COMPARATIVE STUDY OF TECHNO-ECONOMICS OF LITHIUM-ION AND LEAD-ACID BATTERIES IN MICRO-GRIDS IN SUB-SAHARAN AFRICA

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List of Acronyms

DOD	depth of discharge
HVAC	heating, ventilating, and air conditioning
LCC	life cycle cost
Li-ion	lithium-ion
NMC	nickel manganese cobalt
O&M	operations and maintenance
OEM	original equipment manufacturer
PV	photovoltaic
REopt	Renewable Energy Integration and Optimization
SOC	state of charge
TMY	typical meteorological year
VRLA	valve-regulated lead acid
VLA	vented lead acid

Executive Summary

Micro-grids will be a critical element of extending modern electricity services to the roughly 600 million people in sub-Saharan Africa who currently lack it, yet barriers remain to micro-grid deployment at scale. Though more affordable than grid extension for many communities lacking energy access, micro-grids are expensive on a per-kilowatt-hour basis. This report takes a close look at the cost of batteries in micro-grids to evaluate whether lithium-ion (Li-ion) or lead-acid batteries are optimal to minimize costs, and it assesses which operational practices for batteries lead to the lowest life-cycle cost (LCC). Batteries often make up 20%–30% of capital costs during the life of a micro-grid system, so managing these costs and better understanding what drives them are important elements of sustainable business models for developers and funders who are considering investing in this sector.

The purpose of this report is to fill gaps in understanding the role that batteries and battery behavior play in micro-grid operations and economics. Lead-acid batteries in containers with limited cooling represent the most common approach to date in this context. This study seeks to compare that practice to other potential options. For developers, these findings could serve as inputs to battery procurement processes or model data to support assessing design and operational planning decisions. For investors, this report could help parse the risks to micro-grid costs and the relevant trade-offs of decisions developers make. From a research perspective, this study highlights areas that would benefit from additional inquiry, including battery degradation modeling and collecting performance data to calibrate modeling.

This study pulls three different pieces of modeling together to develop a comprehensive understanding of battery life and associated lifecycle costs in a micro-grid:

- **Thermal modeling**: analyzing the temperature inside a battery enclosure or cabinet under a variety of settings in different climate zones
- **Battery degradation**: assessing the battery degradation rates resulting from different temperature profiles
- **Techno-economic analysis**: based on the battery lifetimes, evaluating the LCCs of micro-grids for Li-ion and lead-acid batteries in different scenarios.

In addition to testing the two different battery chemistries, and to make these results as adaptable as possible to a broad context, a number of scenarios and sensitivity analyses were run, including:

- **Five locations**: Kenya (two locations), Zambia, Ghana, and Niger
- **Two load profiles**: community load profiles for a primarily residential customer demand profile and one that includes some limited commercial activity
- **Five heating, ventilating, and air-conditioning (HVAC) configurations for the battery system**: air conditioner, active air circulation using two different fan configurations, direct evaporative cooler, and no HVAC system
- **Four construction materials**: shipping container, wood, brick, and concrete for the enclosure housing the battery bank, inverter, and charge controller.

Thermal modeling was considered first and yielded initial insights into optimal designs for enclosures that house battery banks:

- Wood was the best construction material for keeping the batteries cooler on average. Shipping containers, a common enclosure for a packaged battery solution, performed the worst by a wide margin in terms of managing temperature inside the enclosure.

- Air conditioners provide the most control of the temperature but the amount of energy used to maintain the enclosure temperature within set limits varies widely across climate zones and requires a corresponding larger power system to provide that energy.
- Fans could be effective at decreasing the temperature in the enclosure, with the largest gains in warmer climates, but they were subject to strongly diminishing returns as the number of fans were expanded from four to eight.
- Evaporative coolers performed nearly as well as fans in some settings, but results varied across locations on the basis of temperature and humidity and they require more ongoing maintenance than the other options.

After obtaining temperature inputs from the thermal modeling, the authors turned to assessing battery degradation as a function of charging and discharging, the temperatures the batteries were subjected to, state of charge, and depth of discharge (DOD). Key insights include the following:

- Lithium-ion batteries lasted longer in most cases.
    - In some settings, primarily in warm climates and configurations with limited thermal management, the two batteries produced similar lifetimes of less than 4 years. However, with air conditioners those lifetimes went up by roughly 2 to 4 years (depending on location, battery, load, and construction).
    - Further, the cost-optimal solutions for each location and load profile called for using Li-ion batteries.
- Air conditioners substantially increased the expected lifetime for lead-acid batteries, particularly in warmer climates, such as Lodwar, Kenya, and Niamey, Niger.
- In most cases, wood enclosure construction led to the longest battery lifetimes, which was expected based on its performance in the thermal modeling.

The final step was assessing the LCCs that would result from 20 years of operating the micro-grid across the 800 different scenarios studied. The high-level results of this modeling and analysis are as follows:

- For each combination of a location and load profile (commercial or residential), the optimal combination of HVAC configuration and construction material were assessed. In all 20 cases, the micro-grids with Li-ion batteries resulted in a lower LCC than those with lead-acid batteries.
- The value of HVAC depended heavily on micro-grid system sizing to manage the additional load of an air conditioner or fans (i.e., increases in PV, battery, and inverter sizes to serve the community load and the air conditioner load simultaneously). In the base case of assuming that the system size is increased to accommodate the incremental HVAC system, roughly 30% of the optimal configurations included HVAC systems, whereas for the other 70%, the additional battery lifetime did not offset the incremental cost of the HVAC and larger photovoltaic and battery system. For example, in Lusaka the optimal solution for three of the four load profile and battery combinations was four fans. In other locations having no system was more often the most cost-effective decision because of the trade-off in increased system size.

This report is one in a series that has been developed by the National Renewable Energy Laboratory in support of the Power Africa Beyond the Grid Program. It is a companion to the report *Quality Assurance Framework for Mini-Grids* (Baring-Gould et al. 2016). Other reports in the series investigate productive uses of energy in micro-grids, tariff considerations, customer agreements, and performance monitoring.[1]

[1] See https://cleanenergysolutions.org/qaf for more information.

Table of Contents

List of Figures

List of Tables

1 Introduction

In sub-Saharan Africa alone, there are 600 million people who lack access to modern electricity services. While grid extension remains prohibitively expensive in many rural areas, plunging costs of photovoltaics (PV) and batteries have begun to bring sustainable micro-grid business models within reach. Many barriers to the widespread deployment of micro-grids remain, however, including optimal approaches to designing and operating micro-grids at scale and access to affordable financing.

The selection and operation of batteries in micro-grids touches both of these key barriers to scale. Batteries are a central component of off-grid remote micro-grid systems, and they are without established best practices for this application. In conversations with developers and other stakeholders, stories of batteries degrading much faster than expected are common. From a financing perspective, batteries also loom large, at an average of 20%-30% of total life-cycle costs (LCCs), making understanding their behavior and risk profile of keen interest. This paper takes a close look at batteries in off-grid micro-grids in sub-Saharan Africa, specifically focusing on an increasingly relevant choice between lithium-ion (Li-ion) and lead-acid batteries. It is intended to accelerate industry-wide learning to benefit several important stakeholders, including developers and investors.

To date, the vast majority of batteries in micro-grid applications worldwide have been lead-acid. Lead-acid batteries have a long history of serving both stationary and transportation energy storage needs. Micro-grid applications in sub-Saharan Africa, however, have presented a new challenge to these batteries regarding their ability to perform as needed in this climate and application. Developers have reported a combination of higher temperatures and other design and operational challenges, such as improper commissioning, leading to battery lifetimes that are commonly in the range of 1–3 years, significantly shorter than the lifetime the developers were anticipating.

Meanwhile, Li-ion battery costs have declined substantially. These cost reductions have opened up new markets for Li-ion use cases—from electric cars to stationary power applications. The potential for cost-competitiveness between Li-ion and lead-acid batteries has prompted some developers in sub-Saharan Africa to assess which battery chemistry and performance characteristics are best suited to scale their businesses. This paper seeks to fill a gap by analyzing the techno-economic and operational differences between lead-acid and Li-ion batteries. This analysis also integrates thermal modeling for battery enclosures to assess the most cost-effective combinations of battery type and heating, ventilating, and air-conditioning (HVAC) solutions for a given location to contextualize the relative performance of the two batteries and yield more general insights about operating micro-grids in different climates.

An important element of the modeling and analysis presented here is to highlight trade-offs between the two battery technologies and associated cooling configurations (e.g., four fans or an air conditioner) serving representative load profiles. For example, adding HVAC can require increasing the system size to accommodate the electricity needs of the HVAC system, but this might also increase the battery lifetime by enough to justify the investment. The optimal battery, HVAC system, and enclosure depends on a number of factors, and costs vary greatly across locations; the intention here is to establish a framework for evaluating the context-specific decisions that developers and investors can adapt to their needs. There is no substitute for performance data from operating systems. Ideally, studies such as this one can inform system design and operational planning for developers; then, as data comes in from performance monitoring systems, assumptions can be calibrated over time.

An improved understanding of these critical decision points is necessary for the micro-grid industry to achieve scale and increase the amount of private capital investment. The industry is currently seeing local and regional expansion by some developers alongside a number of pilot or demonstration projects funded by governments or nongovernmental organizations. This report seeks to support several different stakeholder groups that will be critical to industry growth. For example, this assessment can help investors and financiers gain a better understanding of cost drivers and risks to profitability for these systems. Commercial banks in sub-Saharan Africa are a critical group to engage to build a deeper pipeline of capital and grow micro-grid businesses (and potentially capital that is in local currency). This report can improve their ability to do due diligence on micro-grid developers and, ultimately, more precisely target products and services for the micro-grid industry. For developers, this analysis can serve as an input to strategy and operational planning on a number of topics, including procurement, ongoing operation-and-maintenance (O&M) costs, appropriate reserve account levels to replace equipment, and system uptime commitments.

The report begins with the scope and background on the community electricity demand and climate zones before turning to each piece of the analysis. It starts with thermal modeling, then turns to battery degradation, and finally concludes with techno-economic analysis. Sensitivity analyses on costs and other assumptions are included alongside the key insights from the results.

1.1 Scope

This analysis focuses on micro-grid systems comprising solar PV and batteries in sub-Saharan Africa. To make this sufficiently general to cover many applications of PV and batteries in micro-grids while retaining the specificity to draw necessary conclusions, the following key assumptions were made:

- **Batteries**: This report focuses on two battery chemistries—Li-ion and lead-acid. Other battery chemistries are being considered for micro-grid applications, such as flow batteries, but they were excluded from this analysis because of limited market penetration to date, technology maturity level, and a lack of data on degradation behavior over time.
- **Community electricity demand**: Two general categories of communities were modeled—those with primarily residential uses of electricity and those with a mix of commercial and residential uses of electricity. These profiles are drawn from *Tariff Considerations for Micro-grids in Sub-Saharan Africa* (Reber et al. 2018), which is another report in this series.
- **Climate zones**: This report looks at optimal decisions for HVAC and battery technology in five different climate zones across sub-Saharan Africa. These five locations were chosen to include areas with growing micro-grid industries and to capture temperature and solar irradiance variation across the subcontinent.
- **Cost assumptions**: Costs are assumed to be similar across the different economic zones that each climate zone represents. Cost assumptions are described in Section 5.2. In practice, costs will vary across and within zones, but data on regional or local variation are too limited to inform location-specific assumptions in this study. Further, the intention for this modeling is to present a methodology and representative values that can be adapted to a given setting, then recalibrated based on performance data.

Additional background information about the battery technologies considered and how degradation was modeled is included in Section 4. Community electricity demand and climate zones are discussed in Section 2. Cost assumptions are detailed in Section 5.

The four primary categories of scoping decisions (battery type, demand, climate zone, cost assumptions) were made with the objective of producing findings that can be adapted to a wide variety of micro-grid contexts. For example, this paper does not explicitly include hybrid systems with diesel generators, but the findings about battery cost, performance, and degradation over time can be adapted to better understand hybrid system dynamics. A hybrid system with a diesel generator could depend on the solar and storage to serve 90% of the annual load and the diesel generator to serve the other 10%. The primary considerations for adapting this analysis include diesel generator upfront and fuel costs, associated PV and battery sizing adjustments (including decisions on how to account for HVAC electricity use, which may be in part managed with the diesel generator rather than increasing the PV size), and a shift in some O&M costs from PV and storage towards the diesel generator.

1.2 Background

This section provides background information on the community electricity demand, or load profiles, and the locations that were analyzed in this report.

1.2.1 Community Electricity Demand (Load Profiles)

The community electricity demand, or load profiles, are an important input to this analysis. The two load profiles used for this report draw on a literature review and bottom-up load profile development exercise from *Tariff Considerations for Micro-grids in Sub-Saharan Africa* (Reber et al. 2018). The following assumptions went into the development of these load profiles:

- The community is assumed to comprise 100 households.
- Both load profiles assume that there is no variation between weekday and weekend load nor across seasons.
- Residential loads include light-emitting diode lighting, phone chargers, radios, and some higher wattage devices such as televisions or refrigerators.
- The commercial load profile includes two small shops and one school.
- The load profiles are assumed to be the same in all five locations.

This bottom-up approach was used to determine the annual electricity use of the micro-grid, which was set to be 19,711 kWh/year based on the analysis in Reber et al. 2018. The shape of the residential- and commercial-heavy load profiles was taken from data published by PowerGen Renewable Energy (Williams et al. 2017). The residential load profile has limited demands during the day, then ramps up in the evening for typical household activities and lighting. The commercial load has two peaks, one during the day resulting from the demand from the two small shops and the school and an evening peak from the household activities and lighting demand that is also included in the residential load profile. The total daily load in kWh is assumed to be the same to facilitate an easier comparison of the performance and LCC impacts of the load shape.

These two load profiles were chosen to represent points along a spectrum of different load profiles one might expect in a remote community being electrified by a micro-grid. From the perspective of micro-grid design, each profile leads to a different system size and battery charging and discharging pattern. For example, the commercial load profile has a higher percentage of load in the middle of the day, when the solar PV is more likely to be able to serve the load directly, and as a result the batteries can be smaller (by as much as 50% in this analysis). As discussed in more detail in Section 5 on techno-economics, this load profile difference results in LCCs that are roughly $31,000 less on average for commercial load micro-grids than for residential load micro-grids (for both lead-acid and Li-ion batteries). Figure 1 shows the shape of the two load curves.

The shape of the community load curve is an important determinant of heat generated in the battery enclosure as well. The timing of when the system is most heavily in use and how that aligns with outdoor temperature and solar irradiance influences the temperature profile inside the enclosure. For builders of micro-grid systems, however, it can be challenging to estimate load curves both at the initial design of the system and over time as community electricity usage changes.

