Optimize Topology, Component Sizes, and Operating Strategy of Participant's Protype

Cooperative Research and Development Final Report

CRADA Number: CRD-20-17104

NREL Technical Contact: Andy Walker

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5C00-90888
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NOTICE

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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Cooperative Research and Development Final Report

Report Date: July 16, 2024

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Shine Technologies, LLC

CRADA Number: CRD-20-17104

CRADA Title: Optimize Topology, Component Sizes, and Operating Strategy of Participant's Protype

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Sponsoring DOE Program Office(s): Office of Energy Efficiency and Renewable Energy (EERE), Solar Energy Technologies Office (SETO)

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$75,000.00
TOTALS	$75,000.00

Executive Summary of CRADA Work:

NREL provided technical assistance in modeling and testing of JuiceBox3.0, a stand-alone power supply for disaster relief and off-grid use.

CRADA benefit to DOE, Participant, and US Taxpayer:

- Assists laboratory in achieving programmatic scope,
- Uses the laboratory's core competencies

<u>Summary of Research Results</u>:

1.0 SUMMARY OF TASKS COMPLETED

Task 1: Modeling

- NREL created a computer model of system using HOMER to optimize system under different load and climate conditions and enable integration of machine learning or other adaptive technologies to maximize performance in real time during field use and storage.
- NREL provided climate data for all or certain selected climate zones for use in the modeling.
- Shine Technologies LLC provided load scenarios that represent likely use cases such as disaster relief or use by the homeless.
- Shine Technologies LLC provided information on candidate components that are being considered so that NREL could ascertain the parameters required to model those components.
- NREL prepared report and powerpoint of modeling results
- Shine Technologies LLC co-authored reporting of results.

Task 2: Testing

- NREL tested the JuiceBox 3.0 system to demonstrate functionality, efficiency, sequence of automatic operation, and monitoring and control. Testing involved evaluation of lithium cells, charging components, inverter, computer interface, safety and regulatory devices, and thermal performance.
- Shine Technologies provided the system under test (complete JuiceBox 3.0 power system with PV modules, batteries, and controls.
- NREL prepared "Design of Experiment" with input from Shine Technologies LLC
- NREL provided required instruments and datalogger.
- NREL programed the datalogger.
- Shine Technologies operated unit under test during execution of test protocol.
- NREL archived data.
- NREL led analysis with input from Shine Technologies LLC
- NREL prepared report and powerpoint presentation of test results with input and review from Shine Technologies LLC.

This work describes tests of JuiceBox 3.0 devices in a "hardware in the loop" experiment at the NREL Power System Laboratory, room C213 in the Energy Systems Integration Facility (ESIF).

The purpose of the project was to complete testing of Shine Technologies LLC's prototype power system called "Juicebox 3.0." Testing of the prototype using NREL's hardware-in-the-loop capabilities, including a DC power supply programmed to simulate PV module output and provide the JuiceBox 3.0 at the specified power level and with a load bank of sufficient capacity to mimic DC and AC loads connected to the outlets of the Juicebox 3.0. The unit is provided with SAE wire connectors. A photo of a JuiceBox 3.0 unit is shown in Figure 1 below.

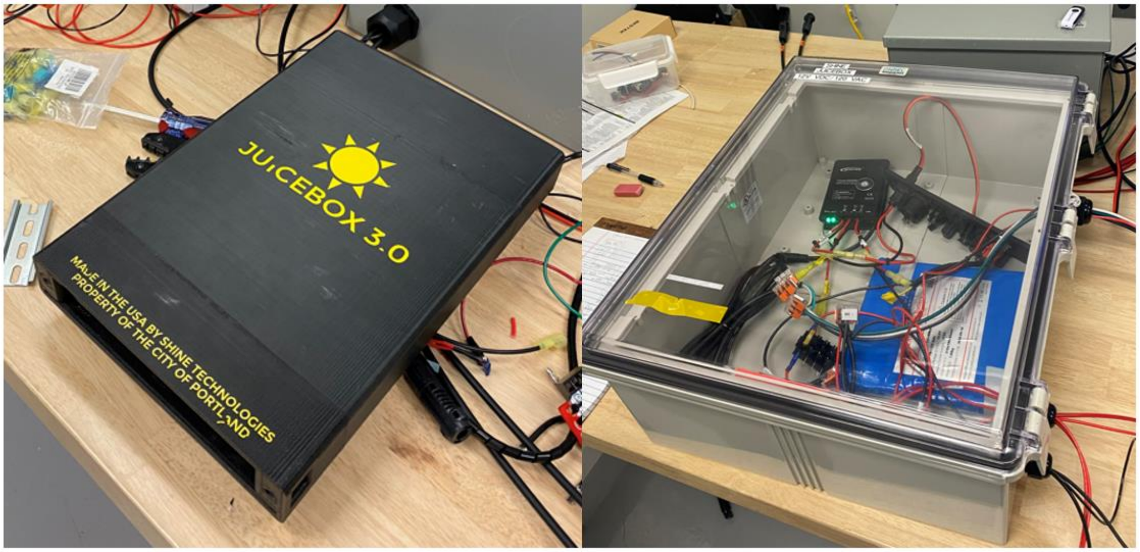

Figure 1. JuiceBox 3.0 Enclosure (left) and components as assembled for testing in safety enclosure (right).

