CrossBoundary

Mini-Grid Innovation Lab

Innovation Insight

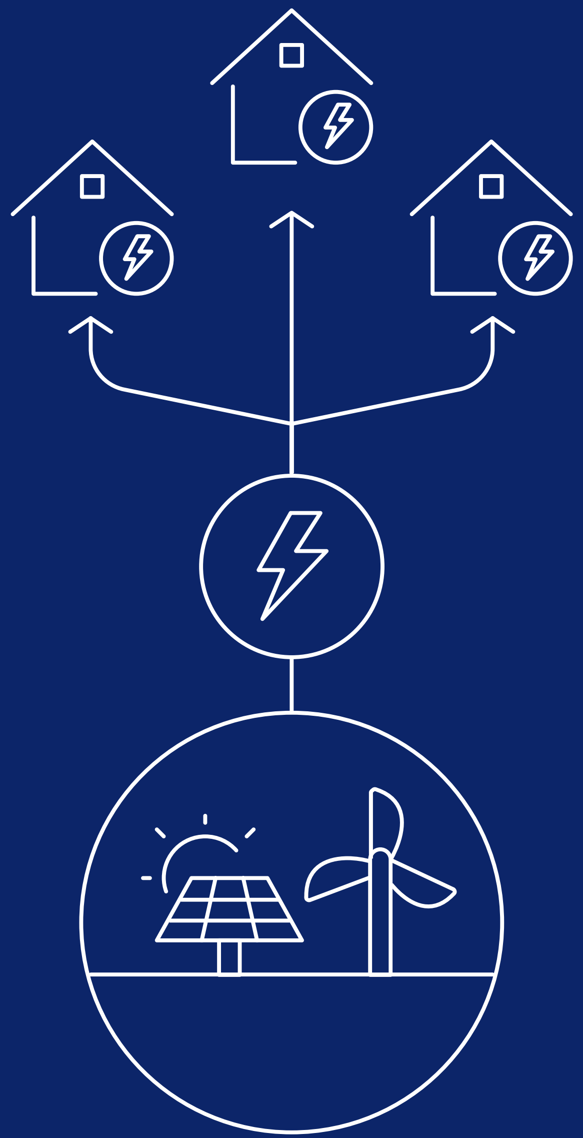
Second-life batteries

A lower-cost energy storage solution for mini-grids

July 2025

UKaid from the British people

Transforming Energy Access



About the CrossBoundary Mini-Grid Innovation Lab

CrossBoundary's Mini-Grid Innovation Lab, part of CrossBoundary Group, is Africa's first R&D fund exclusively focused on testing new business model innovations for mini-grids, designed to close the gap on the 618 million Africans who do not have power. The Mini-Grid Innovation Lab works with developers across the continent to test innovations to make mini-grids a more reliable and commercially viable solution. For additional information, visit **www.crossboundary.com/labs**.

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Funded By:

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Transforming Energy Access

Executive summary

Second-life lithium batteries could offer a lower-cost solution for mini-grid storage without sacrificing performance and reliability.

After distribution costs, batteries remain the largest contributor to capital expenditure (CapEx) for mini-grids. Second-life batteries present an opportunity to drive down this cost as rapid adoption of electric vehicles accelerates available supply.

The lab, in partnership with the FCDO's Transforming Energy Access initiative, is conducting field testing of second-life batteries, including lithium-iron-phosphate (LFP) packs across two sites in South Africa and Nigeria, and Lithium Nickel Manganese Cobalt oxide (NMC) packs in the Democratic Republic of Congo (DRC). These are being benchmarked against LFP packs at matched control sites with new batteries.

Our initial analysis suggests:

- Second-life batteries are cheaper upfront and are projected to have lower lifetime costs. But this will be determined by their technical performance over time:
  - Price benchmarks in SA, DRC, and Nigeria show a consistent **11-28% cost gap** relative to new batteries.
  - Lifetime cost modelling shows second-life batteries are **9-18% cheaper across Nigeria and South Africa** at $564/kWh and $634/kWh, respectively, provided replacement intervals stay at seven years or longer.
  - In contrast, the **NMC packs in DRC are 40% more expensive over the lifetime of the mini-grid at $866/kWh**, despite being the cheapest option upfront, due to an anticipated shorter replacement frequency.

- Since the difference in overall lifetime costs for the batteries is highly driven by replacement frequency, battery operations need to be carefully managed by developers to realize potential cost benefits:
  - The Lab will conduct an analysis of historical battery data as a proxy for capacity fade over time, validated by capacity tests, to confirm capacity retention matches our expectations.
  - The Lab will monitor charge-management practices (tight charge-window management, temperature control, and depth-of-discharge limits) that developers implement to prolong battery life and capture the full economic benefits.

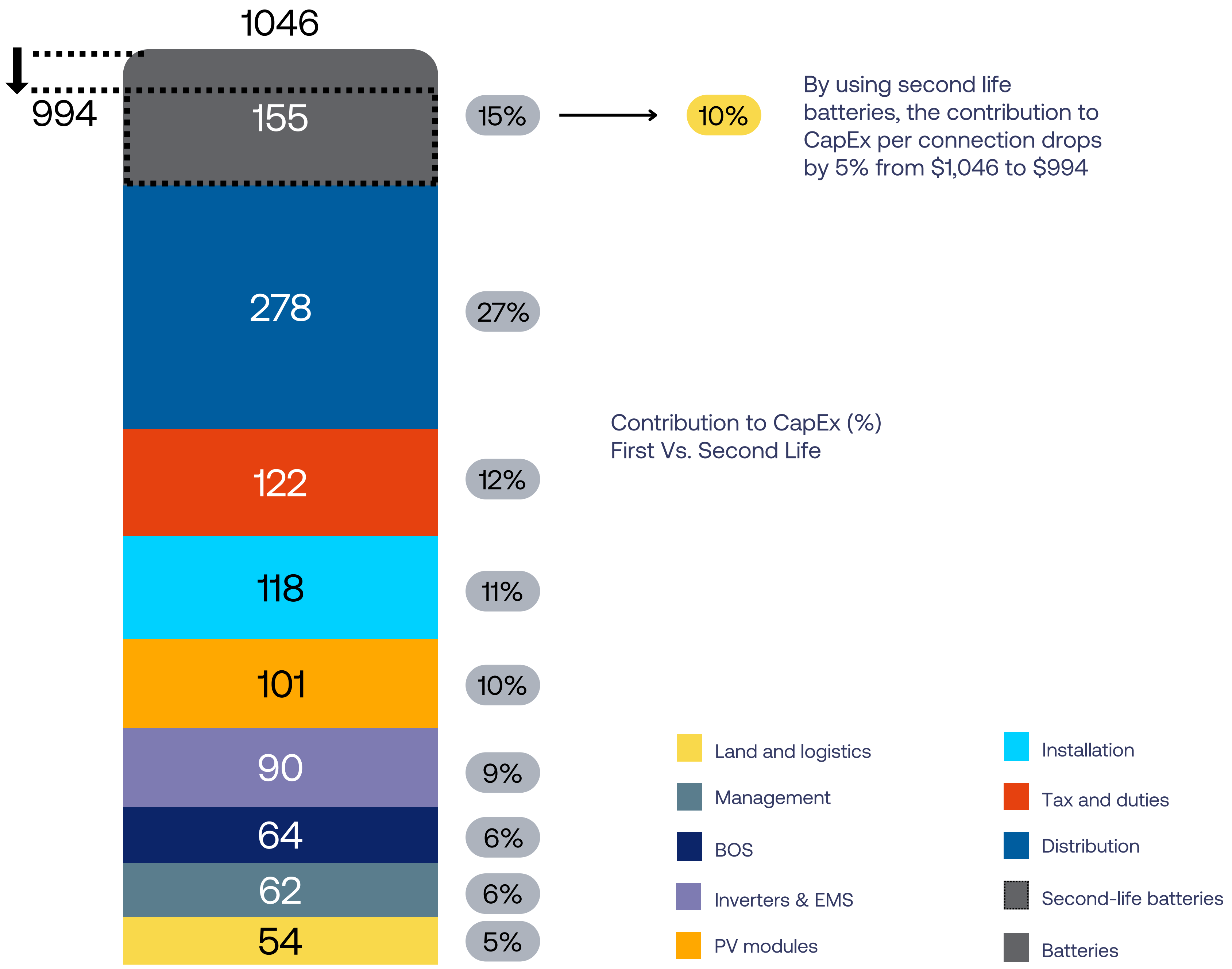
The work will feed into the Lab's recently launched Alpha-Tests, which cover standardized pack design, baseline diagnostics testing, and assessment of cross-border movement. These initiatives aim to address barriers that will unlock scale for second-life batteries and realize their true potential to improve mini-grid economics.

To explore partnership opportunities, please contact minigridslabs@crossboundary.com.

Batteries are a significant cost driver for mini-grids, but the growing supply of second-life batteries entering the market could reduce this.

