The Need for Research Regarding Benefits of Integrating Thermal Energy Storage Batteries in Rural Mini-Grid Electric Systems

John C. Wehner
Email: johnwehner@gmail.com

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ABSTRACT

This paper concludes that the electricity cost reduction benefit could be increased by addition of Thermal Energy Storage (TES) using battery refrigeration anchor customers and a Modularity Grid digital platform. A Modularity Grid platform uses artificial intelligence and block chain to optimize distribution of mini-grid electricity distribution to households, commercial customers, anchor loads and battery charging. The Modularity Grid technology, is being piloted in Uganda. Research is warranted to determine if the potential for reducing electricity cost exists. This research is warranted given that:

• Current literature discussing mini-grid planning and management of mini-grid electricity distribution in developing countries focuses on the cost reducing benefits of integrating conventional commercial anchor loads generally requiring continuous, reliable electricity supply.

• TES batteries have demonstrated commercial viability when charged with intermittent electricity generated from solar and wind generation often used as a source of mini-grid electricity supply.

• As discussed below, TES battery/refrigeration anchor loads combined with Modularity Grid could add economies of scale while reducing mini-grid electricity cost below mini-grids with conventional anchor loads - thus increasing the economic viability of mini-grids serving households as well as commercial refrigeration in developing countries

• There is a significant need for additional commercial refrigeration in rural locations in developing countries to reduce food loss, increase agricultural productivity and provide refrigeration for health clinics.

Keywords: batteries**,** cost reduction, developing countries, electricity, mini-grid, thermal energy storage

JEL Classification: O33, Q42

Introduction

Thermal Energy Storage (TES) batteries store thermal energy (e.g. energy storage in tanks that form and store ice) when there is low cost and/or surplus electricity for use in a refrigeration device when electricity is expensive or not available. If electricity is not available, TES batteries can provide chilling for up to 48 hours[1]. TES battery charging requirements are flexible - meaning that batteries provide commercial refrigeration using intermittent *or* continuous electricity supply.

The following discusses the potential for reducing mini-grid electricity cost by adding TES battery commercial anchor loads connected to mini-grid systems in rural areas of developing countries without access to national power grids.

Typical mini-grid anchor loads discussed in mini-grid research papers are relatively large electricity customers with demonstrated ability to pay and predictable demand such as cell phone towers, grain milling and manufacturing operations that require continuous electricity supply. These "productive use" commercial customers provide a steady source of income for mini-grid owners. Mini-grid research consistently concludes that adding anchor load customers to mini-grid systems contributes to economic viability because these customers increase economies of scale and average use per customer, while lowering the average cost of electricity[2].

[1] See: https://www.inspirafarms.com/products/packhouse/
[2] See: "State of the Global Mini-Grids Market 2020," BNEF, page 114-117.

This paper concludes that the electricity cost reduction benefit could be increased by addition of TES battery refrigeration anchor customers and a Modularity Grid digital platform. A Modularity Grid platform uses artificial intelligence and blockchain to optimize distribution of mini-grid electricity distribution to households, commercial customers, anchor loads and battery charging. The Modularity Grid technology, developed by a London based start-up company founded by Elizabeth Nyeko, is being piloted in Uganda. This technology is described in greater detail below and in the 2018 *MIT Technology Review* publication "35 Innovators Under 35[3]."

Research is warranted to determine if the potential for reducing electricity cost exists. This research is warranted given that:

- Current literature discussing mini-grid planning and management of mini-grid electricity distribution in developing countries focuses on the cost reducing benefits of integrating *conventional* commercial anchor loads generally requiring *continuous,* reliable electricity supply[4]
- TES batteries have demonstrated commercial viability when charged with *intermittent* electricity generated from solar and wind generation often used as a source of mini-grid electricity supply
- As discussed below, TES battery/refrigeration anchor loads combined with Modularity Grid could add economies of scale while reducing mini-grid electricity

[3] See: https://www.technologyreview.com/lists/innovators-under-35/2018/.
Modularity Grid is further described in https://www.mandulisenergy.com

[4] See: 1) "State of the Global Mini-Grids Market 2020," BNEF; 2) "Microgrids for Rural Electrification: A Critical Review of Best Practices," by Daniel Schnitzer, Deepa Shinde Lounsbury, Juan Pablo Carvallo, Ranjit Deshmukh, Jay Apt, and Daniel M. Kammen. Published by the United Nations Foundation, 2014.

cost below mini-grids with conventional anchor loads - thus increasing the economic viability of mini-grids serving households as well as commercial refrigeration in developing countries

- There is a significant need for additional commercial refrigeration in rural locations in developing countries to reduce food loss, increase agricultural productivity and provide refrigeration for health clinics.

