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EVALUATING APPLIANCE PERFORMANCE IN THE FIELD

RESULTS FROM REFRIGERATOR TESTING

APRIL 2023

EFFICIENCY FOR ACCESS COALITION

This field-testing report is one in a series of user insight publications (refrigerators, solar water pumps and milking machines) focusing on assessing the performance of solar-powered appliances in off- and weak-grid settings, in this case direct current refrigerators. The field testing was conducted in Rwanda and India to evaluate the impact of use cases and user behaviour on refrigerator performance. The performance data was complemented by user feedback gathered via baseline and end-line surveys of more than 40 participants. The aim of the report is to provide user-centric insight for refrigerator manufacturers, distributors and other stakeholders engaged in the cooling sector. The report ends with a list of recommendations to improve user satisfaction and enable laboratory testing to better reflect conditions in the field.

This report was developed by Energy Saving Trust and CLASP, on behalf of the Low Energy Inclusive Appliances programme, the flagship initiative of the Efficiency for Access Coalition.

Efficiency for Access is a global coalition working to promote high performing appliances that enable access to clean energy for the world's poorest people. It is a catalyst for change, accelerating the growth of off-grid appliance markets to boost incomes, reduce carbon emissions, improve quality of life, and support sustainable development. Efficiency for Access consists of 20 Donor Roundtable Members, 19 Programme Partners, and more than 30 Investor Network members. Current Efficiency for Access Coalition members have programmes and initiatives spanning 62 countries and 34 key technologies. The Efficiency for Access Coalition is coordinated jointly by CLASP, an international appliance energy efficiency and market development specialist not-for-profit organisation, and UK's Energy Saving Trust, which specialises in energy efficiency product verification, data and insight, advice, and research. The Coalition is co-chaired by UK aid and the IKEA Foundation.

Survey and performance data collection was managed by EED Advisory. EED Advisory is a multidisciplinary Pan-African consulting firm offering technical, analytical and advisory services in energy, water and climate change. In addition to survey and performance data gathering, EED Advisory also led on data analyses and contributed towards the creation of this report.

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TABLE OF ABBREVIATIONS

A	Ampere
AC	Alternating Current
CAPI	Computer Assisted Personal Interviewing
DC	Direct Current
GMT	Greenwich Mean Time
GSM	The Global System for Mobile Communications
L	Litres
LEIA	Low Energy Inclusive Appliances
PAYG	Pay-as-you-go
PURE	Productive Use of Renewable Energy
PV	Photovoltaic
RMM	Remote Monitoring Module
SD	Secure Digitally
SME	Small and Medium-Sized Enterprise
TV	Television
UVLO	Undervoltage Lockout
V	Volt
Wh	Watt Hour
°C	Degrees Celsius

1. INTRODUCTION

1.1 Project background

Refrigerators deployed in off-grid areas can have a significant impact on people's lives and livelihoods, particularly in rural areas without reliable electricity grids where access to cooling tends to be low. Off-grid refrigerators have the potential to improve the quality of life via food waste reduction, diet improvements, time savings and additional income generation for small and medium-sized enterprises (SMEs). Notably, refrigerators were ranked second in the development impact rankings of household appliances for women (with only lighting being more impactful), and sixth for men,[1] which highlights the importance of off-grid refrigeration roll-out on gender equality.

Solar-powered refrigerators continue to improve in performance and reduce in cost according to laboratory testing and market insights.[2] However, 'real-life' performance data and feedback gathered directly from the users[3] are rare. Combining user data and performance data from field testing is one way to close this knowledge gap and inform appliance manufacturers and distributors what works well and what needs to be improved.

Until recently, solar-powered refrigerators had been used primarily by health centers in off- and weak-grid areas[4] to preserve vaccines. Due to the technology improvements and cost reduction of solar photovoltaic (PV) panels, batteries and refrigeration units themselves, standalone solar-powered refrigerators have started to penetrate the household and productive use of renewable energy (PURE) markets. Many entrepreneurs and SME owners are now starting to use solar-powered refrigerators to sell cold beverages as a way to generate additional income and to improve their livelihoods.

Off-grid refrigerators remain fairly nascent and have had limited uptake by consumers to date - less than 3,000 off-grid refrigerators from affiliated manufacturers were sold in the first half of 2022, which is significantly lower compared to other appliances such as fans, televisions, radios or solar water pumps.[5] Therefore, user feedback can be highly beneficial for manufacturers and distributors to understand the needs and expectations from end-users. For programmes like Low Energy Inclusive Appliances (LEIA), where one of its activities is focused on designing test methods and quality standards, the user insights are valuable to improve performance measurements so that the results are reflective of the real field conditions. Performance and user insights from field testing are also valuable when it comes to improving design, identifying use cases, estimating impact on income, evaluating after-sales services and reflecting on user awareness needs to allow for smooth operations.

1.2 Objectives and scope

This project involved field testing of solar-powered refrigerators in India and Rwanda. The field testing was conducted during a 6-month period, and followed guidance outlined in the Efficiency for Access reports: *Designing and implementing field testing for off- and weak-grid refrigerators*,[6] and *Field testing of appliances suitable for off- and weak-grid use - Generic guidance on appliance performance monitoring in the field*.[7]

The main objective was to understand how end-users interact with the refrigerators over time and consequently strengthen an evidence base around:

1. Measurement and evaluation of how the refrigerators perform in the field (real-world environments)
2. Assessment of the interaction between end-users and the refrigerators and the associated impact
3. Recommendations and lessons learned to guide future field testing projects
4. Recommendations to outline suggested adjustments to laboratory testing to better reflect field conditions.

Usage patterns and technical performance of the refrigerators were gathered from retrofitted remote monitoring modules. During this monitoring period, we also collected data on user behaviour, preferences, and impacts. User data was collected in two rounds of surveys (baseline and endline).

1.3 Methodology

1.3.1 Performance data collection via remote monitoring modules

We collected performance data from remote monitoring modules (RMMs), which were installed within the refrigerator electrical systems, and self-reported user data via in-person surveys. The RMM was a plug-and-play remote monitoring device specified for direct current (DC) power systems. The RMM design allowed for real-time measurements of power consumption and other performance indicators via integrated sensors with local storage

1 Efficiency for Access. 2020. Off-Grid Appliance Market Survey. https://storage.googleapis.com/e4a-website-assets/CLASP-MarketSurvey-2020-final.pdf
2 Efficiency for Access. 2021. 2021 Appliance Data Trends. https://storage.googleapis.com/e4a-website-assets/2021-ApplianceDataTrends.pdf
3 "Users" in this report include refrigerator owners as well as any other users that interacted with the refrigerators (including family members and employees). This encompassing term was selected to reflect the fact that performance data was affected by various refrigerator users and interviews were conducted with users who were not necessarily the refrigerator owners
4 Areas that are connected to unreliable centralised electricity grids with frequent power outages
5 GOGLA. 2022. Global Off-Grid Solar Market Report: Semi-Annual Sales and Impact Data. https://www.gogla.org/sites/default/files/resource_docs/gogla_sales-and-impact-reporth1-2022_def_2.pdf
6 Efficiency for Access. 2022. Designing and implementing field testing for off- and weak-grid refrigerators. https://storage.googleapis.com/e4a-website-assets/Designing-and-Implementing-Field-Testing-for-Off-and-Weak-Grid-Refrigerators.pdf
7 Efficiency for Access. 2022. Field Testing of Appliances Suitable for Off- and Weak-Grid Use - Generic guidance on appliance performance monitoring in the field. https://efficiencyforaccess.org/publications/field-testing-of-appliances-suitable-for-off-and-weak-grid-use

on a Secure Digitally (SD) card and upload of data to an online platform using The Global System for Mobile Communications (GSM) network as indicated in Table 1.

Table 1: RMM monitored parameters

	Refrigerator
Energy parameters	Voltage (up to 60 VDC)
	Current (up to 15 A)
	Power (calculated)
	Timestamp (GMT)
Refrigerator-use parameters	Ambient temp (-55°C to 125°C)
	Refrigerator temp (-55°C to 125°C)
	Ambient humidity (relative %)
	Door opening (binary)
Data handling parameters	SD card data
	GSM network

The RMM was designed to transmit data to the Kaiote online platform through available GSM networks. The Kaiote dashboard intended to incorporate data from the RMMs across both sampled countries for analysis and visualisation. However, the online platform was not used during the field testing due to connectivity issues. The performance data was collected during the endline survey by retrieving the SD cards instead. Further information about RMM design can be found in the Efficiency for Access *Evaluating appliance performance in the field report*.[8]

1.3.2 User data collection via surveys

We conducted two in-person interviews with each refrigerator user in India and Rwanda to gather their feedback on the appliance performance and the impact it has had on their livelihoods (most refrigerators were used for income-generating PURE purposes). The surveys comprised of a combination of quantitative (eg on a scale of 0-10, how likely were they to recommend the refrigerator to a friend?), and open-ended questions (e.g. what items were stored in the refrigerator?). This approach allowed us to evaluate user experience, while enabling users to share information without introducing bias.

The household survey was carried out in-person by enumerators using Computer Assisted Personal Interviewing (CAPI), which allows the interviewer to use an electronic device to upload answers to the questions. The first interview (baseline) was conducted at the time of installation of the RMM, and the second interview (endline) during retrieval of the RMM at the end of performance data collection. CAPI allowed for the timestamp (time when the survey was completed), geolocation, and pictures of the deployment to be monitored and recorded. Local enumerators received training on administering the survey in each country so that they are aware of the critical parts of the survey and the socio-cultural dynamics in the user locations.

1.4 Target countries and technology

We selected India and Rwanda to observe refrigerators being used in different climates and by users in different cultural contexts. Participating users in each country were identified by in-country partners (ie refrigerator distributors). Each in-country partner recruited new users who had recently purchased a solar-powered refrigerator. In total, 42 refrigerator owners participated in the field testing (20 in India and 22 in Rwanda) as outlined in Table 2.

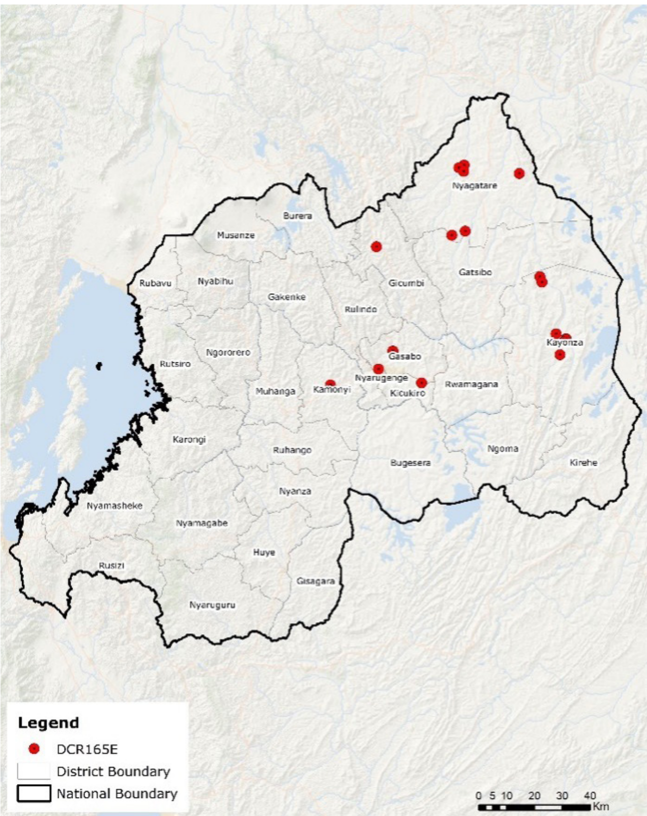
Table 2: Refrigerator type and manufacturer per country

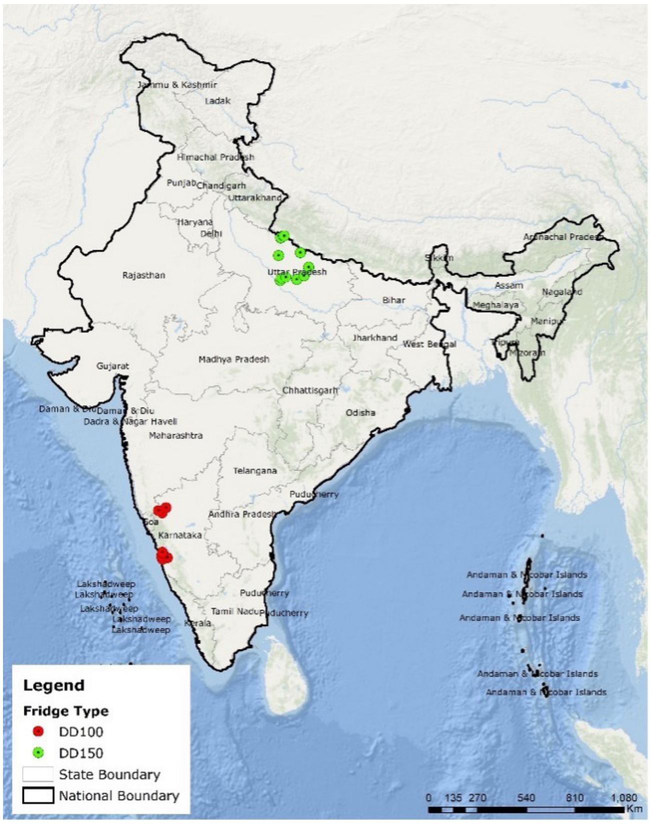
Country	Participating users	Refrigerator type	Volume of the fresh food compartment (litres)
India	20	8x DD100[9]	86
		12x DD150[10]	127
Rwanda	22	22x DCR165E[11]	163
Total	**42**		

The aim was to select refrigerators in various geographical areas to assess how climatic conditions influence use cases and performance. In India, two types of refrigerators were deployed in two distinct regions. Smaller (DD100) refrigerators were located in Karnataka and larger (DD150) refrigerators were located in Uttar Pradesh. Only one refrigerator type was deployed in Rwanda (DCR165E). The Rwandan climate is generally more uniform compared to India. Sensors attached to the refrigerators in Rwanda recorded external temperatures around the refrigerator at between 16 °C and 40 °C and humidity between 27% and 85% across the 22 refrigerators. The refrigerators in India had to operate in more extreme conditions (temperatures ranged between 22 °C and 48 °C, and humidity between 23% and 87%).[12] Figure 1 shows the locations of the field-tested refrigerators in India and Rwanda.

