Evaluating Appliance Performance in the Field: Results from Beta Testing of Remote Monitoring Solutions

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Contents

Acronyms and Abbreviations

API	Application Programming Interface
IoT	Internet of Things
SD Cards	Secure Digital, abbreviated as SD, is a proprietary non-volatile memory card format developed by the SD Association for use in portable devices.
GSM	Global System for Mobile Communications
LoRaWAN	Low Power Wide Area Network
SigFox	French-based low power wide area network which sends small data packets (100bps) from sensors
Pay Go	Pay-as-you-Go business model
RMM	Remote Monitoring Module

Context

The off-grid appliance space, especially for larger productive use appliances, is nascent compared to the conventional on-grid market. Advancements, such as reduced prices of solar power modules, have resulted in new and more powerful solar powered appliances entering the market. This creates a need for asset owners, investors, companies, donors, researchers and industry support organisations to evaluate and compare the performance and impact of these appliances. Adoption of PAYGO business models has seen an increase in the use of remote monitoring solutions to gather data on appliance usage and optimise the performance of appliances.

Assessing the technical performance of off-grid appliances through laboratory testing is becoming common practice through programs like VeraSol and Global LEAP Awards. However, lab testing has limitations in determining the full spectrum of product performance, especially where user interaction is a significant factor. To address these limitations, one can monitor the long-term performance of off-grid appliances in the field while in use by consumers. However, this approach presents unique challenges including, the lack of cost-effective, plug and play solutions that can monitor different parameters across a suite of appliances and a lack of technical expertise to develop appropriate monitoring solutions.

Efficiency for Access beta-tested remote performance monitors to build a replicable approach for field testing solar refrigerators, solar water pumps, and solar milking machines. Various sensors and monitoring equipment were tested to identify and develop an ideal solution that monitors the technical performance of select off-grid appliances. The data collected will inform the development of field-testing guides that stakeholders can apply in the off-grid solar sector and support the revision and development of test methods managed by Global LEAP Awards and VeraSol.

A key finding from the beta testing is that a one size fits all monitoring solution is not appropriate across appliances with different testing needs and complexity. Additionally, external factors such as cost or sensors, communication protocols available in target geography and sensor interoperability significantly affect the measurement methods for field-testing. Thus, the design of an ideal monitoring solution must take into consideration:

- the maximum and minimum power rating of appliances to be monitored;
- data granularity and recording intervals;
- data communication channels and network connectivity; and,
- the intrusiveness of the monitoring solutions

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Introduction

Asset owners, investors, donors, researchers and industry support organisations have various needs in understanding the performance of appliances designed to improve living conditions and increase access to energy in developing countries. Efforts to bridge the existing information gaps include monitoring energy production, measuring energy utilisation by connected electrical products, and monitoring the delivered service to quantify the impact of the products. Efficiency for Access Coalition programs, such as VeraSol and the Global LEAP Awards have developed laboratory test methods for off-grid refrigerators, solar water pumps, and electric pressure cookers. The test methods help understand the appliance performance and promote high-quality, high-performing appliances through product certification and results-based financing mechanisms. While lab testing has contributed to a better understanding of the technical performance of appliances, a critical data gap exists on performance in real-world environments and how user interactions and behaviour affect long-term performance.

To address this, Efficiency for Access launched a field-testing initiative to understand the performance of off-grid refrigerators, solar water pumps and solar-powered milking machines in Kenya, Tanzania, Rwanda, Senegal and India. Monitoring the performance of appliances while in use by consumers presents unique challenges, especially in selecting an ideal solution for remote monitoring. Depending on the technical performance metrics and complexity of the appliances to be monitored, a simple plug and play solution may often be inadequate in providing an end-to-end[1] monitoring solution for off-grid contexts. Such off-the-shelf monitors are becoming increasingly popular in the on-grid space, especially in the Global North, where they can be integrated with smart grids and internet of things (IoT) applications.

For nascent off-grid appliances, remote monitoring technologies for low and high-power (DC) solar energy solutions are gaining traction as more companies adopt Pay-Go systems. Navigating this complex world of remote monitoring solutions requires a comprehensive understanding of the technical specifications of the appliances, communication modules available in each geography and the technical and logistical lift required to implement the final solution. CLASP, supported by EED Advisory LTD, carried out beta testing on select monitoring and communication equipment to validate the technical specifications of the test appliances and evaluate the options for collecting data. This technical note provides insights on the testing and selection of remote performance monitors, including the factors considered, potential challenges and possible mitigations when developing a customised remote monitoring solution.

[1] A fully functional solution that addresses all the monitoring needs for the different appliances in scope.

Methodology

This beta-testing exercise focused on testing the suitability of technical performance measurement equipment to collect data for the different metrics indicated in Table 1. These parameters are based on the Global LEAP test methods for refrigerators and solar water pumps. These key performance parameters are also evaluated in the laboratory testing process, which serve as a baseline for comparison with field testing results. Solar-powered milking machines are a new appliance of focus under Efficiency for Access. Therefore, in this initial testing, only energy performance was monitored.