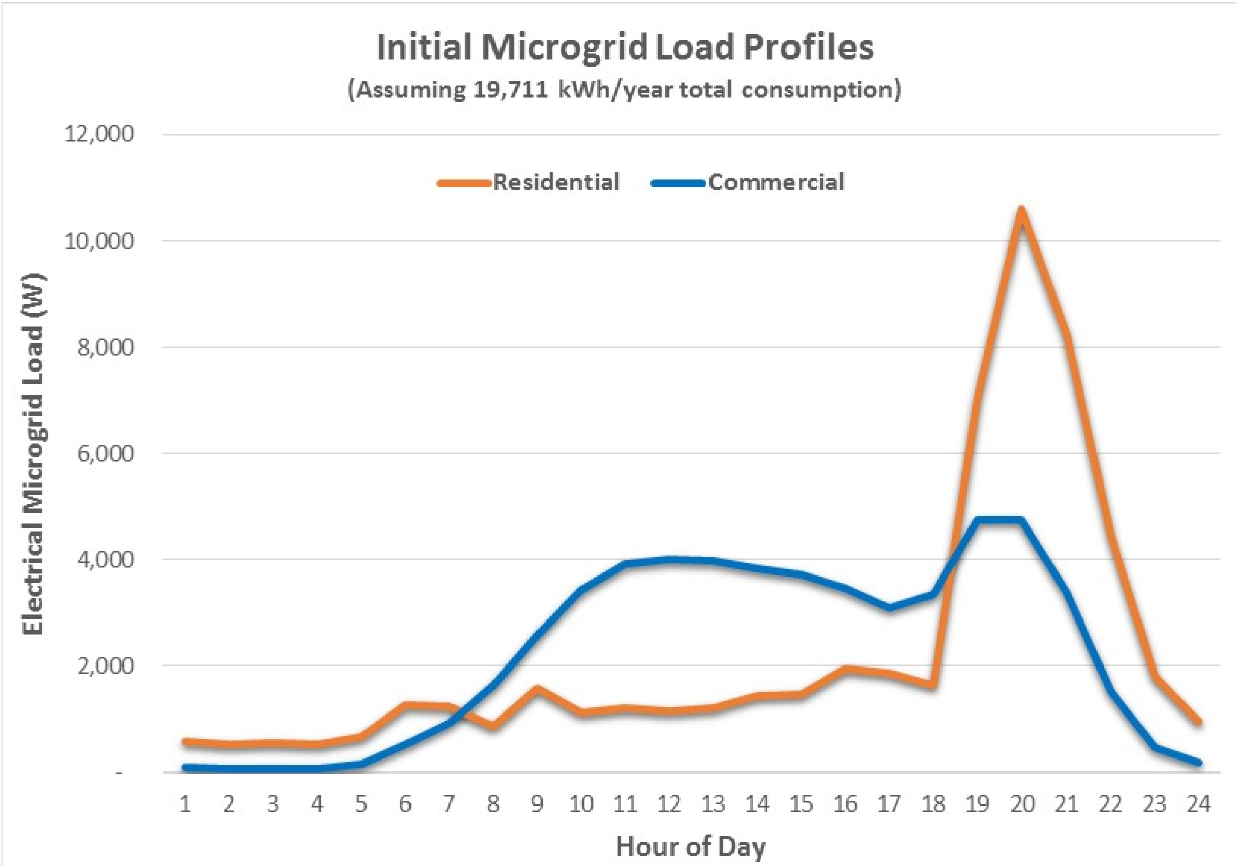

Figure 1. Community load profiles for 1 day

1.2.2 Climate Zones

This analysis draws on five different locations that were selected to represent a broad swath of different climates drawn from the set of countries with developing micro-grid industries. Three locations were initially chosen to represent a western location (Accra, Ghana), an eastern location (Lodwar, Kenya), and a southern location (Lusaka, Zambia) corresponding with the locations used in *Tariff Considerations for Micro-grids in Sub-Saharan Africa* (Reber et al. 2018). Two additional locations were included to broaden the spectrum of climates considered: Nakuru, Kenya, and Niamey, Niger. They represent the coldest and hottest climates, respectively, where hourly weather data are available for sub-Saharan Africa. Figure 2 shows the five locations used for this analysis. The typical electricity demand for a community across these zones was assumed to be roughly similar, and the profiles were not adjusted for differences in customer behavior.

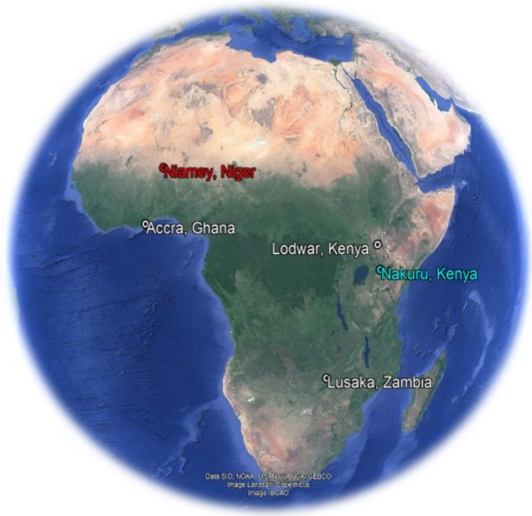

Figure 2. The five locations modeled

The temperature data are summarized in Figure 3. Together, the salient notes about each of the locations are as follows (from warmest to coolest):

- **Niamey, Niger**: hottest climate, dry, August to September rainy season
- **Lodwar, Kenya**: fairly hot, dry, and cloudy, April rains
- **Accra, Ghana**: average temperature relative to these five locations, cloudy, humid, May to June rainy season
- **Lusaka, Zambia**: cooler temperatures, very seasonal with large fluctuations, November to February rainy season, dry and sunny the rest of the year
- **Nakuru, Kenya:** coolest climate, fairly steady temperatures, second most humid, light rains April to August.

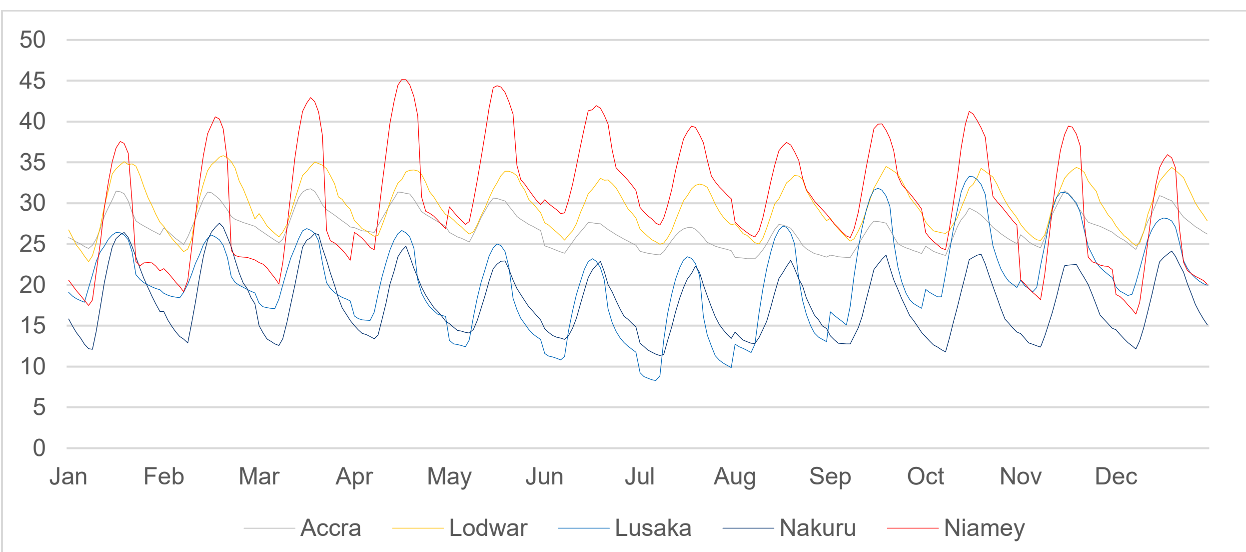

Figure 3. Average daily temperatures by month for the five locations

2 Methodology

The following sections describe the foundational elements of the techno-economic analysis for micro-grids and their associated battery systems. Outputs from thermal modeling and battery degradation modeling are intermediary pieces of the analysis that provide inputs to the LCC analysis, but they also independently provide useful insights for micro-grid design and operation. The primary elements of the analysis are summarized in Figure 4.

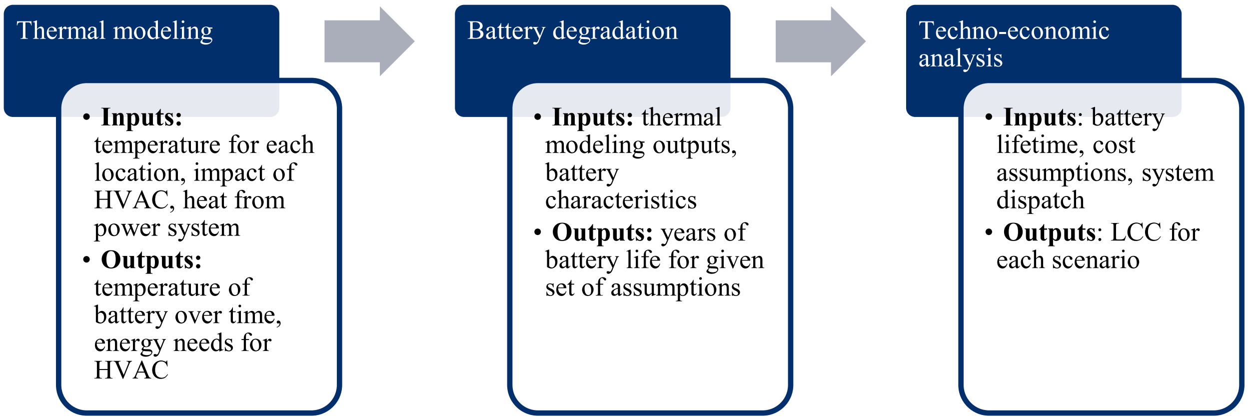

Figure 4. Analysis methodology

This methodology was applied to 800 unique scenarios comprising two battery types, five locations, two community load profiles, four battery enclosure construction materials (each with and without insulation), and five HVAC options (including no HVAC system). The breadth of the different scenarios is intended to make the results broadly adaptable across sub-Saharan Africa and different micro-grid business models.

The remainder of this report steps through each of the three phases of the analysis. Each section includes details on how the analysis was undertaken, the underlying assumptions, how to interpret the results, and the findings for the given step. In the results that follow, subsets or summaries of the 800 scenarios are shown to focus on the key takeaways for each section.

3 Thermal Modeling

An important potential differentiator in the behavior of lead-acid and Li-ion batteries is their recommended operating range for cell temperatures and their tolerance of temperature extremes. Field experience to date for the industry has primarily been with lead-acid batteries, but data availability on performance for micro-grids in sub-Saharan Africa is still limited. Some developers have experienced premature failures in lead-acid batteries that could be attributed in part to consistent operation of the batteries outside of temperature ranges recommended by the original equipment manufacturer (OEM).[2] Li-ion batteries also experience temperature-driven capacity degradation, but they are typically warrantied with an assumed higher tolerance for high temperature (e.g., 45°C) than lead-acid batteries. That said, performance for given temperature profiles needs to be contextualized with cost and other differences between the batteries (e.g., this analysis assumes that Li-ion batteries are 40% more expensive). To begin building toward the comprehensive analysis, this section discusses thermal modeling of the batteries in different enclosures and with different HVAC configurations.

The relationship between temperature and expected lifetime for both battery types makes decisions about how to condition battery enclosures critical in system design and ultimately important determinants of overall project economics. As detailed in later sections, the HVAC, insulation, and building construction material choices for the enclosure can increase battery life by as much as several years by changing the temperatures to which the cells are subjected. The relative economics of different HVAC options is the result of trade-offs between (1) investing in HVAC equipment, (2) increasing system sizing to manage the additional load, and (3) extending battery life to decrease the number of battery replacements and associated downtime.

Much of the existing literature on battery degradation and enclosure best practices focuses on batteries that are kept in ideal conditions, system designs that use conditioning options, or enclosure designs that are either not appropriate or not feasible in the sub-Saharan African micro-grid context. To address this in the techno-economic analysis that follows, this section takes a step back to consider the optimal enclosure and conditioning design for each battery type. The following section evaluates the battery degradation outcomes that result from different enclosure decisions.

The four enclosure materials included in this analysis were shipping containers (steel), wood, brick, and concrete.[3] This analysis also included modeling for each building material with and without thermal insulation. The choices of which options to consider in this analysis were based on experiences working with micro-grid developers in sub-Saharan Africa. Each material and the insulation combinations (eight total) were combined with five different options for HVAC: no system, four fans, eight fans, an air-conditioning unit, or an evaporative cooler.

The evaporative cooler is the only HVAC configuration that has meaningful ongoing maintenance to consider in addition to cost and performance characteristics. This includes adding water on an ongoing basis (frequency based in part on climate), cleaning on a regular basis, and periodic pad replacement. For the purposes of interpreting these results, the results of an evaporative cooler should be viewed alongside the results of having no HVAC system, which would be the outcome if the evaporative cooler were poorly maintained.

With these options, the intention was to cover a sufficiently broad swath of settings while constraining the HVAC and construction choices to those that are potentially locally available and affordable in the five locations modeled. In practice, enclosure and HVAC options might be limited by a developer's business model (e.g., selecting a supplier that only supplies systems in shipping containers with a set number of fans), availability of parts or materials, equipment warranty terms, or available capital and other business constraints. Comparisons are

[2] This assessment is based on the authors' experiences discussing temperature profiles and associated degradation for several developers and comparing the literature on degradation models. Other causes for premature degradation include improper installation and commissioning, poor maintenance, manufacturer defects, and operating batteries outside warrantied SOC ranges.
[3] This analysis does not consider differences in usable lifetimes across the construction material types.

made to shipping containers and configurations with no HVAC where appropriate to help make these findings relevant in more constrained settings.

The first step in this analysis was to develop heat generation profiles for each combination of a battery and a load profile: lead-acid batteries with commercial, lead-acid batteries with residential, Li-ion batteries with commercial, and Li-ion batteries with residential. These profiles were developed based on the efficiencies of the equipment in the enclosure and the corresponding heat released into the space. As discussed, the community load profiles influence the heat generation in the enclosure. The commercial load profile has a midday secondary peak that results in a bump in the heat generation profile as well; however, the midday load is served directly by the PV more often than afternoon or evening loads, so the increase in heat generation during the day is modest. Appendix A describes the heat generation profile development in further detail.

These heat generation profiles were an input to modeling in OpenStudio, which is a building energy modeling tool that models the temperature in the enclosure for a year that would result from the interplay between heat and solar irradiance from the outside environment, heat produced inside the container, and any conditioning or HVAC included in a given configuration (taking into account relevant material properties for each mass in the thermal model).[4] Figure 5 shows the differences in heat generation for the different load profiles. The commercial load profile results in greater daytime heat generation. Appendix C includes additional details on OpenStudio assumptions for material characteristics and HVAC options.