8 Efficiency for Access. 2021. Evaluating Appliance Performance in the Field: Results from Beta Testing of Remote Monitoring Solutions. https://storage.googleapis.com/e4a-website-assets/Evaluating-Appliance-Performance-in-the-Field-Results-from-Beta-Testing-of-Remote-Monitoring-Solutions.pdf
9 VeraSol. 2022. Devidayal DDSF-100. https://data.verasol.org/products/ref/devidayal-solar-solutions8
10 DD150 refrigerator has not been tested under VeraSol
11 VeraSol. 2022. SunDanzer DCR165E. https://data.verasol.org/products/ref/sundanzer46
12 It should be noted that the recorded temperatures may have been affected by the surrounding environment where the refrigerators were placed (e.g. higher temperatures occurring near a heat source).

Figure 1: Location of refrigerators participating in the field testing – Rwanda and India





1.5 Data analysis structure

In both countries, the user data analyses were based on a full sample of 22 users in Rwanda and 20 in India. The refrigerator users were interviewed in two rounds – baseline when the RMMs were installed, and endline when RMMs were being retrieved.

On the other hand, performance data analyses were based on refrigerators with sufficient field testing data. Due to the challenging nature of field testing, where refrigerators are used by users in 'real world' conditions, only four refrigerators in India and 18 refrigerators in Rwanda collected sufficient data for analysis. In Rwanda, performance data collected from the 18 refrigerators were divided into three groups based on data consistency, average internal compartment temperature and occurrence of internal compartment temperature spikes as outlined in Table 3. Examples of full datasets from specific refrigerators in each group are presented in Annex I. In India, refrigerators were analysed as one group since only four refrigerators were suitable for the performance data analysis. Further details outlining limitations and lessons learned are described in Section 2.7.

Table 3: Refrigerator grouping for performance analysis in Rwanda

	Data consistency based on user behaviour	**Average internal compartment temperature**	**Temperature spikes**	**Number of refrigerators**
Group A	Consistent performance data	Consistently below 8°C	No spikes	8
Group B	Inconsistent performance data (occasionally turned on/off by users)[13]	Consistently below 8°C	Significant spikes	3
Group C	Inconsistent (regularly turned on / off by users) but sufficient performance data was collected[14]	Above 8°C	Significant spikes	7
Total				**18**

13 The in-country partner informed us that two customers had infrequent purchases of the pay-as-you-go (PAYG) tokens due to their business activity, and therefore would turn the refrigerator off when not in use.

14 We found that two customers used the refrigerators infrequently and would switch them off when there were no stored items to stop ice build-up. Further, they would remove and reinsert the RMM temperature probes during the cycles of refrigerator use and non-use, which impacted the consequent data analysis. Also, one of the refrigerators was used in a small bar where the door was frequently opened and the RMM temperature probe was unintentionally removed and not reinstalled.

2. RESULTS

2.1 Refrigerator user demographics and use

The refrigerator user demographics and use were based on data from the full sample set (i.e. 22 users in Rwanda and 20 in India).

2.1.1. User profile

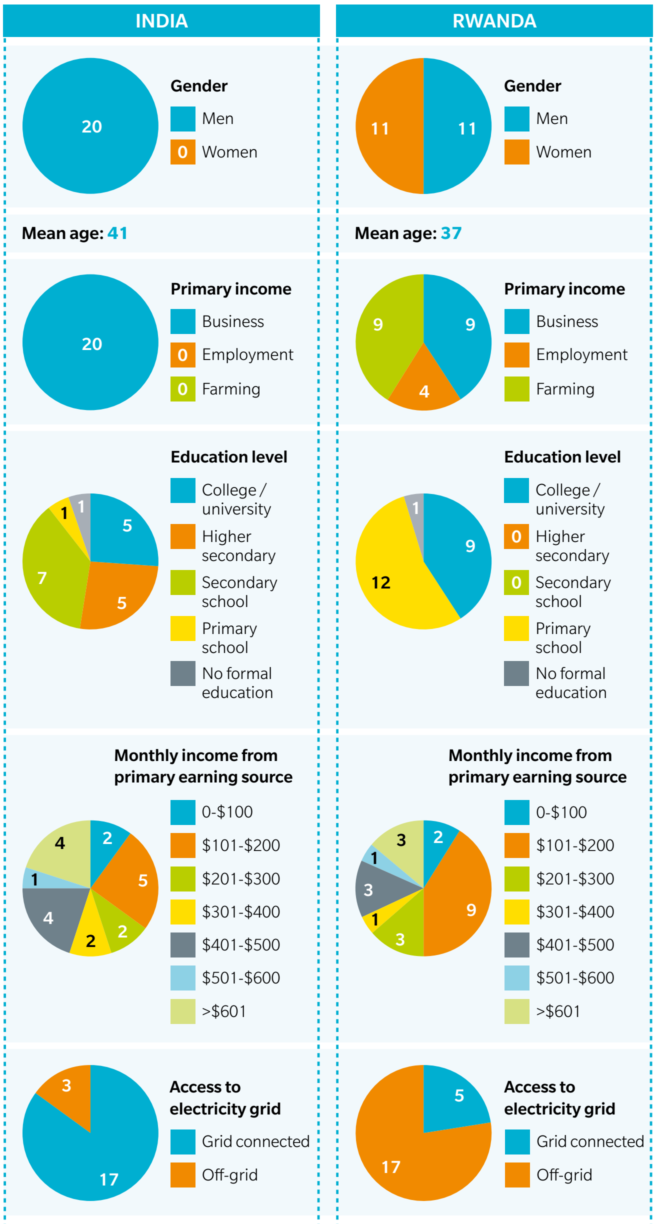
The main criterion for identifying field testing participants was to find a sufficient number of users who recently purchased a solar-powered refrigerator from our in-country partners. Due to the limited sales of refrigerators, we were not able to engineer a preferred sample, although we acknowledge that a more diverse sample would have been ideal for the most robust conclusions. As outlined in Table 4, diversity was achieved in terms of education and income, but not necessarily in gender.

In India, all the refrigerator users were men, while in Rwanda there was an equal split of 11 women and 11 men.
The disproportionate gender split in India was not by design, rather a consequence of most SMEs being owned by men.

With regards to education, only two users had no formal education, one in each country as indicated in Table 4. Although nearly half of the women users across both countries were university educated, none of them earned more than $500 and only three earned more than $200 per month, compared to nine and 21 men, respectively. This reflects the disproportionate gender income gap in the two countries.[15,16]

All the users in India indicated that their primary income was from their business (taking part in trading) while those in Rwanda had a mix of business, farming and formal employment (wage workers). In India, 11 users had general stores (using the refrigerators to sell cold beverages), four fish sellers, four food vendors and one milk factory. Two spouses of the refrigerator users generated additional income via tailoring and running a tea stall, respectively. In Rwanda, the household income source was more nuanced as both women and men conducted income-earning activities (apart from eight users who indicated that income earning is done solely by women in their household and four that income earning is done only by men in their household). Of the 10 households who jointly conduct income-generating activities in Rwanda, nine women took part in business and one in farming, whereas four men were involved in farming, three in employment, and three in business. Based on this analysis we can conclude that the refrigerator supported businesses were mostly run by women while men conducted other income-generating activities in Rwanda.

User profiles[17,18]



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15 UN Women. 2022. Rwanda. https://data.unwomen.org/country/rwanda/

16 UN Women. 2022. The gender pay gap, hard truths and actions needed. https://asiapacific.unwomen.org/en/stories/op-ed/2022/09/the-gender-pay-gap-hard-truths-and-actions-needed

17 It should be noted that findings summarised in this table should not be mistaken for any trends, as the sample design was based on customers who recently purchased solar-powered refrigerators from our in-country partners.

18 The standard currency used throughout this report is a United States Dollar.

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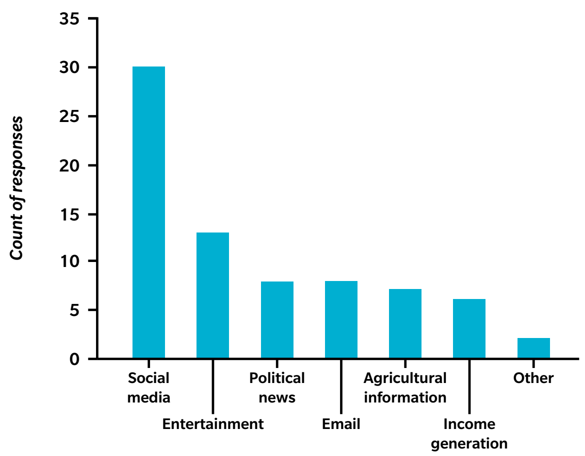
Access to grid connection was very different between the two countries. 85% of users in India had access to the centralised electricity grid, compared to less than 25% in Rwanda. This was not surprising considering the fact that access to electricity is nearly universal in India (mostly served by centralised grid although often unreliable), whereas more than half of the Rwandan population still lacked access to electricity in 2020.[19] It should be noted that all the users who participated in the refrigerator field testing lived in rural areas, which generally have lower electricity access compared to the national average.

The user profile of refrigerator owners in India aligned with the typical product user profile,[20] whereas Rwandan user profiles were more diversified. According to the findings from the Appliances for All: Assessing the Inclusivity of the Solar Lighting & Appliances Sector report by Efficiency for Access,[21] the typical solar product user is a man in his early forties, connected to the grid, living in a rural area, with at least a secondary education and living above the poverty line of USD $3.20 per day. This description applied to
the Indian users who participated in the field testing, whereas the Rwandan user portfolio was significantly more inclusive, particularly since many users were women and all the users were living in off-grid areas (i.e. not connected to the electricity grid).

In both countries, more than 85% of users owned a smartphone for various purposes as outlined in Figure 2. The widespread penetration of smartphones could potentially be leveraged for capacity building and streamlined communications (including remote troubleshooting to enhance repairability) between the appliance users and distributors, particularly in rural areas where frequent face-to-face visits can be costly.

Figure 2: Smartphone use (both countries)



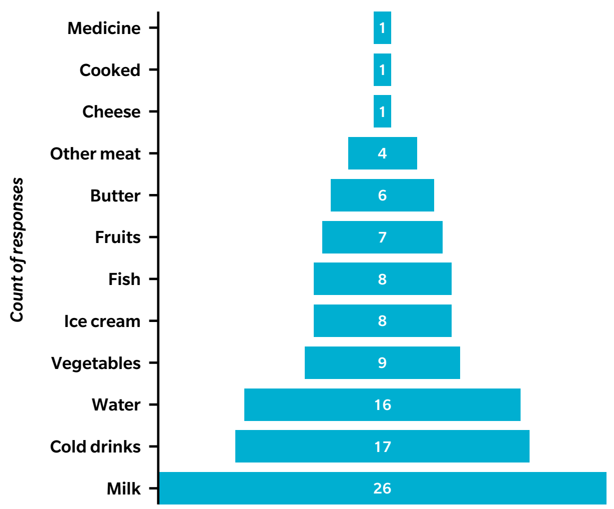
2.1.2. Refrigerator use

Many users who participated in the field testing gained access to modern and reliable cooling for the first time. For most users in Rwanda (more than 75%) this was the first refrigerator they have owned, whereas only 35% of users in India had not owned a refrigerator before. Users who did not own a refrigerator before would cool items by using ice cubes, water immersion, or other traditional methods but the majority (more than 50%) would not cool items at all.[22] The higher ownership of refrigerators in India is consistent with findings from the Off-Grid Appliance Market Survey report by Efficiency for Access,[23] which compared appliance ownership in India and sub-Saharan Africa.

More than one third of users in India and Rwanda indicated that in addition to income generation, they also use the refrigerators for domestic purposes (only 7% of the users used refrigerators purely for domestic purposes). For this reason, the second most frequent user of the refrigerator was the user's spouse according to the survey results.

The refrigerators were used in various businesses but by far the most common business types were: general stores (69%), meat/fish sellers (17%) and food stalls (7%). Regarding specific items users stored in the refrigerators, milk was the most common product (more than 60% of users stored milk in the refrigerators), followed by cold drinks (such as soda) (40%) and water (38%). Other items that users stored in their refrigerators are shown in Figure 3. Most users stored more than one product in their refrigerator.

