



Electrical Engineering Department  
California Polytechnic State University

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Senior Project Report

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Reliability Measurement for Grid-Connected Solar System

Part 1:

Improve Grid-Connected Solar System By Adding Battery Energy Storage System  
(BESS)

February 2023

Sponsor: Eprl GridED

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## Acknowledgment

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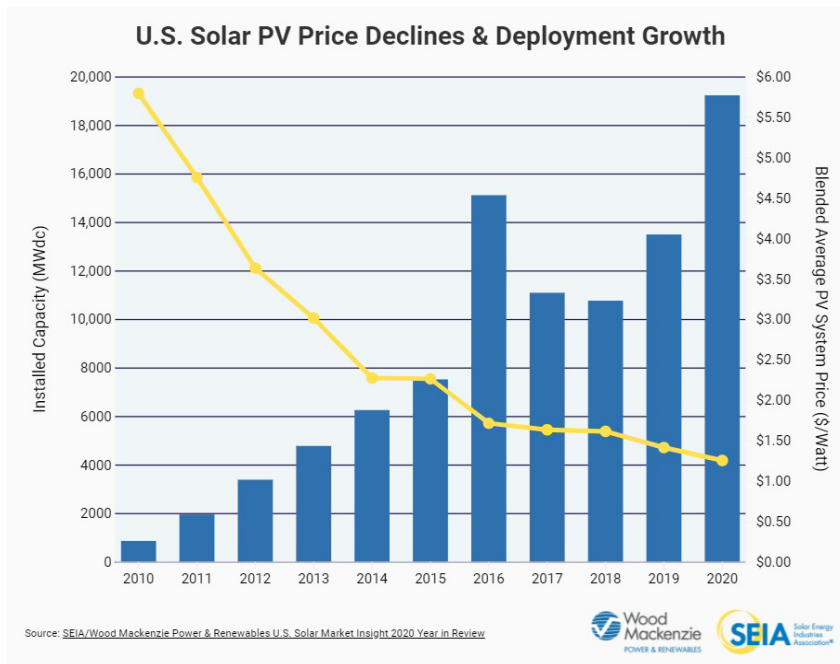
## Project Abstract

The project is the first part of the “Reliability Measurement for Grid-Connected Solar System” project and is about configuring ITECH IT-M3633 and Tabuchi Battery Energy Storage System (BESS) to our small-scale microgrid at EE Department in Cal Poly ( San Luis Obispo). We designed a system to connect ITECH IT-M3633 as a PV solar source to Tabuchi BESS within a grid-connected microgrid system in Room 20-102 at Cal Poly. Initially, we developed a Photovoltaic Thevenin equivalent model and used ITECH IT-M3633 as the DC Input. Cal Poly

### General Introduction and Background

**General Information:** ITECH IT-M3633 comprises a directional power supply and regenerative electronic load. The device is a bidirectional DC power supply. The device can emulate a battery charger or a solar photovoltaic. In addition, this device is also an electronic load and a digital multimeter. The electronic load can act like a variable resistor with an oscilloscope, multimeter, or battery by drawing a constant current. Unlike a typical electric load, ITECH does not generate heat, which takes that power and gives it back to the AC network. It can be programmed for variable loading cycles as well. ITECH can easily set either source mood or load mood while also digitally able to set voltage, current, and power while also protecting over/under voltage, current, and power.

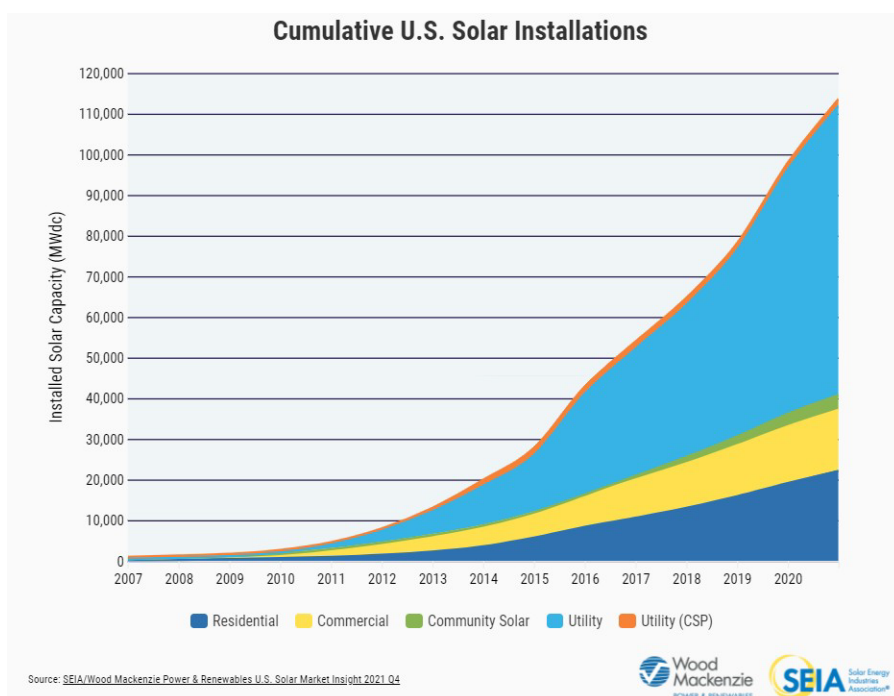
**Background:** Energy production in the United States, particularly in California, is experiencing a shift away from fossil fuels to renewable energy sources, such as wind and solar. California’s Renewable Portfolio Standard (RPS) “requires that 33% of electricity retail sales in California is from renewable resources by 2020, 60% by 2030, and 100% by 2045.” As states require increased reliability on renewables, the development of these technologies is also on the rise. A common expectation is that the cost of production decreases, as is the case with Solar PV, shown in Figure 1.



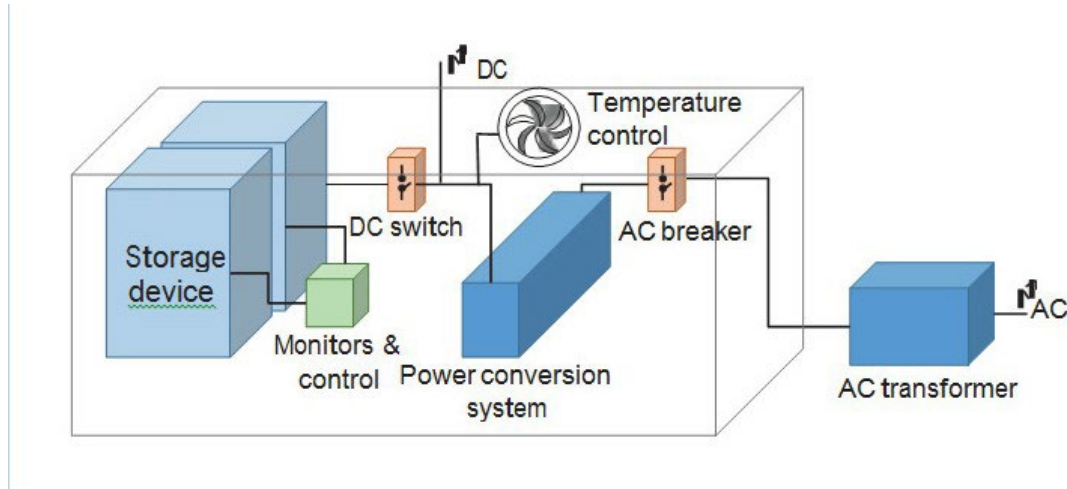
**Figure 1: PV Price Decline vs. Deployment Growth**

According to the Department of Energy, “Solar energy is America’s fastest growing and most affordable source of new electricity. Over 3 million installations have been built across the country, with 1 million being built in the last two years” Overall, most US solar installations within the last decade have occurred between 2015 and 2020, as shown in Figure 2.

**Figure 2: Cumulative Solar Installations**



Renewable energy sources cannot produce power constantly throughout the 24 hours of the day. At some points, they produce their max capacity and hardly any energy. With Solar, PV Arrays produce the most during the middle of the day when there is direct sunlight. The issue is what happens with the excess energy when the PV produces more energy than the load demands. A solution is to store the energy for future use when demand exceeds generation.



**Figure 3: Battery Energy Storage System & Primary Power Components**

Excess energy can be stored through a Battery Energy Storage System (BESS). A BESS system replaces the traditional method used to store energy, such as fossil fuels. Instead of utilizing non-renewable resources, the battery energy storage system uses excess energy from renewables like solar and wind to store them for future use. The building blocks of a battery energy storage system can be shown in Figure 3. Inside the system are the primary components, such as batteries, power conversion, and control systems. Currently, lithium-ion batteries dominate storage technology. Its heavy dependability could be attributed to manufacturing and service needs. Many electronic applications would not have been possible without such a reliable energy storage system.