After distribution costs, batteries remain the largest contributor to CapEx for mini-grids

Benchmark CapEx per connection components breakdown for Nigeria ($/connection)



Lithium-ion (Li-ion) Batteries are a core component of the mini-grid generation system, guaranteeing a round-the-clock supply of energy and mitigating seasonal impacts. They are often supplemented by diesel backup generators in hybrid systems.

Batteries constitute a significant portion of mini-grid capital expenditure (CapEx) costs – up to 15% per connection. They also impact lifetime costs as they require periodic replacement.

While battery costs have dropped by over 60-70% in the last decade[1], further reducing this cost could be a significant lever for improving the mini-grid business case and lowering tariffs for end-users.

Second-life batteries present an opportunity to drive down this cost.

Second-life Li-ion batteries, repurposed from dynamic systems like electric vehicles, could require lower CapEx while performing at the same level as new batteries. Our current data from Nigeria show that the cost per connection drops 5% from $1,046 to $994 when using second-life batteries.

In addition to CapEx relief, providing a second life application for Li-ion batteries has a climate co-benefit: it increases the batteries' circular economy by keeping materials in use longer, reducing life-cycle carbon and delaying the need for recycling. Furthermore, local assembly captures more value in-country, stimulating the local economy.

1. Mini-grids for half a billion people World Bank/ESMAP
Source: CBIL Developer data for Nigeria; World Bank/ESMAP, Press search

Second-life EV batteries available today could power a significant portion of all the mini-grids required for universal access in SSA

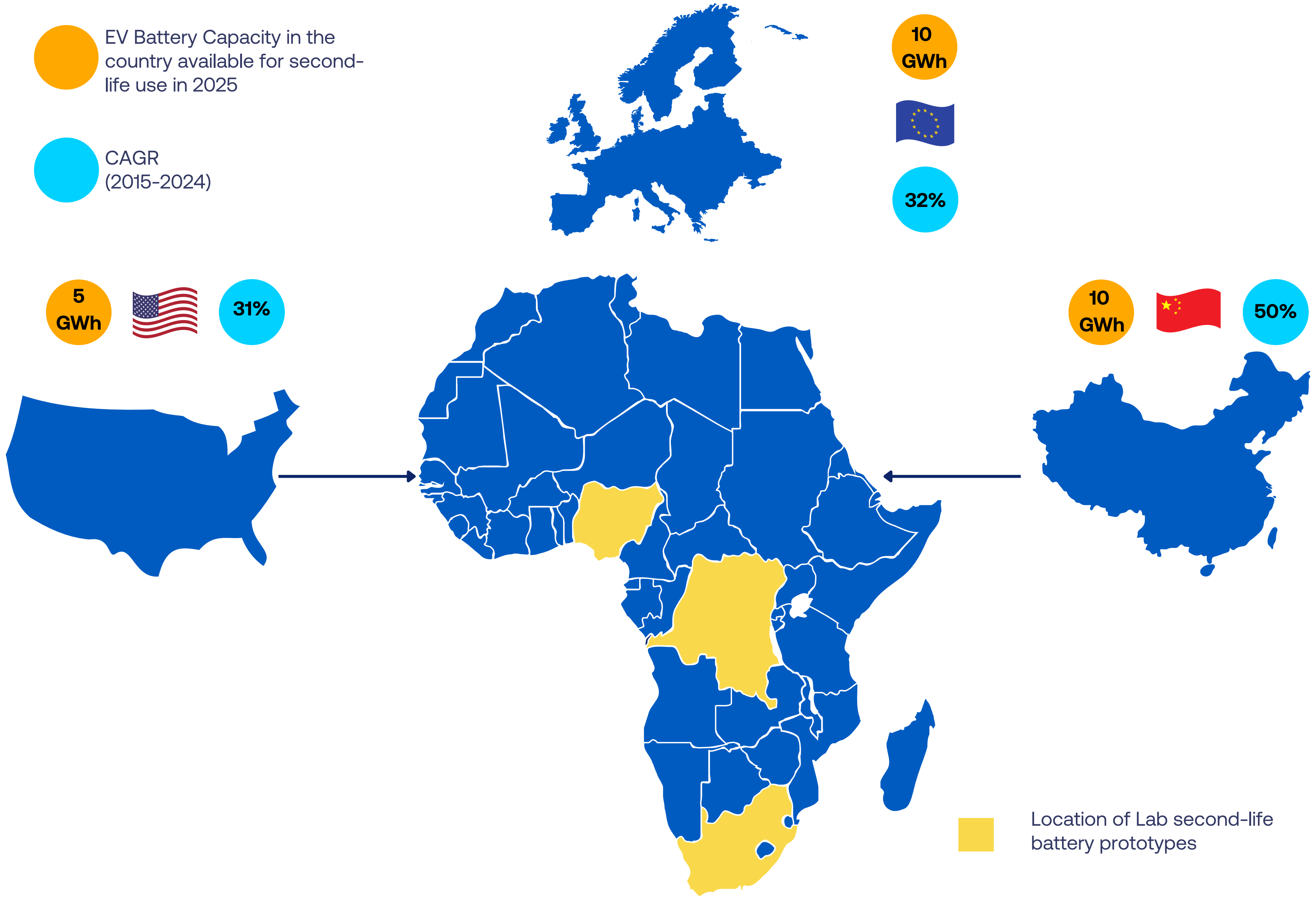
Global EV adoption is creating a large and fast-growing stream of battery demand. Since 2015, passenger EVs in China, Europe, and the United States have deployed ~25 GWh of four-wheel battery capacity. With an assumed 10-year first-life, these packs begin retiring now (2025), freeing a substantial resource for stationary "second life" use.

In the context of global energy access targets, these provide a significant pool of batteries that could be used in mini-grids. The World Bank estimates that 160,000 mini-grids are required across Sub-Saharan Africa (SSA) for universal electrification by 2030, corresponding to ~29 GWh of storage. This first wave of end-of-life EV packs could cover a major portion of this need.

Future availability, however, may tighten as new "battery-passport" rules encourage countries to keep critical minerals at home and surging AI-driven power demand spurs local repurposing of used packs.

Encouragingly, supply from within SSA will soon add to the global pool: although four-wheel EV uptake is modest, electric two-wheelers are expanding at 7% CAGR. By 2030, their retired packs alone could release ~0.4 GWh for reuse in mini-grids.

Figure 1: Potential second-life battery inflows to the African continent (GWh)



Sub-Saharan Africa currently has only 3,100 mini-grids, and an estimated 160,000 mini-grids are needed to achieve universal access. Source: Mini Grids for Half A Billion People: Market outlook and handbook for decision makers - ESMAP.
IEA sales figures for BEVs & PHEVs in China, the EU, and the USA show that 95 GWh of supply was put on the road in 2020. [Global electric car sales, 2014-2024 – Charts – Data & Statistics – IEA](). From these sales figures, the CAGR for those markets was calculated.
60% growth CAGR for SSA approximated using ~100 in 2015 to ~11000 units today (IEA). Insufficient historical data available to estimate capacity for second use in SSA 2025; therefore, projections made for 2030.
Africa's Competitiveness in Global Battery Supply Chains (2024) Manufacturing Africa

Our initial analysis suggests second-life batteries are cheaper upfront and are projected to have lower lifetime costs, but this will be determined by their technical performance over time.

About this prototype: The lab is studying the technical performance of second-life Li-ion batteries in mini-grids in comparison to new batteries' performance

Overview of the second-life batteries alpha-test

The lab is conducting field testing of second-life lithium-iron-phosphate (LFP) packs in South Africa and Nigeria, as well as one Lithium Nickel Manganese Cobalt oxide (NMC) pack in the DRC. We have matched these batteries to control sites, which are all LFP.

The second-life batteries and cells are sourced from Asia and Africa, where they were used in electric vehicles, motorcycles, and server farms. They are then disassembled and reassembled into packs by second-life technology suppliers on the continent.

