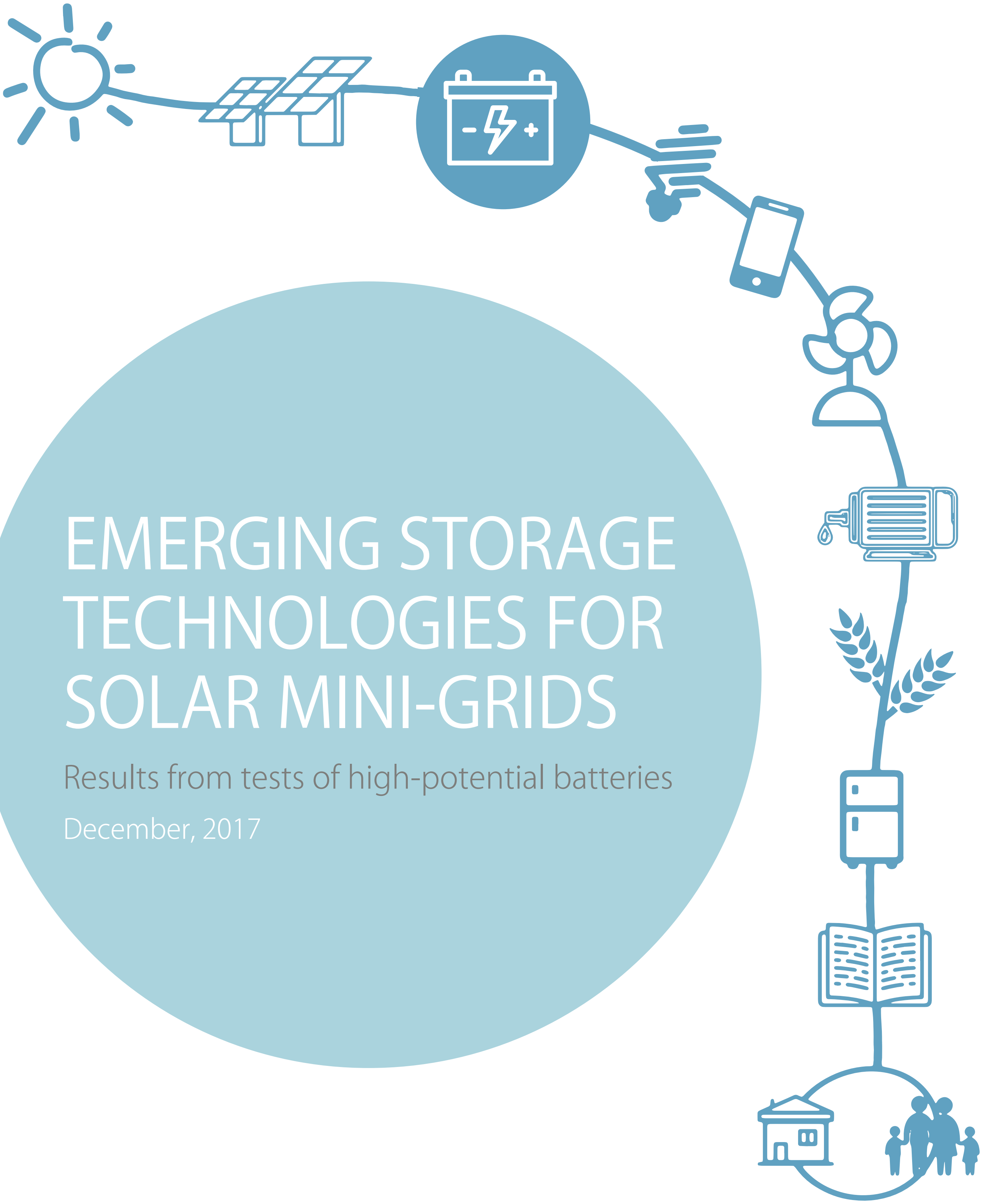
INSTITUTE FOR TRANSFORMATIVE TECHNOLOGIES



EMERGING STORAGE TECHNOLOGIES FOR SOLAR MINI-GRIDS

Results from tests of high-potential batteries

December, 2017

Supported by

125 YEARS OF TATA TRUSTS
PRIVILEGED TO SERVE. SINCE 1892.

TATA POWER-DDL

The ROCKEFELLER FOUNDATION

SCHMIDT FAMILY FOUNDATION

Department for International Development

Attribution

Please cite this work as follows: "Institute for Transformative Technologies (ITT), December 2017. Emerging storage technologies for solar mini-grids: Results from tests of high-potential batteries."

For more information

info@transformativetechnologies.org | www.transformativetechnologies.org

This study has been funded by The Rockefeller Foundation, the Tata Trusts and the Schmidt Family Foundation.

The Institute for Transformative Technologies (ITT) would like to thank the following partner organizations for their support and advice in this effort: Tata Power-Delhi Distribution Limited (TP-DDL), Lawrence Berkeley National Lab, Aquion Energy, Ecoult, Panasonic and Amara Raja. We also want to thank Prokaushali Sangsad Ltd (PSL), Bangladesh, for the technical work behind this study.

ITT's battery test site is located at a grid sub-station operated by Tata Power-Delhi Distribution Limited

CONTENTS

Executive summary

One major challenge facing solar mini-grids serving low-income rural communities in countries like India, is the absence of durable, cost-effective, high-performance storage solutions. Conventional lead-acid batteries, which are the current default, struggle on multiple fronts. As a step towards addressing this problem, ITT identified a number of high-potential battery technologies currently not on the Indian market, and—in partnership with Tata Power-DDL—conducted a series of rigorous tests to determine the technical appropriateness of these batteries for the rural Indian mini-grid context. Three battery types were tested: Advanced lead-acid (ALA), Aqueous hybrid ion (AHI), and Lithium-ion (with lithium-nickel-manganese-cobalt chemistry), along with conventional lead-acid (Absorbent Glass Mat, or AGM) as a benchmark.

While a number of tests to determine longer-term durability are still underway, the first few months of tests have yielded clear results. The tests have shown that each of the three new battery types offers considerable advantages over conventional lead-acid. Li-ion technically offers the best combination of performance characteristics; however, there is considerable unpredictability about when it will become affordable. AHI batteries are robust, can discharge fully without degradation, can provide energy for a long duration, and have the cleanest environmental footprint of the technologies we considered; however, the limited market for batteries exclusively designed for rural solar mini-grids means that manufacturers of this technology may struggle financially.[1] ALA batteries address some of the challenges faced by conventional lead-acid batteries, such as high charge and discharge rates, and the ability to operate at high ambient temperatures; however, they have limited depth of discharge. The next phase of our work will focus on the operational and economic feasibility—and the best path forward—to make these batteries available in India.

[1] This challenge is highlighted by the recent bankruptcy filing by Aquion Energy, the manufacturer of the AHI battery.

Introduction

One of the main challenges facing decentralized solar mini-grids for low-income rural markets is the absence of cost-effective and high-performance energy storage solutions. In India, locally manufactured deep-cycle lead-acid batteries constitute the most widely used affordable mini-grid storage solution. However, the performance and durability of lead-acid batteries degrade when they are discharged beyond 50 percent of capacity and when they are recycled from a partial state of charge. Moreover, the performance of these batteries deteriorates in the high ambient temperatures common in countries like India. In India, where several private rural utilities are planning to build large numbers of solar mini-grids, this problem is proving to be a fundamental constraint.

A number of experts believe that lithium-ion will be the solution at some point in the future, as the growing global market for electric vehicles is driving down the cost and operational viability of lithium-ion batteries, and companies like Tesla are beginning to make and sell versions of that battery as an energy storage solution. However, lithium-ion is still too expensive for low-income rural applications, and experts are divided on how soon it will become affordable.

As things stand, therefore, the only real option for the Indian solar mini-grids industry has been to make do with conventional lead-acid batteries and hope the cost of Li-ion drops soon.

In that context, ITT launched an exercise to identify other potential storage solutions. There are a number of existing and emerging battery technologies which are currently on the periphery of the developing world solar mini-grid ecosystem—either operating at too small a scale for the costs to be affordable, or too new to attract the kind of investment needed to scale up. We conducted an initial assessment on a number of such battery chemistries and brands, and selected a shortlist[2] which we believed could be suited for the rural Indian context. In partnership with Tata Power-Delhi Distribution Limited, ITT has built a battery testing facility at one of TP-DDL's sites, and has conducted several months of rigorous tests to determine which of the batteries are best suited for solar mini-grids under usage scenarios typical to rural India. While a number of the tests for determining the batteries' longer-term durability are still underway, we have enough evidence to draw key preliminary conclusions.

[2] The emerging battery technologies being tested are: Advanced lead-acid, Aqueous hybrid ion. As a benchmark, we are also conducting the same tests on lithium-ion, and AGM (VRLA type currently being used in solar mini-grid installations in rural India). In addition, we are testing an integrated system with Li-ion and VRLA, to determine if the combination can strike a balance between cost and performance.

Lead-acid batteries

Today, deep cycle lead-acid (LA) batteries are the only widely available option for solar mini-grid energy storage space in India, with a purchase price of $125-150 per kWh. There are two primary types of lead-acid batteries for solar mini-grid applications: conventional liquid filled flooded lead-acid (FLA) which require occasional refilling of the electrolyte (without which they malfunction), and valve-regulated lead-acid (VRLA) technologies such as Absorbent Glass Mat (AGM) and Gel batteries, which do not require such maintenance. In addition to needing less maintenance, VRLA batteries are easier to transport and safer to handle than FLA. As a result, VRLA batteries, and in particular AGM, have become the first choice for off-grid solar applications. Despite these advantages, VRLA batteries still have several serious limitations:

- Their operating life degrades if used in ambient temperatures above 30°-35°C. Since much of India experiences temperatures well above that through much of the year, most mini-grid installations in the country are facing this challenge.

- Partial state-of-charge (PSOC) is a condition in which battery remains partly charged over an extended period of time as a result of incomplete recharge (e.g., when there is insufficient sunlight). If left at PSOC, LA batteries experience rapid sulfation at the electrodes, resulting in irreversible degradation of their energy storage capacity.

- Typical LA batteries cannot recover their original capacity when subjected to occasional deep cycling, a scenario which cannot be avoided when demand for electricity is high and/or sunlight is sporadic. This is one of the leading causes of short battery lifecycles in mini-grids, since solar power is not guaranteed to replenish the discharge in every cycle.

Although some deep cycle LA batteries can have usable capacity up to 80 percent, they tend to have a shorter cycle life, since the chemistry forces a compromise between usable capacity and life. While it may be possible to address some of these problems through techniques like charge equalization,[3] other challenges will still remain. As a result of these limitations, lead-acid batteries are not ideal for solar mini-grid electrification in India.

[3] P.T. Krien, "Life Extension Through Charge Equalization of Lead-Acid Batteries", IEEE 24th Annual International Telecommunications Energy Conference, 2002.

Lithium-ion batteries

One commonly mentioned battery technology that has been rapidly emerging on the market for mini-grids is lithium-ion (Li-ion), driven by the fast-growing market for electric vehicles (EV). From the point of view of core performance criteria (e.g., deep discharge capability and operating in extended PSOC), Li-ion batteries can be an ideal choice for mini-grids.

The tremendous growth of (and investment in) the EV market has led to significant reductions in the cost of lithium-ion batteries over the past few years, with market leaders offering batteries at $300/kWh; however, this is still too expensive for the rural Indian context. While Li-ion costs are expected to continue decreasing (Exhibit 1)[4], projections differ on when they will match the cost of existing lead-acid batteries—ranging from the early 2020s, all the way to 2030. It is also important to note that (as of early 2017) there are no Li-ion battery brands that are manufactured in India, leading to additional costs and complications associated with importing; this, however, may change in the near future, with some well-known brands considering either manufacturing or bulk shipping to India.[5]

If the more optimistic scenarios materialize, it is entirely possible that Li-ion will become a realistic and affordable option for solar mini-grids in a reasonably short timeframe. However, until some of the uncertainties are resolved, we believe that it is worth exploring alternatives to Li-ion.