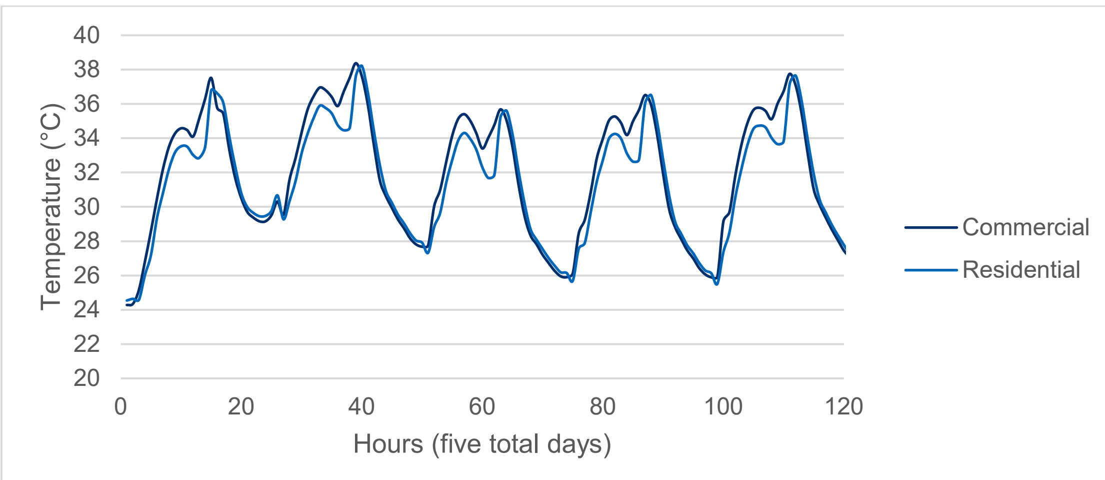

Figure 5. Differences between heat generation profiles for different load profiles

The set point for all the HVAC options is 25°C. This set point was selected based on the authors' experience working with developers and a review of typical battery warranty temperature levels. Nonetheless, the suite of five different HVAC configurations and the selection of a diverse set of climates exposed the batteries to a broad spectrum of temperatures, yielding insights into the potential impacts of different set point decisions.

3.1 Interpreting Modeling Results

This section summarizes the key takeaways from the thermal modeling. A few elements are important to consider when interpreting these findings:

- The HVAC options were intended to be representative, but product specifications will vary meaningfully across offerings. In applying these findings to a microgrid context for a developer, it is important to compare the efficiency and power rating of the options being considered to those included in this analysis to assess the appropriate size and associated temperature and HVAC load impacts.

[4] See Guglielmetti et al (2011) for more information.

- Similarly, construction materials required assumptions for thermal properties that will vary and should be compared to locally available products (e.g., type of material, thickness of wall) to adapt these results to a given context.
- The HVAC and construction material options were also modeled in five different locations using typical meteorological year (TMY) data, so specific temperature profiles of system sites will vary.[5]
- This analysis assumed that the enclosure is partially shaded by the solar array. Though there is no standard for shading with PV or putting the battery bank in a shaded structure, shading was deemed sufficiently common to include it in this analysis across all the scenarios.
- Li-ion batteries are more efficient than lead-acid. In other words, for every kilowatt-hour of electricity passed into and out of a Li-ion battery during charging and discharging, a smaller percentage is lost as heat during the process. The extent of the difference varies by subtype of each chemistry and by the manufacturer. This analysis assumed 90% composite round-trip efficiency for Li-ion batteries and 80% for lead-acid batteries.[6]

Results are shown in annual unmet degree-hours. This metric is a combination of (1) the amount of time the enclosure spends above a certain temperature threshold and (2) the number of degrees by which it surpasses that threshold. Although slightly less intuitive than average temperature or unmet hours (which would be a simple count of how many hours a temperature threshold is breached), degree-hours provide a more complete picture of the temperature in the enclosure.

The following sections describe the results of the thermal modeling, including both building materials and HVAC options. This section begins with the construction material (and insulation) options and a high-level summary of the unmet degree-hours that are associated with each battery-load combination in each location. An evaluation of the HVAC options follows, similarly with a high-level review of each before describing additional details for each option.

3.2 Construction Materials

The results of the construction material modeling are shown in Figure 6. To isolate the impact of the construction material from the HVAC options, the results are all for the no HVAC system configuration. For simplicity, insulation was also not taken into consideration in this initial presentation of results. All the enclosures were modeled to be the same size as a standard shipping container to ease comparisons across them (roughly 20 feet long, 8 feet wide, and 8 feet tall).

A few insights are highlighted below:

- Wood structures performed the best in nearly all the locations and battery/load combinations, but the improvement they represented over brick and concrete was greater in some settings than others.
- A shipping container is a common construction material as part of a packaged solution, but it also resulted in the highest number of unmet degree-hours.
- The lead-acid battery scenarios resulted in more unmet degree-hours because of their reduced efficiency and associated increased heat loss to the enclosure.

[5] TMY data for a given location are the result of analyzing meteorological data over a set period of time to create a representative profile of temperature variation (in this case, on an hourly basis), which somewhat constrains the range of temperature variation. TMY data do not represent a specific year in the past, and future years will vary from the representative TMY.

[6] This analysis assumed AC-coupled PV and battery systems. The composite round-trip efficiency here refers to the combined battery, inverter, and rectifier efficiency. AC-coupled systems tend to be more efficient in applications that involve using PV-generated electricity directly relatively more often, whereas DC-coupled systems tend to be more efficient when PV-generated power is typically stored in the battery before being deployed to serve load. This study assumed AC-coupling for both load profiles. See Table 2 in Section 5.2 for efficiency assumptions for each battery system. This modeling also assumes that all energy lost in conversions is converted to heat in the enclosure.

- The climate zone that the micro-grid is sited in had a much larger impact than the load profile.

Niamey was the hottest location of the five that were modeled. As a result, the unmet degree-hours were greater than the other locations and the differences between the construction materials were greater and more clearly showed the relative performance, as shown in Figure 6 below.

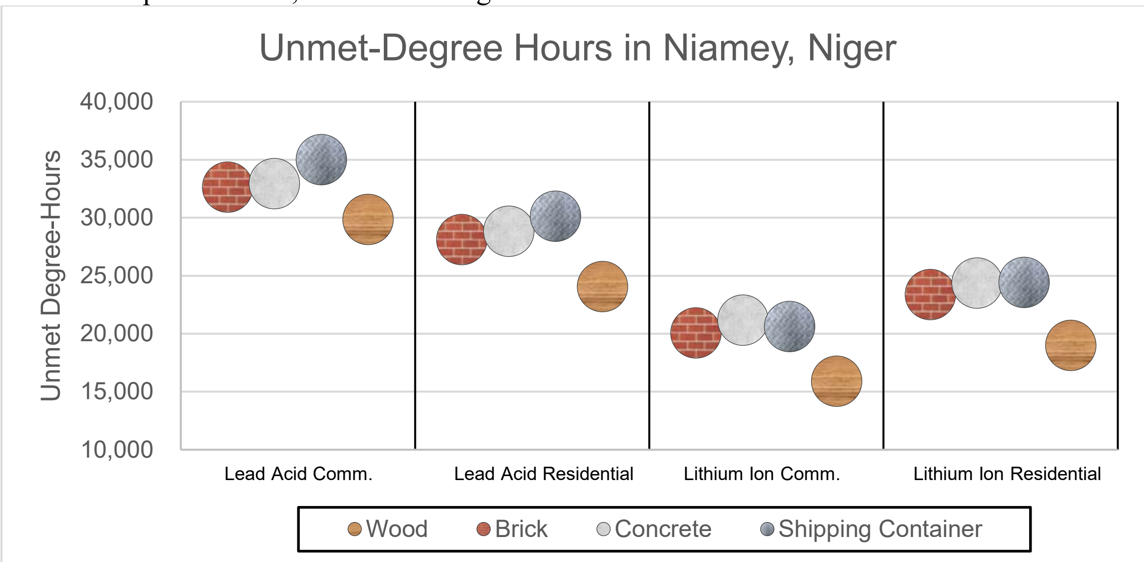

Figure 6. Annual unmet degree-hours (30°C threshold) in Niamey, Niger

Shipping containers performed much differently than the other materials for the following three reasons:

- Thinner: the shipping container is approximately 2-mm thick, whereas the others are approximately 8- to 10-mm thick.
- Greater thermal conductivity: the shipping container's thermal conductivity, which is an expression of how quickly heat is transferred through the material, is approximately 40 times greater than that of wood and approximately 10 times greater than that of concrete or brick.
- Lower specific heat: the shipping container's specific heat, or its ability to hold heat, is a quarter of wood's specific heat and half that of brick and concrete, which means that the shipping container's mass warms faster and it is a poorer insulator for the enclosure from the external environment.

3.2.1 Insulation

Across all the scenarios, the thermal behavior of the enclosure with and without insulation was modeled. The insulation included was modeled after the characteristics of cellular polyurethane and assumed to be approximately 25.4-mm thick. The detailed properties are included in Appendix C. Figure 7 shows the results from the modeling. A few highlights from the findings include:

- **Overall**: insulation had a meaningful impact on unmet degree-hours, but that impact varied across battery, load profile, location, and construction material.
- **Structure type**:
    - Brick, concrete, and wood structures experienced meaningful decreases in unmet degree-hours (i.e., improved performance) across scenarios with insulation.
    - Shipping containers, on the other hand, performed better without insulation because the insulation acted to keep heat trapped inside the enclosure.
- **Load profile** (for brick, concrete, and wood only):

- For lead-acid batteries, the residential load profiles exhibited a larger percentage change in unmet degree-hours with insulation than the commercial load profiles.
- For Li-ion batteries, the opposite was true: commercial load profiles experienced a greater decrease in unmet degree-hours from insulation than the residential load profiles.

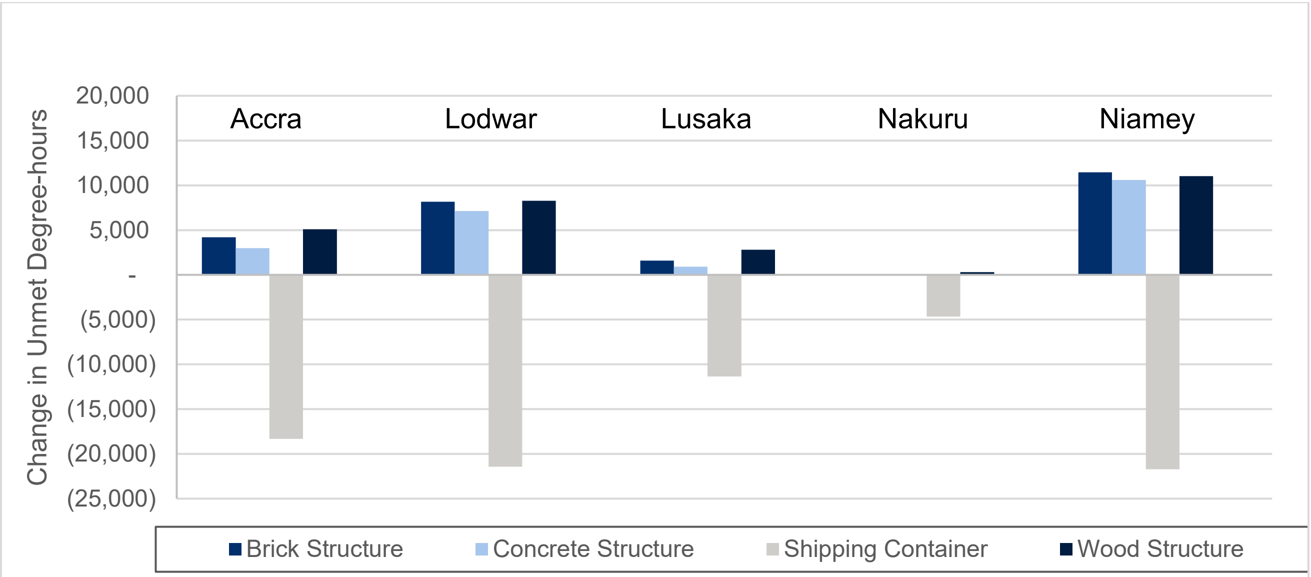

Figure 7. Change in unmet degree-hours (30°C threshold) from the addition of insulation for each enclosure construction material for lead-acid batteries with commercial load profile

Note: Positive numbers represent improvement in thermal performance.

The magnitude of the change in unmet degree-hours was greatest in Niamey, which is the warmest of the five locations, and the most muted in Nakuru, which is the coolest climate in this analysis.

3.3 HVAC Configurations

Five different configurations of HVAC systems were modeled, again in OpenStudio: no HVAC system, four fans, eight fans, an air conditioner, and an evaporative cooler. The set point for the HVAC systems was 25° Celsius. Results are reported in terms of the difference between the HVAC options and the no-system configuration. To make the results more manageable, they are discussed for insulated wood structures (the best performer in our thermal modeling) and uninsulated shipping containers (a common construction material). The HVAC options performed similarly in the brick and concrete structures as they did for the wood structure. As discussed, the two battery types have different efficiencies and thus different levels of heat loss into the enclosure. As a result, the Li-ion battery systems consistently had fewer unmet degree-hours for any given configuration.

A few key insights from the modeled results are as follows:

- As might be expected, differences between the conditioning options were more pronounced in the warmer climates. Nakuru and Lusaka showed relatively minimal changes in unmet degree-hours across the different HVAC options, whereas across battery types and load profiles, Niamey showed dramatic differences between the air conditioner and no-system configurations.
- Fans were subject to diminishing returns. In settings with greater unmet degree-hours, the four-fan configuration produced a greater decrease in unmet degree-hours. Adding an additional four fans, however, made only a small difference. In other words, there was a ceiling to the temperature management that could be done by fans, and it appeared to be nearly reached by four fans in most of the modeled scenarios here. For example, in warm Niamey in a residential microgrid that uses lead-acid batteries, going from four fans to eight fans resulted in only a 5% increase in the improvement in unmet degree-hours. The minimal differences between four fans and eight fans is shown in Figure 10.

- Air conditioners were modeled to be able to keep the space at or below a certain temperature, so the unmet degree-hour decreases were always brought to zero. This resulted in impact on system sizing to manage the energy required for that performance and a meaningful increase in upfront cost, which are discussed in more detail in the following sections.
- Evaporative coolers provided more cooling in drier climates and they were less effective in more humid climates because they depend on the cooling effect of evaporating water and evaporation rates are contingent in part on humidity. Modeling results showed that evaporative coolers have a ceiling similar to fans for effectiveness for a given size. The average improvement on unmet degree-hours was roughly 25% less than four fans; however, the performance varied across locations. In warmer or more humid climates, the fans were meaningfully more effective than evaporative coolers. Again, looking at lead-acid batteries where differences are more pronounced, evaporative coolers in commercial Accra micro-grids decreased unmet degree-hours 57.9% less effectively than four fans. Evaporative coolers also do require maintenance, but they require as much electricity as four fans, so there are trade-offs in LCCs when deploying them. These are further explored in the next section

The wood structure results are detailed in Figure 8, Figure 9, and Figure 10. These results may be taken as representative of the other construction materials.

