Technology Evaluation of the Yotta SolarLEAF: A Panel-Based Thermally Managed Battery Module

Aron Saxon and Willy Bernal Heredia

National Renewable Energy Laboratory

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Executive Summary

Yotta Energy has developed an energy storage system, the SolarLEAF, that provides solar energy storage without increasing the footprint of a solar array. This is particularly useful in applications with limited space (e.g., a building roof) and where large-scale batteries require strict requirements for fire suppression systems. Yotta Energy's SolarLEAF is a PV-coupled decentralized energy storage technology. The prototype utilizes lithium-iron-phosphate battery chemistry and features passive thermal regulation to mitigate fire risk without affecting the equipment lifespan.

As part of the Wells Fargo Innovation Incubator (IN²), the National Renewable Energy Laboratory (NREL) conducted a third-party technology validation of Yotta's SolarLEAF prototypes. Initially, Yotta provided an alpha-level prototype (referred to in this report as the "Alpha Prototype"). During the characterization experiments, Yotta produced a beta-level prototype ("Beta Prototype"), which is closer to production design and retains the core physics around passive thermal management of the battery. NREL and Yotta decided to characterize the Beta Prototype for the remainder of the experiments (including experiments mimicking real-world applications). The Beta Prototype features improvements over its predecessor, such as an internal heater to improve the cold temperature performance of the system. Yotta Energy also provided a baseline version, without Yotta's passive thermal regulation shell, for each prototype to help with comparisons. The experiments conducted are summarized in Table A. This report includes a summary of the objectives, technology description, methodology, and results from experiments conducted at the Thermal Test Facility at NREL.

Table A. Summary of Experiments

Group	Name	Metrics	Details
A	Capacity	Battery capacity and round-trip efficiency	Alpha: 0°C, 30°C, 40°C. Beta: 30°C.
B	Solar Firming Cycle	Electrical cycling performance	Alpha: Results not available due to BMS going into standby mode. Beta: Results available.
C.1	Electrical Stable Condition	Thermal response to ambient changes (no cycling)	Alpha: 25°C → 0°C and 0°C → 25°C, 25°C → 40°C and 40°C → 25°C, 25°C → 45°C and 45°C → 25°C, and 25°C → 50°C and 50°C → 25°C. Beta: 25°C → 50°C and 50°C → 25°C.
C.2	Cycling Condition	Thermal response to ambient changes (with cycling)	Cycling 20% → 80% SoC. Alpha and Beta: 25°C → 50°C and 50°C → 25°C.
D	1-Week Weather Profile	Thermal response to emulated real-world application	Beta: Hot summer week in Phoenix, Arizona. Battery followed a firming cycle.

Passive thermal is especially beneficial in energy storage applications because it eliminates the energy draw of the thermal management system, which allows the system to convert more input energy into storage. Overall, the Yotta passive cooling technique worked exceedingly well at delaying the time the system took to reach an over-temperature ambient condition. In a moderate case, the equilibrium time was shifted by almost 100 hours; for an extreme case, the system was able to delay the time by almost 70 hours. The prototype was also able to reject heat faster than it was absorbed, in most cases. This illustrates its ability to cool off when ambient temperatures fall below the internal system temperature for a short period of time. Fine-tuning of the technology will prevent heat path saturation at higher internal to ambient temperature deltas.

Figure A illustrates how the SolarLEAF Beta Prototype responds to a transition to an elevated temperature. Figure A(a) shows the transition from a soak temperature of 25°C to an equilibrium of 50°C; Figure A(b) shows the

Figure A. Yotta SolarLEAF Beta 50°C thermal response

**Demonstration of the SolarLEAF system to prolong heating.
Also illustrates system's ability to reject heat faster than absorbed.**

transition from a soak temperature of 50°C to an equilibrium of 25°C. The Beta Baseline unit equilibrated at 50°C after about 15 hours, whereas the Beta Prototype equilibrated at about 70 hours (about 4.5x slower than the Beta Baseline unit). The transition of the Beta Prototype back to 25°C was only about 10 hours faster than the 50°C transition. Also noteworthy is that although the full equilibration time between the Alpha and Beta systems was around 60 hours, the time it took the Beta system to take the system below 30°C was around 20 hours, and around 40 hours for the Alpha (see Figure 16). This indicates an improvement in heat rejection between the Alpha and Beta iterations.

The results from the maximum power rate cycling data reveal the temperature variation within the battery system. Under a continuous 300-W charge/discharge cycling between 20% and 80% state of charge, the temperature variation inside the battery pack rose to 7°C. The heat spread of this magnitude was only observed when the SolarLEAF was cycled at a more rigorous rate than the intended application; the system is designed to undergo a maximum of 1–2 cycles per day—not continuously at full power. The temperature variation during less stringent experiments stayed below 2°C.

The final experiment on the Yotta SolarLEAF was a diurnal temperature cycle combined with electrical cycling. The use case for the temperature cycling is a derivation of a typical hot summer week in Phoenix, Arizona. The augmentation of the cycle is to accommodate temperatures that Yotta has observed in field deployments. The electrical cycling was designed to best emulate the system's intended use case. Figure B illustrates the results of this experiment. The Beta Baseline was not able to follow the electrical cycle due to a sensor malfunction, which is discussed in further detail later in the report. This experiment showcased the ability of the SolarLEAF to protect the battery system from temperature extremes. During the experiment, the ambient temperature reached 52°C, while the cooler portions were around 30°C. The maximum temperature measured inside the system was 42°C for the duration of the experiment occurring on simulated day 4. Our work shows that the system can recover from this high temperature. Future experimentation could include a long-term version of this experiment—possibly in a field deployment—to verify whether this behavior is sustained beyond a week.

Figure B. Yotta SolarLEAF Beta response to simulated Phoenix week

Demonstration of system response emulating installation temperature and cycling profile.

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Acronym List

BMS	battery management system
CAN	Controller Area Network
IN ²	Wells Fargo Innovation Incubator
NREL	National Renewable Energy Laboratory
PCM	phase change material
PNNL	Pacific Northwest National Laboratory
PV	photovoltaic
RMS	root mean square
Sandia	Sandia National Laboratories
SoC	state of charge

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1 Introduction

In 2019, the United States installed 13.3 gigawatts (GW) of solar energy production capacity (Solar Energy Industries Association, 2020). This demand for solar will continue to increase as fossil fuels continue to slowly phase out. As the demand for solar energy grows, so does the demand to store this generated energy. It is projected that by 2035, the global demand for stationary energy storage may expand by more than a factor of 10; from 15.2 GWh in 2019 to 222.7 GWh (Lux Research, 2019). The falling cost of energy storage, reforms of electricity markets, and the rising value of resilience due to increased renewable production will drive this demand. Scalable solutions will need to overcome the significant cost and value barriers to reach large-scale adoption.