2. JUICEBOX 3.0 TEST SYSTEM OUTLINE AND PROCEDURE

Figure 2 provides a diagram of the Shine Technologies LLC JuiceBox 3.0 and test equipment. One PV simulator is used to provide DC power charge controller input in JuiceBox 3.0.

2.1. Test Setup and Test Conditions

NREL furnished a power analyzer to make efficiency measurements. The power analyzer is a Yokogawa WT1806E Precision Power Analyzer with Hall-effect current transducers of 1% accuracy.

NREL provided the required simulated PV input using TerraSAS 600V 25A PV simulator.

Shine Technologies LLC provided the unit for test. Two different types of unit output modes were tested (low and high voltage types) at six different power levels.

The approximate size of the JuiceBox 3.0 prototype is: 3”H x 12”L x 16”W.

NREL staff made the electrical connections to Shine Technologies LLC’s JuiceBox 3.0 unit and manually programmed the electronic load achieve the desired 12 V DC output voltage. Six different load levels were each allowed to persist for about 10 seconds to provide time to capture input power, output power, and efficiency at each power level.

A wiring box prepared by NREL staff includes voltage taps and connections to measure the current. The JuiceBox 3.0’s DC and AC outputs are similarly connected to an output box with wiring for voltage and current measurements. The output box is then connected to electronic load (simulated DC and AC loads).

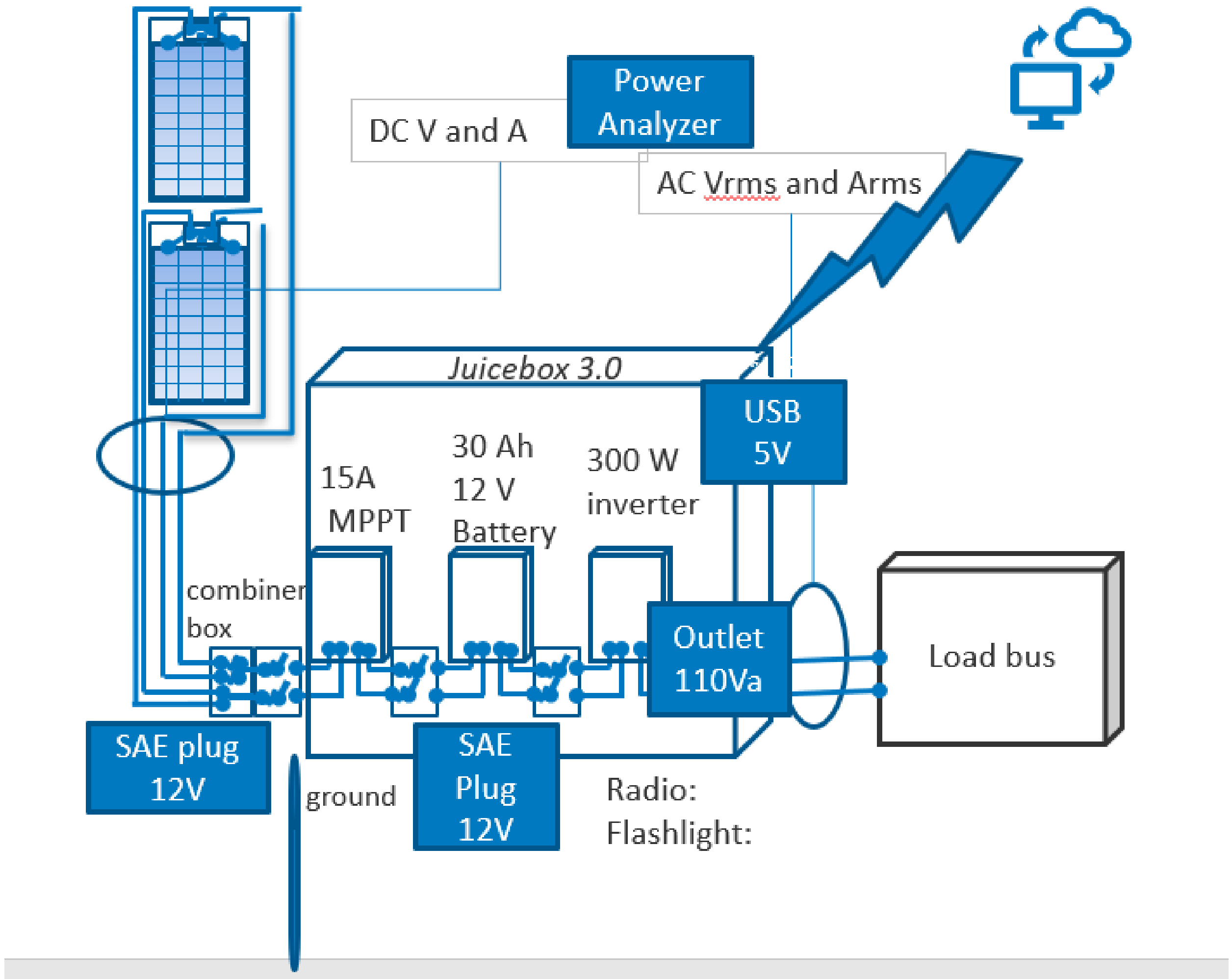

Figure 2. Diagram of JuiceBox 3.0 test apparatus including PV simulator DC power supplies; JuiceBox 3.0 components; electronic DC load bank, and instruments.

