EFFICIENCY FOR ACCESS

Field Testing of Appliances Suitable for Off- and Weak-Grid Use

Generic guidance on appliance performance monitoring in the field

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A	Amperes
AC	Alternating current
AFRETEP	African Renewable Energy Technology Platform
APN	Access Point Name
ARE	The Alliance for Rural Electrification
BLE	Bluetooth low energy
BMS	Battery management systems
C	Celsius
ºC	Centimetre
CT	Current transformer
DAQ	Data acquisition
DC	Direct current
ESMAP	Energy Sector Management Assistance Programme
FATFS	A file system common in flash storage
GHI	Global horizontal irradiation
GOGLA	Global association for the off-grid solar energy industry
GSM	Global System for Mobile Communications
Hz	Hertz
ISO	International Standards Organisation
kWh	Kilowatt hours
LITTLEFS	A high-integrity embedded file system
m	Meter
mm	Millimetre
mV	Millivolt

NFE	Near-field communication
PCB	Printed circuit board
PV	Photovoltaic
RMS	Root mean square
SHS	Solar home system
SOC	State of charge
SOH	State of health
SPIFFS	A high-integrity embedded file system
SQL	Standard Query Language
SWP	Solar water pump
TCP/IP	Transmission Control Protocol/Internet Protocol
US$	United States Dollar
USB	Universal Serial Bus
V	Volts
VoC	Open-circuit voltage
W	Watt

Context

This guide provides a general blueprint on how to field test almost any type of household and light commercial appliance. This publication is relevant for appliance design and development engineers, product managers from appliance wholesaler companies, or suppliers of off-grid power systems, programme managers and implementors who are testing candidate appliances model. This guide is the first in a series of four and is designed to be technology agnostic. The three forthcoming guides will include two technology-specific field testing guides, with one for refrigerators and the other for solar water pumps, and a user data collection guide.

The field testing guide was developed by CLASP, on behalf of the Low Energy Inclusive Appliances programme, a 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 15 Donor Roundtable Members, 17 Programme Partners, and more than 30 Investor Network members. Current Efficiency for Access Coalition members have programmes and initiatives spanning 47 countries and 25 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.

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Introduction

Little is known about how off-grid appliance and productive use equipment perform in real-life environments and how users interact with and perceive these products. While laboratory testing provides a glimpse of appliance performance in a controlled environment, it provides only a limited representation of how products perform under the rigours of real use. While this issue of 'representativeness' is true of laboratory testing in all contexts, it is especially important in newly-developing appliance markets (e.g., remote areas with low-income and first-time users) where there may be little history of appliance usage and thus a limited understanding of how laboratory test results may predict energy performance in the field.

A better understanding of product energy performance can be gained through field testing. Field testing is the process of measuring, collecting and analysing data about a product being used by end-users in a real-world setting, often over an extended period of time. Field testing is typically conducted by appliance manufacturers, at their own expense, and at various stages in the product development process. Successful field testing not only provides information about product performance and user experience, but also *why* products perform the way they do, as well as their impacts on user's life or livelihood. The data and intelligence gathered from field testing informs decisions about product design, financing and business models and more.

But "real use" means challenges for the testing process as well as for the appliance itself: testing will be conducted in remote off-grid or weak grid situations, over an extended time and with people using appliances in their own daily lives, possibly for the first time. The opportunity costs of a failed or inconclusive field test extend to more than wasted money and time, and include delays to product development, loss of competitive edge.

Due the complexity of field testing projects, this guide is intended to inform practitioners seeking advice on designing and implementing field testing projects for appliances and productive use equipment used in off-grid and weak-grid contexts. This guide gathers learnings from those who have conducted field testing, sets out important questions to consider and identifies known problems. The guide aims to strengthen field testing projects from design to implementation so that plans can be more robust, common mistakes can be avoided and the impact of problems can be minimised to deliver results for business and programme decisions.

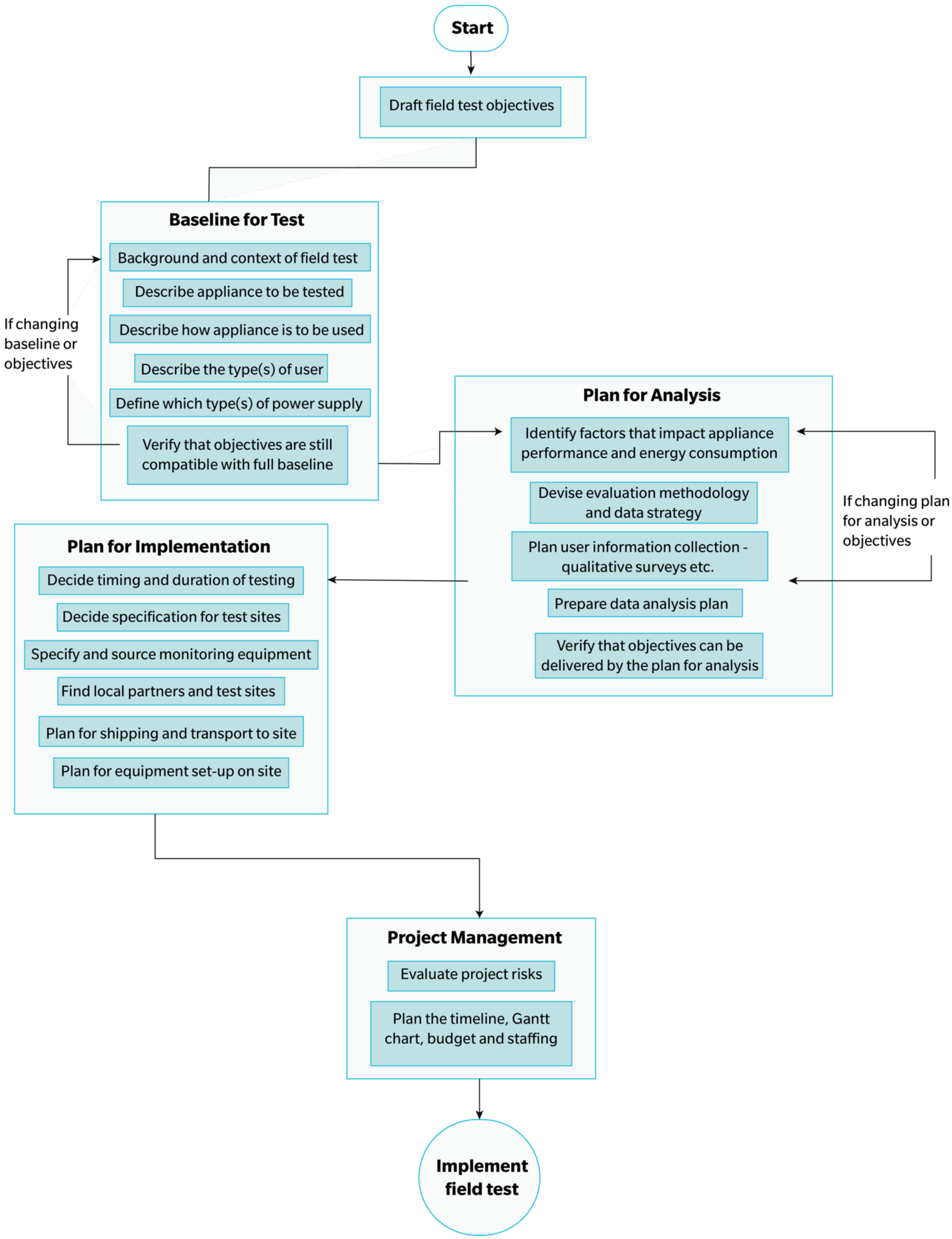
The guide is developed based on desk review of existing research and field testing methodologies, crowdsourcing information from industry and programme stakeholders who have experiences with field testing and lessons learnt from Efficiency for Access' ongoing field testing projects for solar water pumps, refrigerators and milking machines in places such as India, Kenya, Rwanda, Tanzania and Senegal.

While the guide is not exhaustive and does not represent all scenarios, it is a good starting point for market stakeholders that aim to:

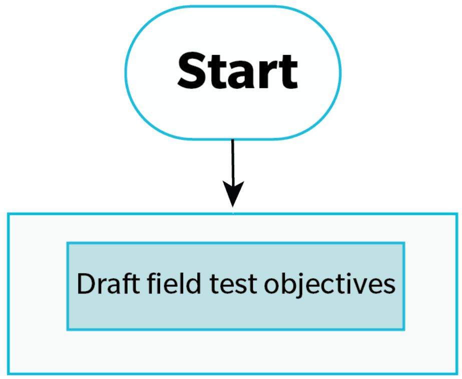
- Quantify energy consumption and performance of appliances over weeks or months;
- Understand power supply conditions, such as the amount of available solar energy generated through photovoltaic (PV) or hours of power outage of weak grids;
- Test single appliances or a batch of appliances in different locations;
- Focus on household type of small commercial appliances;
- Compare performance differences between laboratory testing and field monitoring;
- Gather more insights on user experiences and preferences.

The guide provides a general blueprint on how to design a field testing project for household and light commercial appliance and offers advice on how to navigate challenges that may arise during field testing. This is the first in a planned series that will provide a general field testing framework suitable for almost any type of household and light commercial appliance. Following this guide, two additional product-specific guides will focus on refrigerators and solar water pumps respectively, and a separate guide focusing on end user data collection during field testing. Figure 1 shows a general overview of the field testing process. The plan, however, should always be customised based on situations and needs.

Figure 1: Overview of the field test planning process for any type of off-grid appliance



1. Field Test Objectives and Scope



A problem well-stated is a problem half-solved. Alternatively, 'given only one hour to solve a major problem, spend two-thirds of that hour defining what the problem is.'[1] This leads directly to the first and most important piece of advice to get the most out of a field test:

Work out and document exactly what problems your field test will aim to address.

Make sure the team that coordinates and implements field testing on the ground understands and remembers the aims throughout the project. The aims also may evolve, so revise them if needed.

A general objective might be: '*to demonstrate the performance, acceptability, and compatibility of the appliance in a real use situation*'. But drill down on the objectives: keep asking 'why?' to successive answers, because full insight is needed to design the test well. There may also be important sub-objectives. Examples of objectives to explore may include:

a) To ensure that appliance [X] performs optimally in varied real use. For example, in ambient conditions with certain usage patterns
b) To discover any performance limitations not identified during laboratory tests
c) To rank the field performance of two or more design options or competing appliances
d) To monitor how performance varies with seasonality or over time
e) To Investigate field performance of certain ancillary or associated equipment
f) To determine how energy consumption varies with situation, user, or other factors
g) To determine 'real' appliance usage patterns by measuring / observing user behaviour
h) To evaluate adequacy of packaging for shipping (protecting the appliance in transit)
i) To evaluate adequacy of the tools for installation and set-up
j) To discover additional requirements not evident from earlier research
k) To evaluate end user comprehension of product documentation, e.g. installation instructions, user manuals, trouble shooting and repairs, warning labels, etc.