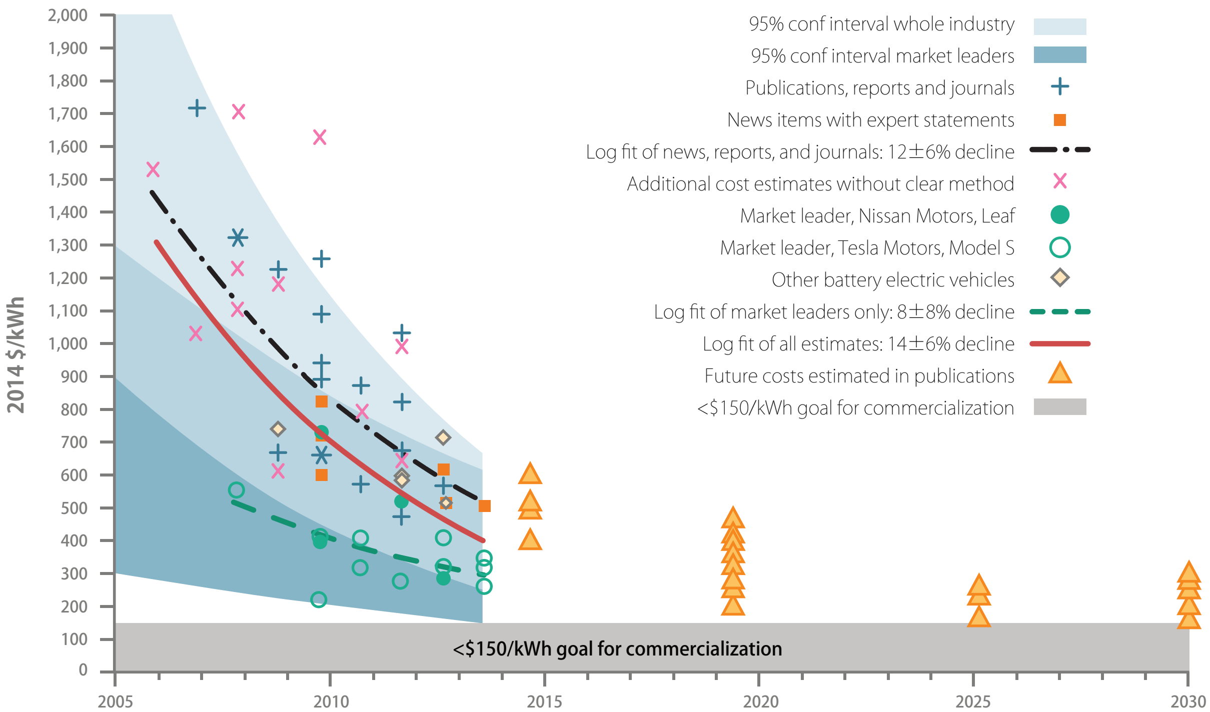


Exhibit 1. The cost of lithium-ion batteries has dropped significantly in recent years, but is still much higher than what mini-grids for developing countries can afford (about $150 per kWh). There are varying opinions on how soon they will become affordable.

[4] B. Nykvist and M. Nilsson, "Rapidly falling costs of battery packs for electric vehicles", Nature, October 2014.

[5] Source: ITT interviews with manufacturers.

Shortlist of battery technologies selected for testing

In ITT's earlier report[6] on the state of battery technologies for rural Indian mini-grids, we analyzed the technical and economic intrinsics of a number of battery chemistries and on-the-market products in various stages of maturity. Exhibit 2 summarizes the current cost (capital, as well as levelized) of the various brands (which are not named, so as to protect proprietary information). As the exhibit shows, conventional lead-acid batteries currently have the lowest purchase price; and while the levelized cost of some of the advanced lead-acid, Li-ion and other emerging technologies is comparable to some of the conventional lead-acid brands, it is currently hard to make the economic case for these improved batteries.

The high-level assessment of these chemistries and products is summarized in Exhibit 3. Based on an understanding of the chemistry, we ruled out those which (we believed):

- were too expensive, without a plausible path to cost reduction through scale or other means;
- would likely not perform well under the stresses common in rural India;
- could need ongoing maintenance requiring skilled technicians;
- could have a worse environmental footprint than current practices;
- were still in their R&D stages.

On the basis of this, we selected two new battery chemistries which satisfied the above criteria[7]:

- Advanced lead-acid (ALA) is a hybrid of a conventional lead-acid battery and a super-capacitor technology. The physical structure of the battery is similar to a standard 12V AGM VRLA battery. In principle, this hybridization enables longer life at cyclic operation under partial state of charge compared to conventional lead-acid batteries, while operating at high charging and discharging rates.

- Aqueous hybrid ion (AHI) is a sodium-ion (salt water) battery—developed in 2014—which uses non-toxic materials with low-cost manufacturing processes. This battery claims high tolerance to partial state-of-charge, and deep discharge fully to 100 percent, without any degradation of performance.

[6] "Achieving universal electrification in India: A roadmap for rural solar mini-grids", ITT, April 2016.

[7] Note that this is a rapidly evolving ecosystem, and new battery technologies are likely to continue appearing on the market since the launch of this exercise in 2015.

In addition to these two new chemistries, we are testing a Li-ion battery (with lithium-nickel-manganese-cobalt chemistry) that is appearing on the Indian market, and—as a baseline—an AGM type VRLA battery commonly used in Indian solar mini-grids. In the future, we will also consider building and testing an integrated storage system which combines (via an overlaid electronic logic control system) AGM and Li-ion batteries.

The AGM battery used in our tests is manufactured by Amara Raja, an Indian brand commonly used for solar mini-grids; the Li-ion battery is manufactured by Panasonic (from Japan). In principle, since there are multiple companies manufacturing these types of batteries, the specific brand is not as critical to the tests. The ALA battery is manufactured by Ecoult, and the AHI by Aquion Energy; in both these cases, the technology is proprietary to the company.

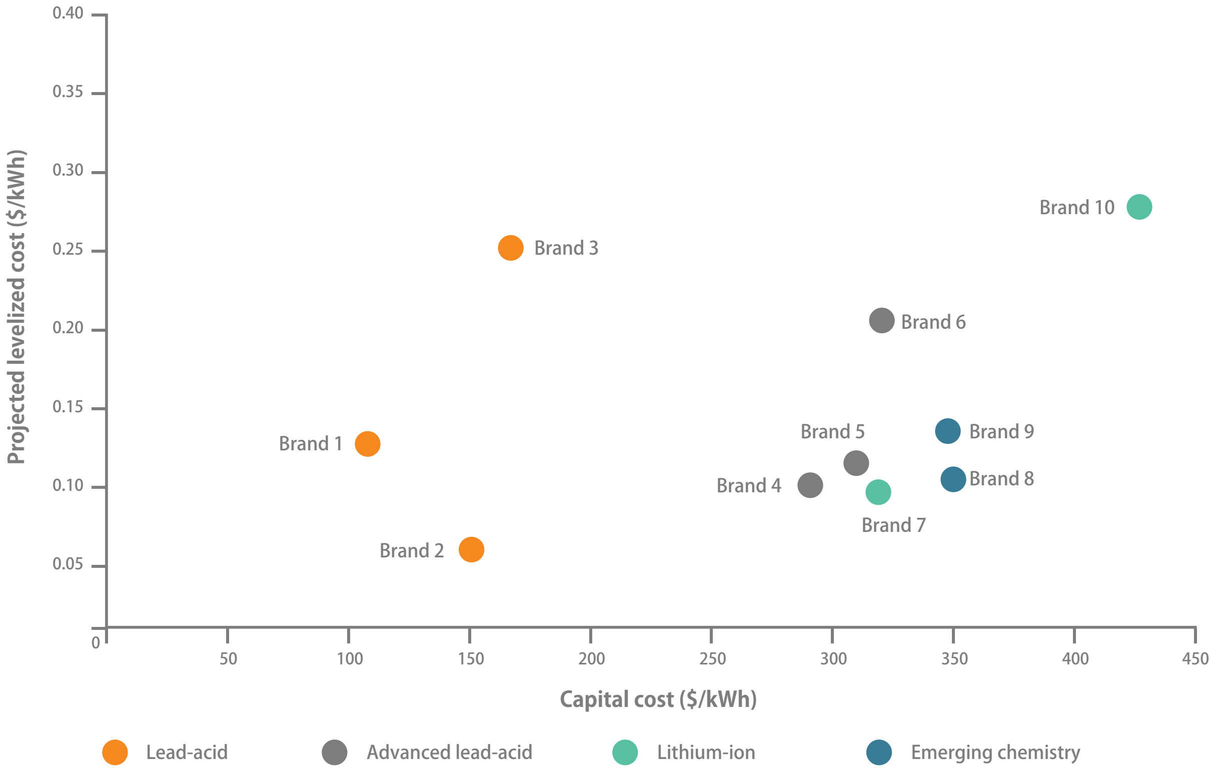


Exhibit 2. There are a number of batteries on the global market that can be used for mini-grids. However, they vary dramatically with respect to initial purchase price as well as projected levelized cost over their lifetime. Please note that the brand names have been redacted in order to preserve confidentiality.

		Capitial cost	Cycle life	Deep discharge	PSoC	High ambient temp.	Maintenance	Environmental footprint	Likely potential for cost reduction via scale/local manufacturing
		Technical/performance parameters							
Mature	Lead-acid	$100-150	800-2,000	◔	○	○	◕	◑	○
Mature	Li-ion	$300-500	2,000-3,000	◕	◕	Varied	◕	◑	◕
Mature	NiFe	$600-800	>7,500	●	●	◑	◕	◕	◔
Emerging	Advanced Lead-acid	$300-350	5,500	◑	◑	◑	◕	◑	◕
Emerging	Li-ion & Lead-acid Hybrid	TBD	TBD	TBD	TBD	◑	◕	◑	◕
Emerging	Flow	$500-1,000	>7,500	●	●	◕	◔	◑	◑
Next generation	Aqueous hybrid ion	$350-500	>5,000	●	●	●	●	●	◕
Next generation	Zn-hybrid	$350	>5,000	◕	◕	TBD	TBD	TBD	◑

Technologies being tested by ITT (Li-ion, Advanced Lead-acid, Li-ion & Lead-acid Hybrid, Aqueous hybrid ion) ● Favorable ○ Unfavorable

Exhibit 3. ITT's preliminary assessment (in 2015) of battery technologies available on the global market at various stages of maturity. Based on this preliminary assessment, two new battery technologies were selected for additional testing: advanced lead-acid (ALA) and aqueous hybrid ion (AHI), in addition to lithium-ion (Li-ion.) We are also testing an integrated system consisting of Li-ion and AGM batteries as a potential short-term measure.

Criteria and tests for evaluating shortlisted batteries

In the tests being conducted at the Delhi battery test facility (see Annex 1), we are using four key performance criteria[8] for determining the technical suitability of the shortlisted batteries for solar mini-grids:

1 Depth of discharge (DOD) capability:

The usable capacity of a battery is measured by its allowable DOD in each charge-discharge cycle. This parameter is specified by the manufacturer as an indicator of the limits of usable capacity—expressed in Amp-hours (Ah)—for achieving a specified number of cycles from a battery. Lead-acid batteries are usually operated down to 50-60 percent DOD (beyond which their cycle life diminishes significantly), while lithium-ion batteries have been proven to operate to 90 percent DOD without degrading performance or longevity. The ALA and AHI being relatively new, their DOD capabilities have not been (to our knowledge) validated externally for a solar mini-grid in rural (off-grid) applications, prior to our tests.

[8] For some applications (e.g., electric vehicles), energy density—the measure of total battery capacity per unit weight of the battery—can be important. This parameter is not important for stationary batteries in rural mini-grids, where space is plentiful.

2 Tolerance to high temperature:

Manufacturers typically specify capacity and battery cycle life at a nominal temperature of 25°C, and some prescribe maximum operating time at higher temperatures. The longevity and performance of lead-acid batteries is known to reduce significantly when subjected to operating temperatures higher than 30°-35°C. Summer temperatures in much of India routinely exceed that; therefore, tolerance to such ambient temperature ranges is critical. The performance of ALA and AHI batteries in high ambient temperatures for mini-grid applications had not been (to our knowledge) validated externally prior to our tests. Li-ion batteries have a mixed track record in high operating temperatures—it has been identified as a clear risk in some Li-ion chemistries.[9] In order to compare the effect of temperature on the operating characteristics of the batteries, we compare performance at 25°C to that at 40°C. Note that while testing batteries, high ambient temperature can also be used as a means of accelerating deterioration—and therefore testing the batteries' longevity. Our protocols include a suite of such temperature-accelerated longevity tests.