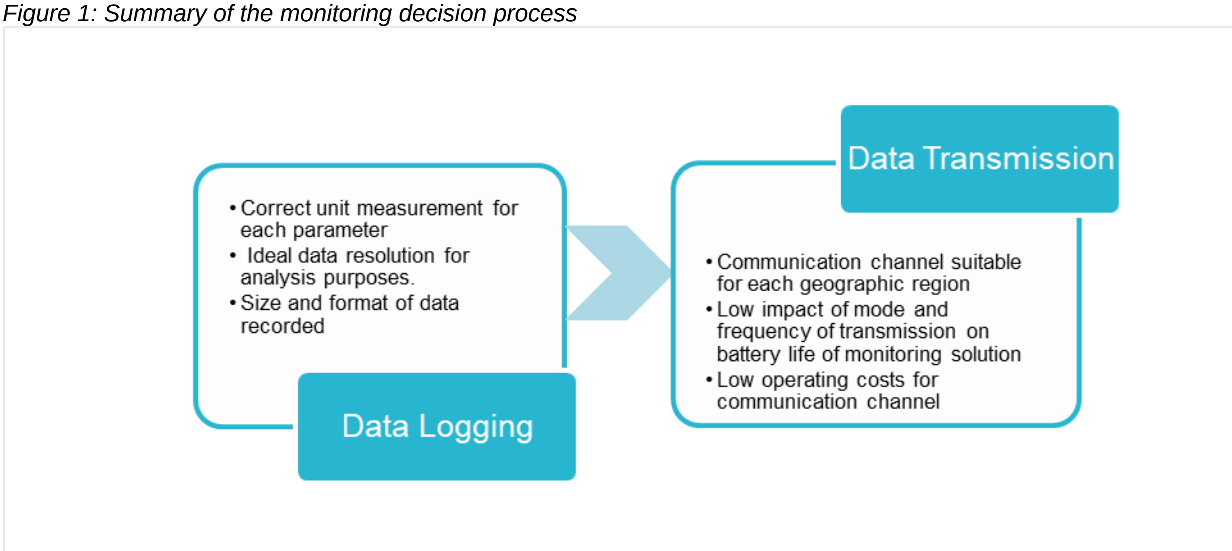
Table 1: Performance testing metrics across test appliances

#	Parameter	Solar refrigerators	Solar water pumps	Solar milking machines
1	Voltage	X	X	X
2	Current	X	X	X
3	Ambient humidity	X		
4	Ambient temperature	X		
5	Internal temperature	X		
6	Door state(open/closed)	X		
7	Flow rate		X	
8	Yield[2]		X	

The guiding criteria in selecting a final monitoring solution were:

1. how to sufficiently record the technical performance data
2. how to transmit the recorded data to a central repository. See Figure 1.

Figure 1: Summary of the monitoring decision process



Remote data transmission was preferred to local storage for data management. It allows for real-time performance and service delivery monitoring and real-time debugging in the event of data logging issues. However, in instances of limited connectivity, local storage is beneficial in preventing data loss. An ideal solution combines remote data transmission and local storage to leverage the benefits of both.

[2] Volume of water pumped in an hour or in a day.

Identifying, Testing and Selecting the Right Sensor

Considering the diversity of the appliances to be monitored and the similarity of some of the parameters, the sensors and equipment were categorised as:

1. Power consumption sensors
2. Service delivery sensors
3. Communications and data handling equipment

Under each of these categories, two main steps guided the selection of the final monitoring solution:

1. Sensor pre-qualification and selection
2. Beta testing, results and learnings

Power Consumption Sensors

Sensors record the voltage and current drawn by the appliances and this in turn is used to calculate power consumption.

Pre-screening and selection

The appliances' voltage and current ratings collected from the appliance datasheets were the main input for screening and selecting the voltage and current sensors (See Table 2). However, in some cases, after preliminary tests using voltage and current meters, the manufacturer-provided ratings indicated on the datasheets were inconsistent with the preliminary readings. In these instances, manufacturers were consulted for clarification.

A maximum voltage and current were selected to determine the upper limits of the power consumption sensors for the appliances. Across all test appliances, this equated to 35 Volts and 14 Amperes; thus, a maximum possible power draw sensing limit of 490 Watts.

Beyond the quantitative measuring capability of the sensor, the following criteria were considered:

1. Consistent performance across the measurement range – which is the repeatability of measurement precision within the measurement range
2. Measurement accuracy of 1% or better, e.g. +/- 0.5 °C for the temperature
3. Availability and affordability of sensor components from the manufacturers

Table 2: Power consumption characteristics across appliance types

Appliances	Maximum voltage across appliances in scope (V)	Maximum current across appliances in scope (A)
Solar Water Pumps	35	14
Milking Machines	24	10
Refrigerators	31.5	8.6

Testing and Results

Voltage – This was measured by the voltage divider rule, which records DC voltage range across the appliance types[3]. A voltage divider is a circuit that converts high voltage into a lower voltage suitable to specific processors. If the high Voltage (V) is converted to low voltage (v), using a ratio of 1/R[4], the processor reads v

[3] Horowitz, Paul, and Winfield Hill. 1989. The Art of Electronics. 2nd ed. New York: Cambridge University Pres

[4] R = Resistance

and multiplies it by R to obtain V as indicated in Equation 1. The same method is also applicable for the measurement of mains AC voltages.

Equation 1: Voltage divider method

$$v = V\ x\ (1/R)\ therefore\ V = v * R$$

Current - The Allegro Microsystems ACS712ELCTR-20A-T current sensor was selected based on CLASP's prior field-testing experience. This sensor converts sensed current into a proportional, measurable voltage quantity that a processor can easily read.

