Catalysing technology innovation in the off-grid market through appropriate product performance testing in the laboratory and field

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Abstract

Appliance efficiency presents a low-cost and often overlooked tool to expand energy access and deliver higher levels of modern energy services to un- and under-electrified households and communities around the world. The scale of the opportunity in the African context is significant, as over 108 TWh of electricity – nearly 18 % of Africa's total consumption in 2014 – could be saved annually by 2030 if governments and markets across Africa transitioned to more efficient lighting, refrigerators, air conditioners, and motors[1].

Refrigerators, in particular, hold unique potential to unlock economic and social progress for the billions of people living without reliable access to electricity globally. Refrigerators enable increased food security, increased access to markets, and decreased health risks relating to food consumption. However, refrigerators intended for use by off-grid consumers must be considerably cheaper and run on far less energy than current industry standard products. A deeper understanding of the unique performance and design considerations for off-grid refrigerators is therefore essential to catalyse necessary advancements in product design and accelerate market growth.

This paper presents an analysis of the performance of off-grid refrigerators based on data generated via laboratory and field-testing processes. The paper includes an introduction of an off-grid refrigerator performance testing methodology developed in support of the Global Lighting and Energy Access Partnership (Global LEAP) program. The test method was used to establish a foundational understanding of the performance of commercially available off-grid refrigerators as well as assess best-in-class products for the first ever Global LEAP Off-Grid Refrigerator competition. The paper then further explores the importance of conducting field-testing as a complement to lab-testing to assess the real-world performance of products tested in the lab using this methodology, and presents the results associated with an Innovation Cash Prize for Appropriate Design and User Experience.

It is observed that the energy consumption delta between lab and field testing is significant. Field testing provides some useful insights on consumer preferences, behaviour, and usage patterns and how these variables affect the technical performance of refrigerators. Analysis of these variables alongside technical performance data provides extremely valuable information that can be used towards innovation of the off-grid refrigerator market as well as contribute to continuous improvements and refinement of the off-grid refrigerator test method.

Introduction

The majority of appliances in use with solar home systems (SHS), being incumbents as used on the grid, have not been optimised for energy consumption. This results in the need for larger SHS, which increases the cost and reduces affordability – a major barrier to energy access among the un-electrified

1. United for Efficiency. (n.d.). Country Assessments. Retrieved February 19, 2019, from https://united4efficiency.org/countries/country-assessments/.

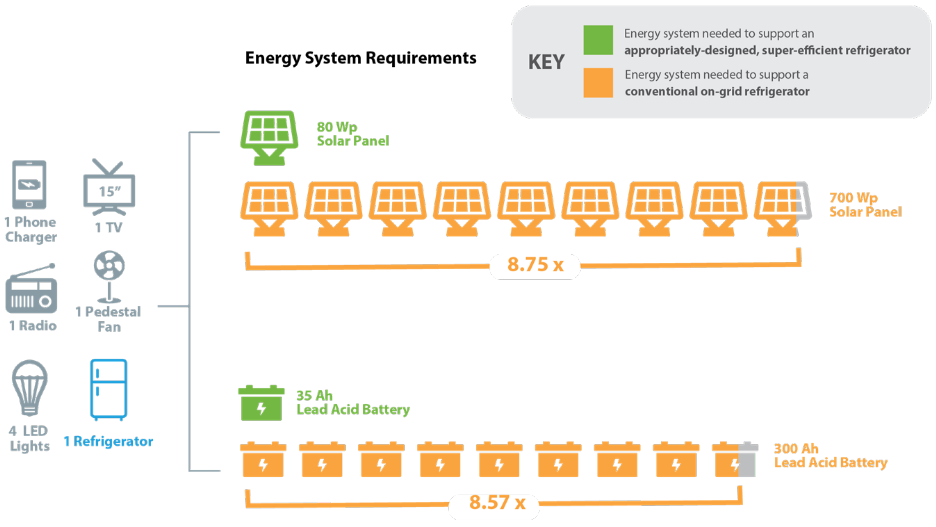

Figure 1. Energy system requirements for efficient vs conventional refrigerators.

poor[2]. Energy optimised appliances have the potential to deliver greater energy services at increasingly affordable prices.

Off-grid refrigerator typically refers to refrigeration powered by decentralized energy systems such as mini-grids, solar home systems, or solar modules with an associated energy storage mechanism. The need for energy storage and the means of the storage defines the two off-grid refrigeration categories currently in use:

Conventional: This is a typical compressor refrigerator[3] or refrigerator-freezer combination unit[4] powered by a solar photovoltaic system and stores electrical energy via a battery (typically lead-acid).

Direct drive: A battery-free solar refrigerator that stores energy by other mechanisms besides electrical energy storage in a battery. Typically, they include thermal energy storage in a phase change material, e.g. an ice bank.

Refrigerator demand continues to grow quickly and there is an increasing demand for refrigeration technologies at all scales.[5] A recent market survey indicated that refrigeration for household, commercial, and agricultural sectors was consistently ranked as top three in terms of potential consumer demand. The results underscore the unique potential for accelerating energy access and income generation for off-grid consumers.[6] Refrigerators traverse the home use vs business use divide. An off-grid refrigerator can be used as a household appliance for food storage and also as an income generating appliance for small-scale entrepreneurs to sell cold beverages.

2. Practical Action. (2018). Poor people's energy outlook 2018: Achieving inclusive energy access at scale. Practical Action Publishing. Retrieved February 19, 2019, from https://policy.practicalaction.org/policy-themes/energy/poor-peoples-energy-outlook/poor-people-s-energy-outlook-2018.