Data collection and analysis

Data collection:

- Battery capacity
- Upfront battery costs
- Yearly Operational Expenditure (OpEx) costs - BMS Software-as-a-Service (SaaS), insurance, cooling, and inspections

Analysis:

- Capacity testing
- Battery degradation estimations

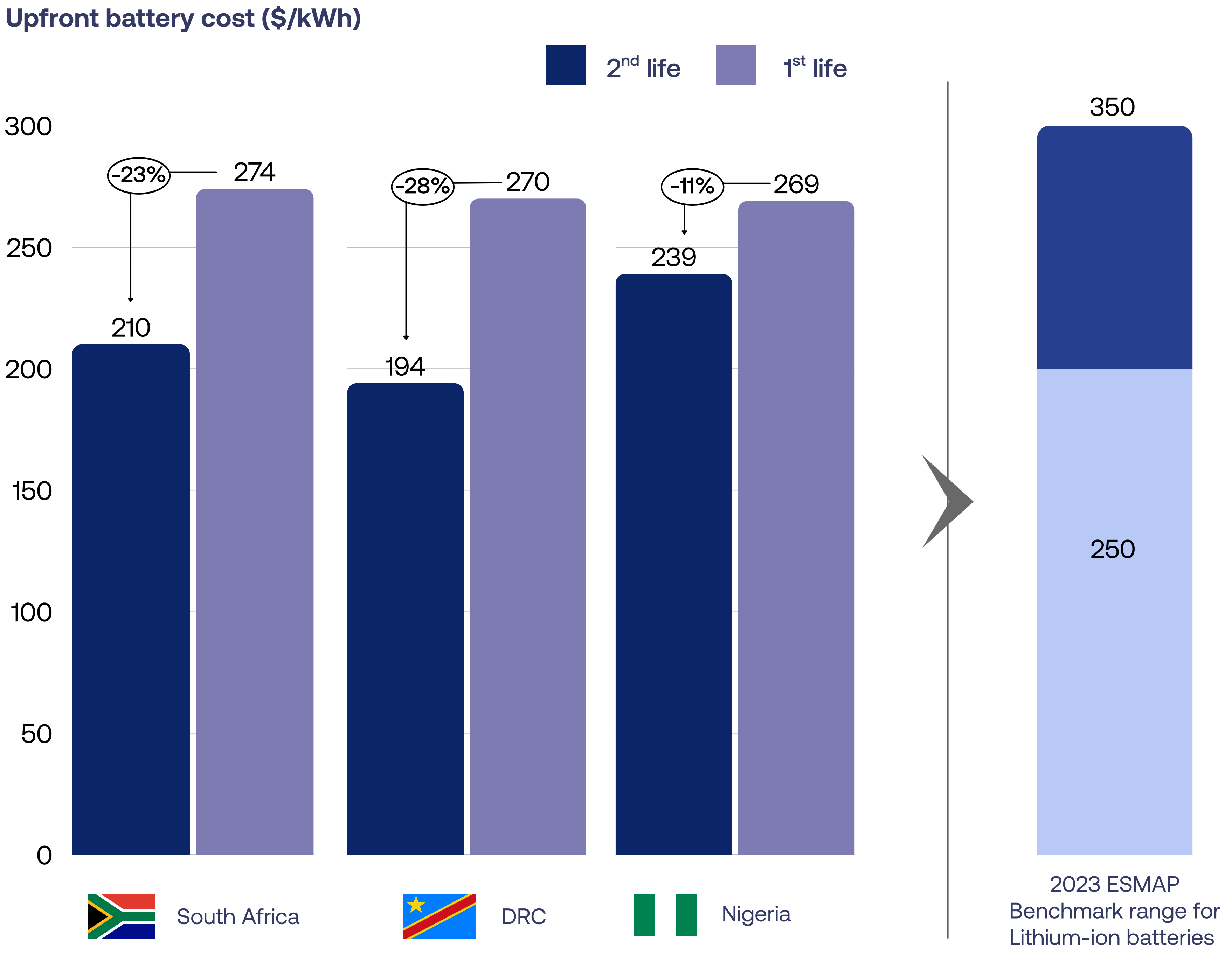
The Lab defined four ingoing hypotheses across cost and technical performance to assess the performance of the second-life batteries

	Ingoing hypothesis	Our rationale	Initial results	What we've seen	Status
	Upfront battery costs (per kWh available capacity) will be 35-40% cheaper for second-life batteries, compared to new batteries	Second-life batteries are cheaper as the high upfront cost was already paid, and re-purposing should be less costly	23% cheaper	Second-life batteries are cheaper but not by as much as expected, likely driven by falling battery costs and high re-purposing costs	Below target
	O&M costs will be the same for second-life and new batteries for at least three years	O&M covers BMS Software-as-a-Service (SaaS), insurance, cooling, and inspections. Any failures that could incur extra costs aren't expected by manufacturers within three years.	No difference	To date, OpEx costs for both types of batteries are the same, with developers reporting comparable costs across sites	Hits or exceeds target
	The overall lifetime cost (initial CapEx, OpEx, and replacement costs) of a second-life battery is 10-20% lower than the lifetime cost of new batteries	If the replacement frequency of second-life batteries is long enough, their lower CapEx and similar OpEx should result in a lower total cost across the lifetime of the mini-grid.	9.3% lower	Battery hardware performance and charge management practices implemented by the developer will impact how regularly the batteries will be replaced	Hits or exceeds target
	Second-life batteries will operate at a capacity that is sufficient to service a mini-grid for more than six years post-deployment	LFP batteries are known for their long cycle life. Upcoming testing will confirm if second-life batteries have enough capacity to support mini-grids beyond six years.	TBC	The lab will evaluate the battery capacity in the coming months and understand the battery degradation	Yet to test target

Source: CBIL lab data and analysis

Hits or exceeds target · Yet to test target · Below target

Upfront battery costs are 11-28% cheaper for second-life batteries, compared to new batteries



What we're seeing

Across the three markets, second-life packs cost 11-28% less per usable kWh than new batteries at control sites, and all of them are below the lower limit for industry benchmarks published by the 2023 ESMAP's report on the status and projections of battery deployment.

The second-life battery in the DRC is an NMC chemistry rather than LFP, which drives further initial cost savings.

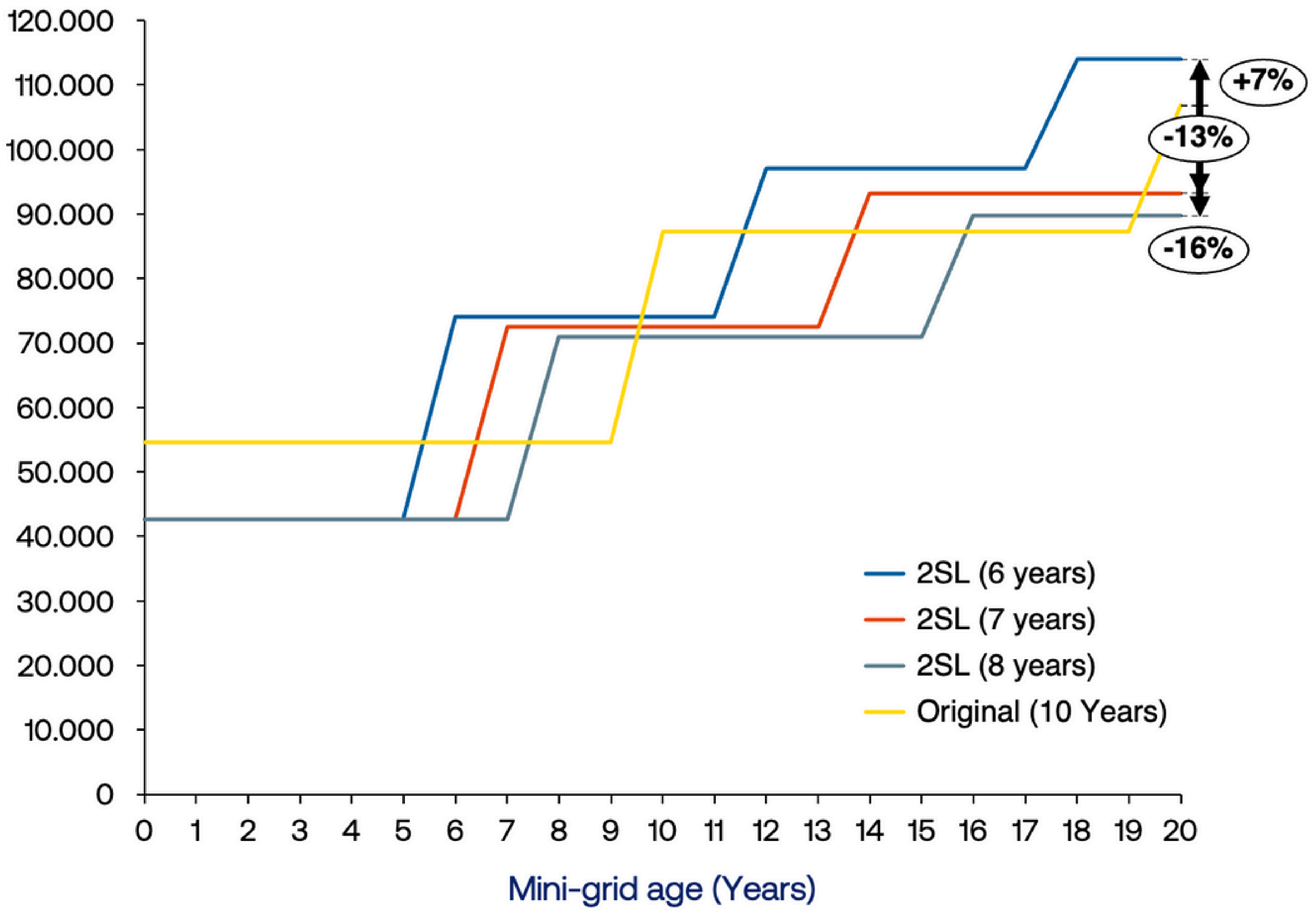
What it means

Currently, second-life batteries are materially cheaper than new batteries for our minigrid developers across the different pack assembly designs, cell origins, and battery chemistries. Cost savings are consistent across all markets, confirming that the price reduction is not location-specific. This means that developers can make savings on CapEx outlay or install more storage for the same budget. More storage means improved reliability, higher revenues, and reduced diesel run-hours.