Figure 3: Items stocked in the refrigerators



19 World Bank. 2020. Access to electricity (% of population). https://data.worldbank.org/indicator/
20 Efficiency for Access. 2022. Appliances for All: Assessing the Inclusivity of the Solar Lighting & Appliances Sector. https://storage.googleapis.com/e4a-website-assets/Appliances-for-All-Assessing-the-Inclusivity-of-the-Solar-Lighting-and-Appliances-Sector.pdf
21 Ibid
22 The percentage is based on user data from Rwanda, since user data in India was insufficient to conduct the analysis
23 Efficiency for Access. 2020. Off-Grid Appliance Market Survey. https://storage.googleapis.com/e4a-website-assets/CLASP-MarketSurvey-2020-final.pdf

Five users had completely stopped using the refrigerators by the endline survey - three in India and two in Rwanda. In India, two users had closed their businesses and one had sent the refrigerator to the distributor due to a product malfunction. In Rwanda, one user was not able to continue with the payments, while the other's refrigerator was being repaired by the distributor. The duration between baseline and endline surveys was only six months. Therefore, further research is required to assess how many of the tested refrigerators are still in use at the end of the warranty period and then again at the end of the product lifetime. The Efficiency for Access *Appliance Impacts Across Time*[24] report concluded that 96% of users who owned a refrigerator for more than four years were still using it but at the same time only 42% of these refrigerators were working as new.

2.2. Refrigerator usage behaviour

2.2.1. Door opening

Two primary factors impacting overall refrigerator performance are the product's ability to keep power consumption low and internal compartment temperature constant. The duration and frequency of door openings have significant impact on these two factors. Therefore, we installed door opening sensors as part of the RMMs. The binary door opening sensor included two magnetic nodes placed on the door and latch sides to monitor the frequency and duration of the refrigerator door openings.

The field teams were constrained to install the door opening sensors in a non-invasive manner that would not damage the refrigerator body (i.e. the refrigerator had to look the same after the sensors were removed at the end of field testing). Based on this requirement, the field teams used a heavy-duty double-sided tape to attach the sensors rather than drilling into the body of the refrigerator. Unfortunately, the tape's strength deteriorated shortly after installation in both countries rendering the sensor recording unusable. As a backup measure, users were asked about their door opening habits during the endline survey. This approach prevented us from conducting detailed analysis where refrigerator power consumption or internal compartment temperature spikes could be directly correlated with door opening.

Only one refrigerator in Rwanda and one in India had complete door opening datasets at the end of the field testing. Therefore, no concrete conclusions can be drawn apart from providing indicative examples from the two refrigerators. In India, the refrigerator was open for less than six minutes per day on average, if we exclude three events when the refrigerator was open for 14 more than hours each. In Rwanda, the refrigerator with complete door opening dataset was open for less than nine minutes per day on average. The vast majority of door openings in both countries was short in duration (i.e. mostly less than three minutes).[25]

2.2.2. Stocking behaviour

Stocking behaviour is another key factor impacting refrigerator performance. Refrigerators perform better when they are restocked less frequently (lower door opening frequency), with items that are pre-cooled or at room temperature, and not overloaded. Stocking behaviour in both countries was generally effective. 75% of the users indicated that they re-stock items when the refrigerator becomes half-empty rather than when specific item is missing or when the refrigerator is completely empty as shown in Figure 4. More than half of the users indicated that items they put in the refrigerators are at room temperature, with the rest being almost an equal split between pre-cooled and hot[26] as outlined in Figure 5.

Figure 4: Re-stocking frequency

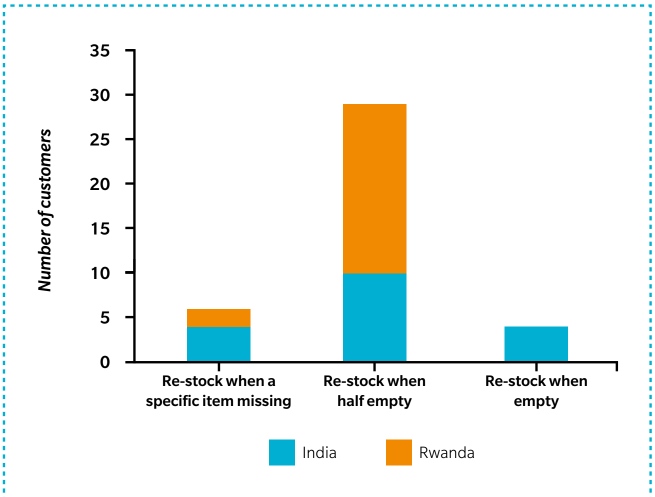
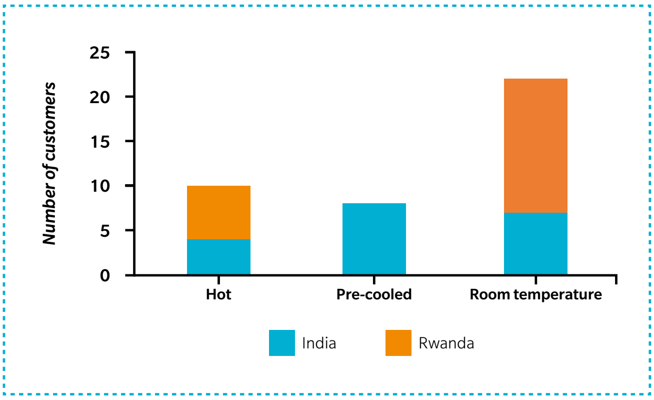


Figure 5: Item temperature when entering the refrigerator



We also asked users about the weight/quantity of items they stock in the refrigerators to understand usage patterns and refrigerator capacity utilisation. In both countries, cold drinks were stored in standard bottles which would fill up a specific volume of the refrigerator compartment limiting how many items could be stocked. A similar pattern was observed for milk,

24 Efficiency for Access. 2023. Appliance Impacts Over Time: Longitudinal insights from off-grid TV, refrigerators, & solar water pumps users. https://efficiencyforaccess.org/publications/appliance-impacts-over-time

25 It should be noted that the data sampling period for our field testing was three minutes per data point. This makes it difficult to conduct a detailed door opening analysis, since the door may be open for less than three minutes during which the data point may not be captured or be captured without knowing the exact duration.

26 'Hot' in this context means higher than ambient temperature. The average ambient temperature measured on the outside part of the monitored refrigerators in India was 31°C, and in Rwanda 27°C.

which is often stored in standardised milk churns. Based on the survey results, less than 25 kilograms or litres of one item type was stored in each refrigerator (approximately 30% of the total internal volume of the refrigerator[27] in India and 15% in Rwanda), apart from one user in Rwanda who reported 60 kilograms of fish being regularly stored in the 163L refrigerator and another user who reported 50 litres of milk. These findings indicate that the majority of refrigerators were not being overloaded with one specific item type.

2.3. Rwanda field performance data

2.3.1. Daily power consumption

Power consumption is one of the key indicators of refrigerator performance. In grid-connected settings, lower daily power consumption means lower electricity bills. In off-grid settings, lower power consumption reduces the electrical system size requirements (i.e. the power generation system, in this case a solar PV panel, and the energy storage system, in this case an electrochemical battery). If the electrical system size remains the same but a more efficient refrigerator is used, the lower power consumption extends cooling reliability during cloudy periods, or increases the cooling capacity (i.e. larger refrigerator compartment with the same electrical system size is possible).[28,29]

Refrigerators draw power based on cooling cycles rather than having constant power consumption. Therefore, we calculated daily power consumption (average, minimum and maximum) of each refrigerator in Wh/day and presented the results based on refrigerator groupings outlined in Section 1.5. Figures 6, 7 and 8 show the average daily power consumption across the three groups (230 Wh/day for Group A, 556 Wh/day for Group B and 289 Wh/day for Group C). When we compare the field testing results to VeraSol, we can see that the laboratory tests yielded a daily power consumption of 191 Wh/day and 343 Wh/day at ambient temperatures of 32°C and 43°C, respectively.[30]

Figure 6: Average daily power consumption (Rwanda) - Group A (average ambient temperature: 27°C)

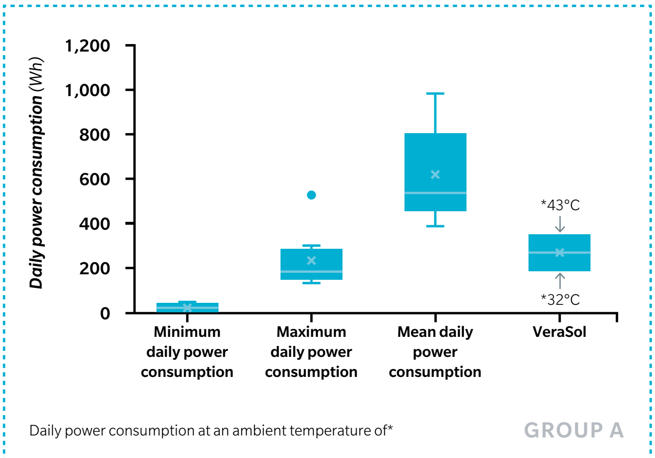


Figure 7: Average daily power consumption (Rwanda) - Group B (average ambient temperature: 28°C)

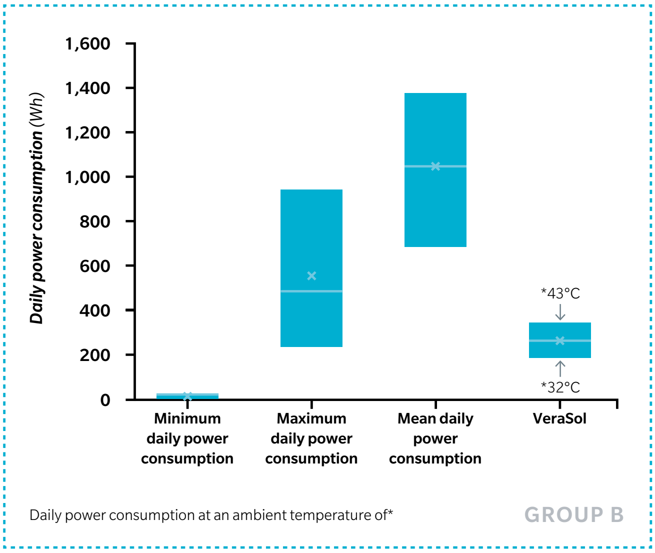
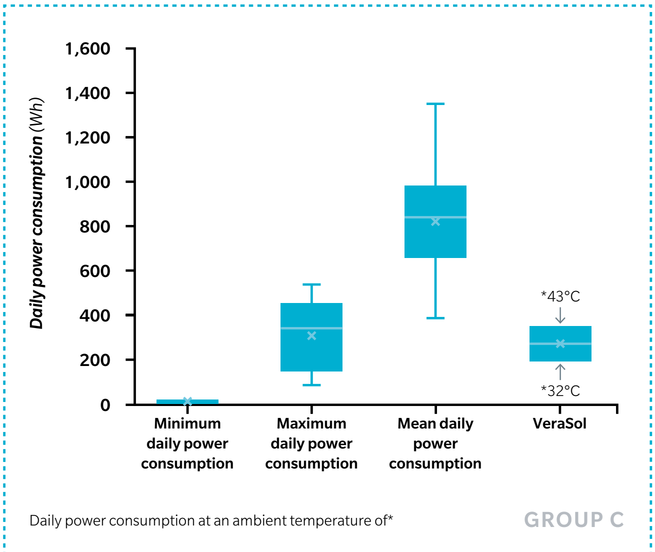


Figure 8: Average daily power consumption (Rwanda) - Group C (average ambient temperature: 27°C)



The field testing results were significantly more varied compared to the laboratory results. This can be attributed to the controlled environment within the laboratory. VeraSol laboratory tests define a day as 24 hours, whereas it was not possible to obtain 24 hours' worth of usage data per day consistently due to many refrigerators being turned off for 12 hours at night (typically between 6pm and 6am) during each 24-hour diurnal cycle. In these instances, we used data that were available in the given 24-hour period (i.e. when the refrigerator was not manually turned off). For this reason, we can ignore the minimum daily power consumption values shown in Figures 6, 7 and 8 in blue, since they are only outliers based on data when the refrigerator was turned on for a very short duration during the 24-hour cycle.

27 Based on the DD100 model, which is smaller than DD150
28 SEforALL. N/A. Reducing cooling-related electricity demand with energy efficiency (SDG7.3). https://www.seforall.org/data-stories/chilling-prospects-2022-special/reducing-cooling-related-electricity-demand
29 SEforALL. 2021. Raising ambitions for off-grid cooling appliances. https://www.seforall.org/system/files/2021-04/Offgrid-Cooling-Appliances-SEforALL.pdf
30 VeraSol. 2022. SunDanzer DCR165E. https://data.verasol.org/products/ref/sundanzer46

The average daily power consumption was generally higher compared to the VeraSol results. This can be attributed to uncontrolled parameters such as door openings and the user behaviour of turning off the refrigerator, which caused higher power consumption when the refrigerator was turning on at the start of the day as shown in Figure 9 (continuous operation) and Figure 10 (refrigerator turned on in the morning).[31] In this case, the overall daily power consumption from the continuously operating refrigerator was nearly half.

Looking at Group A, we can see that the average power consumption was slightly below the VeraSol laboratory results. This can be explained by lower ambient temperatures during the field testing (27°C) compared to the controlled environment within the laboratory (32°C and 43°C). Having said that, Group A demonstrates that solar-powered refrigerators perform well in the field when they are left to operate consistently without being manually turned off by the users compared to higher power consumption of refrigerators which were regularly turned off (usually overnight).