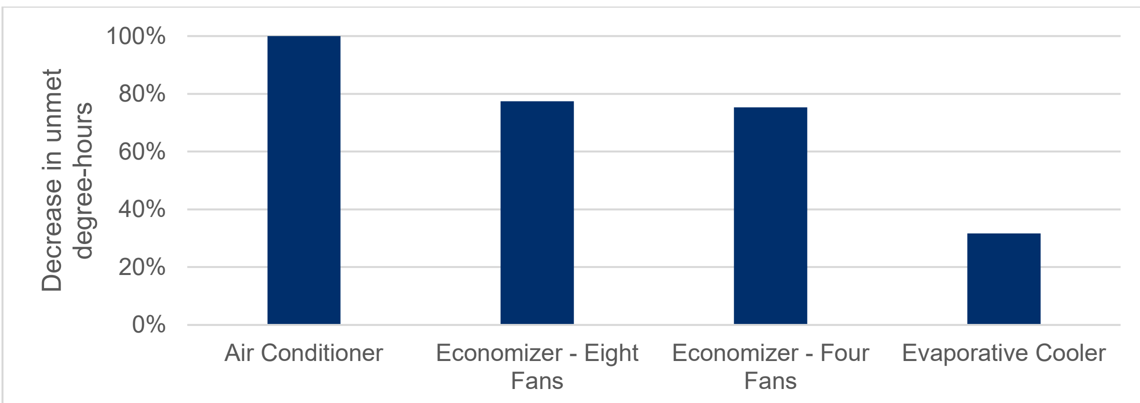

Figure 8. Decrease in unmet degree-hours from adding each type of HVAC unit

Note: Results shown are for Accra, Ghana, for lead-acid batteries in an insulated wood structure serving a commercially oriented community load profile.

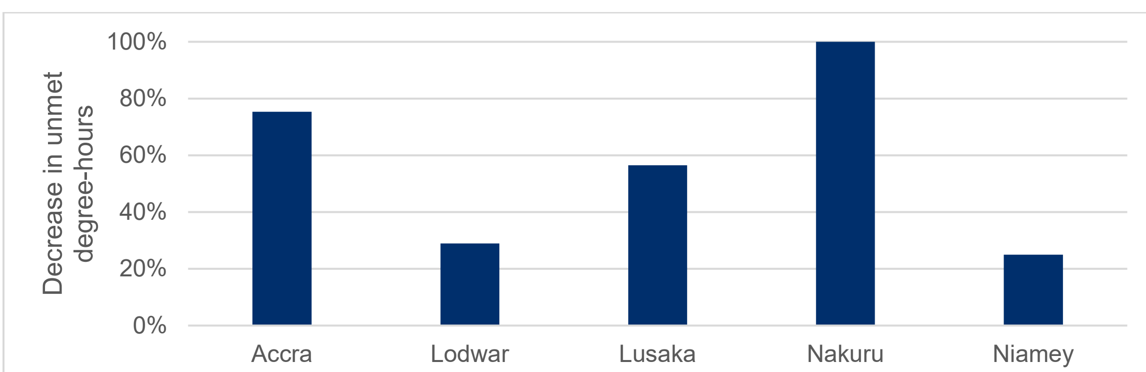

Figure 9. Decrease in unmet degree-hours resulting from adding four fans to systems with lead-acid batteries in an insulated wood structure serving a commercially oriented community load profile

Note: In Nakuru, the four fans provided enough cooling to keep the battery enclosure 25°C year-round (i.e., 100% of the year).

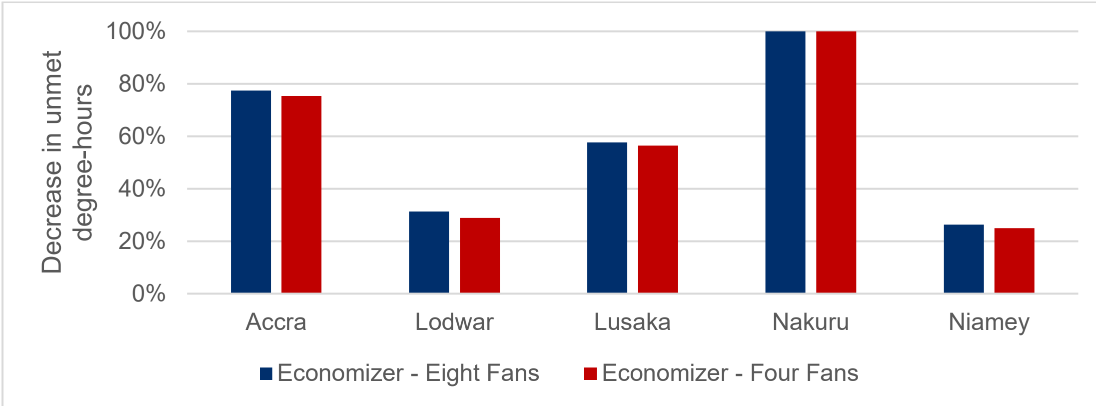

Figure 10. Decrease in unmet degree-hours resulting from going from four fans to eight fans in systems with lead-acid batteries in an insulated wood structure serving a commercially oriented community load profile

For shipping containers, the magnitude of the degree-hour improvements was greater across the board because the heat in the enclosure was greater, but the insights drawn from the wood structure resulted in the three preceding figures remaining the same. Namely, differences were more pronounced in warmer climates; lead-acid batteries produced more heat and resulted in more unmet degree-hours; air conditioners maintained the temperature at or below the set point; fans can be effective at reducing the temperature in the enclosure, but eight fans represented a minimal improvement over four fans; and evaporative coolers can be reasonably effective, but they are more comparable to fans in cooler climates in their ability to reduce unmet degree-hours.

4 Battery Degradation Modeling

The thermal modeling results were inputs into the analysis assessing battery degradation rates and resultant battery lifetimes for each combination of battery type, climate zone, community demand profile, enclosure construction and insulation, and HVAC type. An evaluation of battery lifetimes was one of the primary motivations for pursuing this broader analysis in part because of discussions the authors have had with developers and other stakeholders who have shared that batteries were degrading much faster than expected. This section covers key drivers of estimating battery lifetime, some challenges in modeling battery lifetime in this setting, key assumptions, guidance on applying these results to a given context, and results.

A few important items to consider while reviewing the degradation discussion include:

- **Specific cell type and manufacturer is important**: Modeling battery degradation for stationary power system applications is still a relatively new field, particularly for Li-ion batteries. As a result, the real-world data against which battery models can be calibrated is still somewhat limited. See Appendix B for more information on each degradation model.
- **Technology is constantly changing**: This modeling depends on research on battery degradation that is calibrated to batteries at the time the research was completed, so it represents a snapshot in time for how batteries perform and how long they will last. The analysis period for this report is 20 years, such that batteries that replace those being installed today might be significantly better than current designs. This report does not take a position on possible improvements to battery longevity and does not take potential improvements into consideration in the modeling.
- **The same battery type can be configured many ways**: Battery bank configuration greatly impacts thermal output and battery life. Within a specific chemistry, battery banks can be configured in a wide variety of ways based on a specific module size and the way they are configured to make a bank with a specific rated power and storage capacity. Changes in the design and layout of the battery bank can greatly impact degradation and performance over time.
- **Proper maintenance and care**: This analysis assumes that the battery banks are appropriately installed, commissioned and are well-maintained. Many conditions, such as poor maintenance, improper charging algorithms, and a bad balance between load and energy production can all negatively impact battery life. Although this analysis looks specifically at the role of elevated temperatures on battery life, this may be a secondary effect if other proper batter use procedures are not considered.

4.1 Key Drivers of Battery Degradation

Several critical elements of battery degradation rates determine the lifetime of a battery. Degradation here refers to the decrease in effective capacity of the battery to store and discharge energy over time. For the sake of simplicity, the discussion is divided into cycling, time, and temperature, but note that there are intersections between the three, particularly with temperature and its impacts on both degradation from cycling and time. As a battery degrades, its capacity to store energy is reduced, and generally a battery is assumed to be at the end of its useable life when it can only store 80% of its original available capacity.

4.1.1 Cycling

The most familiar degradation vector is cycling (i.e., the process of charging and discharging the battery). The most typical operating condition for batteries in sub-Saharan African micro-grids approximates a daily cycle in which the battery charges during the day (and PV serves the load) and discharges in the evening and into the night; however, within this straightforward cycling profile, there can be a great deal of variation. Changing weather patterns can influence the amount the battery can be recharged during each cycle. For example, a cloudy day or a few cloudy days in a row can force a battery down toward minimum state-of-charge (SOC) levels. Modeling based on hourly data points for cycling (and given temperatures) for a typical year can capture the range of different charge and discharge profiles, including seasonality in either load or irradiance that have a bearing on battery cycling. There are a number of ways to count cycles for the purposes of degradation modeling. This analysis used a "rainflow" algorithm that accounts for intra-day variation and the impacts of having a midday and evening peak in the load profile. That cycle counting approach is described in more detail in Appendix B.

4.1.2 Time or Calendar Life

In addition to degrading when in use, batteries have rates of ongoing degradation over time. This vector of degradation is also sometimes referred to as shelf life. This time or calendar life effect is in part contingent on what SOC and at what temperature the battery is stored. For example, a Li-ion battery stored at 25°C and 80% SOC will degrade at a different rate than one stored at 30°C and 80% SOC. Similarly, a Li-ion battery stored at 25°C and 50% SOC will degrade at a different rate than one stored at 25°C and 80% SOC. Smith et al included calendar life degradation for Li-ion batteries while Layadi et al did not. In Smith et al, calendar life degradation also relates to cycling patterns because it takes maximum daily depth of discharge (DOD) into account (described in further detail in Section 4.1.4.1 and Section 4.1.4.2, as well as Appendix B).

4.1.3 Temperature

Temperature is a critical factor in battery degradation. This will be familiar to anyone who has tried to start a car in the cold (likely a lead-acid battery) or had a phone overheat (likely a Li-ion battery). For stationary applications, temperature enters into degradation modeling in two important ways:

- **Cycling life:** Potential battery damage is impacted by cycling (i.e., charging and discharging the battery), the charge/discharge current, and temperature, with increased damage occurring at higher rates of charge/discharge and at higher temperatures. For example, powering a community's electricity needs on a particularly hot evening can increase the rate at which the battery degrades relative to an evening at a normal temperature. The load profile of a community, which dictates the current in part, also has bearing on the temperature of the battery with higher charging and discharging rates increasing the battery temperature, and thus associated degradation.
- **Calendar life:** the temperature at which a battery is kept also has bearing on degradation rates, with batteries kept at higher temperatures having shorter life.

All batteries have different operating temperature ratings, which are included in specification sheets from OEMs and in warranties. Battery warranties also typically specify a safe operating range. There is a great deal of variety in required temperature ranges across suppliers and battery types to stay within warranty bounds or those suggested by OEMs. The authors have seen several different ranges for Li-ion battery warranties anecdotally but are not aware of a comprehensive survey of what is most typical.

Some warranties and OEM specifications permit fairly large temperature bands, but those bands do not necessarily translate to optimal performance. For example, some Li-ion batteries can have warrantied ranges up to 45°C. The average temperature in Niamey for an uninsulated wooden enclosure with a residential load profile is roughly 29.5°C and it rarely went above 40°C in the modeling done in this analysis. In Niamey, the no-system configuration yielded an estimated battery lifetime of roughly 2.4 years. Adding an air conditioner with a 25°C set point extended that battery life to roughly 6 years.

4.1.4 Chemistry-Specific Degradation Models

Lead-acid and Li-ion batteries each have their own degradation pathways, which further change based on the specific chemistry and technology used. This report models one particular type of battery chemistry for a lead-acid battery and for a Li-ion battery. Each battery type and degradation model are discussed briefly in the following sections, and additional details are included in Appendix B.

4.1.4.1 Li-ion

A nickel manganese cobalt (NMC) lithium-ion battery chemistry was modeled. This is a common chemistry for stationary applications of Li-ion batteries. Similar versions of Li-ion batteries of this chemistry have OEM-specific proportions of each element and are packaged and integrated differently.

The degradation model for Li-ion is drawn from the "Life Prediction Model for Grid-Connected Li-ion Battery Energy Storage System" (Smith et al. 2017). To develop this model, Smith et al. performed aging tests on a commercial NMC battery and developed an empirical model based on those test results. The model considers cycles, temperature, depth of discharge, and state of charge over time.

Another common Li-ion chemistry for stationary applications is lithium iron phosphate (LFP). While beyond the scope of this study to model a LFP battery, there are a few differences between LFP and NMC to consider, though all performance characteristics will vary with the OEM and configuration or use case of each battery. LFP batteries are typically less energy dense (and require more space) but can also be safer with a lower risk of thermal runaway as a result. Battery lifetimes are specific to use cases and OEMs, but LFP batteries can typically be stored at full charge with less resultant degradation from the shelf life component of degradation.

4.1.4.2 Lead-Acid

The degradation model used for lead-acid batteries is drawn from the "Lifetime Estimation Tool of Lead-Acid Batteries for Hybrid Power Sources Design" (Layadi et al. 2015). Battery degradation is a function of depth of discharge (DOD), which is the percentage of the battery capacity that is used while discharging the battery, and temperature. A review of OEM estimations of temperature sensitivity suggests that this model might err on the side of being a more conservative estimation of battery lifetime because of increased temperature sensitivity. The results that the model produced for this analysis do, however, correspond with the broader literature for lead-acid battery lifetimes.

There are two general categories of lead-acid batteries that are commonly seen in stationary applications: VRLA (including absorbent glass mat or gel-based varieties) and flooded lead-acid batteries or vented led acid (VLA). A VLA lead-acid battery is modeled in this report. VLA batteries are commonly the least expensive options but require ongoing maintenance (including adding water). VRLA batteries manage outgassing during battery operation automatically and should be in ventilated spaces, but they can require less ongoing maintenance.

4.2 Degradation Modeling Results

The following tables and graphics summarize some key findings of the degradation modeling for each combination of battery type, climate zone, community demand profile, enclosure construction and insulation, and HVAC type. The results are organized as follows: lead-acid battery degradation, Li-ion battery degradation, and a side-by-side comparison of the two battery types (for wood construction and the suite of HVAC options only).

