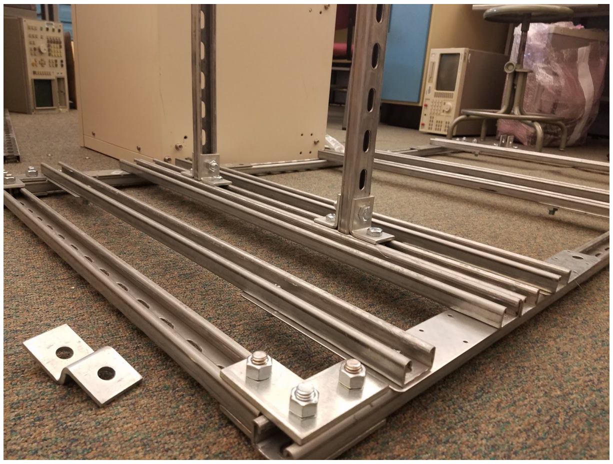
8020 Based Cart							
2.00” X 2.00” T-Slotted Profile - Eight Open T-Slots	2020	80/20 Inc.	Aluminum Structure (8X 102")	$0.57	816	$465.12	https://8020.net/2020.html
2.00” X 2.00” T-Slotted Profile - Eight Open T-Slots	2020	80/20 Inc.	Aluminum Structure (1X 38")	$0.57	38	$21.66	https://8020.net/2020.html
10 Series 8 Hole - Inside Corner Bracket	4114	80/20 Inc.	8 Hole Inside Corner Bracket	$5.35	30	$160.50	https://8020.net/4114.html
10 Series 4 Hole - Wide Inside Corner Bracket	4113	80/20 Inc.	4 Hole Inside Corner Bracket	$4.05	34	$137.70	https://8020.net/4113.html
Bolt Assembly: 1/4-20 x .500" Black BHSCS	3393	80/20 Inc.	Bolt Assembly for Corner Bracket	$0.40	504	$201.60	https://8020.net/3393.html
10 Series Flange Mount Caster Base Plate	2418	80/20 Inc.	Caster Mount Base Plate	$15.75	4	$63.00	https://8020.net/2418.html
Bolt Assembly: 1/4-20 x .500" Black SHCS	3491	80/20 Inc.	Bolt Assembly for Caster Mount Base Plate	$0.37	16	$5.92	https://8020.net/3491.html
10 Series 12 Hole - 90 Degree Angled Flat Plate	4128	80/20 Inc.	Plate for Attaching Corners of Cart	$10.80	16	$172.80	https://8020.net/4128.html
Estimated Subtotal	$1,228.30						

Table 7: Budget for Electrical Components

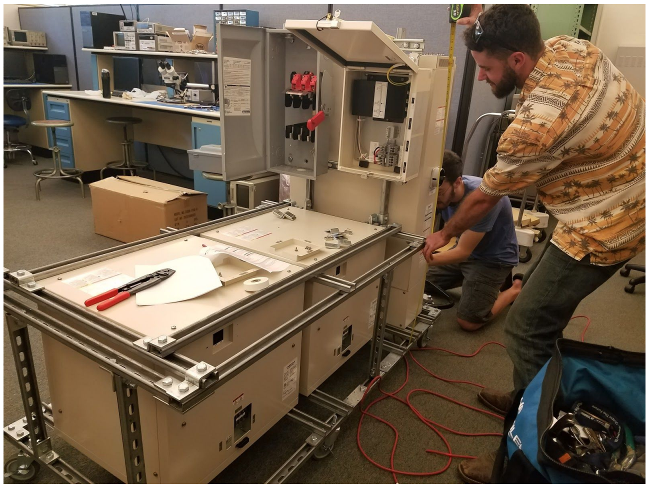
Cables and Additional Connections							
8 AWG Wire, 100ft	20488302	Southwire	8 gage cabling used to connect the inverter	$45.97	2 Spools	$91.94	https://www.homedepot.com/p/Southwire-100-ft-8-Black-Stranded-CU-SIMpull-THHN-Wire-20488302/202519272
8 AWG Ring Terminal	15-095	Gardner Bender	Connections for 8 AWG wire	$3.34	3	$10.02	https://www.homedepot.com/p/Gardner-Bender-8-AWG-1-4-in-Tab-Ring-Terminal-Vinyl-Red-5-Pack-15-095/205846740
100 Amp 240-Volt Fusible Disconnect	TG3223R	GE	Disconnect box preventing inverter damage	$96.11	1	$96.11	https://www.homedepot.com/p/GE-100-Amp-240-Volt-Fusible-Outdoor-General-Duty-Safety-Switch-TG3223R/202978656
20 Amp 250 Volt Fuzetron Fuse	FRN-R-20	Cooper Bussmann	Protects the inverter from current over 20A	$5.47	2	$10.94	https://www.homedepot.com/p/Cooper-Bussmann-20-Amp-250-Volt-Fusetron-HD-Time-Delay-Cartridge-Fuse-FRN-R-20/100188109
					WIRING SUBTOTAL	209.01	