### Eco-Intelligent Battery System (EIBS)

The Eco Intelligent Battery System is an all-in-one solution by Tabuchi Elect. with the following parts:

- Solar and Battery Control
- High-Efficiency AC/DC conversion
- Automatic Transfer Switch
- 3 Solar MPPTs
- 2 Lithium-ion Batteries
- Battery, solar, and whole-house monitoring
- Optimized Energy Management Settings:
  - Self-consumption
  - Dynamic Demand Response
  - Time of Use (TOU)
  - Backup



## System Ratings

Tabuchi Electric provides operational and maximum ratings for the inputs/outputs of the inverter. The maximum ratings are crucial to ensuring the system is not operated in a situation with a safety risk. Three primary ratings are of importance to our project. These include the DC Input (Photovoltaic Elements), Grid-tied AC Output, and Stand Alone AC Output.

### **Input (DC: Photovoltaic)**

| <b>Table 1: Ratings for DC Input</b>    |            |
|-----------------------------------------|------------|
| Max. Open-Circuit PV Input Voltage      | 600 V      |
| Max. Usable Input Power Per String      | 2500 W     |
| MPPT Operating Voltage Range            | 80 - 550 V |
| Number of Independent MPPTs             | 3          |
| Max. Operating Input Current Per String | 12 A       |
| Max. Short Circuit Current              | 15 A       |

### **Output (AC: Grid Tied)**

| <b>Table 2: Ratings for Grid-Tied AC Output</b> |                                       |
|-------------------------------------------------|---------------------------------------|
| Connection Type                                 | Single Split Phase 3-Wire (L1, L2, N) |
| Rated AC Output                                 | 5500 W                                |
| Rated AC Voltage                                | 240 V                                 |
| Nominal AC Voltage Range                        | AC 211.2 - 264 V                      |
| Grid Frequency Range                            | 60Hz / 56.0 Hz to 64.0 Hz             |
| Max. Output Current                             | 22.9 A                                |
| Power Factor at Rated Output Power              | $\geq 0.95$                           |

## Output (AC: Stand Alone)

| Table 3: Ratings for Stand Alone AC Output |                            |
|--------------------------------------------|----------------------------|
| Connection Type                            | Single Phase 2-wire (L, N) |
| Max. Output Power                          | 3.3 kVA                    |
| Rated Output Voltage                       | 120 ± 5V                   |

## ITECH Programmable DC Power Supply

In this part, we explain how the ITECH PV emulator software was downloaded and added to the system, configured, and set up the system to the PV emulator.

### Items Used/Needed:

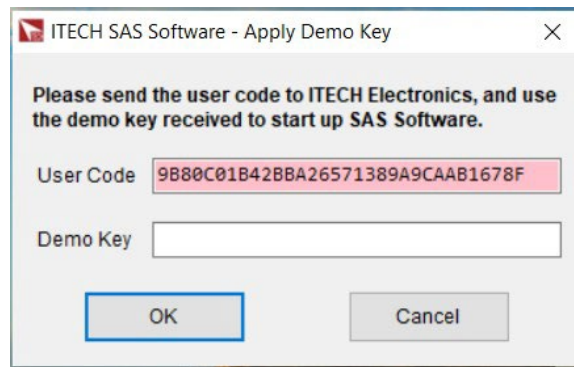
- ITECH DC power supply: Model # IT-M3633
- ITECH Solar Array Simulation SAS1000M Software Key Flashdrive
- ITECH Solar Array Simulation SAS1000M Download Flashdrive
- 7Zip file [download](#).
- NI-VISA [V16.0](#)
- Grounding Wire for IT-M3633
- Flathead ScrewDriver
- Windows 10 (software not available on MAC)

Steps for SoftWare download:

1. Insert ITECH Software/User-Manual Download Flashdrive into a Windows operating system computer.
2. Copy all Solar Array Simulation SAS1000M files. Download Flash Drive onto your computer so that no files are altered/deleted from the flash drive. Safely eject the flash drive after all files have been saved. The files in the flash drive should include the following:
  - a. ITECH\_SAS1000M Software Installation-EN
  - b. ITECH\_SAS1000M Software User Manual-EN
  - c. SAS1000M\_Ver 2.2.0-Setup
3. Download the following files to your computer before launching the SAS1000M\_Ver 2.20-Setup.
  - a. [7Zip compression](#): archiver to open the software setup file.
  - b. [NI-VISA](#): NI instrument driver implementing the Virtual Instrument Software Architecture

(VISA) I/O standard. VISA is a standard for configuring, programming, and troubleshooting instrumentation systems comprising GPIB, VXI, PXI, serial (RS232/RS485), Ethernet/LXI, and USB interfaces.

- i. Instructions for a successful download are within the ITECH\_SAS1000M Software Installation-EN.
4. Insert ITECH Solar Array Simulation SAS1000M Software Key Flashdrive into the computer. The software key is needed after the download is complete. The image below shows the error message when the software key is absent.