The battery cost data comes from five different suppliers across the three countries. The cost excludes shipping, taxes, and insurance. The batteries are second-life lithium-iron-phosphate (LFP) packs across two sites (South Africa and Nigeria) and one Lithium Nickel Manganese Cobalt oxide (NMC) pack in the DRC. The control sites are all (LFP).
The industry benchmarks come from: Energy Storage for Mini-grids: Status and Projections of Battery Deployment- ESMAP report (2023)

Battery replacement frequency will determine the business case for second-life batteries

Total Projected Battery CapEx over the lifetime of the mini-grid ($)



What we're seeing

To determine whether second-life batteries have a strong business case, the CapEx needs to be considered over the expected lifetime of a mini-grid.

In this plot, we've used the average cost of a second-life battery and an original battery pack, which is ~200 kWh, and modeled the different scenarios of replacement to demonstrate how the economics hinge on the frequency of replacement.

Front-loaded savings: second-life packs start at US$214/kWh, 21% below the cost of a new pack, which means all three scenarios begin below the yellow "first-life battery" line.

Replacement timing drives the staircase:

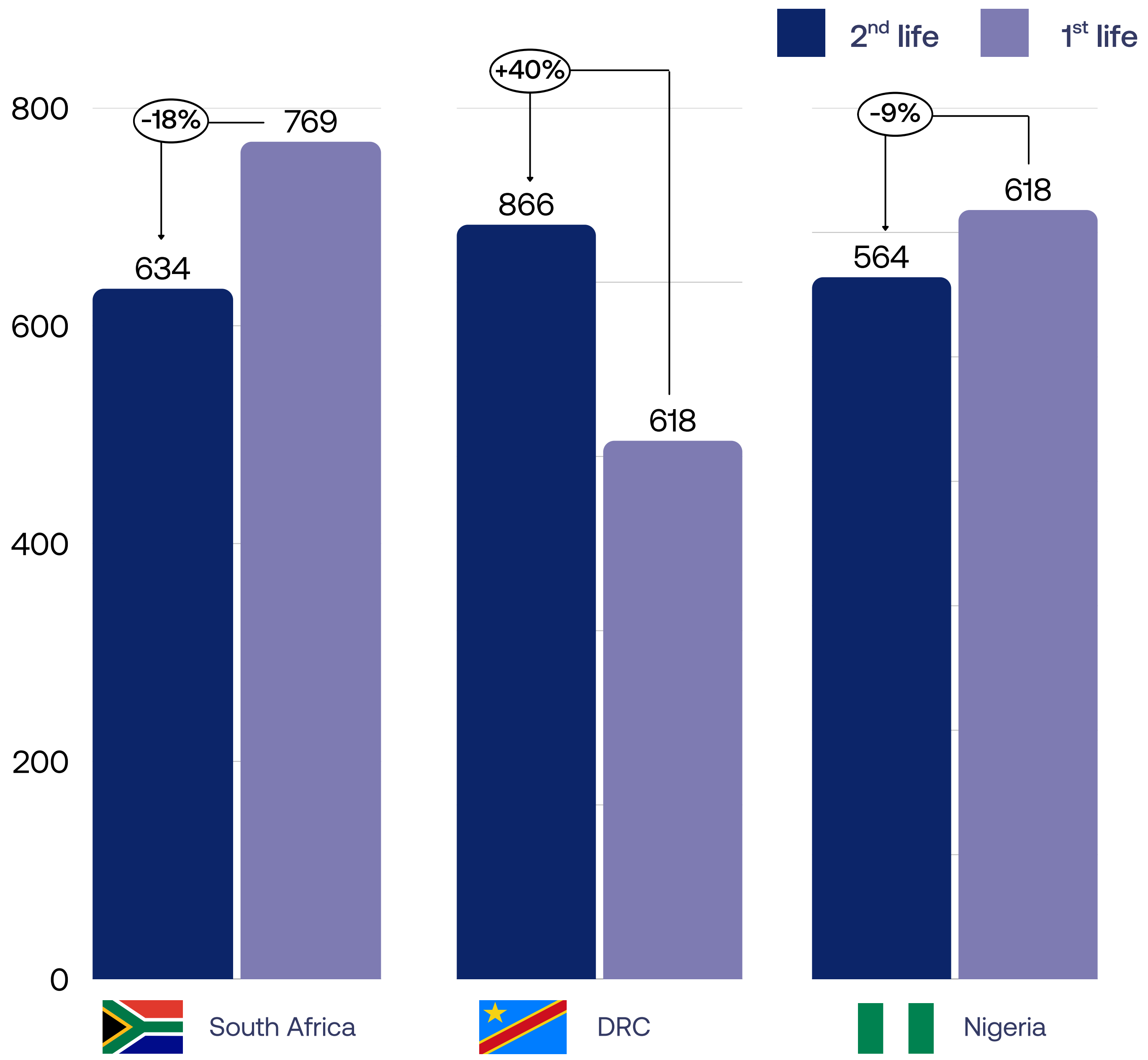
- **6-year swap:** Three replacements before the end of the mini-grid life push the cumulative cost above the new-battery line.
- **7-year swap**: Stays just under the new-battery cost through year 7.
- **8-year swap:** 13% cheaper than an original battery over the course of the mini-grid's life

Economics hinge on how a battery degrades. If field data show packs can last ≥ 7 years, second life wins on lifetime cost and IRR; at ≤ 6 years, the advantage erodes by year 15-18.

Source: Second life and first life battery costs come from the actual purchase invoices for three test sites and three matched control sites. US $214 /kWh is the mean of those three upfront retail prices.
For the "stair step" scenarios, we assume full pack swaps at the start of years 6, 7, or 8 to isolate the effect of replacement timing. Balance of system, installation labour, and inverter costs are held constant across all cases and therefore excluded.
O&M, financing and residual value are likewise omitted to focus purely on cumulative CapEx.

Second life batteries are 9-18% cheaper across the minigrid lifetime in Nigeria and South Africa, but high replacement frequency means the NMC batteries in Congo are more expensive overall

Lifetime Cost of Batteries at a 20-year Minigrid Site ($/kwh)



What we're seeing

We have estimated the battery lifetime cost by summing the upfront CapEx, discounted replacement CapEx, and O&M costs, minus the discounted salvage credit at the end of life, all divided by the storage capacity of the battery. The salvage value used here is 10% of the original CapEx value[1].

In each case, the expected lifetime of the batteries (and thus replacement timeline) has been provided by the supplier, yielding the following results:

- **South Africa:** 18% lower battery costs over the mini-grid life (10-year replacement period)
- **Nigeria:** 9% lower battery costs over the mini-grid life (10-year replacement period)
- **DRC:** 40% higher battery costs over the mini-grid life (5-year replacement period)

What it means

The difference in overall lifetime costs for the batteries is primarily driven by replacement frequency. The second-life NMC batteries are not competitive over a full mini-grid lifetime since they are replaced every five years. This reinforces why developers increasingly favor LFP for both first and second-life applications.

Replacement frequency is itself determined by the battery hardware, but is also significantly impacted by developer operations, which can accelerate degradation, as further detailed later in this report.