The following procedure was used to test the Shine Technologies LLC. JuiceBox 3.0, referenced as the unit under test (UUT) at NREL. (NREL safety processes and requirements were observed all the time when running this test procedure):

1) Set up the UUT for testing. Done one time for any series of tests.
   a. With the UUT on the test bench connect the following:
      i. Input power supply from PV simulator
      ii. Output load to electronic load simulator
      vi. Connections of Voltage and Current Measurements to each channel (6 total) of Power Analyzer
         1. DC Input into Inverter: Voltage and Current
         2. DC Power to DC Loads: Voltage and Current
         3. Battery Terminals: Voltage and Current
         4. AC output from Inverter: Voltage and Current
         5. Not Used
         6. Photovoltaic simulator input to Charge Controller: Voltage and Current
2) For each of the six power analyzer channels above (#5 not used), the following information is recorded:
   a. Input voltage
   b. Input current
   c. Output voltage
   d. Output current
   e. Total output power
   f. Efficiency as calculated within the power analyzer for charge controller and inverter
3) Save power analyzer data onto laptop and memory card
4) Set new power level on PV Simulator, repeat for each of the following power levels:

Table 1. The six power levels at which the JuiceBox 3.0 charge controller and inverter were tested.

Load Step	Total Power (W)
1	10%
2	20%
3	30%
4	50%
5	75%
6	100%

5) Verify data, check for reasonable results

Figure 3. JuiceBox 3.0 unit under test. Visible are (left to right) input wiring box; power analyzer; unit under test; output wiring box; electronic load. Photo by Andy Walker

3. ELECTRICAL TEST RESULTS

3.1. Maximum Power Point Tracking Effectiveness

NREL provided input power required to test the units from PV simulators. Each PV simulator is a TerraSAS capable of 600 VDC and 25 A. The current-voltage (I-V) curve for a representative mono-crystalline silicon PV module of 100 W rated output under Standard Test Conditions was programmed into the PV simulator. The simulated sunlight level was then changed in steps to evaluate the ability of the maximum power point tracking function of the JuiceBox 3.0's integrated charge controller to find the optimal operating voltage (knee of I-V curve). Solar input and MPPT effectiveness are summarized in the following table.

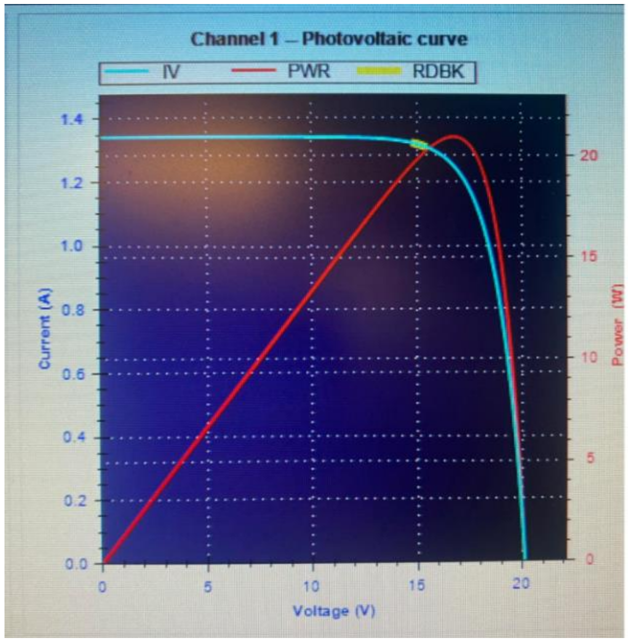

Figure 4. Screen Shot of PV Simulator at 20W power level showing operating point (yellow) and optimal power point (peak of red curve).

The effectiveness of the Maximum Power Point Tracker to identify the optimal power point is plotted in Figure 5 and listed in Table.

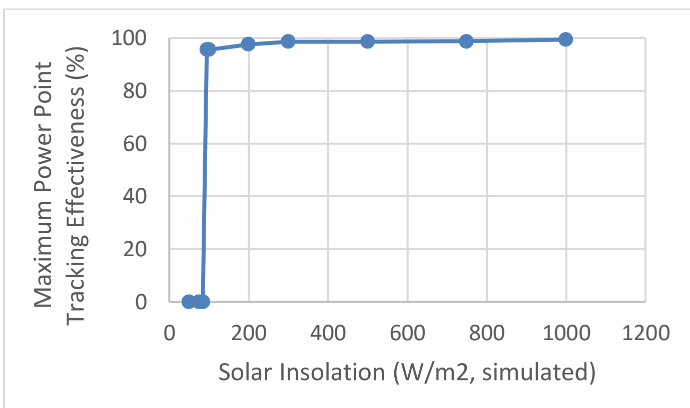

Figure 5. Efficiency of Maximum Power Point Tracker (actual power/optimal power).