The paper also demonstrates that there is a need for additional small/medium enterprise (SME) commercial refrigeration in developing countries and that TES commercial battery investment combined with mini-grid management systems such as the Modularity Grid platform could help meet this need. Finally, the paper discusses the fact that while TES investment is growing, there will likely be growing competition from lithium-ion batteries whose cost is expected to decline rapidly.

The above suggests the need to confirm whether active management of TES battery charging with Modularity Grid technology would reduce total cost of electricity, while increasing the supply of much needed, affordable refrigeration in area served by rural mini-grids. The above also suggests the need to calculate the break-even cost of lithium-ion battery storage with TES battery energy storage and when/if this breakeven cost is likely to occur.

What's the Status Quo?

Thermal Energy Storage (TES) batteries in developing countries are often charged with electricity from mini-grid electricity distribution systems not connected to the main power grid. These systems often receive a large portion of electricity supplied by intermittent renewable energy (e.g. solar PV, hydro, wind supplemented by diesel generation and conventional lead acid and lithium ion batteries). To illustrate the significant and growing mini-grid reliance on intermittent electricity BloombergNEF reports that in 2019 55 percent of operating mini-grids incorporated PV[5]. The TES batteries are typically used to provide thermal chilling capacity *backup* for chilling when intermittent/unreliable electricity provided by renewable solar and wind generated electricity is not available for conventional electric refrigeration. There is limited research related to the electricity cost reduction benefit of using Modularity Grid or other electricity management systems to manage TES battery charging in conjunction with allocation of intermittent electricity to residential and commercial customers, charging conventional batteries as well as commercial anchor load TES batteries.

Potential Untapped Synergies

The hypothesis discussed below is that use of a cloud-based system such as Modularity Grid to actively manage distribution of electricity has several potential synergies that may not yet be fully recognized or exploited. These synergies relate to:

[5] "The State of the Global Mini-Grids Market Report 2020," BloombergNEF

1. TES battery ability to increase productive use of unexploited, *intermittent* electricity that may otherwise not be utilized

   It is assumed that a mini-grid system with an anchor load able to use intermittent electricity supply could utilize a larger percentage of available intermittent electricity than a system with more constraints related to serving anchor loads requiring continuous power.

2. Fuller use of renewable generation and conventional battery storage capacity may reduce the average cost of electricity by creating the opportunity to amortize mini-grid fixed generation, distribution, conventional battery storage and energy management system capital costs over more kWh sales leading to lower fixed cost per kWh.
3. Increased availability of refrigeration made possible by TES batteries and more affordable electricity supply may provide income-generating investment opportunities that could provide refrigeration for health clinics and reduce significant post-harvest food losses which, according to the United Nations Food and Agricultural Organization (FAO) June 21, 2018 announcement, "…. can reach [in Africa] up to 20% for cereals, 30% for dairy and fish, and 40% for fruit and vegetables[6]."

[6] Rockefeller Foundation, FAO Supporting Africa to Halve Food Loss, June 21, 2018. https://reliefweb.int/report/world/rockefeller-foundation-fao-supporting-africa-halve-food-loss.

Modularity Grid Management of Mini-grid Sources and Uses of Electricity

As discussed in the *MIT Technology Review*, there is a need to improve the integration of mini-grid sources and uses of electricity to increase utilization of electricity by conventional anchor electricity loads. Modularity Grid technology, currently being piloted in Uganda,[7] is being used to increase the utilization of mini-grid electricity generation and distribution capacity. The *MIT Technology Review* reports that:

> … "electricity demand of individual customers is very hard to track, which typically leads to overproduction of power, inefficient use of fuels, and inflated electricity prices.

