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PERFORMANCE AND EFFICIENCY OF OFF-GRID APPLIANCES WITH POWER CONVERTERS

OCTOBER 2020

PHASE 2 – TESTING OF MULTIPLE APPLIANCES AND AN INVERTER COMPRESSOR REFRIGERATOR

CONTEXT

This report summarises the findings of laboratory tests that were conducted to provide a better understanding of the efficiency, performance and costs of common use cases of power supply and appliance types in off- and weak-grid areas. The findings should assist market stakeholders to understand the role power converters play in providing access to low-cost, efficient appliances.

The testing conducted was split into two phases. Phase 1 tests aimed to assess the performance and cost of ownership and operation for single AC- and DC-rated appliances, operated outside of their native modes for different use cases. Testing was conducted on AC and DC refrigerators, fans and TVs. Phase 2 tests built on Phase 1 tests by assessing the performance and costs of multi-appliance systems running on power converters, as well as exploring appliances further at the component level.

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GLOSSARY

AC	Alternating Current
Ah	Ampere-hour
BLDC	Brushless Direct Current
COP	Coefficient of Performance
DC	Direct Current
DIN	Deutsches Institut für Normung
Inverter	A power converter that receives DC power and outputs AC power
kWh	Kilowatt-hour
MEPS	Minimum Energy Performance Standards
MSW	Modified Sine Wave
Native mode	An appliance operated directly from its rated power supply, without the need for power conversion
Non-native mode	An appliance operated from an incompatible power supply (AC or DC) with a power converter that provides the rated power of the appliance
PAYGo	Pay-As-You-Go financing
PF	Power factor
PSW	Pure Sine Wave
PV	Photovoltaic
Rectifier	A power converter that receives AC power and outputs DC power
SERC	The Schatz Energy Research Center
SHS	Solar Home System
SMPS	Switching mode power supply
SQW	Square Wave
THD	Total Harmonic Distortion
TSC	Upfront Total System Cost
TV	Television
UPS	Uninterruptible Power Supply
Wh	Watt-hour
Wp	Watts-peak

Background and context

Increasing electrification in sub-Saharan Africa and South Asia involves a continually evolving and complex ecosystem of AC electrical grid extension, AC or DC mini-grids, and AC or DC solar home systems (SHSs). While governments continue to develop grid extension plans to reach off-grid areas, companies are either focusing on reaching off-grid areas through AC or DC mini-grid development, or SHS distribution in both off- and weak-grid areas.

This varied approach to electrification is reflected in the mix of AC and DC appliances used in off- and weak-grid areas, which the Low Energy Inclusive Appliances (LEIA) programme observed through its extensive market surveys of refrigerators, fans, TVs and solar water pumps in developing countries. Off-grid consumers have also been observed to use AC appliances with a DC SHS as a result of DC appliances being unavailable in their market. Given this mix of electrification approaches and appliance types, compatibility issues between AC and DC power supply and AC and DC appliances need to be addressed.

Off- and weak-grid appliance use cases

Observations from off- and weak-grid use cases suggests that we need to learn more about how operation on different power supply options affects appliance efficiency, performance and durability.

Appliances may be rated for use with DC or AC, and powered by the electrical AC grid, DC or AC mini-grids, or DC Solar Home Systems (SHSs). Where the power supply and appliance are not directly compatible, a power converter – an inverter or a rectifier – is required. An inverter converts DC power to AC power, while a rectifier converts AC power to DC power. Using power converters increases power consumption, the complexity of the system set-up, as well as cost and quality considerations.

This study explores the following use cases of appliances and power supply in use in off- and weak-grid settings, by simulating the use cases through laboratory tests. This study defines 'native' mode as an appliance operating directly from its rated power supply at its rated voltage without the need for power conversion. 'Non-native' mode refers to an appliance operating from an incompatible power supply using a power converter that provides the rated voltage of the appliance.

Table 1: Use cases of power supply and appliances in off- and weak grid settings

#	USE CASE	POWER SUPPLY TYPE	APPLIANCE TYPE	POWER CONVERTER
1	DC appliances in native mode	DC power supply *(DC SHS or DC mini-grid)*	DC appliances	None
2	AC appliances in non-native mode	DC power supply *(DC SHS or DC mini-grid)*	AC appliances	Inverter
3	AC appliances in native mode	AC power supply *(AC grid or AC mini-grid)*	AC appliances	None
4	DC appliances in non-native mode	AC power supply *(AC grid or AC mini-grid)*	DC appliances	Rectifier

Phase 2 of this study builds on the previous Phase 1 report, 'Performance and efficiency of off-grid appliances with power converters: Phase 1 – Single appliance testing of refrigerators, TVs and fans'. Phase 1 involved testing to measure the performance and costs involved with operating single refrigerator, TV and fan appliances in the different use cases above. Phase 2 testing further explored these use cases by testing combinations of multiple appliances and testing an AC inverter compressor refrigerator.