3. Refrigerators (denoted "R" in the following analysis): one or more fresh food compartments for the storage and preservation of unfrozen food and beverages.

4. Refrigerators-Freezer Combination Units (denoted "R-F"): at least one fresh food compartment and at least one freezer compartment.

5. Efficiency for Access. (2018). Off-Grid Appliance Market Survey: Perceived Demand and Impact Potential of Household, Productive Use and Healthcare Technologies. Retrieved February 19, 2019, from https://storage.googleapis.com/e4a-website-assets/Market-Survey-2018.pdf.

6. Ibid.

The impacts associated with home-use of refrigerators – such as reduced food loss, time saved in food buying and daily preparation, and increased dietary variations that lead to improved nutrition – are mirrored in refrigeration used in business-settings. In addition, sale of chilled and or frozen items represents an easy entry point for both home based and retail businesses.

An appropriately-designed DC solar refrigerator requires approximately a tenth of the energy delivery systems of a conventional refrigerator (Figure 1).

Although the off-grid refrigerator market is evolving with the development of innovative technologies, the sector remains nascent. For performance assessment, there is a lack of appropriate standards, test protocols, and easily available testing infrastructure for comparative evaluation of these technologies. To progress to efficient refrigerators, the first step has to be a thorough understanding of the current energy consumption and a comparative assessment for best-in-class products as a benchmark from which to suggest targets towards efficiency. The lack of a robust technical foundation in the evaluation of off-grid refrigerators limits competitive benchmarking, impeding moves towards efficiency and assured service delivery and therefore proven impact to the underserved.

Building technical foundation for off-grid refrigerator testing

GLOBAL LEAP AWARDS COMPETITION FOR OFF-GRID REFRIGERATORS

To address this market intelligence shortfall alongside interlinked market barriers, the Global Lighting and Energy Access Partnership (Global LEAP) Awards was launched in 2012[7]. The programme uses a competition-based approach to drive innovation in early stage technologies, while building valuable technical and commercial market infrastructure. By vetting appli-

7. Power Africa, DFID, and EnDev have all contributed to the Global LEAP Awards and/or RBF program administered by CLASP.

ances for quality and performance and identifying the world's best-in-class off-grid appliances, the Global LEAP Awards remains a singularly useful source of off-grid appliance performance data and market intelligence. Each Awards competition round (i.e. competition year) consists of a research and planning phase before the launch, followed by product testing by accredited laboratories for their energy performance, quality, and reliability, evaluation by a panel of off-grid market experts, and, ultimately, an announcement of winners and dissemination of product information[8].

The inaugural Global LEAP Awards competition took place in 2013 for off-grid LED room lighting and TVs. Since the inaugural competition, two more rounds of the Global LEAP Awards have been run, following signals that the off-grid appliance market emerged as a critical piece of the larger global off-grid clean energy market. In 2015 (the second round), the Awards expanded to include TV and fan competitions, and in 2017 (the third round), TV, fan, and refrigerator competitions.

The 2016–17 Global LEAP Awards Off-Grid Refrigerator Competition was aimed at identifying and promoting the world's best off-grid refrigerators. The competition was focused on off-grid refrigerators designed for household or small retail application, and was open to commercially available, late-stage prototype products[9]. Of the 55 product nominations received, 20 models from 11 companies were identified as quality off-grid appropriate refrigerators and included in the published Global LEAP Buyer's Guide[10].

Refrigerators are more complex and energy intensive than anything now sold in the off-grid market at scale. As such, designing a Global LEAP competition for refrigerators presented a unique challenge as they are one of the most challenging off-grid appliances to design and develop to be both energy efficient and cost-effective. The off-grid markets for technologies from previous competitions – LED lights, fans, and TVs – are relatively mature[11]. These markets are reaching commoditization as new players continue to enter the market with innovations in technology and/or cost.

Given the nascent off-grid refrigerator market, to catalyse much needed technology and design improvements, a unique feature was added to the 2016–17 Global LEAP Awards Off-Grid Refrigerator Competition with inclusion of three $200,000 cash prizes for refrigerator products that demonstrated market-leading innovation in (1) Energy Efficiency, (2) Overall Value, and (3) Appropriate Design and User Experience[12]. Winners of the first two prizes were announced in January 2018 at the Global Off-Grid Solar Forum and Expo[13]. The winner of the third innovation prize was announced in November 2018 at the Unlocking Solar Capital Africa conference[14] following the conclusion of the Competition's field-testing process.

The aim of field testing was to demonstrate how these products perform in 'real life' conditions and provide information from end users about their experience using these products. Following the successful completion of the laboratory testing process in the Netherlands, two units of all eligible refrigerators were shipped from the testing laboratory to Uganda and installed in pre-selected entrepreneur shops. Market dynamics indicate that small retail buyers are the most likely early adopters of refrigeration technology, given both the high cost of the products and their potential to generate new revenue sources. The field testing was therefore selected to take place in retail shops. Development of the field-testing protocol and results from the process are discussed further in this paper.

OFF-GRID REFRIGERATOR LABORATORY TEST METHODS

Independent laboratory testing validates products' performance with reference to their energy efficiency and quality. Standardized test methods can be used to evaluate off-grid product characteristics, quality, and energy performance, thus enabling consistent product-to-product comparisons. However, currently there are very few test methods that are specifically designed to simulate off-grid environmental conditions and use cases and thus cannot provide a comprehensive evaluation of off-grid appliances.