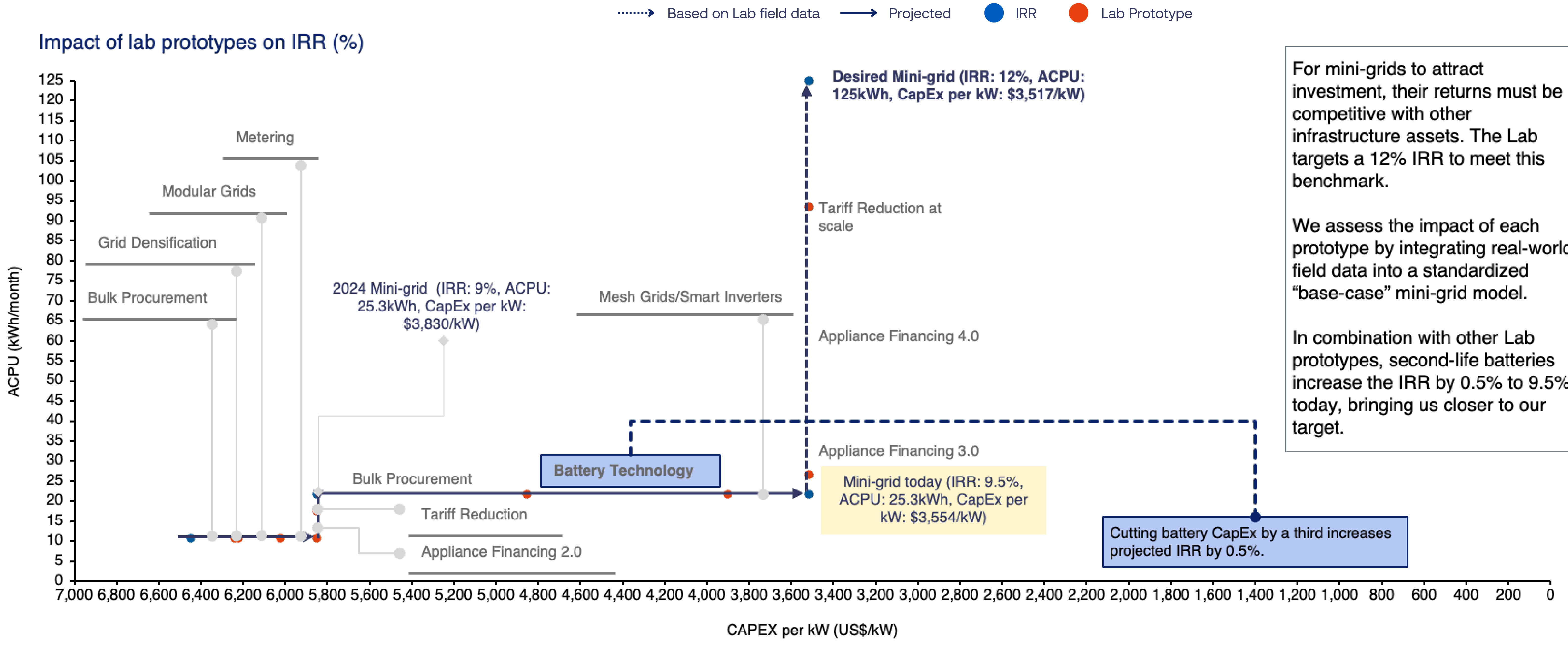
In the following pages, the lab examines the drivers of this degradation, reviewing field data from batteries to illustrate some of the implications of these factors.

Data Source: The battery cost data comes from five different suppliers across the three countries. The cost does not include shipping, taxes, or insurance. The batteries are second-life lithium-iron-phosphate (LFP) packs across two sites (South Africa and Nigeria) and one Lithium Nickel Manganese Cobalt oxide (NMC) pack in the DRC.

1. The salvage cost is from: Energy Storage for Mini-grids: Status and Projections of Battery Deployment- ESMAP report (2023).

If battery replacement frequency is managed, then using second-life batteries gets us closer to our 12% mini-grid IRR target

Impact of lab prototypes on IRR (%)



For mini-grids to attract investment, their returns must be competitive with other infrastructure assets. The Lab targets a 12% IRR to meet this benchmark.

We assess the impact of each prototype by integrating real-world field data into a standardized "base-case" mini-grid model.

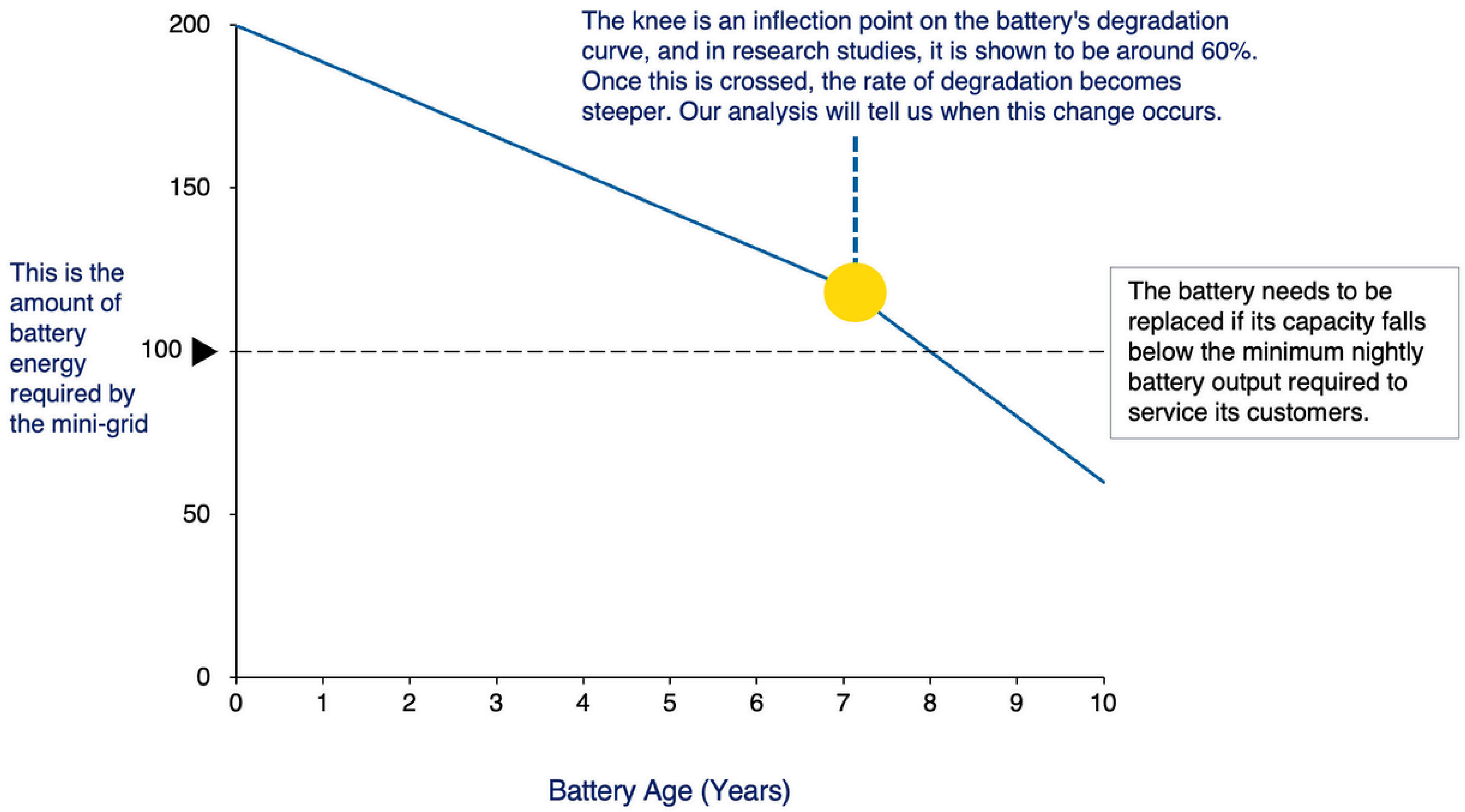
In combination with other Lab prototypes, second-life batteries increase the IRR by 0.5% to 9.5% today, bringing us closer to our target.

Notes: Axes for capex reduction read right to left to visually demonstrate progression towards a higher IRR target. Modular Grids consist of two distinct innovations (Increasing Capacity and Extending Reach). A grid would, however, only be eligible for one of the two innovations at any given time. Increasing capacity was used in this chart. The Connecting Beyond the Meter innovation is excluded from this graph as it delivers the combined impact of Appliance Financing and Grid Densification. The Tariff Reduction prototype subsidizes a mini-grid's tariffs to test the impact on customer consumption and developers' revenues.

To realize the potential economic benefits of second-life batteries, battery degradation will need to be carefully managed by developers.

To understand how long the batteries last in the field, we will conduct capacity tests on the sites we're monitoring

Energy that the battery can discharge (kWh) over time



What we're looking to test

Each battery has a certain amount of energy that it can discharge. Over time, the amount of energy that a battery can release from a 100% charge decreases. The rate at which it decreases is known as the degradation rate.

To assess the extent to which a battery is degraded, capacity tests are conducted. These require that the battery must be fully charged to 100%, allowing each cell in the battery to become balanced, and then discharged to 0%. Recording the energy released and comparing it to previous recordings provides a degradation rate.