Table 2. Effectiveness (actual power/optimal power) of Maximum Power Point Tracker

Solar Insolation (W/m2, simulated)	MPPT Effectiveness (%)
50	0
75	0
85	0
95	95.6
100	95.6
200	97.6
300	98.6
500	98.7
750	98.8
1000	99.4

Maximum Power Point Tracking is very effective at Solar Insolation levels above 95 W/m2, but at lower power levels the device searches for, but does not find, the optimal voltage. Power output is erratic but low as the voltage bounces back to open circuit voltage.

3.2 Charge Controller: Capacity and Efficiency

Charge controller efficiency is defined as DC power to the load or battery terminals divided by DC power from the PV module, at the voltage controlled by the maximum power point tracker.

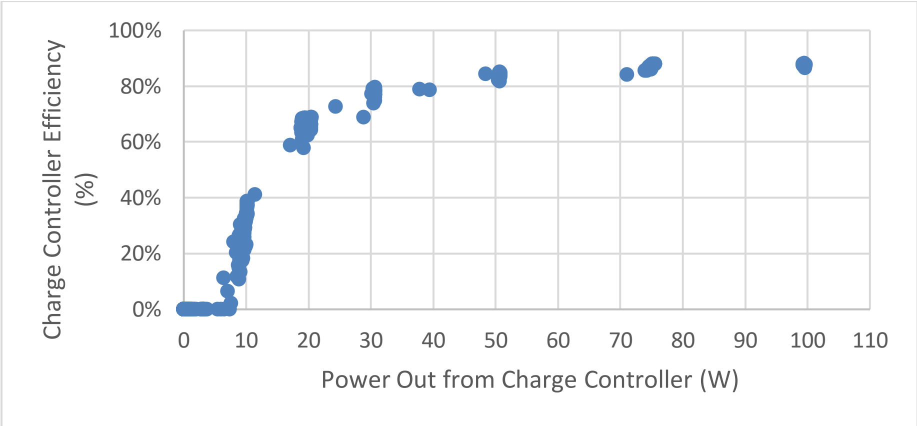

Figure 6. Efficiency of Charge Controller (power in/power out) as a function of output power level.

The charge controller maintains a high efficiency from 50 W to 100W, but efficiency drops precipitously at output power less than 30 W and fails to operate at levels less than 10 W output. Table 3 shows the measured efficiency at each power level and a "weighted" efficiency based on weighting factors at each power level.

Table 3. Efficiency (power out/power in) of Charge Controller at different power levels with weighted efficiency.

Power Out (W DC)	10	20	30	50	75	100
Charge Controller Efficiency (%)	22	64	74	82	86	87
Weighting Factor	0.04	0.05	0.12	0.21	0.53	0.05
Weighted Efficiency (%)						80.11

3.3 Battery Capacity and Round-Trip Efficiency

Battery capacity and round-trip efficiency were measured by fully discharging the batter to Low Voltage Disconnect (LVD) and then fully charging the battery to Over Voltage Disconnect (OVD). Power (voltage*current) was integrated to measure energy into the battery during charging and energy recovered from the battery during discharge.

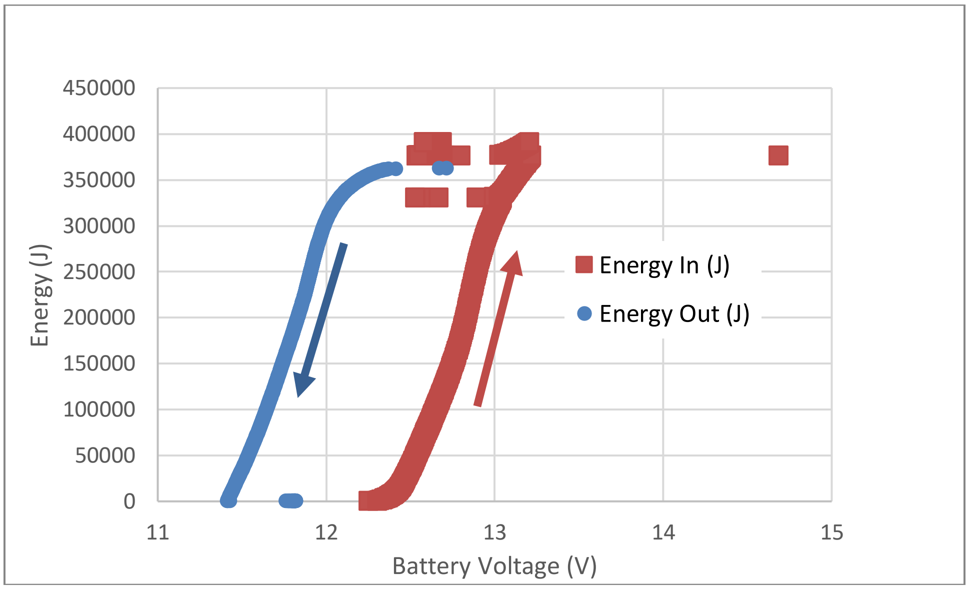

Figure 7. Energy into battery during charging (orange) and energy out of battery during discharging (blue) as a function of battery voltage.