Most large solar deployments exist in hot desert conditions. High temperatures can significantly shorten battery life, which increases cost due to replacement. To avoid this downfall, thermal management is critical to maintaining proper cell temperatures (e.g., inside specific bounds and balanced across battery packs) efficiently and cost-effectively. Active cooling technology, such as air or liquid systems, requires additional energy and can significantly increase the complexity of the system. Alternatively, thermal management through phase change material (PCM) can provide passive thermal regulation to the module. This technology is garnering attention because PCM can effectively regulate temperature due to its high latent heat of fusion.

Yotta Energy recently developed an energy storage system, the SolarLEAF, that features passive thermal management through PCM integration. The rack-mounted design avoids increasing the footprint of the solar array. This is particularly useful in applications with limited space (e.g., a building roof) and where large-scale batteries necessitate strict requirements for fire suppression systems. The Yotta strategy is to disperse the storage throughout the solar installation. In a large storage system, the risk of collateral damage is significant. By distributing the storage throughout the installation, the risk of large-scale failure is also minimized. The system can “piggyback” off the footprint of the solar array by having it installed on the backside of the solar panel. This application does not add system complexity to the power electronics because it feeds directly to the solar array’s DC bus.

As part of the Wells Fargo Innovation Incubator (IN²), NREL conducted a third-party technology validation of two of Yotta Energy’s SolarLEAF prototypes. Initially, the evaluated prototype system was an alpha-level prototype (referred to in this report as the “Alpha Prototype”). Later on, a beta-level prototype (“Beta Prototype”) was presented by Yotta with improved features and performance.

This report is organized as follows: chapter 2 lists the agreed-upon objectives that NREL, Yotta, and IN² reached for with this technology demonstration, chapter 3 presents the Yotta Energy Leaf and the specifications of the two evaluated prototypes, chapter 4 describes the methodology and experimental setup to evaluate this technology, and chapter 5 details the electrical and thermal response of the prototypes. Finally, chapter 6 summarizes the results and makes recommendations for future experimentation.

2 Objectives

To benchmark the technology, NREL, Yotta, and IN² developed the following primary objectives for the laboratory evaluation of Yotta Energy's SolarLEAF:

1. Assess the electrical characteristics of the battery (e.g., capacity)
2. Evaluate the thermal response of the system based on existing evaluation guidelines as well as customized experiments
3. Evaluate the thermal and electrical performance of the battery module for a specific weather pattern (e.g., 1-week weather profile for a hot climate).

The performance assessment was conducted for two prototypes at NREL.

3 Technology Description

Yotta Energy's SolarLEAF is a photovoltaic (PV)-coupled decentralized energy storage technology. The prototype utilizes a lithium-iron-phosphate battery chemistry and features passive thermal regulation to mitigate fire risk without affecting the equipment lifespan (see Figure 1). By leveraging the decentralized storage feature and the thermal management system, SolarLEAF aims to conserve building space, suppress the need for fire-mitigation systems, and increase solar capabilities.

Figure 1. Yotta's SolarLEAF technology and sample installation

SolarLEAF's passive thermal management system does not act as a parasitic loss on the energy storage system (e.g., external fans, refrigeration system). The prototype uses a phase change material (PCM) to modulate the temperature within the battery pack. By introducing a material that is tuned to a specific temperature, the temperature inside the battery system can be controlled within safe limits to minimize temperature aging. The PCM acts as a heat buffer and absorbs the heat energy that would normally be transferred to the battery system. Because the PCM's latent heat is considerably larger than its specific heat, the system can sink heat without incurring a considerable temperature rise. With additional heat, the PCM will eventually completely melt and have its temperature regulation greatly reduced. This process minimizes the ambient heating effects on the battery and absorbs heat generated from within the battery itself.

Additionally, the system includes a process that dumps internal heat faster than it is absorbed. This process helps freeze the PCM once the ambient temperature has dropped below the transition temperature. The cold side is protected by a built-in heat transfer cut-off around 20°C. This plus the high levels of insulation retain the battery's generated and external (buffered) heat to make the heater more efficient even in deep-freezing conditions. This heat could be beneficial to keeping the battery system above ambient temperatures and inside the "Goldilocks zone" longer. Yotta addressed this in the second prototype that NREL received by adding an internal heater.

As mentioned, Yotta provided an alpha-level prototype, a beta-level prototype, as well as a baseline version (without PCM) for each prototype to help with comparisons. Specifications for the Alpha Prototype and its comparable baseline units are in Table 1. The Beta Prototype is closer to production design and retains the core physics around passive thermal management of the battery. Once NREL received the Beta Prototype, the team shifted to only characterizing the Beta Prototype for the remainder of the experiments (including experiments mimicking real-world applications). The Beta Baseline had the same configuration as the Beta Prototype, but without Yotta's passive ther-

mal regulation shell. The specifications for the Beta Baseline and the Beta Prototype are in Table 2. As mentioned, the Beta Prototype features an internal heater (not found in the Alpha) to improve the cold temperature performance of the system.

Table 1. Yotta Alpha Baseline and Alpha Prototype Specifications

Specification	Alpha Baseline	Alpha Prototype
Storage Capacity	480 Wh	490 Wh
Nominal Voltage	48 V	49 V
Cell Cycling Limits [Lower/Upper]	2.8 V/3.5 V	Cell-Level Voltage Not Available
Maximum Input/Output Power	96 W/480 W	300 W/300 W
Maximum Input/Output Current	2 A/10 A	8 A/8 A
Battery Type	Lithium Iron Phosphate (LiFePO ₄) 16S3P	Lithium Iron Phosphate (LiFePO ₄) 16S3P
Temperature Range	-10°C to 60°C	-20°C to 55°C
Dimensions (L x W x D)	29.9"x 20.9"x 3.7" 76.0 cm x 53.2 cm x 9.5 cm	29.9"x 20.9"x 3.7" 76.0 cm x 53.2 cm x 9.5 cm
PCM	No	Yes
Internal heater	No	No

Table 2. Yotta Beta Baseline and Beta Prototype Specifications

Specification	Beta Baseline	Beta Prototype
Storage Capacity	875 Wh	875 Wh
Nominal Voltage	48 V	48 V
Cell Cycling Limits [Lower/Upper]	2.8 V/3.49 V	2.8 V/3.49 V
Maximum Input/Output Power	400 W/400 W	400 W/400 W
Maximum Input/Output Current	10 A/10 A	10 A/10 A
Battery Type	Lithium Iron Phosphate (LiFePO ₄) 12S8P	Lithium Iron Phosphate (LiFePO ₄) 12S8P
Temperature Range	-10°C to 55°C	-10°C to 55°C
Dimensions (L x W x D)	15.75"x 26.25"x 4.25" 40 cm x 66.7 cm x 10.8 cm	15.75"x 26.25"x 4.25" 40 cm x 66.7 cm x 10.8 cm
PCM	No	Yes
Internal heater	No	Yes

4 Approach

Our analysis of the Yotta Energy prototype units can be broken down into two categories: electrical evaluation of the energy storage system and thermal evaluation of Yotta's novel thermal management system. To evaluate the energy storage aspect, we referenced the Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems (David R. Conover, et al, 2016), developed by Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratories (Sandia). NREL evaluated the energy storage system following the guidelines outlined in Chapter 5.2 and 5.3 in the Protocol.