The *Technology Review* goes on to say that with the Modularity Grid, "…. an intelligent cloud-based platform …. enables operators to better track and predict individual consumption; it then redirects excess electricity to specific users in need of *constant* power, called anchor loads."

Mini-grids relying primarily on solar and wind power serving rural communities in developing countries have a demonstrated need for improved matching intermittent electricity supply with demand using the Modularity Grid platform. The need for improved management is illustrated by a mini-grid case study where engineers from Amrita School of Engineering in Kerala, India designed, developed and deployed a mini-grid (without a Modularity Grid platform) in rural India. The case study is described in a paper, "When Academia Meets Rural India: Lessons Learned from a Mini Grid Implementation," published for the 2016 IEEE Global Humanitarian Technology Conference.

[7] https://www.wired.co.uk/article/mini-power-grids

The mini-grid design, based on a simulated load profile using HOMER Pro[8] was developed for a rural village consisting of 42 households (300 inhabitants). Each household was assumed to have three 11-watt CFL bulbs and a 35-watt charger for mobile phone/tablet charging 1 hour per day. The load profile in the simulation reflects the fact that the primary use of electricity is for lighting and cell phone/tablet charging. The simulation also assumed solar panels are used to provide battery stored electricity for use at night. While there is demand for electricity during daylight hours, the simulated communal supply is assumed to be curtailed with timers during daytime hours to ensure availability of sufficient electricity from solar panels for conventional battery charging during the nighttime. The simulation estimates electricity waste in the rural village will range from 100% to 455% - depending on the percent capacity shortage customers experience. For instance, the simulation showed that a 10% capacity shortage design, would result in 100% electricity wastage, while a 0.5% capacity shortage mini-grid design with more kW electricity generation capacity would result in 455% electricity wastage.

If a Modularity Grid platform were added to the system, existing timers that curtail total electricity use during the day could be eliminated while directing variable electricity supply to its highest and best use that may be households, conventional battery storage as well as small/medium scale commercial TES battery commercial refrigeration anchor loads able to productively use intermittent power. As a result, a greater percentage of electricity would be used – thus reducing overproduction of unused electricity resulting in a reduction in the average cost per delivered kWh.

[8] Software originally developed at the United States National Renewable Energy Laboratory

It is this ability to productively use intermittent electricity supply that distinguishes TES battery anchor loads from typical commercial anchor loads such as cell phone towers, rice hullers and wheat millers that require constant electricity supply throughout the day.

Benefits of Adding Anchor Loads to Mini-grids

The direct cost reduction benefit of adding anchor loads to mini-grids is illustrated by the following conclusion of a mini-grid research study titled, "The Critical Role of Anchor Customers in Mini-Grids[9]":

> Through mini-grid design simulations, it is shown that when anchor customers represent around 30% of the load[10] (load factor[11] of 0.4), the cost of electricity can be reduced by 22% for a mini-grid powered by wind and solar energy and by 48% for a solar mini-grid, compared to a village with less than 10% of anchor users (load factor 0.2). It is thus critical to include anchor customers at the mini-grid design stage in order to provide affordable energy in rural areas.

Integrating relatively high load factor TES battery anchor refrigeration loads providing cold storage and milk chilling able to use intermittent electricity was not discussed in the study conducted in India. Instead the focus was on benefits of adding anchor loads requiring constant electricity supply.