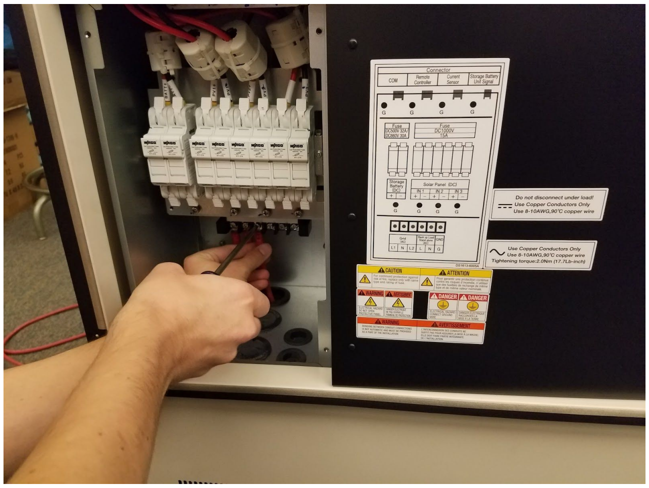
14. Assembly Iteration and Challenges

We began our construction with four 20 foot beams of 12 Steel Unistrut which we then cut down to size to match our CAD design. Each piece was measured and cut with a miter saw rented from the Cal Poly machine shop. From there, each piece was transported back to building 20, where they were laid out and categorized for assembly. Assembly began with the baseplate ring, which would serve as the bottom supporting structure for the remainder of the cart. Utilizing ½ inch bolts as well as a series of adapter plates and spring-locking channel nuts the unistrut could be easily fitted together. From this base, uprights were constructed to hold the second layer and caster wheels were fitted to allow for our desired mobility. However, upon completion of the second layer we met our first obstacle. The heads of the bolts inserted into the channels of the unistrut were too bulky to be reached by a ratchet or wrench. As such, these bolts were only able to be tightened minimally with pliers. Being unsatisfied with the unstable result, we set about performing an almost entire rebuild. This required us to drill through some parts of the Unistrut to enable the use of bolts that would travel through the entire structure and allow us to put more torque on the bolts when



tightening them. Moving past this issue, we mounted the batteries, and secured them via the second layer's ring. We began to mount the inverter as well, but again ran into a snag. We had previously thought that the two upright bars would be strong enough to support the inverter and prevent tipping, but we felt as though this design may not hold up under repetitive relocation. Using L and S brackets, we affixed the upright bars to our second layer, causing the cart to be much more stable overall. Next, we mounted the DC disconnect and connection box to the rear of the inverter, utilizing open space as efficiently as possible. This was a challenge, as the devices had differing space requirements and wiring methods to consider. Once all of the peripherals were mounted to the cart, we started on the wiring. We cut our measured wire to size, with 25 feet being dedicated to each of the three grid-tied connections. The remainder of the wire was used to interconnect the system. We ran the 25 foot length wire first, using Hampden plug heads on one end and connecting the other to our DC disconnect. The disconnect (With three 20 Amp fuses installed) was then wired to the 240V split phase input of inverter by way of crimped ring terminals for easy connection/disconnection. After this, we completed the interconnection by wiring the batteries to the inverter via the





connector box using 10 gauge wire. Finally, we interconnected the batteries, inverter, and two current monitors to the control panel, allowing the entire system to be controlled simultaneously.

15. Project Significance and Applications

This project is centered around a battery-based storage system or BESS. This BESS is designed for a consumer as a DC-coupled solar energy storage system, which consists of two 10 kWh, 86 V batteries, a grid-tie or standalone inverter, and some control electronics. These nature of these control electronics allows for this group to manipulate the operation of the BESS to suit the needs of this Senior Project.