**Figure 4: Missing Software Key Error Message**

5. After a successful download, the initial software page should look similar to the image below.

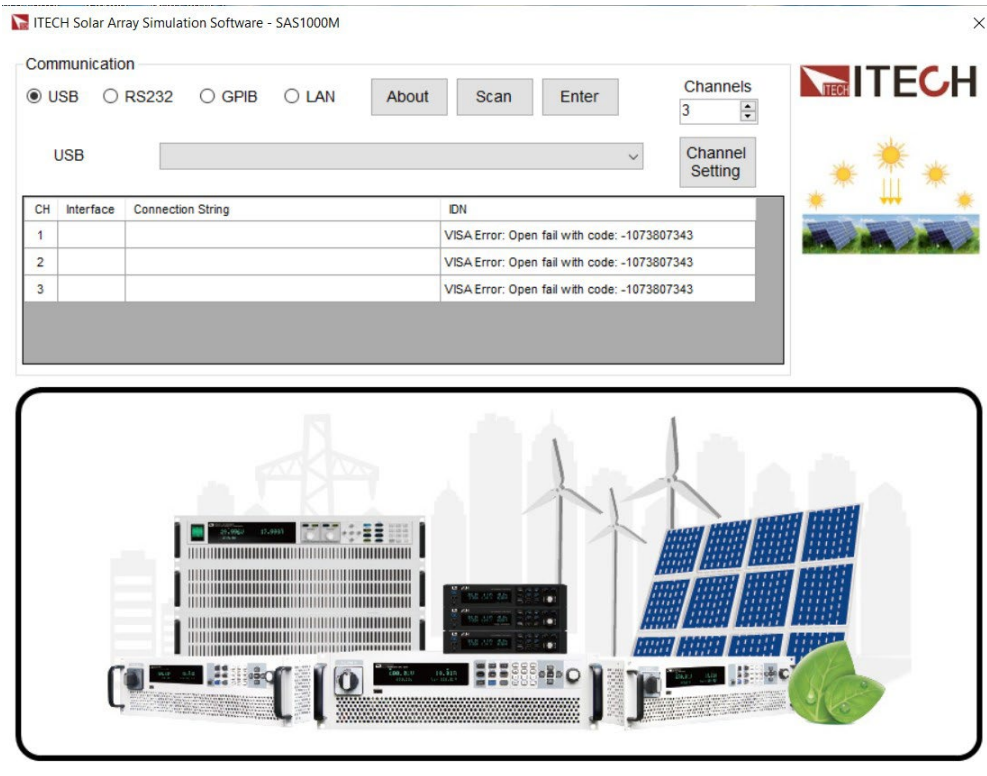


Figure 5: Initial ITECH Software Screen

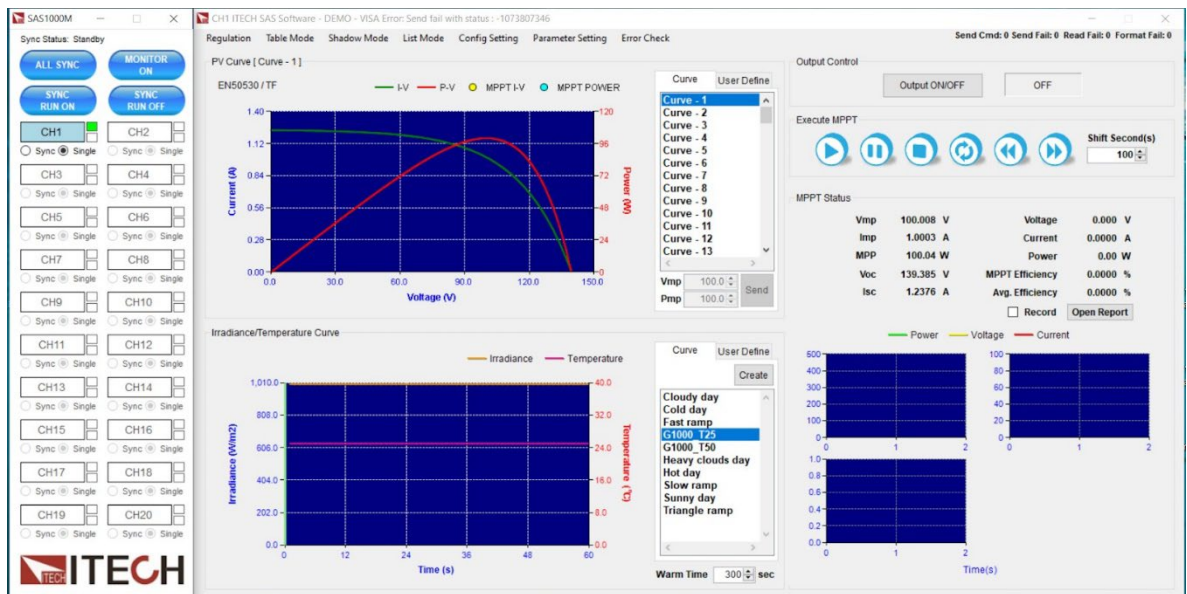
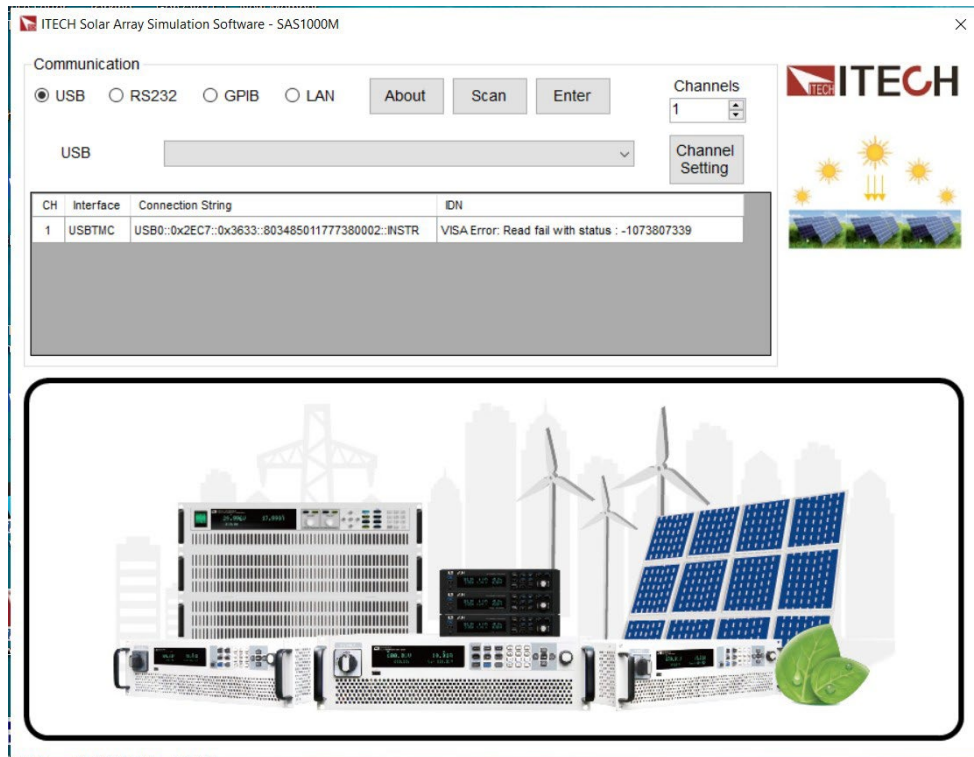


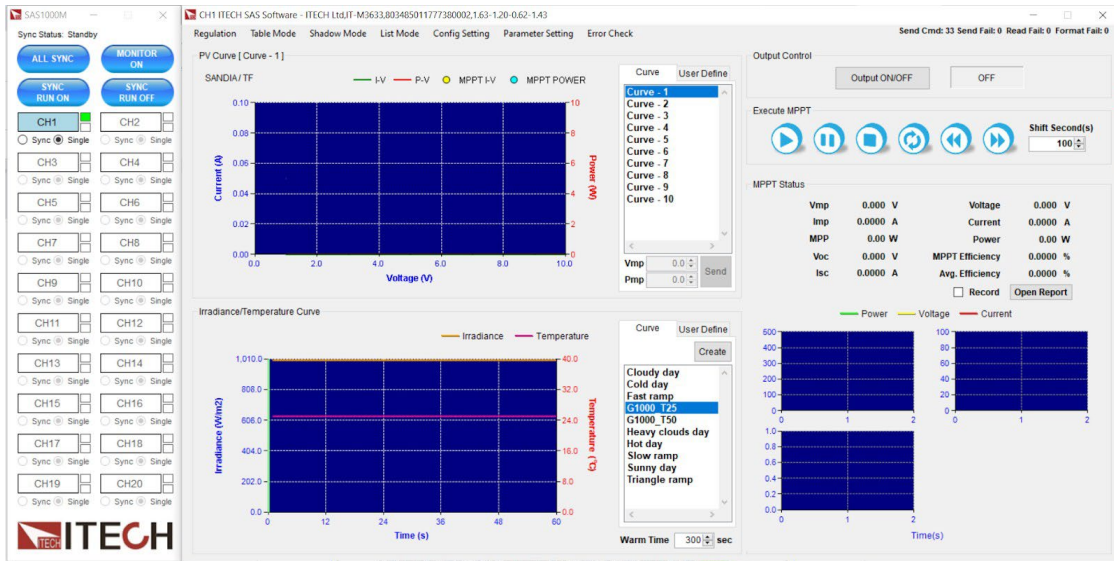
Figure 6: ITECH Photovoltaic I-V Curve Simulation Screen



## No Error Message



**Figure 9: No Error ITECH Photovoltaic Simulation Screen**



**Figure 10: Successfully Connected ITECH Photovoltaic Simulation Screen**

Once the ITECH and its software have successfully connected, the screen displays Figure 10. This simulation software allows users to simulate a photovoltaic system with its 10 default curves, where one can change the  $V_{mp}$  and the  $P_{mp}$  to fulfill specific specification requirements. Figure 11



shows what the ITECH device looks like once it is on.



Figure 11: ITECH Regenerative Power System

## ITECH Modes of Operation

The IT-M3633 belongs to the IT-M3600 model family. Most of the variation between each of the models in this family is related to the maximum power output of each unit. The IT-M3633 has three main modes of operation: **Power Supply Function**, **Load Function**, and **Multi-Function**. The Power supply mode of operation is for various testing procedures, including adjustable voltage and or current source, variable output impedance, and multiple protection settings. The load function setting includes power regeneration, programmable current rise and fall time, and battery discharge test. This model also has multi-unit functionality, capable of joining sixteen units in parallel. The multi-machine operation can increase the current and power output relevant to the number of combined units, assuming each unit is identical to the IT-M3633. The following section highlights multiple.

IT-M3633 features and functionality and provide possible applications for future use to the battery energy storage system.