Phase 1 tests – single appliances using power converters

In the Phase 1 tests, laboratory tests were conducted to measure the energy consumption of refrigerators, TVs and fans operating in the different use cases. This enabled an estimate of the associated size and cost of the solar PV system required for DC supply, or the electricity cost from a grid or mini-grid for AC supply. The effect of the power converter on appliance performance was also observed, in order to consider longer-term operational issues and costs for the user. Cost estimates were compared to identify the optimal use case of appliance and power supply for the different scenarios. The main conclusions were:

- Single DC appliances run natively on SHSs are generally more cost-effective compared to AC appliances run with inverters on SHSs.
- Converter quality and cost is highly variable.
- Using rectifiers to power off-grid DC appliances on AC supply appears viable, but quality issues may be encountered.
- Hybrid and efficient AC technologies are viable options for off-grid appliances.
- Further cost reduction in DC appliances is necessary to gain the full benefits of their efficiency.

The Phase 1 report can be found on the Efficiency for Access website **here**.

Phase 2 tests – multiple appliances using power converters and testing of an inverter compressor refrigerator

The Phase 2 tests built on Phase 1 by testing multiple AC appliances running simultaneously on an inverter, and multiple DC appliances running simultaneously on a rectifier. This simulated the usage pattern of a household or business that owns multiple appliances, which helped assess the optimal appliance choices for this use case. As in Phase 1, tests were conducted in the laboratory to simulate real-life use cases of off-grid and weak-grid users.

Productive use appliances, defined as appliances used for work and income generation, were included in the testing. A sewing machine, hair clipper and drill were tested alongside domestic appliances: a refrigerator, fan, TV, lights and a phone charger. These tests helped investigate the performance of these generally higher-powered appliances when run on inverters. Various off-grid energy service providers provide product packages such as these in their offerings. Solar Now provides packages for small businesses starting at 150Wp[1], and Lumos Global's 160W Panel system[2] considers power provision for sewing machines, laptops and hair clippers, as part of its 'Prime' package.

A number of areas identified through Phase 1 tests were explored further in the Phase 2 tests. These included differing surge power requirements of AC and DC refrigerators, energy consumption in low load conditions when using power converters, and the performance of different types of converters of varying quality.

In addition, testing was conducted on a refrigerator that incorporated a newer, inverter compressor technology. This helped compare it with existing AC and DC refrigeration technologies and assess the viability of its use for off- and weak-grid use cases.

1 Solar PV system and appliance packages from Solar Now https://www.solarnow.eu/solar-solutions/small-business-solutions/
2 Solar PV and system and appliance packages from Lumos Global https://www.lumos-global.com/products-services/

Conclusions

In the case of multiple appliances operated on a SHS, this study found the use of DC appliances natively more cost-effective than the use of AC appliances with inverters. This is in line with the findings from the single appliance tests in Phase 1. For the full set of DC appliances modelled, the report authors estimated that the energy to run them could be provided with a solar photovoltaic (PV) array of around 420 Wp and battery capacity of around 200 Ah. The AC appliances, on the other hand, were estimated to require a PV array of around 750 Wp and battery capacity of around 350 Ah.

As anticipated, this report found that operating multiple AC appliances with an inverter was more cost-effective than operating a single AC appliance with an inverter. However, the quality of inverters and appliances must be considered. Running multiple AC appliances on an inverter enables more efficient use of the available PV system power and a more optimised loading of the inverter. This is especially evident when running a refrigerator. Operating a single refrigerator requires an oversized inverter, which can provide sufficient surge power for the refrigerator's high in-rush current. In a multi-appliance set-up, the same size inverter can still be used. This is because the additional appliances' energy consumption mostly contributes to increasing the continuous power requirement from the inverter, rather the surge power requirement.

This report estimated that running DC appliances on a DC mini-grid was more cost-effective than running equivalent AC appliances using an inverter on a DC mini-grid. While the combined upfront purchase cost of the DC appliances was over 50% higher than for the AC appliances, this was offset by the reduced electricity cost over the modelled period of six years. It is also important to consider that inverters have often been observed to be a source of PV system failure (Formica, Khan, & Pecht, 2017). Testing in Phase 1 and 2 showed that use of a pure sinewave (PSW) inverter is a safer and more reliable option for running appliances compared to a modified sinewave (MSW) inverter. Testing DC appliances on an AC supply using a rectifier showed that these can be effectively powered in this way, but also exposed some issues with this non-typical use case, such as problems with unexpectedly high-power consumption at low load levels. Ultimately, operating appliances on their native power source may be preferable.