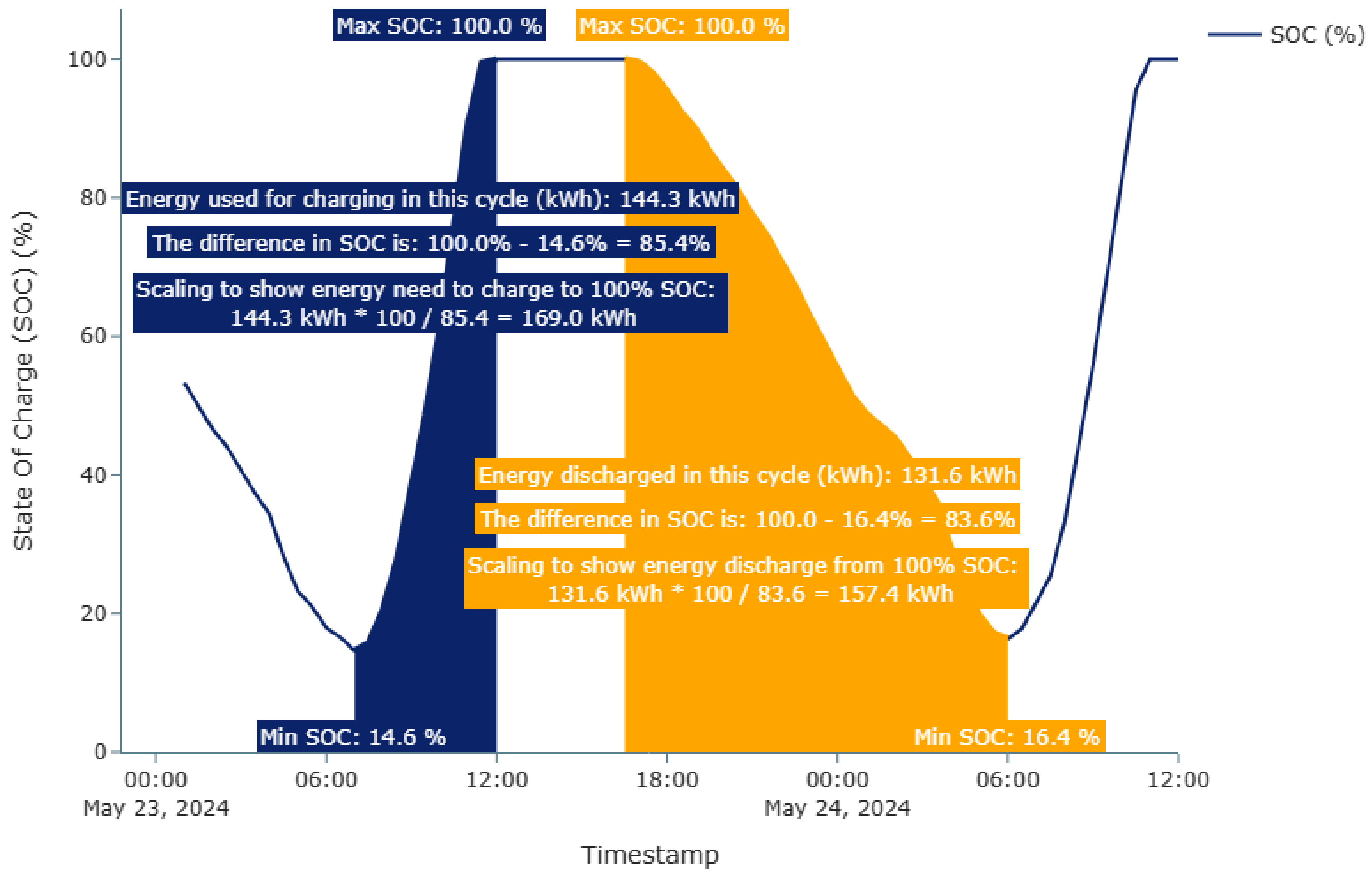
The Lab will conduct periodic battery capacity tests with our partners and will report how the capacity has degraded since installation.

In the interim, the Lab has explored how to mimic this curve using IoT data as outlined in the following pages.

Source: A Comprehensive Review on the Characteristics and Modeling of Lithium-Ion Battery Aging" which shows how Lithium-ion batteries reach an inflection point before degrading at a faster rate than before. This point is something we're looking to detect.

We're estimating charge and discharge energy using battery telemetry data to approximate battery degradation

Battery State of Charge (SOC) progression, over one cycle (%)



What we're measuring from IoT data

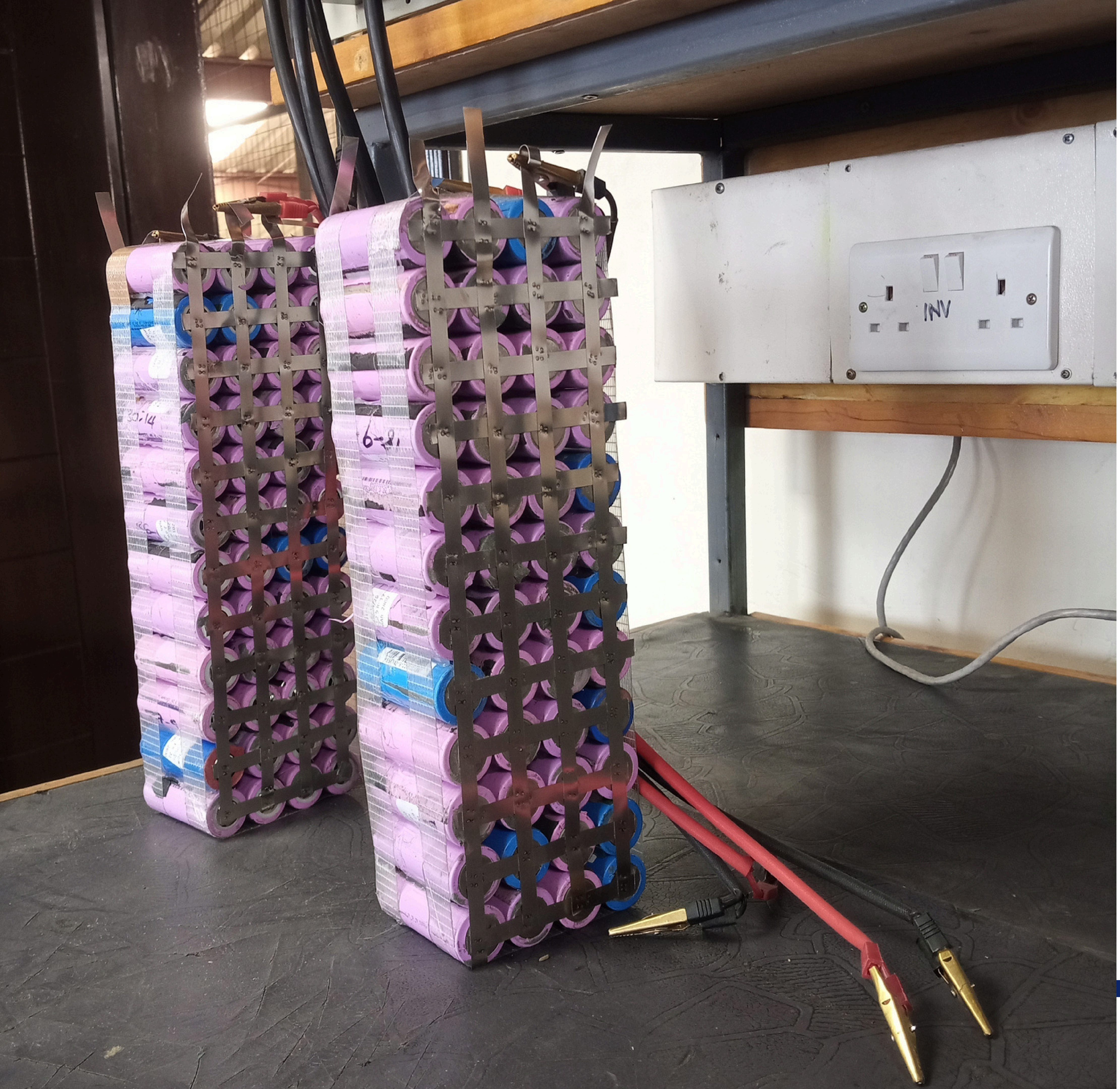
In the example shown, we've taken data from a battery data recording device at the site that records the State of Charge (%), as well as the energy entering and leaving the battery (kWh), every 30 minutes.

We determine the maximum and minimum State of Charge points, and we can then calculate the energy required between these two values.

Once we have those values, we can scale the values to the energy needed to charge to 100% or the energy that would be released when discharging from 100%.

This initially shows a proxy for round-trip efficiency, but when we examine this over time, which we do in the next slide, we get a proxy for capacity fade.