[1] Attributed to the head of Industrial Engineering of Yale University. A similar quote is often attributed to Albert Einstein.

Qualitative research aspects to explore through interviews or questionnaires might include:

a) How the appliance is used and for what
b) Environmental impact (e.g., natural resource consumption)
c) How users feel about the appliance when using it - what they like, what they don't like
d) Impacts on the user's daily life
e) Ease of installation or set-up, whether instructions are understandable
f) How easy users find the controls or interfaces
g) Whether power availability has affected appliance use, if it is switched off for periods
h) Changes in behaviour compared with the status quo and compared to what was expected
i) Further user needs and user wants (these are usually different![2]) and how this differs to what the appliance provides; separately, designers must balance satisfaction with affordability
j) Factors affecting durability (damage, corrosion, wear and tear), which are hard to assess but very important

Iterate between objectives and available budget to balance usefulness of findings and value for money. Consider:

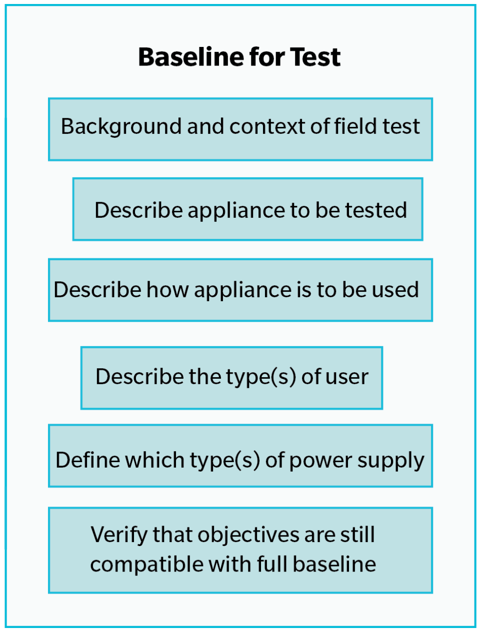
- Relative importance of each objective to your work as some cannot simultaneously be addressed.
- Success and failure criteria for the objectives (how to know if the objective is met)
- Is testing of a baseline appliance needed, with which to compare results?
- How many appliances must be tested to meet the objectives? In how many locations?
- Must appliances be tested under two or more different usage conditions?
- What will be done with equipment at the end of the test? Consider how waste implications reflect your business values; minimise waste and dispose of it through recognised channels.

Prioritise one to three primary objectives, with some supplementary objectives if the plan can accommodate them. Once some objectives are drafted, more detailed planning can begin, starting with a very clear statement of the baseline for the test.

Suggestion*:* Consider if any of the objectives could be delivered through extrapolation from lab testing, which is likely to be cheaper.

[2] A customer may *need* no more than 40 litres volume in a refrigerator but *wants* at least 100 litres plus an ice box - they may reject appliances that deliver less.

2. Baseline for Test



2.1 Background and Context of the Field Test

Briefly describe the context of the field test. Include basics because, even if obvious to the writer, the wider team can make important contributions or spot problems early if they understand the situation. This can include items such as why or how the testing has come about, the culmination of previous testing events, etc.

2.2 Description of Appliance(s) to Be Tested

Describe the equipment to be tested – its key functionality, size, input electrical power, noteworthy (new) components, type of controls, inputs and outputs, special features and functions, known strengths and weaknesses. Be clear what items will be received by the user. Describe the optional components, maintenance needs and any associated storage space or access.

2.3 Define the Appliance 'Use-Case'

The conditions in which the product is tested needs to be reasonably well-aligned with the product's real use-case, or how it is designed to be used. Therefore, it's important to define use-cases early on and select appropriate field testing users accordingly. For example, field testing a vaccine refrigerator in a small business setting is unlikely to yield meaningful results, and so it would be necessary to test the refrigerator in a clinic setting with clinic workers. Even if the research is aiming to find out what users do with the appliance, it is worth considering the range of possibilities. It's important to document the following:

a) What the intended **functional use** for the appliance is:

- What do users achieve through use of the appliance? Will it vary by user? Consider primary and secondary uses. Brainstorm uses and decide if any should be explored.
- Quantify intensity of usage, at least indicatively. How often per day or per week; continuously or intermittently; variability by users or situation. Write down expected minimum and maximum hours, weight, volume, quantity, number, frequency, etc.
- Are there any implications if the appliance is idle for an extended period during the test?
- How long should the appliance stay in service in normal use and for the test?
- Are there unanticipated uses that might impact the product performance and quality, e.g., a refrigerator with the door left open, unplugging products overnight, etc.

b) Describe the **intended users** of the appliance – if not known in advance it should be a priority topic for the baseline survey:

- What types of users are envisaged? Consider occupation, education and literacy level, gender, relevance of age, physical and cognitive capabilities, income levels, heigh or strength. Consider installation and maintenance too.
- What will be the familiarity level of the user with equipment? Will they be trained?
- How many different users will operate the appliance per day or over the test period?
- Consider the diversity of user profiles, noting the particular importance of gender and ability. Are there any known/anticipated gendered or ability-restrictive considerations of use? For example, if heavy lifting is involved, do you expect less usage by women or disabled people?
- What changes to normal user behaviour or routines will be required to use the appliance? How keen will users be to use the appliance properly or as instructed?

c) Describe the **intended usage environment** that the appliance is designed for:

- Outdoors or indoors, protected from or exposed to weather and sunshine, high or low altitude, hard or soft water area, quality of water (clean versus turbid), in presence of salt water/sea spray, contaminants, etc.
- Is it used in a professional or home setting, or a mix of both?
- Does the public, employees or children have access to the appliance? Is it supervised?
- Is it used with other appliances?
- Is there protection needed from extreme conditions, rough handling, incorrect set up or use?
- If the appliance performs unexpectedly or fails, will the user call for help, attempt repairs or stop using it?

***Suggestion**:* Identify deal-breaker issues, to recognise when you have to turn down a potential test site or user type. Use this information to refine the objectives, specify test locations, and set criteria to identify types of end-users that should be engaged in the field testing projects.

2.4 Type of Power Supply to Be Used

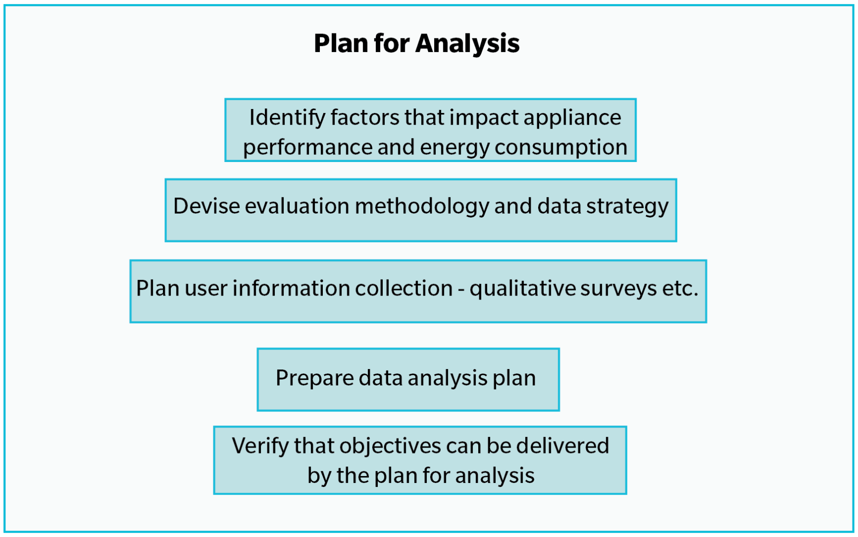
Define the type(s) and quality of power supply with which the appliance is designed to be used, and any constraints on the specification of power available during the test period. In particular, any constraints known to impact appliance performance, such as voltage fluctuations, outage durations, etc. Power requirements are needed to determine test sites and what is to be monitored during the test.

Questions to consider include:

- Type of power provision: weak-grid, mini-grid, solar direct drive, solar home system (SHS), uninterruptible power supply, PV panels.
- product under test? And if there is no independent power supply, how will the power availability and quality affect the measurement equipment, logger and data communications? What's the back-up plan? For example, a battery may be needed to ensure data consistency in the event of a prolonged power outage.
- Any voltage converters used in the system and their technical specification. Consider whether to step up or step down voltage; direct current (DC) to alternating current (AC); AC to DC; voltage rating, etc. Converters also incur power losses, which must be taken into account.
- Battery types: chemistry, capacity, availability of remote monitoring system (see section 5.3.4).
- Impact of other loads on the local power network: size, timing, likelihood of change during the test period.
- Limits on voltage variability during the test period: spikes or swings up or down, provision of a voltage lower than expected for any weak grid connection, etc. Also, whether the appliance is used with a voltage protector device.
- Required reliability of connection, including how many brownouts can be tolerated and for how long.

Suggestion: Having thought through and written down the full baseline for the test – go back and check that the draft objectives are still compatible with the baseline; adjust objectives and/or the baseline as necessary. Consider pre-testing appliances in a simulated power supply condition in a controlled setting, such as a test laboratory, to validate that the product could function appropriately before field deployment.

3. Plan for the Analysis



This section leads through developing the details of an analysis that can meet the objectives.

3.1 Factors That Affect Appliance Performance and Energy Consumption

Identify the most important factors external to the appliance that may affect its performance. Some may be under the user's control while others are associated with the environment in which it is used. In field testing, these factors cannot necessarily be controlled but if identified in advance they can be measured or noted during the test so that results can be properly understood. If an important factor is not assessed then it could make the results hard to interpret or even useless, especially if results are not as expected, *which often happens*.

Consider factors such as:

- Efficiency of energy supply system, as well as the quality and stability of power input.
- Types of connectors used.
- Climate or season of the test. For example, if the test is only performed during the summer, will it be representative?
- Test duration: is it multi-season and long enough to show any decline in performance?
- Weather and environmental conditions during the test: what if there's unusual weather during the test?
- Maintenance needs and intervals: how can the functionality of the appliance be affected by dirt, dust, sun, etc.? What sorts of damage are likely or possible and how does the affect the validity of the test?
- Where and how the appliance is eventually set up? i.e., indoor or outdoor or closer to other external factors that may affect performance of the appliance.