Off-grid appliances, in many ways, use similar technologies, components, and design considerations to products used in developed on-grid markets. However, off-grid appliances are often used in rural areas in Sub-Saharan Africa and South Asia, where the ambient weather conditions tend to be extremely warm and humid. Because these appliances are often used with a solar PV and battery module, products are also exposed to voltage fluctuations, causing a higher failure rate[15]. The quality and durability of off-grid products are therefore extremely important considerations for off-grid consumers living in these regions, many of whom live in extreme poverty and have to invest a relatively large portion of their disposable income on solar systems or accompanying appliances. They also live in remote areas with almost no access to repair technicians or replacement components. When appliances stop working, most off-grid households cannot afford to repair or replace faulty products.

To enable improved comparisons of off- and weak-grid appropriate refrigerators, the Global LEAP Program developed a set of test methods to evaluate energy performance, quality, and durability of appliances used in off-grid and weak-grid settings. The

8. Global LEAP Awards. (n.d.). Retrieved February 19, 2019, from https://globalleapawards.org/.

9. Global LEAP Awards. (2016, September 20). 2016–17 Global LEAP Awards Competition Terns & Conditions. Retrieved February 19, 2019, from http://globalleap.org/s/Global-LEAP-Awards-2016-17-Off-Grid-Refrigerator-Competition-Overview-20-Sep-16.pdf.

10. Global LEAP Awards. (2017). 2017 Global LEAP Awards-Refrigerators. Retrieved February 19, 2019, from https://storage.googleapis.com/e4a-website-assets/Global-LEAP-Buyers-Guide-Refrigerators.pdf.

11. GOGLA estimates that over 7 million solar lanterns and multi-light systems were sold in 2017. Source: https://www.gogla.org/the-voice-of-the-off-grid-solar-energy-industry.

12. The prizes were sponsored by the U.S. Global Development Lab and DFID's Ideas to Impact program as part of their commitment to the Scaling Off-Grid Energy: A Grand Challenge for Development.

13. Energy for Impact. (2018, January 22). Official announcement of the winners of the first two Innovation Prizes. Retrieved February 19, 2019, from https://www.energy4impact.org/news/global-leap's-grid-refrigerator-competition-and-innovation-prize-winners-announced.

14. Efficiency for Access. (2018, November 8). Global LEAP Awards Announces Winner of Off-Grid Refrigerator Innovation Prize for Appropriate Design and User Experience. Retrieved February 19, 2019, from https://efficiencyforaccess.org/updates/global-leap-awards-announces-winner-of-off-grid-refrigerator-innovation-prize-for-appropriate-design-and-user-experience.

15. Times of India. (2015, May 23). Voltage fluctuation damages several electrical appliances. Retrieved February 19, 2019, from https://timesofindia.indiatimes.com/city/chandigarh/Voltage-fluctuation-damages-several-electrical-appliances/articleshow/47391929.cms.

Table 1. Off-grid refrigerator test method overview.

Test	Description	Ambient Conditions	Target Temperature
Steady-State Operation	Measure a product's energy consumption (in kWh per day) at specified ambient temperature and humidity conditions	+16 °C / +32 °C +43 °C +10 °C (for refrigerator-freezer combination units only)	Average temperature +4 °C
Pull-down	Measure the cooling time (in hours) of a product's of the fresh food compartment from the ambient condition to a specified target temperature	+32 °C	Stabilization < +4 °C
Autonomy	Measure the time (in hours) for which a product can maintain a specified range of temperature after a product is disconnected from the power supply	+32 °C	Test discontinue when > +12 °C
Voltage Fluctuation	Measure a product's performance at high (+20% of rated voltage) and low voltage (-10% of rated voltage) input	+32 °C	Average temperature +4 °C ± 0.5
Freezing Capacity	Measure the time for a product to freeze a specific amount of filling materials. Only applicable to refrigerator-freezer combination units.	+32 °C	Average temperature to -6 °C, -12 °C, -18 °C

off-grid refrigerator test method leverages existing international test methods – such as those by International Electrotechnical Commission (IEC)[16] and World Health Organization (WHO)[17] – that are commonly used to measure energy performance of on-grid refrigerators and off-grid vaccine refrigerators. These test methods, in some cases, are slightly modified to better enable the evaluation of specific "off-grid characteristics." For example, voltage fluctuation testing was based on the storage test in IEC 62552 and modified with high and low input voltages during the test.

Table 1 is an overview of the test method used to evaluate off-grid refrigerator performance in test laboratory settings. The test methods were developed through a rigorous research, consultation, and review process that included a working group of off-grid energy industry stakeholders, appliance manufacturers, policymakers, and test facilities. The test data used in the following analyses are measured based on the off-grid refrigerator test methods listed in Table 1.

FIELD TESTING PROTOCOL DEVELOPMENT

Given the lack of established field-testing criteria for off-grid refrigerators, the field-testing process was formulated to enable meaningful comparison across all competing products in the 2016–17 Global LEAP Awards Off-Grid Refrigerator Competition. The methodology was developed based on the hypothesis that, given the cost of off-grid refrigerator technologies is beyond the purchasing power of most rural off-grid households, the only practicable route to large scale adoption of this technology will be if the refrigerator is also used to generate income, thereby improving its affordability.

16. International Electrotechnical Commission. (2015, February 3). IEC 62552-1,-2,-3: 2015: Household refrigerating appliances – Characteristics and test methods. Retrieved February 19, 2019, from https://webstore.iec.ch/publication/21805.

17. World Health Organization. (2018, February 2). WHO/PQS/E003/RF05-VP.4: Refrigerator or combined refrigerator and water-pack freezer: Solar direct drive without battery storage. Retrieved February 19, 2019, from http://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/catdocumentation.aspx?id_cat=17.