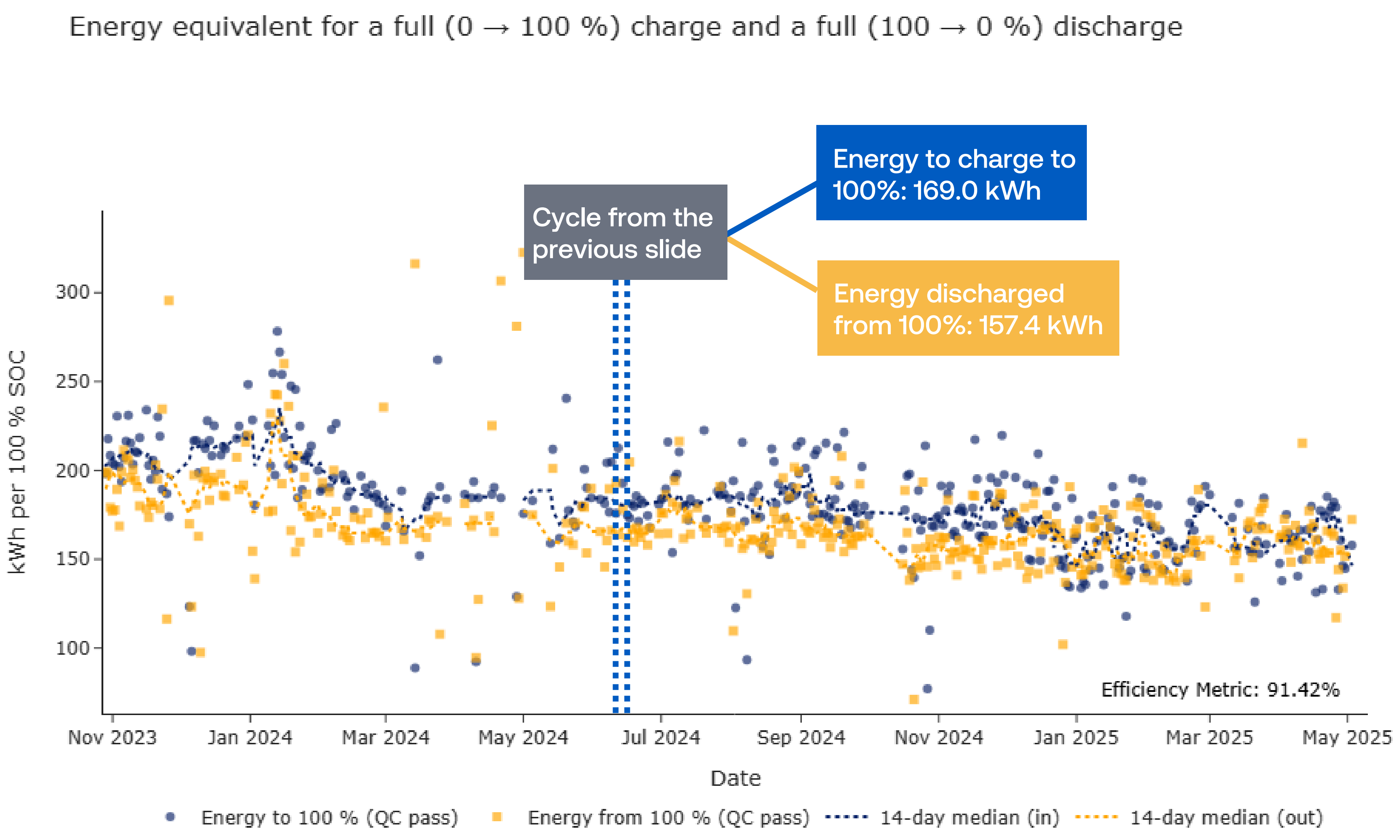
In this plot, we analyze data from a single site in Nigeria. We're taking a sample day to showcase our calculation.
We use a linear interpolation to replace missing figures, considering only days with 70% or more actual recordings.
We only include cycles that have a minimum number of points to create the estimate, and no gaps longer than 4 hours.



There are some important caveats regarding this analysis and the data we're using

- This analysis does not reflect cell aspects that impact fade, including wiring, charge–discharge rates, and other system-level variables
- The batteries need to reach 100% to recalibrate correctly, and if they don't, the SOC figure can be incorrect.
- Data can be missing if the IoT device can't communicate with the server. Missing 30-minute recordings are interpolated to replace missing figures, and this contributes to noise.

The energy required to charge or discharge to and from 100% shows a proxy for degradation over time



What we're expecting from this battery data

In the plot, we're showing the cyclical amount of energy required to reach 100% or the energy released for 100% where the labels show the cycle from the previous slide

Tracking this number over time allows us to create a proxy for fade, compare sites, and project approximate end-of-life dates.

The dotted lines represent a rolling median that removes daily noise and highlights the long-term trend.

From this plot, we can see that the battery can now store ~165 kWh for a full cycle, which represents a ≈ loss of ~15% in 14 months from the initial storage capacity of ~200kWh in 2023.

We will track this data for the second-life batteries over the course of the next year to help us project what the true replacement frequency might be, given the reality of mini-grid operations. These projections will be validated by periodic capacity tests.

In this example, we're using IoT data from a battery pack at a minigrid site in Nigeria over 18 months.

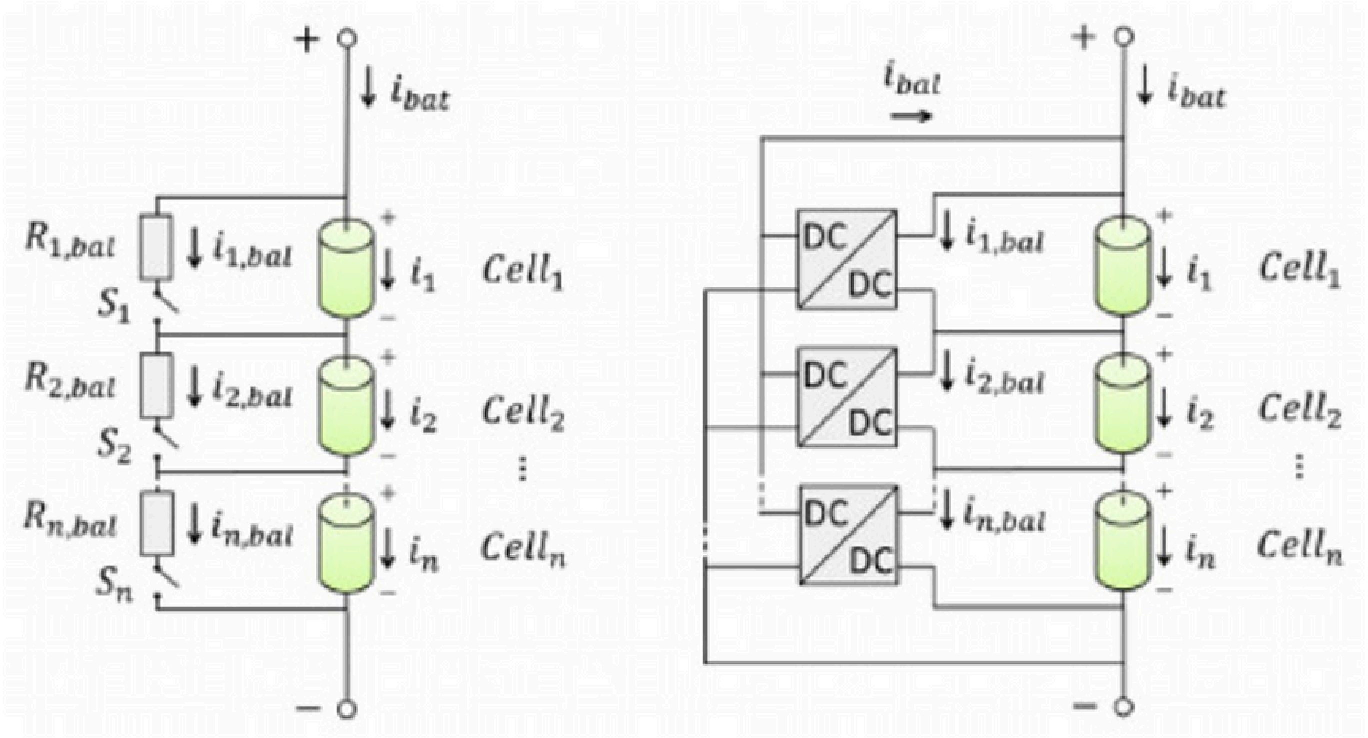
The batteries need to be charged fully for a few hours a day, for a few consecutive days, to become balanced and then capacity tested

Battery cells in a pack charge and discharge at slightly different rates. To keep them aligned, systems use balancing circuits that equalize charge levels across cells.