Our evaluation of the thermal management aspect of Yotta's technology followed a custom protocol. This protocol was developed to map how the Yotta system minimizes cell aging when ambient temperatures are elevated outside of regions where lithium-ion batteries thrive. The region where batteries thrive is between 20°C and 30°C, where there is a balance between aging minimization and performance maximization (known colloquially as the Goldilocks zone).

The thermal experiments outlined later in this section were designed to analyze the effectiveness of the PCM. This approach consists of an ambient temperature step response and a dynamic diurnal cycle.

4.1 Equipment

For this suite of experiments, we recorded the temperature and system voltage data using a National Instruments Compacted Data Acquisition System coupled with a custom National Instruments virtual tool that was designed for this experiment. The battery cycler used to charge and discharge the SolarLEAF was a Bitrode FTV-4 model with limits of 300 A and 100 V. The system temperature was controlled using a Cincinnati SubZero ZP32 environmental chamber.

4.2 Instrumentation

We instrumented the Alpha Baseline, Alpha Prototype, Beta Baseline, and Beta Prototype with thermocouples to map the temperature rise and gradient within the battery pack. K-Type thermocouples were used for these measurements. All cold junction compensations were corrected to ensure that the measurements were accurate. This was done using a water bath and cycling the measured temperature of the probes outside of their expected use range to ensure the measured range fell within calibration (we used a calibration range of -20°C to 75°C for this experiment). Figure 2(b) and Table 4 show the layout and location of the thermocouples inside the Alpha Baseline unit; Figure 2(a) and Table 3 show the layout and location of the thermocouples inside the Alpha Prototype. Similarly, Figure 3(b) and Table 6 show the thermocouples placement inside the Beta Baseline unit, while Figure 3(a) and Table 5 show the placement inside the Beta Prototype.

Table 3. SolarLEAF Alpha Prototype Thermocouple Locations

Thermocouple Number	Location
1	Battery middle right
2	Battery middle center
3	Battery middle left
4	Battery rear right
5	Battery rear center
6	Battery rear left
7	Battery front center
8	Electronics temperature
9	Internal case temperature
10	Exterior case temperature

Figure 2. Thermocouple instrumentation for the Alpha baseline and Alpha prototype enclosures.

Table 4. SolarLEAF Alpha Baseline Thermocouple Locations

Thermocouple Number	Location
11	Battery middle right
12	Battery middle center
13	Battery middle left
14	Battery rear right
15	Battery rear center
16	Battery rear left
17	Battery front center
18	Internal case temperature
19	Exterior case temperature

Figure 3. Beta thermocouple instrumentation

Table 5. SolarLEAF Beta Prototype Thermocouple Locations

Thermocouple Number	Location
1	Battery back left
2	Battery back center
3	Battery back right
4	Battery front left
5	Battery front center
6	Battery front right
7	Internal case temperature
8	Electronics temperature
9	Left outer PCM temperature
10	Center outer PCM temperature
11	Right outer PCM temperature
12	Heat pipe outlet temperature
13	Exterior case temperature

Table 6. SolarLEAF Beta Baseline Thermocouple Locations

Thermocouple Number	Location
14	Battery middle right
15	Battery middle center
16	Battery middle left
17	Battery rear right
18	Battery rear center
19	Battery rear left
20	Battery front center
21	Electronics temperature
22	Internal case temperature
23	Exterior case temperature

4.3 Experimental Methods

We divided our analysis of the Yotta SolarLEAF into four experimental groups: Group A, Group B, Group C, and Group D. A summary of the experiments group and description is shown in Table 7. Group A is focused on the evaluation of the SolarLEAF's storage capacity. Group B is focused on the ability of the SolarLEAF system to work in its intended use in the field under a controlled environment. Group C is focused on the thermal response of the novel thermal management system. Group D is intended as a capstone study and brings together all components from the previous three experiments.

Table 7. Summary of Experiments

Group	Name	Metrics	Details
A	Capacity	Battery capacity and round-trip efficiency	Alpha: 0°C, 30°C, 40°C. Beta: 30°C
B	Solar Firming Cycle	Electrical cycling performance	Alpha: Results not available due to the BMS entering standby mode. Beta: Results available.
C.1	Electrical Stable Condition	Thermal response to ambient changes (no cycling)	Alpha: 25°C → 0°C and 0°C → 25°C, 25°C → 40°C and 40°C → 25°C, 25°C → 45°C and 45°C → 25°C, and 25°C → 50°C and 50°C → 25°C. Beta: 25°C → 50°C and 50°C → 25°C.
C.2	Cycling Condition	Thermal response to ambient changes (with cycling)	Cycling 20% → 80% SoC. Alpha and Beta: 25°C → 50°C and 50°C → 25°C
D	1-Week Weather Profile	Thermal response to emulated real-world application	Beta: Hot summer week in Phoenix, Arizona. Battery followed a firming cycle.

4.3.1 Experiment Group A

Experiment Group A was designed to evaluate the energy storage capabilities of the Yotta system. Group A follows the test procedure outlined in Chapter 5.2 in the manual developed by PNNL and Sandia (David R. Conover, et al, 2016). Additionally, an experiment was included to quantify system resistance. The resistance measurement is helpful for any future modeling activities and to better track the battery degradation. Toward this purpose, the hybrid pulse power characterization experiment found in Chapter 3.4 of the Battery Test Manual for Electric Vehicles (Jon P. Christopherson, 2015) was conducted to acquire this measurement. The order of planned experimental runs and their associated reference manual can be found in Table 8. Capacity, round-trip efficiency, and pulse characterization were planned at 0°C, 30°C, and 45°C; all other experiments were planned to run at 30°C only.

Table 8. Experiment Group A: List of Experiments

Description	Reference
Capacity and round-trip efficiency	PNNL/Sandia 5.2.1 and 5.2.2
Response time and ramp rate	PNNL/Sandia 5.2.3
Standby energy loss (contactors closed)	PNNL/Sandia 5.2.4
Self-discharge rate (contactors open)	PNNL/Sandia 5.2.5
Pulse characterization	Battery Test Manual for Electric Vehicles 3.4

Response time/ramp rate, standby energy loss, and self-discharge experiments were deemed low priority and omitted from the experiments.