### General Features:

- One button switch between the source and sink on the panel
- Bidirectional energy flow and support battery simulation
- Support on/off delay
- Automatic detection of power grid state to realize reliable grid connection
- Temperature measurement function, over temperature protection
- Anti-reverse protection function through optional accessories
- Power off protection
- High-speed measurement, 10/s

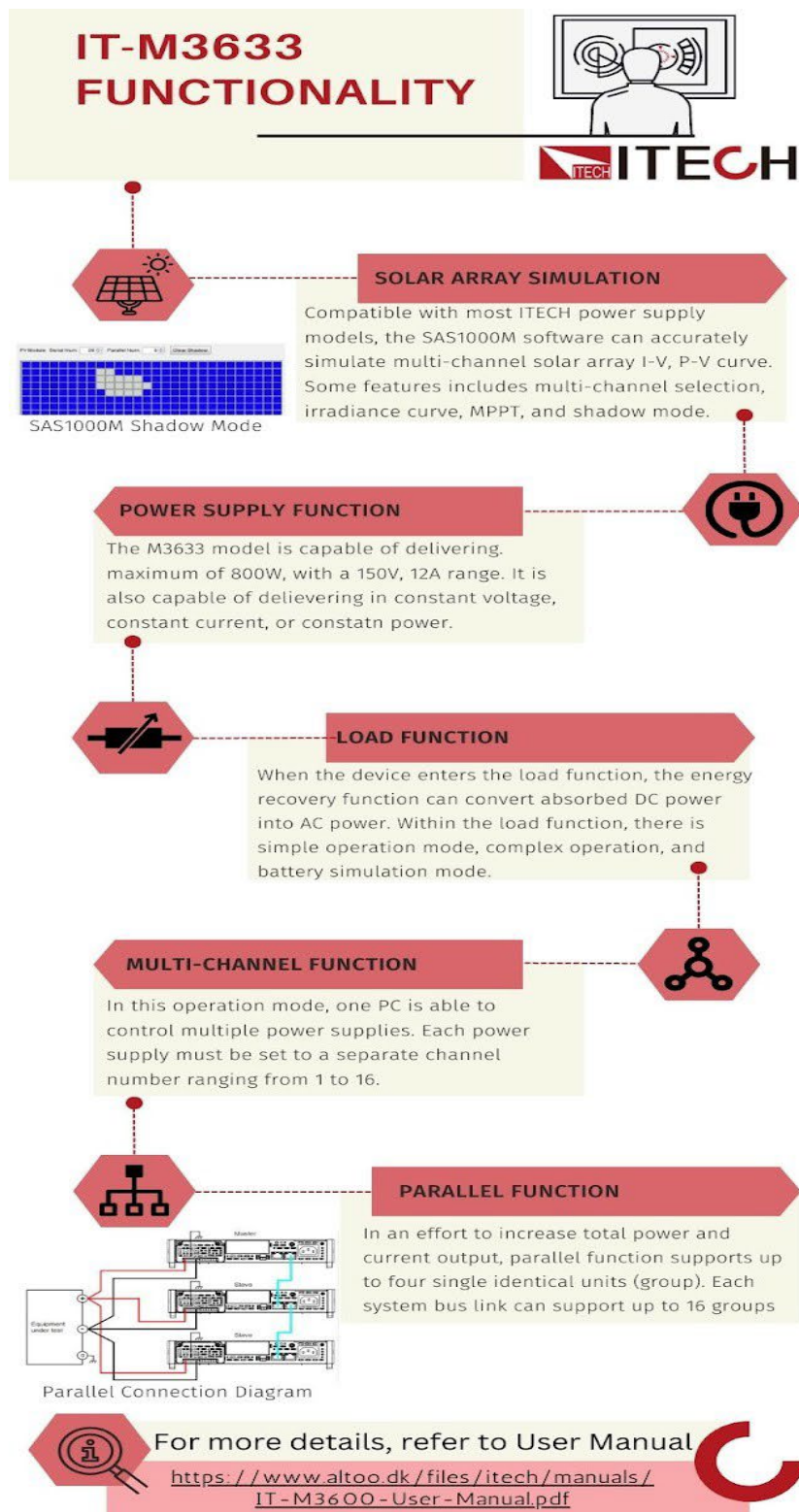


Figure 12: ITECH Functionality and Mode Infographic

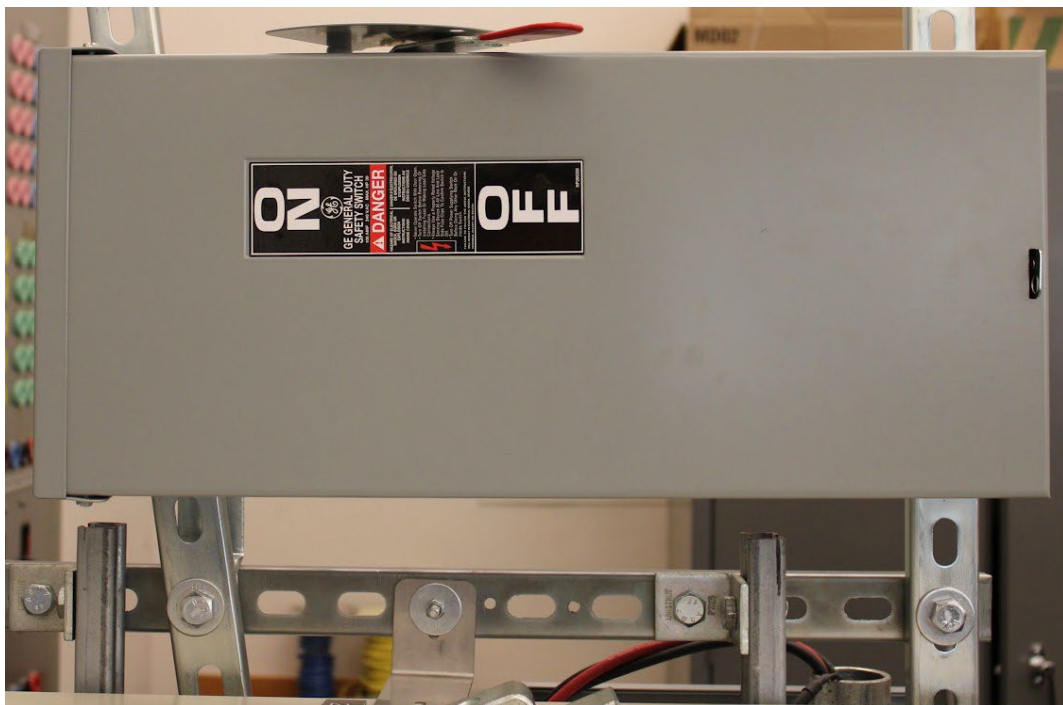


## Preparing Inputs/Outputs for Energization

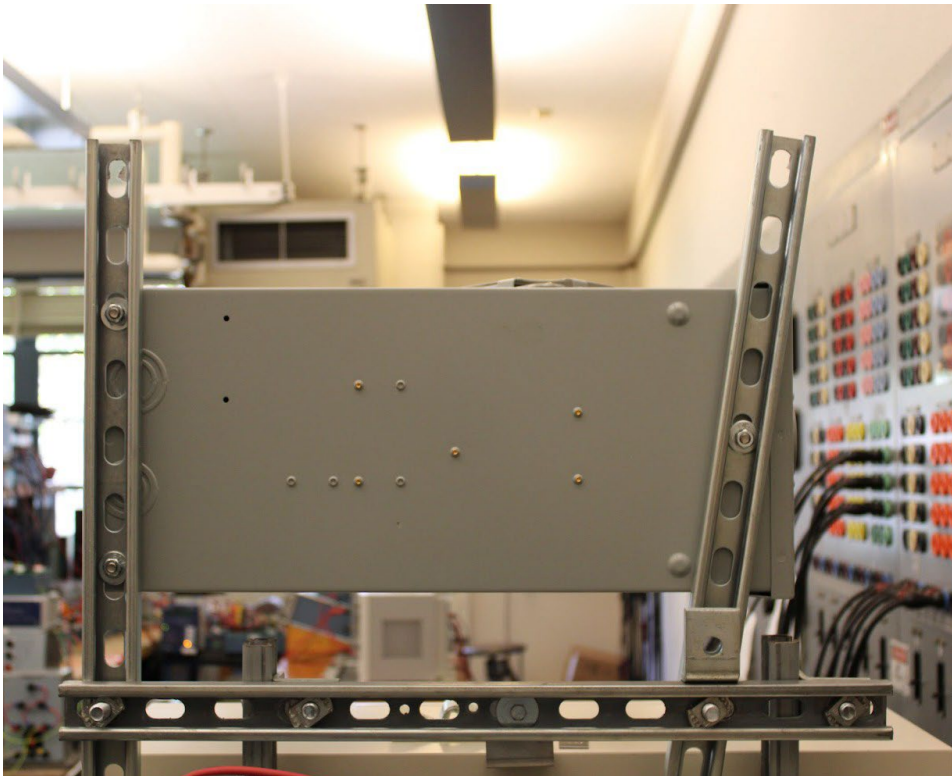
As the project began, it was necessary to ensure that we could interface with the inverter safely, allowing us to connect to external equipment that could act as source, load, and measurement equipment. Work from previous groups involved installing a fused AC Disconnect to interface with the AC input of the inverter.