- How the appliance is used, by whom, and for what purpose? Be specific. For example, if testing a solar mill, what specific grains will be milled?

Suggestion: Try to rank the factors by importance to your test, then think carefully about the top factors. Can you quantify the scale of external factors on the impact of the test results? For example, if the ambient temperature goes up by five degrees, does energy consumption go up by 1%, 10% or more? Use this list of factors to inform your thinking on test sites, objectives, what is measured during the test and the strategy for data analysis.

3.2 Evaluation Methodology and Data Strategy

This section explains how to plan for the data that will be recorded during the test. This is especially important because if the data is poor then the entire field test may be useless. Information in this section can guide your decisions or help you discuss your needs with and cross-check what is advised by monitoring equipment specialists.

3.2.1 Identify the Data Streams to Be Recorded and Sampling Frequency

Suggested steps:

1. Identify what information is needed to fulfill the objectives. Take into account all of the factors that impact consumption from Section 4 and decide which of those must be known to achieve the objectives. For example, how performance varies over time, the output of a product over a given time period, etc.

2. Deduce what parameters have to be measured by thinking through the data evaluation procedure: how the data is manipulated to calculate the results that deliver the objectives. For example, temperature of the air inside a freezer compartment or kilowatt hours (kWh) of the appliance and as delivered by the PV panels.

3. Decide what data recording interval or frequency is necessary *for each data stream separately*. This makes a crucial difference to the sensor types, data storage, cost and ease of analysis. Decide which of the following approaches for data capture apply to each parameter for your situation. Data streams could be:

    a. Measured instantaneously at regular intervals, but where timing of measurement is not crucial (and so could be a stand-alone instrument, independent of other measurements)
    b. Measured instantaneously at precisely known intervals and times (e.g., to match it with another timed data stream or position of the sun. This could be anything from every 5 seconds to once a week).
    c. Event triggered data. For example, when a door is opened on a refrigerator, and data is recorded only at that point.
    d. A cumulative total at the end of the period. This is similar to a home electricity meter that records the endpoint total but will not record how consumption varied during the period, unless readings are taken in between and separately recorded.

4. Set the frequency of recording parameters to capture the events and processes of interest within constraints of data storage/transmission capacity and to minimise energy consumption of monitoring and storage equipment.

   a. Choose the lowest frequency consistent with needs to avoid high equipment costs and time for data processing. For example, it takes up to ten seconds for a typical temperature probe to register a change in reading, longer if it is attached to a solid object, and for field monitoring a reading every five or ten minutes should be more than adequate. Otherwise, having too much data can be costly and timely when analysing the results. A sample rate of six times per minute might be manageable for a 24-hour lab test, but for a 6-month field trial could be impossible to analyse without very sophisticated software. Microsoft Excel, for example, cannot cope with very large data sets. A lower frequency may also be acceptable because over several months, even transient cyclical events are likely to be captured occasionally.

   b. Transient events could be important for troubleshooting but may not be useful for general monitoring. For example, starting a conventional motor causes a transient surge current which can cause a voltage swing and other unexpected effects. Alternatively, some monitoring systems can record the maximum seen during a period rather than recording every second.

5. Consider if a calculated average value is needed, and if so, over what period(s)? Are maximum or minimum values over given periods also useful to know? These can be automatically generated.

6. Determine expected ranges of the main measurements (minimum/maximum) so that outlier data is easily spotted. Also set up automated alarms if possible. This can help easily indicate problems.

Suggestions:

- Ask yourself ‘do I really need all of that data and have to pay for its storage, transmission and analysis? Could I get adequate results with much less?’
- If you do need intensive data for some parameters, does it have to be intensive for the whole test period, or would an intensive burst for [one day per week] be enough?
- Choose a sub-set of the appliances to monitor intensively with others at low frequency. Perhaps chosen after it is clear which sites are working properly and interesting.
- Consider if data collection rates can be reduced during periods when the system has low or zero power to increase battery life.
- To reduce data quantity, see if a normally low data rate can be increased on an event trigger for a period after the event; or if rates can automatically be lowered during known or measured ‘quiet periods’.
- With your objectives and target audience in mind, draft a list of what will need to be discussed and decided in your ‘final report’ to ensure that all necessary information is included in the data strategy.

- Consider if a data sharing agreement will need to be in place among participants, possibly non-disclosure agreements. In any case, consider what results will be shared in which format, when and with whom.
- Decide in which language(s) the information and data must be presented at each main stage of the process. This should be considered not only for reporting, but also when checks have to be made in the field.
- Split the list of data into 'essential' and 'nice to have' to help with budgeting.

3.2.2 Data Logging Strategy: How and Where the Data is to Be Stored

Monitoring should provide a holistic picture of how the appliance is performing in the field and the data is stored by the logging system. The main components of a monitoring and logging system are:

1. Sensors: to measure energy and appliance performance parameter and transmit for storage.
2. Communications: to receive data from sensors and deliver it to remote and/or local storage (could be wired or wireless).
3. Data logging and storage: how data will be dated/time-stamped and saved. This could be stored on a local storage, such as a flash drive and/or cloud-based.
4. Local storage lifetime: Not all local storage types are created equal. Each storage type has a lifetime quoted as the 'number of read/write cycles' – before failure. Industrial storage devices are typically more resilient when compared to consumer storage devices by having a higher number of read/write cycles, and are tested taking into account harsh environmental factors, such as dust, radiation and abrupt power loss. Software: controls operation of the system, data retrieval, processing of data and reporting. Usually just 'configured', sometimes 'programmable'.
5. Online dashboard: For real time data monitoring for debugging.

Monitoring hardware options include:

- Standalone monitoring device with embedded or local storage for measured data;
- Monitoring device with built-in TCP/IP compatible network connections (LAN, Wi-Fi or cellular);
- Monitoring device with wireless links to a base station or gateway;
- Monitoring device with a combination of the above.

There are two basic approaches to the storage of data:

1. Remote data collection at intervals (perhaps daily), which could be fully automated or manually initiated.
2. In-person data collection from the site, at intervals or at end of monitoring period.

The two approaches could be mixed, with simple data from cheap sensors stored locally and data from other sensors uploaded to the cloud. You can also combine local storage and cloud transmission for the same devices.

Table 1. Comparison of potential risks and benefits of local data storage versus local storage with upload to cloud (remote server) storage.

Local storage at test site	Local storage plus upload to cloud storage
Cheapest for hardware, but cost of staff for physical collection (i.e. travel and labour costs) must also be factored in	Higher cost for hardware to transmit data plus data connection contract and server rental. However, it's not necessary to visit the site for data collection after set-up
Can only be quality checked when present on site, so there's a risk that major problems are only discovered at end of a monitoring period	Easy to check data via remote server and spot problems early and plan action to correct them
Risk of total data loss if local storage is lost or corrupted	A remote server is automatically backed up, but data is made 'safe' only after a successful remote connection. Mobile network connectivity cannot be guaranteed at any one site, nor from day-to-day and so contingency plans are needed if the connection is unreliable. These back-up options can include satellite data connection, alternative networks, additional on-site back-up storage, etc.
Local storage capacity is limited, especially if cost is highly constrained which could limit sampling frequency (though micro-SD cards can now hold 100GB at a low cost)	Data storage capacity is virtually unlimited at a very low cost, but data transmission has associated costs, possibly limiting sampling frequency
Low power consumption can be achieved for local storage, though this varies by systems and processing overhead may be appreciable	Generally higher power consumption to transmit data over satellite and mobile data networks

As well as data sampling frequency (above), data strategy considerations include:

a) Get advice on whether data management software is necessary for the task.
b) Make sure it is clear what the units of the data are to avoid analysis mistakes (if it can happen to NASA[3], it can happen to a field test).
a) Ensure that the local device data is stored in an optimal file system (e.g., LITTLEFS, FATFS or SPIFFS) for easy retrieval. The ideal file system depends on the nature of the data and how it is collected, accessed and processed.
c) Ensure that the cloud data is stored in an optimal structure (e.g., SQL or NoSQL) for easy retrieval. The ideal structure depends on the nature of the data and how it is collected, accessed and processed.
d) Ensure that local and cloud data files have appropriate variable headings and metadata file describing properties, to ensure analyst confidence that they have the correct data and format.
e) Ensure that the data transfer protocol handles failed uploads automatically, with interim local storage and subsequent upload that achieves a consistent and traceable database format.
f) Consider what will happen to your data and the logging system if there is a total loss of power at the test site and what data would be lost. Will the data logger reset itself to continue working as before when power is restored?

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[3] Loss of the 1999 Mars orbiter resulted when navigation commands were sent in US units that were incompatible with the metric system used in the orbiter's onboard systems.

g) If logging equipment runs off the system power supply, then the logging equipment's consumption must be taken into account in power calculations. A logger could easily use several Watts, and data transmission has a higher energy consumption.
h) If the instruments are battery powered, check how long the battery will last and if/how it can be re-charged or exchanged.
i) Lesson learnt: Small solar PV panels used to power monitoring equipment are attractive for charging mobile phones or other uses and should be kept secure or out of sight.

Suggestions:
Test out as much of the sensor, data logging and data transfer system as possible before reaching the field. Costs associated with lost or missing data can be significant including wasted money and time on the trial, delays to product development, or loss of competitive edge. Some suggestions include:

- Test monitor compatibility with the product and map out the data acquisition pipeline.
- Map out the data storage and transfer chain for each type of sensor through to final report. Consider what could go wrong at each step.
- Consider how often the data set should be reviewed for potential problems or to identify a change of circumstances at the test site, and to decide whether stored locally, remotely, or using a hybrid option.
- For extra data security, consider consolidating into a snapshot archive[4] at certain intervals.

[4] Similar to autosave in Microsoft Office applications where a document is autosaved at different intervals.