4.3.2 Experiment Group B

Experiment Group B was designed to evaluate how well the SolarLEAF performs under a dynamic cycle matching the system's end use. Three cycles were initially considered to evaluate the system (all found in PNNL/Sandia manual under Chapter 5.3): peak shaving duty cycle, renewable (solar) firming duty cycle, and PV smoothing duty cycle. Peak shaving is designed to smooth out the peak electrical demand on the grid. This cycle was selected to best emulate the system's intended operation; the primary Yotta SolarLEAF function is to interface directly with the solar panel and act as an energy buffer between the solar panel and the inverter. The two other cycles considered were the PV smoothing and renewable firming cycles. Those two are similar but have different purposes: PV smoothing is intended to limit ramp rates at the inverter, whereas the renewable firming cycle spans the gaps where renewable generation falls short or overgeneration occurs. Additionally, smoothing is applied for shorter periods (from seconds to minutes) while firming is applied in 15-minute to several-hour-long periods. The renewable firming cycle matched the design intent of the Yotta system more closely. This cycle was performed at 30°C.

4.3.3 Experiment Group C

Group C evaluates how the Yotta SolarLEAF thermal management system responds to controlled temperature changes. This group was divided into two focus areas to fundamentally understand how the system responds to ambient temperature changes.

Subgroup 1 ran with the system in an electrically stable condition: the battery was at a static 50% state of charge (SoC) and not cycling. The soak reference temperature was set to 25°C, then the ambient air temperature was changed and the internal temperature change was measured. The four soak temperatures that were chosen were 0°C, 40°C, 45°C, and 50°C. Both test articles, one prototype with its respective baseline, were placed in a 25°C controlled environment and soaked until a temperature variation of less than 0.5°C was observed across the battery pack. Once this level of thermal equilibrium was achieved, the ambient temperature was changed to the associated soak temperature and the system was left until the same 0.5°C temperature variation was achieved. We repeated this process for a total of three runs for the temperatures of 0°C and 50°C. The other two temperature profiles were omitted due to time constraints.

Subgroup 2 is a variation of Subgroup 1—this time, the battery was cycled during the ambient temperature changes. The purpose of this experiment was to analyze how well the thermal management system can handle the extra heat from cycling the battery system. The cycling profile was a simple square wave at the maximum rated power of the system (300 W). For each prototype, both the baseline and the prototype units were cycled at the same power—even though it was outside the manufacturer's recommended power level for the Alpha Baseline—for comparison. The temperatures were monitored closely and shutdown conditions of internal pack temperature of 50°C were used to protect the battery systems. For this experiment, the batteries were cycled between predetermined voltage-based SoC windows. The SoC was determined by running a "pretest" from 0%–100% SoC and recording equivalent voltages to equivalent energy levels. A dynamic SoC voltage reference was used to account for additional resistances within the battery system that skew the measured voltage; Lithium iron phosphate has a fairly flat voltage curve that makes predicting SoC difficult. 20% SoC voltage was determined by using the equivalent voltage under load where 80% of the total battery's energy was removed under discharge; 80% SoC voltage was determined to be the point where 80% of the total battery's energy was added under charge. This experiment was conducted on both the Alpha systems and the Beta systems (baselines and prototypes) at a reference temperature of 25°C, a soak temperature of 50°C, and an SoC window of 20%–80%.

4.3.4 Experiment Group D

The temperature profiles for these experiments were designed to emulate a summer week in a hot and dry climate. These experiments cycled the battery following the renewable firming cycle. Figure 4 provides the temperature distribution for a typical meteorological year and a specific year (2011) in Phoenix, Arizona. The typical weather data was preferred to avoid biasing the results by using extreme years. This experiment group was designed to evaluate how the Yotta SolarLEAF system would respond to hot weather patterns under typical load profiles.

Due to the modular design of the SolarLEAF system, the battery pack might be placed on rooftops, where the ambient air temperature can have significantly different temperatures than ground level. That bias is caused by differ-

ences in surface characteristics (e.g., material, color) and additional considerations (e.g., shading, proximity heat sources) (Brian D. Griffith, 2000). To address these roof-to-ground differences, the parameter M was used, which considers the impact of global horizontal irradiance (GHI) on the rooftop temperature; the M adds a fraction of the GHI to the ambient temperature profile, as shown in Figure 5. Figure 6 shows the two module temperature profiles used: $M=0.005$ reflects a moderate discrepancy between air and module temperature (5°C), whereas $M=0.013$ produces a 13°C differential at certain times. For the latter profile, the module temperature surpassed 55°C during the hottest time. This case might correspond to a dark roof with limited ventilation. These temperature profiles were selected to showcase the technology performance at high temperatures and emulate similar temperature peaks Yotta had encountered during its technology deployments.

The SolarLEAF charges and discharges during the use period as a way to balance the solar generation with the site's energy usage. The renewable firming cycle—used in Group B—was used to best emulate how the SolarLEAF would be cycled over a typical day. The cycle was repeated continuously to accentuate the heat generation of the battery system. In a field deployment, the cycling would be less rigorous because the battery system would only be charged by solar power. Therefore, no charging would occur during the nighttime. The root mean square (RMS) power of the cycle is a small portion of the rated system power, so the thermal impact from the additional charging is expected to be minimal. Since the system uses a small portion of the rated power, it is possible to trade a portion of the power potential for an increase in storage potential.

The Beta Prototype became available prior to running Group D experiments, so NREL and Yotta agreed to perform this set of experiments only on the latest prototype. Thus, only the results of the Beta Prototype are presented here.

Figure 4. Frequency of high temperatures

Figure 5. Weather curves according to elevation and roof characteristics

Figure 6. 7-day temperature profiles used in Group D experiments

5 Experimental Results

5.1 Experiment Group A Results

Group A was designed to study the potential of the Yotta SolarLEAF prototype as an energy storage system. To measure stored energy, the SolarLEAF unit was discharged at 200 W until the minimum cell voltage reached the lower cell voltage limit outlined in Table 1 and Table 2 for the respective system. It then rested for 5 minutes and was followed by charging until the maximum cell voltage reached the upper cell voltage limit. This cycle was repeated five times at each temperature: 0°C, 30°C, and 45°C. The first discharge was omitted from the capacity measurement because the starting SoC for that discharge was not controlled and thus was not a complete discharge. The capacity experiment was also run on the baseline units. Those data plots are available in Appendix B.