Prior to the development of the methodology, a baseline study was conducted in the test location (Uganda) to validate the theorised use case. No sizeable sample size of off-grid refrigerator users could be surveyed due to the almost non-existence of this technology in Uganda at the time, therefore rural on-grid businesses with similar capacity refrigerators were surveyed as proxies for rural off-grid users. The result of the study validated the choice of the use case and guided the design of the field-testing protocol[18].

FIELD TESTING DESIGN AND IMPLEMENTATION

A total of 36 refrigerator samples were shipped from the testing laboratory in the Netherlands in December 2017 and installed in pre-selected small retail shops[19] in rural Uganda. Retail shops in the study typically sold bottled drinks as well as an assortment of fast-moving consumer goods. The introduction of the refrigerator marked the first time these retailers were able to offer chilled items in their shops.

Each entrepreneur received a refrigerator and accompanying SHS and batteries to power the appliance. Each entrepreneur was at liberty to determine what they stored in the refrigerator as long as it was directly linked to generating income for their shop. The refrigerators were mainly used to store bottled drinks and in some cases locally produced juices and milk. Qualitative and quantitative data was collected over a 3-month period.

Remote monitoring devices were used to gather the following technical performance data:

a. Internal compartment temperature (in degrees Celsius, to a resolution of 0.1 °C), at equal measuring intervals not exceeding 1 hr.

18. Ireri, M. (2017, November). Grid Powered Refrigeration for Productive Use: A Study of 172 micro-enterprises in Uganda to understand the case for off-grid appliances. Retrieved February 19, 2019, from https://www.energy4impact.org/file/1946/download?token=2Li0aJN0.

19. Home-based retails shops, typical in rural East Africa, are where the family resides in the same premises as the retail business they run (usually a general store).

b. Ambient temperate and relative humidity data (in degrees Celsius and %, respectively).

c. Instantaneous power consumption (in Watts, to a resolution of 0.1 W, at equal measuring intervals).

d. Accumulated energy consumption over every 24-hour period (in Watt-hours, to a resolution of 0.1 Wh).

e. Daily power available to the product from the solar home system/battery.

This technical data was backed by qualitative data collected through entrepreneur interviews administered by a team of trained field researchers. The aim of these surveys was to collect more nuanced feedback on perceived technical performance, ease of use of the technology, perceived value, and overall socioeconomic impact of this technology on first-time users.

The data collection process also included direct observation, particularly to determine changes in the number of customers and items sold in the shops that could be directly linked to introduction of first-time refrigeration.

The physical integrity and durability of the product was also assessed by recording the physical condition of the fridge through a visual assessment and recorded on a standard form, with photos as supporting evidence.

Off-grid refrigerator performance

RESULTS FROM LABORATORY TESTIN

Early in the evolution of the Global LEAP Off-Grid Refrigerator Competition, we undertook a product testing effort, using the newly defined test method, to establish a performance baseline for off-grid refrigerators available in the market as of mid-2016. The primary purpose of this effort was to develop a performance baseline that would inform the evaluation process for the innovation prize component of the 2016–17 Global LEAP Awards.

The laboratory testing was conducted in two phases:

1. **Baseline Testing:** Testing focused primarily on two common types of commercially available refrigerators. A total of 36 products were procured online, direct from manufacturers, and through field agents in off-grid areas. Among the 36 test samples, 24 were refrigerator-freezer combination units (67 %), and 12 were refrigerators only (33 %). Off-grid appliances were identified through a series of market scoping surveys, which collect basic product information such as brand and model names, product sizing, rated power consumption, and retail price. About 10 % of the products surveyed and identified from the retail markets were then randomly selected and procured from Tanzania and Guinea to undergo further performance testing according to the off-grid refrigerator test methods mentioned earlier. These products represent the options that rural off-grid customers have access to, and the performance of these products are defined as the off-grid refrigerator market baseline as of mid-2016. In this analysis, these are defined as "Baseline" products.

2. **Awards Testing:** A total of 55 products were nominated by 28 companies for the Global LEAP Awards. Among the 55 products, 20 products were selected as preliminary finalists and tested according to the same Global LEAP off-grid refrigerator test methods. Based on the test results and evaluation of expert judges, 5 Winners and 12 Finalists were identified across five size categories.[20] In this analysis, these Winners & Finalists are defined as "Awards" products.

The analysis on laboratory-tested performance results presented further in this paper are based on the test data from samples obtained through these two phases of laboratory testing.

Daily energy consumption at various ambient temperatures

Empirical analyses of on-grid refrigerators have shown that ambient air temperature is a key factor influencing energy consumption of refrigerators. Typically, a product's energy consumption increases as ambient temperature increases[21].

Steady state operation testing measures a refrigerator's energy consumption, in kWh per day, at specified ambient temperature and humidity conditions. To observe the difference in energy performance at different ambient conditions, steady state operation testing was conducted at low ambient (10 °C), medium ambient (16 °C), high ambient (32 °C), and harsh ambient (43 °C) temperatures. Figure 2 demonstrates the average daily energy consumption values of 36 baseline products, 5 Awards Winners, and 12 Awards Finalists, at various steady state ambient temperature conditions.

The data confirms that, as expected, the daily energy consumption of off-grid refrigerators increased as ambient temperature increased. The average value of daily energy consumption at 32 °C was 0.739 kWh/day, while the average daily energy consumption at 43 °C was 1.254 kWh/day – a 70 % increase. The data also indicated that off-grid refrigerators typically consume less energy than refrigerator-freezer combination units.

Results also show that for refrigerators, baseline products – the generic products that were available in the retail markets in 2016 – consume more energy than Awards Winners and Finalists. However, for refrigerator-freezer combination units, the difference between baseline and Awards products is minimal, especially in higher ambient temperatures. At 32 °C and 43 °C ambient conditions, results show that baseline products perform slightly better than Awards Finalists.