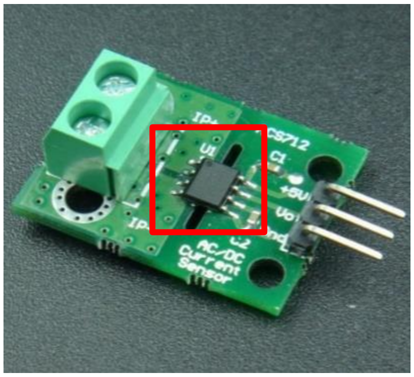


Figure 2: ACS712 Current sensor and performance characteristics

This sensor has the following advantages:

- Measurement accuracy – The sensor is documented to have a 1.5%[5] total output error. The construction is well controlled and the hall effect circuitry is contained within the semiconductor die. As a result, the sensor is factory calibrated and does not experience drift as a function of time or installation orientation compared to external Hall Effect sensors.
- Affordable and readily available – It can be purchased at less than USD10 per unit in single quantities from electronic suppliers such as Digikey.
- Measurement range – The sensor can measure above the required 14 Amperes of current. See Table *2*. The measurement total output error is also consistent regardless of changes in ambient temperature, with a maximum +/-1.5% variation between -25 degrees Celsius to 150 degrees Celsius.

Appliance Specific Performance Sensors

Solar Water Pump Flow Meter

Pre-screening and Selection

Solar water pump yield is measured by calculating the volume of water pumped within a given period. The majority of flow meters (ultrasonic, magnetic, turbine and vortex meters, among others) have a maximum flow rate specification. Exceeding this would give inaccurate readings. For this project, selecting an ideal flow meter was based on the diameter of the outlet pipe and the maximum flow rate as specified by the manufacturer.

Table *3* highlights the various outlet pipe diameters and the specified maximum flow rate for the different test SWPs from the manufacturers.

[5] Allegro Microsystems. https://www.allegromicro.com/en/products/sense/current-sensor-ics/zero-to-fifty-amp-integrated-conductor-sensor-ics/acs712.

Table 3: Water flow rate across solar water pump types

Manufacturer	Largest outlet diameter (in)	Maximum flow rate (M^3/Hr)
A	2	14
B	2	13
C	1.25	3.6
D	1.25	3.6

Other criteria used in screening the flow meters include:

- Ability to remotely send data uniformly across various geographies – Due to the wide geographic scope (multi-country) and the in country geographic spread of the pumps to be monitored, the ideal flow meter must be able to record and transmit the data uniformly without the need of additional communication and data logging equipment.
- Reliability of measurement – this is determined by the presence of calibration data for the sensor.
- Availability of technical information such as datasheets and Application Programming Interfaces (APIs) to support measurement retrieval.
- Resistance to water ingress – Most smart flow meters are designed for industrial settings and are sometimes unsuitable for outdoor use. Given SWPs are typically installed outdoors, the ability to protect electronics against rain and groundwater intrusion is critical.
- Potential for sourcing at desired quantities at an affordable cost[6]
- Ability to work in turbid[7] water – Some pump users use groundwater sources that can be turbid, requiring meters such as the turbine and other mechanical flow meters to undergo routine maintenance caused by clogging.
- High data resolution[8] for more straightforward correlation analysis, especially with energy performance data.
- An Independent power source with low energy consumption is ideal for long monitoring periods.

Testing and Results

Figure 3: BECO X GSM ultrasonic flow meter and the YF-S201 Hall Effect[9] water flow meter, respectively

Due to their availability and affordability, two measurement sensors (Figure 3) were pre-selected for testing and evaluation.

- The YF-S201 flow meter contains a pinwheel magnetic sensor, which measures turbine rotations and converts this to the volume of fluid swept/passed per unit rotation. When paired with an intelligent

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[6] Majority of GSM enabled meters with the required data recording frequency cost more than USD 200 each. For our case, The selected flow meter cost less than USD 100 a piece.

[7] Turbidity is a measure of the cloudiness or haziness of water generally from dissolved and tiny suspended particles.

[8] Resolution in this case translates to the data recording interval where the more the recording frequency, the higher the data resolution.

[9] The working principle of the Hall Effect water flow rate sensor is that a small rotor is present within the meter body. As water goes through the meter it rotates the rotor which causes a voltage difference to be induced that is the measured by the adjoining hall effect sensor. The water flow rate is directly proportional to the voltage induced by the rotation of the rotor.

platform such as a microprocessor, this can be summed up and additionally sent to the cloud given the appropriate hardware.

- The BECO X flow meter sold by Jiaxing Bove Intelligent Technology Co., Ltd uses sound waves between two transducers by measuring the transit times to measure flow rate. The BECO X flow meter records cumulative volume and sends this data once a day to the cloud.

The two sensors were further evaluated based on the criteria in Table 4.