Group A originally included a hybrid pulse power characterization cycle to measure the DC internal resistance of the battery system. Upon early cycling, the output voltage of the Yotta system would drop out, indicating that the contactor had opened the electrical pathway to the battery system. This happened at the beginning of charging or discharging. If the program was able to finish the first or second charge or discharge steps, the system would complete the cycling. Upon discussing this observation with Yotta, we determined that the battery management system (BMS) on the Alpha Prototype was likely detecting a fault condition and opening the contacts. We also noted that the system utilized a solid-state contactor. On the other end of the circuit, the battery cyclers act as a current source, relying on the battery's capacitance to reach the target current. If the system capacitance is too low or the DC resistance too high, the battery cycler will ramp the current rapidly. The current ramp momentarily pushes past the current setpoint. This causes the BMS on the SolarLEAF to detect an overcurrent situation and protect the battery system. The workaround for this system was to change the cycling steps to controlled ramp rate steps to prevent the current spike. The switch from a steep current profile to a softer, more gradual current profile minimizes the effectiveness of the DC internal resistance measurements. To avoid further delays, NREL and Yotta agreed to deprioritize every experiment in Group A except for the capacity and round-trip efficiency measurements. This equipment mismatch is not expected to impact the system in a field deployment. It is an artifact of the laboratory conditions.

5.1.1 Alpha Prototype Results

30°C Data

A reference temperature of 30°C was used because it covers the zone where the battery can perform the best for the longest life. Figure 7 shows the results for all temperatures. Figure 7(c) shows the voltage/current plot and the regions omitted from the calculation. The average charge energy was measured as 439.3 Wh over four cycles, and the average discharge capacity was measured as 404.9 Wh over four cycles. The derived coulombic efficiency from these measured values reached 92.18%. For comparison, a single cell at these same conditions generally has a coulombic efficiency near 99%. The largest source of energy loss within a battery pack is due to the BMS and the BMS's balancing system. A simple experiment could be designed to measure the power consumption of the BMS under these conditions to determine what percentage of the energy was used by the management system. The cell balancing is a little more difficult to calculate because each cell within the pack has its balancing system and is generally internal to the BMS circuitry.

45°C Data

45°C is the first temperature to be compared against the 30° reference. Figure 7(d) shows the voltage/current plot and the cycles that were omitted from the calculations. The third charge cycle was omitted from the calculation because the accepted capacity of that cycle was much larger than the other three cases. This was because the maximum temperature inside the battery pack reached the temperature safety limit. The charge cycle was halted, but the BMS continued drawing energy—without any entering the battery. When the cycle was resumed, that energy loss was made up for, resulting in an artificially high charge acceptance. The measured average charge capacity was 437.8 Wh over three cycles, and the measured average discharge capacity was 399.1 Wh over four cycles. The derived coulombic efficiency from these measured values was 91.22%. Both the charge capacity and the discharge capacity

(a) Alpha Prototype capacity and round-trip efficiency summary

(b) Alpha Prototype voltage and current profile 0°C (red box indicates measurement omitted from calculation)

(c) Alpha Prototype voltage and current profile 30°C (red box indicates measurement omitted from calculation)

(d) Alpha Prototype voltage and current profile 45°C (red box indicates measurement omitted from calculation)

Figure 7. Alpha Prototype capacity results

Note: See Appendix A for more detailed figures.

were very similar to the 30°C case (within 1%). The measured discharge capacity was the most different of the two cases, but this is likely due to the increased cell balancing need at the elevated temperature.

0°C Data

The second temperature to be compared against the 30°C reference case is 0°C. Figure 7(b) shows the voltage/current plot and the cycle omitted from the calculations. The average measured capacity at 0°C was 383.4 Wh over four cycles under charge, and 350.2 Wh over four cycles under discharge. This equates to an available energy loss of about 12% from 30°C. These results are within expectations for the temperature change. The calculated coulombic efficiency at 0°C is 91.36%, which is very similar to the 45°C and 30°C cases. This result indicates that the ancillary loads on the system scale with temperature.

5.1.2 Beta Prototype Results

The Beta Baseline and Beta Prototype were only subjected to the Experiment Group A cycling at 30°C to provide a baseline comparison to the Alpha system. The observed results of the different temperature cases—0°C and 45°C—should be similar for the Beta system because the battery cell chemistry did not change between prototypes. The physical size of the battery pack was changed to accommodate more energy storage and power capabilities, but that will not impact cycling at the soak temperatures. Both additional cases are either well above or well below the PCM transition temperature.

30°C Data

Figure 8 and Table 9 present the results of the initial cycling of the SolarLEAF Beta Prototype at 30°C. Figure 8 shows the current and voltage trace of the battery system under a 5A charge and discharge; Table 9 shows the measured energy retained during charge and available under discharge. The measured discharge capacity of 830.4 Wh is slightly lower than the nameplate specification of 875 Wh. Again, this is primarily due to the parasitic losses discussed in section 5.1.1. The energy required to fully charge the system was around 20 Wh greater than the nameplate for the same reason. The coulombic efficiency quantifies this discrepancy. The calculated coulombic efficiency of the Beta Prototype was very similar to the Alpha Prototype: 92.69% for the Beta, and 92.18% for the Alpha.

Figure 8. Beta Prototype voltage and current profile for 30°C

Table 9. SolarLEAF Beta Initial Capacity Results for 30°C

	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Average
Charge Capacity (Wh)	895.6	892.7	897.2	897.5	895.8
Discharge Capacity (Wh)	830.4	827.3	832.4	831.1	830.3
Coulombic Efficiency	92.72%	92.67%	92.78%	92.60%	92.69%

5.2 Experiment Group B Results

5.2.1 Alpha Prototype Results

The results for the Alpha Prototype are not available for the solar firming cycle at 30°C because the system went into standby mode during the experiment. The solar firming cycle calls for extended periods when the charge or discharge power drops to around 10% of the system's rated output power. The BMS has a feature to minimize the overdischarge of the system; after about 5 minutes of inactivity or current below 0.5 A, the system goes into standby mode. The contactor opened under standby mode, which caused the test to halt because the voltage measurement dropped out. To resolve this issue, we considered monitoring the voltage on the battery side of the contactors, but we determined that it could trigger a loss of control condition because the cycler might not be able to pass current through the contactor. Figure 9 shows the limited data acquired due to the halts from the system entering the standby mode.

Figure 9. Alpha Prototype voltage and current of solar firming cycle

5.2.2 Beta Prototype Results

The issue with running the solar firming cycle on the Alpha Prototype was resolved on the Beta Prototype. The fix included introduction of a communication line that prevents the BMS from entering standby mode while the system is connected to a tablet through Bluetooth. This experiment was used as a demonstration case before running this cycle under the Group D protocols. Figure 10 illustrates the voltage and current measurements of the Beta Prototype during the solar firming cycle.

Figure 10. Beta Prototype voltage and current of solar firming cycle

5.3 Experiment Group C Results

Group C studies the reaction of the SolarLEAF system to transients in temperature compared against the baseline system. Group C.1 is in a static electrical state, and Group C.2 is under a condition where the battery is being cycled. The Alpha Prototype was cycled under all conditions found in Group C; the Beta Prototype was cycled under the most rigorous cases to benchmark system improvements between the Alpha and Beta systems. This included the most extreme cases from Section C.1 (0°C and 50°C equilibrium following 25°soak as well as the inverse) and a repeat of Section C.2.