3 Power and energy output:

The power output is a measure of the maximum continuous peak power output of batteries, and their usability in the event of a high power draw or surge (e.g., when a large motorized load turns on). There is sufficient evidence to suggest lead-acid chemistry lends itself to a high power draw, as does Li-ion. However, the performance of the AHI chemistry on this issue has been unclear prior to our tests. A second parameter which is arguably more critical (than power) for rural mini-grid settings, is energy output (i.e., the ability to sustain low power for an extended period of time). In this regard, Li-ion batteries have been continuously improving over the past few years, and there is strong evidence to suggest that this may be a limitation for conventional lead-acid batteries. However, there has been little evidence on whether the improvements to the basic lead-acid chemistry that the ALA provides, improve energy output. The AHI chemistry appears to lend itself to high energy output, but this has not been independently verified. The ideal battery can meet both power and energy requirements.

4 Cycle Life:

One iteration of complete charging of a battery followed by complete discharge of energy, constitutes one cycle. The number of cycles, therefore, is a direct measure of the battery's longevity. Batteries are usually rated for a specific number of cycles under operating parameters such as operating temperature, discharge rate, and depth of discharge. Over time, battery deterioration manifests itself in the inability to charge to original capacity, and in loss of round-trip efficiency (the discharge-to-charge ratio). Within their lifecycle, lead-acid batteries may have an efficiency loss of 20 percent, while more advanced batteries may lose 10 percent. Longevity—by definition—can only be demonstrated over time, and there is ultimately only one certain way to determining if a battery that claims to last 10 years, truly does so: by running it for 10 years in realistic conditions. As mentioned earlier, temperature is an accelerant for lifecycle-related deterioration; as such, we are conducting a number of lifecycle tests under high ambient temperatures.

[9] Sony, "Lithium-ion rechargeable batteries: Technical handbook", 2009.

One standard procedure that is performed as a part of the tests described above is the capacity test, used to determine the basic characteristics of any type of battery, e.g. battery's usable capacity and operating voltage vs. its SOC profile at different discharge rates (I_5, I_{10} and I_{20}, corresponding to full discharge in 5, 10 and 20 hours, respectively). Note that the "standard" discharge rate for most batteries is I_{10}. Table 1 describes the specific tests conducted against each of the above criteria.

Criteria	Test(s)	Indicator(s) of strong performance for solar mini-grid (off-grid) application
1. Depth of discharge (DOD), based upon capacity available for regular cycling	The battery is discharged at the standard rate of I_{10} (i.e., full discharge over the course of 10 hours) until the manufacturer's specified lower threshold (cutoff) for discharge is reached. Throughout the process, the state of charge (SOC) is calculated, and the ratio of discharged capacity at the cutoff point to total capacity is considered the maximum allowable DOD.	The closer the maximum allowable DOD is to 100 percent, the better. As a benchmark, conventional lead-acid batteries can typically go to 40-50 percent DOD, without experiencing any degradation of performance.
2. Tolerance to high temperature (25°C vs 40°C)	**a.** As the ambient temperature increases, so does the operating voltage for any given SOC point. The higher difference in voltage between 25°C and 40°C, the greater the likelihood of deterioration. Hence, we measure the voltage as a function of SOC at 25°C and 40°C. **b.** We are also measuring the change in internal resistance due to increase in temperature, but such changes are expected to become apparent after many more cycles.	**a.** The closer the operating voltage at 40°C is to that at 25°C (for any given SOC), the more likely the battery is to be tolerant to an increase in ambient temperature. **b.** The measure of internal resistance and its relation with the SOC of the battery gives us the idea about the state-of-health (SOH) of the battery, especially for LA batteries operating at high temperatures. Increase of internal resistance by 50 percent from its new condition is indicative of poor SOH.

Criteria	Test(s)	Indicator(s) of strong performance for solar mini-grid (off-grid) application
3. Power and energy output	**a.** Power output: Change in voltage upon introduction of a high power draw (i.e., higher than the batteries' I_5 rate). This simulates motorized loads being turned on. **b.** Energy output: It is measured through the capacity test, where kWh for the maximum recommended DOD is recorded.	**a.** A suitable battery for mini-grid application should sustain high power (I_5 or greater) for more than 1 hour. **b.** A battery optimized for energy will provide higher kWh of output for each Amp hour (Ah) discharged.
4. Lifecycle	**a.** Round-trip efficiency test: It is the ratio of the amount of Ah that can be discharged (and thus usable) from the amount of Ah used to recharge the battery. **b.** Accelerated lifecycle test at PSoC[10]: This test determines the ability of the battery to withstand continued cycling, measured through the standard capacity tests. The test is performed at 40°C to accelerate its degradation.	**a.** Round-trip efficiency of 85 percent at the end of life is an indicator of good battery health. **b.** The C_{10} capacity should not be less than 80 percent of the manufacturer's rated capacity for at least three years under standard conditions. Under accelerated conditions, the timeline will be approximately 1 year.

Table 1. Summary of key assessment criteria, with the corresponding tests and indicators of success.

[10] For the accelerated lifecycle test, a minimum of three complete IEC cycles (150 cycles) should be achieved.

The test facility: the only one in the world geared towards testing batteries explicitly for developing world settings

To conduct the above tests, ITT has been working closely with Tata Power Delhi Distribution Limited (TP-DDL) to build and operate a battery testing facility that is (to our knowledge) the only one of its kind, aimed at testing current and emerging battery technologies for use in developing country settings. Located in the Delhi suburb of Rohini, the testing facility has been built at one of TP-DDL's sub-stations, which has 150 kW of solar arrays, out of which our tests are using 20 kW. The test facility (details of which are described in Annex 1) consists of two areas, each with independent control and data acquisition systems:

1 Controlled test bed with DC charging and loads designed for DC loads:

One of the test beds is a fully controlled environment in which the batteries are charged with a DC charger, and discharged with adjustable resistance (rheostats). The chamber is also temperature-controlled, in order to study the effect of high ambient temperature. Such a setting allows precise control of protocols and ambient conditions, and helps us replicate international[11] and Indian industry standard tests as well as tests recommended by the manufacturers. As described in Table 1, the tests being conducted at ITT's test bed include capacity/DOD test, tolerance to high ambient temperature test, power and energy output test, and lifecycle test.

2 Mini-grid simulator, with solar PV charging and AC loads simulating rural usage patterns:

The purpose of second configuration is to evaluate a battery's performance in conditions closely resembling those in actual field settings. The setup has three scaled models of mini-grids designed, built, and configured to operate as independent rural mini-grids. The daytime load and battery [re]charging energy comes from the solar panels; the nighttime load is supported solely by the batteries. The batteries and related hardware are maintained in a temperature-controlled room, in order to simulate mini-grid operations in moderate (25°C) and high (40°C) ambient temperatures. A programmable load simulator is used to generate consumption patterns from villages in India and Bangladesh (with solar mini-grids installed over the past 2-3 years).[12] There are three test beds (one each for the ALA, AHI and Li-ion batteries), connected to total 20KW of PV modules. Each of the three test beds operates simultaneously, to ensure that all the batteries are charged with identical solar insolation captured by the PV modules.[13]

While the immediate purpose of the test facility is to determine which of the shortlisted batteries is most appropriate for use in rural India in the relative near term, it will continue to be available to battery manufacturers and researchers for years to come. To our knowledge, this is the only facility in the world geared towards testing batteries explicitly for developing world settings.

[11] "Stationary Valve Regulated Lead Acid Batteries – Specification", IS 15549, 2005, Reaffirmed 2010; "Secondary Cells and Batteries for Solar Photovoltaic Application — General Requirements and Methods of Test", IS 16270, 2014.

[12] H. Khan, et al, "Energy Usage Pattern of Off-grid Population in Bangladesh", International Conference on Developments in Renewable Energy Technology, 2016.

[13] Note that the tests conducted in this setup are still in their early stages, and we are collecting early data with dedicated test beds for the new batteries (ALA, AHI and Li-ion). Data for the AGM battery will be collected in one of these test beds; if necessary, a fourth test bed may be added.

A summary of the test results

1 Depth of discharge (DOD)

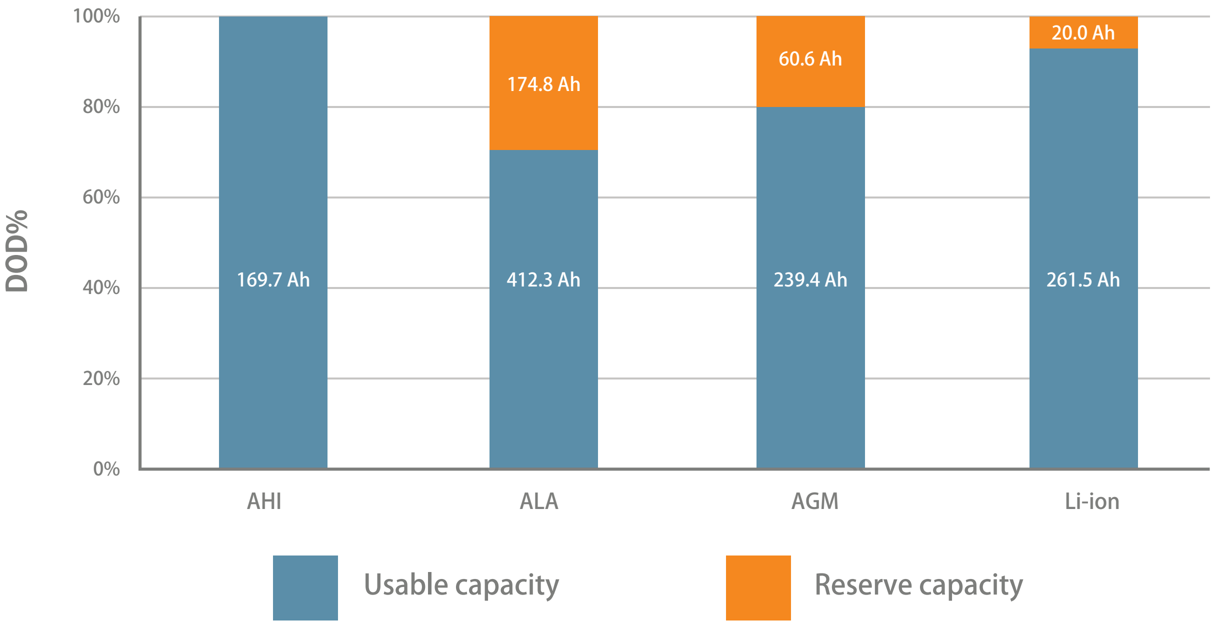


Exhibit 4. In our tests, the AHI battery demonstrated the ability to fully discharge without any negative effects. The Li-ion, AGM and ALA batteries went down to 93 percent, 80 percent and 70 percent[14], respectively, before being cut off based on the manufacturer's recommended voltage threshold for a specified number of cycles.

To ensure that batteries do not exceed their maximum specified DOD, they are designed to operate within certain voltage ranges, beyond which point they are not recommended for use. The AGM battery has a life of 2,000 cycles when discharged to 50 percent; this reduces to 1,200 cycles if discharged to 80 percent DOD. The ALA battery manufacturer recommends operating between 30 percent and 90 percent range of charge (which provides about 2,000 cycles).[15] The AHI battery manufacturer allows complete discharge of the battery down to DOD 100 percent. Finally, the Li-ion has integrated electronics to automatically switch the battery off when the battery reaches its recommended maximum DOD (of approximately 90 percent). Our load simulations were designed as per the manufacturer's recommendations for maximum possible Ah discharge.