Table 4: Evaluation criteria for water flow rate meter

Selection criteria	BECO X Ultrasonic Flow Meter	YF-S201 Hall Effect Flow Sensor
Ability to remotely send data uniformly across countries	Yes	No. Needs additional hardware to allow for data recording and interpretation
Availability of manufacturer datasheets	Yes	Datasheets were provided but with insufficient information. Manufacturer details are also unavailable.
Available at an affordable cost (less than USD 100 for our case)	Yes	Yes
Resistance to water ingress	Yes (IP-68)	No
Maximum flow rate within the range of solar water pumps in scope (Maximum pump flowrate is $14m^3$/ hr)	Yes, up to $20m^3$/ hr for a 2-inch outlet diameter	Yes. Working Flow Rate: $1.8m^3$ /hr
Frequency of sending data remotely and its impact on expected battery life	From marketing information: six years battery life while sending data once a day.	Dependent upon the hardware it interfaces with. The sensor also needs a battery. The effect of data transmission frequency on the battery is therefore unknown at the sensor level.
Ease of retrieving the data for analysis	Yes, but it requires additional server-side software to retrieve the data from the manufacturer's servers.	No, Requires additional hardware design, firmware and server-side software.
Easily calibrated	Yes	No

The BECO X ultrasonic flow meter was selected because it meets more selection criteria than the hall-effect flow sensor.

Refrigerator Performance Sensors

Ambient temperature, internal fridge temperature and humidity sensors

Pre-Screening and Selection

The selection of the ambient temperature, internal fridge temperature and relative humidity sensors was based on two main criteria and governed by:

1. Ranges for each of the parameters to be monitored
2. Ease of installing the sensor on the fridge or alongside other sensors. See Table 5 below.

Table 5: refrigerator specific sensor selection criteria

	Measurement Requirements	Installation constraints
Ambient temperature	Ambient temperature range of 0°C - 60°C	- Limited interoperability with other sensors and ancillary hardware such as the real-time clock and GSM module within the remote monitoring module.
Relative Humidity	0-95%	- Limited interoperability with other sensors and ancillary hardware such as the real-time clock and GSM module within the remote monitoring module. -
Internal refrigerator temperature	Temperature range from ambient to -20°C	- Ability to have various placements in the fridge/freezer to avoid impeding the regular use of the appliance across various devices.

Testing and Results

Ambient temperature and relative humidity – The DHT22 temperature and humidity sensor was selected. It is temperature compensated[10] and factory calibrated with an accuracy of +/- 0.5% degrees Celsius and +/-1% relative humidity. The recommended data retrieval interval is 2 seconds. It is widely available and has suitable specifications for adequately measuring the range needed in the project.

Figure 4: DHT22 temperature and humidity sensor

Internal fridge/freezer temperature sensor

An extendable waterproof temperature sensor was selected for monitoring the internal fridge/freezer temperature. This sensor can be placed away from the refrigerator walls, which are typically cooler than other refrigerator parts, allowing for a more accurate recording of the internal temperature. The flat cable allows placement through the refrigerator door thermal seal without any possible leaks. See Figure 5.

[10] Temperature compensation refers to the ability of a sensor to counteract or correct undesired temperature influences.

Figure 5: Waterproof DS18B20 temperature sensor probe placement through fridge thermal seal

Table **6** highlights some of the sensor characteristics that make it ideal for monitoring internal fridge temperature.

Table 6: Temperature sensor characteristics

Requirements	DS18B20 temperature sensor probe Characteristics
Ability to measure to -20 degrees Celsius	Yes. Operates from -55 to +125 degrees Celsius
Calibration	Factory calibrated
Accuracy	+/-0.5 degrees Celsius.
Ease of installation	It is easily wired from outside the fridge to the internal chamber of the fridge

Refrigerator door state sensor

Pre-screening and Selection

Ideally, a door state sensor records the number and duration of door openings when a fridge is in use. While this metric does not directly measure the technical performance, it is crucial for interpreting the measured technical data. For example, in understanding how different users interact with their fridges and how this affects temperature variation. In selecting an ideal door state sensor, two main factors were considered, i) Ability to accurately record data for both top load and front load fridges and ii) ease of installation on the fridge and in relation to other sensors on the fridge.

Testing and Results

Two-door state sensors were pre-selected for sampling and further testing. Figure 6 shows a magnetic switch and an accelerometer switch.

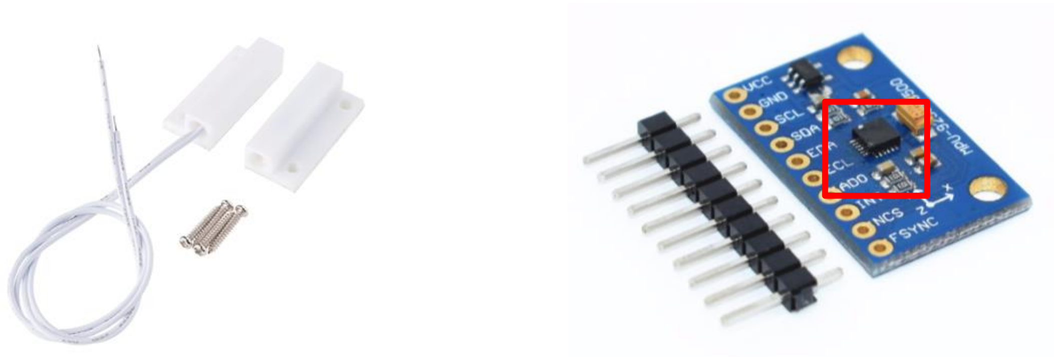


Figure 6: A magnetic door sensor and accelerometer

The magnetic switch operates by sensing the proximity of the magnetic field when the door is closed and when open. A timer will record the time and duration of each event. The accelerometer senses the change in direction during door opening and closing. However, this depends on the installation orientation and number of directions supported (up to 6 axes) and may need software calibration, further complicating the installation process.