5.3.1 Experiment Group C.1 Results

Group C.1 studies the natural response of the thermal management system. The battery system was placed at 50% SoC and did not cycle for this experiment since the Yotta SolarLEAF thermal control is completely passive.

5.3.1.1 Alpha Baseline and Prototype Data

25°C to 0°C and 0°C to 25°C

Figure 11 illustrates the cold temperature performance of the SolarLEAF thermal management system. Figure 11(a) shows the transition from the soak temperature of 25°C to an equilibrium of 0°C; Figure 11(b) shows the transition from the soak temperature of 0°C to an equilibrium of 25°C. The phase transition of the PCM is above 25°C, so this experiment illustrates the ability of the system's insulation to prolong the effects of the cold temperature ambient condition. From both 25°C to 0°C and 0°C to 25°, it took about 8 hours for the baseline unit to reach thermal equilibrium and about 25 hours for the SolarLEAF Alpha Prototype to reach thermal equilibrium. The response at this temperature is primarily due to the insulation that is added to the system and the added thermal capacitance of the PCM. The temperature variation within the SolarLEAF Alpha unit remains fairly uniform in both cases, indicating there is nothing limiting the heat transfer.

Figure 11. Alpha 0°C thermal response

25°C to 40°C and 40°C to 25°C

Figure 12 shows the SolarLEAF Alpha Prototype responding to an equilibrium just above the PCM transition temperature. Figure 12(a) shows the transition from a soak temperature of 25°C to an equilibrium of 40°C; Figure 12(b) shows the transition from a soak temperature of 40°C to an equilibrium of 25°C. The baseline unit equilibrated at 40°C after about 10 hours of transitioning from 25°C to 40°C. The Alpha Prototype transitioned from 25°C to 40°C in about 95 hours (9.5x slower than the Baseline unit). The Alpha Prototype transition time back to 25°C was much faster, with a total time of about 60 hours. This experiment indicates that the SolarLEAF thermal management system can expel heat faster than it is retained. On the transition from 40°C to 25°C, the slope of the temperature is relatively steep until it hits the phase transition plateau and slows down as the PCM solidifies. Also, when the PCM is undergoing the phase change, the temperature variation throughout the battery pack increases. This indicates the possibility of poor heat transfer within the PCM. The level of variation within the battery pack is still within 0.5°C.

25°C to 45°C and 45°C to 25°C

Figure 13 illustrates how the SolarLEAF Alpha Prototype reacts to elevated temperatures. Figure 13(a) shows the transition from a soak temperature of 25°C to an equilibrium of 45°C; Figure 13(b) shows the transition from a soak temperature of 45°C to an equilibrium of 25°C. The Baseline unit equilibrated at 45°C after about 8 hours, whereas the Alpha Prototype equilibrated at about 70 hours (about 9x slower than the baseline unit). The transition of the Alpha Prototype back to 25°C was only about 10 hours faster than the 45°C transition. Also noteworthy is that although the transition time from 40°C to 45°C decreased by about 30%, the transition time was almost the same between the cooldown from 45°C and 40°C. This is attributed to the temperature delta between the PCM transition temperature and the ambient air condition being the same. The transition from the elevated equilibrium temperature to the phase transition temperature is relatively quick and has little bearing on the overall equilibration time. The temperature variation that was observed in the 40°C to 25°C case also exists at 45°C to 25°C, and appears very similar in variation. However, the temperature variation within the prototype at the phase transition plateau during the 25°C to 45°C run appears to be around 1°C.

25°C to 50°C and 50°C to 25°C Further characterization of the Yotta SolarLEAF temperature response can be found in Figure 14. This experiment provides an equilibrium right at the system's maximum operating temperature. Figure 14(a) shows the transition from a soak temperature of 25°C to an equilibrium of 50°C; Figure 14(b) shows the transition from a soak temperature of 50°C to an equilibrium of 25°C. The Baseline unit equilibrated at 50°C

Figure 12. Alpha 40°C thermal response

Each curve is an individual thermocouple

Figure 13. Alpha 45°C thermal response

Each curve is an individual thermocouple

after about 50 hours. The transition time from 50°C to 25°C was about the same as the 45°C and the 40°C back to 25°C cases. In this case, the return time to 25°C was longer than the time it took to reach 50°C. This possibly indicates that the heat path between the warmer system internals to the cooler ambient temperature is saturated; the total amount of energy in and out is the same because there are no heat sources within the battery system. Also, the temperature variations on cooldown remain the same at about 1°C. The temperature variation observed at the end of the heating phase transition increased to about 2°C.

Figure 14. Alpha 50°C thermal response

Each curve is an individual thermocouple

5.3.1.2 Beta Baseline and Prototype Data

The Beta systems were tested using a 50°C ambient condition and returned to 25°C. This experiment provided a “worst-case” comparison scenario against the Alpha system.

25°C to 50°C and 50°C to 25°C

Figure 15 presents the response time of the Beta Baseline and Prototype to a 50°C ambient condition, (a), and a 25°C ambient condition, (b). Under the 50°C ambient condition, the Beta Prototype was able to keep the battery pack under 45°C for around 45 hours. The temperature variation within the battery is tightly grouped. The response to a 25°C ambient shows a significant decrease in time when compared to the heating condition. The Beta Prototype can expel heat at a rate that brings the system down below 30°C in about 20 hours and equilibrates at 25°C after another 40 hours. This anisotropic response provides validation of the system’s ability to expel heat while also protecting against heat absorption.

5.3.1.3 Alpha and Beta Prototype Comparison

The Beta Prototype demonstrated improvements over the Alpha Prototype in both the 50°C ambient case and the 25°C ambient case. Figure 16 shows the comparison between the Alpha and Beta Prototypes responding to these cases. The first takeaway from this comparison is the increased ability of the Beta unit to keep the battery cooler for longer. The Alpha system reached 45°C after about 30 hours and equilibrated to 50°C after around 40 hours. The Beta system, by contrast, kept the battery below 45°C for 45 hours and took around 70 hours to fully equilibrate. The observations made earlier in this report in regards to the Alpha Prototype taking longer to cool down than to heat up have been solved with the Beta system. The Beta system is shown to equilibrate at 50°C after around 70 hours and return to equilibration at 25°C after only 45 hours. This change demonstrates an improvement in the heat rejection system as well as an improvement in the resistance to heat absorption.