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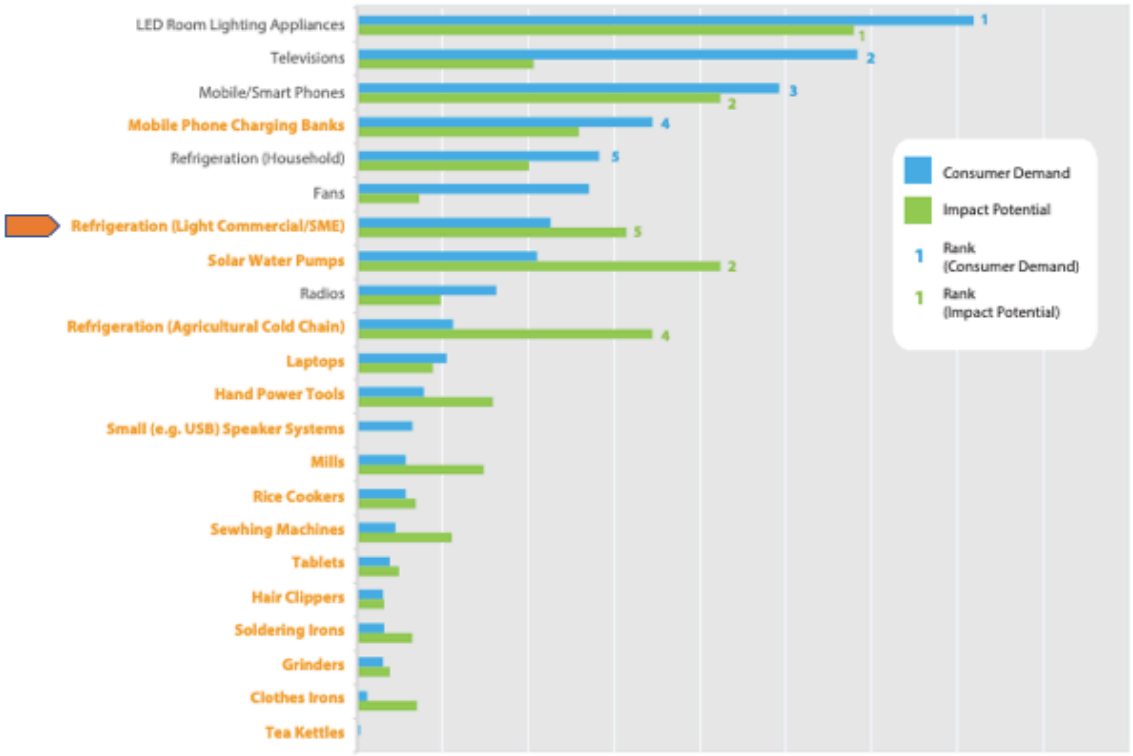
[9] "The Critical Role of Anchor Customers in Mini-Grids," Robert, Gopalan, Sisodia. Paper presented at the 2017 International Conference on Computation of Power, Energy, Information and Communication (ICCPEIC). Published by IEEE (Institute of Electrical and Electronic Engineers).

[10] Load measured in kilowatts (kW).

[11] Load factor is average load divided by peak load during a specific period of time. For instance, a 100-watt light bulb turned on 100% of the time would have a 1.00 load factor. If the bulb were turned on 50% of the time it would have a load factor of 50% or 0.50.

There is A Significant Developing Country Demand for Refrigeration

Large potential demand for and positive socio-economic impact of additional commercial refrigeration is reflected in Figure 1 that summarizes the results of a 2017 Off-Grid-Appliance survey completed by LEAP (Learning, Evaluation and Analysis Project, USAID[12]).



** The survey respondents were asked to rank top 5 household/SME off-grid appliances based on anticipated off-grid consumer demand and potential contribution to socioeconomic development and poverty reduction for the next 3-5 years.*