Testing an inverter compressor refrigerator demonstrated that this AC-based technology is significantly more efficient compared to AC single-speed compressor refrigeration. Given little available data on the performance of this type of refrigerator in off- and weak-grid markets, the refrigerator tested and procured from India provided a performance benchmark for this technology. The authors noted that the refrigerator was not less efficient compared to best-in-class DC refrigerators designed for off-grid use. However, test data suggests that this technology could increase the viability of operating AC refrigerators on a DC supply with an inverter, as an alternative to running DC refrigeration natively.

The relatively low cost of the inverter compressor refrigerator contributed to a lower upfront total system cost than that calculated for most DC appliances of a similar size for which data was held. However, the test results cannot yet be taken to mean that using this technology with an inverter is the optimal choice for running a refrigerator on a DC supply. Inverter performance and selection provided challenges, as was seen in Phase 1 results, with the inverter adding to the energy consumption, particularly in low-load conditions (i.e. when the compressor cycled off). Provisional market research also suggested that the price point of the refrigerator from India was not typical of other off-grid markets such as those in Africa. However, the tests results demonstrated that this type of AC refrigerator, when run with a good quality and appropriately sized inverter, shows viability for use on DC or hybrid AC/DC environments.

Projections, such as those outlined in the State of the Off-Grid Appliance Market Report (Efficiency for Access Coalition, 2019), suggest that a 'Hybrid AC/DC environment' is likely to develop in off- and weak-grid areas in the future, where both AC and DC options will be used and overlap in these areas. Phase 2 tests explored further use cases and technology types beyond those seen in Phase 1, adding more qualitative and quantitative test data to this topic. The results enable identification of areas that warrant further research and recommendations to key actors for addressing AC/DC related compatibility challenges. They also provide information, which can assist stakeholders to better prepare for and adapt to future hybrid environments. Additionally, the report's cost comparisons have identified instances where the most efficient, appropriate and reliable technology may be DC-based, but has not achieved significant market penetration due to its higher cost. This contributes to the evidence base for deploying policy instruments, which help support the market for appropriate and optimal technologies for off- and weak-grid areas in developing countries.

Phase 1 report

This study was conducted in two phases. The background information provided for this study was given in the Phase 1 report and has been repeated in the Phase 2 report, below, to enable it to be read as a standalone document. However, it is recommended that the Phase 1 report is read prior to the Phase 2 report to provide further context and background. It can be found on the Efficiency for Access website **here**.

Background

AC and DC power supply and appliances

Alternating current (AC) is a type of electrical current that periodically reverses direction following a sine waveform. It is the standard form of electric power used in electrical grids worldwide, with most standard appliances designed for use with AC power ('AC appliances'). Direct current (DC), in contrast, is a type of electrical current that flows in one direction. It is produced by PV modules and batteries and is required to internally run most electronic systems and some motors (e.g. brushless DC motors). DC appliances for domestic and commercial use are mainly manufactured for use in off-grid and automotive contexts.

AC and DC power are not directly compatible. As such, where the power supply and appliance are not compatible, a power converter – an inverter or a rectifier – is required. An inverter converts DC power to AC, while a rectifier performs the reverse conversion of AC to DC. This study explores the use cases of operating AC and DC appliances outside their 'native' mode. Native mode is defined as an appliance operating directly from its rated power supply, without the need for power conversion, e.g. a DC appliance running directly from a DC power supply of matching voltage. The term 'non-native' mode refers to an appliance operating from an incompatible power supply using a power converter that provides the rated power of the appliance (AC or DC).

Off-grid electrification pathways

AC grid connections were the primary means of increasing energy access between 2012 and 2016 in Africa (IEA, 2018). However, grid connection costs can often be outside the financial means of citizens. The estimated cost for an electrical utility to add a single new connection to the grid in sub-Saharan Africa, using Tanzania as a benchmark, varies from around US $750 in an urban area to around US $2300 in a rural area (McKinsey, 2015). Additionally, grid reliability varies in developing countries, and weak grids result in power outages and voltage fluctuations. This has a range of negative consequences for domestic life, work, education and healthcare, including the potential to damage appliances[3].