5.3.2 Experiment Group C.2 Results

Group C.2 is designed to stress-test the battery system. This extreme case provides the best signal-to-noise ratio for studying the temperature within the battery pack. For this test, the battery was cycled at maximum power with

(a) 25°C to 50°C

(b) 50°C to 25°C

Figure 15. Beta 50°C thermal response

Each curve is an individual thermocouple

(a) 25°C to 50°C

(b) 50°C to 25°C

Figure 16. Alpha and Beta 50°C thermal response comparison

Each curve is an individual thermocouple

an SoC window of 20%–80%, starting both battery systems at 50% SoC. At the onset of cycling, the ambient temperature was changed from 25°C to 50°C. Cycling ended when the maximum temperature inside the battery pack reached 50°C. This experiment was run on both the Alpha and Beta Prototypes to benchmark the improvements between the systems. The maximum power for the Alpha and Beta Prototypes is 300 W and 400 W, respectively.

5.3.2.1 Alpha Baseline and Prototype Data

Figure 17(a) shows the temperature rise within the Alpha system during this experiment as well as the voltage plot. The Baseline unit reached 50°C after a single discharge. The baseline cycling was interrupted during the initial discharge and cycling was resumed, due to the temperature limit being too conservative for the experiment. This interruption, however, did not significantly impact the thermal response, as the temperature had already risen 20°C and was within 5°C of the test conclusion temperature. The Alpha Prototype continued for a total cycle of just above 10 hours (until the fifth charge cycle). This experiment exemplified the ability of the PCM to delay the over-temperature condition.

Figure 17. 300-W cycling of the Alpha unit from 20% SoC to 80% SoC with ambient temperature change from 25°C to 50°C

Each temperature curve is an individual thermocouple

This experiment also showed a potential drawback in the Alpha system. Figure 17(b) shows the temperature difference within the battery pack. At its peak, the internal temperature distribution reached a maximum of 9°C between the warmest and coolest points inside the battery pack. This could primarily be attributed to the heat not being able to move freely within the PCM. The PCM is at two different phases across the battery system at this point and unable to diffuse the heat throughout the battery pack.

5.3.2.2 Beta Baseline and Prototype Data

Figure 18 illustrates the Beta Prototype temperature response. The Beta system vastly outperformed the Beta Baseline. The Beta Baseline reached the maximum temperature on the second discharge cycle, or after 3 hours; the Beta system hit the temperature cutoff on the fifth discharge, or around 10 hours of cycling. Similar to the results from the Alpha system, the results show the effectiveness of the passive thermal management to delay the ambient temperature effect.

The early temperature variation indicates there is a heat imbalance caused by a delay in distributing the heat within the battery system. Looking at the data, there appear to be two tightly grouped clusters, whereas the Alpha sys-

Figure 18. 400-W cycling of the Beta unit from 20% SoC to 80% SoC with ambient temperature change from 25°C to 50°C

Each curve is an individual thermocouple

tem had a fairly even spread at the highest temperature variation. This grouping indicates that there may be a heat source—or rejection on the cold side—driving this temperature variation. Diving further into the data, the hottest three thermocouples are all toward the front of the battery pack when viewed from the orientation of Figure 3. The Beta Baseline also suffers from this divergence, as seen in Figure 18(b). The three higher temperature measurements are closest to the electronics, while the three cooler thermocouples are closer to the heat pipes and rejection fins. Those conditions might contribute to the temperature imbalance. However, without additional instrumentation, that cannot be confirmed. The heat flow within the battery pack appears to be adequate because the temperature variation tightened after an initial spike.

5.3.2.3 Alpha and Beta Prototype Comparison

The performance of the Beta system was similar to the Alpha from the standpoint of cycle time duration. In both cases, it took about 10 hours to reach the cycling cutoff temperature of 50°C. These comparative results can be found in Figure 19.

Figure 20(a) shows the average battery temperature of both units. Both systems increase temperature at similar slopes until around 37°C. Looking at the average battery temperature, the Alpha system temperature plateaus at this point, whereas the Beta system continues to rise until around 40°C. From here, the Alpha system stays at a relatively constant temperature for 4 hours until the battery temperature increases significantly. Unlike the Alpha response, the Beta system never fully plateaus. There are prominent peaks and valleys in the temperature. These peaks correspond to the end of the charge and discharge, where the internal resistance and heat generation rate are the highest. The magnitude of the peaks indicates that heat builds up and then is expelled from the system. This indicates adequate heat transfer to ambient, but internal heat flow could improve. The Alpha system appears to have better heat absorption from the PCM. This, however, caused localized PCM saturation, and the heat was unable to be distributed throughout the pack or rejected to ambient.

The similarities observed in the average internal temperature performance do not carry over to the internal temperature difference. Figure 20(b) shows two very different results when it comes to internal temperature variation. The

Figure 19. Comparison of battery pack temperatures between Alpha and Beta Prototypes

Figure 20. Average temperature and temperature delta of Alpha and Beta systems during experiment C.2

Note: Alpha and Beta heat generation rates are different

Alpha Prototype temperature spread increased rapidly to around 4°C then recovered back down to around 3.5°C, before the PCM appeared to saturate and the spread increased to 9°C. The Beta unit has almost the inverse response. The temperature spread within the system rapidly increased to 7.5°C before stabilizing to a variation of 4–6°C for the remainder of the cycling. This is indicative of improved heat flow within the system and better heat rejection. The level of temperature variation is still on the high side—especially considering the size of the battery pack—but there are significant measurable improvements in this regard between the Alpha and Beta Prototypes.

5.4 Experiment Group D Results

The first run of Group D consisted of the ambient temperature cycling with the battery system on stand-by. The main purpose of this run was to ensure the temperature cycle performed as expected. In Figure 21, the maximum ambient temperature reached 45°C and dipped down around 30°C. The Beta Baseline followed the temperature swings fairly closely. The temperature was delayed about 2.5 hours from ambient and stayed within 2.5°C of the ambient temperature extremes. The Beta system stayed much more consistent to its start point of 35°C (the start temperature caused by the residual heat following the conditioning to 50% SoC) and appears to equilibrate at that temperature after about 90 hours.

Figure 21. Temperature response for Group D (no cycling)

Following the initial solar firming cycle, a temperature sensor on the Beta Baseline stopped functioning. The BMS was detecting an under-temperature fault, and due to the fact that the system was well above the lower temperature limit, we decided that the sensor had failed. Unfortunately, this impacted the results for the Group D experiments because the Beta Baseline was not able to complete the cycle. The NREL and Yotta teams agreed to conclude the experiment with only the Beta system cycling. Figure 22 presents the results of the combination cycling and temperature diurnal cycle. The Beta Baseline would have initially cycled for about 2 hours before the BMS stopped the cycling due to the under-temperature error. The Beta system reached 37°C on the first day and maintained that temperature fairly consistently throughout the remainder of the experiment. Battery daily temperature fluctuation throughout this cycle is within 3°C following the initial temperature rise.