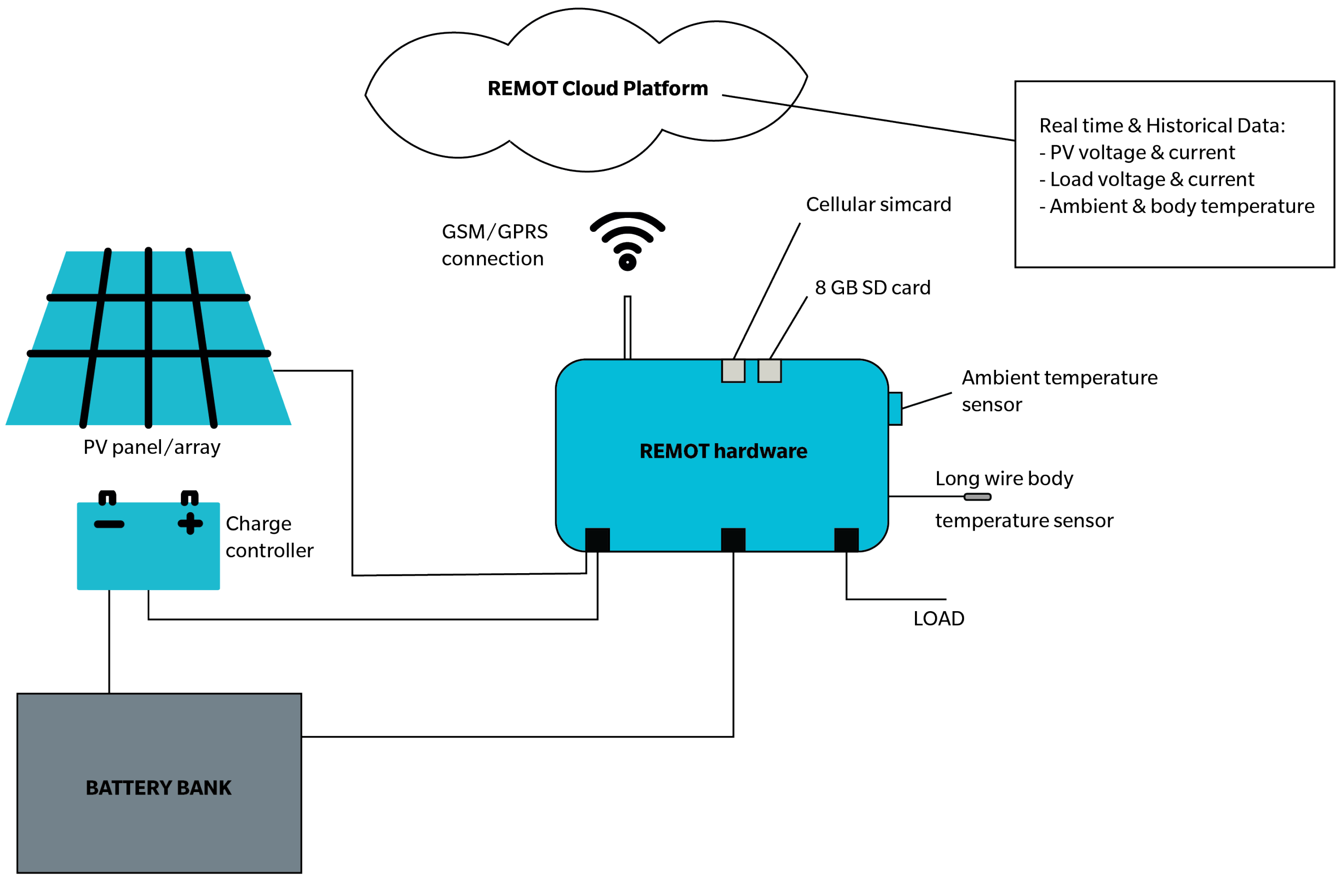

Figure 2. One example approach to data logging. This system uses a central logger with SD card storage combined with mobile data connection to a cloud platform (image provided by Innovex).

3.3 Plan User Information Collection – Surveys and Questionnaires

Interviews with appliance users before, during and after a field test can reveal information that technical measurements cannot. These may be the most useful part of the findings and include information on user opinions, preferences and behaviours that inform trends and patterns from technical measurements.

More details on collecting user experience, impact and other non-technical data will be shared in an upcoming user information collection guide.

3.4 Data Analysis Plan

Draw up the outline data analysis plan before specifying the monitoring equipment to ensure that all essential data are measured or assessed in the field:

- Decide how the data analysis will deliver the field test objectives from Section 2.
- Document the data analysis methodology so that it can be verified or replicated.
- Consider how the qualitative data from surveys and interviews will be analysed and if/how that can complement quantitative data. For example, user attitudes from surveys may explain unexpected results or enable adjustment factors to compare with results from other sites.

- If data gaps in measurements are identified during the field test, consider whether questions to users or others might help plug the gap.
- Before starting the analysis, aim to screen the data for errors and outliers that may need to be removed. For large data sets, full screening may not be practical. So, examine samples of the data for systematic errors. Outliers are more easily spotted and can be identified by showing the data on a scatter plot with a regression line, sorting the data high to low, or calculating by how many standard deviations data points are from the mean value[5]. It is worth checking why outliers are occurring.
- Double check information about the appliance, its usage and factors impacting performance as part of the analysis. Compare this with the anticipated baseline (from Sections 3 and 4).
- Archive raw data sets in case they are needed for reference or troubleshooting later.
- Ensure that sub-sets of data of interest can be easily extracted from storage, especially if the data set is large.
- Identify mechanisms for filling gaps in the data and replacing missing data with substituted values ('imputation' as the statistical term with several approaches possible[6]).

***Suggestion**:* If large quantities of data are expected (e.g., dozens of appliances, several sites, or many months) then proprietary analysis software will probably be necessary. Seek further advice on this.

3.5 Risks to Data

Consider what could go wrong with data capture, storage and analysis, and make mitigation and contingency plans. It is not uncommon to lose data from 25% to 50% of sites in a field test, even with careful planning. Consider these and more:

- Data network is inaccessible at the site
- Data network is temporarily unavailable at the time when one or more data uploads are planned
- Any of the many links in the data transfer chain (e.g., sensors, loggers, mobile data networks and computer storage) from appliance to final analysis fail. The data monitoring system should be tested before it is moved into the field
- Sudden loss of external power to the equipment and for how long
- Loss of data storage equipment on site (e.g., theft of or damage to a data storage device)
- Data is out of expected range when remotely checked (perhaps equipment tampered with or moved or there's a change of circumstances on site)
- Data is stored in a sub-optimal way that makes retrieval and analysis more difficult
- Gaps in data due to failed uploads
- Mismatch in the sensor data significant digits and the required data significant digits. Knowing significant digits prevents storing/sending more data that is necessary especially when working with fixed point number systems (e.g., storing 23.600 whereas the sensor is only precise to .1, only the representation 23.6 is needed)

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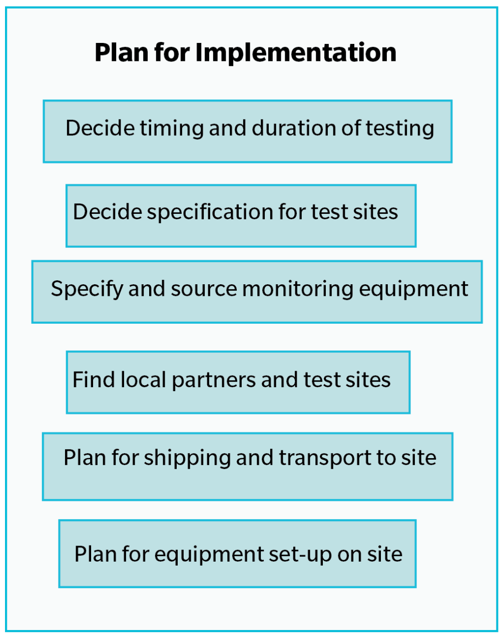
[5] Called the Z-score, for which less than -3 or higher than +3 would be an extreme outlier.

[6] Options include substituting a mean value, regressions analysis and "last observation carried forward" but each of these introduces errors or bias and statistical methods should be applied for any substantive gaps in data.

- Data range mismatch at the device level could lead to data overflow, underflow, or truncation and cause misrepresentation of the data. For example, fridge temperature of -2 degrees Celsius stored in an unsigned 8 bit integer (range 0-255) would read as 254 degrees Celsius.

Suggestion: Having completed the plan for analysis, go back and check compatibility with the draft objectives; adjust objectives and/or the plan for analysis as necessary.

4. Plan for Implementation



4.1 Timing and Duration of the Field Test

The duration of the test is inevitably a compromise. The minimum time for field evaluation of a simple product or small development might be one to two months. Thorough research for product development might require up to one year, which impacts budget and data strategy.

Considerations include:

- Do the objectives require data over a full season or more than one season, due to impact of weather, seasonal changes in usage due to planting/harvesting, etc.
- Time must be allowed at the beginning to resolve problems with shipping, installation, monitoring, data, etc. It will likely be weeks later than expected when the equipment is finally running in a stable condition. For example, CLASP and Energy for Impact estimated that the deployment time for 36 appliances from the Netherlands to sites around Uganda was 3 months. Due to customs and shipping issues, the refrigerators weren't deployed until 6 months (see Section 4.5).
- The longer the equipment is in the field, the higher the chance of circumstances changing (e.g., business or family grows or changes its behaviour), equipment failure, change to local energy provision etc.

4.2 Specification of Test Sites and Users

The choice of site(s) for testing affects energy consumption and performance of the appliance as per findings from Section 4.1. The analysis must recognise and manage this, especially when comparing results from different sites. Having first clearly defined the appliance to be tested, its intended use case and type of users, knowing which factors influence performance and with a clear set of objectives, selection of sites can begin.

Full details of the test site may not be known until the equipment is there, so the plan will have to be flexible. In any event, it will be important to record details of how the appliance is finally situated, including photos.

Basic considerations to identify candidate sites include:

- How many sites are needed? Considering budget and objectives and how statistically robust and representative results must be. Experience suggests that you should plan for at least one quarter of sites to fail on delivery of all or most data.
- Which country or countries should be involved in the evaluation? Consider the target markets, what is accessible and affordable for testing, and where contacts are already established.
- For testing the typical performance of off-grid equipment, sites should not be the most challenging and remote, nor should they be easily accessible and urban.
- For solar PV power, does local solar irradiation meet expectations? (See Section 5.3.5)
- Is one or more 'control site' needed, with which data recorded in real use can be compared?
- Do different climates or other conditions exist in the country that will impact performance? If not, are sites in multiple climate zones necessary for a complete picture?
- What type(s) of environment are needed to achieve the objectives? For example, are the sites representative of low-resource communities, urban, peri-urban and/or rural, geographical location and altitude, etc.?
- Are grid electricity, mobile telephone and/or data networks available in the area for the appliance, monitoring equipment and its set up? A logger could be taken intermittently to a better GSM signal location to do data uploads, but this is far from ideal.
- What are the local rules and regulations, customs, tariffs and culture impacting shipping and access to the area for set-up?
- How far away are facilities and resources that can help with problem-solving, maintenance or repairs?