The BESS is capable of operating on its own as an islanded system and operating as a grid-tied DC to 240 V split-phase system. Both of these generalized operational modes are useful to this project and the ability to island is essential to the predicted uses of this system. There are more details to these operational modes, but it is important to note that the BESS is capable of charging on AC and DC, and discharging via AC.

The Tabuchi BESS is capable of operating strictly as a standalone system, however this group wishes to use the system in conjunction with the Laboratory Voltage Distribution System (LVDS) for charging purposes. The BESS is potentially capable of absorbing, storing, and supplying power to the LVDS. As this project stands right now, the drawing of supplemental power from the BESS to the LVDS is not feasible. It is possible however to charge the BESS because the LVDS is capable of supplying the 240 V split-phase AC power that the BESS is designed to handle when operating in grid-tied mode. Once charged, the BESS would need to be disconnected from the LVDS and operated in standalone mode in order to discharge the stored energy through the user’s choice of load. The transition between modes of operation is achieved via the control panel of the BESS and the disconnection of the BESS from the LVDS is achieved in 20-102 by disconnecting the appropriate plugs, a similar activity is done regularly by students in the EE 295 and EE 444 labs.

The LVDS is an older system that was not designed with storage in mind. The Cal Poly Outdoor Solar Lab, an addition planned for the near future outside of building 20 of the Cal Poly campus, could feature infrastructure which could better incorporate the BESS as a storage device capable of supplying supplemental power. These features would need to be discussed with the appropriate authorities.

16. Peripherals

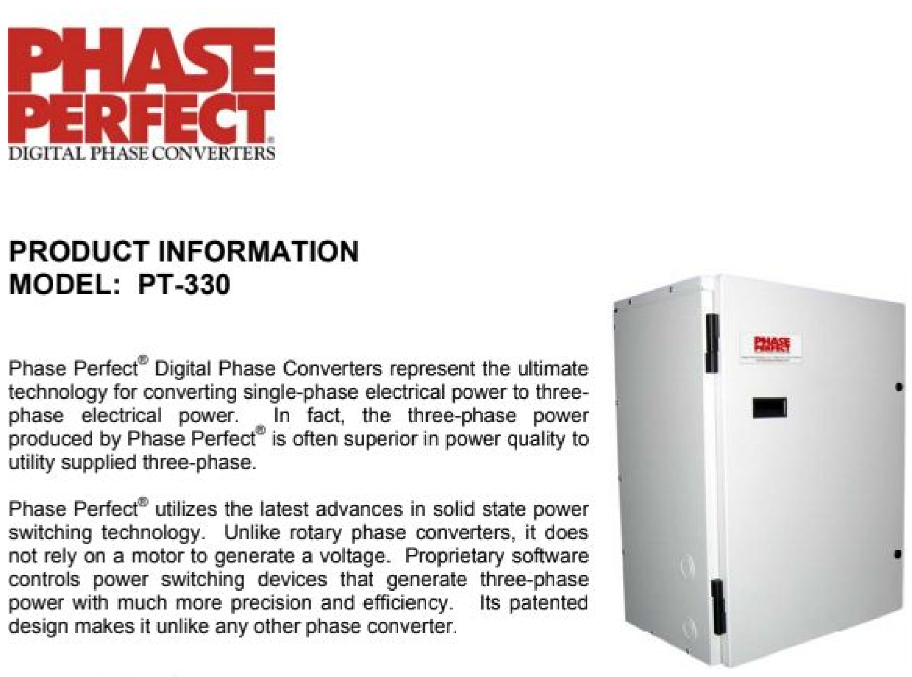
The main peripheral necessary at the time of assembly for this project was the addition of an AC disconnect box with 20 amp fuses inside. This was added in place of what would have been the inverter's connection to the residential electrical panel. The disconnect was deemed necessary in order to assure that the system could be safely disconnected from the source or load; the fuses inside the disconnect are to assure that if a fault were to occur within the system then the system's components as well as the connected load or charging system would incur minimal damage.

To make the AC connections for charging/discharging the system a set of 8 AWG stranded copper conductors were fitted with Hampden Engineering Co. plug connectors. These plugs allow the project to connect directly to the Hampden sockets on the wall of Cal Poly Building 20 Room 102, giving the system access to 240 V split-phase AC power.

There are a few options for expansion of this project with the addition of further peripherals. These peripherals were either inaccessible at the time of this project's assembly or were outside of the budget available to the project team at the time of this project's assembly.