Mini-grids are a cost-effective option for the electrification of denser off-grid communities. Mini-grids may operate on AC voltages of 110V or 220-240V, or DC voltages of 12V, 24V or 48V. 48V DC mini-grids are an emerging option in India (Mishra, Panguloori, & Boeke, 2011), in particular, where the Bureau of Indian Standards has developed a standard for 48V DC microgrids and there are plans for the development of a 48V DC ecosystem with 48V DC appliances[4]. Mini-grids currently account for a smaller share of off-grid power supply penetration compared to Solar Home Systems (SHSs), having attracted around 15% of corporate investment in off-grid energy, compared to 80% for SHSs at the end of 2018[5].

3 Abhilash Botekar, The Times of India, 2020, "Voltage fluctuation damages 100 household appliances", https://timesofindia.indiatimes.com/city/nashik/voltage-fluctuation-damages-100-household-appliances/articleshow/73178858.cms
4 48V DC appliance range available from Cygni, https://www.cygni.com/products/48v-dc-appliances/
5 F. Sadouki, Green Tech Media, 2019, https://www.greentechmedia.com/articles/read/the-land-of-opportunity-for-off-grid-energy

Some mini-grid companies sell appliances to their connected customers, which may be used alongside those already owned or subsequently procured from other sources; these may again be a mix of AC and DC products.

SHSs are particularly suitable for remote households that are not easily served by the grid or mini-grids, and their use continues to increase rapidly. Installed SHS capacity grew at a rate of around 33% every six months between 2016 and 2018 (Efficiency for Access Coalition, 2019). SHSs are natively DC systems, as PV modules and batteries both operate in DC power. Typically, SHS are 12V DC systems and used to power 12V DC appliances. However, SHSs can be used to run AC appliances when combined with an inverter. Typically, SHSs are bundled with appliances (30–80% of SHSs) (Efficiency for Access Coalition, 2019). They may also have the flexibility to add further power supply capacity and appliances beyond the initial investment, with subsequent appliance purchases often through the same supplier, ensuring compatibility, servicing and warranty. However, a user may also acquire an appliance from another source, such as an AC appliance where DC appliances are not available.

The International Energy Agency's (IEA) 2019 Africa Energy Outlook states that to achieve the goals of "Agenda 2063" (Africa's economic and industrial strategy), the least-cost option for around 45% of the population without electricity access is AC grid extension and densification. Mini-grids are the least-cost option for 30% of the population while stand-alone SHSs are the least cost option for around 25% of the population.

The 2019 State of the Off-Grid Appliance Market (SOGAM) report (Efficiency for Access Coalition, 2019) identifies three scenarios for off-grid appliance market development. They include an 'AC domination' scenario where the AC grids expand faster than expected combined with very rapid AC mini-grid growth and slower than expected development of the SHS market and DC mini-grids. This scenario results in high levels of investment and improvements in efficient AC appliances, rather than off-grid DC appliances. A second 'DC domination' scenario involves explosive growth of the SHS market and DC mini-grids leading to off-grid efficient appliances becoming the de-facto standard.

However, the SOGAM report identifies that a third, 'Hybrid AC/DC environment' scenario is most likely. This scenario would involve extensive AC/DC competition and cooperation, with AC and DC mini-grids and SHSs all achieving rapid growth and overlapping with each other. In this scenario, hybrid AC/DC appliances become commonplace in both rural and urban areas and the market shows extensive demand for "universal" efficient appliances which can integrate seamlessly with both AC and DC power sources. This implies that off-grid appliance enterprises, donors, and governments must be prepared for a broad range of market outcomes and be prepared to support an efficient appliance ecosystem that is not siloed but flexible, and responsive simultaneously to AC, DC, and hybrid AC/DC settings.

The market for off-grid appliances and power converters

Appliance purchase options in off- and weak-grid markets may result in the ownership of a mix of AC and DC appliances. AC appliances are currently more widely available in off-grid markets in sub-Saharan Africa and South Asia. In recent market surveys in India, 89% of TVs seen were AC rated, with the use of inverters reported as common by shop owners. 88% of fans were marketed as AC/DC compatible, and most refrigerators seen (67%) were small sized AC models (Efficiency for Access Coalition, 2020). Users relying on the grid as their primary means of power provision are more likely to own AC appliances.