Further considerations when screening or prioritising possible site(s) include:

- How far is the testing site from the supply chain and the local base for testing team? Ensure that there is sufficient and timely access to the site at a reasonable cost. If testing the supply chain and security in transit is part of the test objectives, then it could be longer
- Is the site flexible on when testing starts and ends?
- If hosts at one site hear about appliances being tested at a nearby site, could it cause problems? For example, a host rejects an appliance because a contact of theirs is testing a larger/better appliance
- How well is the size or capacity of the appliance able to serve needs at that site? If it is under- or over-sized, then the results may be skewed

- Where will the products/test samples be installed? Consider if it's inside or outside, the shading, weather protection, proximity of other equipment, exposure to dust and debris, etc.
- Who will have access to the site? This could include family, children, employees, public, and curious non-users. Consider the security/integrity of the equipment when not attended.
- What languages are needed for access, set-up, user instructions and training, interviews/feedback/surveys, including if literacy is low or unknown?

4.3 Specifying and Sourcing the Monitoring Equipment

4.3.1 Drawing Up the Monitoring Sensor Specifications

Based on the list of data streams to be recorded and sampling frequency from section 4.2, draw up a specification for each sensor and for the monitoring equipment for use in discussion with supplier(s). Selection of sensors means assessment of:

- Technical properties of sensors (accuracy, range, measuring frequencies, uploading frequency, etc.)
- How robust and reliable
- Ease of installation
- Upfront cost of equipment and software
- Running costs (such as GSM link and subscription to cloud platforms, often paid per device)
- Access to support and troubleshooting, including matching of time zones for support calls

Depending on the complexity of the task and the overall budget, the specification considerations should include:

a) List of the parameters to be measured and associated measurement frequency and accuracy (Section 3.2.1)
b) Which data streams must be synchronised in time (e.g., power mapped to flow at the same instant)
c) Frequency and mode of data transfer to storage and/or upload to remote server (Section 3.2.1)
d) Relative importance of having weatherproof and robust equipment, tolerance of harsh conditions and mistreatment
e) How secure or concealed equipment must be on site, how to prevent tampering (from curiosity or possibly malicious) and theft
f) How to minimise inconvenience to users and limit unwanted attention on the equipment. Optimise equipment location between convenience and 'best spot to measure' (e.g., we want the temperature in the centre of the storage space, but that's where users want to store produce)
g) Can the appliance be modified to install monitoring equipment (e.g., holes for routing sensor wires)? This could affect warranty and what is done with the appliance after testing.
h) Is wireless connection between sensor and data logger desirable? Balance routing of wires and snag/breakage risks against the extra cost, power and difficulty fault-finding of wireless connections.
i) How will the current and voltage sensors be connected into the appliance and system cabling? Wiring access is ok for custom-built systems but SHS kits often have bundled wiring looms with proprietary connectors, and warranty is voided if integrity of the wiring is breached.

j) Decide what will happen to the monitoring equipment at the end of the test (links with how much is spent on it). Take into account cost of retrieval, shipping, likely wear and tear, etc.
k) Consider the cost of the sensors, wiring, communications and installation against your budget.

Annex II of this guide provide a basic introduction to sensor technologies and types, with examples and indicative price ranges:

- Voltage sensors in Annex II Section i and Table 2
- Current sensors in Annex II Section ii and Table 3
- Power sensors in Annex II Section iii and Table 4
- Data loggers in Annex II Section iv and Table 5
- Temperature sensors in Annex II Section v and Table 6
- Solar irradiation assessment in Annex II Section vi
- Battery status in Annex II Section vii

Get the sensors and data acquisition system working on an appliance *before* sending it out to the field, including testing out how and where the sensors will be mounted and wires routed. Solve as many problems as possible in the workshop first as it's much harder in the field.

4.3.2 Power, Voltage and Current Sensors

Sensors for AC power supplies are generally different to sensors for DC power supplies. Monitoring equipment for single-phase AC voltage, current, power is widely available at many levels of sophistication, automation, accuracy and price. However, monitoring equipment for DC, especially power meters, are harder to source and there are fewer options available, sometimes resulting in the need to develop a bespoke system for some situations.

When selecting a sensor, the measurement range of the sensor should be carefully matched with the appliance specs, usually above the mid-point of the range of the sensor. This is because sensors are generally most accurate in the upper part of their range, and readings are less accurate at the lower part of the sensor range. Remember that DC currents can reach tens of amps and meters will fail if overloaded. Also bear in mind that appliances often use more instantaneous power than manufacturer provided average specifications.

For field measurements, a power meter that automatically integrates the energy consumption over time will almost certainly be the preferred option. These meters will also generally record how energy consumption varies with time. Separate voltage and current data streams may not be needed, though they can be useful to understand more details of performance and some meters will have the option to output these too. Many types and prices of power meter are available for AC circuits, but they are harder to source for DC circuits.

4.3.3 How to Store Data and Identify Suitable Data Loggers

A data logger is an electronic device that autonomously records data from one or more sensors and stores it with a date and time stamp[7]. Data loggers for AC systems are widely available at a range of levels of sophistication and price, from single channel/single purpose at less than US$50, to multi-channel configurable and networked units upwards of US$2,000. In addition, there are 'homemade' ways to record data that are possibly worth considering under certain rare conditions, as below. DC data logging solutions can be found off-the-shelf but are generally much harder to source than AC systems and configuration requires technical insight.

Data logging systems can be set up to suit a very wide range of budgets as below, illustrated with examples in Table 5:

- A low-cost way to record data (not actually a 'datalogger') could be a US$25 electrical power live display panel with data submission via mobile phone by the appliance user by sending an image of the panel at arranged time(s) each day. This is only viable for infrequent readings, requires an incentive for the user and reliability of the data link could be low.
- Temperature and humidity single channel data loggers are available that upload data files to a smartphone via near-field communication (NFC) or Bluetooth low energy (BLE) connection (see Table 6).
- A low hardware cost solution is using a kit-form hobbyist micro-processer programmable system to collate, process, save and/or transmit data (see Annex II Section iv). Kits cost tens of US$ up to low hundreds of US$ depending on requirements. However, technical knowledge and programming experience is essential, and it requires more time to design, construct, programme and test the system, even if an off-the-shelf kit is bought. Reliability can be challenging to achieve and this approach is inadvisable without significant experience.
- Mid- to higher-cost solution would be using proprietary plug-and-play multi-channel data logging systems. These cost several hundreds to a few thousand of US$ and have robust and weatherproof options available.

In discussions with data logger suppliers, they noted that the majority of field tests would be 'data monitoring' situations with recording frequency around 1 recording cycle per second to one every couple minutes/hours. They would not necessarily call these data acquisition (DAQ) situations.[8] The main considerations to discuss with suppliers when seeking a data logger are[9]:

a) How many sensor inputs are needed?
b) What types of sensors are available and what are their input ranges?
c) How often must data be recorded (sampling frequency – see also Section 3.2.1)
d) What's the required accuracy (how close to a true measurement) and precision(smallest discernible change in reading)?
e) How much memory is needed for data storage?

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[7] Adapted from the paper 'What is a data logger?' by CAS Dataloggers, available from https://www.dataloggerinc.com/wp-content/uploads/2019/12/19-What_is_a_Data_Logger.pdf.
[8] DAQ or 'high speed data loggers' involve data storage rates of tens or hundreds of readings per second (some in GHz range) and very unlikely to be needed for field testing.
[9] Source: 'Choosing the Right Data Logger for your Application' brochure published by CAS Dataloggers. Available from https://www.dataloggerinc.com/download-guide/.

f) What's the environment of use (power supply, ambient conditions, weatherproof, etc.)?
g) How will you retrieve the data (USB, wireless, GSM, etc.)?
h) Do you need alarm capability?
i) Is there a potential need for back-up power to the loggers if data is needed during power interruptions?

Suggestion: *Calibrate sensors and check that the readings of the sensors are stable and in line with expectations before leaving the site. Cross-check readings where possible. This may require additional equipment, such as a handheld temperature sensor, voltage and clip-on current meter.*

4.3.4 Battery Status

As discussed previously, some off-grid systems may need an electrical storage battery to ensure reliable service provision. The performance of this battery is crucial to monitor because the quality and performance of batteries can vary significantly, and price is *not* a reliable indicator of quality. This is at least partly due to most high quality and competitively priced batteries being channelled into the electric vehicle sector, with the off-grid sector tending to be supplied with batteries of quality tier 3 or tier 2. Introductory guidance on battery monitoring is provided in Annex II Section vii.

The battery state of charge (SOC) and state of health (SOH) should be tracked. SOC is important to the daily usage cycle. Whilst SOH does deteriorate over a period of years, very little deterioration of SOH would typically be expected over a field trial, but SOH should be monitored in case of any significant battery quality or compatibility problems that might otherwise cause undiagnosed system failure. Battery Management Systems (BMS), or systems designed to manage a battery's performance, can monitor SOC and SOH and range widely in terms of cohabitational, functionality, and price (from a few dollars for a small appliance BMS up to hundreds of dollars for a local grid BMS. Talk to your battery supplier and negotiate provision of a BMS that will deliver the battery data needed for the test.

4.3.5 Solar Irradiance Assessment

If the power system used during field testing relies on solar PV power, then it may be worth monitoring the solar irradiance (kWh/m^2/day) that is available. This can be compared with power actually delivered and used by the appliance(s). Solar irradiation sensors are available that can be mounted by the PV panel and cost between US$ 150 to US$ 250 per sensor, see Annex II Section vi and Table 7. An assessment of available solar energy may also be worthwhile when first choosing test sites and can be found from published sources. Sources of data on global horizontal irradiation (GHI) include:

- Companies specialising in providing solar irradiance data for most parts of the world, such as Meteonorm[10] and Solargis[11]. Some solar irradiance data at specific locations of your choice is available free of charge.

[10] See https://meteonorm.com/en/.
[11] See https://solargis.com.

- In June 2020 ESMAP and the World Bank published a study called Global Photovoltaic Power Potential by Country[12] which explains the basic concepts and ranks all likely countries by their GHI and practical PV power potential.
- Further solar energy mapping and other resources are collated under the European Union's African Renewable Energy Technology Platform (AFRETEP) initiative[13].