Exhibit 4 shows the maximum allowable DOD that could be achieved from each of the batteries tested in our lab. The usable capacity of each of the battery was determined by conducting standard capacity tests according to International Electrochemical Commission (IEC) standards. Each of the batteries was discharged down to the manufacturer's specified lower-bound cutoff point at the I_{10} rate. The AHI battery could be discharged to 100 percent DOD, while the Li-ion reached 93 percent, and the AGM and the ALA reached about 80 percent and 70 percent, respectively. Based on this metric, the AHI and Li-ion battery appear capable of deep discharge, and hence seem well suited for rural mini-grids.

[14] The manufacturer of the ALA battery used in our tests recommends that the capacity below 30 percent SOC be used as reserve for infrequent events, and warranties the battery for up to 25 reserve events over 5 years.

[15] Within this range of charge, the number of cycles can go up considerably if the discharge cycles are short (i.e., 10 percent DOD per cycle); however this is not representative of usage in mini-grid applications.

2a Tolerance to high ambient temperature: Voltage change

The enhanced chemical reaction from operating under higher temperatures—which accelerates corrosion and reduces the cycle life—is also associated with higher Ah discharged from the battery. At any particular SOC, a higher operating voltage at 40°C (compared to 25°C) implies an increase in energy output (kWh) from the battery per Ah discharged. Many inverters are optimized for use in an operating temperature of 25°C. Therefore, they calculate the relationship between SOC and voltage at 25°C, and cut off discharge according to that voltage. As the ambient temperature increases (e.g., to 40°C), if the cutoff voltage is not proportionally increased, then the battery will discharge more than its recommended DOD.

Exhibit 5 illustrates this phenomenon for the AGM battery: at the recommended cutoff voltage of 48.3V, the SOC at 40°C is about 33 percent, compared to 50 percent at 25°C; in this scenario, at 40°C the inverter will let the battery discharge to 33 percent, likely causing damage to the battery.

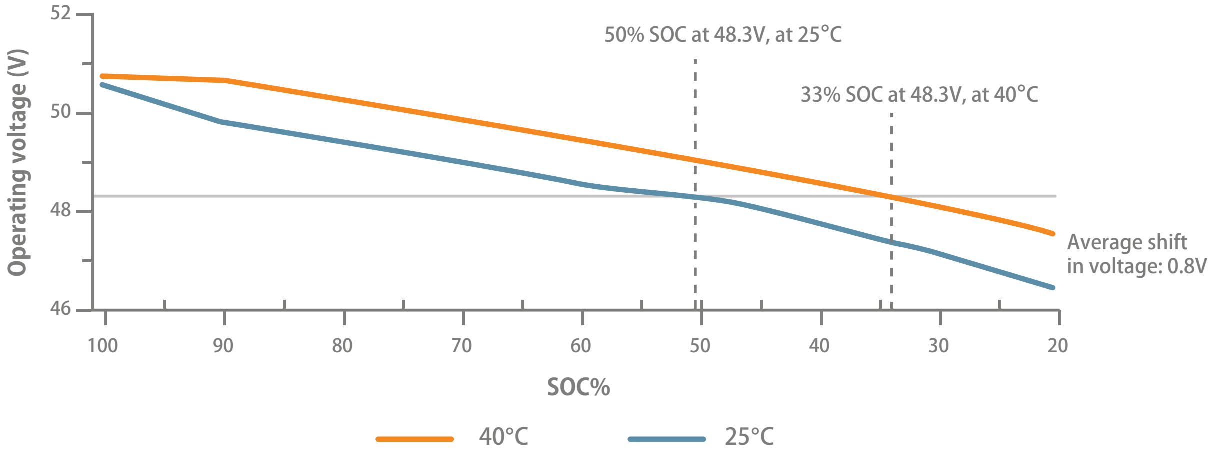


Exhibit 5. As the ambient temperature increases, so does battery voltage at a given SOC. The higher the shift in SOC, the greater will be the damage to the battery. In our tests, the AGM battery—with a recommended cutoff voltage of 48.3V—is discharged to 33 percent SOC at 40°C, compared to 50 percent SOC at 25°C. This can cause considerable damage to the battery over time.

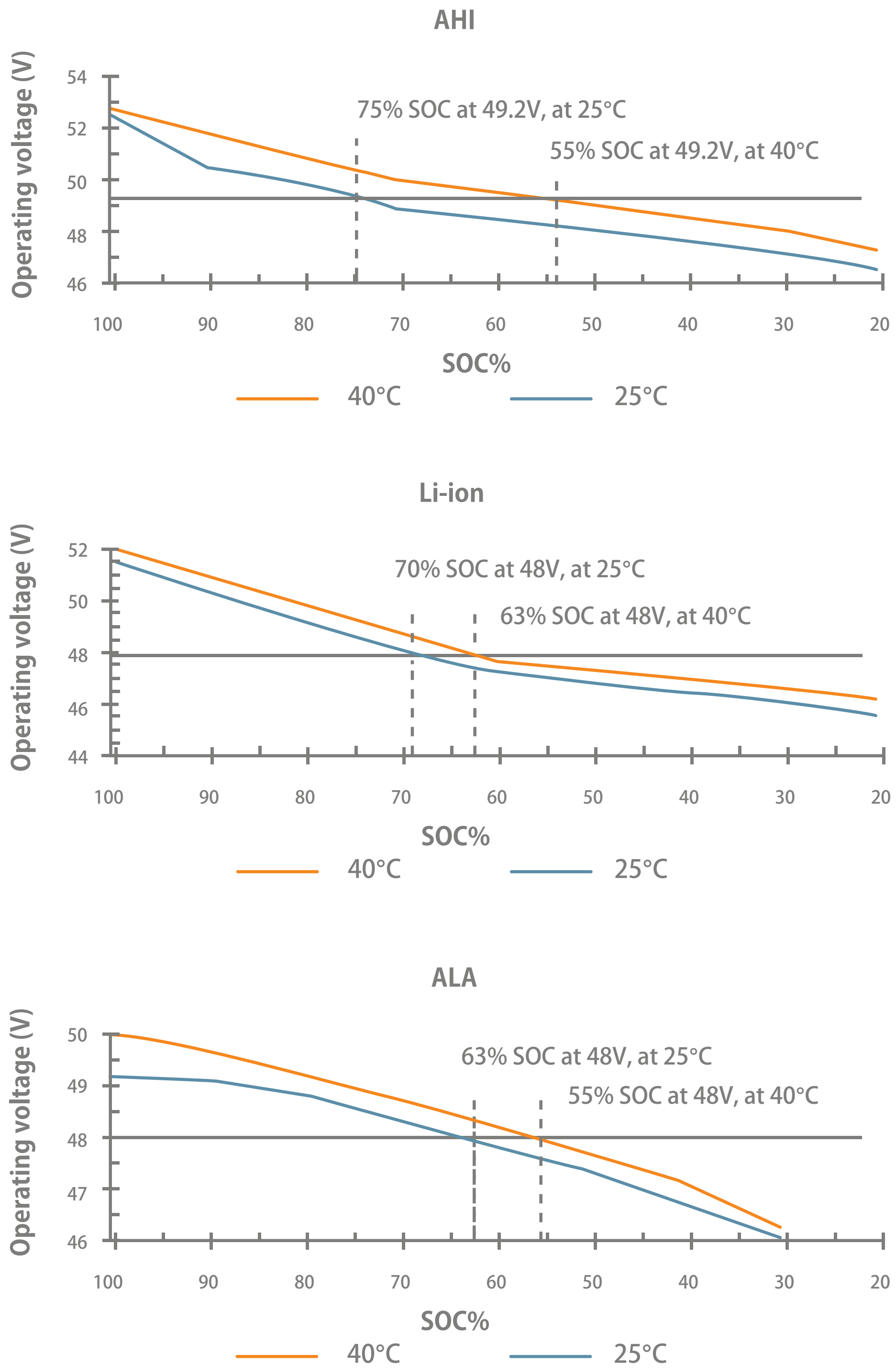


Exhibit 6. All the tested batteries experience an upward shift in voltage as a function of SOC, between 25°C and 40°C. However, the shift in the Li-ion and ALA batteries, and to a smaller extent in the AHI battery, is well within the safe SOC range, which means that they are significantly less vulnerable to high ambient temperature.

Exhibit 6 shows the corresponding voltage shift experienced by the AHI, ALA and Li-ion batteries. While they all experience an upward shift, all three of them are likely less vulnerable than the AGM battery, since the shift in SOC associated with the change in voltage is well within the safe range. The ALA battery used in our tests was specifically treated for operation at high temperatures (up to 50°C); hence it shows less variation in voltage compared to the AGM battery, and performed similar to Li-ion battery.

2b Tolerance to high ambient temperature: Internal resistance

A battery's internal resistance is a measure of restriction against rapid charge and discharge. Hence, the effective delivery rate of stored energy from the battery depends on its internal resistance. A battery with a low internal resistance ensures quick response (with short duration) to high demand from large loads with high pulse current, which is typically found in power applications. On the other hand, batteries with high internal resistance are suitable for slow discharge rates and long duration. The less a battery's internal resistance changes with use, the more stable it is. As such, internal resistance is a good indicator of deterioration over time or under high temperature.

The internal resistance of conventional lead-acid batteries is low (but is known to increase over time due to sulfation and corrosion of their electrodes). ALA batteries (since they are a form of lead-acid) are similarly known to have low internal resistance, and their ultra-capacitor configuration is designed to keep it low by limiting sulfation and corrosion. Li-ion batteries have high internal resistance, which is known to be stable over time. AHI batteries also have high internal resistance, but its stability has not been independently verified.

In the tests conducted so far, we have not observed any meaningful changes yet as a result of temperature variation, and expect to begin seeing changes over the next 3-4 months as the batteries age in lifecycle testing conditions. However, as a function of SOC (Exhibit 7), the AGM and LA batteries tended to show an increase in internal resistance, while the AHI and Li-ion remained relatively unchanged. This may be an early indicator that the AHI and Li-ion batteries may be less vulnerable to time and temperature. Although both the AGM and ALA batteries show an increasing trend of internal resistance with SOC, the gradient for the ALA is lower than that of the AGM.

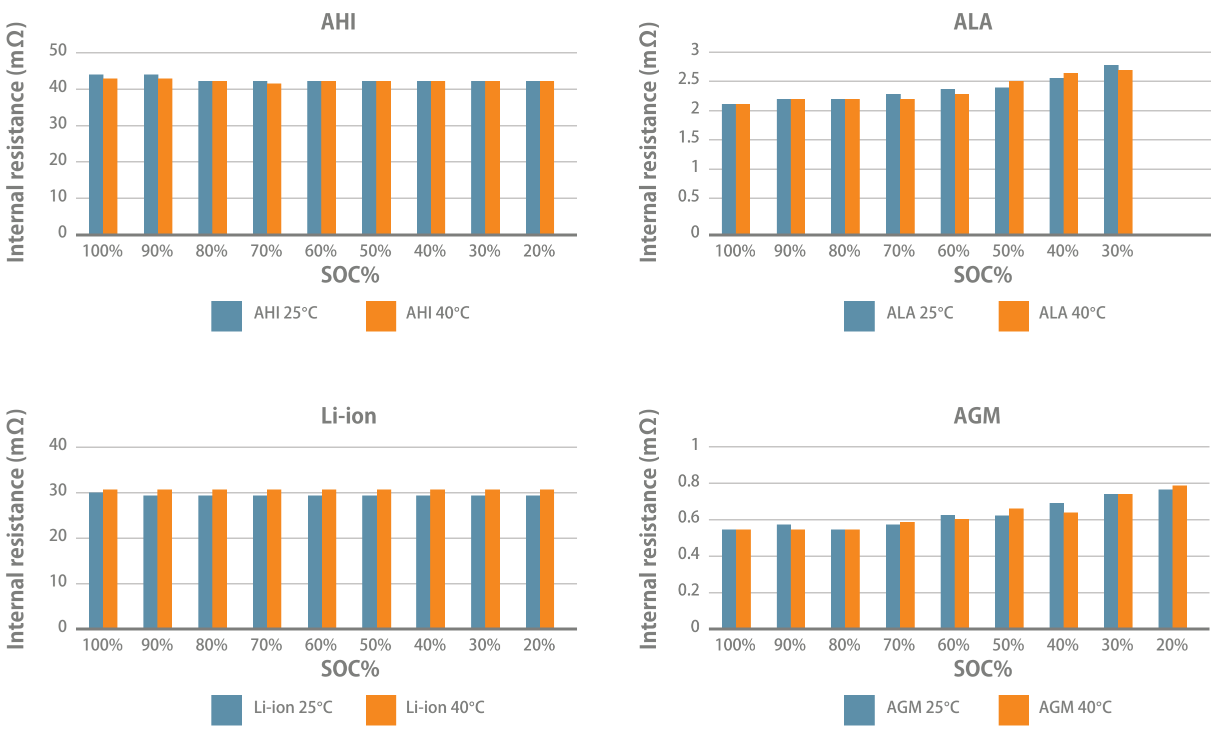


Exhibit 7. If a battery is vulnerable to high ambient temperature, the rate of increase of its internal resistance at 40°C will be higher than the rate of 25°C. This phenomenon becomes more pronounced over time, and our tests in the first few months have not yet observed any changes. However, the internal resistance of the AGM and ALA batteries tends to increase as a function of SOC, which is a characteristic of LA batteries. Note that due to their different configurations, the internal resistance of each battery could only be measured at different levels of aggregation (e.g., 2V cells for the AGM, a 12V block for the ALA, an 8V stack for the AHI, and a 48V block for Li-ion); as a result, their axes are along different scales in the graphs shown above.