Figure 9: Example of one day (13/12/2021) power consumption profile (continuous operation) - 24-hour data sample, average ambient temperature: 29°C, daily power consumption: 136 Wh/24h

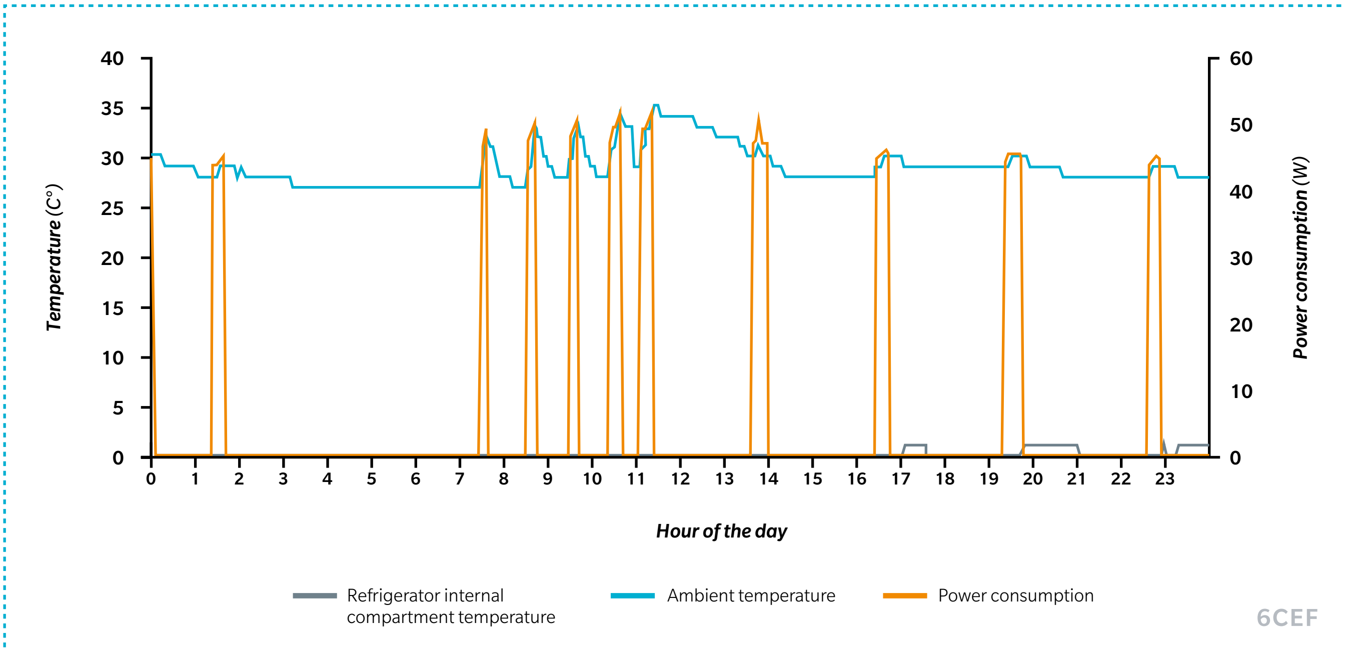
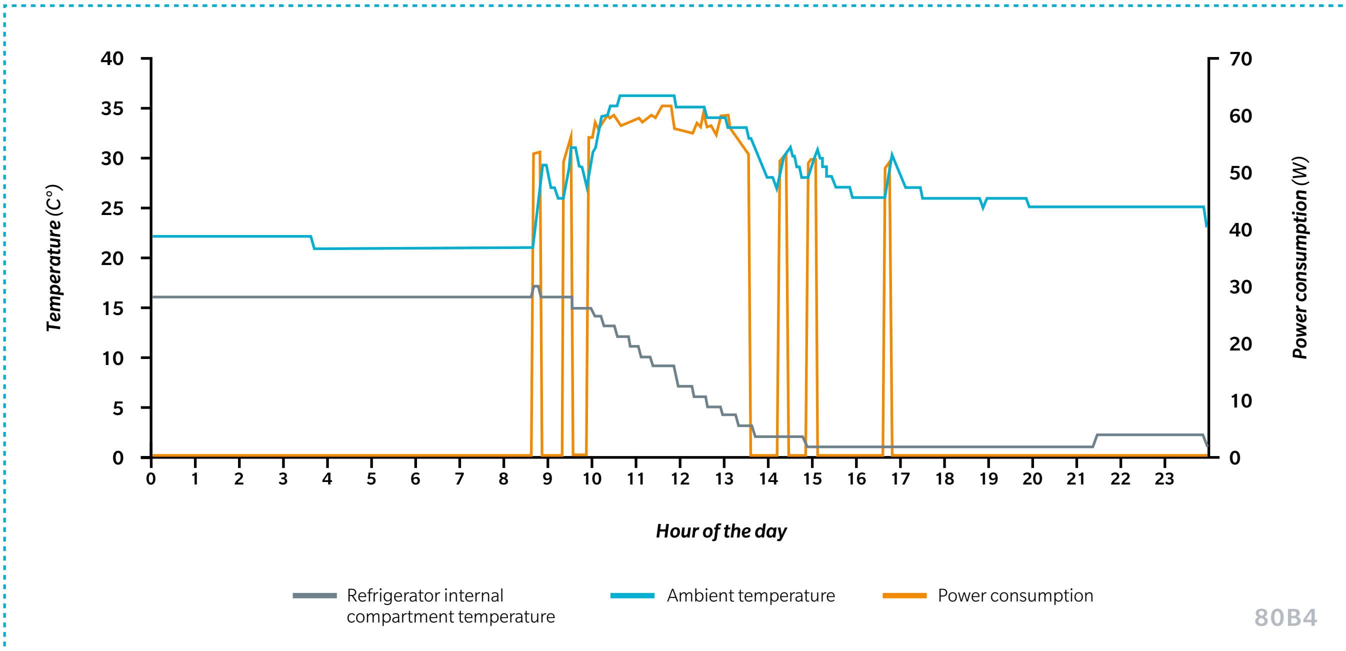


Figure 10: Example of one day (18/09/2021) power consumption profile (refrigerator turned on by the user in the morning) - 24-hour data sample, average ambient temperature: 26°C, daily power consumption: 266 Wh/24h



31 24-hour data samples were selected for comparison to demonstrate how user intervention influences power consumption (i.e. refrigerators that are manually turned on overnight result in higher power consumption overall). We were not able to triangulate this analysis with door opening due to the lack of data

2.3.2. Maximum instantaneous power consumption

The maximum instantaneous power consumption is a valuable parameter to consider when sizing the electrical cables and associated accessories. Exceeding rated power consumption can lead to electrical failures and hazards, such as electrical fires caused by electrical heating of the cables that connect the refrigerator to the solar controller and battery. This parameter can also be useful for future field testing purposes by ensuring that the remote monitoring modules can measure the power consumed without failure caused by overheating and short circuits.

The highest instantaneous power consumption measured across all refrigerators was 89 Watts.[32] Measuring instantaneous power consumption is important from a reliability and safety perspective. From a reliability point of view, the power supply system needs to be sized appropriately so that the refrigerator has sufficient power to get started. From a safety perspective, this parameter informs the installers that electrical cables should be able to handle at least 7.4A of current at 12V to prevent electrical failures. For manufacturers, communication of this parameter to installers through product manuals is important to avoid warranty claims caused by electrical failures due to undersized cabling.

2.3.3. Minimum internal compartment temperature

Assessing the minimum internal compartment temperature recorded within each refrigerator is important for two reasons; we can evaluate if it stayed within the technical specification range of the refrigerator type and prevent the stocked items from freezing. We analysed the minimum recorded temperature during the field testing across all refrigerators and concluded that all of them reached 0°C, apart from one refrigerator that reached 2°C. These results are well within the manufacturer specified temperature range of -1°C to 9°C. Therefore, we can conclude that the minimum internal compartment temperature test was successful during the field testing exercise.

2.3.4. Hourly temperature versus power consumption

Generally, the hourly power consumption curve should be broadly aligned with the ambient temperature curve. This is one of the reasons why solar power generation and cooling work well together (i.e. more cooling is required during the day when the sun is out). However, it also means that the compressor needs to work harder to keep the internal temperature consistent at a higher ambient temperature. To conduct this assessment, we averaged the hourly ambient temperature, and plotted this against the hourly power consumption.

Refrigerators in Groups A and B have their hourly power consumption profiles broadly aligned with the ambient temperature profile as shown in Figures 11 and 12. It should be noted that the average power consumption for Group B was significantly higher compared to Group A, which could be a result of the user interruption by occasionally turning the refrigerators off but also the smaller sample of refrigerators in this group (only three refrigerators were in Group B compared to eight in Group A and seven in Group C).

We chose Group A to assess average power consumption increase associated with ambient temperature rise since refrigerators in this group operated continuously without user interruption. Figure 11 shows that if ambient temperature rises from by 4°C (from 25°C to 29°C), the energy consumption increases by 16 Wh (from 3 Wh to 19 Wh).[33]

Power consumption profiles in Group C clearly show a lack of alignment between the power consumption and ambient temperature data – see Figure 13. This was caused by incorrect user behaviour when most refrigerators were regularly turned off between 6 pm and 6 am the following morning.[34]

This analysis can be particularly useful for user awareness programmes focused on correct refrigerator use. Keeping the refrigerator running overnight is particularly important for items that are susceptible to spoilage (eg meat, fish, milk, fruit or vegetables), while not costing the user more money to operate since the refrigerators are solar-powered (not grid powered). In addition, correct refrigerator usage yields lower average power consumption, lesser electrical strain on the battery systems, extends the battery lifetime, and defers battery replacement costs after the end of the warranty coverage period.

32 It should be noted that the data sampling period for our field testing was three minutes per data point, whereas an inrush current (also known as instantaneous power surge) occurs for significantly shorter period when electrical devices are turned on. Therefore, we were only able to analyse maximum instantaneous power consumption from the available data.

33 The observed increase in power consumption is purely based on ambient temperature but not other behaviours such as warm item stocking in the morning or potentially more frequent door opening in the morning.

34 It should be noted that in all the groups, the average hourly power consumption is leading the average hourly ambient temperature. This could be related to other factors such as product stocking in the morning and more frequent door opening, neither of which can be confirmed with the collected data – see Section 2.7 for further details.