4.4 Finding Local Partners and Test Sites

Finding local delivery partner and test sites gets easier the more you expand your network, and any of these organisations can help you to do that:

- The LEIA programme from the Efficiency for Access Coalition[14]
- VeraSol test lab network[15]
- Energy system supplier industry associations such as GOGLA (global association for the off-grid solar energy industry) and ARE (The Alliance for Rural Electrification)
- Local business cooperatives
- Social enterprise and self-help organisations
- Initiatives such as Alliance for a Green Revolution in Africa (for farmers) and Shamba Shape Up (for agricultural small businesses in Kenya)
- Consumer representative groups can be contacted via an umbrella group such as Consumers International[16]
- University departments undertaking related research (one relevant networking initiative is the AFRETEP[17]
- Charities working in the communities such as Practical Action.

4.5 Shipping and Delivery Plan for Equipment

Getting the equipment to the test site is often a challenging part of field testing, and each country has its own legal and administrative requirements.

Protecting the appliance and equipment for rough transit is crucial, but easy compared with the administrative and logistical hurdles associated with import and duties. Protection is not only for long-haul shipping journeys, but also from the port to the remote field site, which may involve bouncing along poor roads on the back of a motorbike or truck for many hours. Most appliances and packaging are not designed for this sort of rough condition.

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[12] ESMAP. 2020. Global Photovoltaic Power Potential by Country. Washington, DC: World Bank. Available at: https://documents.worldbank.org/en/publication/documents-reports/documentdetail/466331592817725242/global-photovoltaic-power-potential-by-country.

[13] See https://europa.eu/capacity4dev/afretep/wiki/maps-and-data-sources.

[14] See https://efficiencyforaccess.org/leia and contact info@efficiencyforaccess.org.

[15] See https://verasol.org/test-labs and contact info@verasol.org.

[16] Consumers International has member associations in many African Member States, see https://www.consumersinternational.org.

[17] See https://europa.eu/capacity4dev/afretep/members.

Considerations include:

- Read the Efficiency for Access' Practical Guidelines for Shipping Off-Grid Appliances (see section 8.1), which discussed how to estimate costs for shipping, understand import and export requirements, and how to package a product for shipment.[18]
- To a significant extent, it is the shipping company that determines how the rules are implemented in practice, not the country, exporter or importer. It is worth taking advice from several companies to judge the best approach.
- Ensure that the required tools, equipment, all connectors and leads for set up will also be on site. Check what leads are necessary and which are included with each item.
- Get advice on suitable packaging for the envisaged journey considering impact, vibration, water, drop, etc.
- Batteries (especially Lithium based) and other materials, such as refrigerants, that are considered 'dangerous goods' can be difficult to ship. It may be helpful to engage a company that specialises in shipping these products.
- Decide which equipment will be shipped back at the end of testing and how that will be packaged.
- Get a good, experienced shipping agent and ensure that they take account of:
    - Local regulations: these may vary by appliance and according to the value of goods in each shipment
    - If the appliance will be considered a commercial good for sale, and thus must meet relevant regulations. For example, if the appliance is gifted to the user after the test, then the appliance has indeed been supplied to the internal market
    - Fees and tariffs that apply or could apply
    - Customs clearance paperwork
    - Labelling of appliances, meeting safety requirements and protective packaging

4.6 Equipment Set-Up on Site

When setting up the equipment on site, bear in mind:

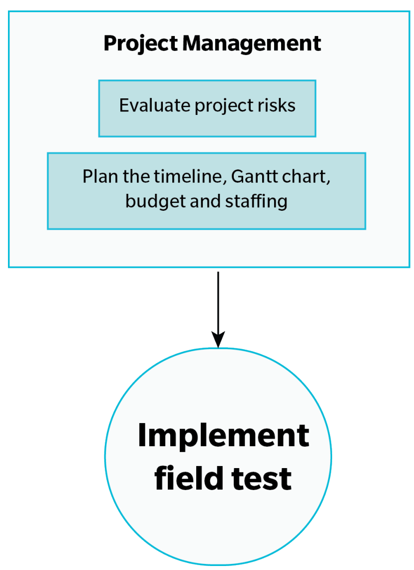
- Keep equipment out of sight and out of the way of daily activities of the users to reduce accidental changes or breakage. Even if the equipment is weather-proof, it is advisable to keep it sheltered where possible.
- Take account of losses in cables. Keep cables as short as practicable and make voltage measurements as close as practicable to the point of interest.
- Avoid electrical noise on sensors by keeping sensor wires apart from power wires, particularly AC power. Use twisted pair wiring and shielded and grounded cables. Beware of ground loops in shielding that cause additional noise.
- Check that any PV panels are clean and intact. This should be done during each visit by whoever collects the data or equipment.
- Check that sensor data is being stored correctly both on the local storage and remote server.

[18] The guide on shipping off-grid appliances is available from: https://efficiencyforaccess.org/publications/practical-guidelines-for-shipping-off-grid-appliances.

- Check polarity of wired connections as sensors wired wrongly give nonsense data. and could irreparably damage the monitoring device Find ways to ensure that cannot happen.
- Check that data network SIM cards work before heading off to the site, especially any Access Point Name (APN) settings issues or delays in configuring data services.
- Check that the GSM signal at the site is strong enough and that data upload is working. Confirm data streams from the online endpoint.
- Explain to the users or host what the monitoring kit does, including reassurance that it has no effect on appliance performance. Be sure to allay any privacy concerns regarding the nature and handling of the data. Also mention the person to contact in case of any further questions or in the event of an emergency
- Check the connections and stability of the power supply for the logging and modem kit, especially if it is separate to the overall system.

Suggestion: Consider taking a spare antenna to improve the signal for connections at site (though a long antenna cable may end up no better than a built in one).

5. Project Management



5.1 Risks and Remedies

A checklist of generic risks in the testing plan should identify and propose mitigation strategies for risks listed below:

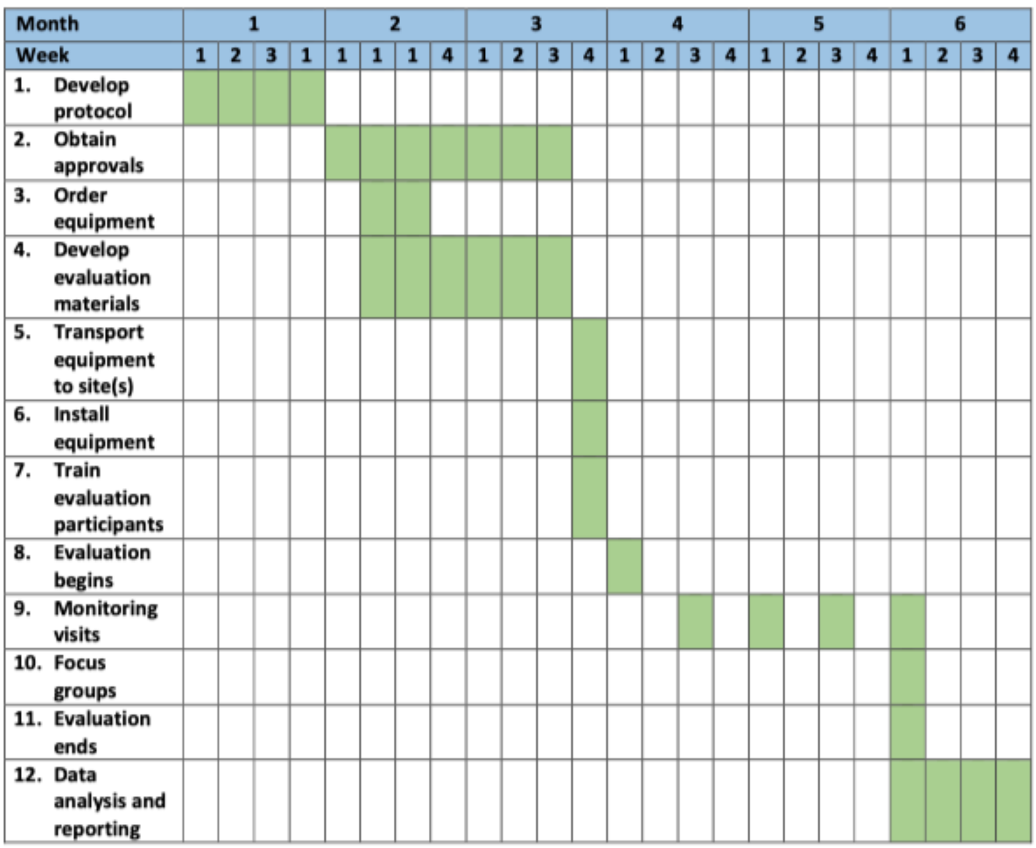
- Appliance failure, especially if early in the programme. Have a plan for replacement or repair, work out how spare parts will be obtained and delivered (preferably via a local partner with technical skills and tools; involve them in equipment set-up).
- Language difficulties at test site, for training/instructions, or anywhere along the delivery chain. Keep language simple and enroll local partners.
- Change of circumstances of users during test period. For example, if the electricity grid arrives, a shop changes use or owner, users change, new family members, or new types of customers. Check for changes at intervals and be prepared to recalibrate the set up if required.

- Lack of vigilance once the test is underway. Field tests fail through complacency after set-up when attention is diverted to other priorities. Plan for checking data streams and results at regular intervals during the field test.

5.2 Timeline, Budget and Staffing

This is a reminder to apply basic project management principles. This includes working out and monitoring the project budget and allocating staff with specific roles and responsibilities that are written down and understood by all. It’s also important to plan for the many timeline considerations, which are mentioned throughout the guide, particularly in section 5.1. A Gantt chart is an essential visual tool for management that sets out the tasks, timing and dependencies. It can be as simple or complex as needed (see example Gantt chart in Figure 3).

Figure 3. Example Gantt chart for a field test (source: WHO/PQS/GENERIC/GUIDE.1.1).



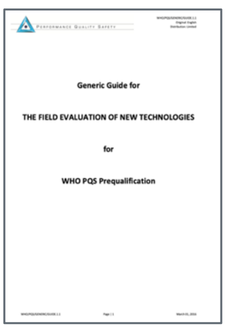
5.3 Next Steps and Upcoming Publications

While the exact field testing plan should be tailored to unique appliance types and objectives for field testing, these are general considerations and guidelines that apply across the board for anyone looking to carry out an appliance field testing exercise. This guide was primarily developed to inform the design for the Efficiency for Access field testing projects at the time and is meant to be a live document to be improved upon as new knowledge becomes available and new challenges uncover.