The first not-yet-realized peripheral is the option to charge via solar panels which would require a DC connection to be wired into the inverter of the BESS. This is the hope of those professors who oversaw this project: that the BESS might be integrated into a solar-inclusive microgrid of some kind on the Cal Poly campus. Our team has circulated talk regarding a rooftop installation of an array of panels, to be fed into room 102, and take up space on the power wall. This allows for truly renewable, standalone DC power supplied to the BESS by simply maneuvering the cart into room 102 and connecting. Ben Johnson and other maintenance personnel at Cal Poly

Another set of peripheral options is the conversion of the system's AC connection from 240 V split-phase to 208 V three-phase power. The desire for this conversion was expressed by professor Ahlgren regarding the creation of a three-phase microgrid within Engineering East on the Cal Poly campus. This conversion would require two devices: a phase converter and a transformer. It is the belief of this group that the cheaper of the two possible setups for this conversion would be to transform 240 V single-phase to 208 V single-phase and then convert single-phase to three-phase. This addition to the system would be expensive but could allow for more learning opportunities regarding three-phase power which is still very relevant in today's power systems.



PHASE PERFECT
DIGITAL PHASE CONVERTERS

PRODUCT INFORMATION
MODEL: PT-330

Phase Perfect® Digital Phase Converters represent the ultimate technology for converting single-phase electrical power to three-phase electrical power. In fact, the three-phase power produced by Phase Perfect® is often superior in power quality to utility supplied three-phase.

Phase Perfect® utilizes the latest advances in solid state power switching technology. Unlike rotary phase converters, it does not rely on a motor to generate a voltage. Proprietary software controls power switching devices that generate three-phase power with much more precision and efficiency. Its patented design makes it unlike any other phase converter.

Figure 11 : Phase Converter to be Purchased in Future

17. Project Continuation

So far in this project we have completed the task of making the system mobile and power the system when tied to the “grid” when plugged into the 240 V split phase power coming from the wall in room 102. We have also managed to do all the wiring that connects the batteries to the inverter.

From this point moving forward, the biggest step that must be taken is either plugging the system into a PV array or equip more wires with Hampden plug heads so that we can interface the system into DC power from room 102 in order to bypass the need for a PV system. This must be done to set up the inverter and fully turn it on and have access to the batteries. When we powered the system on when it was only connected to the grid the system would not allow us to configure the converter or access the charge that was stored in the batteries. Once the batteries power can be accessed, what we do with that power would be up to the user. Our thought was that we should have a converter that can take the DC power that is output from the batteries and convert it into three phase power that could potentially be used in a EE lab in the future. Other options may be viable but this is the one that came to our minds.

One last change to our design that may be considered as well is the wheels that make the cart mobile. The only wheels that we were able to find that somewhat work have a single bolt that holds them in place. Due to the heavy weight of the batteries and the inverter, the wheels can have the tendency to lean as they only have a square washer to push against. If possible, heavy duty caster wheels with a standard four bolt plate might make a better alternative if possible to attach to the Unistrut.

As part of the future work for this project, studying the operation and the model of the PV-BESS system is of great importance. Three major areas can be divided into studying its control systems, inverters, and how the battery energy systems work together. High penetration of renewable energies in power systems brings opportunities such as zero emission but it can bring challenges too. The alternative nature of renewable energies unlike the conventional sources are keep changing which requires new controlling algorithms for having a stable power system. The first step before proposing new controlling algorithms, is to make sure that the comprehensive modeling of these systems are available (PVBESS in this case). Many efforts have been done in the literature in finding the detailed modeling of microgrids including the inverters [1] that can be used as a guidance for modeling of this system. New proposed controlling algorithm can now be applied to these models for evaluating their performance before applying on the real-world systems. However, since the number of power electronics components are increasing in the power system, the nature of the controlling methods are changing from the centralized methods to the one that does not rely much on just a single central node. These algorithms can be used among different microgrids to control the power systems' variables such as the voltage in the distributed mode [2]. In the future, in an effort to connect this Microgrid system to other parts of the Microgrid at CalPoly, we can investigate these methods and investigate their performance on controlling the voltages and frequencies.

Another important part of the future work that can be considered to be done is to analyze the cost benefit of this system. Since this PVBESS is connected to an alternative source (photovoltaics system), only gathering an enormous amount of information will enable us to do such an analysis. These data such as the temperature, humidity, cloud direction and speed, time of the day can be collected on a long term basis and then by using big data analytics given in [3], we can find a model that can give us the desired cost benefit analysis.