Figure 11: Ambient temperature versus power consumption – Rwanda Group A

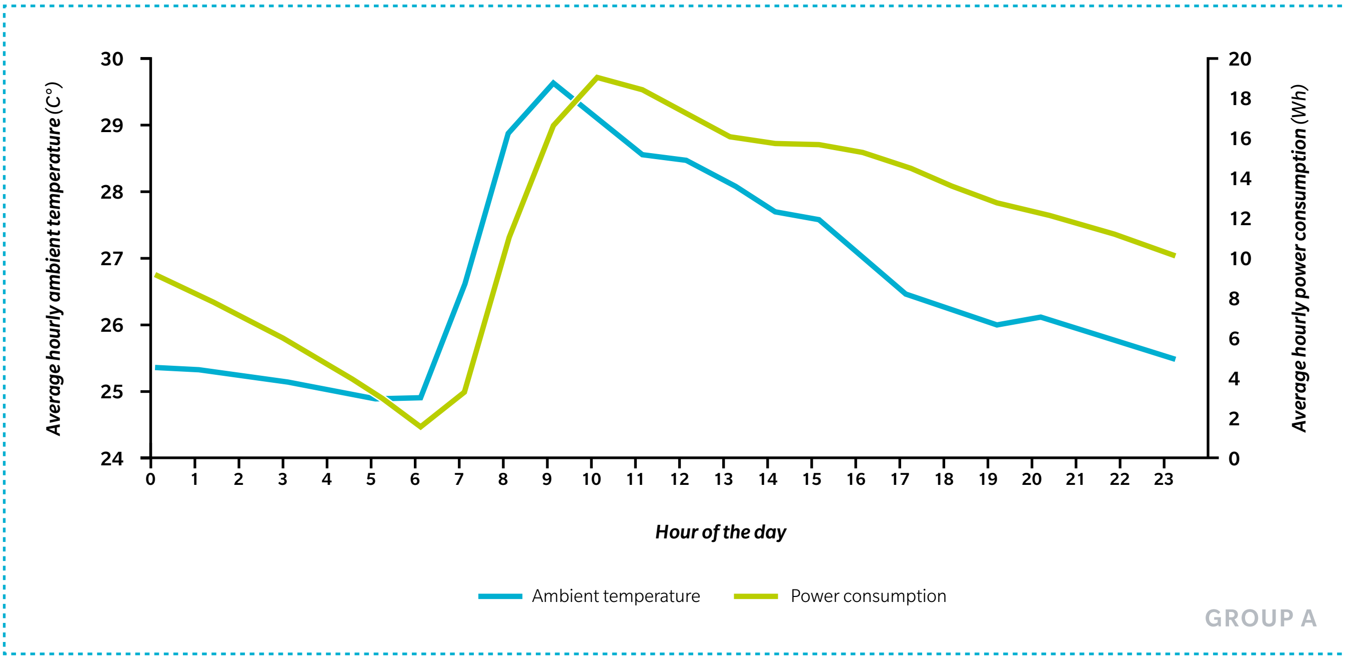


Figure 12: Ambient temperature versus power consumption – Rwanda Group B

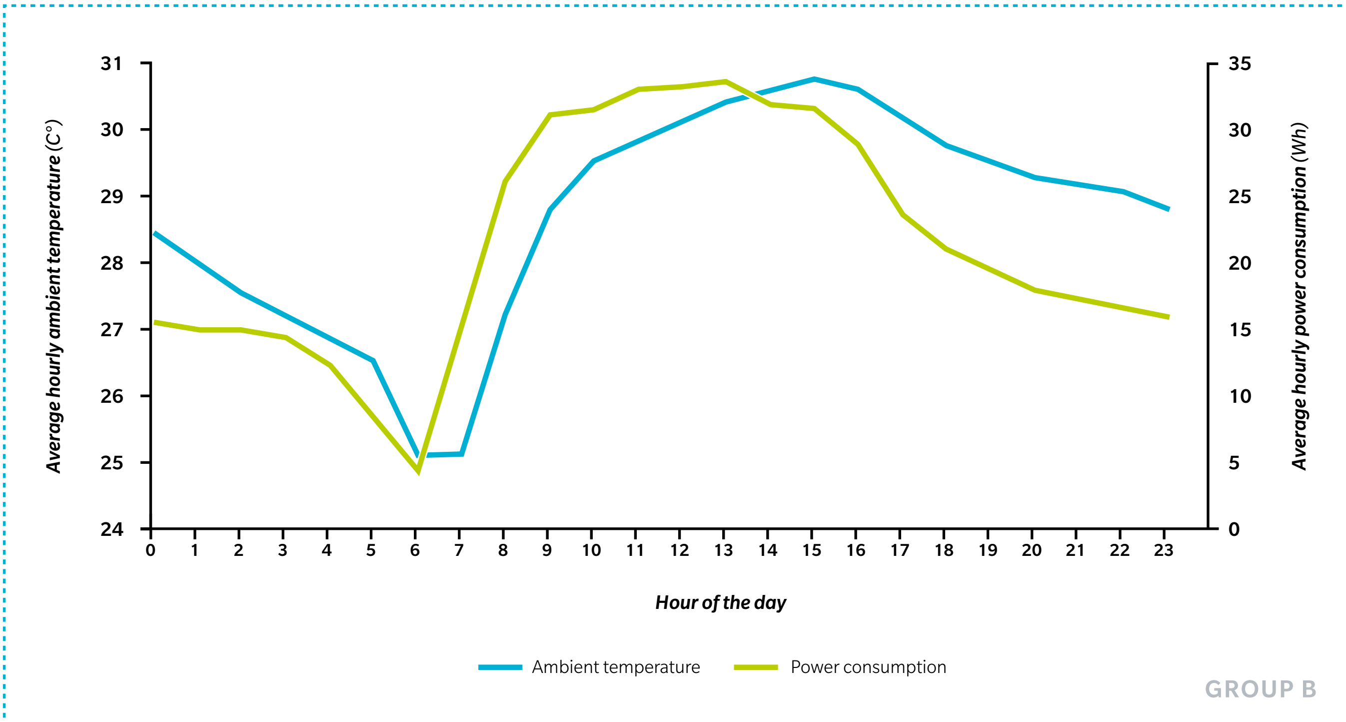
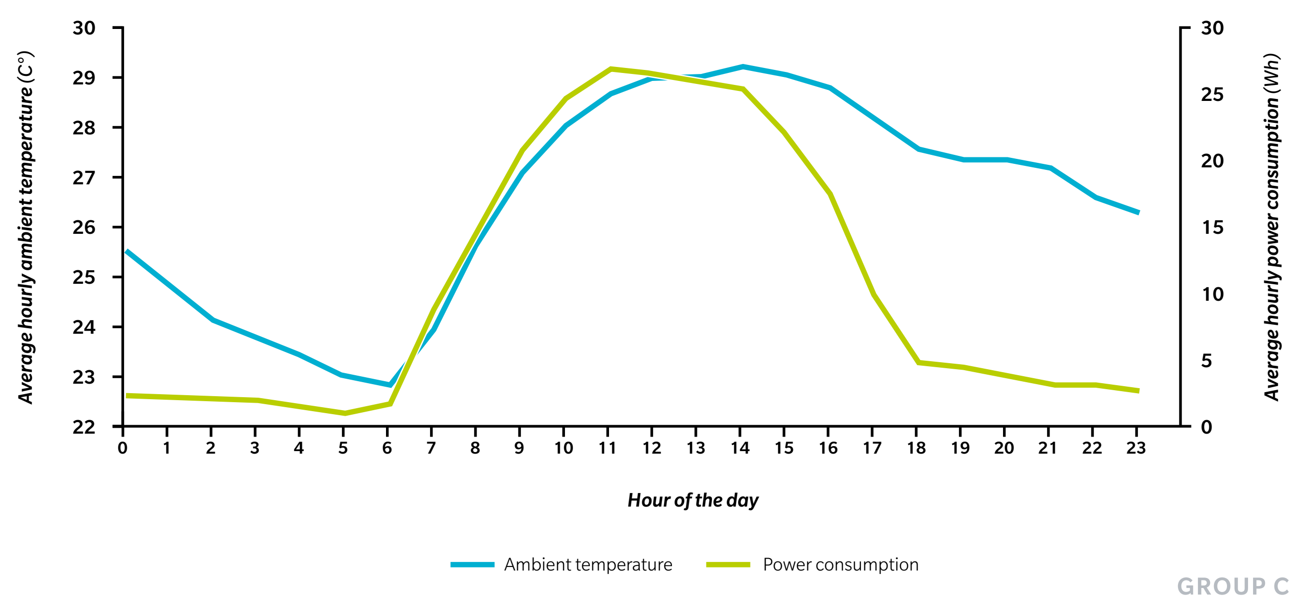


Figure 13: Ambient temperature versus power consumption – Rwanda Group C[34]

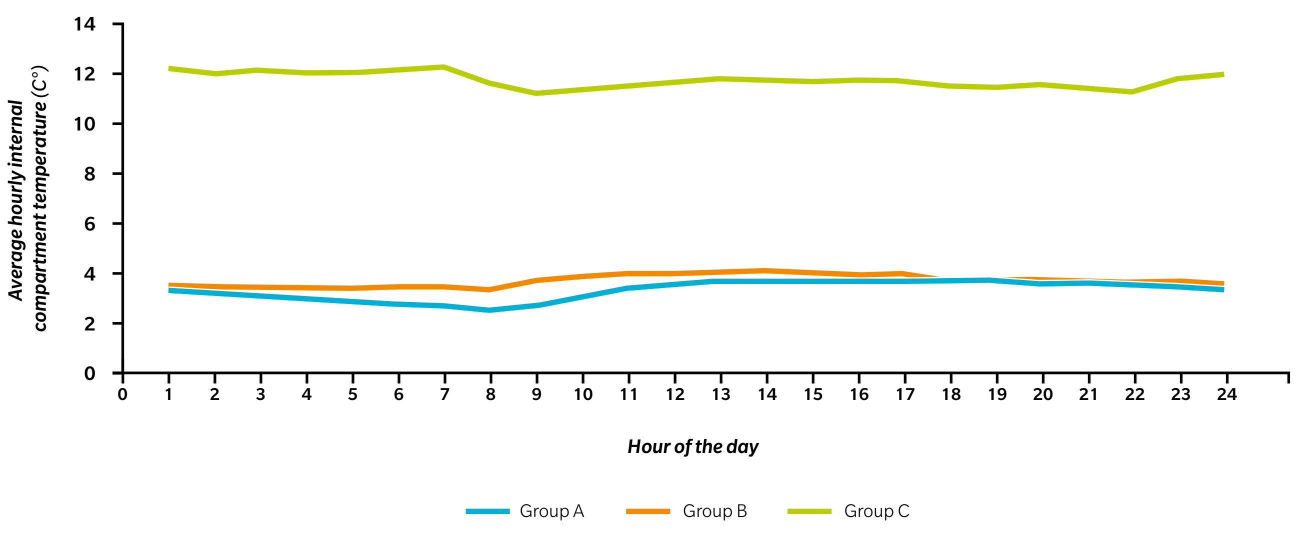


As part of the refrigerator performance analysis, we also looked at the average hourly internal compartment temperature, which is one of the key delivery parameters when it comes to cooling. As outlined in Table 3 and Figure 14, the average internal compartment temperature was very stable for Groups A and B (I.e. between 2 °C and 4 °C) even with fluctuating ambient temperature during the day, whereas Group C shows high average internal compartment temperature during the 24-hour cycle. It should be noted that these results may have been caused by sensor issues and user behaviour (frequently turning refrigerators off) and not necessarily by the refrigerator performing poorly – see Section 2.7 for further details.

2.3.5. Undervoltage and overvoltage analysis

Staying within the designed voltage range is important for safety and durability reasons. Mild cases of undervoltage may increase the current and cause heating and reduced lifetime of electronic components. In extreme cases of undervoltage, electronic components are susceptible to damage especially where protection mechanism have not been considered in the design of the refrigerator's electrical systems such as undervoltage lockouts (UVLO) protection systems. Overvoltage is the more dangerous of the two parameters.

Figure 14: Average internal compartment temperature – all refrigerator groups in Rwanda



35 The average hourly power consumption was above zero between 6pm and 6am since most refrigerators were manually switched off by the end-users overnight but not all of them every night.

The refrigerator should be designed with overvoltage protection in mind as high voltages can lead to user injury and permanent appliance failure. Overvoltage may be caused by loose neutral connection, an abrupt decrease in appliance power draw and failure of the voltage regulator circuitry.

The Verasol testing procedure for refrigerators provides a relevant basis for measurements of these parameters. VeraSol defines 10.8V and 14.4V as the thresholds to consider for undervoltage and overvoltage, respectively, for a typical 12V supply. We used the same thresholds in the field testing analysis since all the refrigerators were 12V systems.

Undervoltage events were relatively frequent with 418 instances across 13 refrigerators throughout the testing period of six months.[36] The lowest measured undervoltage was 2.31V recorded by three refrigerators and longest duration was 15 minutes recorded by two different refrigerators. There were two refrigerators with high number of undervoltage events at 105 and 213 voltage events throughout the testing period of six months, respectively – see Annex II for further details. It is likely that these two refrigerators were overloading the power supply for short periods (the longest undervoltage event lasted 6 minutes) when power consumption was high.

Overvoltage events were relatively less frequent with 20 overvoltage events (18 events from one refrigerator in Group B and 2 events from one refrigerator from group C) throughout the testing period of six months. The highest overvoltage was 19.63V, which is 64% higher than the rated supply voltage of 12V and 15% higher than the rated maximum input voltage indicated in the manufacturer's specifications – see Annex II for further details. This surge in voltage could potentially be damaging if it was sustained over long period.[37]

2.3.6. Autonomy

Autonomy performance of solar-powered refrigerators is particularly important to sustain cooling reliability and reduce the capacity of energy storage required. Autonomy is defined as the duration that the refrigerator can keep internal compartment temperature below 12°C without consuming any input power (i.e. low temperature is sustained by insulation). We identified autonomy instances starting at 4°C and measured the time it took to reach 12°C without any input power, similar to laboratory testing under VeraSol.

We identified only a few instances where autonomy occurred. Refrigerators within Group A did not experience any autonomy (i.e. they maintained low temperatures consistently throughout the field testing period of six months without being manually turned off by the refrigerator users). One refrigerator in Group B and five refrigerators in Group C experienced autonomy, mainly because they were regularly turned off by the users. There was a significant difference between autonomy durations across the refrigerators, ranging between two hours and nearly three days – see Annex III for further details.

These results show that the autonomy duration strongly depends on the conditions such ambient temperature, door opening, quantity and temperature of products stored but most importantly on the use of thermal storage. The field tested refrigerators were designed with thermal storage, as they were initially going to be used in a solar direct drive format. The units were repurposed with a battery before being sold in Rwanda, which enabled them to use a combination of battery storage and thermal storage. Based on a field trip assessment conducted by the refrigerator manufacturer, some refrigerators were used without thermal storage, which indicates that customers may have taken it out.[38] This explains the substantial difference in autonomy durations across the field tested refrigerators.

The autonomy results from field testing are difficult to directly compare with laboratory result from VeraSol, which was 1.83 hours.[39] Firstly, the ambient temperature was generally lower in the field compared to VeraSol. There was one autonomy event when ambient temperature in the field was 34°C compared to 32°C in VeraSol but the rest of the events were between 4°C and 14°C lower than VeraSol. There was a correlation between the ambient temperature and the autonomy duration (i.e. the longest autonomy event happened at lowest ambient temperature and vice versa). Secondly, refrigerators tested under VeraSol were empty, whereas refrigerators used in the field were filled with items of various type and quantity. Once these items were cooled down, they essentially become thermal storage by reducing the speed of temperature rise with their gradual heat exchange. In addition, the refrigerators tested under VeraSol did not include thermal storage, whereas many refrigerators used in the field did. Finally, since the door sensors were not working (see Section 2.2.1 for further details), we could not verify if the autonomy happened with the doors closed throughout the entire duration.

2.3.7. Pull-down

Rapid pull-down is important to extend the shelf life of fresh products[40] and ultimately avoid food waste of products that are prone to get spoiled. Pull-down refers to the duration taken for a refrigerator to reduce internal compartment temperature from ambient to desired operating temperature. VeraSol tests refrigerators at a start temperature of 32°C and end at 8°C and 4°C, respectively. There were no instances where refrigerators participating in the field testing would match the exact VeraSol conditions.[41] Therefore, we identified and analysed instances when the internal compartment temperature was above the

36 It should be noted that this is an observation of the entire electrical system (including power generation and storage) rather than the refrigerator alone.