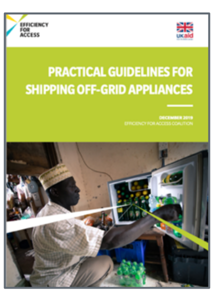
The authors welcome and encourage further contributions and feedback from stakeholders to help us improve and enhance the field testing guide.

Efficiency for Access curates a collection of reports that can help inform various aspects of field testing design (see Annex I for further guidance). In addition to these existing resources and following this first guide, Efficiency for Access plans to develop a series of field testing design and implementation guides. Upcoming guides will include: 1) a user data collection guide that serves as a blueprint for non-technical data collection; 2) a refrigerator field testing technical guide that dives into technical performance data monitoring for refrigerators, including technical parameters, methodology, templates for data collection, and considerations for selection of remote monitoring equipment; and 3) a solar water pump field testing technical guide that highlights approaches and considerations for monitoring technical performance data in the field. These guides will be published in March 2022 on EfficiencyforAccess.org.

ANNEX I: SOURCES OF FURTHER GUIDANCE



Generic Guide for the Field Evaluation of New Technologies for World Health Organisation (WHO) Performance Quality Safety (PQS) Prequalification, WHO/PQS/GENERIC/GUIDE.1.1, March 01, 2016.



Practical Guidelines for shipping of off-grid appliances, Efficiency for Access, December 2019.

Guidelines to evaluating, selecting and testing remote monitoring solutions for refrigerators and solar water pumps, Efficiency for Access, September 2021.

A substantial ‘open source’ knowledge base on the basic principles, hardware and techniques for low-cost AC electrical monitoring is available at this UK web site[19]: https://learn.openenergymonitor.org/electricity-monitoring/ac-power-theory/introduction

ANNEX II: BASIC PRINCIPLES FOR MEASURING AND RECORDING VOLTAGE, CURRENT AND POWER DATA

I. VOLTAGE MEASUREMENT (AC OR DC)

Basic principles:

- To measure the voltage at a point along a wire requires an electrical connection of two cables from the sensor, one to the wire in the positive cable and one to the wire in negative (or ‘ground’) cable that feed power to the appliance. Voltage sensors are widely available for all types of circuit.
- AC mains voltage is often first isolated, per phase, and passed through a small step-down transformer or using isolation for increased safety by clearly separating the high input voltage from lower “safe” voltages. The low voltage can then be lowered further for signal acquisition (voltage measurement) purposes using a voltage divider and positively offset to prevent any negative voltage from being fed into the sensor chip and therefore damaging it. These signal processing steps may be integrated partially/wholly into a single sensor unit/chip depending on the sensor vendor.
- DC voltage can be measured using a simple voltage divider (depending upon the sensor input range, e.g., 0-10V, 0-100 millivolt (mV) with a decoupling capacitor as close as possible to the measuring/sensing chip. The resistors of the voltage divider must be picked to handle the power dissipation at the anticipated maximum DC voltage.
- Measure the voltage as close to the appliance as reasonably accessible, ideally within a few tens of centimetres (cm) of wire from the appliance, for accurate assessment of delivered voltage (and power). This is because electrical resistance results in AC and DC voltage dropping slightly along the length of a power supply cable, especially if the cable is long, of poor quality, or if the power carried is high for the grade of cable. DC is more adversely impacted by voltage drop due to higher current. 10 amps (A) at 12V DC is equivalent power to 0.5A for 220V AC. Note: no current passes through the wires to the voltage sensor (it

[19] This is a third-party website and no endorsement or guarantee of accuracy by Efficiency for Access is given nor implied by provision of this link.

measures only the potential or voltage) and so there should not be any voltage drop along the length of the wire from power lead to the sensor. The length of that cable is not as important.

- Bear in mind that in an open circuit situation, solar panels can deliver a voltage 50-100% above their normal operating one and the sensor must bear this without damage. Check the open-circuit voltage (Voc) rating. For example, a 12V DC system can deliver 18V to 24V.

Below are some examples of types of voltage sensor available in the market. Images of products are shown in the tables that follow for illustration purposes only and endorsement of specific products is neither given nor implied.

Table 2: Example types of voltage sensor

Ref	Type of sensor	Indicative description (examples)	Data, communication & storage	Indicative price (US$)	Photo of example sensor
A	Live DC electrical meter display	Digital display meter for DC power and energy, voltage, current	Visual display only, for example 6-100V DC; 0-100A; 0 to 10kW; 0-9999 kWh. Accuracy +/-1%.	US$ 25 to 75	
B	Voltage sensor module	Voltage sensor module, up to 25V. Arduino compatible. Feeds voltage signal to logger. Must be integrated into data system.	GSM / cloud-based solution for enthusiast kits	US$ 5 to 25	
C	Stand-alone DC voltage automated data logger	DC voltage logger between 2.5V and 30V. Storage for 1 million readings at 4Hz rate = just over 2 days logging time between downloads. 10-year battery life. Competitive cost with integrated backup, but no built-in data communication.	Data download via USB, removable data storage card, infrared, Wi-Fi, or Bluetooth.	US$ 100 to 400	

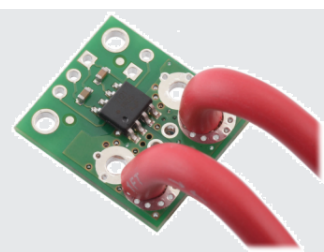
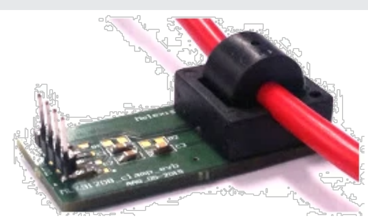
II. CURRENT MEASUREMENT (AC OR DC)

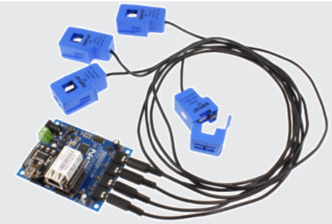
Basic principles of current measurement

- Current in a wire can be measured without electrical contact with the conductor by using a current sensor of which several types are available.
- AC current is usually measured with a current transformer (CT).
- Current sensor carriers are also available which are wired into the circuit and the current to be measured is passed through the sensor.

- DC current is typically measured using Hall Effect sensor or using a shunt resistor to transform the current into a voltage signal that can be readily measured. Some Hall Effect sensors do not require electrical contact, provided the needed electrical isolation, but may suffer from drift as well as offsets. Shunt resistors suffer minimal offsets and near zero drift but may distort the measurement by introducing a phenomenon known as burden voltage.
- Some Hall Effect sensors double as CTs. They are referred to as Hall Effect CTs, and are typically capable of measuring both AC and DC current.
- The most common types of current sensor have a split ring coil so that the unit can be clamped around the conductor without breaking the circuit.
- A CT measures the total net current passing through the ring of its coil and so generally only one conductor passes through the coil. If, mistakenly, the supply and return conductors both pass through the coil then the CT will (correctly) read zero net current!
- The proprietary bundled cables often used in SHSs must first be split to isolate the conductor to be monitored.
- Most types of CT for AC power, especially cheaper ones, are calibrated to show root mean square (RMS) current correctly when the wave form is sinusoidal. If the AC wave form is not sinusoidal, which happens if a fluorescent lamp ballast is in the circuit or often for weak-grid connections, then accuracy of measurement could be poor.

Table 3. Example types of current sensors

Ref	Type of sensor	Indicative description (examples)	Data, communication & storage	Indicative price (US$)	Photo of example sensor
A	Live DC electrical meter display	Same as Table 2 A			
B	On-board chip-based AC current sensor carrier	Current passes through device so circuit must be interrupted to install. Size to allow margin 1.5x to 2.5x the maximum expected current. Easy retrofit to existing installations and high accuracy but have to be wired into appliance.	Wire to microprocessor for data transmission or data logger to a display screen. +/-0.8% 'typical error'.	US$ 5 to 25 for 50A AC model	
C	On-board split core Hall Effect sensor for AC or DC	Split coil can be assembled over the conductor. Example covers 5 to 30A, for DC and AC power. High accuracy but can't be easily retrofitted or moved.	Wire to microprocessor for data transmission or data logger to a display screen.	US$ 25 to 100	

D	Off-board split core 4-channel Hall Effect sensors for AC only	Split core sensors, up to 100A options AC only. Can gather more than one input of current data; convenient to retrofit. Lower accuracy and higher price.	Wire to microprocessor for data transmission or data logger to a display screen.	US$ 100 to 400	
E	DC current sensor, split core Hall Effect sensor	Measures DC current up to 200A, 21 millimetre (mm) opening, Requires +/-15V power supply.	Requires output voltage analyser. Accuracy +/-0.5%.	US$ 50 to 200	

III. POWER MEASUREMENT (AC OR DC)

Basic principles of electrical power and energy consumption measurement

- AC power (W or kW) and energy consumption (kWh) can be measured using widely available combined meters that measure voltage, current, power factor and often also frequency and more, and are highly cost-effective.
- If the power supply is AC, then the power factor in the circuit must be taken into account when calculating the energy consumption[20], which is dependent on the energy consumption type required (true energy or apparent energy). Do note that in domestic consumer systems, the power factor loss is not usually billed in some countries hence only true energy is required. In contrast, due to the larger consumption by industrial customers, power factor loss is usually billed to encourage efficient design of industrial power systems - hence apparent energy is required which takes into account power factor.
- For weak-grid AC situations, the voltage, frequency and power factor may vary significantly from nominal and less sophisticated sensors, which may give poor accuracy. Check with suppliers.
- Commonly-available AC power meters may not, however, be designed to capture non-energy data such as temperature and humidity.
- Equipment for direct measurement of DC power and energy consumption is hard to find ‘off-the-shelf’. Customised systems may be necessary, with technical insight.
- Electrical power can be calculated from voltage and current readings, as long as readings are synchronised (i.e., the two readings can be multiplied together if they are known to be valid at the same instant).
- Energy consumption is calculated by adding up the power consumed over time. This is done automatically within a power meter or can be done in software by applying calculus methods

[20] Power factor is a property of the circuit associated with the relative phasing of the alternating current and alternating voltage. Power factor is the ratio of the real power absorbed by the appliance to the apparent power flowing in the circuit and generally has a value just less than one, though can approach zero.

such as integration (area under the curve) of the instantaneous current and voltage data streams.

Table 4. Example types of power meters.