6 IEA, Country report - Africa Energy Outlook, 2019, https://www.iea.org/reports/africa-energy-outlook-2019

DC appliances and machinery, such as fans, solar water pumps and grain mills that incorporate a brushless DC (BLDC) motor, or refrigerators with variable speed DC compressors, are often inherently more efficient than AC equivalents. When specifically designed with power management for off-grid use, they can be used with relatively small SHSs. It has been estimated that, for residential appliances generally, switching to DC-inherent technologies from AC-based ones can provide energy savings of around 33%, and a further 14% can be saved in the mini-grid context (Opiyo, 2019).

The market for off-grid appropriate DC appliances, however, is still relatively nascent, with some DC appliances significantly more expensive than AC equivalents. Based purely on purchase cost, AC appliances may appear more attractive for low-income consumers. However, to operate on a DC supply, a higher PV and battery capacity may be needed, in addition to the cost of an inverter. This can make the whole system more expensive and less reliable than a system designed for DC appliances. Low quality inverters may result in unexpected appliance performance issues, reduced lifetime of components and increased power use.

Another possible scenario occurs when a household or business has already purchased a DC appliance and subsequently gains AC grid access. In this case, the user may wish to purchase a rectifier to operate their DC appliance from an AC power supply. Given prevalence of the various power supply options described above and the availability of both AC and DC appliances, consumers and businesses may find themselves in possession of an appliance that is not directly compatible with their desired power supply.

In off-grid markets, inverters are commonly available and are sometimes provided bundled with SHSs and appliances. Rectifiers, however, are typically found in on-grid markets, e.g. as phone chargers or computer power supplies. They are rarely sold as an independent product in off-grid markets. The use of an inverter or rectifier adds additional power consumption, and increases the complexity of the system set-up, as well as adding cost and quality considerations.

It is important to note that the required PV capacity for some productive use appliances, such as solar water pumps, may be up to around 2000 Wp[7]. Meeting the power demands of many of these motor-driven and productive use appliances often requires operation at voltages above 12V. Higher voltage systems have the benefit of reducing the required current and line losses and improving the affordability and safety of wiring.

As mentioned above, 48V is an emerging option in the off-grid sector with some examples including Agsol's solar grain mills[8] incorporating 48V BLDC motors and companies such as Cygni offering 48V DC compatible domestic appliances [9].

Previous research on power converters

Some previous research was identified on power converters used in off- and weak-grid areas:

- A study by Opiyo (Opiyo, 2019) on DC- versus AC-based mini-grids explored the extent of conversion losses. The research concluded that power conversions cause the most losses in mini-grids and identified that fewer conversion stages are generally observed in DC mini-grids. The study assessed various power conversions taking place within mini-grid infrastructure, along with appliance efficiency comparisons between AC and DC appliances, and estimates of the losses seen at various stages (such as cable losses). However, testing of appliances and power converters was not reported in this study.
- System design guidelines for component-based SHS over 1 kWp were recently developed for a World Bank programme in Uganda (World Bank Group, 2019). This standard is being used as a basis for a new IEC standard focused on a component-based SHS. The standard incorporates guidelines on inverter types, compatibility, safety, performance, and sizing.
- The 2019 State of the Off-Grid Appliance Market Report (Efficiency for Access Coalition, 2019), discusses the emerging off-grid landscape in relation to AC and DC electricity and the resulting need for flexible and hybrid solutions with discussion of the key challenges around power conversion.

The writers found that there is a dearth of research on how an appliance's performance, efficiency and durability is affected when run on a power converter. There is also a lack of studies investigating the performance of the power converters themselves.

7 Suryottam solar water pump range, https://www.suryottam.com/solar-water-pumps/
8 Agsol solar mill catalogue with 48V BLDC machines, https://agsol.com/wp-content/uploads/2020/07/Agsol-Catalogue.pdf
9 48V DC appliance range available from Cygni, https://www.cygni.com/products/48v-dc-appliances/

Testing Overview

Use cases

This study aims to provide a better understanding of the efficiency, performance and costs of the following common use cases of power supply and appliance types in off- and weak-grid areas, by simulating the use cases through laboratory tests. This should support market stakeholders to understand what effect the use of power converters has on expanding access to efficient appliances at a lower cost. The testing conducted was split into two phases. Phase 1 tests aimed to assess the performance and cost of ownership and operation for single AC- or DC rated appliances (refrigerators, TVs and fans), operated outside of their native modes for different use cases. Phase 2 tests built on Phase 1 tests by assessing the performance and costs of multi-appliance systems running on power converters, as well as testing an AC refrigerator utilising newer inverter compressor technology.