The Low Voltage Disconnect (LVD) was found to be 11.4 V, and the Overvoltage Disconnect was found to be 13.2 V. During charging at 100 W rate the battery absorbed 391 kJ of energy corresponding to 9.0 Ah at nominal 12V. During discharging at 50 W rate the battery returned 362 kJ of energy corresponding to 8.38 Ah. The batteries are rated at 30 Ah capacity which at 80% depth of discharge would be 24 Ah but acknowledge that this measured capacity is limited by the setpoints of the charge controller and low voltage disconnect, so not dependent fully on the battery but rather the effective capacity realized by the system. These charge and discharge rates were selected as representative given that the system can charge mainly for the midday hours when solar is maximum and can discharge at any time of day or night.

Table 4. Voltage setpoints (LVD and OVD) and energy quantities measured during charging and discharging of battery, with round-trip capacity and efficiency.

Charging

LVD Voltage (V)	11.376
OVD Voltage (V)	13.208
Energy In (J)	390843.6
Charge in (Ah, 12 V)	9.047306
Energy In (Wh)	108.5677

Discharging

LVD Voltage (V)	11.415
OVD Voltage (V)	12.714
Energy out (J)	-362111
Charge out (Ah, 12 V)	-8.38221
Energy out (Wh)	-100.586

Battery Capacity	100.59	Wh, @ 50 W rate
Battery Efficiency	92.65%	

The effective capacity of the battery between LVD and OVD, and at the representative charge/discharge rates applied here, is 100.6 Wh, corresponding to 8.4 Ah at nominal 12V.

The round-trip efficiency of the battery measured in this test with these charge and discharge rates and room temperature is 92.6%

3.4 Inverter Capacity and Efficiency

The JuiceBox 3.0 was provided with a “Bestek 150” inverter rated for 150 W output. However, as shown in Figure 8 the inverter was not capable of supporting 150 W output and failed to support output voltage above 100W. In order to investigate whether this problem was caused by the inverter or the capabilities of the battery the test was repeated with a dedicated power supply rather than the JuiceBox battery with similar results. Two additional inverters were purchased and tested, one labeled “LVYuan 150” and the other labeled “Foval 150” and both rated for 150 W output. None of the three inverters was able to achieve the rated 150 W output.

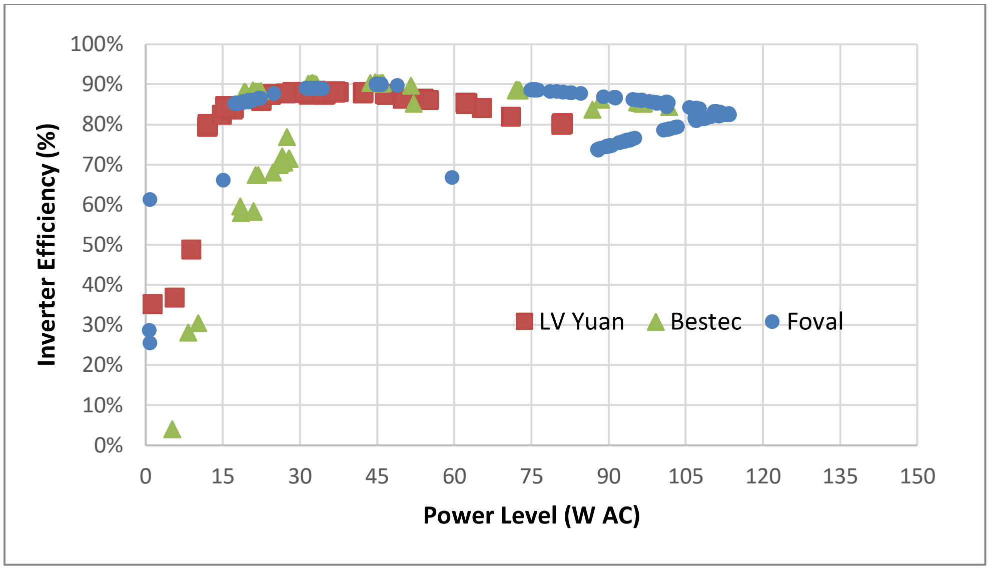

Figure 8. Efficiency as a function of power output (W) for three different inverter make/model tested.

Performance of the "Foval 150" was better than the other two in that it achieved a higher power rating of 113.6 Watts and also maintained a higher efficiency than the other two as shown in Figure 8. Because of its better performance, we calculate a weighted efficiency for the Foval 150 inverter in Table below.

Table 5. Inverter efficiency measured at six different power levels for three different make/model of inverters. Weighted efficiency is calculated for "Foval 150" inverter.

	Power Level (W)					
	15	30	45	75	112.5	150
LV Yuan	85.2%	87.3%	87.5%	80.0%	fail	fail
Bestec	50.0%	71.3%	89.7%	88.5%	fail	fail
Foval	82.4%	88.9%	89.7%	88.5%	84.2%	fail
CEC Weighting	0.04	0.05	0.12	0.21	0.53	0.05
					CEC Efficiency	0.817

Considering the Foval 150 inverter, the capacity was measured at 113.6 W and the efficiency at a weighed value of 81.7%.

3.5 Thermal Considerations

The JuiceBox 3.0 prototype provided was fabricated using a 3D printer of plastic, and thus lacked an aluminum heat sink or ventilation fan. Because we separated the components in a separate test enclosure, the potential for overheating was not investigated, but thermal management and passive or active cooling measures should be employed in the final product.