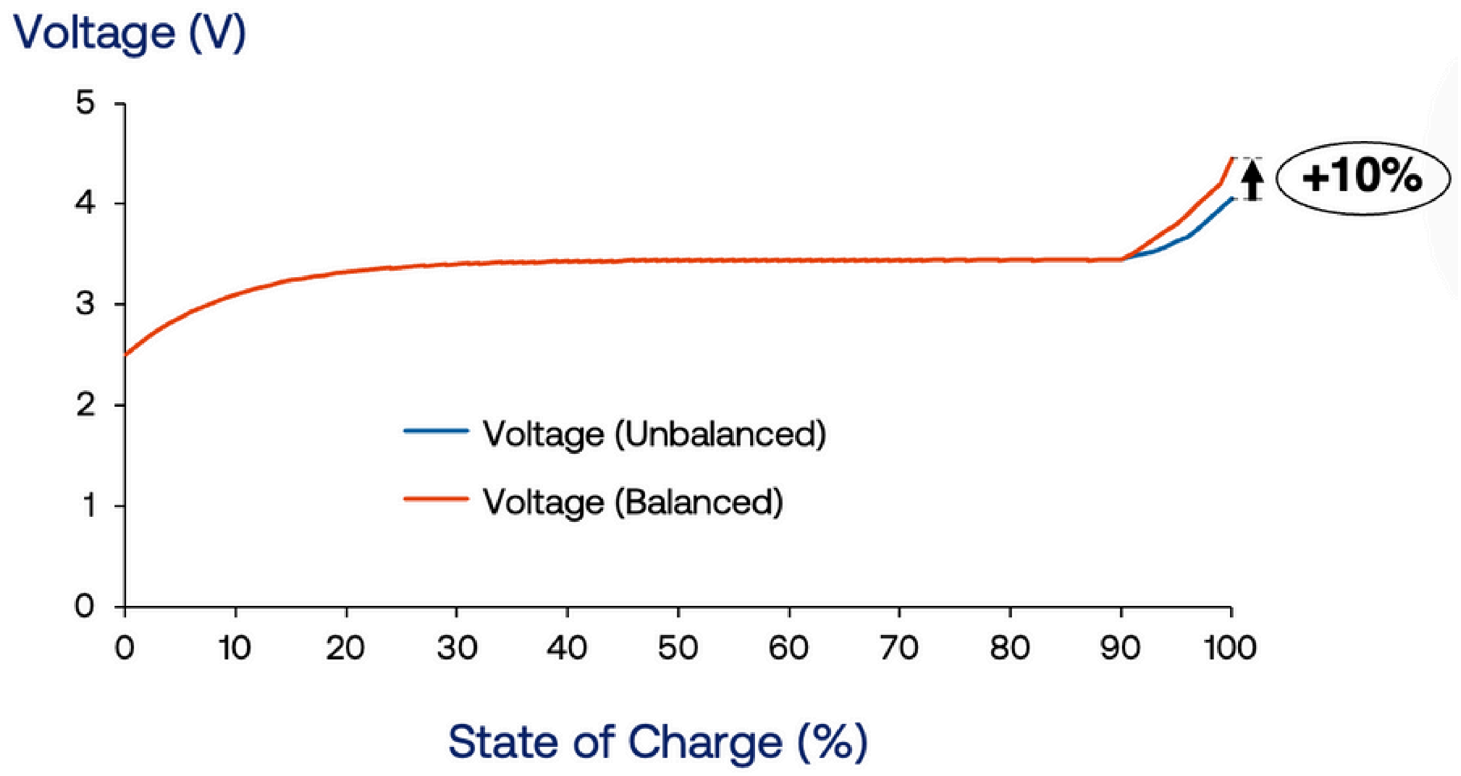
There are two main types of balancing:

1. Passive balancing uses resistors to release excess energy as heat
2. Active balancing uses DC–DC converters to shift charge between cells efficiently

Most advanced battery systems use active balancing, where the Battery Management System (BMS) monitors each cell and controls when and where charge should flow. Keeping cells balanced extends battery life and helps maintain accurate state-of-charge readings.



To accurately measure capacity, the battery needs to be fully charged for several hours over a few days. This allows the BMS to detect when all cells reach full voltage and trigger balancing. We monitor voltage peaks during charging as a signal that the pack is fully charged and ready for testing. If the battery isn't well balanced, some cells may be undercharged, which can reduce usable capacity



CrossBoundary will conduct field tests of the batteries after concluding that the voltage is sufficiently high to do so, to show that the batteries can operate at a sufficient capacity to service a mini-grid for more than 6 years post-deployment

Source: How to charge Lithium Iron Phosphate lithium ion battery packs including packs with high current and High Capacity.
A Review of the Technical Challenges and Solutions in Maximising the Potential Use of Second Life Batteries from Electric Vehicles

In the interim, developers can lengthen lithium-ion battery life by tailoring proven charge-management practices to minigrid conditions

Degradation drivers that developers should consider

	Cycle Ageing from charge-discharge	Calendar Ageing from sitting at 100% charge	Temperature Stress for warmer climates	Cells developing imbalances over time	High current rate events
	Poorly managed charging cycles can lead to capacity fade and resistance rise	Sitting at a 100% State Of Charge (SOC) contributes to lithium plating, which blocks energy released	Higher environmental operating temperatures accelerate ageing reactions	Charging to 100% is needed otherwise cells become imbalanced and this leads to replacement	Large surge currents raise local heat and increase likelihood of lithium plating
Mini-grid Relevance	Battery use is unsteady and peaks in the evenings	Solar charges batteries to 100% for ~ 3 hours daily	Tropics + sealed containers	Common with second-life cells of mixed history	Larger than expected loads coming online
Mitigation best practices	Limit daily depth of discharge to < 70% using battery management systems (BMS)	Cap target SOC at 80 - 90% but still schedule a full charge-discharge weekly	Install ventilation, use white paint for containers and automatic thermostatic fans	Ensure cell traceability (cell/battery passports), per-cell grading at assembly and warranties	Inverter should be 1.2× peak kW and stagger high load appliance starts to reduce surges in current

Avoid keeping the battery at full charge, especially when hot –-BU-205 notes that while $LiFePO_4$ is "more tolerant to full charge," it is "still stressed if kept at high voltage for a prolonged time," and elevated temperature further shortens service life. batteryuniversity.com

Cycle depth - Xu et al., Frontiers in Energy Research 13 (2025). $LiFePO_4$ modules aged ~1.6 × slower when depth-of-discharge stayed below 60 % (recommended 20-80 % SOC "shallow DOD" window). frontiersin.org

Song et al., "The Degradation Behavior of $LiFePO_4$/C Batteries during Long-Term Calendar Aging," Energies 14 (2021). Reports that $LiFePO_4$ cells stored at high SOC (90-100 %) and 55 °C lose capacity fastest, confirming the calendar-aging, high-temperature stress highlighted on the slide. mdpi.com

As a next step, the Lab will refine this analysis and launch Alpha-tests to accelerate the scale-up of second-life batteries

Over the next year, we will continue to track the technical performance of the second-life batteries across our sites to validate these initial findings

Track technical performance
Continue tracking capacity retention via SOC and efficiency analysis

Monitor operational costs
Track maintenance labour, component swaps, cooling, and EMS/BMS licence costs

Track charge-management behaviour
Record adherence to target SOC windows, firmware updates, and set-point changes

Conduct a degradation audit
After one year, conduct a comprehensive SOH test through capacity testing

The work will feed into the Lab's Alpha Tests that aim to address barriers that will unlock scale for second-life batteries, and realize their true potential to improve mini-grid economics

Background

- The Innovation Lab brought together key stakeholders in the battery supply chain to collaboratively explore several initiatives for scaling the adoption of second-life batteries in Africa.
- This consortium includes **SLS Energy, Vittoria Technology, Soleil Power** and **Mobility for Africa**.

Barriers to scale

- A **fragmented supply chain** between African second-life battery off-takers and global OEMs/ suppliers limits the volume of second-life batteries being deployed.
- **Inconsistent battery pack designs** make repurposing complex and costly.
- **Lack of standardized diagnostic testing** to assess battery health, lifespan, and safety.
- **Regulatory bottlenecks** related to import/export restrictions across countries slow down the movement of second-life batteries.

Outcomes

- Determine whether **standardized battery packs** can reduce the cost and deployment time of second-life batteries.
- Develop and validate a **baseline set of diagnostic testing procedures** that can be adopted industry-wide to ensure safety, reliability and performance
- Evaluate how **harmonizing cross-border regulations** might improve access to second-life batteries across the continent.

We aim to publish findings by December 2026 – please reach out to minigridslabs@crossboundary.com to collaborate!

August 2025
Second-life alpha tests kick off

September 2025
1st batch of second-life packs imported via Lagos & Durban routes

Capacity tests performed at sites

November 2025
Diagnostics testing and working group established

Recoverable battery pack design developed

January 2026
Diagnostics testing protocol v1 developed

March 2026
Second Capacity tests performed at sites

June 2026
Diagnostics testing protocol finalized

Recoverable battery pack design finalized

August 2026
Battery trade-route simulation complete

October 2026
Innovation Insight #2 published focused technical performance

December 2026
Final report & open-source pack design released

Battery trade-route report published

- Battery diagnostics testing
- Battery trade-route simulation
- Recoverable battery pack
- Field testing of batteries

Disclaimer and acknowledgements

The Lab is supported by the University of Massachusetts Amherst, Rochester Institute of Technology, and Duke University, which support experiment design and analysis of results. The Lab's work and the results presented here are strongly endorsed by the Africa Minigrid Developers Association (AMDA).

The Lab's Innovation Insight series provides ongoing, early insights on the prototypes so minigrid developers, governments, and funders can act on the results as they emerge. All results and analysis in these series is therefore shared as actionable business intelligence rather than scientific evidence.

While these series are not intended to meet the standards of an academic paper, the Lab will publish more complete reports at the end of each prototype, and has partnered with the University of Massachusetts Amherst, Rochester Institute of Technology, and Duke University to publish academic papers on certain prototypes.

CrossBoundary Group

Unlocking capital for sustainable growth in underserved markets

crossboundary.com/labs

For more information, please contact:
mini-gridslabs@crossboundary.com