Power converters tested

In the case of mini-grids, a power converter may be centralised at the powerhouse to provide one supply option to all households connected, or converters may be utilised at the single household level (one converter per household). A centralised power conversion at the origin is generally more efficient (Opiyo, 2019), but households may also still have to convert power depending on their appliance type. This study is focused on testing use cases where converters are utilised at the single household level, to power a sole appliance (in Phase 1 tests), and to power multiple appliances (in Phase 2 tests).

The power converters used in this study were selected based on market research that identified a representative sample of brands, costs, specifications, and technologies in off-grid markets. The market research included both an in-field survey in Ugandan retail stores and a survey of online retail product data. The research found that inverters were commonly available products in off-grid markets. Rectifiers, however, were not found through the in-field market survey of Ugandan retail stores. The rectifiers were instead identified through a survey of online stores and were sourced from those stores. Rectifiers identified included DIN rail-mounted and switching mode power supplies (SMPS) of a range of cost and quality.

Table 2: Use cases of power supply and appliances in off- and weak grid settings

USE CASE	POWER SUPPLY TYPE	APPLIANCE TYPE	POWER CONVERTER
1 DC appliances in native mode	DC power supply *(DC SHS or DC mini-grid)*	DC appliances	None
2 AC appliances in non-native mode	DC power supply *(DC SHS or DC mini-grid)*	AC appliances	Inverter
3 AC appliances in native mode	AC power supply *(AC grid or AC mini-grid)*	AC appliances	None
4 DC appliances in non-native mode	AC power supply *(AC grid or AC mini-grid)*	DC appliances	Rectifier

Figure 1: Use case - AC loads running on DC SHS power supply with inverter

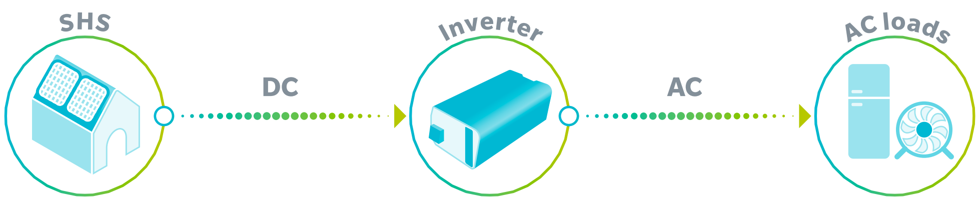
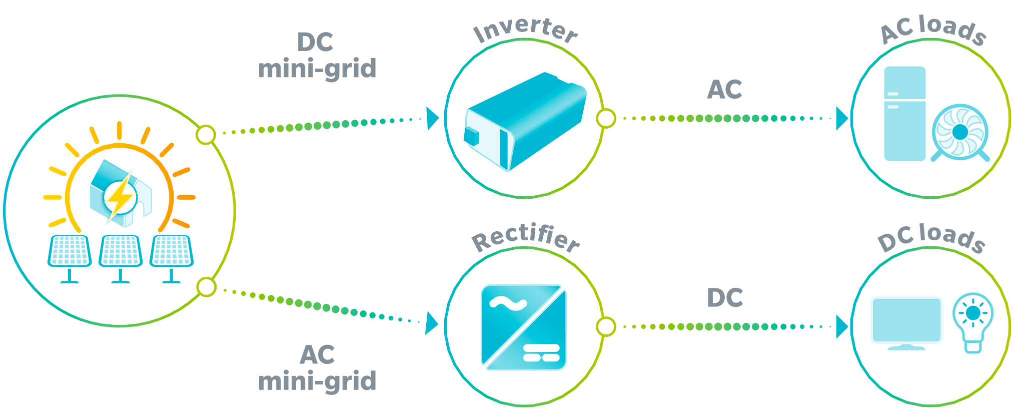


Figure 2: Use case – AC loads running on DC mini-grid with inverter; and DC loads running on AC mini-grid with rectifier



Power converter efficiency and sizing

The efficiency at which converters convert power from AC to DC, or DC to AC, is mainly dependent on the amount of power they are converting, following an efficiency curve. Examples of inverter and rectifier efficiency curves are provided in Figures 3a and 3b. Generally, the efficiency of a converter is close to its peak rated efficiency when it is outputting 20% to 100% of its rated power. As the output of a converter falls from 20% to 0% of its rated power, however, its conversion efficiency drops sharply towards 0%. Higher quality converters would generally be expected to have both higher peak efficiencies and more generous efficiency curves across their output power.
The converters selected for testing were sized as close as possible to the rated power consumption of the appliances being tested to ensure that the converters outputted at close to peak efficiency. The size of converters selected, however, was subject to market availability.