3a Ability to supply high power output

One essential measure of a battery's ability to meet user demands is its ability to sustain a sudden, high power draw, such as those exerted by motorized loads. This ability can be measured by the change in voltage with quick discharge caused by sudden exposure to a high load—the lower the voltage drop, the stronger the ability of the battery to support a high power draw. Exhibit 8 shows the voltage drop in each of the batteries caused by the sudden introduction of a 3.5 kW load at a high (I_2) discharge rate. According to our tests, the AGM, ALA and Li-ion batteries all appear capable of supporting a sudden, high (3.5kW) power draw, whereas the AHI battery is less so.

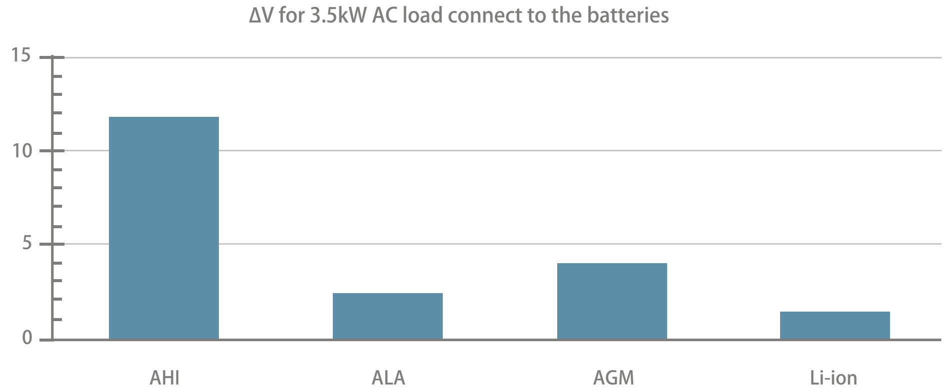


Exhibit 8. When subjected to a high (3.5kW) power draw, batteries with the ability to support that load will experience limited voltage drop. As this exhibit shows, out of the four batteries we tested, the ALA and Li-ion batteries appear best suited for this purpose, while the AHI battery is least suited.

3b Ability to supply high energy output

In low-income rural settings, it is likely that the heaviest power draw is from small mechanical appliances like fans, drills and small milling machines. Such appliances, even in aggregate, may not account for a large power draw. Indeed, all current data on mini-grids serving small rural communities suggests that it may be more important for a battery to provide low power loads for an extended period of time. Batteries used in energy applications are designed to charge and discharge at slow rates. A single charging cycle of a battery connected to a PV mini-grid typically constitutes daytime solar charging for 8 hours, accompanied by part daytime and full evening discharge with loads. The amount of energy available from a fully charged battery depends on its discharge voltage and allowable Ah discharged using the manufacturer's specification for DOD. Exhibit 9 shows the estimated energy output from 600Ah batteries of each of the four kinds, using the test results for voltage and available Ah (using their respective maximum discharge conditions). With a higher operating voltage during discharge, the AHI battery appears most capable of supplying high energy output, followed by Li-ion, AGM and ALA.

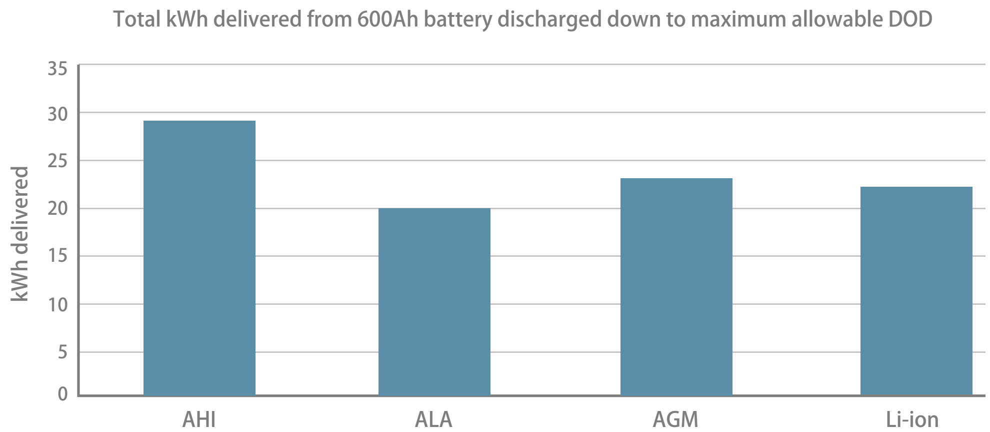


Exhibit 9. The AHI battery provides the higher energy for a given capacity, followed by Li-ion, AGM and ALA.

4a Cycle life: Round-trip efficiency

The round-trip efficiency of a battery is represented by the ratio of total Amp-hours (Ah) discharged at I_{10} rate, and Ah input at the manufacturer's rated current. In general, a round-trip efficiency of over 85 percent is indicative of good state of health for a battery during its usable life. Since the batteries we are testing are relatively new, all of them demonstrated high round-trip efficiency (97 percent and higher). Exhibit 10 shows the results of these early tests. We will continue to measure round-trip efficiency via the accelerated lifecycle tests, and we expect these efficiencies to change over time.

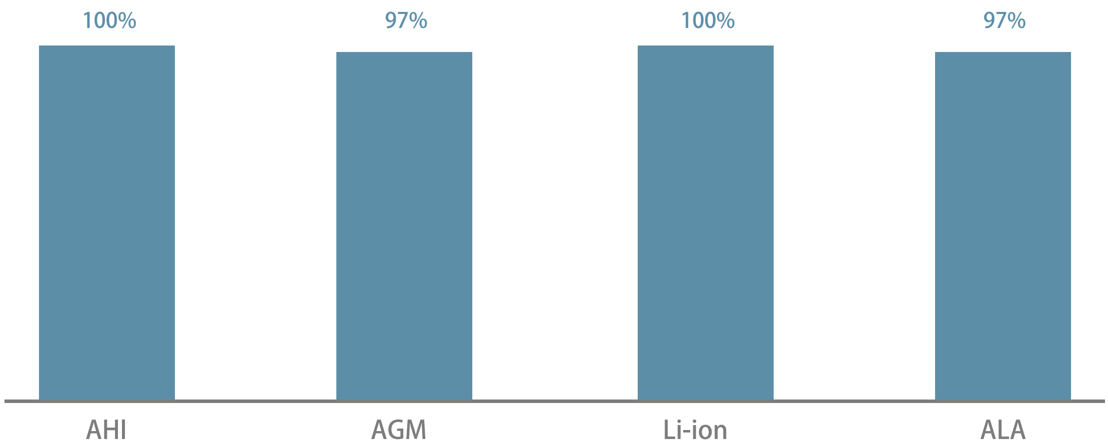


Exhibit 10. Since the batteries being tested are all new, their round-trip efficiencies are still high. We expect this to deteriorate over time, particularly among the batteries which are less durable.

4b Cycle life: Accelerated lifecycle test at PSOC

The accelerated lifecycle tests are underway, and we expect interesting results to emerge in the months to come. These tests will be performed for a long period of time (4 months) at 40°C to accelerate its degradation (as illustrated in Annex 2 of the report), with fully controlled charge-discharge rates. The test will be carried out in two phases based on IEC standards: the first is with shallow cycling at low SOC, and the second with shallow cycling at high SOC. For the accelerated lifecycle test, a minimum of three complete IEC cycles[16] (150 cycles) should be achieved; at the end of the lifecycle test, the C_{10} capacity[17] should not be less than 80 percent of the manufacturer's rated full capacity.

[16] According to IEC 61427 standards, 1 test life cycle = 50 shallow cycles at low SOC + 100 shallow cycles at high SOC; which represents 1 year of service life in a PV application.

[17] The C_{10} capacity of a battery is the capacity upon recharge, after fully discharging over a period of 10 hours.

Test results from solar PV simulation test bed: load profiles of rural consumers

While there is abundant sunshine throughout most of India through much of the year, there are times during the year—e.g., during the monsoon season, or the foggy winters of northern India—when there isn't enough predictable insolation to both support the daytime load, and to sufficiently charge the batteries. Hence, the ideal battery will extract charge from limited light and achieve maximum depth of discharge during nighttime, without deterioration. To determine the ability of the batteries to deal with such non-ideal conditions, we are conducting a number of tests under the Delhi sunlight, simulating various energy and power consumption patterns observed in rural India. In this setup, the batteries are charged by a PV array under sunlight, and discharged by a combination of a programmable load bank and appliances specifically chosen for their importance to rural small enterprises (e.g., drills). Note that these tests are designed to be conducted over the course of several months; as such, the results discussed below do not illustrate any meaningful differences between the batteries.

Each test bed is attached to a 5.5kW PV array. The size of the battery stack was determined on the basis of the battery's actual capacity and recommended DOD, to achieve homogeneity of usable capacity we used four stacks of AHI (8.8kWh), two strings of ALA (14.1kWh), and three modules of Li-ion (7.8kWh).[18] The batteries are charged via solar PV radiation over the natural course of the day (i.e., sunrise through sunset).

We designed a number of load profiles based on usage data from villages in India and Bangladesh. These load profiles include a base load representing typical residential and small commercial use (combinations of lights, fans and TVs), and peak loads through a combination of a submersible pump (1.8kW), a drill machine (0.6kW) and a blower (0.6kW).

Exhibit 11 illustrates the highest-stress scenario—commercial-level heavy motor loads at 40°C ambient temperature—over the course of a 12-hour day (10:00 am–10:00 pm). The 3kW peak load is applied for 45 minutes at about noon. The load is applied sequentially to each of the three test beds, followed by a 1.89kW evening peak load, and all procedures are in accordance with international industry and IEC standards procedures.[19, 20, 21]

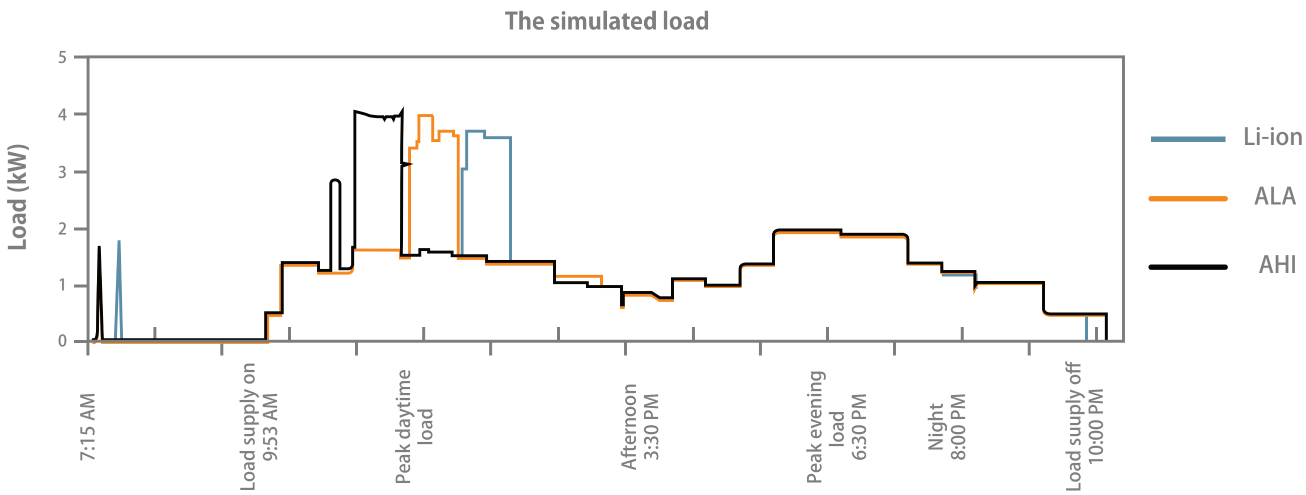


Exhibit 11. The load profile consists of a combination of—(a) several resistive and inductive loads from the load bank; and (b) motor loads from a 0.6kW drill, a 0.6kW blower and a 1.8kW submersible pump, running in 45-minute stretches.