Table 7: Fridge door opening sensor characteristics

Selection criteria	Magnetic door sensor*	Accelerometer
Affordability	Yes	Yes
Ease of sourcing	Yes	Yes
Consistent performance across the top load and side load fridge types	Yes	Yes, but it is sensitive to installation position as a given sensor may support 1, 3, 9 measurement axes depending on the sensor model. It requires calibration during installation.

The magnetic door sensor was selected because of the ease of installation across the top and sideload fridges/freezers. Figure 7 shows the final placement on a top-load refrigerator.

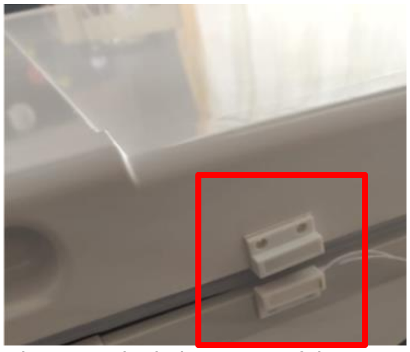


Figure 7: Final placement of the magnetic switch door state sensor

Milk Flow and Yield Meter

Most food-grade flow meters are used in industrial settings where routine maintenance takes place. For the solar-powered milking machine in our scope, it is nearly impossible to retrofit a flow sensor without voiding the warranty of the milking machine and interfering with the regular practice of the user. The milk flow meter would require routine hygiene maintenance, including cleaning, to avoid the risk of contaminating the milk. The flow meter also can't differentiate the type of fluid, I.e. water vs milk passing through the flow meter. We explored other remote monitoring options, including using a level sensor in the milking container. This method was not ideal as it would interfere with the regular usage of the milking machine where the user has to remove the sensor during cleaning and possibly capture erroneous data when other fluids are poured into the container.

To address this measurement challenge, we proposed an alternative method in place of absolute quantities. It is observed during beta testing that quantity of yield is correlated to power consumption. The power consumption increases as milk yield from the cattle increases. As such, the power consumption data would indicate when milking process is happening, while daily SMS surveys will be administered to milking machine users to record the actual amount of milk pumped using the milking machine. This data will be correlated with power consumption data to understand the energy performance versus service delivery of the solar-powered milking machines.

RMM data handling (real-time communication and local storage)

For field testing, reliable data storage and timely communication of collected data are just as necessary as the accurate measurement of performance metrics. In beta testing, we explored various communication options available in each target country, including:

- Global System for Mobile Communications (GSM), which is the most common mode for communication service providers,
- Long Range Low Power Network - (LoRaWAN) - LoRaWAN is a communication protocol designed to connect battery-operated devices to the internet in regional, national or global networks. Device data must pass through a LoRaWAN base station to reach the internet. LoRAWAN communication base stations and devices are available in some markets. However, these are only applicable for a smaller geographic spread of up to a few kilometres per base station, typically 10 kilometres or less. There is no centralised management of LoRaWAN base stations, allowing smaller organisations to run private networks.
- Sigfox, a French-based low power wide area network communication company and local storage (storage within the remote monitoring module).

Each communication channel presents its unique challenges in terms of hardware, cost of equipment, power consumption in data recording and transmission, and logistical requirements for data retrieval in the case of local storage. Due to the wide geographic spread of some of the appliances to be monitored (up to 30 KMs apart), the preference was for a solution that can work over long distances and be replicable across different countries

Real-time communication through GSM – This communication protocol was preferred over other protocols such as Sigfox or LoRa. Unlike LoRa or Sigfox, all the countries within the project scope have compatible mobile operators meaning that a single communication RMM will work seamlessly across these regions. However, signal quality and strength above-100dB is recommended for the RMM to avoid delays in sending the data.

Backup local storage – Industrial grade Secure Digital (SD) cards were preferred due to their ability to withstand high temperatures, unpredictable power cycling, and higher quality construction instead of consumer-grade SD cards. Though more expensive, a balance between cost and quality had to be evaluated. The chosen size was 512MB and sourced from ATP Electronics from their industrial-grade Micro SD card product line. A Real-Time Clock (RTC) chipset was also used to maintain a timestamp of stored and sent data using the **hh-mm-ss-dd-mm-yy** format.

Discussion on Selected Monitoring Solutions

Based on the complexity and requirements for performance measurements of each test appliance, a one-size-fits-all RMM could not be applied across the board. The final design of the solar water pump and milking machine RMM (referred to as the base RMM) incorporates the standard sensors required to measure common performance parameters across the two appliance classes: power consumption, real-time data communication and local data storage. Further, sensors to measure performance parameters specific to each test appliance were added and are detailed in the sections below.

Design solution for monitoring refrigerators

The fridge RMM varies from the base RMM to include an internal temperature sensor and a magnetic door-opening sensor. Further, the fridge RMM has a battery to monitor internal temperature continuously and door opening events without solar/battery power (see annexes for refrigerator RMM design). The sensors selected for developing the fridge/freezer RMM and the description of the overall workings and placement of the RMM are indicated in Table 8.