Energy efficiency

To compare refrigerator performance across various types and sizes, refrigerator energy efficiency index (EEI) is used in the following analysis. Refrigerator EEI is defined as units of surface area (meter square) per daily energy consumed[22]

20. Global LEAP Awards. (2017). 2017 Buyer's Guide for Outstanding Off-Grid Refrigerators. Retrieved February 19, 2019, from https://storage.googleapis.com/e4a-website-assets/Global-LEAP-Buyers-Guide-Refrigerators.pdf.

21. Lloyd Harrington. (2012, July). Investigation into Ambient Temperature Correction Formula for Steady State power Measurements -- IEC58M/35/CD Annex B.

22. Energy consumed per surface area (kWh/m^2) is used instead of energy per unit volume (kWh/m^3) to enable comparison of refrigerators and refrigerator-freezers of various sizes. Refrigerator heat gain is dictated by the surface area and not volume. The surface area is calculated as volume to the power 0.67. Source: Harrington L. (2015). Household Refrigeration Appliances: New Star Rating Algorithm Proposal for the IEC Test Method. Resource document. Energy Efficient Strategies for the Department of Industry, Innovation and Science. http://www.energyrating.gov.au/document/report-household-refrigeration-appliances-new-star-rating-algorithm-proposal-iec-test. Accessed June 2018.

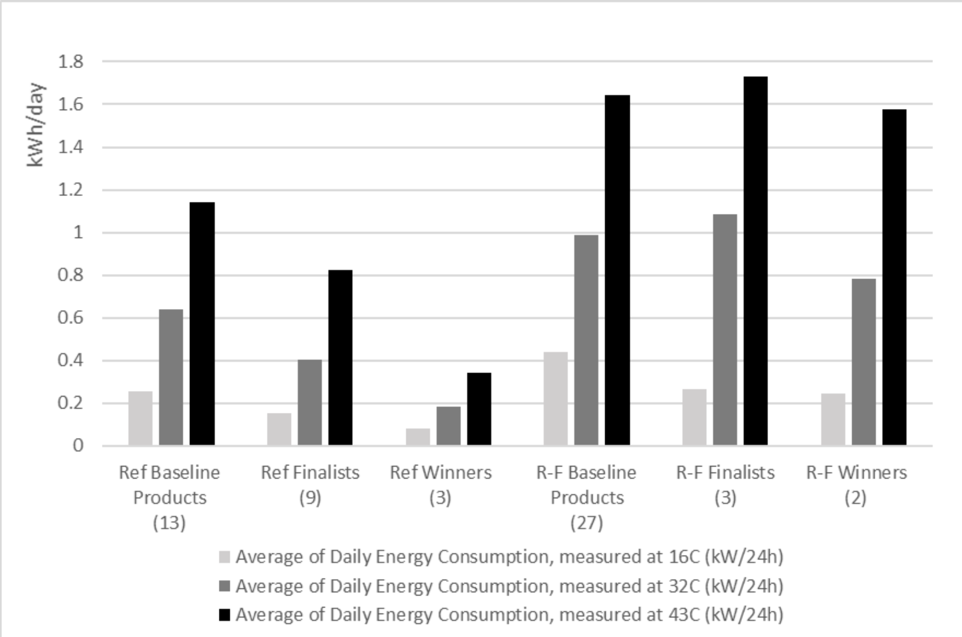

Figure 2. Average Daily Energy Consumption by Refrigerator Type and Sample Type.

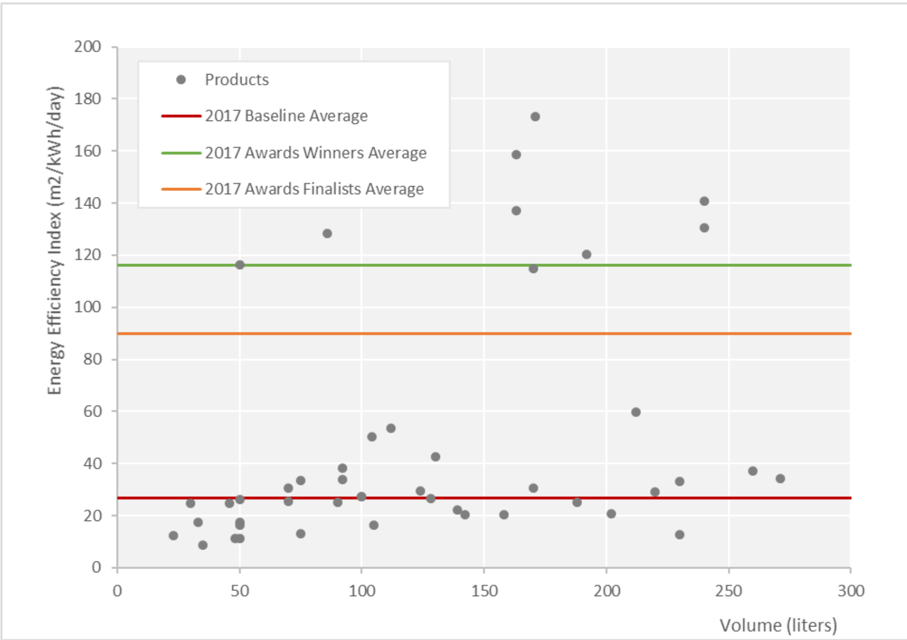

Figure 3. Off-Grid Refrigerator Energy Efficiency Trends – Comparing Average Efficiency of Baseline and Awards Products.