3.6 Experimental Uncertainty

The measurement uncertainty of each instrument is listed in the following table (Yokogawa 2018).

Table 6. Accuracy of each instrument involved in the test.

Quantity	Instrument	Make	Model	Accuracy	Reference
DC Voltage	Power Analyzer	Yokogawa	WT1806E	+/- 0.05% of range down to 0.1% of range	Yokogawa WT1800 Manual & Output data from Power Analyzer
DC Current	Power Analyzer	Yokogawa	WT1806E	+/- 0.05% of range down to 0.1% of range	Yokogawa WT1800 Manual & Output data from Power Analyzer

The relative measurement uncertainty of each instrument was combined in a "root mean square" method to estimate the combined uncertainty of current multiplied by voltage (Hogan, 2015). The uncertainty in power measurement is thus $\sqrt{(0.0005^2 + 0.0005^2)}$= 0.000707 or 0.071%. This points out the difficulty of efficiency tests that involve measuring small differences in input and output power, where the uncertainty in the measurement is significant compared to the phenomenon to be measured. Strategies to reduce uncertainty employed here include:

1. Very high accuracy (0.05%) current and voltage measurements via sophisticated power analyzer (much better than revenue grade meters commonly available).
2. Configuration of circuits to measure in order: input current, then input voltage, then output voltage, then output current. The arrangement excludes voltage drop through current measurement.
3. Adjust range (auto range feature of power analyzer) to near the magnitude of the current being measured to minimize absolute error (in units of amps) for a given relative error in measurement.

4.0 SYSTEM SIMULATION MODEL (HOMER MODEL)

The utility of these test results is to normalize the parameters of a computer model, so that the performance of the JuiceBox 3.0 can be evaluated under different circumstances of solar resource and load profile. Such a computer model is created using the HOMER software.

4.1 Component Models

PV Module

The simulated PV module is a generic (no particular brand name) with the following specifications:

Rated Power (STC Rating Conditions)	100 W
Temperature Coefficient of Power	-0.4 % /C
Nominal Operating Cell Temperature	47 C
Reference Efficiency at 25C	20 %

Charge Controller

Based on the experimental results described above, the efficiency of the maximum power point tracker/charge controller is as listed in the following table.

Input Power (% of rated)	Efficiency (%)
100	87
75	86
50	82
30	74
20	64
10	22

Battery

The battery was modeled with the specifications in the following table based on the results of the experiment. The capacity is measured between the Low Voltage Disconnect Voltage and the Overvoltage Disconnect Voltages so this entire capacity is exercised.

Nominal Battery Voltage	12 V
Battery Charge Capacity	8.38 Ah
Battery Energy Capacity	101 Wh
Maximum Charge Current	10 A
Maximum Discharge Current	15 A
Round-trip Efficiency	92.7%

Inverter

The inverter converts 12 V battery voltage to 120 VAC single phase power for conventional household appliances that plug into the JuiceBox 3.0 power outlet. The inverter is modeled with a peak capacity of 150W and an average weighted efficiency of 81.7%.

4.2 Climate Data for use in Computer Simulation: Hurricanes Irma and Maria, Puerto Rico 2017

The computer simulation can accept climate data for any location and dates for which data is available. In order to examine the model performance in a hurricane disaster situation data corresponding to the time of Hurricane Maria is selected from the NREL National Solar Radiation Database [nsrdb.nrel.gov, Sengupta et al, 2018] for San Juan Puerto Rico, the year 2017.

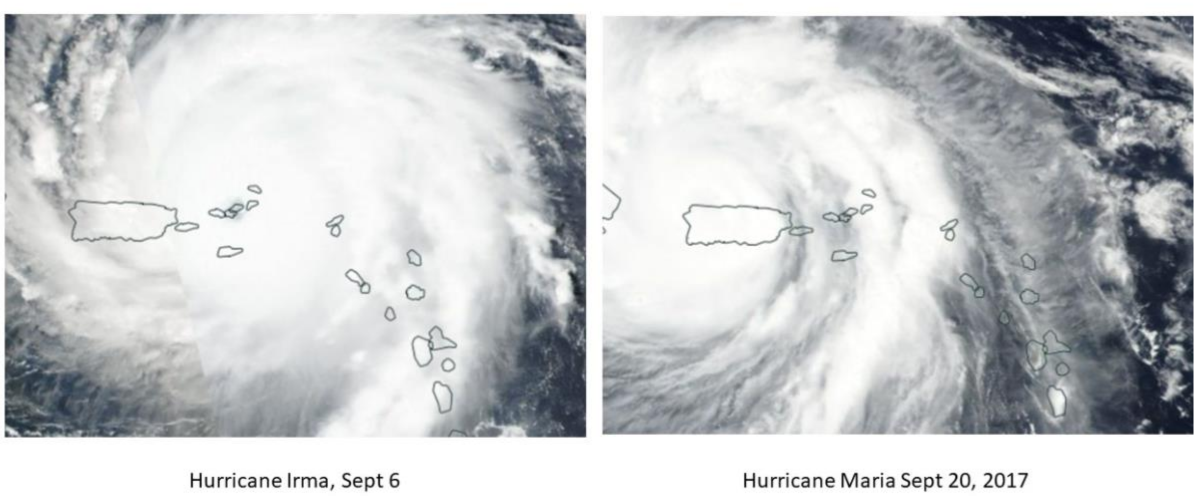

Figure 9. Performance of JuiceBox3.0 is modeled using conditions of Hurricanes Irma (left) and Maria (right) which hit San Juan Puerto Rico on Sept 6 and Sept 20, 2017 (images from worldview.earthdata.nasa.gov, 3/14/2022)

Global Horizontal Insolation for these dates is shown in Figure 10, illustrating how the available solar radiation is reduced by the hurricanes in September of 2017.