Figure 1
Ranking Overview: Household or SME Off-Grid Appliances

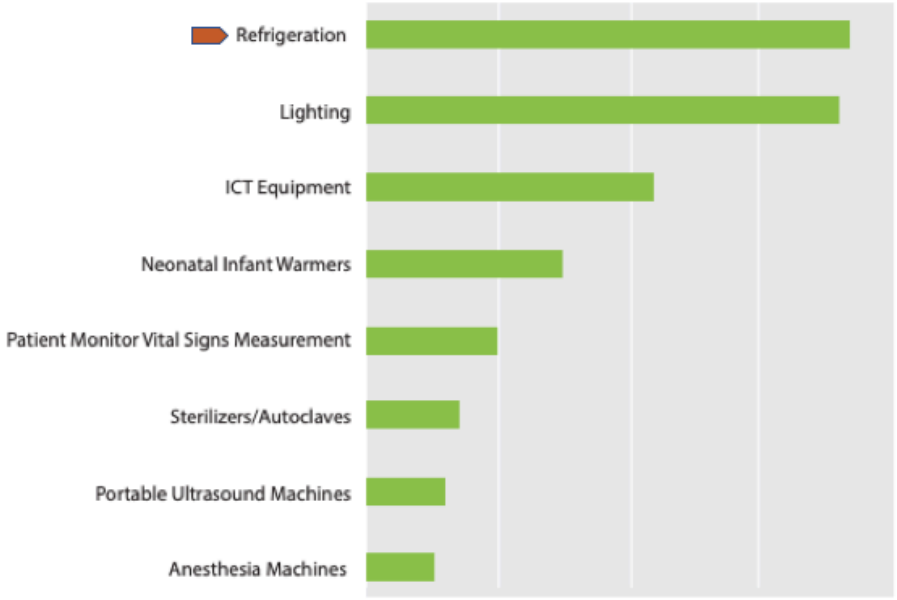
[12] https://storage.googleapis.com/clasp-siteattachments/2017-Off-Grid-Appliance-Survey-Summary.pdf. Note SME = Small-Medium Enterprise.

The chart shows Light Commercial and Small-Medium Enterprise (SME) refrigeration ranks fifth in the survey in terms of contribution to positive impact potential, while 7th in Consumer Demand. LEAP, in their application for the 2016-2017 Off-Grid refrigeration competition, describes positive economic and socio-economic impacts of refrigeration as follows[13]:

> Refrigeration holds the potential to unlock economic and social progress for the 600 million people living off-grid in sub-Saharan Africa. Refrigeration can prolong the nutritional value of food, diversify diets, enable income-generating activities, and reduce the time spent acquiring food.

LEAP also surveyed respondents regarding the need for healthcare and clinical products. LEAP reports the following results showing refrigeration (e.g. for vaccine refrigeration), ranked number 1 in terms of contribution to positive impact potential.

[13] See http://globalleap.org/refrigerators/



** Global LEAP asked survey respondents to rank top 5 healthcare and clinical appliances based on impact upon healthcare outcomes (i.e. the relative importance of each in delivering healthcare services to rural and/or under-electrified populations).*

figure 2
Ranking Overview: Impact Potential of Healthcare and Clinical Appliances

While the LEAP mentioned that it would not recommend drawing broad conclusions from the study because the sample size for the healthcare and clinical products survey was small, given the growing and critical need for vaccine refrigeration it is reasonable to assume increased availability of affordable TES refrigeration to serve the health care industry could yield significant social benefits.

Review of Successful TES Battery Companies in Developing Countries

Promethean Power System Batteries

Promethean Power Systems has installed more than 1,200 milk chiller and cold storage units with TES batteries (referred to by Promethean Power Systems as thermal storage systems or "TSS")

in India, Bangladesh and Sri Lanka[14]. One of the advantages of the Promethean Power System TES batteries is the fact that they have a demonstrated commercial track record providing backup cooling in areas with unreliable grid power. The ability to operate with intermittent power supply would give an energy management system such as Modularity Grid a high degree of flexibility to direct a relatively large percentage of intermittent energy supply to the highest and best use, while reducing the amount of unused micro-grid electricity production.

Figure 2 illustrates a commercial Promethean Power System farm produce cooling system with TSS backup. Figure 3 shows the components of the produce cooling system[15].

[14] See https://coldchainmanagement.org/2020/01/09/in-conversation-with-mr-jiten-ghelani-ceo-promethean-power-systems/
[15] https://coolectrica.com/wp-content/uploads/2016/08/Cold-Storage-Solutions-Data-Sheet-10022016.pdf.

promethean power systems
redefining refrigeration

Farm Produce Cooling Solution (CSS)

*Farm Produce Chilling **without** Diesel Generator Backup*

Promethean's CSS is the most economical way to chill, store and transport fresh fruits, vegetables and other perishables. Chilling the fresh produce immediately at the source is the most optimal solution to India's cold-storage challenge. This stationary cooling system can chill farm produce under erratic grid conditions without requiring a diesel generator.

At the heart of the CSS is Promethean's ***Thermal Storage System*** that can store and release large amounts of thermal energy and can be applied to various cooling applications.