Therefore, the conversion efficiencies between different appliances on the same converter cannot be directly compared. The measured conversion efficiencies provide an indication of the realistic effect of the converter on the energy use of different appliances.

Inverter types and power quality

Two different types of inverters were tested in this study:

- Pure sine wave (PSW) – PSW inverters provide a high-quality AC sinewave that is very similar to a grid-quality AC waveform.
- Modified sine wave (MSW) – MSW inverters are a lower cost technology that produce a lower quality AC waveform that approximates the shape of a true AC sine waveform but has greater harmonic distortion.
- A third type, square wave (SQW) inverters, are the lowest cost inverter technology and provide the lowest quality AC waveform with the greatest harmonic distortion. Samples of these were tested in Phase 1.

Their different waveforms are shown in **figure 4**.

The total harmonic distortion (THD) measurement is used to measure harmonic distortion of AC power. THD is one way to gauge power quality. Higher harmonic distortion in AC waveforms, such as those produced by MSW and SQW inverters, can cause core loss in motors, leading to a build-up of excess waste heat[12], and affect the ability of the motor to magnetise rotor and stator components[13]. This leads to earlier malfunctions and lower lifespans for motor-based appliances such as refrigerators and fans. Some appliances are sensitive to poor power quality and may not function on anything other than an AC sine waveform produced by a PSW inverter.

Figure 3a: Example of inverter efficiency curves[10]

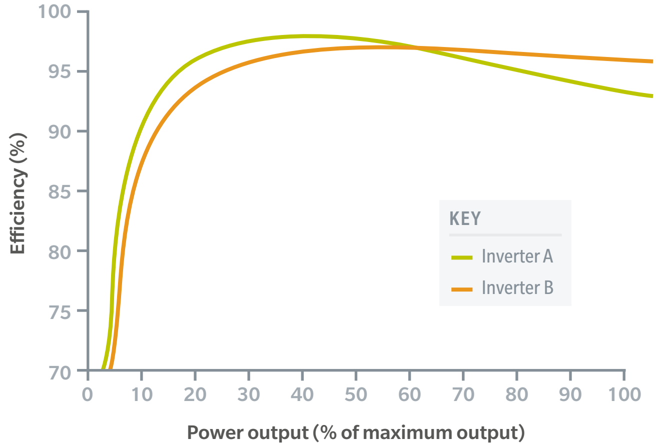


Figure 3b: Example of rectifier efficiency curves[11]

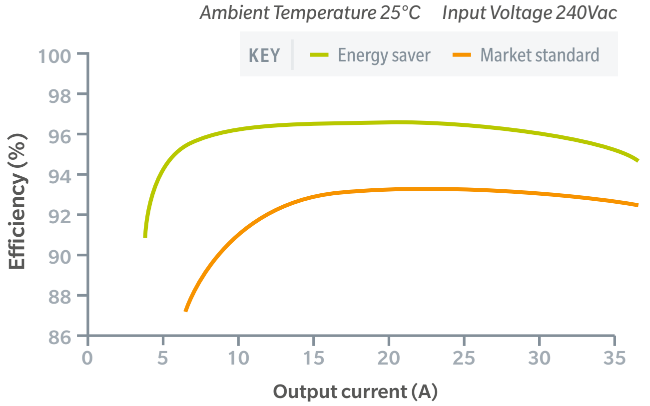
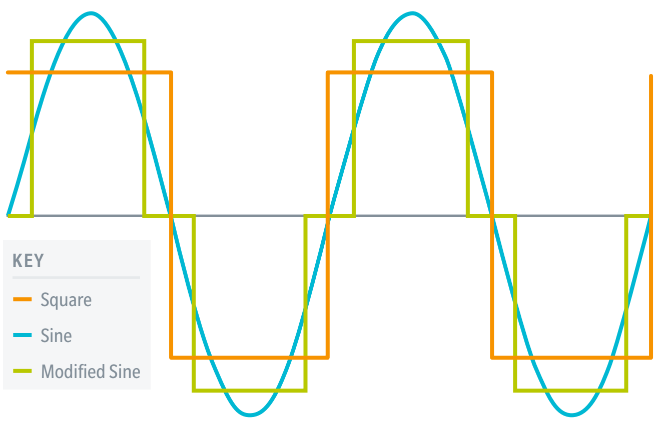