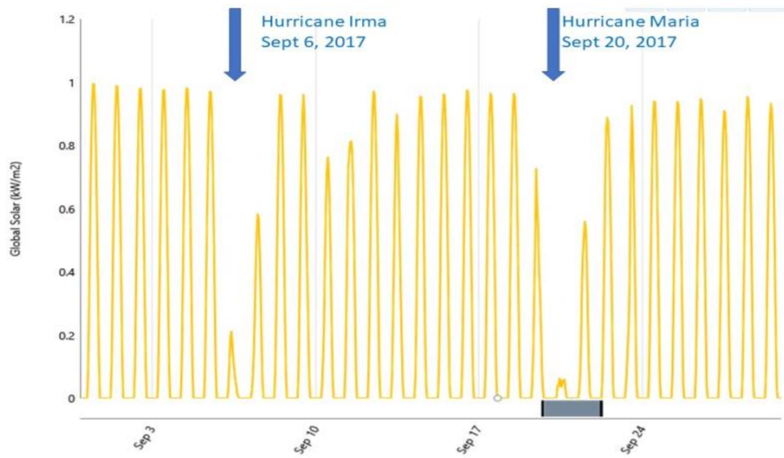

Figure 10. Global Horizontal Insolation (W/m2) for the Month of September 2017, San Juan Puerto Rico, showing the lack of solar radiation during Hurricanes Irma (Sept 6) and Maria (Sept 20).

4.3 Capability of system to support Load in Hurricanes Irma and Maria, Sept 2017

The specified JuiceBox 3.0 system (PV module, battery, charge controller, and inverter) was modeled using the 2017 Puerto Rico weather data and with both AC and DC loads varying from 50 Wh/day to 160 Wh/day. For the load of only 50 Wh/day, there are no hours of unmet load during Hurricane Irma and only one hour of unmet load during hurricane Maria as shown in Figure 10.

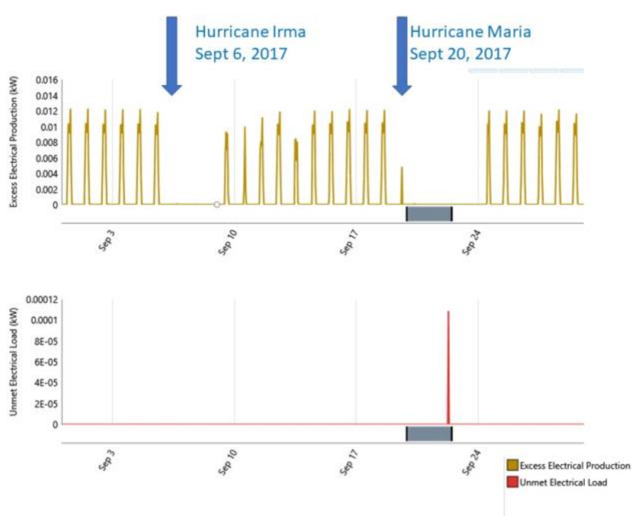

Figure 11. Excess Electrical Production and Unmet Electric Load for the Month of September 2017, San Juan Puerto Rico, showing the lack of excess generation during Hurricanes Irma (Sept 6) and Maria (Sept 20), and a small amount of unmet electric load on Sept 23. The load is 50 Wh/day, AC.

4.4 Example Performance Prediction: The year 2020, Puerto Rico.

Figure 11 shows Excess Electricity Production (kWh/year) and Unmet Load (kWh/year) for Direct Current (DC) loads using weather data from San Juan Puerto Rico for the year 2017 (Jan 1 to Dec 31). For the direct current loads, the system reliably carries a load of about 100 Wh/day, with load quantities greater than that resulting in more unmet load.