Feature	Benefits
Cooling farm produce at the source	• First cool then transport principle enables longer shelf life and higher margins on quality produce • Capture more farmers in the catchment area. • Eliminates post harvest losses.
Cold Storage Backup	• Eliminates diesel generator. • Low maintenance & operating costs. • Unlike electrical batteries, thermal battery does not need to be replaced every 3 to 5 years.
Simple flexible Design	• Single phase connection at farms • Easy to operate

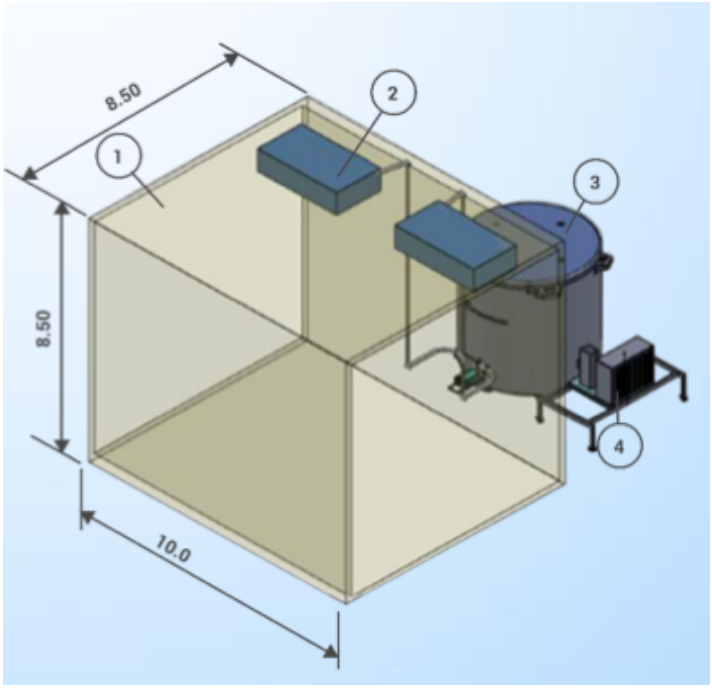
OUR TSS

The TSS is the energy storage technology which provides cold energy for all of Promethean's refrigeration products:

- **Backup cooling power** - for areas with unreliable grid power
- **Instant cooling power** - for rapid cooling of fruits, vegetables, milk and other perishable food products
- **Load shifting** - from day-time to night-time to reduce energy bills

Description	Specification	Units
Compressor Model	ZB-21	
Average Cooling Power	5	kW
Minimum Grid Hours Required for 1 charge	4-5	Hours
Quantity of Produce	2.5	Tons
Room Size	640	Cu. Ft.
Battery Back-Up Capacity with 100% charge (Ambient to 4 deg C)	10-12	Hours
Battery Back-Up Capacity with 100% charge(Maintaining 4 deg C)	20	Hours
Output Temperature Range	4 and above	Deg C
Floor Area Required	150	Sq. Ft.
Single Phase Electrical Connection	6.5	HP

figure 2
Promethean cold storage unit with thermal storage systems (TSS) battery cold storage backup



Component #	Component
1	Cooling Chamber
2	Fan Coil Units
3	Thermal Storage System
4	Chiller Unit

figure 3
Promethean cold storage components

InspiraFarms Batteries

InspiraFarms offers commercial TES batteries in Africa and Central America. According to InspiraFarm's product brochure[16],

> All units come equipped with a thermal storage backup system to provide a buffer

[16] See: http://www.inspirafarms.com/products/#

> against unreliable electrical grids and ensure active operation during power outages. Fully charged, the system will provide up to 48 hours of backup power, providing a lifeline for those in regions susceptible to grid failure, or usually dependent on diesel generators.

InspiraFarms' products include: cold rooms, pack houses and ripening chambers.

Growing Lithium-ion Battery Competition

TES batteries for refrigeration have advantages relative to conventional batteries (e.g. lead acid and lithium-ion). Current TES battery advantages when connected to mini-grids include lower cost than conventional battery back-up, low maintenance cost, reduced chemical toxicity/environmental impact and longer life. It is important to recognize, however, that conventional lithium-ion battery storage costs are expected to drop significantly and this cost reduction may make TES battery technology less competitive in the future. According to a December 2019 announcement by Bloomberg New Energy Finance (BNEF)[17]

> Battery prices, which were above $1,100 per kilowatt-hour in 2010, have fallen 87% in real terms to $156/kWh in 2019. By 2023, average prices will be close to $100/kWh.