(kWh per day, measured at 32 °C ambient temperature) – m^2/kWh/day. The higher the EEI, the more efficient the refrigerator.

Results indicate that efficiency values vary significantly across the refrigerators tested and a significant gap exists between baseline and Awards products. The worst performing refrigerator in the dataset uses 19 times more energy per unit surface area than the most efficient refrigerator tested (Figure 3). On average, the efficiency of baseline products is 28 m^2/kWh, while the average efficiency is 57 m^2/kWh for Global LEAP Awards Finalists and 84 m^2/kWh for Awards Winners – representing a 92 % and a 114 % efficiency improvement compared to the baseline average, respectively.

Other performance metrics

Refrigerator autonomy – the ability to keep a sealed refrigerator compartment cool without input of power – is one of the refrigerator characteristics most valued by consumers living in off- and weak-grid environments with highly constrained and/or intermittent electricity supply[23]. To customers, refrigerators with longer autonomy represent a lower risk of having spoiled food or warm beverages in the event of power outage. In Ugan-

23. Ireri, M. (2017, November). Grid Powered Refrigeration for Productive Use: A Study of 172 micro-enterprises in Uganda to understand the case for off-grid appliances. Retrieved February 19, 2019, from https://www.energy4impact.org/file/1946/download?token=2Li0aJN0.

Table 2. Autonomy and pull-down performance.

	Autonomy (hours)	Pull Down (hours)
Average of baseline products	1.0	2.4
Average of Awards Winners & Finalists	2.8	1.1

da, customers often believe that better autonomy means lower energy costs because they can switch off refrigerators overnight to save energy and expect their food and beverages to stay cold[24]. In the Global LEAP test method, autonomy is a measure of the time it takes the temperature within a refrigerator compartment to rise from 4 °C to 12 °C with no external power supply. The results, as seen in Table 2, indicate that baseline products can stay cold for an hour on average, while Awards Winners & Finalists' autonomy is 2.8x longer than baseline products.

Pull-down testing measured the time required to lower the temperature of a refrigerator compartment from ambient temperature (32 °C) to a desired cooling temperature (4 °C). A shorter pull-down time means a refrigerator can cool a compartment to a target temperature faster. Data indicates that Awards Winners and Finalists take less than half of the time that baseline products required to cool down to a desired temperature.

Refrigerators that are intentionally designed for the off-grid and weak-grid environment, like those identified through the Global LEAP Awards, often use thicker cabinet insulation than baseline products, one of the key factors contributing to better thermal management in both tests.

Voltage fluctuation testing was performed to verify whether the refrigerators can sustain over-voltage condition, defined as 20 % increase of the rated voltage, and under-voltage condition, defined as 10 % decrease of the rated voltage. The majority of refrigerators were able to continue functioning under these conditions – with a few models that are designed to start at the exact rated voltage.

Freezing capacity testing measures the time, in hours, required to lower temperature of a compartment to -6 °C, -12 °C and -18 °C target temperatures at 32 °C ambient temperature. -18 °C is the recommended freezer temperature by the International Institute of Refrigeration and other national bodies like the US Food and Drug Administration and the European Commission.[25] However, during testing, we observed a high failure rate for the refrigerator-freezer combination units in all products tested including both baseline and awards products: 61 % of all tested products, could not reach -6 °C and 83 % failed to reach -18 °C. For Awards products, there are five refrigerator-freezer combination units and freezing capacity, time required to reach -6 °C, ranges from 6.1 to 12 hours. The results indicate that the majority of the products would not be able to keep food in a frozen condition at 32 °C ambient temperature and that the average freezing performance of refrigerators requires considerable improvement.

24. Ibid.

25. US Food and Drug Administration. (2018, April 6). Are You Storing Food Safely? Retrieved February 19, 2019, from https://www.fda.gov/ForConsumers/ConsumerUpdates/ucm093704.htm.

The Global LEAP off-grid refrigerator test method is the first attempt to evaluate off-grid refrigerators and provide performance data that is repeatable, consistent, and comparable. Despite best efforts to simulate off-grid conditions, it is later found through field testing that the daily energy consumption data from the lab-testing is significantly lower than the average actual energy consumption observed in the field. These results are discussed further in the following sections. Field testing is a necessary complement to laboratory testing to help understand consumer behavior and usage patterns and the observations from the field testing can be used to strengthen the laboratory test methods.

RESULTS FROM FIELD TESTING

Energy efficiency and retail price

Price sensitivity is a key characteristic of off-grid consumers, hence striking a balance between efficiency and price is a critical business consideration for market actors in the off-grid sector. Figure 4 provides an overview of efficiency values and retail price of field tested products. The grey bars represent the energy efficiency values, and the black dots represents retail prices (in Euros). The black trend line shows the correlation between these two metrics.

The analysis indicates that: (1) the price of refrigerator products varies considerably amongst all refrigerator types, (2) there is no clear link between energy efficiency and price, and (3) small refrigerators/refrigerator-freezer combination units tend to be the least efficient products.

Field vs Lab Testing Performance Comparison

ENERGY CONSUMPTION

The power consumption of a given refrigerator depends on the refrigerator settings, amount of refrigerant used, speed regulations of the compressor, as well as the relative humidity (RH) and ambient temperature of the location. In lab tests, these metrics are standardized or controlled for to enable direct comparison of refrigerator performance. As previously mentioned, one of the key tests performed in the lab is the steady-state operation, which measures a product's energy consumption (in kWh per day) at specified ambient temperatures and humidity levels.