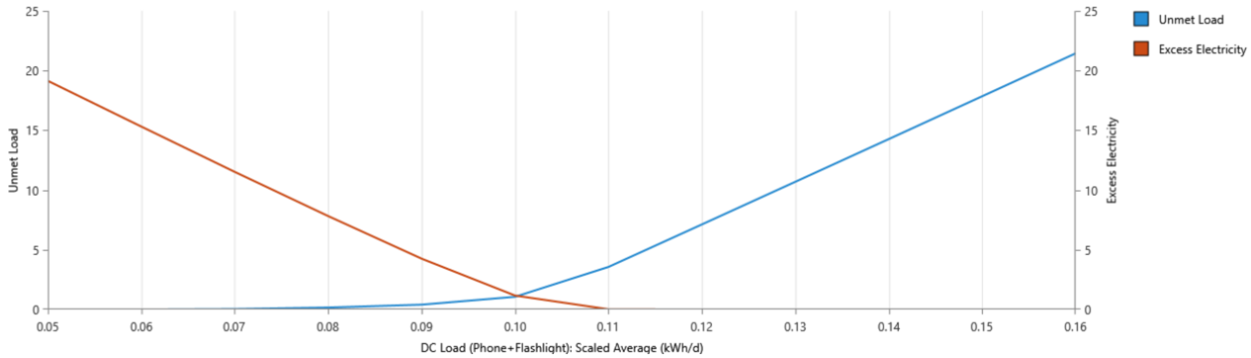

Figure 12. Excess Electric Production (right) and Unmet Load (left) as a function of Direct Current (DC) Daily Load (kWh/day) from 50 Wh/day to 160 Wh/day for the JuiceBox 3.0, climate data is 2017, San Juan Puerto Rico.

Figure 12 shows the same performance metrics, Excess Electricity Production (kWh/year) and Unmet Load (kWh/year), for Alternating Current (AC) loads using weather data from San Juan Puerto Rico for the year 2017 (Jan 1 to Dec 31). For the AC loads, the system reliably carries a load of about 80 Wh/day, with load quantities greater than that resulting in more unmet load. The system is capable of carrying less AC load than DC load due to the additional losses associated with inverter efficiency.

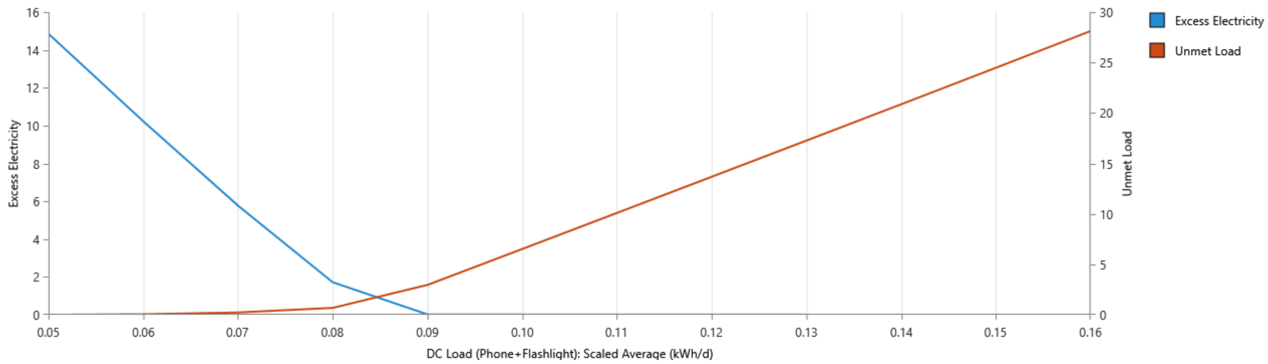

Figure 13. Excess Electric Production (right) and Unmet Load (left) as a function of Alternating Current (AC) Daily Load (kWh/day) from 50 Wh/day to 160 Wh/day for the JuiceBox 3.0, climate data is 2017, San Juan Puerto Rico.

5. CONCLUSIONS AND FUTURE WORK

The JuiceBox 3.0 is a stand-alone power system consisting of a 100 W PV module, charge controller, battery, and inverter to serve DC loads (USB and DC outlets) and AC loads (110V AC outlet). Several tests of the unit were conducted to measure parameters that describe system performance. The following results were achieved through testing:

- The efficiency of the charge controller was measured at six different power levels with a weighted average efficiency of 80.1%.
- The Battery was rated for 30 Ah, 360 Wh capacity. The capacity measured between the Low Voltage Disconnect and Overvoltage Disconnect voltage of the charge controller was found to be 8.38 Ah or 100.6 Wh battery capacity at a 50 W discharge rate.
- The round-trip-efficiency of the battery was measured to be 96.2%.
- The inverter supplied with the Juicebox (Bestec 150), although rated for 150W, delivered only 50W Alternating Current. Other small inverters used in its place also failed to produce the full 150W (Yoval 150 and LVYuan 150), however, the Foval unit provided the most, at 110 W AC output, and so the measured efficiency of this inverter model was used in the modeling. The efficiency of the Yoval 150 inverter was measured at six different power levels with a weighted average efficiency of 81.7%.

The system was modeled using the HOMER computer program and the performance parameters (capacity and efficiency) measured in the testing phase. The model analyzed performance of the system using weather data for San Juan Puerto Rico, and for 2017 which includes the weather effects of both Hurricanes Irma and Maria in September of 2017. A daily load profile varying from 50 Wh/day to 160 Wh/day was modeled for both DC and AC loads. The following results were achieved through modeling:

- Even at the lowest load level of 50 Wh/day, the system had one hour of loss-of-load during Hurricane Maria but served the 50 Wh/day load through the preceding Hurricane Irma with no loss of load.
- Considering the whole year of 2017, the system as modeled could reliably serve a DC load of 100 Wh/day or an AC load of 80 Wh/day, with the difference being caused by the inverter efficiency.

6. REFERENCES

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Subject Inventions Listing:

None.

ROI #:

None.