18. Department Future

As mentioned before, the hope of this project is to be expanded into the to-be-built Cal Poly Solar lab. This allows for standalone testing and off-grid analysis of power systems. Eventually, we hope the Tabuchi EIBS can be used as a storage platform in a class session that focuses on renewable energy. Of course, this means design and implementation of a PV array at the Cal Poly EE building is necessary. There are numerous administrative hurdles that need to be tackled prior to the realization of the system's full potential; large-scale solar projects have been attempted in the past, but have faced strong resistance from Cal Poly at large.

Expanding the power systems subdepartment has the potential to breathe new life into a somewhat dying class of Electrical Engineering. According to former IEEE Power and Energy Society president John McDonald, the average age for people working in the power sector of Electrical Engineering is ten years older than the average age of every other IEEE discipline. It is widely considered to be a relatively stagnant field of study; infrastructure is usually old, underfunded, and not as flashy as, say, electronics. However, with the Tobuchi system, we have the platform to show new Cal Poly students that, in fact, there is significant research and modernization occurring in the power sector. This realm of occupation which was historically seen as mundane, has now been recently introduced into the premier club of high tech. With new developments in smart grids, problems involving sustainability, protection, and economization can now be addressed on any scale. The chord which we hope to strike with the audience of Power Systems is that what has traditionally worked in power is phasing out. On the whole, we need ingenuity and new ideas, and the Cal Poly EE department is the perfect environment to foster that.

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Appendix A: Senior Project Analysis

Project Title: PV Hybrid Inverter BESS

Students: William Dresser, Owen McKenzie, Derek Seamen, Jacob Sussex, Jonathan Wharton

Adviser: Ali Dehghan-Banadaki

1. **Summary of Functional Requirements**

Our project makes the heavy Tabuchi Inverter and batteries that weigh over 700 lbs mobile and easy to move around to different locations in the EE building. It was designed to fit through doors and easily move in and out of different rooms. The final product will be able to be charged by the power in room 102 and then moved to a different location where the power from the batteries can be used to power labs, machinery, or anything that the user desires. The system will also be capable of charging from solar panels mounted on the roof of the EE building.

2.**Primary Constraints**

The biggest challenge that needed to be solved in this project was making the entire Tabuchi inverter and battery system mobile. This system weighs over 700 lbs and it was difficult finding a material that would be able to handle this much weight while also staying under our allocated budget for the project. The cart that was designed to mobilize this system had many design iterations due to this challenge. We looked at two main materials, 8020 aluminum beams and Unistrut, to build the cart. Once we decided on the material we had to design a cart that would allow the end user to access all the components for maintenance or repair in the future which was also challenging. After settling on a design we had to assemble the cart and cut all the material down to length. While assembling we had to improvise as we went because the design that was built in the computer did not work out exactly like we wanted in reality. Finally, figuring out how to correctly wire the system and do so in a safe manner was also very challenging. We had to flip through the user manual and use our own knowledge to complete the wiring correctly in order for the system to operate properly.

3.**Economic**

This system is manufactured by a company that recently went out of business called Tabuchi. It is a very expensive system as it is complicated to build and required many man hours of assembly and engineering design to manufacture. In addition to this the cart and the electrical components that were used to achieve our functionality requirements took time and money for companies to manufacture so that we could implement them in our design. The costs of this system during its lifecycle accrue during any maintenance that may be required due to normal wear and tear. There are also many benefits to this product during its lifecycle such as saving money using solar cells and battery backup during power outages. Below are the budgets for the cart and the electrical components that were used in the design.