[18] This represents usable capacity of 8.8kWh for the AHI (assuming 100 percent DOD), 8.46kWh for the ALA (assuming 60 percent DOD), and 7.3kWh for the Li-ion, (assuming 93 percent DOD).

[19] "Secondary Cells and Batteries for Photovoltaic Energy Systems – General Requirements and Methods of Test", IEC 61427, 2013.

[20] "Secondary Cells and Batteries for Solar Photovoltaic Application – General Requirements and Methods of Test", IS 16270, 2014.

[21] "Stationary Valve Regulated Lead Acid Batteries – Specification", IS 15549, 2005; Reaffirmed 2010.

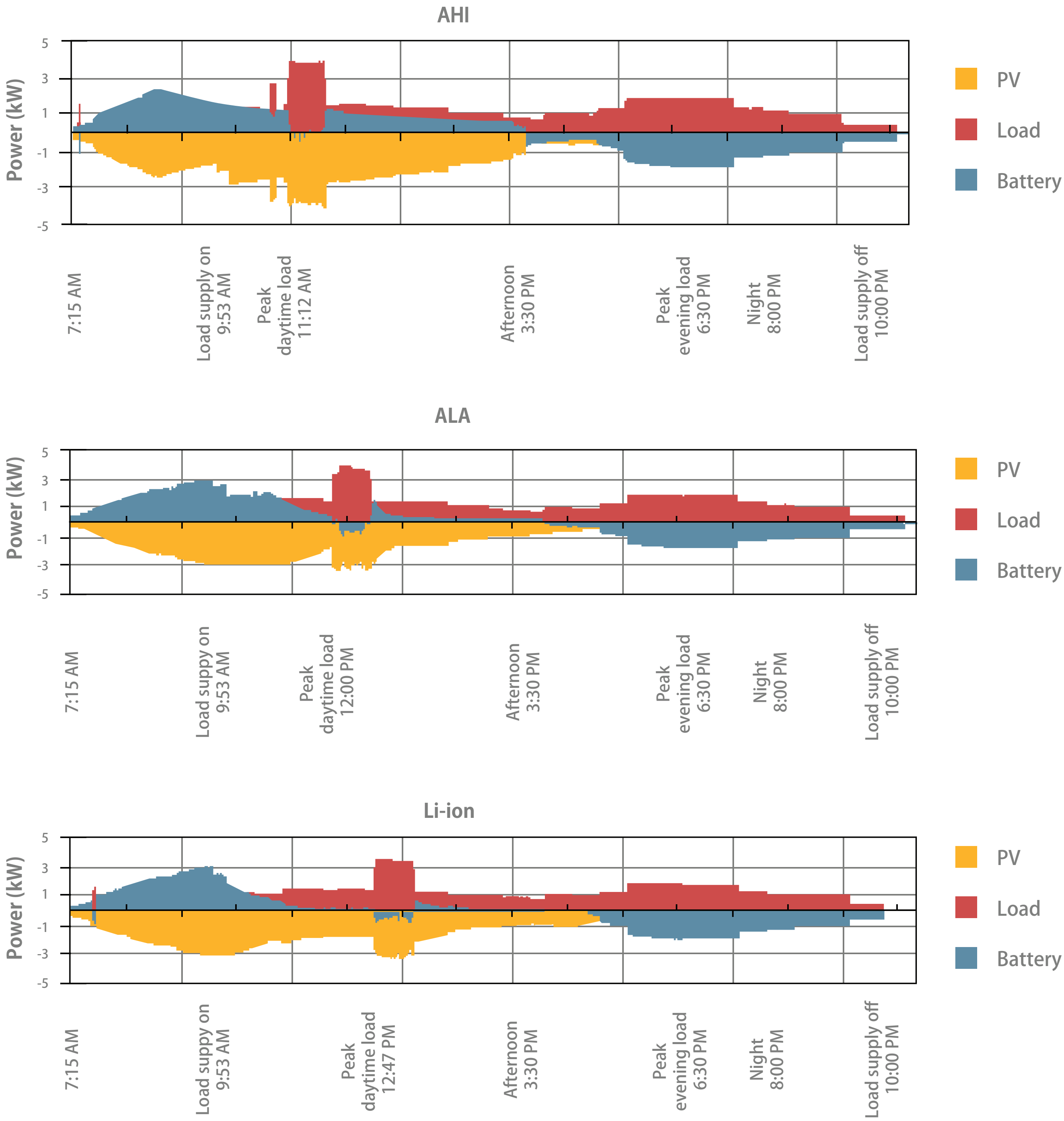


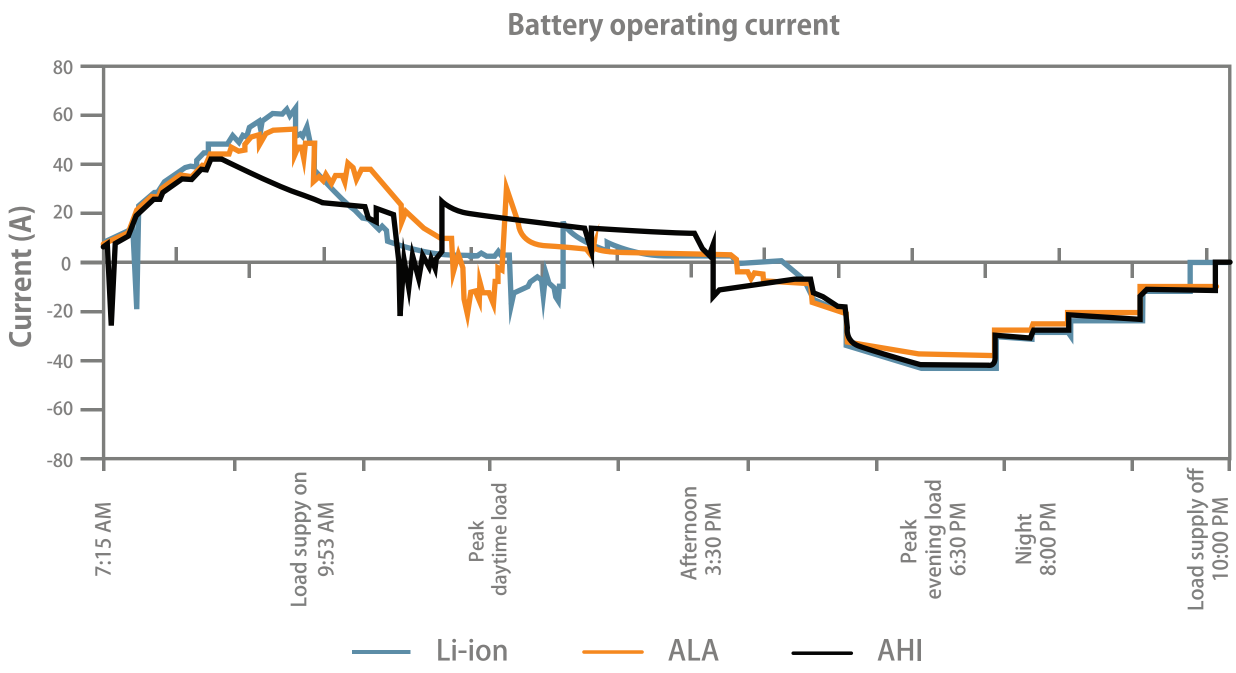
Exhibit 12. The behavior of each of the batteries in the simulated mini-grid tests is monitored over the course of the full day. Over the next few months, we will monitor the battery's performance with respect to how much energy they continue to store, supply, and have left over.

Exhibit 12 shows the power flow between the PV panels, batteries and loads. By simultaneously monitoring the individual batteries on their respective test beds, we are able to measure critical parameters under the same operating conditions. The energy input to the system is monitored through the total power generated by the PV panels, divided between the daytime load and battery storage. The evening and nighttime loads, along with a portion of the peak daytime load, are supported by the battery.

The PV power, battery power, load power are all monitored and measured through the data acquisition system (DAS). In this example, each battery is at a different SOC at the beginning of the cycle (again, simulating realistic conditions), and reaches full charge condition before peak noon. Table 2 summarizes the total energy in, out, and left over, for each battery—metrics we will continuously track over the course of the next few months to determine battery long-term performance.

Parameter Description	AHI	ALA	Li-ion
Total bank size (kWh)	8.8	14.1	7.8
Initial battery SOC (approx.)	20%	30%	10%
Initial energy in battery (kWh)	1.8	4.2	0.8
Energy supplied to battery (kWh)	9.3	9.0	7.5
Load supplied by battery (kWh)	7.5	7.3	7.3
End of day SOC (approx.)	16%	50%	11%

Table 2. Over the course of several months and many cycles, we will continue to monitor the batteries' performance with respect to energy in, load supplied, and energy remaining. Note that the difference in the SOC for the various batteries depends both on manufacturer recommended DOD, as well as battery size. For example, the ALA manufacturer recommends using only 60 percent of capacity within the range of 30 percent to 90 percent SOC.



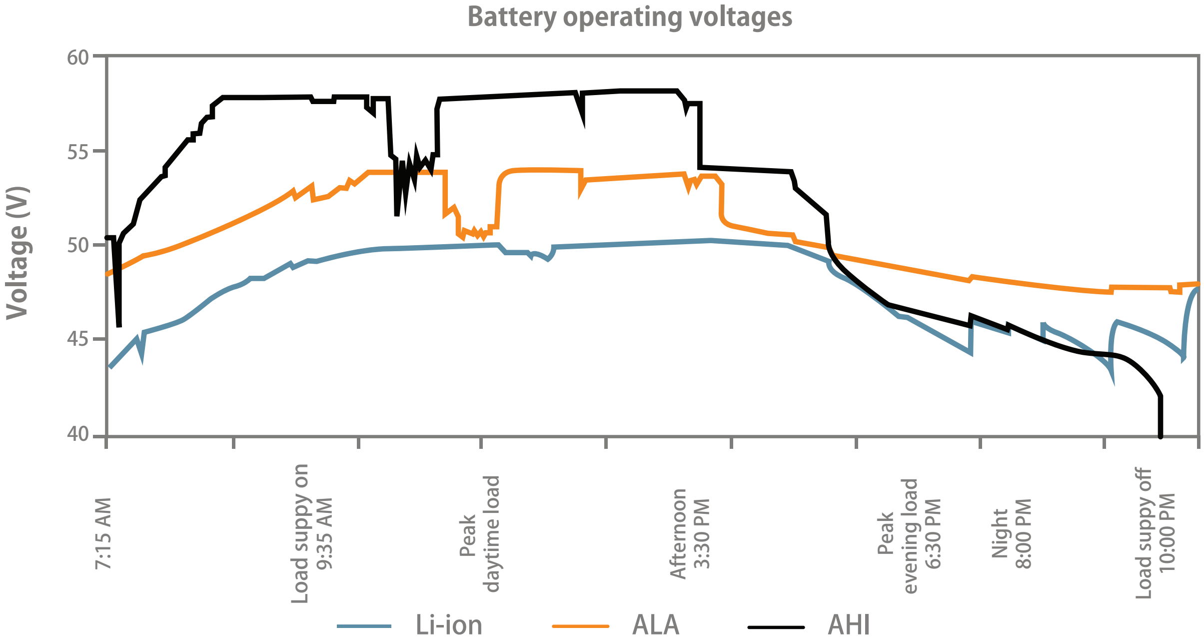


Exhibit 13. We are also monitoring current and voltage as indicators of battery performance and health. Consistent with the controlled tests described earlier, the AHI battery experiences a voltage drop after the introduction of high power loads, while the ALA and Li-ion batteries maintain relatively stable voltages. Note that the Li-ion battery voltage drops off a little earlier than the others because it is a slightly smaller battery.