### DC Disconnect

The preliminary idea was to have some photovoltaic emulation into the DC input of the inverter. It was necessary to include an additional layer of safety in the form of a fused DC breaker. The Disconnect Switch available was a General Electric General Duty Safety Switch, TG3223R, with a 100 amp rating. The images below showcase the breaker installation on the system.

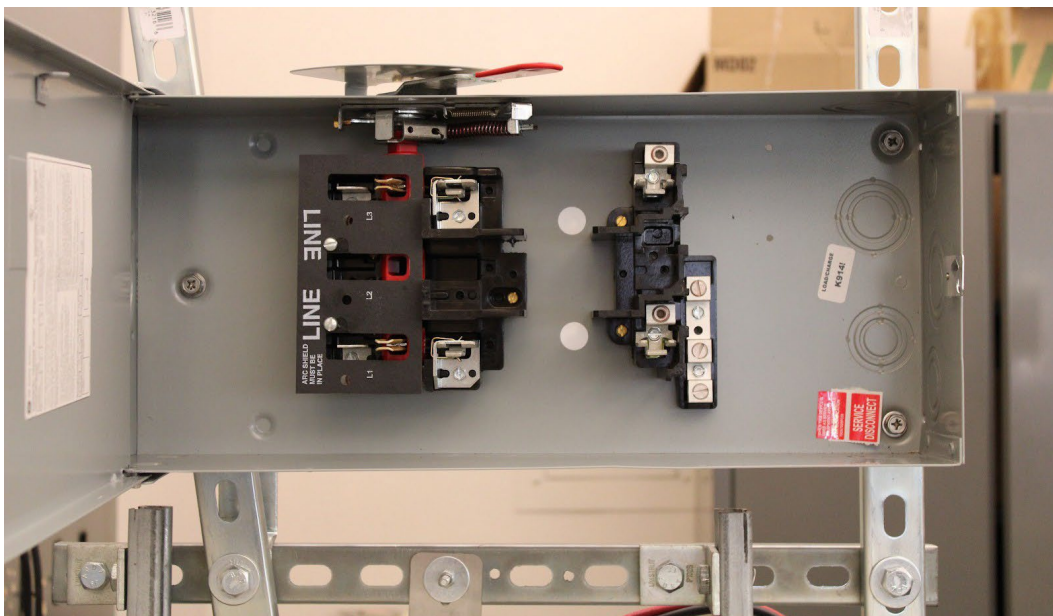


**Figure 13: DC Breaker Installation**



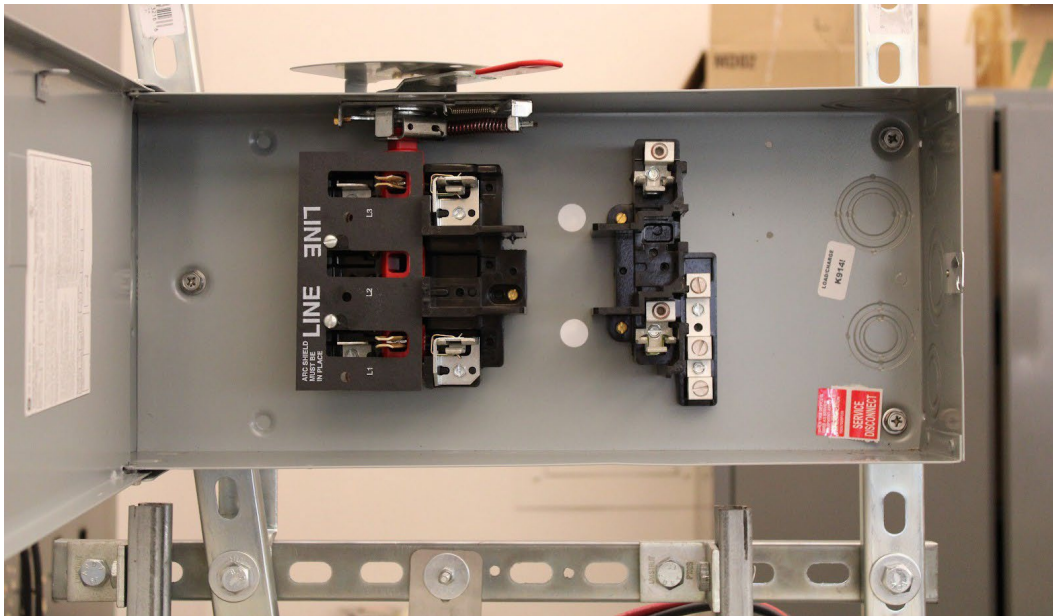
**Figure 14: Back of Disconnect Switch**

Figures 13 and 14 show that the disconnect switch was mounted on top of the Tabuchi inverter structure using two (2) U-shaped mounting bars. Figure 12 displays the disconnect switch before the fuses, and the connection to the inverter and DC power supply.



**Figure 15: Inside the Disconnect Switch**

## DC Fuses



**Figure 16: Inside the Disconnect Switch Before Adding Fuses**

Adding a fuse to the switch is crucial for the switch to be operational. The fuse selection was determined based on the system's ratings.



**Figure 17: Bussmann Fusetron FRS-R-15 Fuse**

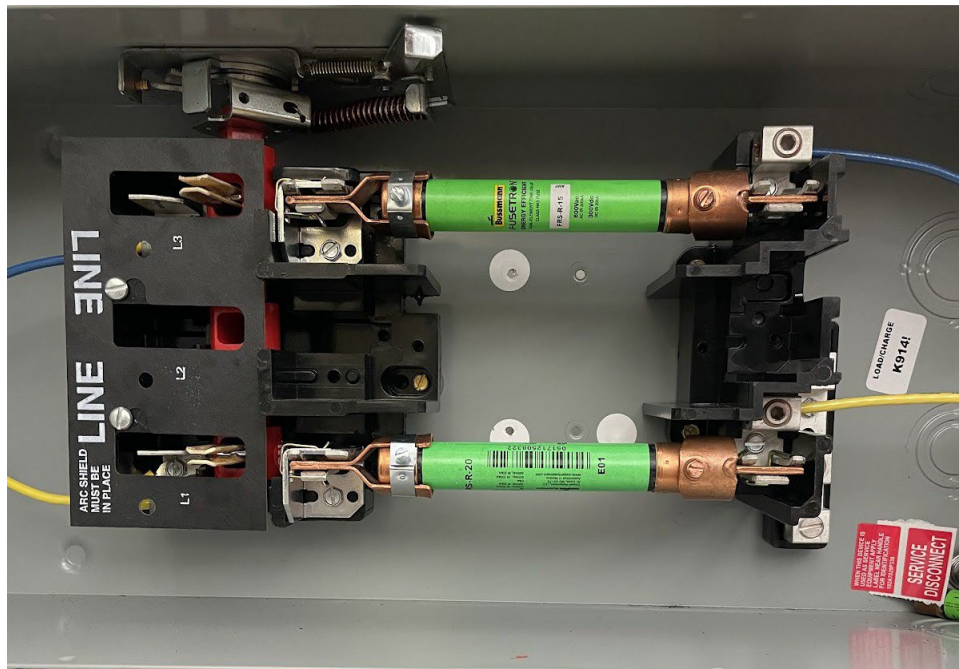
According to the system ratings, the appropriate fuse to utilize is that with a rating of 15A at up to 600V. The Bussman Fusetron FRS-R-15 was purchased to implement in the system.





**Figure 18: Bussmann 216-R Fuse Reducers**

It was impossible to insert the fuses in and of themselves into the disconnect switch as the disconnect switch is rated to accept fuse size capable of 100A. To adapt the disconnect switch, fuse reducers needed to be installed. Bussmann 216-R was utilized in the disconnect switch.