The initial diurnal temperature cycle was modified to capture the temperature extremes that Yotta has recorded through field deployments. The maximum temperature was increased to around 52°C while keeping the cooler portions around 30°C. Figure 23 illustrates the Beta system response to this more extreme temperature profile. Following the initial temperature rise from start conditions, the battery temperatures remain fairly steady around 37°C for 3 days. On day 4, the battery temperature reaches a maximum of 42°C. This temperature increase indicates the point where the PCM saturates and the phase change occurs. The system can expel the additional absorbed heat, and it brings the temperature back down around 35°C during the cooler portion of the ambient temperature cycle. The next temperature peak—following the “daytime” temperature—reaches 41°C. Again, the system can keep up with the additional heat and bring the internal temperatures back down to around 35°C.

(a) Temperature and power plot

(b) Temperature difference in pack

Figure 22. Phoenix diurnal cycle

(a) Temperature and power plot

(b) Temperature difference in pack

Figure 23. Modified Phoenix diurnal cycle

6 Conclusion

We conducted an in-depth analysis of the Alpha and Beta Prototypes of the Yotta Energy SolarLEAF to assess their thermal and electrical performance in typical and extreme conditions found in solar deployments. From a pure energy storage standpoint, the Alpha Prototype had a measured capacity of around 400 Wh at 30°C and 45°C. The capacity at 0°C was slightly lower at 350 Wh. This drop-in capacity agrees with lithium-ion systems. The average round-trip efficiency across these three temperatures was around 91%. The Beta Prototype was significantly more energetic than the Alpha version, at a measured capacity of 830 Wh and round-trip efficiency around 93%. The prototypes were subject to the solar firming cycle derived from the Sandia and PNNL test protocol that mimics an anticipated cycle in a standard installation. The use case in this study only utilized a fraction of the available system power. It would be possible to design the system with a lower power potential and increase storage capacity without impacting the overall footprint of the system.

SolarLEAF's Controller Area Network (CAN) communication capabilities provided a robust way to control and cycle the battery. The system was reliable and responsive throughout our cycling experiments and intuitive to set up. The over-temperature safety and idle shutdown performed as expected; the battery disconnected if temperature surpassed 45°C, and the BMS went to sleep after 5 minutes of idling time to save energy. The addition of the Bluetooth communication in the Beta systems worked reliably and enabled the running of all the experiments that the Alpha system was unable to perform.

The Yotta passive cooling technique worked exceedingly well at delaying the time the system took to reach an over-temperature ambient condition. In the more mild case, the equilibrium time was shifted by almost 100 hours (Alpha at 40°C); in the more extreme case, the system was able to delay the time by almost 60 hours (Beta at 50°C). The system was also able to reject heat faster than it was absorbed in most cases. This illustrates the system's ability to cool off when ambient temperatures fall below the internal system temperature for a short periods. Fine-tuning of the system will prevent heat path saturation at higher internal to ambient temperature deltas.

The results from the maximum power rate cycling data reveal the temperature variation within the battery system. Under a continuous maximum power charge/discharge cycling between 20% and 80% SoC, the temperature variation inside the battery pack rose to 9°C for the Alpha system and 7°C for the Beta system. The heat spread was observed when the SolarLEAF was cycled at a more rigorous rate than the intended application; the system is designed to undergo a maximum of 1–2 cycles per day.

In the Alpha Prototype, the graphite matrix that houses the PCM transfers heat around the battery pack, but the heat builds up after multiple cycles. The temperature variation within the batteries can lead to an aging discrepancy between matched cells; a cell at a higher temperature will age much faster than a cell at a lower temperature, which then causes a self-deprecating cycle of the more aged cell working harder. Between the Alpha and Beta Prototypes, Yotta Energy incorporated an aluminum heat spreader to mitigate this issue. This incorporation provided an observable difference in the temperature distribution within the battery pack. The maximum temperature delta decreased almost 2°C and happened toward the beginning of cycling, and tightened up as the test progressed. This ability of the Beta system to rein in the temperature spread demonstrated improved heat flow within the system and heat rejection to ambient. The observed temperature delta is still considered high and can be identified as an area of possible improvement.

The diurnal temperature cycling brought together all the pieces of the other three experiment groups to best replicate how this system would perform in field deployment. This final experiment ran on the Yotta SolarLEAF was a diurnal temperature cycle combined with electrical cycling. The use case for the temperature cycling is a derivation of a typical hot summer week in Phoenix, Arizona. The augmentation of the cycle is to accommodate temperatures that Yotta has observed in field deployments. The electrical cycling was designed to best emulate the system's intended use case. The Beta Baseline was not able to follow the electrical cycle due to a sensor malfunction. This experiment showcased the ability of the SolarLEAF to protect the battery system from temperature extremes. The maximum temperature measured inside the system was 40° on day 4 of the experiment. Our work shows that the system can

recover from this high temperature. Future experimentation could include an extended version of this experiment—possibly in a field deployment—to verify that this behavior is sustained beyond one week.

Appendix

A In-Depth Alpha Data

Figure 24. Alpha Prototype capacity and round-trip efficiency summary

Figure 25. Alpha Prototype voltage and current profile 0°C

Figure 26. Alpha Prototype voltage and current profile 30°C

Figure 27. Alpha Prototype voltage and current profile 45°C

B Additional Alpha Baseline Data

30 degree

	Cycle 2	Cycle 2	Cycle 3	Cycle 4	Average
Charge Capacity (Wh)	521.1	520.2	519.6	518.8	519.9
Discharge Capacity (Wh)	489.2	488.5	487.9	487.7	488.3
Coulombic Efficiency	93.88%	93.91%	93.90%	94.01%	93.92%

45 degree

	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Average
Charge Capacity (Wh)	544.3	529.3	526.0	518.8	529.6
Discharge Capacity (Wh)	493.4	491.6	489.7	489.0	490.9
Coulombic Efficiency	90.65%	92.88%	93.10%	94.26%	92.72%

0 degree

	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Average
Charge Capacity (Wh)	455.8	449.8	446.4	443.7	448.9
Discharge Capacity (Wh)	408.1	404.6	402.3	400.2	403.8
Coulombic Efficiency	89.53%	89.95%	90.12%	90.20%	89.95%

(a) Baseline unit capacity and round-trip efficiency summary)

(b) Baseline unit voltage and current profile 0°C)

(c) Baseline unit voltage and current profile 30°C)

(d) Baseline unit voltage and current profile 45°C)

Figure 28. Baseline unit capacity results

Figure 29. Baseline unit voltage and current of solar firming cycle

C Alpha Prototype Heat Flow Coefficient Data

Figure 30. Alpha Prototype: 0°C thermal coefficient

Figure 31. Alpha Prototype: 40 $^{\circ}\text{C}$ thermal coefficient

Figure 32. Alpha Prototype: 45°C thermal coefficient

Figure 33. Alpha Prototype: 50°C thermal coefficient

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