This analysis assumed that batteries that had degraded to 80% remaining capacity needed to be replaced. In practice, 80% is only a general guideline; each developer or system operator will need to balance the trade-offs of allowing batteries to degrade further (e.g., system sizing considerations, replacement costs). Many warranties will cover degradation down to 60% of remaining capacity after a certain number of cycles. Some batteries can be kept in service beyond that point, but, theoretically, as the battery degrades further, either (1) the load would need to decrease, (2) the percentage of time the load is met would need to decrease, (3) the system would need to have been oversized at the outset, (4) additional storage would need to be added in a modular fashion, or (5) if there is a diesel generator, it will need to be run more frequently.[7] This report focuses on solar plus storage systems, but in hybrid systems as the battery degrades further it would force the power system to compensate for the lost storage, which could increase system operating expenses and run time of diesel generators.

4.2.1 Lead-Acid Battery Degradation

Figure 11 and Figure 12 summarize modeled battery lifetimes for lead-acid batteries for the four different construction materials and the different HVAC options. Following are a few highlights:

[7] This discussion also does not cover secondary uses of batteries, which could include reusing the battery in a second (potentially different) application. Similarly, there have been proposals to reuse electric vehicle batteries in stationary applications, but that approach has not yet been validated and is outside the scope of this analysis.

- In most cases, wood was the best performer in terms of battery lifetime, though brick and concrete structures were similar.
- Air conditioners substantially increased the expected lifetime for lead-acid batteries, particularly for warmer climates. For Niamey, the air conditioner extended the lifetime by roughly 2 years. In the warmer climates the differences between the fan and evaporative cooler options were minimal, reflecting limitations in the effectiveness of those HVAC options in those settings as contrasted with the air conditioner that keeps the temperature at or below the set point year-round.

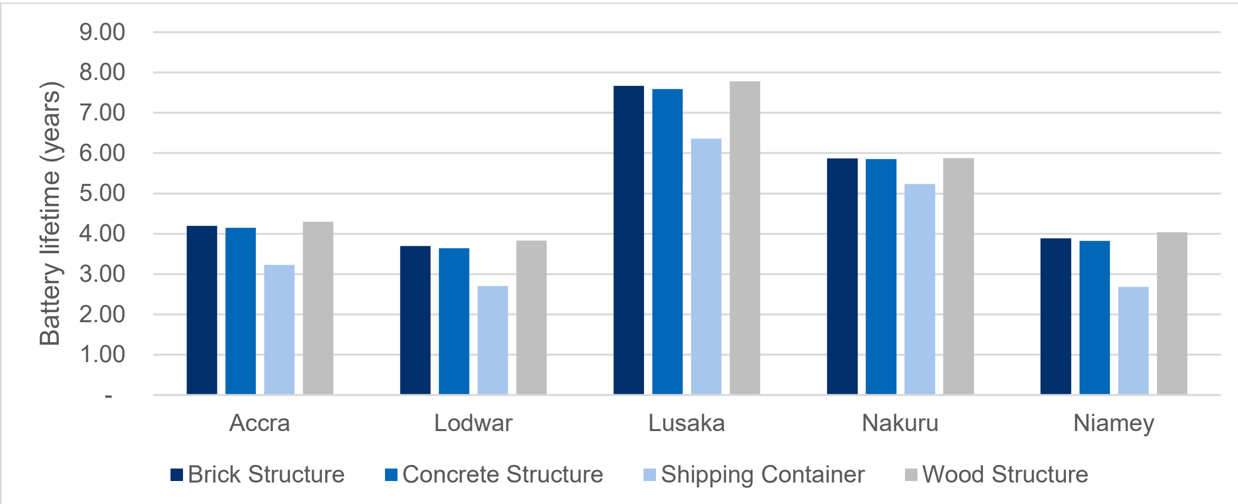

Figure 11. Battery lifetime for lead-acid batteries with different enclosure construction materials (commercial load profile, no HVAC system, insulated)

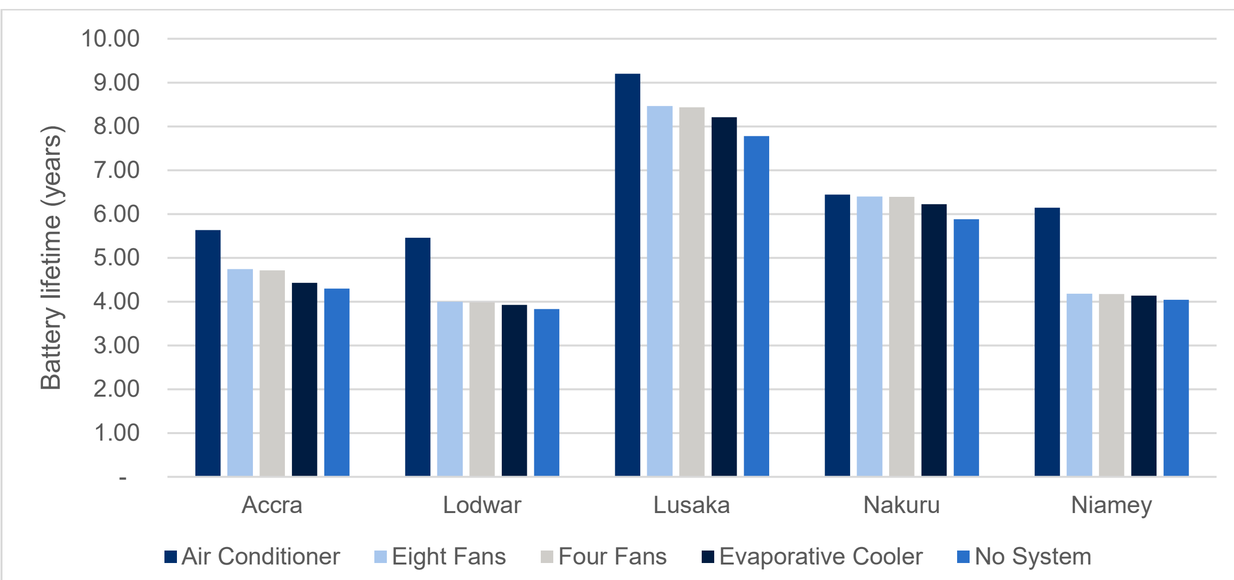

Figure 12. Battery lifetime for lead-acid batteries with different HVAC configurations (commercial load profile, four fans, insulated, wood enclosure)

4.2.2 Li-ion Battery Degradation

Li-ion battery degradation modeling results are detailed in Figure 13 and Figure 14. A few key findings from this analysis include:

- Wood structures were optimal for battery lifetimes in Accra, Lodwar, and Niamey, whereas wood, brick, and concrete were all similar for the other locations.

- For HVAC options, the results were similar to those of the lead-acid batteries, with a few key differences:
    - All the battery lifetimes were longer for each location/HVAC combination.
    - In some settings, there were limited differences between the HVAC options. This is because the temperature in the enclosure typically stayed below the set point for the majority of the year. This was driven in part by the lower heat generation because of the increased efficiency for Li-ion batteries.

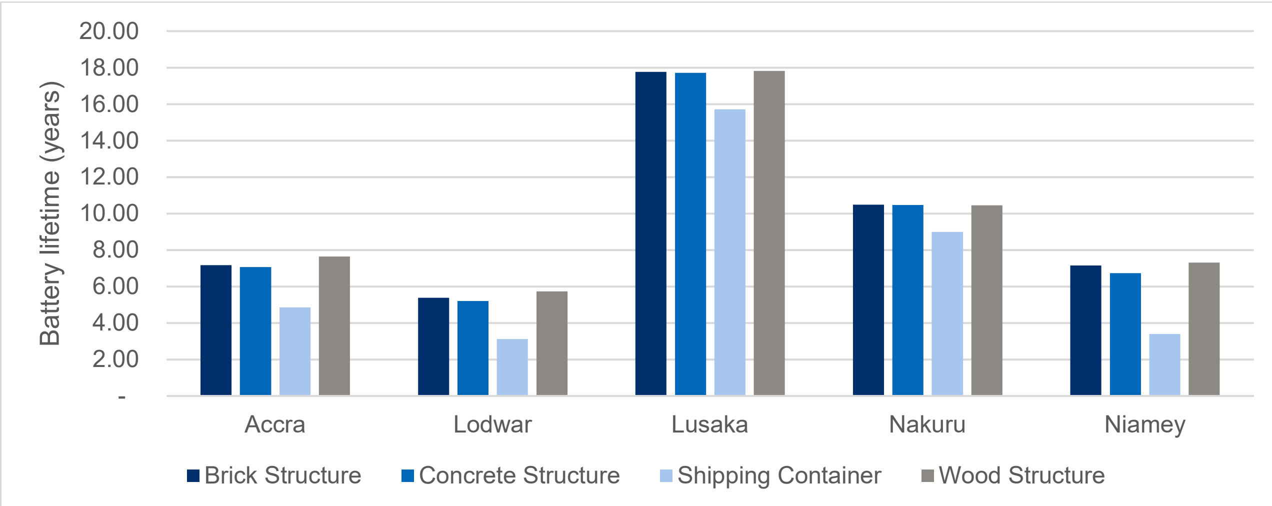

Figure 13. Li-ion battery lifetimes for different enclosure construction materials (commercial load profile, four fans, with insulation)

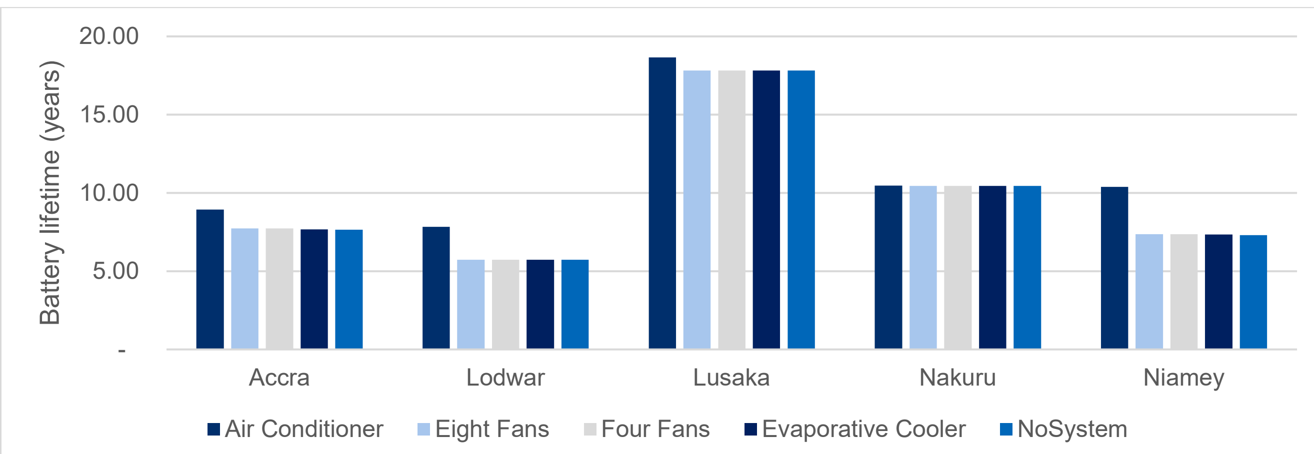

Figure 14. Li-ion battery lifetimes for different HVAC configurations (commercial load profile, wood structure, insulated)

These modeled results include long lifetimes for Li-ion batteries that have not yet been observed in the field in this context. In all cases the lifetime will depend on usage and the specific cells used in a given battery. As additional stationary systems are installed, actual lifetimes should be monitored and compared over time. The results are based on modeling that is calibrated with commercially available cells, but the tests are conducted for shorter time periods and generalized. A practical consideration for developers considering batteries with long lifetimes is the track record of the supplier that is providing a warranty for the battery.

Figure 15 shows a sample comparison of lead-acid and Li-ion batteries for a given HVAC setting (four fans) across the five locations and Figure 16 shows the different HVAC options for one location (Accra, Ghana), which represents a reasonable mean between the sites considered.

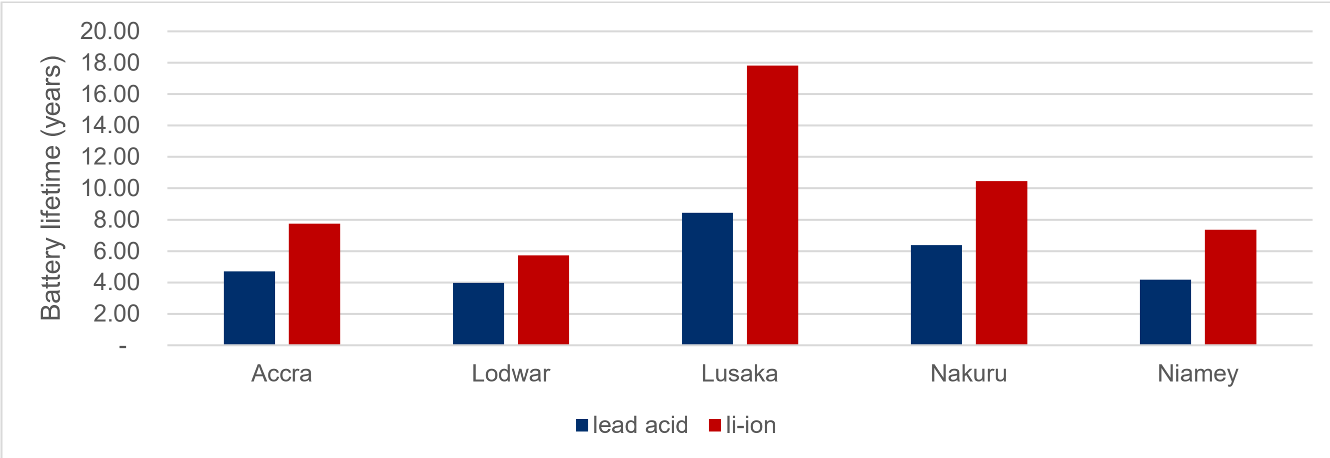

Figure 15. Comparison of battery lifetimes between lead-acid and Li-ion batteries for different locations (commercial load profile, insulated wood enclosure, four fans)

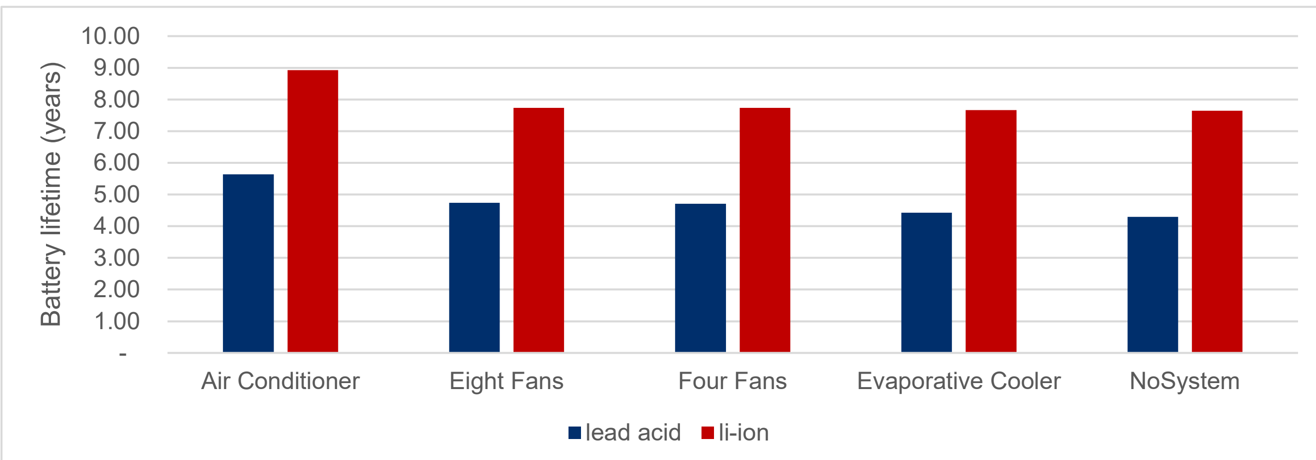

Figure 16. Comparison of battery lifetimes between lead-acid and Li-ion batteries for different HVAC configurations (commercial load profile, insulated wood enclosure, located in Accra)

5 Techno-Economic Analysis

The objective of this techno-economic analysis was to assess which battery type might make the most sense in each climate zone based on LCC. This section combines the battery lifetimes and associated replacement time frames with battery and HVAC capital costs as well as HVAC energy usage to look at the trade-offs between battery type, HVAC system selection, system size, and other related considerations. This section begins with a description of what goes into LCC calculations and provides guidance on interpreting these results before turning to several different questions and answers about the LCC analysis.