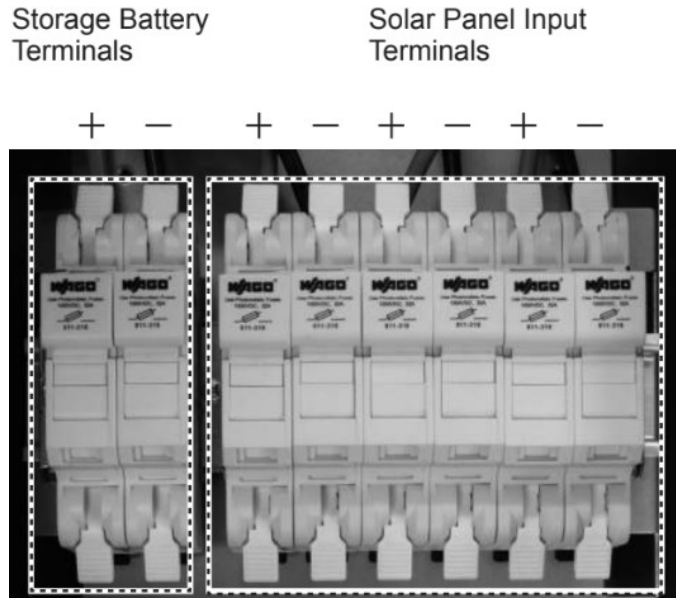


**Figure 19: Inside Finalized DC Disconnect Switch**

The disconnect switch, by default, was not sized to accept the length of the FRS-R-15 fuse. Upon further research, it was difficult to locate suitable fuse or fuse reducers that would enable the immediate implementation of the fused disconnect switch. To adapt the disconnect switch, it was

necessary to relocate the internal components on the right side further to the right to fit the fuse. This relocation can be observed in the drilled hole patterns behind the fuse.

## DC Wiring



**Figure 20: Tabuchi DC Wiring**

On the system's inverter, there are up to three photovoltaic inputs on the system's figure 20. Initial wiring of the system involved only connecting to the first available input. This configuration did not produce the desired results; therefore, the daisy chain approach to the wiring was introduced after further reading the "Stand Alone Operation Check" shown in Figure 21. Therefore, it was determined that all Solar Panel Inputs on the inverter needed to be connected for operation.

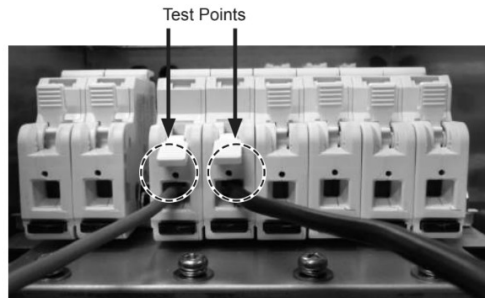
### 1 Check wiring to the solar panels.

**CAUTION** Do not set the DC Switch-Disconnecter on the inverter to the ON position yet.

- ① Confirm that there is a sufficient amount of sunlight.
- ② Connect the cable between the solar panels and the inverter.
- ③ Confirm the voltage to all solar panel input terminals is as written in the box below.

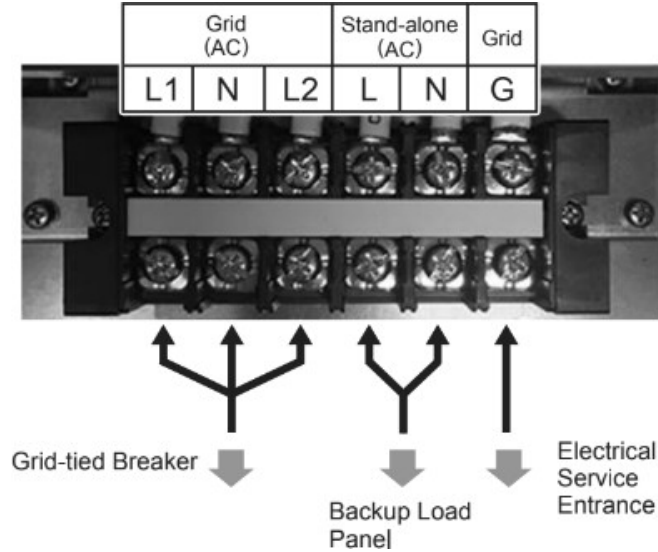
Measure voltage at the test points shown in the picture on the right.

(Pay attention to polarity.)  
Voltage between N terminal (-) and P terminal (+):  
80 to 600 V DC



**Figure 21: Stand-Alone Operation Solar Panel Test Points**

## AC Wiring



**Figure 22: Tabuchi AC Wiring**

There were no changes to the AC input of the system, as these had been prepared by the previous group that had worked with the system. The AC output of the system could either be taken at the installed AC breaker or directly from the AC connection on the inverter shown above. The stand-alone AC outputs are only available directly on the inverter. The decision was to take the stand-alone AC output on the inverter. To connect to these terminals, a 10 gauge wire was used. These were connected to the energy conversion lab benches to make current, voltage, and power measurements on the output, as shown in the figure below.

## Interfacing Inputs and Outputs

The following figures show the power flow diagram and interconnected components to attempt to initialize the system. Figure 23 depicts how the system is intended to work. Based on this diagram, it can be seen that the inverter takes inputs from the grid, a solar array, and the battery. The resulting power from any given source is stored in the battery or redirected into the primary/ backup panel for use in the residence. Since the system deals with AC and DC signals, the hybrid inverter is believed to have the capability of functioning as a rectifier and an inverter. However, the green line of Figure 23 only addresses the general power flow from the grid to the storage batteries. The line could be better observed to interpret how power is managed through different appliances. Essentially, the line is served to direct users on efficiently storing or delivering the power. Unfortunately, the green line does not consider the DC and AC parameters. This wouldn't benefit the user of how much power is consumed or lost. Similarly, the blue and red line from the solar array and batteries only depicts the DC power flow through the system. Upon the successful initialization of the system, it is believed that the hybrid inverter's rectifier and inverter capabilities could have been tested and studied more in-depth.