We are also monitoring operating current and voltage as additional indicators of battery performance and durability (Exhibit 13). As shown in this early example, the operating currents of all three batteries indicate consistent charging via solar PV until the afternoon, and continuous discharging thereafter. All batteries also show additional discharge when the 3kW peak load is introduced. Immediately following the discharge due to the peak load, the batteries continue to be recharged again by solar PV at different rates. These recharging rates are voltage driven, which is a result of its inherent chemistry. In general, large variations in the magnitude of operating currents is due to the introduction of heavy motor loads, while smaller fluctuations can be attributed to variation in solar intensity during the day.

Except for Li-ion, all the batteries were able to meet the planned nighttime load; however, the Li-ion's premature disconnect was due to its lower capacity (1kWh less than the others). The AHI and the ALA are discharged down to 85 percent DOD, and the Li-ion by 93 percent. For batteries of these sizes, the PV charging was adequate on this specific day of testing. However, on days with lesser solar insolation, like on a cloudy day, or during the monsoon season, we can expect the batteries to get inadequate charge. Hence, the performance will vary at less than full charge, which may require the on-set of a generator.

The operating voltage of the three batteries during a full charge-discharge cycle is controlled by the set points of the charge controller and inverter. Even though the tests simulating mini-grid patterns are in their very early stages, one important characteristic of the AHI battery (demonstrated in the controlled tests described earlier) is already apparent: its inability to sustain high power loads for long periods of time. As Exhibit 13 shows, the operating voltage of the AHI battery drops from 49.7 to 44.8 within two hours under the peak evening load; by comparison, the Li-ion voltage drops from 48.9V to 45.8V, and the ALA voltage drops from 49.6V to 48.2V. It indicates that if the load power is higher, or the load duration is longer, the battery will reach the low disconnect point of 40V before the day is over, thus interrupting supply or triggering a backup generator.

Discussion of results, and implications for use in solar mini-grids

To recap, the tests described above had two objectives: first, to understand the strengths and weaknesses of the shortlisted batteries, and second, to determine which of them is the best alternative to conventional lead-acid batteries for rural India. The following is a summary of our findings based on the tests we have conducted. Please note that these findings are not conclusive; they reflect our best projections based on a few months of rigorous testing. As we continue to run tests in the months to come, the performance of any of the batteries may deviate from current trajectories. We will synthesize and report all new findings in subsequent reports.

Advanced lead-acid battery

The ALA battery sustained high power discharge for a long time during the stress tests simulating a sudden power surge with a motor. Another strength of the ALA battery is its high/rapid charging capability; in the slow-charging solar PV context, however, this is less of an advantage. This battery demonstrated a relatively flat operating voltage as a function of SOC, and less sensitivity to temperature rise compared to the AGM battery. This ALA battery has been designed for partial SOC operation, strictly remaining in the 30-90 percent range in a normal cycle (with the remaining 30 percent SOC serving as reserve capacity). As a result, only 60 percent of the battery's capacity is usable, which is comparable to conventional lead-acid batteries. The combination of strengths and drawbacks suggests that the ALA battery is well suited for use in rapid charge-discharge cycle typical to large, main grids frequency regulation.

Aqueous hybrid ion battery

The AHI battery demonstrated the highest operating voltage along with a wide operating voltage range, compared to the other batteries we tested. This resulted in highest energy transfer per Ah discharged. The capacity test of the AHI battery also showed high Ah discharge capability, leading to 100 percent DOD repeatedly without any degradation or loss of original capacity, which was observed even at higher than recommended discharge rates. Hence, we believe it is suitable for long duration, relative slow charge-discharge stationary applications like solar mini-grids, especially with residential and small commercial loads. One limitation is that this battery cannot sustain a high discharge rate for a long period. Hence, the battery will not be ideal for use cases with high power draw and rapid discharge, such as large commercial loads.

Li-ion battery

In principle, there are a number of Li-ion batteries with characteristics (e.g., NMC chemistry) similar to the Li-ion unit we tested; hence, these findings can be expected to apply to other brands as well. The battery appears to be stable under high ambient temperatures. The discharge capability (voltage vs. SOC) remains relatively constant at the various discharging rates, which indicates its capacity to endure conditions of low as well as high power loads. This battery has a usable capacity of 80-90 percent, and hence very suitable for solar mini-grids. The battery also performed well in the high power tests. In principle, therefore, the Li-ion battery with NMC chemistry combines the benefits of both advanced lead-acid and aqueous hybrid ion.

Summary conclusion

Even as a number of the technical tests—particularly those assessing the longer-term durability of the batteries—are continuing, we believe we have enough evidence to draw the following conclusions about the batteries' performance. Note that these conclusions are strictly based on technical performance in our tests. We have not exhaustively compared these findings with other reported results; nor do these conclusions take into account economic factors, which is the focus of our future work.

Li-ion batteries (with the NMC chemistry) appear to be the most suitable for use in solar mini-grids with high power loads, high energy demands, as well as operational stresses such as high ambient temperature, deep cycling and partial state of charge. They combine the advantages of the other battery technologies. In addition, global market forces appear to be continuously driving down costs globally. However, there remains significant unpredictability in the future cost of this technology, particularly in India if the batteries have to be imported from another country. As such, waiting for the costs to drop below the acceptable threshold may be a high-risk proposition.

The AHI battery shows high potential in deep cycling at slow charge-discharge rates typical to the rural solar mini-grid context with residential and small commercial users. Its limitation to handle a high power draw can be compensated with larger battery capacity, or a diesel backup generator managed by a relatively simple control system. Its environmental footprint also appears to be the cleanest of the various battery technologies we examined. Our early analysis of the chemistry and manufacturing process also suggests that it may be possible to make them in India at a reasonable cost. However, this battery lacks one major advantage that Li-ion has—demand in an application with large and fast-growing market, namely electric vehicles. With the global market for mini-grids still being small, battery technologies like AHI will likely struggle to be financially sustainable. Indeed, the recent news on Aquion Energy[22] underscores the challenges this technology will face. As such, this battery technology will likely be feasible only if it can be made (or at least assembled) in India.

The ALA battery addresses a number of the technical challenges associated with conventional lead-acid batteries. It can also be easily accommodated into the manufacturing processes of existing lead-acid battery factories, as evidenced by the recent agreement between Ecoult and Exide, in India.[23] Our analysis suggests that this battery addresses some of the challenges faced by rural solar mini-grids, namely high power demand, and operation at high ambient temperature.

Next steps

Over the next few months, ITT will conduct in-depth analyses of the feasibility and economics (capital cost, as well as total cost of ownership) of making Li-ion, AHI and ALA batteries available and operational in India. We will also work closely with relevant manufacturers to explore the various options, including local manufacturing, advanced/bulk procurement, etc. In the meantime, we will continue conducting lifecycle tests, as well as rigorous assessments of the batteries' environmental footprint and recyclability. In the months and years to come, we will continue exploring relevant new battery technologies and low-cost energy-efficient appliances, and will conduct similar tests on them, as appropriate.

[22] PV Magazine, "Aquion files for Chapter 11 bankruptcy", March 17, 2017. (https://www.pv-magazine.com/2017/03/09/aquion-files-for-chapter-11-bankruptcy/)

[23] Greentech Media, "With Millions From Australia, Ecoult Takes Its Hybrid Superconductor and Lead-Acid Battery Global", February 27, 2017. (https://www.greentechmedia.com/articles/read/ecoult-aims-for-worldwide-presence-by-2019)

Annex 1: Description of the battery test facility

Overview of the test facility

ITT, in partnership with Tata Power-Delhi Distribution Limited (TP-DDL), has built a battery test facility in the Delhi suburb of Rohini. There are two separate sets of test beds at this battery testing facility—(a) a DC platform to test battery performance through basic characteristics tests; and (b) a solar PV mini-grid simulation (with power from a solar PV array, and load generated by a load bank and real appliances).

DC test bed

The DC test bed is a fully controlled environment used to perform basic tests for validating core battery characteristics: capacity test, round-trip efficiency test, characteristics test, and accelerated lifecycle test (at partial state of charge). The test protocols described in Annex 2 follow international standards[24] for battery testing, where precision tests are performed in a controlled manner. In this setup, the test bed is equipped with a DC charger, and batteries are discharged with adjustable resistance (rheostats). A multichannel data acquisition system (DAS) is used for automated data collection from the test beds. The chamber is also temperature-controlled, in order to study the effect of high ambient temperature.

Solar PV simulator for battery testing

The solar PV simulator has a total PV capacity of 20kW, diverted to three parallel battery test beds from the TP-DDL sub-station's existing capacity of 150kW (shown in Exhibit 14). This test facility, with Delhi's climate—winter fog, summer heat, monsoon rains and abundant sunlight in the more favorable seasons—provides a broad range of test conditions.

Exhibit 14. The battery test site is located at a grid sub-station operated by Tata Power-DDL, which has 150kW of solar arrays. 20kW of that is diverted for three parallel PV simulation test beds.

[24] Stationary Valve-regulated Lead-acid batteries – Specification, IS 15549: 2005; Reaffirmed 2010.

The simulation test beds are set to operate like solar mini-grids for typical Indian villages, where the PV modules are connected to the batteries via charge controllers, while the simulated AC loads are connected via the inverters. Each battery type comes with its own commercial size (rated Ah), specification (rated V), and operational characteristics (DOD in percent). As such, the three separate test beds can be operated with different ranges of PV power, battery capacity, and inverter configurations. For uniformity, the batteries in all three test beds are subjected to similar load patterns and stresses using programmable load banks, and their relative performance is assessed using industry standard charge and discharge rates.

The tests for each load pattern (simulating residential and small commercial loads) are conducted at moderate (25°C) and high (40°C) ambient temperatures, in controlled environments. A data acquisition system (DAS) has been set up for collecting battery response in voltage, current, and internal temperature synchronized with input conditions of PV, load and ambient temperature.

The test beds are equipped with industry standard communication hardware from the inverter supplier. The batteries are supplied with their own BMS modules, which communicate with the inverter power system electronics, to optimize performance.

Test bed for the Advanced Lead-acid (ALA) Ultraflex battery by Ecoult

The total PV input for this test bed is 9.2 kW. As shown in Exhibit 15, the UltraFlex stack has 16 mono block batteries (146Ah, 12V) arranged in a rack-and-fuse system provided by Ecoult, with a total capacity of 28.2kWh at 48V.

Exhibit 15. The test bed for Ecoult's Ultraflex ALA batteries, with a 6kW inverter coupled to 60Amp and 80Amp charge controllers, configured with a capacity of 28.2kWh. This battery stack comes with an integrated BMS.

Exhibit 16. Ecoult's Ultraflex batteries are 16 mono blocks supplied with an inbuilt rack and a BMS that displays voltage, current, state of charge and battery temperature.

Test bed for the Aqueous hybrid ion (AHI) battery by Aquion

The AHI test bed is connected to 5.52kW of PV power with an 80A charge controller, and a total battery capacity of 8.8kWh. These batteries represent a new chemistry using non-toxic sodium sulphate based salt water as electrolyte material. They are arranged in vertical S line 48V stacks. Four stacks of S30 - 080—each weighing about 120 kgs—are placed in the battery test bed with its own BMS and a stack monitoring interface (SMI). With battery capacity of 8.8kWh, the test bed uses a 6kW inverter coupled to a Schneider 80Amp charge controller. Exhibit 17 shows the test bed.

Exhibit 17. The Aquion AHI batteries are stacks of connected cells, for a total capacity of 2.2kWh at 48V.