Ref	Type of sensor	Indicative description (examples)	Data, communication & storage	Indicative price (US$)	Photo of example sensor
A	Live DC electrical meter display	Same as Table 2 A			
B	Live AC electrical meter display	Colour LCD display panel meter for 80 to 300V AC, 100A, 450kW	Energy consumption sampling 2Hz with data saved.	US$ 10 to 30	
C	DC and AC energy meter system	Measure 2 or more DC or AC voltages, currents and power with data available on a cloud platform.	Typically ±2% error Various options of channels for voltage, current, power.	Meter for DC solar powered system US$ 200 to 500 Meter for DC solar powered system with inverter US$ 300 to 600 Cloud platform subscription may apply.	

IV. DATA LOGGER SYSTEMS

Table 4 shows examples of simple up to sophisticated ways to log data.

Note: One solution if the team has programming and electronics assembly experience is to use a customised or kit-form hobbyist micro-processer system to automatically collate, process, save and/or transmit data. These could be based around an Arduino (basic level) and/or Raspberry Pi (more versatile) micro-processers for which data logging hardware would cost several tens of dollars up to low hundreds of dollars, depending upon the requirements. These systems require technical knowledge and time to construct, even if built from off-the-shelf kits, plus time to programme and test the system. Off-the-shelf kits and ready-made solutions are highly recommended over custom systems unless highly experienced, because reliability can be challenging to achieve without experience. Many of the kits use bread boards and simple jumper cable wires which are not suitable for field trials due to risks of lost connections. Variants are available with more sturdy plugs to connect to the sensors or with sensors mounted directly on the board.[21] Printing and assembly of these circuit boards costs US$10 to US$20 per board (not including components or delivery and with minimum order quantity of 50 units).[22] An enclosure (box) for the system must also be bought to prevent ingress of dust and moisture to the sensitive electronic components (ideally to reach appropriate IP ratings, costing around $15[23]). Even with off-the-shelf hobby kits, time must be allocated for assembly, testing and integration with the system and experience suggests that the time and labour cost to achieve reliability may be orders of magnitude above the hardware cost of a plug and play data logger product.

Table 5. Example types of data logger systems.

Ref	Type of sensor	Indicative description (examples)	Data, communication & storage	Indicative price (US$)	Photo of example sensor
A	Live DC electrical meter display with mobile phone camera	Digital display power meter for DC voltage, current, power and energy consumption, accuracy +/-1%. Options with power factor and more available (higher price).	This example 6-100V; 0-100A; 0 to 10kW; 0-9999kWh. User sends image of meter at suitable intervals.	US$ 25 to 70, plus cost of mobile camera phone and data contract	 
B	Programmable PCB system kit, such as Arduino or Raspberry Pi	Low-cost sensors can be wired to the PCB board. Programming required to carry out data processing and onward transmission via on-board USB socket to external modem or other storage.	Available as PCB board alone or as kit of components to make a logger.	PCB US$ 10 to 50 Parts for kits US$ 20 to 100 including housing	
C	ICE3 EXTRA – 16 channel data logger for wired sensors	Example has 16 input ports for temperature, humidity, energy metering etc., with DC options. Stores data for up to 110	Uses global SIM cards with options to connect to multiple networks in each country. Can run for year or more on internal battery.	US$ 300 to 900 including annual access to online portal with high quality data presentation,	

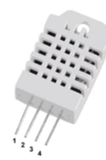
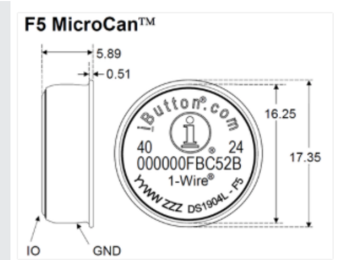
[21] Arduino Shields and Pi HATs (Hardware Added on Top) are PCBs which stack on top of the Arduino or Raspberry Pi and allow connection through the GPIO pins without using jumper cables. https://www.raspberrypi.org/forums/viewtopic.php?t=85492
[22] Approximate costs obtained from https://pcbshopper.com and https://www.pcbastore.com/quotesmt.html for printing and assembly of double-sided PCB with typical dimensions and number of components of an Arduino Shield or Raspberry Pi HAT.
[23] See https://www.telerex-europe.com/en-gb/in-box-pc-two-piece-plastic-enclosure-with-sealing-c7012012.

		days, uploading when connected.		processing and alarms.	
D	DC and AC Energy meter system	As Table 4 C			

V. TEMPERATURE SENSORS

Note that some temperature loggers designed for medical and vaccine applications are sold as full package monitoring, data handling and secure data platform access – some of these are not available as stand-alone devices and cannot be used for non-medical applications.

Table 6. Example temperature sensors.

Ref	Type of sensor	Indicative description (examples)	Data, communication & storage	Indicative price (US$)	Photo of example sensor
A	Basic, low-cost digital temperature and humidity sensor	To be built into Arduino and similar self-build monitoring system kits. -40ºC to +80ºC +/-0.5ºC accuracy. 0-100% humidity with 2-5% accuracy. Size 60mm x 30mm.	Connect to data logger or Arduino or similar.	US$ 5 to 20, plus labour costs to assemble	
B	Button temperature sensor	High-resolution button sensors can contain complete temperature logging system for cold chain, food safety, pharmaceuticals. -40 to +85ºC and accuracy +/-0.5ºC, resolution 0.5ºC. Data accessed also when battery exhausted.	Linked with host computer via ‘1-wire protocol’. Can log thousands of values; log rates 1 per sec to one per 200 hours; battery 10 days at 1 per second; over 300 days for 1 per minute.	US$ 25 to 100	
C	Near Field Communication (NFC) Temperature Data Logger	Temperature logger designed for tracking storage temperatures for logistics. Battery lasts up to 100	Data file output via NFC connected smartphone for subsequent upload to	US$ 100 to 200 per logger (not including smart phone)	

		days depending upon logging frequency. Options for GPS and humidity.	cloud server. CSV, XLSX and PDF format files.		
D	WIFI Temperature and Humidity Data Logger	Wired or wireless sensor probes to place inside cooled compartment for air temperature and/or humidity, with user display. -40 to +80ºC accuracy +/- 0,5ºC. Rechargeable battery lasts 3 months.	Wi-Fi, GSM & data access over web. Stores 20,000 temperature records.	US$ 100 to 200	
E	Remote Temperature Monitoring Device	Robust remote temperature-monitoring device with onboard or wired sensors (-20 to +55ºC; accuracy +/-0.2ºC) plus door status. Minimum log interval once per minute. Programmable via web browser. LCD display.	Dual-SIM global connectivity and no external power supply needed (can run for over 3 years). Option for real time GPS tracking.	US$ 300 to 3000 depending on sensors, some include data portal access	
F	Remote monitoring (for medical cold chain)	Wireless remote temperature monitoring designed for vaccine refrigerators with up to 5 temperature sensors. Battery life up to 3 days without power so needs power supply for longer periods. World Health Organization Performance, Quality and Safety approved (E006/039)	GSM contract	US$ 50 to 200, plus access to data portal annual contract	
G	Cold chain temperature data loggers (for food	Several suppliers of similar systems with multi-channel	Options for USB or GSM connectivity or link to	US$ 50 to 200	

	logistics and similar use)	temperature recording.	networked gateway.		
H	Consumer Bluetooth temperature and humidity logger	Thermometer and hygrometer data logger; log intervals set from per 10 seconds to per 30 minutes. Power by two button batteries.	Read by smartphone App, auto-connects when in range using Bluetooth. Data can be stored on the sensor for about 20 days.	US$ 50 to 100 (not including smart phone)	
I	Consumer digital hygrometer or thermometer	Monitor humidity and air temperature of the ambient environment. Two temperature sensors. -40 to +60ºC, accuracy +/-0.3ºC and +/-1ºC. 2xAAA batteries.	Bluetooth/Wi-Fi. Logs up to 30,000 data points, Log intervals set from per 10 seconds to per 30 minutes.	US$ 50 to 200	

VI. SOLAR IRRADIATION SENSORS

Table 7. Example solar irradiation sensor.

Ref	Type of sensor	Indicative description (examples)	Data, communication & storage	Indicative price (US$)	Photo of example sensor
A	Solar irradiation photodiode	Photodiode (silicon pyranometer) achieving +/-5% accuracy on measurements of 0 to 2000 W/sq.m irradiation.	Typically operates in 9 to 30V with power supply. Current is proportional to incident radiation.	US$ 150 to 250	

VII. ASSESSING THE STATUS OF BATTERIES DURING FIELD TESTS

Although the type of battery and monitoring system needed varies across appliances, this section presents some generic and indicative guidance for battery SOH and SOC monitoring systems:

SOC: the level of charge of a battery relative to its capacity at that moment and is expressed as a percentage (100% + full; 0% = empty)

SOH: a figure indicating the condition of a battery compared with its ideal condition and is expressed as a percentage where 100% is the ideal condition of charge capacity typically achieved at its point of manufacture.

SOH deteriorates over time and for typical batteries may be down to 80% after 3 years. Over the period of a field trial, very little deterioration of SOH would typically be expected. However, SOH should still be monitored to screen for any significant battery quality or compatibility problems. There are many suppliers of Battery Management Systems (BMS), which in general are designed to learn the behaviour of a particular battery within the system to determine its SOC and SOH. BMS can cover a wide range of sophistication, functionality and price ranging from a few dollars for a small appliance BMS up to hundreds of dollars for a local grid BMS. There are two types of battery control:

a) Most lithium ion and similar low-cost battery packs are sold with integrated basic safety management features in a printed circuit board (PCB) that includes short circuit, over-current and over-discharge protection, although this not generally available for sealed lead acid batteries. These do not include any charge or health monitoring outputs and are not suitable for any monitoring functions.
b) Any BMS will address the basic battery safety requirements, and so can replace the basic PCB. In addition, for a full picture of battery performance the BMS should also monitor and report:
    i. Temperature of battery cells
    ii. Voltage
    iii. Current
    iv. SOC
    v. SOH

Battery performance can be assessed more easily in the lab, but if it is a priority in the field test, the battery supplier may be able to provide a BMS that will deliver the necessary battery data with voltage outputs for any data logger. If the battery is of poor quality with variable behaviour, or if the battery is poorly matched to the system and gives varying results, then the BMS cannot 'learn' to interpret battery behaviour and the recorded SOC and SOH could be unreliable and hard to interpret.
For further information see, for example, a BMS supplier website such as Texas Instruments[24].

[24] See https://training.ti.com/battery-management-deep-dive-technical-training.