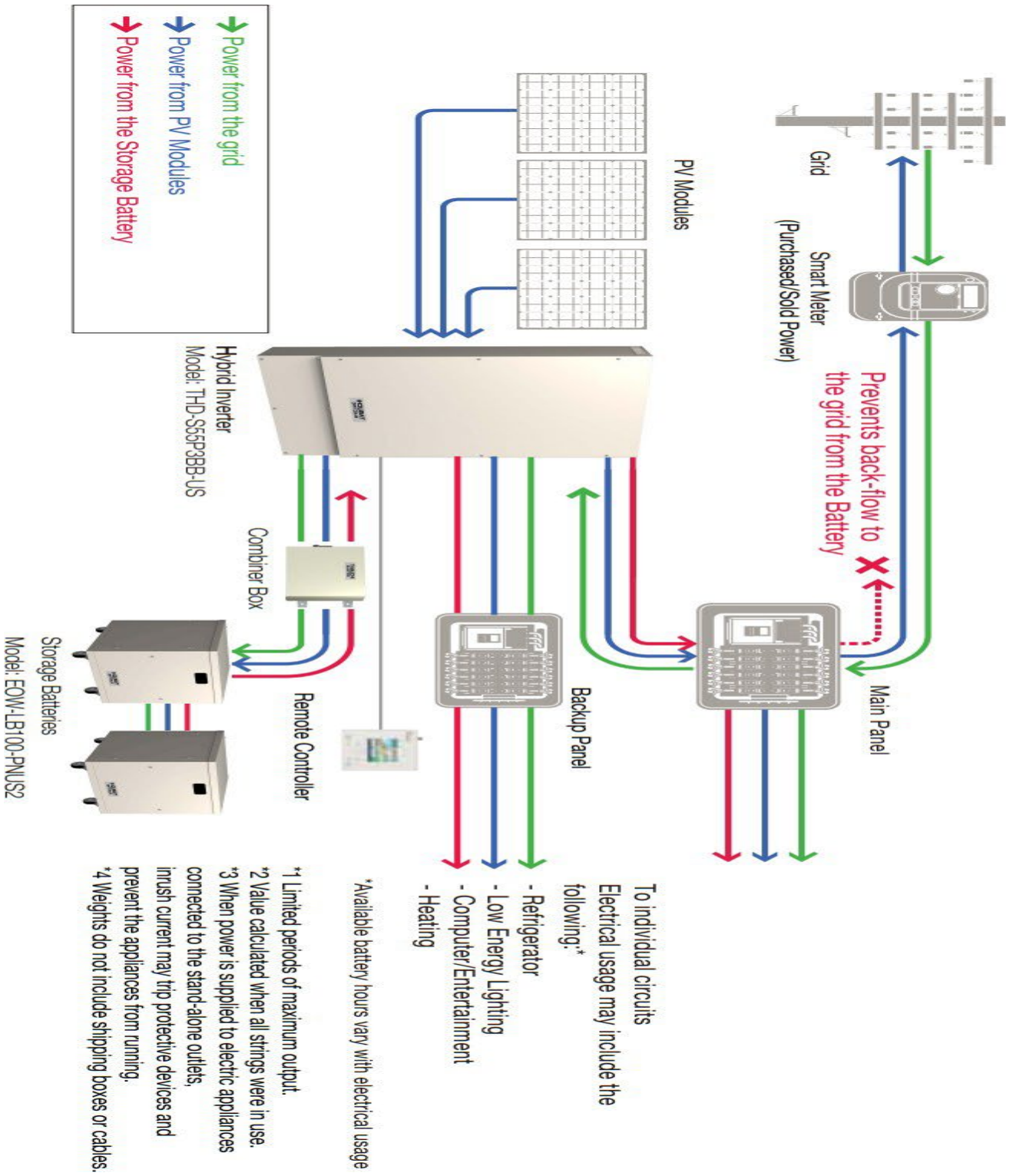


Figure 23: Tabuchi Wiring Diagram





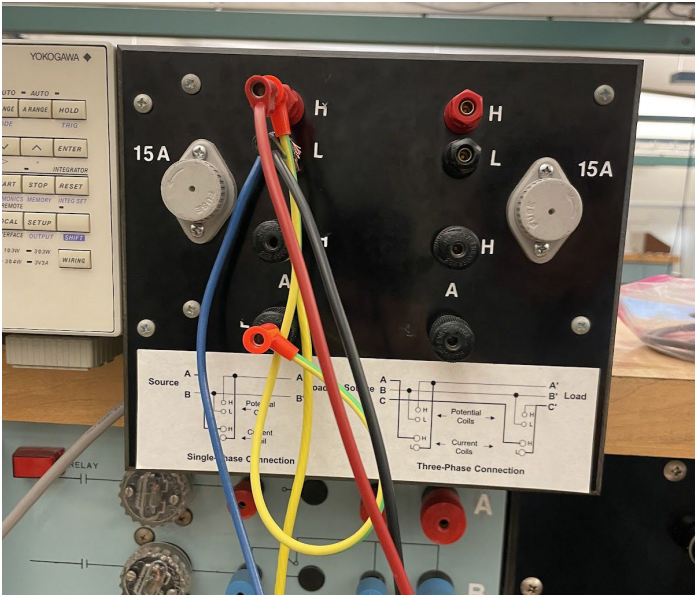
**Figure 24: Interfacing of Tabuchi BESS, ITECH Power Supply, and Lab Bench**



**Figure 25: TabuchiInverter's Inputs/Outputs**



The image above, Figure 25, shows the wiring input into the hybrid inverter. The first two fuses on the left-hand side represent the connection between the inverter and the two battery modules on the chassis. The remaining six fuse boxes represent the connection of the three photovoltaic arrays, with fuses on both the negative and positive terminals of the array. Initially, we connected the IT-M3633 to only the PV1 connection. Initial testing with the PV emulator, in both stand-alone and Grid-tied operations, did not yield conclusive results and did not turn on the inverter. After re-examining the Tabuchi Hybrid inverter user manual, the team hypothesized that the remaining two PV inputs must be connected to turn on the inverter successfully. That is why you will see two cables on the input of the PV1 fuse: one wire is connected straight to the DC power supply, and the other is connected to the input of PV2. A similar connection is shared between PV2 and PV3. This wiring connection is our attempt to supply power from one DC source to all three inputs on the hybrid inverter. This connection did not lead to conclusive results.

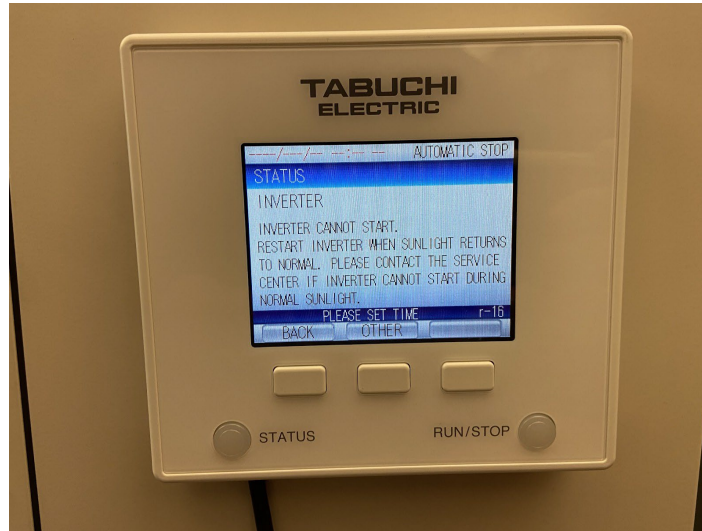


**Figure 26: Interface with Lab Bench Wattmeter**

### Implementation of Programmable DC Power Supply

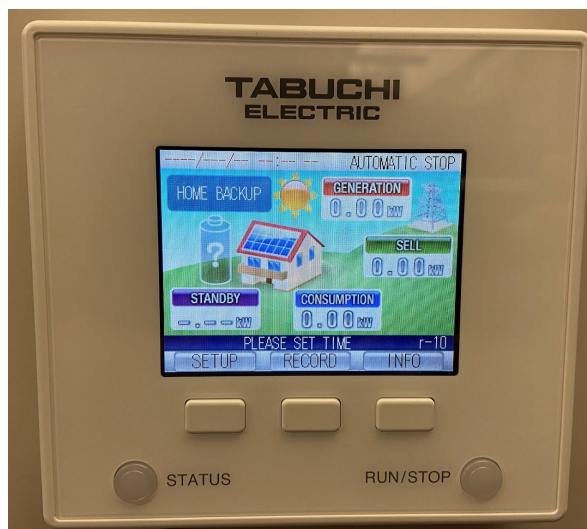
#### DC Input

The system was turned on after connecting the BESS to the Grid and the ITECH Photovoltaic Emulator. Originally it was hypothesized that the system would start up and begin charging the batteries by supplying the system with a constant DC power supply alongside the AC supply. However, it was observed that although the BESS received enough AC and DC power, the PV emulator provided a low current of 0.25 A, and the system inverter was not operational. The system controller verified that the inverter was not starting up, as it displayed the error message shown in Figure 27.

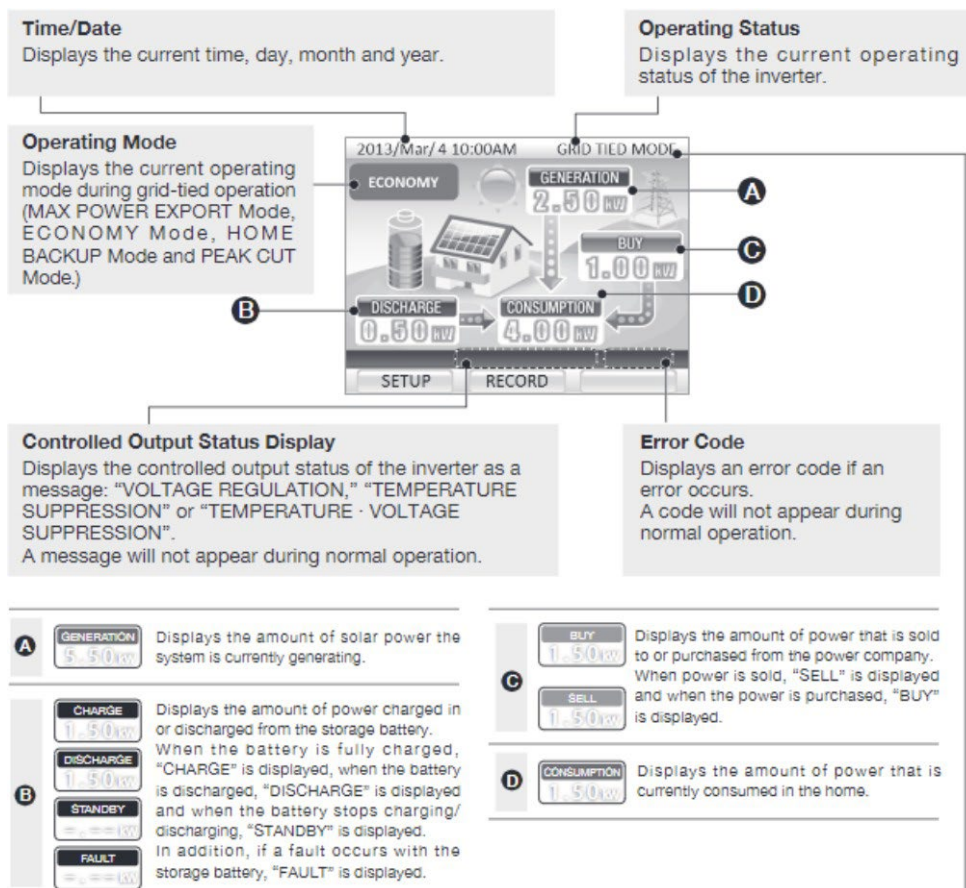


**Figure 27: Inverter Error Status**

Upon initial consideration, the inverter looks at the characteristic I-V curve seen with photovoltaic systems instead of needing a constant DC input. To test if this was likely the issue, the ITECH simulated a cloudy day with the output power supplies of the inverter. While running this power function to the inverter, the ITECH consistently supplied a low current to the inverter. Additionally, the DC limit was 3 A. After providing a power function to the inverter to verify if the system was looking for a realistic PV system, the Tabuchi system had an unsuccessful start-up.