Exhibit 18. The Aquion battery has an integrated stack monitoring system (SMI).

Test bed for the Lithium-ion NMC battery by Panasonic

The Panasonic Li-ion batteries being used in these tests use Lithium-Nickel-Manganese-Cobalt (NCM) chemistry, with a nominal voltage of 46.8V housed in a completely closed enclosure, monitored and controlled by its own integrated BMS.

Exhibit 19. The Panasonic Li-ion system consists of 5 fully enclosed 2.6kW batteries, each with its own integrated BMS.

The battery bank is connected to a 5.52kWp PV through an 80Amp charge controller. The batteries are being tested through different load conditions using a 6.8kW inverter with the load simulator. There are five batteries in the Li-ion battery test bed, each with capacity of 56.28Ah and weighing 25kg.

VRLA AGM battery by Amara Raja

The VRLA AGM battery is manufactured by Amara Raja. This battery is a 300Ah, 48V module, connected to a 5.52kWp PV through an 80Amp charge controller. The 14.4kWh battery will be tested under different load conditions through the 6.8kW inverter using the load simulator. Unlike the other batteries being tested, this does not come with its own battery management system.

VRLA Gel battery by Exide

A VRLA Gel battery manufactured by Exide will also be tested on the PV simulation test bed. This battery is a 300Ah, 48V module, connected to 5.52kW of PV through an 80Amp charge controller. Like the VRLA AGM battery, the 14.4kWh Gel battery will be tested using different load patterns connected to the 6.8kW inverter.

Hybrid combination of lithium-ion and conventional lead-acid batteries

We plan to build and test an integrated system consisting of a VRLA battery combined with a Li-ion battery. The charge-discharge configuration of the hybrid battery is yet to be determined.

Data Acquisition System (DAS)

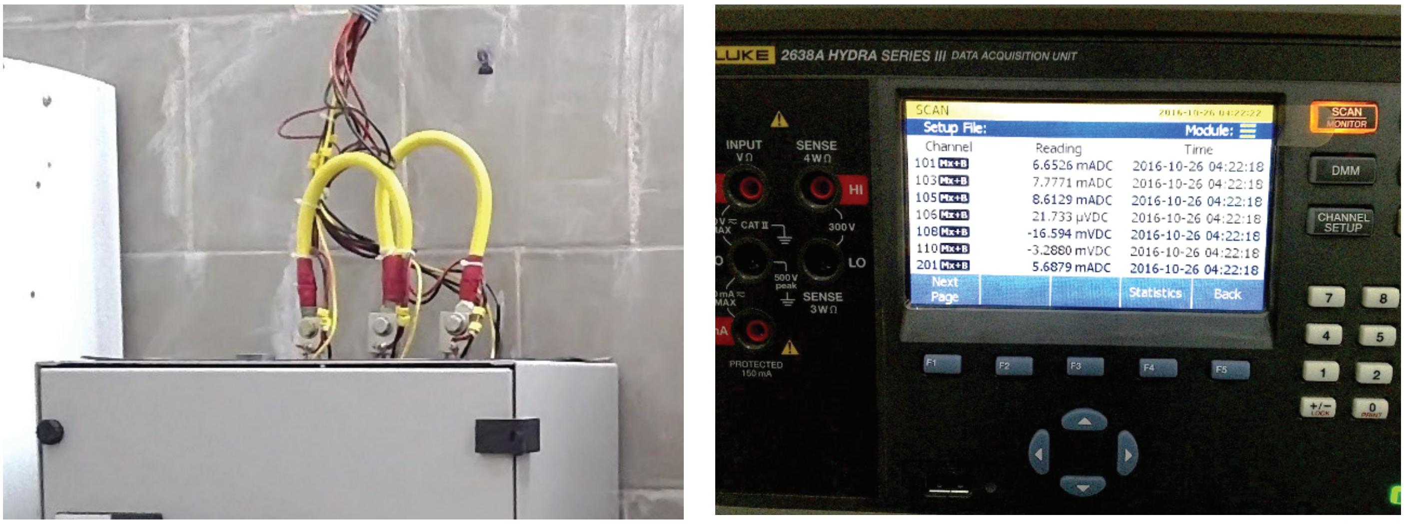


Exhibit 20. Fluke DAS with data logger with shunt connection and display.

The microprocessor-based multichannel DAS (Exhibit 20) used in the test configuration includes high speed communication for collecting data from the three test beds simultaneously.

Annex 2: Battery testing protocols

1 Capacity test

The objectives of the Capacity test are to measure—(a) effective capacity of the batteries in actual operating conditions; (b) operating voltage vs. SOC profiles for different operating conditions; (c) usable capacity under extreme loading and ambient conditions; (d) internal impedance and effect of temperature; and (e) aging and seasoning of the batteries.

Test procedure

- The battery is charged fully per manufacturer's instructions at a constant voltage for 24 hours.
- After completion of charging, the battery is left standing on open circuit for no fewer than 2 hours, and no longer than 24 hours.
- The battery is discharged via variable resistance at constant current at an I_{10} rate (± 1 percent). The discharge currents of the tested batteries are:
  - $I_{AGM} = 30A$
  - $I_{Li\text{-}ion} = 5.63A$
  - $I_{ALA} = 58.75A$
  - $I_{AHI} = 16.9A$
- The discharge was stopped at the manufacturer's specified disconnect threshold (80 percent DOD or low voltage disconnect). The tests were repeated—(a) at all settings to minimize errors, (b) at I_5 and I_{20} rates, and (c) at 40°C.

Pass criteria

At the first discharge, the battery should not provide less than 90 percent of rated capacity. Within 5 discharges, it should provide 100 percent of rated capacity. Once the rated capacity has been met on any discharge, further discharge cycles for capacity need not be continued.

Data collection

- Time required for meeting the manufacturer's specified higher threshold voltage is recorded as the total charging time.
- Time required for the battery terminal voltage to reach the lower voltage threshold is taken as period of discharge.
- During both charging and discharging, the battery terminal voltage and battery charging current are recorded at 30-minute intervals.
- The internal resistance of the battery is measured using the Fluke battery analyzer.
- The time, current, and voltage data is used for calculating transferred charge and energy.
- Ah and Wh efficiency are evaluated.
- The tests are repeated at 40°C.

2 Round-trip efficiency test

The purpose of the round-trip efficiency test is to determine charge absorption and discharge capability at different rated currents (I_5, I_{10} and I_{20}), at 25°C and 40°C.

Testing standards[25] require the ambient temperature to be maintained within ±2°C, and the battery to be discharged at specified rates, with ±1 percent variation.

Procedure

- A fully charged battery is discharged at the I_{10} rate down to the manufacturer's specified low voltage cutoff, and the amount of Ah discharged is calculated.

- The battery is recharged at I_{10} rate by the amount of Ah discharged, and allowed 2 hours in an open circuit to recover. The battery is discharged again at I_{10} until the manufacturer's specified low voltage cutoff, and the Ah is calculated. The cycle at each charging rate is repeated at least 2 times to reduce the probability of error. The procedure is repeated at 40°C at different charging rates (I_5 and I_{20}).

Pass criteria

The round-trip efficiency should not be less than 90 percent at the I_{10} rate.

Data collection

During both charging and discharging phases in all the operating conditions, the battery operating voltage and current are recorded at 30-minute intervals.[26] The temperature of the negative electrode is considered as the temperature of the electrolyte.[27] The internal resistance of the battery is measured using the Fluke battery analyzer at different points in time during operation, as well as during recovery.

3 Accelerated lifecycle test at PSOC

The objectives of the lifecycle tests at PSOC are to determine—(a) the expected number of cycles in the useful life of the battery under high ambient temperature and partial discharge; and (b) the impact of temperature, using industry standard accelerated cycle procedures. The test is being carried out in two phases simulating the operating conditions of a standalone PV system over the course of a year: 50 shallow cycles at low SOC, and 100 shallow cycles at high SOC.[28]

Test conditions

The ambient temperature is maintained at 40°C for 16 hours, and the battery is in 40°C ±3°C throughout the test. The test is started with the battery fully charged.

---

[25] "Stationary Valve Regulated Lead Acid Batteries – Specification", IS 15549: 2005; Reaffirmed 2010.

[26] The time interval for data collection may vary depending on DAS setup.

[27] Not applicable for Aquion batteries, since they have no open terminals/points to connect probes for measuring temperature or internal impedance.

[28] One IEC 61427 cycle = (50 shallow cycles at low SOC) + (100 shallow cycles at high SOC) = 1 year of service life in a PV setting.

Procedure[29]

- The battery is charged fully per manufacturer's instructions (or at a constant voltage) for 24 hours;
- After completion of charging, the battery is left standing on an open circuit under ambient temperature of 40°C for 16 hours;
- Phase A of shallow cycling (low SOC) is conducted as follows:

1. From fully charged state, the battery is discharged for 9 hours at I_{10};
2. Then charged for 3 hours at $1.03I_{10}$;
3. Then discharged for 3 hours at I_{10};
4. The cycle (steps 2 and 3) is repeated 49 times before proceeding to phase B (shallow cycling at high SOC).

- Phase B of shallow cycling (high SOC) is conducted as follows:

5. The battery is fully charged and allowed 16 hours to stabilize to the ambient temperature;
6. Then discharged for 2 hours at $1.25I_{10}$;
7. Then charged for 6 hours at I_{10} (manufacturer recommended high voltage threshold should not be exceeded during this time);
8. The cycle (steps 6 and 7) is repeated 99 times;
9. After completing phase B, the battery is cooled down to 27°C and allowed to stabilize for 16 hours;
10. The C_{10} capacity test is conducted.

Test end condition

- During the phase A: when the cell voltage measured during discharge is lower than 36V.
- After the phase B: when the capacity measures lower than 80 percent of rated capacity.

Pass criteria

The minimum number of complete IEC cycles (150 cycles) achieved should be 3, and the C_{10} capacity should not be less than 80 percent of rated capacity at the end of the test.

Data collection

- The battery operating current is monitored continuously, and adjusted if necessary.
- The battery terminal voltage, operating current, and negative terminal voltage are measured at 5-minute intervals.
- The internal impedance of the battery is recorded every 10 cycles to assess degradation in life.
- The data for the capacity test at the end of 1 IEC cycle is recorded.

[29] "Secondary Cells and Batteries for Solar Photovoltaic Application — General Requirements and Methods of Test", IS 16270 : 2014, 2014.

4 Rural scenario simulation tests[30]

The purpose of this test is to compare battery performance under different loads, simulating rural mini-grid energy consumption.

Test conditions

- The PV size, battery capacity and inverter size have been selected to represent a scaled-down model of typical mini-grids.
- The system has been setup just as it would have been for any typical off-grid PV power plant, where the battery inverter is the main control point of the system.
- The system runs like a typical off-grid PV power plant.
- Manual involvement is limited to—(a) programming electricity usage patterns (as load profiles on the automatic load simulator), (b) running the data acquisition system, and (c) in case of any emergency.

Procedure

- Different kinds of load profiles simulating rural usage patterns (based on data from active mini-grids) are programmed into the load simulator.
- The system and the load simulator are programmed to run the pattern from 10:00 am till 10:00 pm.
- The PV array charges the batteries, and the load simulator generates various kinds of energy and power consumption patterns.
- Several different scenarios are simulated to test different aspects of each battery.

Pass criteria

- The effective capacity of the battery test should be adequate to supply daily energy requirements.
- Throughout this test, the battery must operate between the high and low voltage thresholds, as determined from the capacity tests and input-output characteristics.
- The battery must be able to provide instant support, with reaction time shorter than 0.5 seconds.
- The PV array must be able to sufficiently recharge the battery to support daily loads.

Data collection

The DAS data along with inverter combox data are used to obtain battery terminal voltage, battery current, PV load current, and negative terminal temperature measured at 5-minute intervals for the complete daily cycles.

[30] "Secondary cells and batteries for photovoltaic energy systems (PVES) – General requirements and methods of test", IEC 61427, 2013.

INSTITUTE FOR TRANSFORMATIVE TECHNOLOGIES

The next generation of breakthrough technologies
to combat global poverty

www.transformativetechnologies.org