37 The refrigerator electronic controls were not damaged based on a visual inspection conducted during the RMM retrieval at the end of the field testing.

38 We were not able to cross-reference which refrigerators lacked thermal storage with the performance data from individual refrigerators but it is likely that refrigerators with shorter autonomy duration may have been the ones without thermal storage.

39 VeraSol. 2022. SunDanzer DCR165E. https://data.verasol.org/products/ref/sundanzer46

40 F. A. Zainalabidin, M. S. Sagrin, W. N. W. Azmi, A. S. Ghazali. 2019. Optimum postharvest handling-effect of temperature on quality and shelf life of tropical fruits and vegetables. Journal of Tropical Resources and Sustainable Science 7 (2019): 23-30

41 This is due to the fact that performance data collection started when the refrigerators were already running, and when pull-down occurred, the ambient temperature was lower than 32°C tested under VeraSol.

target temperature (i.e. 8°C) and power consumption was drawn continuously without cycling until it reached the target temperatures of 8°C and 4°C, respectively.

Pull-down occurred primarily within refrigerators that were turned off regularly for prolonged periods to provide sufficient time for the temperature to rise above 8°C. Therefore, there was only one pull-down instance in Group A, since refrigerators in this group operated consistently without user interference (i.e. not being manually turned off) throughout the field testing. On the other hand, all the refrigerators in Categories B and C experienced pull-down events.

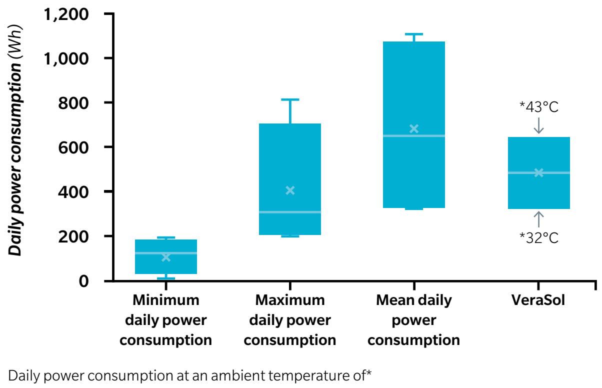
Similar to autonomy, pull-down duration in the field cannot be directly compared to the laboratory test results due to different starting temperatures, various types and quantities of items stored within the refrigerators but also the use of thermal storage. Refrigerators with thermal storage take longer to pull down due to the increased thermal mass. Due to these reasons, all the refrigerators in the field required longer pull-down durations to achieve 8°C and 4°C, respectively, compared to VeraSol results. This is not surprising considering that the refrigerators were filled with items and thermal storage mass which had to be cooled down compared to laboratory testing where the only substance to be cooled down is air within the internal compartment (no thermal storage was used during the VeraSol testing). The fastest pull-down that occurred during the field testing was 0.3 hours from 30°C to 8°C. The same refrigerator reached 4°C in 2.1 hours at starting temperature of 13°C. This is significantly longer than VeraSol results of 0.64 hours from 32°C to 4°C. This refrigerator type was not tested for 8°C under VeraSol. The pull-down difference between field tested refrigerators was substantial, between 0.3 hours and 4.15 hours to reach 8°C – see Annex IV for further details. However, this is also not a like-for-like comparison since starting temperatures, types/quantities of items and presence of thermal storage varied significantly.

2.4. India performance data

2.4.1. Daily power consumption

The average daily power consumption of refrigerators in India was broadly aligned with the VeraSol laboratory results. The average daily power consumption across the four refrigerators with sufficient performance data was 400 Wh/day compared to 329 Wh/day at 32°C and 641 Wh/day at 43°C under VeraSol.[42] Having said that, the daily power consumption varied significantly as shown in Figure 15. This is not surprising due to the extreme ambient temperatures that the refrigerators were exposed to (up to 48°C)[43] as well as the user-selected freezer mode option for the multi-temperature refrigerator model (DD100), which resulted in high daily power consumption.[44]

Figure 15: Daily power consumption (India)



2.4.2. Minimum internal compartment temperature

Most refrigerators reached minimum temperature below 0°C. There was only one refrigerator where the lowest recorded internal compartment temperature was 0°C. The other three reached temperatures well below freezing, with one refrigerator repeatedly reaching -20°C. These results show that most users decided to use the freezer mode function within the DD100 refrigerator model, which is a multi-temperature refrigerator that is designed to provide both, refrigerating and freezing, depending on the selected user mode.

2.4.3. Maximum instantaneous power consumption

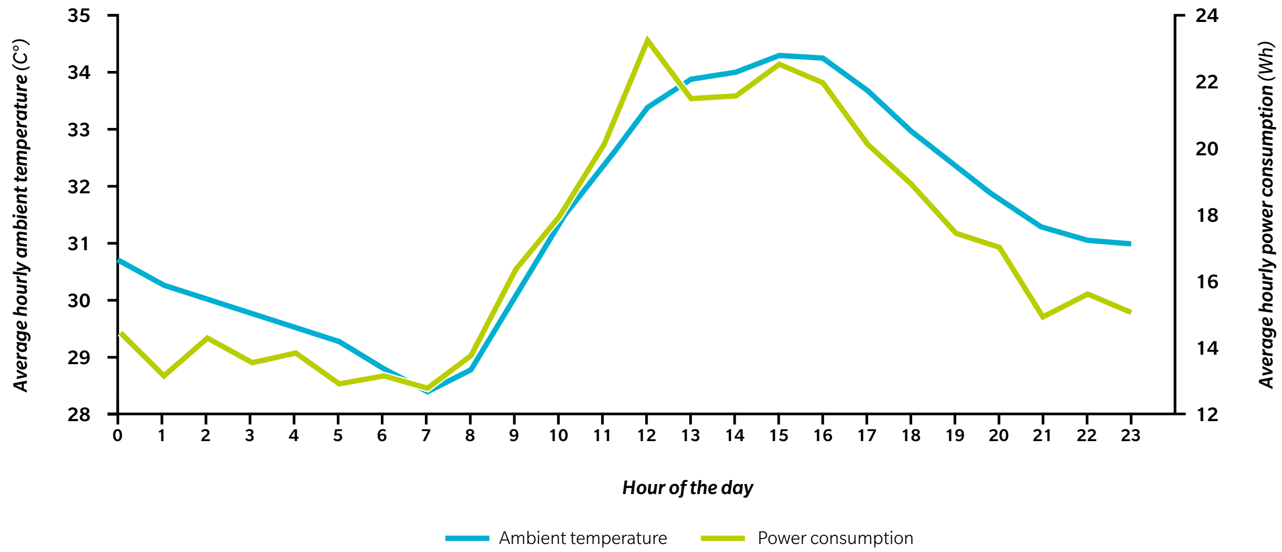
Maximum instantaneous power consumption results were extremely positive in India. All four refrigerators ranged between 45W and 59W which is well within the manufacturer's maximum specification of 95W. This confirms that there was no risk of electrical failures due to undersized cabling.

2.4.4. Hourly ambient temperature versus power consumption

The correlation between average ambient temperature and average hourly power consumption was clearly visible from the aggregated data of four refrigerators in India as shown in Figure 15. The refrigerators consumed power at night which indicates that users kept them running without manually turning them off. Figure 15 shows that if ambient temperature rises from by 6°C (from 28°C to 34°C), the energy consumption increases by 10 Wh (from 13 Wh to 23 Wh).[45]

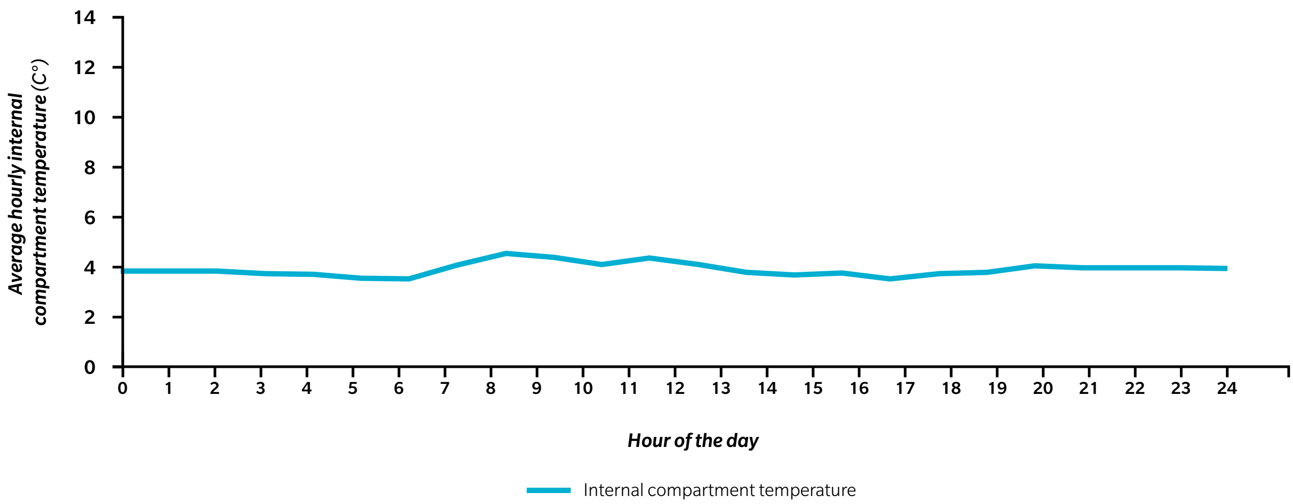
42 VeraSol. 2022. Devidayal DDSF-100. https://data.verasol.org/products/ref/devidayal-solar-solutions8
43 It should be noted that this temperature was measured at the outside part of the refrigerator, which could be influenced by heat sources in the near vicinity of the refrigerator, rather than the average ambient air temperature in the location.
44 It should be noted that during the VeraSol testing process, all the multi-temperature refrigerators are only tested for their refrigerating mode, not freezer mode.
45 The observed increase in power consumption is purely based on ambient temperature but not other behaviours such as warm item stocking in the morning or potentially more frequent door opening in the morning.

Figure 16: Hourly ambient temperature versus power consumption (India)



Although most users with sufficient performance data used the freezer function throughout the field testing period of six months, data suggests that the freezer mode was not used consistently (i.e. the multi-temperature refrigerators were sometimes used as refrigerators and sometimes as freezers). This explains why the average internal compartment temperature was stable at 4°C as shown in Figure 17.

Figure 17: Average internal compartment temperature – India



2.4.5. Undervoltage and overvoltage analysis

There was not a single overvoltage event (above 14.4V) recorded across the four refrigerators. On the other hand, undervoltage events were very common in three out of four tested refrigerators.

The cause of the undervoltage events may be the use of lead acid batteries that lack a voltage controller that would implement a low voltage cut-off threshold. This protection feature is common among battery management systems used in lithium-based battery systems. Undervoltage conditions are usually caused by abrupt increases in power consumption drawn by the appliance, however, where prolonged they could be caused by a loose connection or short circuit.

Despite long undervoltage durations (up to 105 minutes) and high number of undervoltage events (several thousands) across the three refrigerators, the nominal values of the undervoltage events were relatively modest. The lowest recorded was 9.67V which is only 1.13V lower than the threshold of 10.8V – see Annex II for further details. This means that excessive heat was unlikely to be generated by this modest breach. On the other hand, the long durations of the events may have prevented the batteries from fully recharging, which could potentially lead to appliance failure.

2.4.6. Autonomy

Two out of four refrigerators underwent autonomy (i.e. temperature increase from 4°C to 12°C without any power consumption) during the field testing in India. The autonomy durations were 2.8 and 9.8 hours, respectively – see further details in Annex III. As outlined in Section 2.4.6, the results cannot be directly compared with VeraSol (1.49 hours)[46], due to significant differences between laboratory conditions and site/user specific conditions in the field (apart from ambient temperatures which were relatively similar across all three scenarios: 32°C VeraSol, and 29°C to 30°C field testing).

2.4.7. Pull-down

Three out of four refrigerators in India recorded pull-down from ambient temperature to 8°C and 4°C, respectively. VeraSol results for this specific refrigerator type only include pull-down from an ambient temperature of 32°C to 8°C, which took 0.44 hours. Pull-down events recorded in the field were longer (shortest recorded duration was 1.4 hours). The same refrigerator continued pull-down all the way to 4°C, which took another 0.6 hours (2 hours in total from an ambient temperature of 21°C to 4°C) – see Annex IV for further details. Once again, the field testing pull-down results cannot be directly compared to VeraSol as outlined in Section 2.7.