Table 8: Design considerations for measurement of the fridge

#	Design characteristics	Design and equipment installation decision
1	RMM	The RMM will be located outside the fridge, along with the appliance's power cable.
2	Voltage	Depending on the type of connectors used from the power source to the appliance, we will pre-fix the RMM with the appropriate connectors to allow for an easy plug and play connection without damaging any cables. The RMM measures a voltage of up to 60 volts.
3	Current	Depending on the type of connectors used from the power source to the appliance, we will pre-fix the RMM with the appropriate connectors to allow for an easy plug and play connection without damaging any cables. The RMM measures a current of up to 15 Amperes.
4	Ambient temperature and relative humidity	The ambient temperature sensor will be housed within the RMM. The temperature sensor will measure ambient temperatures between -20°C - 85°C. The temperature sensor will measure humidity between 0% - 85% relative humidity.
5	Fridge temperature	A cable will run from the RMM to the fridge's internal compartment. This cable will pass through the thermal sealant and should be of an acceptably small diameter. The most appropriate positioning for the entry of the cable is away from the hinges and door handles. A sufficiently long cable will be used to avoid exposing the cable to mechanical stress during door movement. The temperature sensor will be suspended in the fridge to avoid placement too close to the top, bottom or on the sides of the fridge where the temperature might be lower or higher than other parts of the fridge.
6	Sampling interval	Data recording/sending for the fridge RMM is event-based. The RMM samples all measurement parameters at the same time instant. The sampling interval is 5 seconds. After taking the measurement, the RMM compares the instantaneous values per measurement variable with its previous value and records/sends the data if it varies from the previous measurement. For example: Door state has changed to open; the temperature has changed by two °C, et cetera, triggering a data record. If there is no variation in the measured parameter over 5 minutes, only one measurement is recorded/sent. The most appropriate SD cards to be used are industrial SD cards that have been rigorously tested.
7	Door opening/closing	The RMM will utilise magnetic reed switches to detect when the door has been opened or closed. This approach will work well for front load fridges as well as top load fridges.

8	Diurnal solar irradiance variation and power outages	In a power outage, the RMM will switch to battery power to continuously record temperature changes and instances of door openings.

Design solution for monitoring the performance of solar water pumps

The solution will combine the base RMM and a separate ultrasonic GSM enabled flow meter for solar water pump testing. Both the RMM and the meter will transmit data to a central data repository for storage and analysis. See Table 9 for the sensors selected for developing the SWP RMM and a description of the overall workings and placement of the RMM and flow meter.

Table 9: Design considerations for the measurement of the solar water pump

#	Design considerations	Design and equipment installation decision
1	RMM placement	The RMM will be placed along the appliance's power cable.
2	Voltage	Depending on the SWP model, the RMMs will be pre-fixed with PCB and or three-pin power connectors which will be plugged onto the SWP power cords. The RMM will measure a voltage of up to 60 volts.
3	Current	Similar to voltage sensing, plug and play cables will be pre-fixed to the RMM and plugged onto the SWP power cords. The RMM will measure a current of up to 15 Amperes.
4	Flowrate	Flowrate will be measured using a calibrated ultrasonic water flow meter. The water meter has the capability of sending data remotely through GSM 900/1800 networks. Beco X ultrasonic meters have been selected varying in pipe size from DN25, DN 32 and DN 40 depending on the maximum flow rate (Qmax) of the studied SWP's.
5	Sampling interval	The RMM samples all measurement parameters at the same time instant. The sampling interval is 30 seconds, with data being recorded/sent at a similar time interval. Industrial grade SD cards will be used to store data locally in cases of connectivity issues.
6	Diurnal solar irradiance variation	As the RMM is solar-powered, it will usually record data during the day and send it to the data collection server. For direct drive pumps, there is no need to have a battery system for the RMM in this case because direct drive pumps will only work when there exists sufficient solar irradiance. In the case of battery-driven and direct drive pumps, the RMM is powered from the same power source supplying the pump hence measuring pump data only when the pump is activated.

Design solution for monitoring the performance of milking machines

As described above, the solar-powered milking machine remote monitoring module will only monitor the power consumption data. This will thus consist only of the base RMM. Table 10 summarises the final design consideration and installation protocols.

Table 10: Design considerations for the measurement of the milking machine

#	Design considerations	Design and equipment installation decision
1	RMM placement	The RMM will be placed along the milking machine's power cable.
2	Voltage	The RMM power cables will be connected to the milking machine power cords. The RMM will measure a voltage of up to 60 volts.
3	Current	Plug and play cables will be pre-fixed to the RMM and plugged onto the milking machine power cords. The RMM will measure a current of up to 15 Amperes.
5	Sampling interval	The RMM samples all measurement parameters at the same time instant. The sampling interval is 30 seconds, with data being recorded/sent at a similar time interval. Industrial grade SD cards will be used to store data locally in cases of connectivity issues.
6	Diurnal solar irradiance variation	As the RMM is solar-powered, it will usually record data during the day and send it to the data collection server.

Best Practices for RMM Installation

Besides the technical and design considerations for installing the remote monitoring solution, there are other considerations to ensure that the users welcome the solution, it does not interfere with their everyday operations and is not destructive to the appliance. Table 11 provides some of the installation considerations and best practices when installing the RMMs.