Item Name	Part Number	Manufacturer	Description	Cost per Unit	# Units	Total Cost	Purchase Link
Unistrut Based Cart							
HHXN - Hex Nut	HHXN050	Unistrut	Hex Nut		150		https://www.unistrut.us/product-details/hhxn
P1026 - 2 Hole, 90 degree Fitting	P1026 (Cheapest Material)	Unistrut	2 Hole "L" Bracket		20		https://www.unistrut.us/product-details/p1026
P3045 - 2 Hole, "Z" Shape Fitting	P3045	Unistrut	2 Hole "Z" Bracket		18		https://www.unistrut.us/product-details/p3045
P1036 - 3 Hole, Flat Plate Fitting	P1036	Unistrut	3 Hole, Flat Plat Fitting		16		https://www.unistrut.us/product-details/p1036
P3300T - 1-5/8" X 7/8", 12 Gage, Slotted	P3300T (Cheapest Material)	Unistrut	1-5/8" X 7/8", 12 Gage, Slotted (20')		4		https://www.unistrut.us/product-details/p3300t
HHCS - Hex Head Screw	HHCS050094 15/16EG	Unistrut	Hex Head Screw		150		https://www.unistrut.us/product-details/hhcs
P3006 Channel Nut	P3006	Unistrut	Inter-channel bracer		125		https://www.unistrut.us/product-details/p3006-thru-p3013
Spacer Bracket	P1062	Unistrut	.25" Spacer		2		https://www.unistrut.us/product-details/p1062-thru-p2490

Cables and Additional Connections							
8 AWG Wire, 100ft	20488302	Southwire	8 gage cabling used to connect the inverter	$45.97	2 Spools	$91.94	https://www.homedepot.com/p/Southwire-100-ft-8-Black-Stranded-CU-SIMpull-THHN-Wire-20488302/202519272
8 AWG Ring Terminal	15-095	Gardner Bender	Connections for 8 AWG wire	$3.34	3	$10.02	https://www.homedepot.com/p/Gardner-Bender-8-AWG-1-4-in-Tab-Ring-Terminal-Vinyl-Red-5-Pack-15-095/205846740
100 Amp 240-Volt Fusible Disconnect	TG3223R	GE	Disconnect box preventing inverter damage	$96.11	1	$96.11	https://www.homedepot.com/p/GE-100-Amp-240-Volt-Fusible-Outdoor-General-Duty-Safety-Switch-TG3223R/202978656
20 Amp 250 Volt Fuzetron Fuse	FRN-R-20	Cooper Bussmann	Protects the inverter from current over 20A	$5.47	2	$10.94	https://www.homedepot.com/p/Cooper-Bussmann-20-Amp-250-Volt-Fusetron-HD-Time-Delay-Cartridge-Fuse-FRN-R-20/100188109
					WIRING SUBTOTAL	209.01	

The main person that will benefit from this product economical will be the customer. They will save money using this system because it will reduce their power costs and make it so they can power their home when the power goes out. However, there also exists an operating cost as this system must be tied to the grid and requires power to work.

This project overall took more time then we were initially anticipating. The part of the project that ended up taking the most time was the design and assembly of the cart as many options had to be considered. After this project we hope that more tests will be completed with the system by future senior project groups.

4. If manufactured on a commercial basis

If this product was to be manufactured on a commercial basis, there are many factors that would need to be taken into account. We hope to sell approximately the same number of these systems as there are houses built in the United States. This seems to be a good estimation because most new houses will be built with solar panels in the coming years. We also expect to sell some of these systems to be sold to schools as educational tools for students to learn about photovoltaics. Each mobile system will cost approximately $2,000 on top of the cost of the inverter and battery system.

5. Environmental

The biggest environmental impact that is associated with the manufacturing of this system is the manufacturing of the lithium ion batteries that are used. For example, building the battery for an electric car emits twice as many emissions as the production of a petrol vehicle. The mining of lithium also impacts the environment greatly. Many of the machines used to mine the lithium are powered by oil products that pollute the atmosphere with carbon emissions. The mining can also destroy natural resources and ecosystems that thrive around the area that is being mined. The system will ultimately improve the ecosystem and natural resources of residential areas but impact the ecosystems where the batteries are manufactured. Further, the species that thrive in the area where lithium is found will ultimately suffer from the mining that occurs due to the explosives used to blow away the earth and the machines that destroy the air quality.

6.**Manufacturability**

The biggest problem that we face when manufacturing our product is the construction of the cart. It is the biggest problem because it requires the most time in the manufacturing process since the batteries will most likely be purchased from another company. The cart also has many parts that must fit together perfectly to ensure stability of the cart when loaded with the inverter and the batteries. The steel is also hard to cut fast and accurately so automated machines will most likely be needed to complete the carts.

7.**Sustainability**

One of the biggest challenges when maintaining the completed system will be the weakening of the cart over time from rust and strain. Over the systems lifetime parts of the cart may need to be replaced, such as wheels or even parts of the frame. The project impacts the sustainable use of resources greatly because of the production of lithium batteries. Lithium is not a renewable source and must be mined from the earth. This resource will someday eventually run out and that is why it is very important that the batteries be recycled after they stop performing over time. In order to improve sustainability of the system a new battery chemistry might be used that does not use the lithium. In the future renewable battery technologies might make this possible. The main issue with this upgrade is that a fully renewable batteries have not yet been developed but hopefully in the future they will be a viable option.