This dramatic price decline is shown in Figure 4.

[17] See: https://about.bnef.com/blog/battery-pack-prices-fall-as-market-ramps-up-with-market-average-at-156-kwh-in-2019/

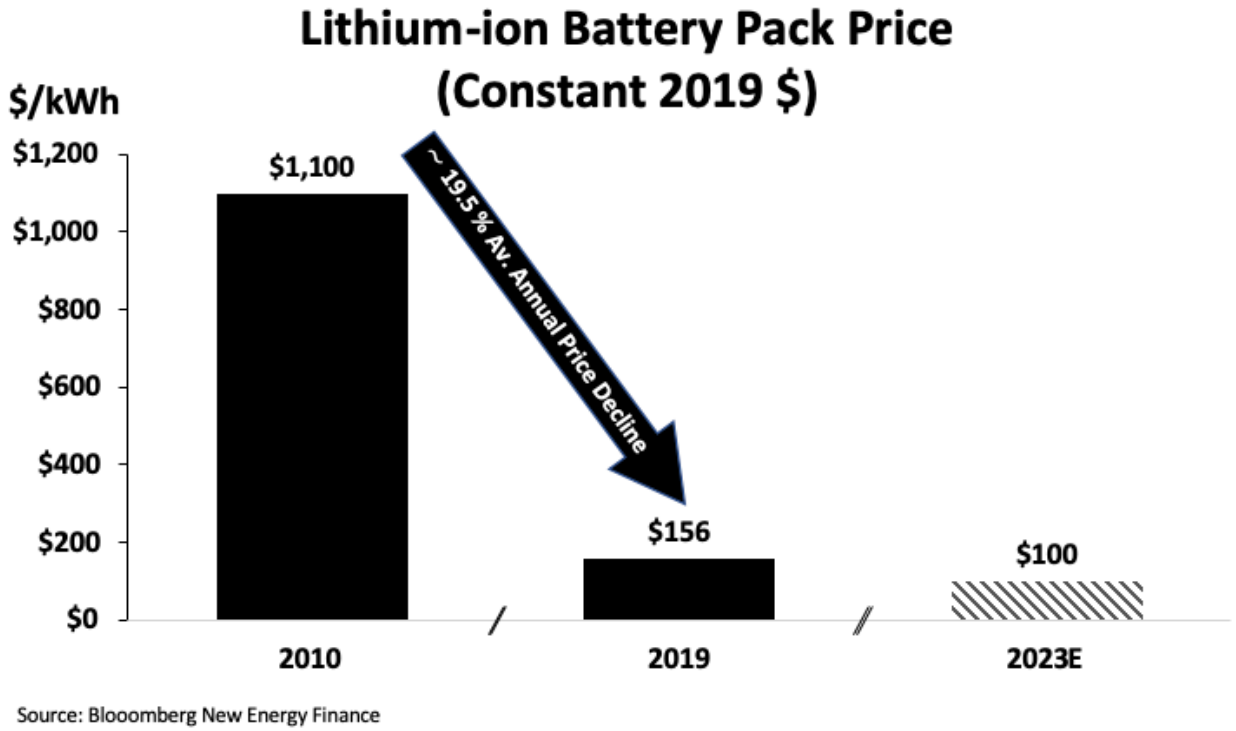


figure 4
Lithium-ion Battery Pack Price Trends

Given the above cost trends, there is a need to determine breakeven conventional battery storage cost relative to TES battery energy storage cost per kWh for various number of hours of battery storage. Knowing breakeven lithium-ion battery cost as well as battery cost reduction trends would improve future mini-grid feasibility study analysis.

Research Rationale

As previously discussed, addition of TES batteries could enable fuller use of intermittent electricity supplying rural mini-grids. Thus, research documenting the incremental benefit of adding TES batteries in conjunction with mini-grid generation and distribution management technology such as Modularity Grid is warranted.