Table 11: Best practices for the deployment of the remote monitoring solutions

Refrigerator RMM	• For more accurate average internal temperature, the internal temperature probe must not be installed closer to the refrigerator walls as they are cooler than other areas of a fridge. • The Internal temperature probe should not interfere with the normal functioning/usage of the refrigerator. • Ambient and relative humidity sensors should not be installed close to the refrigerator compressor or anywhere where temperature readings might be above room temperature. • A pre-fitted power cord with appropriate connectors ensures that installation does not interfere with the power cables of the appliance even after the monitoring period is over and the RMM has been retrieved. • Drilling through the fridge walls or the thermal seal should be avoided. Cabling and placement of sensors should be done either through tape or mild glue that can be easily removed.

Solar Water Pump RMM and Flow Meter	• A pre-fitted power cord with the appropriate connectors ensures that installation does not interfere with the power cables of the appliance even after the monitoring period is over and the RMM has been retrieved. • For portable SWPs, the RMM should be secured tightly to the pump to avoid falling off or damage to the power cables or the ports. • The flow meter should be installed along the main conduit pipe from the pump. • RMM casing must be waterproof to avoid water damage to internal RMM components
Milking Machine RMM	• Placement of milking machine RMM should not interfere with the normal functioning/usage of the milking machine. • Pre-fitted power cord with the appropriate connectors ensure that the installation does not interfere with the power cables of the appliance even after the monitoring period is over and the RMM has been retrieved.

Conclusions and Recommendations

Conclusions

Beta-testing is a crucial part of field testing

From the learnings of this beta testing exercise, we cannot understate the importance of beta testing of sensors, communication modules and other ancillary hardware before deploying the selected solution in the field. As was found in this beta testing exercise, manufacturer specifications may be inaccurate and manufacturer's datasheets may not provide the required data for accurately selecting a final monitoring solution. Beta testing is essential for a smooth monitoring process and ensures that the data collected meets the required accuracy and utility conditions. Once the remote monitoring solution are deployed, minor fixes that may have been overlooked can sometimes damage the appliance, further affecting data quality and reducing the end user's confidence in the monitoring process.

Anticipate that field monitoring equipment will require some customisation

When appliances have varied technical specifications and complexity, a one size fits all monitoring solution is impossible to find from local or international retailers. Off the shelf monitors that can be easily customised to suit different appliances can sometimes be very costly. They may not always be interoperable with other sensor equipment or ancillary software. Additionally, most of the off the shelf sensors and loggers considered for this beta testing have in-built communication modules which relay data to the manufacturers in house platforms. Accessing this data attracts additional charges, which in some cases are levied per device, further elevating the cost of large-scale field monitoring. As is evident from this beta testing exercise, custom-built modules can only be shared across appliances with similar energy requirements. Although custom monitors are time-consuming and require specialised technical skills, the ability to adequately calibrate and align the data resolution in a single monitor allows for easier comparisons across performance metrics.

Adapt communication protocols based on local network provider frequencies

The scale of deployment and prevailing connectivity challenges in the area of study can largely affect the choice of data storage and communication channels. Most off-grid areas are sometimes plagued by poor GSM connectivity, which affects data transmission from the data logger to the cloud server. In such cases, local storage or different communication protocols can be considered. In this beta testing exercise, the RMM communication module was calibrated for local network providers' ideal frequency. Understanding the network providers' landscape in the target countries is crucial in developing an adaptable solution that can work even in the worst of connectivity conditions.

Designing with the end-user in mind

Sensors and sensor components must be selected based on their technical capabilities and their fit in the final design of the monitoring solution. This is especially important to ensure that the monitoring solution does not

affect the usability of the appliance, does not void the warranty of the appliance or it may cause the user to deviate from usual practice. Voiding the warranty of appliances may negatively affect relationships between the parties involved in the field testing. In addition to usability considerations, it is crucial to ensure that the design of the final monitoring solution does not affect the aesthetics of the appliance. This includes any destructive retrofitting that may void the warranty of the appliance or may not be to the liking of the appliance owner.

Recommendations

Understand the technical depth and scope of monitoring options available in the market
Beta testing is a very technical process and requires specialised technical skills to carry out the process successfully. At the minimum, an understanding of the technical specifications of the focus appliances, the parameters to be monitored and the potential measurement instruments is required. From this understanding, organisations and individuals looking to carry out beta testing should assess measurement options and possible methodologies to help achieve the objective. Other aspects to consider are potential suppliers, cost and logistical constraints and compatibility with communications protocols in the study area. This can significantly narrow down the focus in terms of sourcing the desired options for testing.

Engage partner company/appliance manufacturer in the design process
Engaging the manufacturer of the test appliances in the scoping and design stage of the monitoring solution, especially in cases of a third party led process, is crucial in ensuring the development of an acceptable monitoring solution. In our case, we have found this quite helpful, especially in recommendations on the connectors to use and the compatibility of the monitoring options with appliance hardware.

Pre-test the prototype
Like any other production prototype, it is crucial to conduct a pre-test of the monitoring solution in a real-world setting to identify any nuances that may affect the monitor's performance. For such a time consuming and costly exercise as beta testing, there is no room for errors, especially once the monitors have been mass-produced and already installed in end-user homes.