8.Ethical

When using this system we had to keep in mind that there was going to be very high DC voltage which can be dangerous if someone was to get electrocuted. For this reason, we designed the cart so that this may not happen to any user. The only people that will be able to access the most dangerous parts of the system will be technical engineers that know what they are doing and how to handle the high voltage. During manufacturing the safety of the employees will also be important. The manufacturing of the batteries will use chemicals that may be harmful to humans so the workers must be protected from these chemicals. As for the cart, many steel pieces will have to be cut to length using large blades. To prevent any injury from the blades we can automate this part of the manufacturing process so no workers will have to go near the spinning blades.

9.Health and Safety

The health and safety of the manufacture workers will be of utmost importance. The workers that handle the toxic battery chemicals will have to be protected so they do not ingest any of them into their bodies. The workers that work on the cart will have to protected from the cutting blades used for the steel. To make sure they are safe we will automate this part of the manufacturing so the employees will not have to approach any of the cutting equipment while the blades are running. We also had to make sure that the cart was low to the ground so that it can not tip over and potentially hurt someone. Furthermore, we made sure that the cart was sturdy and structurally sound as to make sure it would not ever come down on someone’s foot or other body part. The electrical system is also completed enclosed where there is exposed wire. Since we are dealing with high DC voltage it is imperative that we make sure no one including customers or workers can get electrocuted.

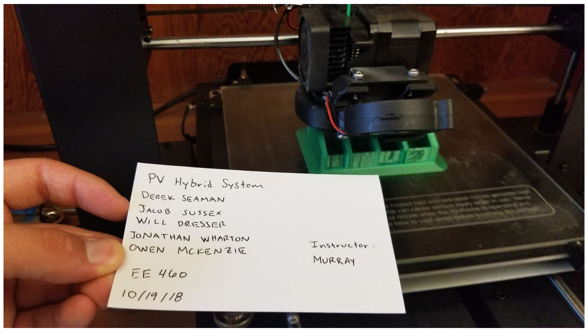
10. **Social and Political**

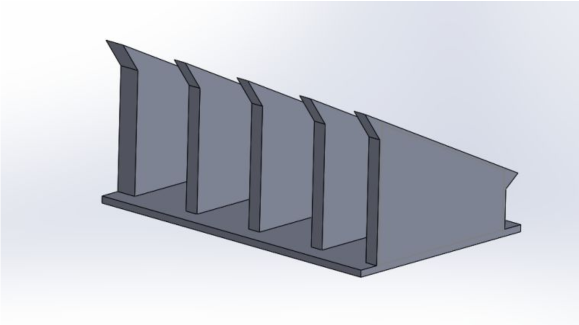
The only social issue that this system may impact is that it will contribute to the lithium mining industry that many people may be against due to the emissions that may occur. This system will hopefully only impact the customers that are intended to use it my saving them money and giving them power in case of power outages. The direct stakeholders in this matter are the customers that will use the product and the indirect stakeholders are the people who benefit from a cleaner environment due to people who use the product instead of always taking electricity from the grid where the power is most likely from coal powered generators. The customers will ultimately pay the cost of buying and running the system while the population will gain the environmental cleanliness for no price at all. The stakeholders that will own this system will most likely be middle class because that system will be somewhat expensive and the customer will most likely have to own a house to install the system in.

11. **Development**

When developing this mobile inverter and battery system we did not have to use any new tools or techniques. All of the assembly and wiring of the system used traditional tools and techniques. The only thing we referred to constantly was the instruction manual that was provided with the Tabuchi inverter system. We used this manual to ensure proper wiring of the batteries and inverter so that we wouldn’t break the system and so we could operate it in a safe manner.

Appendix B: Preliminary Design Analysis





Design Revision 1

Design Revision 2

Our original design was to mount the inverter and batteries on a single mobile platform using 80/20 support struts to secure it. We moved away from this design however, as the inverter unit did not need to be transported alongside the batteries, and its bulk made the system overly large and clumsy to move. We then considered design revision two, where the batteries and inverter could be moved separately. This design is overall superior due to its increased mobility, ability to interchange multiple battery racks, and cheaper construction.