**Figure 28: Service Mode Menu**

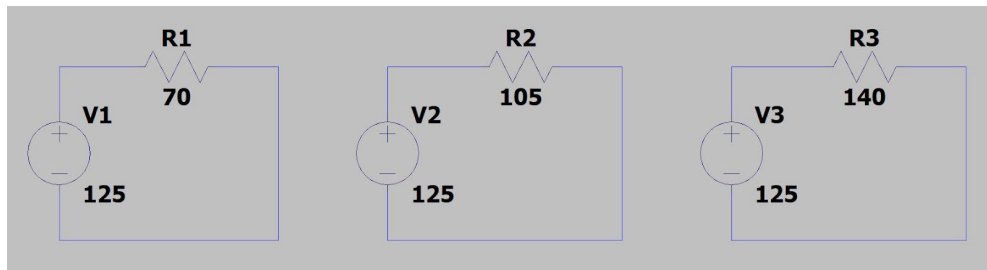


**Figure 29: Tabuchi System Status Modes and Meaning**

Ideally, we would expect to see the service mode screen displaying the mode of operation and the battery status as charging once the system is fully operational. For example, figure 28 shows the initial screen displaying “Automatic Stop” as the inverter status and “Standby” as the battery status. However, according to the Inverter Manual (Figure 29), if the system were initialized correctly, the service mode screen would display the operation status as “Stand Alone” or “Grid Tied” and the battery status as “Charge.” Had the controller shown this, it would have solidified the nature of our system being fully functional.

## Photovoltaic Emulation

Once the whole system had been set up for operation, the ITECH was used to input a DC signal into the Tabuchi Battery System Inverter. Upon initial start-up, the simulation of the I-V curve for the Photovoltaic Emulator showed that although the system was outputting 400W, the system was having a hard time staying at the maximum power point of the photovoltaic I-V curve. Since the system had difficulty reaching the MPPT, it became more evident that the inverter couldn’t operate under the various modes without a good DC input source. The BESS continuously displayed the service mode menu before displaying the inverter error message shown in Figure 27. After considering multiple reasons why the inverter didn’t turn on, the inverter manuals were referenced again. After inspecting the manual, it was noted that three (3) DC inputs may be needed for the inverter to turn on. Given our availability of one PV emulator, we decided to daisy chain the DC inputs to simulate three different PV inputs—the same inverter error message is displayed again.



**Figure 30: MPPT Mode Test Setup**

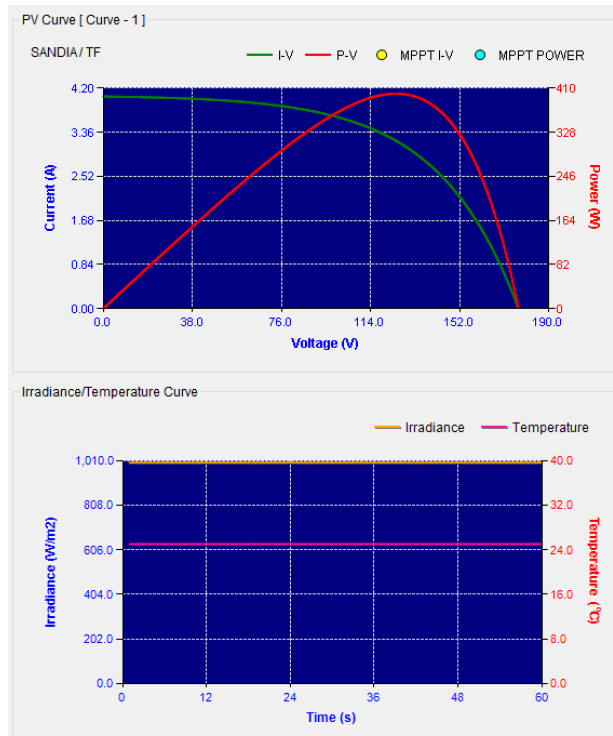
| <b>Load</b>        | R ( $\Omega$ )        | 70    | 105   | 140   |
|--------------------|-----------------------|-------|-------|-------|
| <b>PV Emulator</b> | P (mp)                | 400   | 400   | 400   |
|                    | V (mp)                | 125   | 125   | 125   |
| <b>Wattmeter</b>   | Resulting Current (I) | 1.085 | 0.722 | 0.542 |
|                    | Resulting Voltage (V) | 77.4  | 77.4  | 77.4  |
|                    | Resulting Power (W)   | 334.6 | 223.7 | 167.8 |

After testing whether three (3) PV inputs could cause the inverter to be unresponsive and continuously output the same error message. We considered that there was a lack of input power. We tested the PV emulator independently from the BESS to test if this was the case. As shown in Figure 30, the PV emulator was utilized as the voltage source while the resistance was varied. The results in Table 4 show that as the resistance was increased, the current and power output would decrease. This test verified that the MPPT mode works correctly on the ITECH, regardless of load. Based on our findings, it was determined that the ITECH MPPT mode was working appropriately. With the inverter still displaying an error message upon turning it on, we hypothesized that the inverter had difficulty synchronizing to the grid. All grid-tied inverters must provide a stable, sinusoidal AC waveform that matches grid voltage and frequency according to utility standards. When not synchronized, the zero-crossing is not synchronized between the inverter's sinusoidal signal and the grid, causing the inverter to malfunction and never actually turn on.

### I-V Characteristics of PV Emulator

After testing to see if the inverter would turn on with the input of the PV emulator, the inverter was still not delivering adequate power. This was due to the possibility that the inverter was expecting a minimum power input since solar panels deliver a power function instead of voltage.

To understand why the inverter was not operating at its nominal state, the PV emulator was verified by turning on the system to display a power curve that would display the ideal 200W of power. A load of 214 ohms was used to produce the curve.



**Figure 31: I-V & P-V Curve of PV Emulator**

Figure 31 shows the PV Emulator’s general I-V and P-V curve, which is not connected to the BESS for testing. The curve display was vital because it signified that the PV emulator was functional alone. Essentially, the characteristics of the curve determine the basic parameters of a component or device, which is used to model the behavior of an electrical system.

## Future Steps

After various unsuccessful attempts to energize the battery energy storage system, it was determined that a different approach was needed. While we could not continue working on the system, there is a follow up idea that future projects groups may attempt to bring the system into the entire operation. Initial assessments indicated that more power may be needed to operate the system. Each ITECH power supply is capable of It is supplying a maximum of 800W. The inverter is rated at 5500W. The maximum power a single ITECH power supply can provide is 800W, approximately 15% of its capacity. Since Figure 17 indicates a maximum of 3 inputs, it is hypothesized that connecting an individual ITECH to each PV input may provide enough power to initialize the system properly. The maximum input power that may be supplied by doing so is 2400W, which is approximately 45% of the inverter rating. If more ITECHs are added to a single input, special precautions may be taken when operating the ITECHs in parallel operation, as highlighted in Figure 9; further investigation will be required to determine the best approach.

After consulting with Professor Poshtan, another potential area of concern that may be causing the inverter to not start in Grid-Tied mode is synchronization to the AC grid. If increasing power to the PV input to the inverter does not allow the system to be initialized, synchronization issues may need to be investigated.

## Lessons Learned

Even though the PV emulator could not provide sufficient power to operate the BESS and tests different functional modes within the system, a lot was learned from the emulator's functionality alone. For instance, the solar array simulation allowed us to generate a general I-V and P-V curve which could be done and tested on different systems. Using the ITECH software would allow future groups to utilize its different functions to gather and generate various data. Overall, the failure to operate the BESS provided us with different possibilities to connect the emulator to the system and consider parameters such as voltage and current when making connections.

Other areas of the project that could help future groups that plan on conducting tests on the BESS would be attention to detail. Obtaining materials such as wire type and fuses used to turn on the system safely amounted to a majority of the project time. To reduce some of the time, closer attention to data sheets and the organization of materials at hand would be ideal. This would narrow our focus on the specific type of equipment required without researching the general aspects.

## References

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