2.5. User satisfaction

It should be noted that sections 2.5 and 2.6 were based on survey data which included the full sample set (i.e. 22 users in Rwanda and 20 in India).[47]

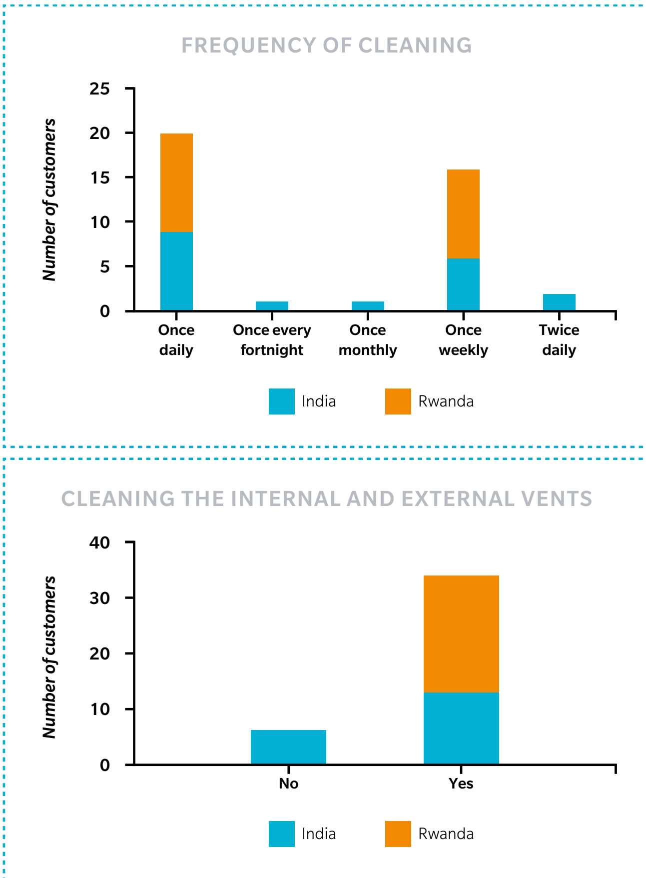
2.5.1. User experience

In both countries, users found the refrigerators easy to use despite a majority not owning a refrigerator before nor receiving formal training on how to use them. As outlined in Section 2.1.3, training from refrigerator distributors would be particularly beneficial for these new users to understand how to operate the refrigerators effectively. The same training could also be useful to users who had owned a refrigerator before since owning a refrigerator does not necessarily guarantee sufficient operational knowledge. Based on the survey results, 55% of users in India and 36% users in Rwanda did not receive training when they purchased the refrigerator.

Related to the low training rate, 85% users in India and 32% users in Rwanda reported that they do not know how to operate the refrigerator to reduce power consumption. This was evident from the performance and survey data, which confirmed that many users did not tend to close the refrigerator door during stocking, placed the refrigerator in near vicinity to a heat source and manually turned the refrigerator off overnight.

The vast majority of users in both countries cleaned their refrigerators on a regular basis. 55% of users cleaned their refrigerators at least once a day and 40% cleaned them once a week. The remaining 5% cleaned their refrigerators at least once a month. Regarding internal and external vents, all users in Rwanda and 65% of users in India cleaned them on a regular basis. Figure 18 shows the frequency and depth of cleaning. On the other hand, only 41% of users in Rwanda and 14% of users in India reported that they know the correct procedure for removing ice build-up in the refrigerator. It should be noted that the user manual from the refrigerator manufacturer in India clearly outlines instructions for cleaning and defrosting, in addition to providing new customers with basic "*How to Use and How to Maintain*" training during the time of installation and handover.

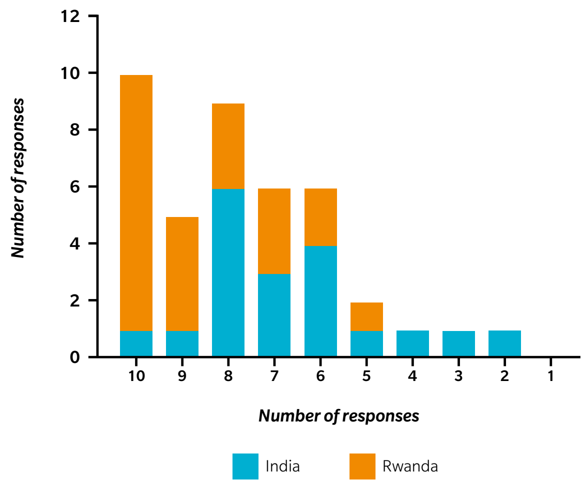
Figure 18: Frequency and depth of cleaning



46 VeraSol. 2022. Devidayal DDSF-100. https://data.verasol.org/products/ref/devidayal-solar-solutions8
47 For responses included in the endline survey, the sample set in India was 19 since one customer decided not to participate in the endline survey.

User satisfaction varied across the tested refrigerators in both countries but it was generally more positive in Rwanda compared to India. Four users in India and two in Rwanda indicated that their refrigerators have not been working well since they started using them. In India, only one of these dysfunctional refrigerators was repaired at the time of the endline survey. In Rwanda, one was repaired while the other was operational but did not provide as much cooling as it did at the time of purchase. As shown in Figure 19, 85% of the users in both countries indicated that they would recommend the refrigerator to a friend with a score of 6 or above (95% in Rwanda and 79% in India).[48] Furthermore, nine users in Rwanda reported the highest possible score when it comes to recommending the refrigerator to their friend compared to only one user in India. This variance can be attributed to factors such as refrigerator performance, previous experience with other refrigerators, frequency of use as well as quality of after-sales service. Having said that, the performance data also indicated that the field tested refrigerators in Rwanda generally performed better compared to India.

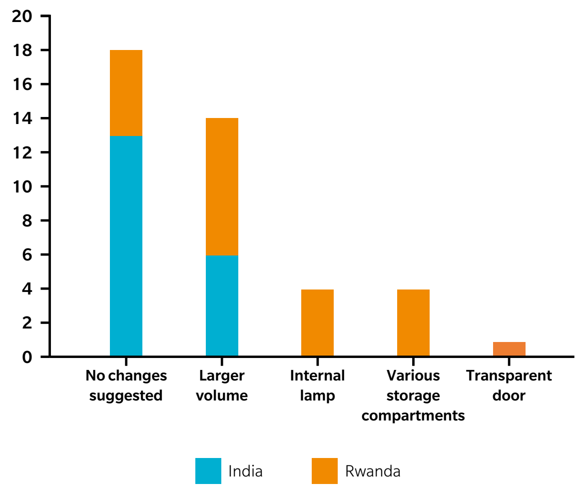
Figure 19: User satisfaction rate[49]



2.5.2. Design considerations

Gathering user feedback related to design considerations was an important part of the field testing survey to inform manufacturers about potential improvements to be made. Eight users in Rwanda would prefer to have larger internal compartment volume, four indicated they would like an internal lamp, another four would like to see the internal compartment being subdivided into different storage sections to allow for easier use, and one would prefer a transparent door to allow their users to view items without opening the refrigerator. In India, most users were satisfied with the current design of the refrigerator but six users indicated that they would prefer larger internal compartment. A summary of design considerations in both countries is shown in Figure 20.

Figure 20: Refrigerator design suggestions reported by users



Feedback related to accessibility and inclusivity of the existing design was broadly positive. Users were explicitly asked if there are any persons with disability using the refrigerator. Across the two countries, there were two instances in Rwanda where users employ or have a person with a disability in their household. One person had paralysis[50] while the other had hearing and eyesight challenges. In both cases, the users did not report any challenges with regards to access or usability of the refrigerators by the persons with disability.

2.6. Affordability and quality of life impacts

2.6.1. Affordability

Affordability remains to be a major barrier preventing a wider deployment of solar-powered refrigerators in off- and weak-grid areas. Therefore, we asked the users who used the refrigerators for productive use (90%), how long it would take them to earn back the upfront investment. It should be noted that users participating in the field testing were able to benefit from a subsidised cost when purchasing the refrigerator. In India, 80% of the refrigerator cost was subsidised by the LEIA programme with the end-user contribution of 20%. In Rwanda, 50% of the refrigerator cost was subsidised by the IFAD Green Technologies to Facilitate Development of Value Chains for Perishable Crops and Animal Products (GreenTech) grant.[51]

Bearing in mind the substantial end-user subsidy, the self-reported results were broadly positive. 92% of the users confirmed that they are able to cover the repayments entirely from the new income generated by using the refrigerator. Users in India reported that they would require an average of 7 months to repay the subsidised

48 It should be noted that user satisfaction should be decoupled from the number of refrigerators analysed in the performance data section since many refrigerators may have been working but there were issues with the remote monitoring modules – see Section 2.7 for further details.

49 With 10 being extremely likely to recommend the refrigerator to a friend, and 1 being not at all likely.

50 The survey response did not provide details regarding the type of paralysis.

51 IFAD. 2022. Green Technologies to Facilitate Development of Value Chains Perishable Crops and Animal Products. https://www.ifad.org/en/web/operations/-/project/2000001635

cost of the refrigerator compared to 22 months in Rwanda.[52] It needs to be reiterated that these results were self-reported and influenced by the amount of subsidy in each country, which explains the shorter repayment period in India compared to Rwanda. Therefore, these self-reported estimates cannot be used to make broader conclusions regarding affordability.

The vast majority of users (86% in Rwanda and 95% in India) used the solar-powered refrigerators for productive use activities to increase their income. The increased income was generated by more sales as well as energy cost savings (for grid-connected users who owned another refrigerator before). The self-reported income increase varied significantly across the two countries ranging between as little as $2 to as high as $150 per user per month. The income associated with the use of refrigerators also varied across seasons as reported by 53% of the users.

2.6.2. Quality of life

Most users across both countries reported an improvement in quality of life resulting from the refrigerator use. Improvement in quality of life was reported by 85% of users in India and 82% in Rwanda. The reason for remaining users who did not report improvement in quality of life in India was because two had owned another refrigerator and one reported low profit, whereas four users in Rwanda interpreted the question that it related to household use but they used the refrigerators in their businesses only. Apart from the financial impact of the refrigerators on the user income outlined in Section 2.6.1, additional impacts were reported by the users including reduced food waste, change in diet (more fresh food consumption including fruit), reduced food spoilage, having access to cold drinks, and fewer instances of illness from consuming unpreserved food, and ability to order products in bulk.

Users particularly valued time savings resulting from the refrigerator use. Users reported that they can buy products in bulk, therefore not have to go to the market as often (e.g. once a week rather than daily). Some users also cooked less often as they were able to cook larger quantities and store surplus food in the refrigerators for the next day.

Users also reported that they were able to store fresh produce safely for longer. 60% of users in India and 68% in Rwanda reported reduced food spoilage after purchasing the refrigerator. Users reported savings of $50 and $21 per month on average due to the reduced food spoilage in India and Rwanda, respectively. The remaining users reported that they do not store food in the refrigerator. Reduced food spoilage was related to storing fruit, vegetables, meat, fish, milk, butter and curd, although one user in Rwanda reported that milk sometimes goes off even when using the refrigerator. This may be because milk in churns was not being stirred inside of the refrigerators, which could result in disproportionate milk cooling speed throughout the churn. Further research is required to investigate the reasons and solutions to this issue.

2.7. Limitations and lessons learned

Both, survey and performance data collections during field testing were proven to be challenging so the aim of this section is to outline the key limitations and lessons learned for future field testing projects.

The distributors in Rwanda and India found sufficient number of users, although slightly below the target sample (the target was 25 users in each country) mainly due to the limited number of users who had recently purchased a refrigerator from them.

In total, 42 users took part in the field testing exercise and participated in both surveys apart from one user in India and one in Rwanda who declined to take part in the endline survey because the faulty refrigerators had not been repaired by the distributor. In India, some of the baseline and endline surveys were carried out with different people due to the unavailability of the first respondent, which meant that opinions and user experiences may vary.

Collecting performance data was proven to be more challenging compared to the survey data collection. In Rwanda, 18 refrigerators had sufficient data for consequent analyses. Two RMMs had corrupted SD cards, and two were removed by the in-country partner shortly after installation by the field team and not reinstalled.

Of the 20 refrigerators monitored in India, only eight refrigerators had sufficient data to be analysed. In addition to two refrigerators which had corrupted SD cards, there were ten refrigerators were used infrequently for various reasons such as breakdowns with users indicating that the repairs were not done or were delayed by the distributor, closing down the shop for prolonged periods (e.g. during winter), or using an alternative refrigerator. In total seven users mentioned not using their refrigerators due to breakdowns either throughout the testing period or for significant durations of the study time.

Of the eight refrigerators with sufficient data in India, four had internal temperatures aligned with ambient temperatures. Further query to the users indicated that the RMM temperature probes may not have been installed correctly or removed for two devices while the other two refrigerators were not working properly with users awaiting resolution from the distributor. Therefore, we analysed the remaining four refrigerators that had robust performance data without splitting them into different categories as we did for Rwanda.

We found that close collaboration with in-country partners and regular check-ins with users is key when collecting longitudinal field testing data. In some cases, performance data was very consistent when it comes to power consumption and internal compartment temperature, in which case data can be directly analysed without further interaction with the in-country partner or the user. However, in other cases we saw significant spikes in internal compartment temperatures which did not correlate with power consumption or ambient temperature

52 These are users' self-reported income generation and repayment estimates. There are no quantitatively-derived figures for income to triangulate these self-reported values

data. Subsequently, we found that some users removed the temperature probes by accident and returned them back later on, whereas others did not reinsert them back. This insight would be very difficult to identify by simply looking at the performance data alone. We experienced similar challenges in both countries where we conducted the refrigerator field testing.

We found that the most important lesson learned to improve data quality is to strike the right balance between encouraging more regular check-ins with users who participate in the field testing, while not overburdening them with too many requests for information. The users already spent significant amount of time participating in the baseline and endline surveys. Therefore, 2-3 brief, focused phone calls throughout the 6-month testing period with the express aim of understanding system health, disruption in use, and any unexpected performance behaviours should be sufficient for this purpose. This approach is particularly important if the data is not uploaded on the cloud in real-time but saved only on SD cards instead.