Figure 5 compares the product's daily energy consumption as measured under high ambient conditions (+32 °C/RH 75 %) in the lab compared with the product's recorded average daily energy consumption as collected by remote monitors in the field. Due to a variety of technical issues with originally sourced meters, though desired, the following data was not collected for the entire duration of the field test: Internal compartment temperature, Ambient temperature, Relative humidity. Instantaneous baseline temperature and humidity readings collected at the start of the field-testing exercise however indicate that these products were operating at an average baseline temperature of 27 °C and humidity of 69 %.

The graph indicates that most products included in the study consume significantly more energy when operating in the field. One reason for this is that the refrigerators deployed in this study are primarily being used to cool beverages. Entrepreneurs will try to maximize the utility of their refrigerators by filling them to capacity with drinks. Throughout the day, they will take out cold drinks and re-fill the fridge with much warmer drinks to replace those being sold. This cycle of constant replacement greatly affects the power consumption of the refrigerator, as well as the amount of time needed to cool down drinks.

The graph also indicates that there are already a few efficient off-grid refrigerators whose daily energy consumption is, as expected, lower when operating at temperatures below high ambient temperature. While more field testing is required to better understand environmental conditions and usage patterns and how these affect power consumption, qualitative feedback collected from entrepreneurs indicates that predictable performance is an important requirement for an off-grid appliance. The following section focuses on two possible negative impacts of unpredictable refrigerator behavior.

IMPACT OF INCREASED ENERGY CONSUMPTION IN THE FIELD

Figure 5 shows that medium and large refrigerators in particular require much larger energy systems to operate than anticipated, consuming on average 124 % and 80 % more energy respectively. This variance in energy consumption between lab testing and field observations has significant implications for energy system sizing. If 24-hour operation is needed, these units would need to be installed with much larger PV and battery systems, which in turn means a greater total cost of product for the end consumer.

The potentially incorrect sizing of PV units and batteries has secondary implications on service delivery for the end con-

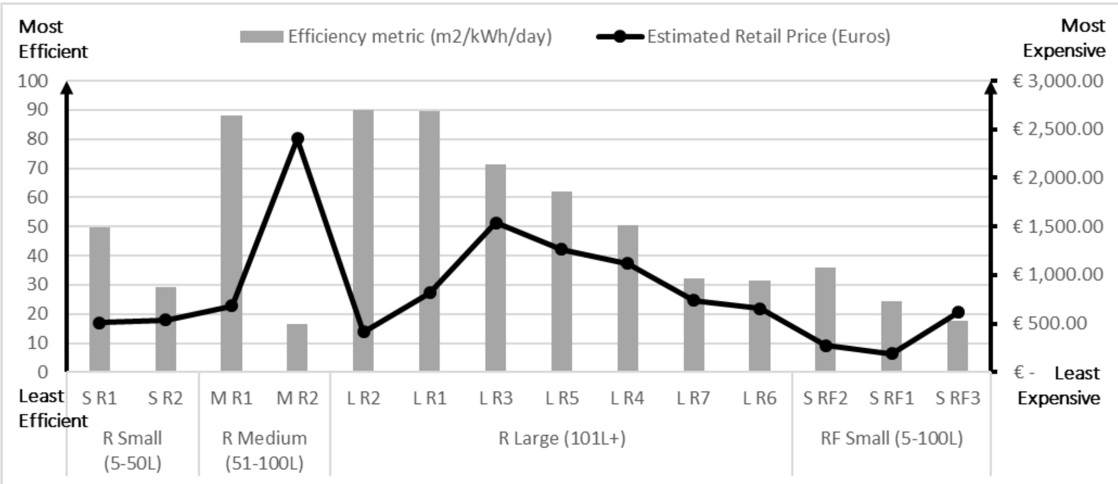

Figure 4. Efficiency metric vs retail price by refrigerator size.

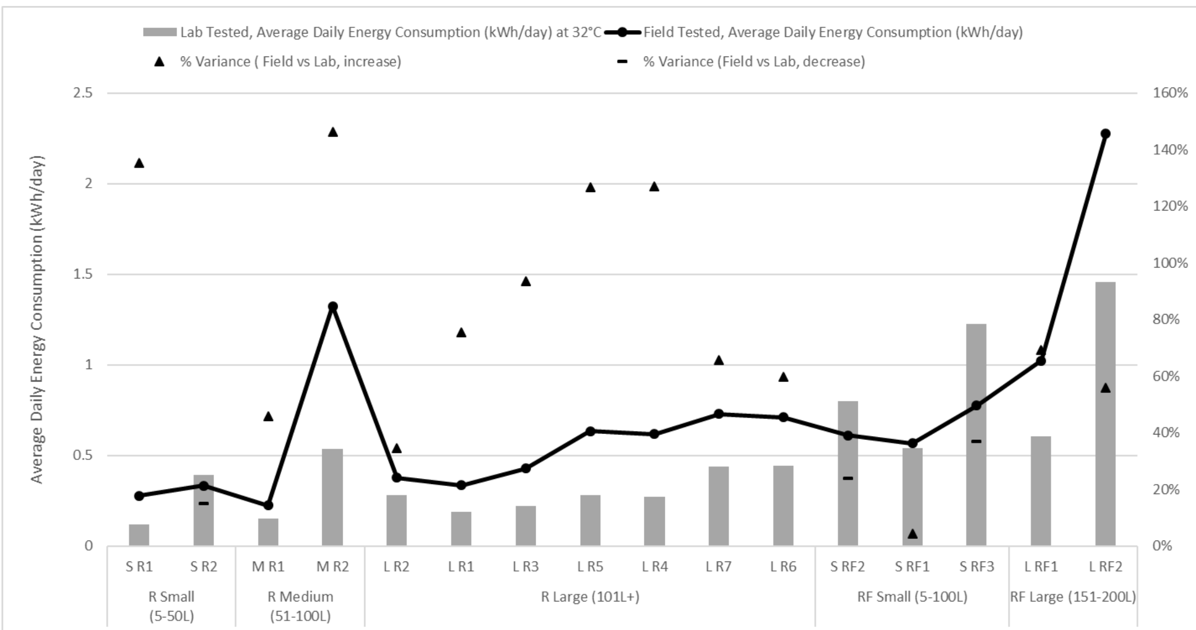

Figure 5. Average daily energy consumption – field vs lab.