5.1 System Sizing and Dispatch

This analysis used REopt™, the Renewable Energy Optimization and Integration tool, which is a techno-economic optimization tool developed by the National Renewable Energy Laboratory.[8] The tool takes inputs from the thermal modeling and battery degradation, assumptions on cost, solar resource data, and constraints on system configuration (e.g., AC- or DC-coupling or minimum SOC for the battery) and produces optimal sizes and dispatch (i.e., when batteries should be charged and discharged) for PV and storage that minimize total LCC for each scenario. REopt has perfect foresight of loads and PV generation so its results should be considered the best-case scenario for what is achievable in practice. The dispatch does not take incremental degradation into account such that it would adjust dispatch for a given hour to improve battery lifetime and therefore LCC.

The system sizing before system expansion to accommodate HVAC systems and assuming 7-year life for lead-acid batteries and 10-year life for Li-ion batteries before adjusting based on degradation modeling is shown in Table 1. There are a few important considerations to note for sizing PV-plus-storage in micro-grids. The model accounts for seasonal variation in the solar resource and sizes the system to serve the community load year-round. As a result, an important driver of system sizing in a PV-plus-storage micro-grid is the distribution of cloudy days and latitude for the site. For example, a location such as Accra is much cloudier in April than in November. The April cloudy period would likely be the constraint that the system is designed for, resulting in extra capacity during the sunnier November days. Figure 17 shows solar irradiance data for each location, highlighting both the absolute differences between locations in the quality of the solar resource and the variation that might cause the systems to be overbuilt during some seasons and just big enough to meet load in others.

[8] See Cutler et al (2017) for more information.

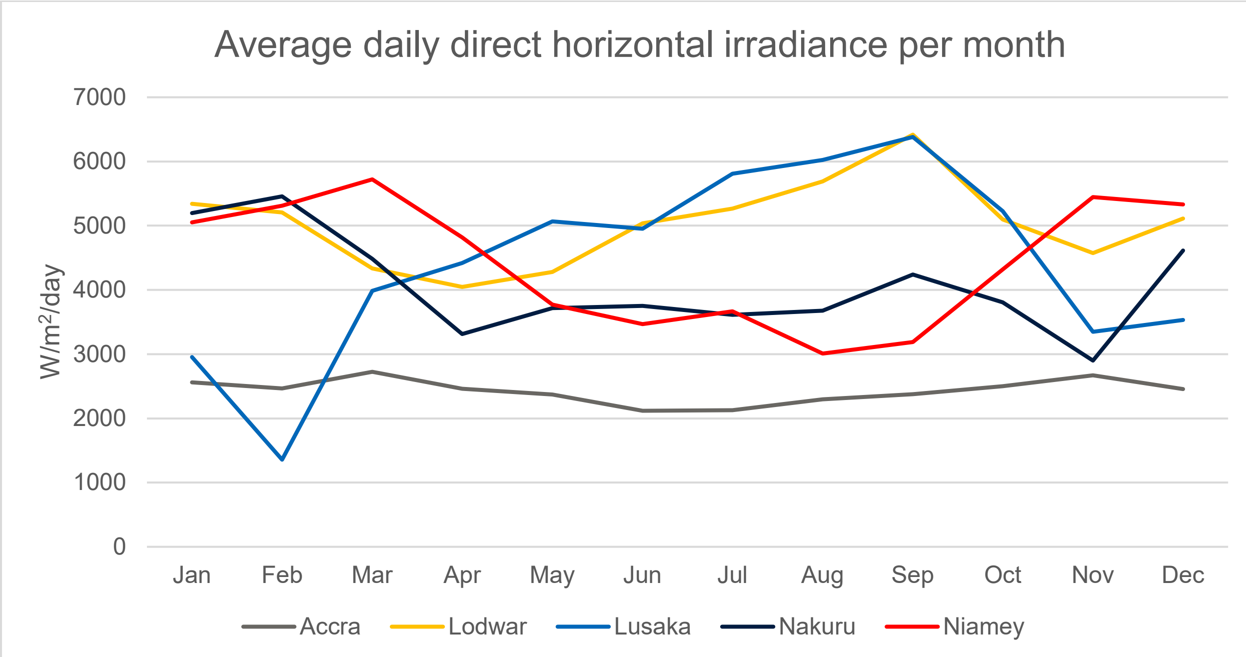

Figure 17. Average daily direct horizontal irradiance in each of five locations

The community electricity demand profile was built up from devices that do not require a great deal of power, and there were only 100 households in the communities modeled here, such that HVAC options could consume a meaningful percentage of the total power produced by the micro-grid. When an HVAC system was included its load was added to the community load and the system was resized to be able to serve that new, combined load. This process was repeated again due to the increased heat generation from the larger system to settle on the final system size. As discussed, this size increase for HVAC demands might not always be necessary, depending on the business model and developer's operational practices.

In practice, electricity demand is estimated before the system is built, but it often takes time to develop after the system is built and may be variable over time. Accurately predicting demand can be challenging, particularly in a community that has limited access to electricity before the micro-grid is developed. Systems are often oversized to make space for growth, particularly growth in productive uses of energy that can improve the amount and reliability of revenue for the micro-grid developer or operator.

This analysis assumed that the load was met 99% of the time, allowing unplanned system downtime that collectively totaled less than 4 days per year. This assumption is intended to track what could be expected to be achieved in practice and avoids the REopt model assigning system sizes that are too precisely matched to annual solar low points based on TMY weather data. This assumption also makes it easier to adapt these results to settings in which a diesel generator is used. Developers that integrate diesel generators need to manage fuel supply and equipment maintenance but also benefit from additional flexibility in sizing to meet community load.

Finally, REopt generates an optimal dispatch that takes the load, solar generation, and battery SOC into account. It is important to note, however, that the degradation modeling is not integrated into the REopt tool dispatch process itself. The HVAC configurations, construction materials, and locations determined the modeled battery lifetime, which REopt then used to optimally size the system. In other words, at each hour REopt decided whether to serve the load with PV or energy storage and whether or not to charge the battery but did not also simultaneously try to keep the batteries in a certain temperature range or at a certain SOC by shifting when the battery would produce heat charging or discharging. In practical terms for this modeling, for Li-ion batteries there might be occasions when there could be an opportunity to extend battery life by tweaking the SOC profile of the battery.

That said, the authors are not aware of any commercially available control solutions nor sufficiently cell- and OEM-specific degradation models to make this possible. There is limited room for changing hourly dispatch based on an assigned degradation function in this system design with just PV and storage. The modeling approach taken here is realistic to real-world conditions and technology options in which the system operator can make construction and HVAC decisions to improve battery life.

Table 1. Initial System Sizes (REopt Optimal)

	Accra	Lodwar	Lusaka	Nakuru	Niamey
Lead acid/residential					
PV size (kW)	22.43	19.62	33.50	22.58	24.32
Battery size (kWh)	66.01	65.00	85.16	65.72	66.79
Battery power (kW)	10.62	10.62	10.62	10.62	10.62
Li-ion/residential					
PV size (kW)	20.61	18.07	28.27	20.75	22.44
Battery size (kWh)	49.64	48.86	72.37	49.42	50.17
Battery power (kW)	10.62	10.62	10.62	10.62	10.62
Lead acid/commercial					
PV size (kW)	20.94	18.12	30.35	20.94	22.42
Battery size (kWh)	37.83	34.70	60.01	36.13	36.99
Battery power (kW)	4.76	4.76	4.76	4.76	4.76
Li-ion/commercial					
PV size (kW)	19.87	17.33	27.29	19.90	21.25
Battery size (kWh)	28.79	26.27	51.97	27.81	28.69
Battery power (kW)	4.76	4.76	4.87	4.76	4.76

5.2 Financial Analysis and Assumptions

REopt analysis calculates a net present value of the cost of building and operating the micro-grid during a 20-year period.[9] REopt analyzes up-front costs, ongoing O&M costs, and equipment replacements for each year and discounts them appropriately to sum to an aggregate LCC. The baseline assumption is that the real discount rate (i.e., adjusted for inflation) is 15%. LCC calculations are sensitive to the discount rate, particularly in settings in which up-front costs make up a large percentage of total costs.

Table 2 and Table 3 summarize the cost and battery assumptions that went into the results that follow.

[9] Equipment that still has usable life at the end of the 20-year analysis period is assigned a prorated salvage value based on the amount of years remaining in its usable life. For example, if an inverter has 5 years of usable life remaining at the end of the analysis period out of an anticipated 10 years of service, then 50% of the cost will be effectively refunded to the LCC to account for the unused value (i.e., it is treated as though it could be resold for a percentage of its initial cost). The purpose of this salvage value methodology is to establish a level playing field across all the scenarios in which pieces of equipment are at different stages of their useful life when the 20-year analysis period ends (but it does not intend to imply that equipment performance declines on a simple linear basis).

Table 2. REopt Modeling Assumptions: Batteries		
Battery Type	**Li-ion**	**Lead Acid**
Storage costs	$350/kWh	$250/kWh
Replacement cost	$350/kWh	$250/kWh
O&M costs	$20/kWh-installed/year	$20/kWh-installed/year
Composite AC-AC round-trip efficiency	90%	80%
Round-trip efficiency	97.5%	86.8%
Inverter efficiency	96%	96%
Rectifier efficiency	96%	96%
Minimum SOC	20%	40%
Initial SOC	100%	100%

Table 3. Other Costs and Financial Assumptions			
Discount rate	10%–15% (real)	**Fan cost**	$50/fan (20-year life)
Analysis period	20 years	**Evaporative cooler**	$1,400/unit (10-year life)
Installed PV costs	$1,600/kW	**AC cost**	$1,750/unit (10-year life)
Capacity O&M	$32/kW/year	**Distribution system**	$20,000
Inverter cost	$600/kW	**Pre-operating expenses (based on peak load at site)**	$1200/kW
Inverter useful life	10 years	**Labor**	$3,000/year
Inverter replacement cost	$300/kW	**Land lease**	$800/year

No additional O&M costs were assigned to the HVAC options. Enclosure costs are assumed to be the same across construction materials.

5.3 Considerations in Interpreting Results

A few additional considerations to note while interpreting the results in Section 5.4 include:

- **Sensitivity to cost parameters**: Each category of cost varies substantially from one region and system to another. When adapting these results, note that substantial changes in cost assumptions can lead to different optimal sizes (particularly in hybrid systems), which alter several other outputs (such as battery throughput, temperature, and resultant degradation)
- **Analysis period:** This analysis assumed a 20-year analysis period, but equipment costs (e.g., the cost of battery maintenance) were not assumed to change substantially over time in this core set of scenarios.
- **Sourcing considerations**: This analysis assumed that batteries and all the other associated equipment with similar characteristics could be sourced in each of the locations.

5.4 Results

The results from the techno-economic analysis are described in this section. A few important high-level takeaways include:

- Li-ion batteries resulted in lower LCCs for every combination of location and load profile. This finding is sensitive to the assumed cost of each battery type. Li-ion battery prices in the range of $450–$550/kWh (depending on load profile and location) were found to bring lead-acid and Li-ion LCC to parity (compared to the $350/kWh assumption).

- The value of HVAC depended heavily on whether or not system sizing was increased to accommodate the additional load and what discount rate was assumed. If the system size were increased to accommodate the new load, then 30% of the load/location combinations would call for integrating HVAC to minimize LCC. If the discount rate were decreased to 10% from 15%, that increased to roughly 50% of the load/location combinations calling for HVAC. If the system were not up-sized to accommodate HVAC loads (but did assume a discount rate of 15%), that number would grow to roughly 70% of the scenarios calling for HVAC systems to reduce LCC.

The subsections that follow discuss these high-level findings in more depth.

1. Which battery type has the lowest LCC for each climate zone and with what construction and HVAC configuration?

Table 4 shows the construction, insulation, and HVAC type that resulted in the lowest LCC in each location and for each load profile. The lowest LCC for each battery type is shown for comparison purposes. Following are a few insights to glean from these high-level results:

- Li-ion batteries resulted in a lower LCC in every case.
- Wood structures were the best construction material for managing temperature, and, understandably, they were the cost-optimal choice in many settings.
- In many settings, the best HVAC option was having no HVAC system. This initial result is interrogated further in the tables that follow to unpack what drives that high-level result. In some instances, an HVAC option might still be optimal for reasons discussed in the following sections.

Table 4. Optimal Construction, Insulation, and HVAC Combination to Minimize LCC for Each Combination of Battery, Load Profile, and Location

	Load Profile	Final LCC	Construction	Insulation	HVAC Type
Accra					
Lead-acid	Commercial	$119,172	Wood structure	Insulated	No system
Li-ion	Commercial	$110,806	Wood structure	Insulated	No system
Lead-acid	Residential	$150,129	Wood structure	Insulated	No system
Li-ion	Residential	$143,939	Wood structure	Insulated	Air conditioner
Lodwar					
Lead-acid	Commercial	$113,626	Wood structure	Insulated	No system
Li-ion	Commercial	$107,106	Wood structure	Insulated	No system
Lead-acid	Residential	$146,263	Wood structure	Insulated	No system
Li-ion	Residential	$138,536	Wood structure	Insulated	Air conditioner
Lusaka					
Lead-acid	Commercial	$140,176	Wood structure	Insulated	Four fans
Li-ion	Commercial	$131,621	Wood structure	Insulated	No system
Lead-acid	Residential	$171,358	Wood structure	Insulated	Four fans
Li-ion	Residential	$156,256	Wood structure	Insulated	Four fans
Nakuru					
Lead-acid	Commercial	$113,369	Concrete structure	Uninsulated	No system
Li-ion	Commercial	$108,102	Shipping container	Uninsulated	No system
Lead-acid	Residential	$142,002	Concrete structure	Uninsulated	No system
Li-ion	Residential	$135,823	Shipping container	Uninsulated	No system

Niamey					
Lead-acid	Commercial	$122,158	Wood structure	Insulated	No system
Li-ion	Commercial	$113,556	Wood structure	Insulated	No system
Lead-acid	Residential	$156,627	Wood structure	Insulated	No system
Li-ion	Residential	$150,442	Wood structure	Insulated	Air conditioner

2. How low would lead-acid prices need to decrease to reach parity with LCCs for Li-ion systems? And vice versa?

This analysis assumed that lead-acid batteries cost $250/kWh and that Li-ion batteries cost $350/kWh. That cost was an important determinant of which battery was optimal in each location because the changing price for each battery resulted in a decreased or increased upfront cost and discounted replacements in the out-years.[10] The battery capital cost made up an average of 20%-30% of the total LCC.