3. CONCLUSIONS

3.1. Summary of key observations

The combination of performance and user data collection enabled us to gain insight and draw parallels between user experience and refrigerator performance. The user data collection provided us with qualitative feedback from the refrigerator users. Due to the relatively small sample size, we were able to ask detailed open-ended questions which would not be possible with a short questionnaire conducted remotely. This user data supported the consequent performance data analyses, which was invaluable especially where performance data such as internal compartment temperature and power consumption were inconsistent. The close correlation between refrigerator performance and after-sales services, and user satisfaction was confirmed.

Testing refrigerators in two different countries was valuable to compare refrigerator performance in diverse climate conditions, different refrigerator manufacturers and distributors, varied user profiles, and unique uses cases. Refrigerators in India generally faced harsher conditions (ambient temperature and humidity) compared to Rwanda. All users in India were men and gained primary income from business whereas the gender split in Rwanda was equal between men and women and primary income was generated from various sources including business, employment, and farming.

Most users used refrigerators for productive use, which enabled them to increase income and offer fresh produce and cooled products to their customers. 90% of users across both countries used refrigerators to generate additional income by selling fresh produce and cold beverages. The income associated with the use of refrigerators varied significantly per user, country, and season.

Refrigerator performance was heavily influenced by user behaviour. More than one third of users in Rwanda turned their refrigerators off every night which negatively impacted the internal compartment temperature and power consumption when turned back on. We observed similar situation in India, where some users turned their refrigerators off for even longer periods. This was related to the fact that 85% users in India and 32% users in Rwanda reported that they do not know how to operate the refrigerator to reduce power consumption. Therefore, they may have turned the refrigerators off assuming that it will reduce power consumption, although the refrigerators are designed to provide consistent cooling at night and during cloudy days by using the incorporated battery and thermal storage.

The availability of user training and quality of after-sales services was non-uniform. User training provided by the refrigerator distributors varied across the two countries. This was evident from the performance and survey data, which confirmed that many users did not tend to close the refrigerator door during stocking, placed the refrigerator in near vicinity to a heat source, did not know the correct procedure for removing ice build-up in the refrigerator, and manually turned the refrigerator off overnight. In both countries, there were instances where distributors did not repair dysfunctional refrigerators by the time of the endline survey.

The overall user satisfaction was relatively high although improvements related to performance, training and after-sales services are still required. Most users across both countries indicated that they would recommend the refrigerator to a friend with a score of 6/10 or above (95% in Rwanda and 79% in India). Furthermore, nine users in Rwanda reported the highest possible score when it comes to recommending the refrigerator to their friend compared to only one user in India. Users with low satisfaction rate complained about refrigerator performance, poor training, and inadequate after-sales services when it comes to repair.

Field testing data collection is challenging, especially when it comes to performance monitoring. Survey data collection was relatively straightforward. The main challenge was related to the user availability, which resulted in a small sample of interviews were baseline and endline surveys were completed by different respondents (e.g. shop owner versus family member or shop employee). Remote performance data monitoring was significantly more challenging. All the door opening sensors (apart from one in each country) became loose soon after installation, four SD cards were malfunctional and the real-time data platform was not working. Having said that, we were able to retrieve and analyse performance data for the remaining refrigerators (apart from the ones that were being repaired, not being used by the users for prolonged periods, or sensors being removed and not reinstalled by the users).

Direct comparison of field testing results with laboratory results is challenging due to the variety of ambient temperatures, user behaviour and products stored. One of the aims of the research was to compare field testing data with VeraSol.

Refrigerators tested under VeraSol operate in controlled ambient temperatures and humidity, without door openings and with empty internal compartments. However, none of these parameters can be controlled in the field. We collected ambient temperature and humidity data but we lacked door opening data (frequency and duration) and products being stored in the refrigerator at the given time including type, quantity and temperature when entering the refrigerator.

3.2. Recommendations and next steps

1. Further field testing of refrigerators is required to evaluate the appliance performance under real conditions (e.g. the impact of door opening on performance losses) to inform more manufacturers and distributors about what works well and what needs to be improved.
2. Conducting user surveys and allowing them to answer open-ended questions removes bias and provides unforeseen insight.

3. Carrying out more frequent but brief and focused phone calls throughout the testing period with the express aim of understanding system health, disruption in use, and any unexpected performance behaviours has the potential to improve the quality of data and user satisfaction.
4. Improved user training and after-sales services are required for retaining users and achieving high satisfactory rates.
5. More controlled environment is required to test refrigerator performance and compare results. Robust testing requires to control and monitor ambient temperatures, humidity, door opening frequency and duration, but most importantly the type, quantity, and temperature of stored products.
6. Further standardisation is required to allow for a like-for-like comparison between different refrigerator types, uses cases and user profiles.

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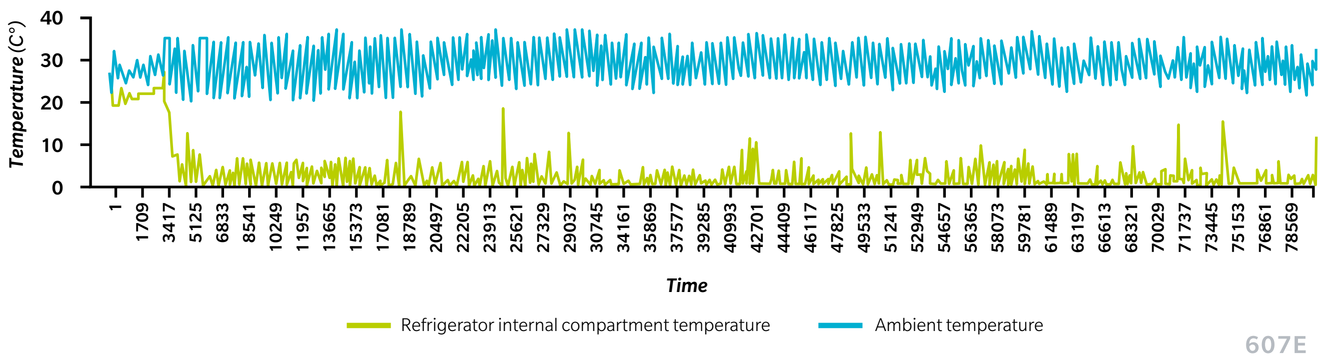
ANNEX I: EXAMPLES OF REFRIGERATOR DATA

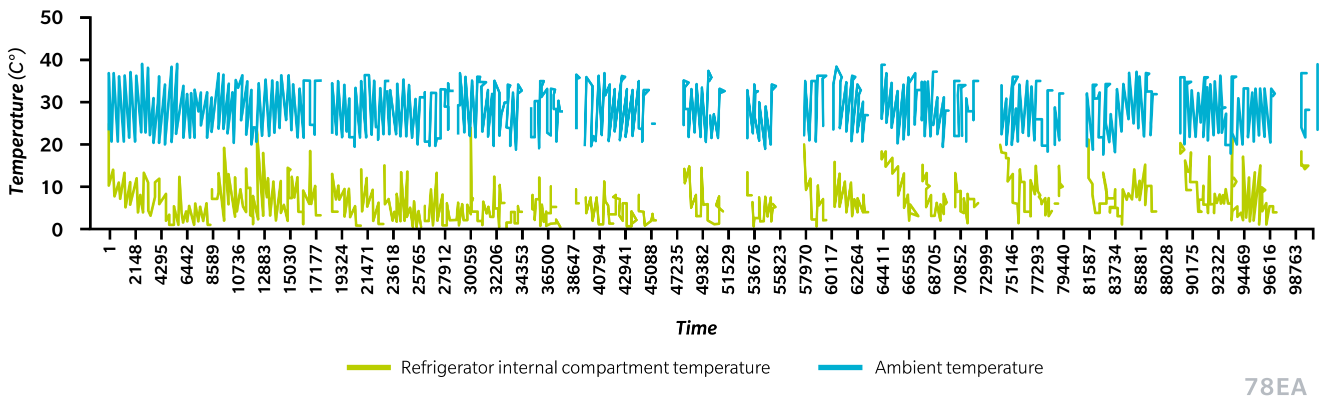
Rwanda Group A: Example of a specific refrigerator (full dataset)

Annex I.I. Rwanda Group A example – full dataset



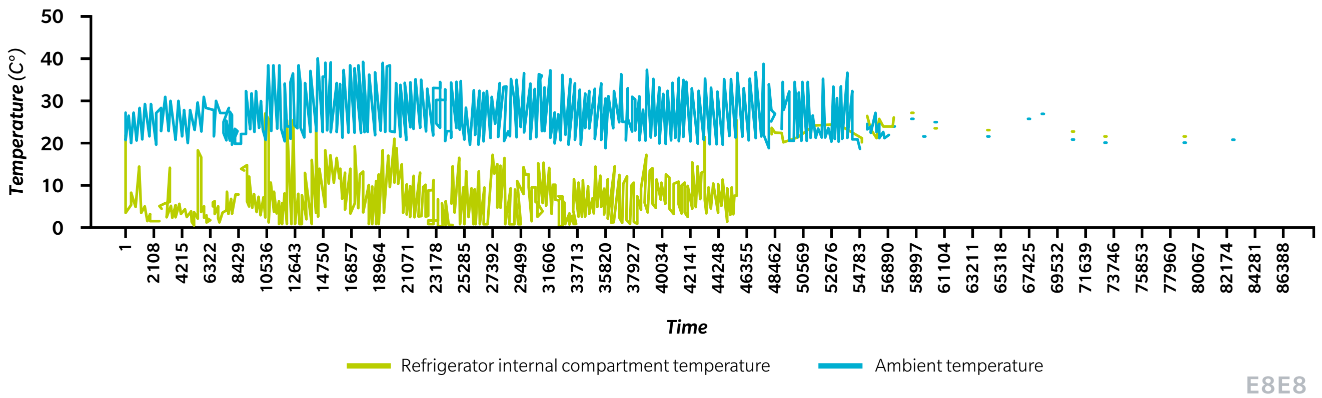
Rwanda Group B: Example of a specific refrigerator (full dataset)

Annex I.II. Rwanda Group B example – full dataset



Rwanda Group C: Example of a specific refrigerator (full dataset)

Annex I.III. Rwanda Group C example – full dataset



ANNEX II: UNDERVOLTAGE AND OVERVOLTAGE

Annex II.I. Undervoltage events – Rwanda

#	Device	Number of sustained undervoltage events	Minimum undervoltage value (V)	Longest undervoltage duration (minutes)
Category A				
1	607E	1	9.32	3
2	68FB	25	8.35	15
3	6CEF	1	8.45	3
4	E8FD	2	3.37	3
Category B				
5	34B1	213	2.31	6
6	78EA	1	5.63	3
7	80B4	24	9.93	15
Category C				
8	68EB	1	10.23	3
9	68FE	1	10.67	3
10	6CF8	25	8.19	9
11	78F9	13	2.31	3
12	E8E8	105	2.31	6
13	FCF8	6	4.56	3

Annex II.II. Undervoltage events – India

#	Device	Number of sustained undervoltage events	Minimum undervoltage value (V)	Longest undervoltage duration (minutes)
1	F007	4896	10.1	102
2	F012	6645	9.67	105
3	F018	3421	10.31	87

Annex II.III. Overvoltage events - Rwanda

#	Device	Number of sustained undervoltage events	Minimum undervoltage value (V)	Longest undervoltage duration (minutes)
Category B				
1	34B1	18	14.49	3
Category C				
2	FCF8	2	19.63	6

ANNEX III: AUTONOMY

Annex III.I. Autonomy from 4°C to 12°C – Rwanda

#	Device	Duration (hours)	Ambient temperature at start (°C)
Category B			
1	78EA	2.0	34.0
Category C			
2	6CF8	6.85	25.0
3	68EB	48.65	23.0
4	68FE	69.15	20.0
5	E8FA	56.85	26.0
6	78F9	2.45	28.0

Annex III.I. Autonomy from 4°C to 12°C – Rwanda

#	Device	Duration (hours)	Ambient temperature at start (°C)
1	F012	9.8	29
2	F018	2.8	30

ANNEX IV: PULL-DOWN

Annex IV.I. Pull-down to 8°C and 4°C – Rwanda

#	Device	Starting refrigerator internal compartment temperature (°C)	Target temperature (°C)	Duration (hours)
Category A				
1	607E	10	8	1.35
		10	4	2.9
Category B				
2	34B1	10	8	1.25
		10	4	6.05
3	78EA	11	8	4.15
		No data	4	No data
4	80B4	15	8	2.0
		No data	4	No data
Category C				
6	78F9	13	8	2.8

Annex IV.I. Pull-down to 8°C and 4°C – Rwanda (continued)

#	Device	Starting refrigerator internal compartment temperature (°C)	Target temperature (°C)	Duration (hours)
Category C				
6	78F9	11	4	3.65
7	68FE	10	8	0.55
		10	4	1.55
8	E8FA	11	8	0.4
		11	4	1.6
9	E8E8	13	8	1.5
		13	4	5.45
10	78F9	13	8	2.8
		11	4	3.65
11	FCF8	14	8	3.65
		No data	4	No data
12	68EB	15	8	2.3
		No data	4	No data
13	6CF8	30	8	0.3
		13	4	2.1

Annex IV.II. Pull-down to 8°C and 4°C – India

#	Device	Starting refrigerator internal compartment temperature (°C)	Target temperature (°C)	Duration (hours)
1	F018	21.0	8	1.4
		21.0	4	2.0
2	F012	15.0	8	1.7
		15.0	4	3.2
3	F007	28.0	8	1.6
		28.0	4	2.2

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