A summary of the status quo relative to the proposed investment scenario to be evaluated is provided in Table 1. The table also summarizes potential benefits of adding TES batteries to a mini-grid. These benefits relate to the fact that of TES battery charging enhanced with Modularity Grid technology could potentially lower overall micro-grid electricity costs while providing more affordable electricity for both household customers as well as much needed refrigeration in rural areas served by micro-grids in developing countries.

table 1. Status Quo vs. Proposed Investment Scenarios to be Evaluated

Status Quo vs. Investment Scenario to be Evaluated	Sources and management of Intermittent Electricity	Price and Use of Intermittent Electricity	Potential Incremental Benefits of Adding TES Batteries
Status Quo	Solar, wind, diesel generation.	1) Price of electricity to serve residential customers and conventional anchor loads requiring constant power. 2) Assume conventional lead-acid, lithium-ion battery back-up.	**NA**
Investment Scenario to be Evaluated	Add grid management platform (e.g. Modularity Grid) to make fuller use of mini-grid intermittent electricity supply	Assume addition of commercial TES battery load and simulate mini-grid electricity price effect of adding TES batteries (and if necessary generation capacity) to serve commercial refrigeration anchor load.	1) Higher mini-grid capacity utilization, 2) Lower electricity cost 3) Increased commercial refrigeration availability 4) Reduced food losses and greater aggricultural output 5) Greater availability of refrigeration for healthcare

Given the above potential incremental benefits of adding TES battery load, further study regarding the benefits of increased integration of TES batteries with Modularity Grid is warranted – considering current and expected future cost of TES batteries relative to conventional lithium-ion batteries. Research regarding the potential future competition between TES and lithium-ion batteries and benefit of this research is summarized in Table 2.

table 2. Questions Regarding Long-term Conventional vs. TES Battery Competition	
Questions	**Potential Benefit of Research**
1. What's the breakeven cost of lithium-ion vs. TES Batteres?	Greater certainty regarding long term viability of TES batteries relative to lithium-ion batteries
2. Will lower cost lithium-ion batteries make TES batteries obsolete? If so, when?	

Case Study and Next Steps

Assuming the simulation described in Table 1 demonstrates positive net benefits of combining a grid management system with incremental TES battery load it is proposed that a case study be conducted to evaluate the incremental benefit of adding and operating a Modularity Grid platform to an existing micro-grid with unexploited electricity supplied by intermittent electricity from solar or wind electricity generation. The system should include conventional anchor loads and be lacking:

- An electricity management system such as the Modularity Grid
- A TES battery anchor load such as a Promethean Power Systems or InspiraFarms cold storage system able to productively use intermittent electricity supply.

The intent of the study would be to evaluate the incremental benefit of adding an electricity management system as well as TES battery anchor load such as a Promethean Power System or InspiraFarms cold storage system able to make productive use of the intermittent electricity supply.

Assuming the marginal cost of supplying electricity to the commercial TES battery customer enables the owner of the TES battery refrigeration customer to earn a competitive return on investment, the incremental benefit metric would be measured in terms of the decline in the average cost of electricity resulting from increased percentage use of previously unexploited

electricity. The incremental benefit would then be compared with the incremental cost of adding the electricity management system. Assuming benefits are greater than the costs, information collected from this case study could be used to accelerate investment in both micro-grid management systems in conjunction with much needed cold storage systems using TES batteries.

Finally, information collected from the above case study could be used to answer the question regarding breakeven lithium-ion battery cost per stored kwh relative to the cost of TES batteries. This cost could then be compared with forecast cost of lithium-ion batteries to determine if or when TES batteries would likely be replaced by lithium-ion batteries.

Biography

John Wehner is with Wehner Consulting, The Villages, Florida. He has Masters Degrees from the Harvard Kennedy School of Government and the MIT Sloan School of Management. He is a Chartered Financial Analyst (CFA) and has lectured in Kenya and Haiti with Cambridge Resources International, Inc. Before moving to the Villages Mr. Wehner worked 26 years with NextEra Energy, Inc. in Juno Beach, Florida. NextEra Energy is the world's largest producer of wind and solar energy.