To investigate the sensitivity to these assumptions, two analyses were completed:

- What if Li-ion prices are typically higher than the $350/kWh that this analysis assumed? For each location/load combination, the price of the Li-ion batteries was raised to the point at which the LCC of the Li-ion and lead-acid batteries were equal. For example, for a commercial-heavy micro-grid in Accra, Li-ion batteries resulted in an LCC reduction of $8,366 with baseline assumptions. If the Li-ion prices in Accra were, in fact, actually $560/kWh instead of $350/kWh, that would increase the Li-ion battery LCC by $8,366, meaning that there would be no difference in LCC between the two battery technologies.
- Similarly, what if the assumption about the lead-acid battery cost was too high? Again, taking the case of a micro-grid in Accra with commercial-heavy community demand, if lead-acid batteries could be procured there for $145/kWh instead of $250/kWh, then the LCC for the lead-acid and Li-ion batteries would be equivalent.

Table 5 shows that lead-acid parity price is the price for lead-acid batteries that a developer would need to secure for the lead-acid battery-based systems to achieve the same LCC as a system with Li-ion batteries procured at the baseline assumption of $350/kWh. Similarly, the Li-ion parity price is the price for Li-ion batteries that a developer would need to secure for Li-ion battery-based systems to have the same LCC as a system with lead-acid batteries procured at the baseline assumption of $250/kWh.

[10] The REopt model optimal system sizes shift with prices, but in a PV-and-battery-only system, there is limited latitude for PV to compensate for battery cost changes, so the optimal system size is somewhat price inelastic in this setting.

Table 5. Lead-Acid and Li-ion Price Parity				
	Load Profile	**Final LCC**	**Lead-Acid Parity Price**	**Li-ion Parity Price**
Accra				
Lead-acid	Commercial	$119,172	$145	
Li-ion	Commercial	$110,806		$560
Lead-acid	Residential	$150,129	$210	
Li-ion	Residential	$143,939		$420
Lodwar				
Lead-acid	Commercial	$113,626	$175	
Li-ion	Commercial	$107,106		$490
Lead-acid	Residential	$146,263	$195	
Li-ion	Residential	$138,536		$450
Lusaka				
Lead-acid	Commercial	$140,176	$155	
Li-ion	Commercial	$131,621		$505
Lead-acid	Residential	$171,358	$135	
Li-ion	Residential	$156,256		$535
Nakuru				
Lead-acid	Commercial	$113,369	$150	
Li-ion	Commercial	$108,102		$520
Lead-acid	Residential	$142,002	$190	
Li-ion	Residential	$135,823		$440
Niamey				
Lead-acid	Commercial	$122,158	$140	
Li-ion	Commercial	$113,556		$560
Lead-acid	Residential	$156,627	$210	
Li-ion	Residential	$150,442		$425

3. What are the LCC impacts of each of the different HVAC options for a given construction?

Table 6 shows the LCCs for each HVAC option for the commercial load profile and wood construction. In some cases, the overall differences between the HVAC options were fairly small for a given battery in a given location. Those small differences mask fairly large differences in the system's behavior.

With each HVAC system, there was both the upfront cost of purchasing the HVAC system and increasing the size of the micro-grid system to meet the extra power demanded by the HVAC. The cost of increasing the system size could be as high as $7,000 of additional upfront costs for air-conditioner cases. That increased system cost was from increasing the sizes of the battery, inverter, and PV system and the attendant increases in O&M costs because those are scaled on the basis of system size.

On the other hand, the number of life-cycle replacements of the battery could decrease by one or two (e.g., from four replacements to three replacements during the 20-year analysis period). Table 7 shows that the cost of the system size increases to accommodate the additional load of an HVAC system while still being able to meet the community load. The impact of these opposing forces is mediated in part by the discount rate, so the sensitivity to decreasing the discount rate to 10% is included in the following sections.

Table 6. LCC for Differing HVAC Options

	Accra	Lodwar	Lusaka	Nakuru	Niamey
Lead-acid batteries					
Air conditioner	$123,720	$117,786	$142,797	$116,981	$126,851
Eight fans	$124,409	$119,097	$140,454	$114,364	$127,837
Four fans	$121,722	$116,270	$140,176	$114,114	$125,000
Evaporative cooler	$120,701	$115,227	$142,080	$115,724	$123,811
No system	$119,172	$113,626	$140,811	$114,424	$122,158
Li-ion batteries					
Air conditioner	$113,262	$109,187	$133,613	$110,313	$116,976
Eight fans	$113,443	$108,367	$132,088	$108,595	$115,661
Four fans	$112,252	$107,781	$131,844	$108,401	$114,661
Evaporative cooler	$112,570	$108,838	$133,323	$109,870	$115,304
No system	$110,806	$107,106	$131,621	$108,164	$113,556

Table 7. Average Costs of Increasing System Size to Accommodate HVAC Load for Each Location (only commercial load profiles are displayed)

	Accra	Lodwar	Lusaka	Nakuru	Niamey
Lead-acid batteries					
Air conditioner	$5,112	$5,611	$1,555	$1,166	$6,857
Eight fans	$5,075	$4,520	$190	$316	$4,501
Four fans	$3,034	$2,408	-	$264	$2,382
Evaporative cooler	$209	$226	$128	$129	$228
Li-ion batteries					
Air conditioner	$1,379	$2,381	$95	$29	$3,679
Eight fans	$2,053	$743	$72	$36	$1,640
Four fans	$1,182	$429	$24	$40	$940
Evaporative cooler	$76	$27	$3	$9	$64

4. What if a developer chooses not to increase the size of the micro-grid to accommodate increased HVAC electricity needs?

As noted above, a meaningful upfront cost was assigned to HVAC systems in our modeling to allow the micro-grid to cover the additional load. Specifically, the incremental additional system size was driven by the times of the year when the system was most strained in its ability to serve the load. There are a few settings for which it could be relevant to microgrid development to consider the benefits of increased battery life without the increased system size, including:

- **Dispatchable generation**: If a micro-grid includes a diesel generator that is typically run at a low utilization rate in support of a PV-plus-storage system, the generator might be able to cover increases in coincident net peak. In that case, rather than increasing the size of the system, the incremental capacity cost for the HVAC electricity needs could be accounted for at the price of the kilowatt-hour of diesel generation needed to cover short periods of high overall demand.
- **Oversized systems**: If a micro-grid is oversized to make room for load growth, the conditioning could be operated until community demand reaches the maximum available power without incremental system sizing cost. This would lead to replacing the battery sooner, but the worst-case scenario would be reverting to the battery lifetime associated with no HVAC system (which is the natural alternative to size increases and running the HVAC).
- **Demand response**: A form of a demand response program could also be applied to mitigate the need to increase system size. In other words, if a subset of customers were compensated for some additional unplanned downtime or load shifting, that would be the implied cost of the HVAC system and increased battery lifetimes.

Table 8 shows the optimal construction and HVAC configuration if the system size increase were removed from the LCC calculation (assuming that one of the three scenarios described here is the case). The most notable shift is an increase in air-conditioning use without the incremental up-front cost of increasing system size.

Table 8. Optimal Construction for Each Combination of Load Profile, Battery, and Location if System Size Increases to Accommodate HVAC Electricity Needs Are Removed from the LCC Calculation

	Load Profile	Final LCC	Construction	Insulation	HVAC Type
Accra					
Lead-acid	Commercial	$118,608	Wood structure	Insulated	Air conditioner
Li-ion	Commercial	$110,806	Wood structure	Insulated	No system
Lead-acid	Residential	$148,571	Wood structure	Insulated	Air conditioner
Li-ion	Residential	$141,531	Wood structure	Insulated	Air conditioner
Lodwar					
Lead-acid	Commercial	$112,175	Wood structure	Insulated	Air conditioner
Li-ion	Commercial	$106,807	Wood structure	Insulated	Air conditioner
Lead-acid	Residential	$143,401	Wood structure	Insulated	Air conditioner
Li-ion	Residential	$135,092	Wood structure	Insulated	Air conditioner
Lusaka					
Lead-acid	Commercial	$140,192	Concrete structure	Uninsulated	Eight fans
Li-ion	Commercial	$131,621	Wood structure	Insulated	No system
Lead-acid	Residential	$171,321	Wood structure	Insulated	Four fans
Li-ion	Residential	$156,127	Wood structure	Insulated	Four fans
Nakuru					
Lead-acid	Commercial	$113,362	Concrete structure	Uninsulated	Four fans
Li-ion	Commercial	$108,102	Shipping container	Uninsulated	No system
Lead-acid	Residential	$142,002	Concrete structure	Uninsulated	No system
Li-ion	Residential	$135,823	Shipping container	Uninsulated	No system
Niamey					
Lead-acid	Commercial	$119,994	Wood structure	Insulated	Air conditioner
Li-ion	Commercial	$113,297	Wood structure	Insulated	Air conditioner
Lead-acid	Residential	$152,009	Wood structure	Insulated	Air conditioner
Li-ion	Residential	$145,907	Wood structure	Insulated	Air conditioner

5. What if the relevant discount rate for the system is actually 10%, instead of the baseline 15% assumption used in the rest of the analysis?

As mentioned, this analysis hinged on changes to replacement costs that occurred in the future and the associated trade-offs in upfront costs. As a result, the discount rate applied to translate those replacements into current dollars played an important role in the relative LCCs. Table 9 shows the changes to the optimal solutions with a 10% discount rate instead of the baseline assumption of 15%. Following are a few aspects to highlight:

- LCCs increased across the board, as expected, because future costs were discounted at a lower rate.
- For 6 of the 20 scenarios, there was a change from no system to either 4 or 8 fans. This is a reflection of the increased present value of battery replacement costs resulting in a stronger incentive to increase battery lifetime.
- Concrete and brick structures replaced wood in some settings as cost-optimal (though, as discussed, the difference between these three materials was often fairly small)

Table 9. Changes to Optimal Configurations Resulting from Switching to 10% Discount Rate	Load Profile	Construction Change	HVAC Option Change
Accra			
Lead-acid	Commercial	Wood to brick	*No change*
Li-ion	Commercial	*No change*	*No change*
Lead-acid	Residential	*No change*	*No change*
Li-ion	Residential	Wood to concrete	*No change*
Lodwar			
Lead-acid	Commercial	Wood to brick	*No change*
Li-ion	Commercial	*No change*	No system to four fans
Lead-acid	Residential	*No change*	*No change*
Li-ion	Residential	*No change*	*No change*
Lusaka			
Lead-acid	Commercial	*No change*	*No change*
Li-ion	Commercial	Wood to concrete	No system to eight fans
Lead-acid	Residential	Wood to concrete	*No change*
Li-ion	Residential	Wood to brick	Four fans to eight fans
Nakuru			
Lead-acid	Commercial	Concrete to wood	No system to four fans
Li-ion	Commercial	Shipping to brick	*No change*
Lead-acid	Residential	*No change*	No system to four fans
Li-ion	Residential	*No change*	No system to four fans
Niamey			
Lead-acid	Commercial	Wood to concrete	*No change*
Li-ion	Commercial	Wood to brick	*No change*
Lead-acid	Residential	*No change*	*No change*
Li-ion	Residential	*No change*	*No change*

5.5 Other Considerations in Comparing Li-ion and Lead-Acid Batteries

In addition to the performance and financial analysis, a few key differences between the two battery technologies that would enter into the business decision of which battery to select for a micro-grid include:[11]

- **Battery management system (BMS) and performance monitoring**: Li-ion batteries typically require a BMS, which is necessary to manage the risk of a thermal runaway. The BMS offers some built-in capabilities to provide additional data and, more importantly, manages the treatment of individual cells in the batteries. However, poor battery management, which can be caused by a low quality BMS, can lead to lithium-ion battery thermal runaway and fires. Care should be taken in choosing a lithium-ion battery and BMS supplier.
- **Potential modularity options**: Because of the integrated BMS, Li-ion battery installations can also potentially be more easily expanded to increase capacity or to address specific low-performing cells. Lead-acid batteries require more attention to the configuration and number of strings, which should be minimized. Additionally, old lead-acid battery cells should never be combined with new ones (as the new ones can be excessively strained due to their lower internal resistance and will degrade much more quickly).
- **End-of-life deposition**: Lead-acid batteries have a long history of being recycled, owing in large part to their role in automobiles and associated regulation of their lead content. As a result, greater than 90% of the material in lead-acid batteries can be recycled. Li-ion batteries, on the other hand, still have relatively nascent recycling industries, and current designs have a lower theoretical ceiling on the maximum percentage of the battery that can be feasibly recycled.

These additional considerations do not enter directly into this report because they are specific to location, battery technology, and business model, but they are important to take into account when applying the results of this analysis.

[11] See Walker et al (2018) for additional PV and battery O&M considerations.

6 Conclusion

This analysis is intended as input for developers and other stakeholders to consider when evaluating which battery technology and HVAC approach makes the most sense for their context and constraints. For a developer, the report could serve as an input to battery procurement processes or a data point in considering the impacts on performance of their systems of expanding to a new region. For an investor, this report could help refine questions they might ask to hone their understanding of the risks and opportunities of a given micro-grid investment. For stakeholders who are looking to support micro-grid scaling, this report describes some of the gaps and challenges to effectively deploying batteries in this context.

From a research perspective, this analysis is something of a point of departure. This study points to a great deal of additional research to be done on battery degradation in micro-grids, in particular taking existing models and calibrating them to the ever-growing amount of real-world data coming from micro-grid systems to improve the accuracy of performance forecasting and economic analysis. Further, as battery technologies change over time, there is a need to constantly validate and update models of their behavior over time. Also, this report begins with a relatively straightforward design for a micro-grid; there are opportunities to expand these findings to other types of micro-grids as well.

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Appendices

Appendix A: Micro-grid Equipment Heat Generation Profiles

Batteries, charge controllers, and inverters are common micro-grid components. These components are commonly located in an enclosure (e.g., shipping container) to keep people safe, to protect the equipment from the environment (e.g., rain, dirt, direct sunlight), and to protect them from tampering. Calculating the heat generation inside the space by the equipment was one of the first steps in this analysis.