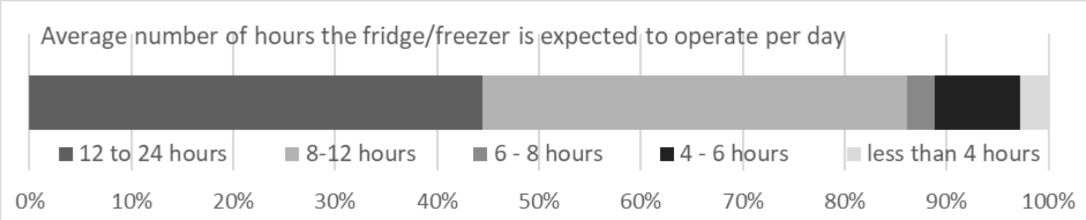

Figure 6. Average expected operational hours per day.

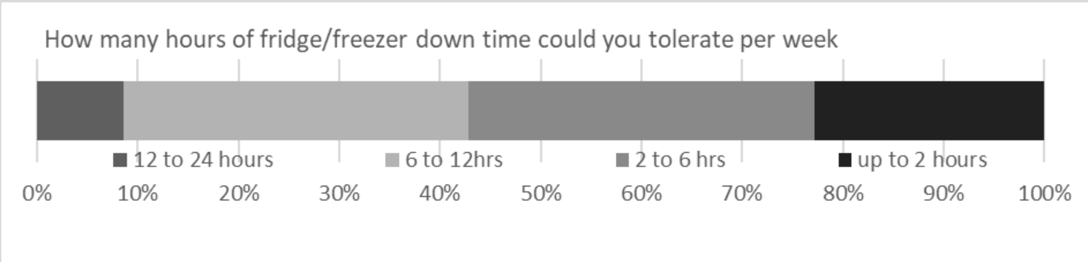

Figure 7. Average tolerable fridge outage hours/week.

sumer. In our field test sample, approximately 85 % of users expected a refrigerator be operational for between 8 to 24 hrs per day, see Figure 6, and more than 50 % could tolerate no more than 6 hours of down time a week, which translates to less than one hour a day, see Figure 7.

Incorrectly sized energy delivery systems would compromise service delivery by increasing operation down time. Given the extremely low outage tolerance of users, additional downtime could damage trust in this nascent technology, limiting adoption and follow on market growth.

LIMITATIONS OF CONDUCTING AUTONOMY AND PULL DOWN PERFORMANCE TESTING IN THE FIELD

While the lab-tested performance metrics on autonomy and pull down provide useful insight into how well the refrigerators maintain a range of desirable temperatures, these tests are challenging to conduct through field testing as they require robust and reliable equipment to monitor the compartment temperature accurately. An attempt to couple both energy and environmental sensing into one monitor resulted in severe technical malfunctions of the devices during the Global LEAP field test. Availability of top tier devices that combine energy and environmental monitoring, specifically for high current DC application at a reasonable cost, in East Africa, has proven to be a challenge. The monitoring solution used was an attempt at demonstrating local innovation towards this much needed solution. The challenges encountered led to inaccurate and inconsistent temperature and humidity data which was discounted from further analysis. The authors of this paper recognize that this is an area that can be improved upon in future refrigerator field testing projects.

Conclusion

This paper provides a summary of off-grid refrigerator laboratory and field test results and includes a variety of analyses focusing on key refrigerator performance metrics. The information included here, while not exhaustive, constitutes the most extensive effort to date to understand the energy performance and service delivery of commercially available off-grid refrigerators at an early stage of the market's development.

Field testing is a topic of growing importance for off-grid refrigerator market development. The paper underlines the importance of conducting complementary lab-testing and field-testing to develop a comprehensive picture of off-grid refrigerator performance. The controlled laboratory testing process delivers consistent performance data that enables product-to-product comparison, while field testing factors in different use cases and user behaviours to deliver critical insights into durability and product performance. This is especially important for off-grid appliances, since in many cases, consumer use cases and preferences are not well understood.

Initial observations of the variance in performance of refrigerators in the lab and field points to the need to extend the research to include larger sample sizes that will help quantify the energy consumption delta between lab and field testing and unpack its likely causes. One potentially unexplored impact of the delta in energy consumption in the lab and field could be the increased inability to conduct energy performance tests in the lab that will provide reliable information on expected product performance in the field. Reliable tests are necessary to protect consumers by holding manufactures accountable to a "truth in advertising[26]" standard of sorts. In addition, improperly sized energy systems for refrigerators could lead to dissatisfaction of consumers and damage their confidence in this nascent technology.

Much more consumer research is needed to understand off-grid refrigeration use cases and consumer behaviour and how these affect the overall performance of the refrigerators. Such research would lead to improvements not only to laboratory test procedures, but also to the design of products that offer expected service delivery, growing the market for this crucial appliance.

26. Lighting Global. (n.d.). Our Standards. Retrieved February 19, 2019, from https://www.lightingglobal.org/quality-assurance-program/our-standards/.