ANNEX: RMM TECHNICAL SPECIFICATIONS

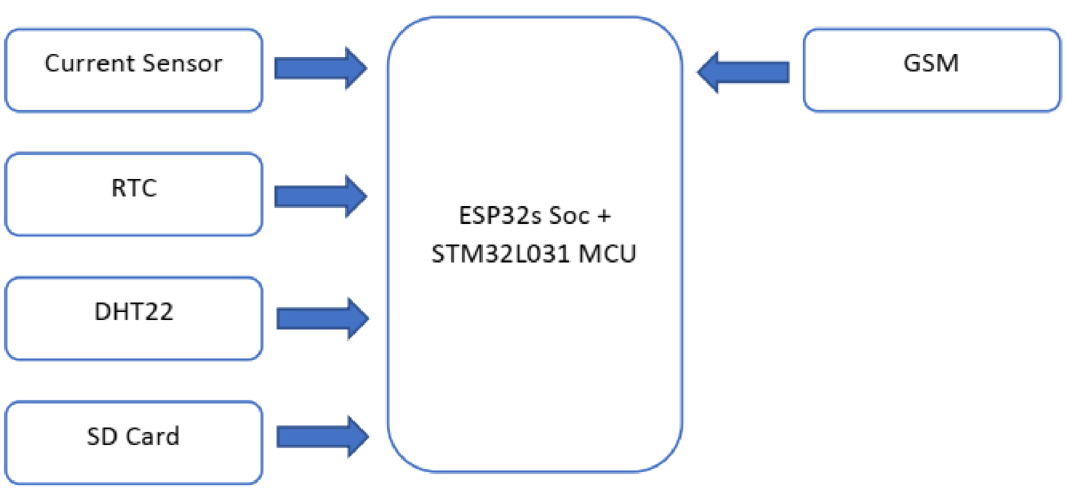


Figure 8: Overview of the design of the refrigerator energy performance monitor

Legend
RTC – A system used to keep proper time and date in electronic systems. It is also present in laptop/desktop computers to maintain the correct time and date.
DHT22 – A generic temperature and humidity sensor.
SD card – A common form of digital storage in mobile phones and portable electronic systems such as video cameras.
ESP32 SOC – ESP32 System on Chip from Espressif systems. This is a standard microprocessor with WiFI communication capabilities.
STM32L031 – A microcontroller from ST Microelectronics, an integrated circuit manufacturer. This is a product from their low power microprocessor product portfolio.

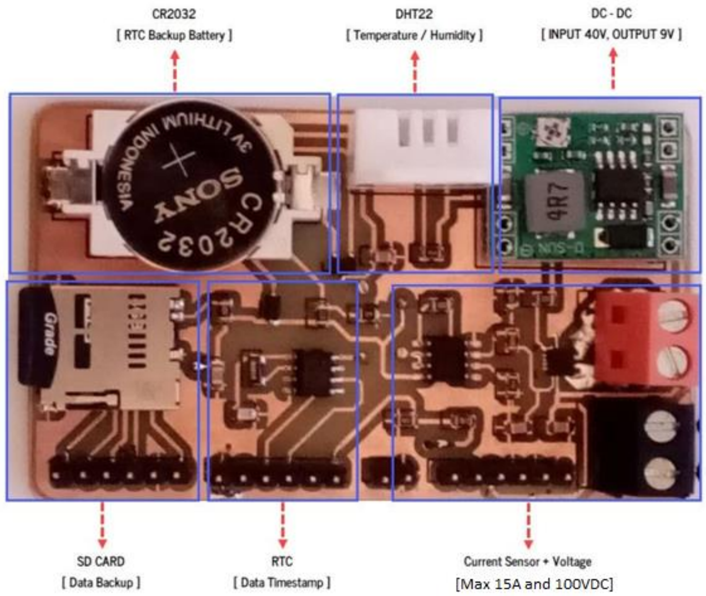
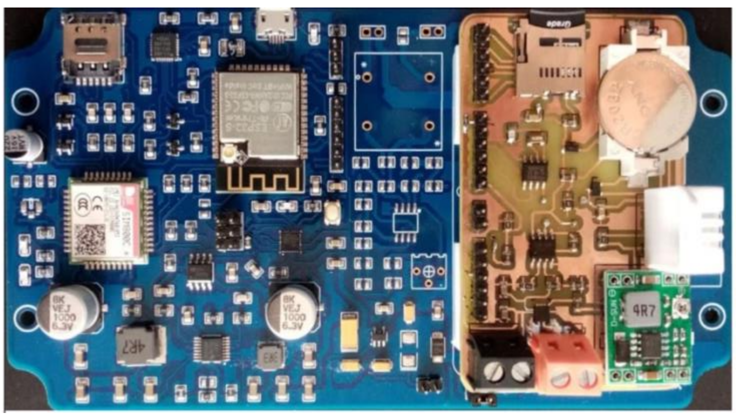


Figure 9: Refrigerator RMM prototype.

RMM prototype PCB



Data packet format of RMM prototype (4 bytes)

Current	1 Byte
Value	0x00 – 0x7D
Decimal Offset	0x7E – 0xFF

Voltage	1 Byte
Value	0x00 – 0x7D
Decimal Offset	0x7E – 0xFF

Temperature / Humidity	1 Byte
Temperature	0x00 – 0x7D
Humidity Offset	0x7E – 0xFF

Hardware Status / Reserved	1 Byte
Value	0x00 – 0xFF