The type of battery technology used impacts the amount of heat generated within the micro-grid enclosure. As discussed, lead-acid batteries are less efficient than Lithium-ion (Li-ion) batteries and will generate more heat when they are charging or discharging. Further, lead-acid batteries might have a tighter acceptable operating temperature range than Li-ion batteries, which can contribute to higher cooling loads.

The AC electric load profile of the micro-grid impacts the amount of heat generated by the batteries, charge controller, and inverter. The heat generated by these micro-grid components was estimated using hourly REopt dispatch, including the hourly battery state of charge (%), discharge rate (W), and charge rate (W). For this analysis, it was assumed that there are three distinct heat generation regimes:

1. The first heat generation regime is during hourly time steps when the batteries are fully charged and in float.
2. The second heat generation regime is during hourly time steps when the batteries are being discharged.
3. The third heat generation regime is during hourly time steps when the batteries are being charged by the photovoltaic system.

The equations that govern the heat generation for the three regimes are as follows:

$$q_1 = (1 - \eta_{Inverter}) \times P_{AC}$$

$$q_2 = (1 - \eta_{Inverter}) \times P_{AC} + (1 - \eta_{Battery}) \times P_{Discharge}$$

$$q_3 = (1 - \eta_{Inverter}) \times P_{AC} + (1 - (\eta_{Battery} + \eta_{ChargeController})) \times P_{Charge}$$

where:

- q_1 is the heat rate in watts for hourly time steps in the first heat generation regime
- q_2 is the heat rate in watts for hourly time steps in the second heat generation regime
- q_3 is the heat rate in watts for hourly time steps in the third heat generation regime
- $\eta_{Inverter}$ is the inverter efficiency
- $\eta_{Battery}$ is the battery efficiency
- $\eta_{ChargeController}$ is the charge controller efficiency
- P_{AC} is the total hourly micro-grid power throughput in watts
- $P_{Discharge}$ is the total hourly power discharged from the batteries in watts
- P_{Charge} is the total hourly power to charge the batteries in watts.

The hourly heat generation in watts for an entire year was calculated using these equations. The average daily heat generation profile was then calculated by taking an average of each hour of the day from the annual hourly data. A total of 20 heat generation profiles were generated and include the five locations, the two battery technologies, and the two load profiles. Figure A-1 shows the micro-grid equipment heat generation profiles for the 20 cases along with the average. As shown, there was relatively close agreement between the heat generation profiles across the five locations and the various load profiles and battery technologies.

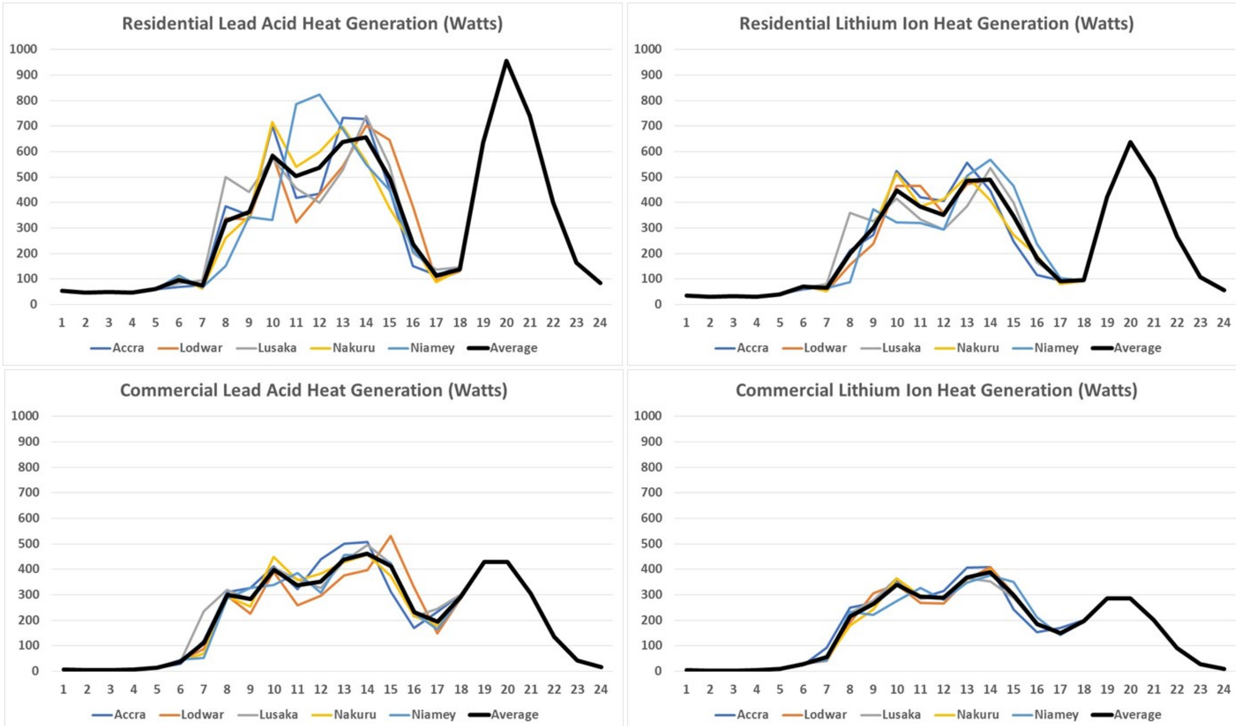

Figure A-1. Initial heat generation profiles

The heat generation profiles shown in Figure A-1 were normalized to the maximum heat generation hour to determine how closely the profile shapes followed each other. Figure A-2 shows a summary of the normalized heat generation profiles. It was determined that the profile shapes were close enough so that one heat generation profile shape could be used in the OpenStudio modeling for each load and batter combination. The maximum value for each hour is the profile shape that was used in the OpenStudio modeling because this was the most conservative approach.

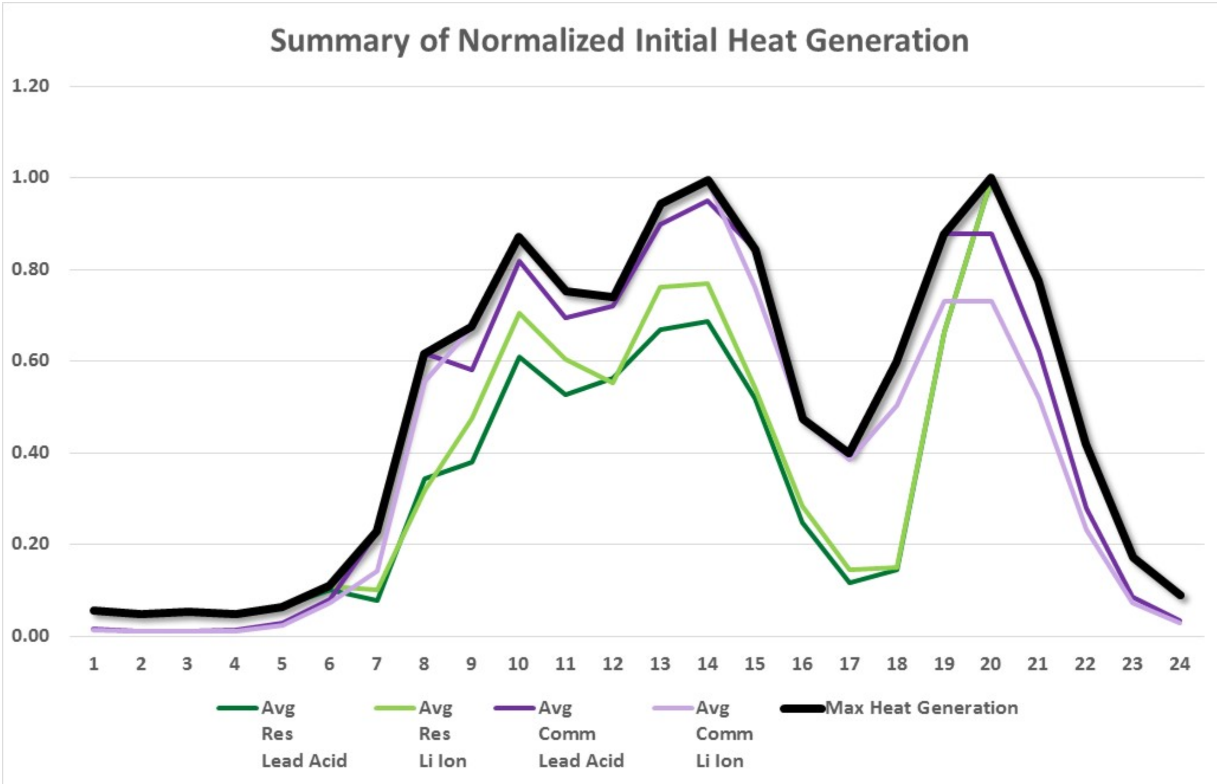

Figure A-2. Summary of normalized initial heat generation profiles

The magnitude of the normalized maximum heat generation profile was adjusted by the maximum value for each case.

Appendix B: Battery Degradation Models

In this analysis, a "bucket" battery model was assumed that considered a battery energy storage system as an energy storage medium that holds energy in units of kilowatt-hours. As a simplification for linearization, battery voltage and current were ignored. The battery energy storage system had a fixed set of efficiency parameters (e.g., not dependent on current or state of charge [SOC]) with some assumed losses occurring during charging and discharging. Degradation was not assumed to impact the battery dispatch; minimum allowable SOC constraints were imposed, and degradation was assumed to reduce this minimum SOC "reserve."

Modeling was done in 1-hour time intervals for a typical year (8,760 time steps), and this dispatch was assumed to repeat each year for the 20-year analysis period. The analysis assumed that end of life for both lead-acid and Li-ion batteries occurs when the battery degrades to a point where 80% of the beginning-of-life capacity remains. Battery degradation was modeled based on that repeating annual dispatch up until the battery reached 80% remaining capacity.

Battery degradation as a function of depth of discharge (DOD) was estimated for Li-ion and lead-acid batteries. For both chemistries, temperature impacts on degradation per cycle were included and battery temperature was assumed to be the same as enclosure temperature. For Li-ion batteries calendar or shelf life degradation was also calculated. Battery cycle counting was done using the four-point counting algorithm descried by Amzallag et al. (1994) in the paper "Standardization of the Rainflow Counting Method for Fatigue Analysis" and using the pseudo code for the algorithm included in the paper on "Equivalence of Four-Point and Three-Point Rainflow Cycle Counting Algorithms" (McInnes 2008).

The degradation model used for the Li-ion batteries was taken from Smith et al. (2017), "Life Prediction Model for Grid-Connected Li-ion Battery Energy Storage System." Temperature dependence of degradation from that reference was also included. The authors performed aging tests on commercial graphite/nickel-manganese-cobalt Li-ion cells and presented an empirical model based on those test results.

Lead-acid cycle degradation as a function of DOD and temperature was modeled per Layadi et al. (2015), "Lifetime Estimation Tool of Lead-Acid Batteries for Hybrid Power Sources Design." In this paper, dependency of cycle degradation by temperature for lead-acid batteries is described to follow Arrhenius' law for corrosion rates. For lead-acid batteries, Layadi et al. (2015) presented cycle degradation for multiple lead-acid batteries based on manufacturers' data. In this analysis, a vented battery with positive tubular plates, the Exide model OPzS Solar is assumed. Other references (e.g., vendor catalog) describe a weaker temperature function, and further research is warranted to determine if the impact of temperature on these results is overly conservative.

Appendix C: OpenStudio Thermal Modeling Assumptions

For the thermal modeling, each material (construction and insulation) had assumed characteristics. These characteristics are summarized in Table A-1.

Table A-1. OpenStudio Assumptions for Construction Materials and Insulation

	Brick	Concrete	Metal Ship. Cont.	Wood	Insulation
Thickness (m)	0.102 (4 in)	0.102 (4 in)	.00191	0.0889	0.0254
Roughness	MediumRough	MediumRough	Smooth	Smooth	Rough
Conductivity (W/mK)	1.31	1.73	14.03	0.367217	0.0245
Density (kg/m^3)	2082.4	2243.0	7612.0	126.15	24.0
Specific Heat (J/kgK)	921.1	837.0	460.6	1556.3	1590.0

Following are a few additional assumptions to note:

- The R-value of the insulation is R-13.
- Wood is modeled after a wood-framed building with 4-in. studs, 16-in. on center.
- Wood and brick structures have a metal roof and two layers of 5/8-in. Wood assumed to be Douglas fir sandwiching the wooden studs.
- Shipping containers were assumed to be sitting on a concrete slab (MAT-CC05 8-in. heavyweight concrete)

Humidity for each location was taken into account in calculating the cooling capacity of evaporative coolers in OpenStudio. Figure A-3 shows the average relative humidity by month for each location for reference.

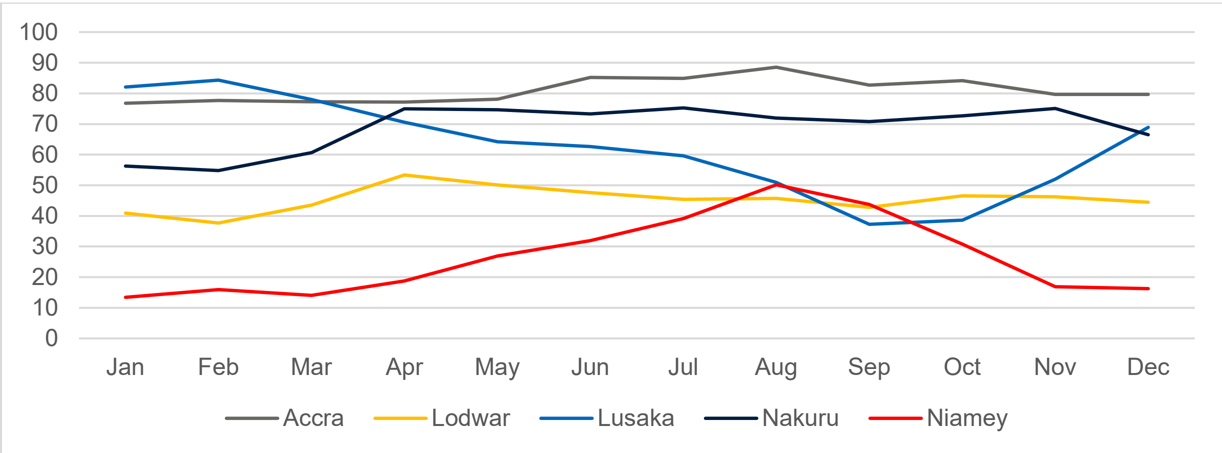

Figure A-3. Average relative humidity by month (%)

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The Power Africa, USAID, and NREL Partnership addresses critical challenges to scaling up the implementation and investment in micro-grids for energy access through technical support partnerships and application of NREL's Quality Assurance Framework.