Figure 4: Inverter waveforms



10 F. Peacock, Solarquotes Blog, 2012, https://www.solarquotes.com.au/blog/two-reasons-you-must-look-at-efficiency-curves-when-choosing-your-solar-inverter/
11 Eaton – efficiency curve for market standard and energy saving rectifier http://dcpower.eaton.com/3G/ESR-efficiency.asp
12 Associated Power Technologies - Total Harmonic Distortion and Effects in Electrical Power Systems, https://www.aptsources.com/wp-content/uploads/pdfs/Total-Harmonic-Distortion-and-Effects-in-Electrical-Power-Systems.pdf
13 N. Dyess, Motors@Work, 2018, https://www.motorsatwork.com/from-the-blog/troubleshooting-series-total-harmonic-distortion/

Figure 5: Rectifiers (above) and inverters (below) available in online retailers in Kenya

Cost analysis assumptions

The following assumptions were made as part of the cost analyses conducted in this study:

- The upfront total system cost (TSC) was estimated for appliances run on a SHS. The TSC is defined as the capital cost of the appliance plus the capital cost of a power system that has been appropriately sized to run that appliance, i.e. an appropriately sized SHS (PV module, battery, charge controller, and balance-of-system components) and an appropriately sized power converter if needed. The sizes and costs of solar PV modules, batteries, charge controllers and balance of system components were estimated based on a system sizing and cost model calculator[14] developed by the Schatz Energy Research Center (SERC) for the Efficiency for Access 'Use Cases and Cost Breakdown of Off-Grid Refrigeration Systems' study (Lam, et al., 2020). The SERC calculator calculates the estimated size of PV modules, batteries and other components of a SHS based on the daily energy consumption of the appliance(s) run on it, solar insolation, battery depth of discharge, and module efficiency, amongst other factors. Cost estimates of the PV, batteries and other components were then derived from SERC's internal database of cost data for these components to establish an estimated TSC.
- The simple lifecycle cost was estimated for appliances run on an AC grid or mini-grid. The simple lifecycle cost is defined as the capital cost of the appliance and power converter, where needed, plus the electricity cost over the lifetime of the appliance. Grid and mini-grid electricity costs were assumed based on data sources for their cost in specific markets, as detailed in the analysis sections below. These electricity costs were not modified to discount future costs or account for potential inflation.
- All costs are denominated in US dollars. The costs of samples purchased in other currencies was converted to US dollars using an exchange rate at the date of purchase.
- The following data sources were used for appliance and power converter cost data:
  - **In-person retail purchases of test samples from off-grid markets** – These purchases were made either as part of this study or the LEIA programme's market surveys and may have been subject to bargaining in some countries. The sampling agent was instructed to attempt to purchase samples at the best price.
  - **Online retail purchases of test samples from off-grid markets** – These purchases were made either as part of this study or the LEIA programme's market surveys and may have been subject to bargaining in some countries. The price paid was assumed to be a reliable retail price. In some cases, power converters were purchased from online retail markets in Europe or China, rather than off-grid markets. This was done where the same or an equivalent model from an off-grid market was identified in order to speed up the shipping process.
  - **Trade cost data submitted to the Global LEAP Awards by appliance manufacturers** – Appliance manufacturers provided their appliances' FOB (Free on Board) price. A correction factor of 1.8 times the FOB price was then applied to estimate the final retail price, based on estimates provided by appliance manufacturers of the likely retail price.

The TSC and simple lifecycle cost estimates do not consider Pay-As-You-Go (PAYGo) models, such as those from M-KOPA[15], Azuri[16] and Solar Now[17]. PAYGo is an increasingly popular distribution model designed to improve the affordability of SHS and appliances for rural and lower-income households by allowing consumers to pay for systems and appliances over time. Payment packages are typically designed around the

14 Lam NL, Wallach EW. (2020). Off-Grid Refrigeration System (OGReS) Cost Model (Version 1.0). Schatz Energy Research Center.
15 Solar PV system and appliance packages from M-KOPA, http://www.m-kopa.com/products/
16 Solar PV system and appliance packages from Azuri, https://www.azuri-group.com/products/
17 Solar PV system and appliance packages for domestic and business use from Solar Now, https://www.solarnow.eu/solar-solutions/small-business-solutions/

incomes of their target users, to increase affordability. PAYGo models, however, increase lifecycle costs as they include a financing cost.

E.g. Average incomes in rural Kenya are estimated to range between $50 and $190 per month[18, 19], with estimates of $124/month in the Mount Kenya region and $191/month in the Lake Naivasha region (Anker & Anker, 2016). Monthly payments for PAYGo systems are set to be affordable for off-grid customers, and range from around $15 for a basic system over 14 months (e.g. the M-KOPA 5 system, including only LED lamps and mobile phone charging), to around $28 over 30 months for larger SHSs with a 24" TV and supplementary devices such as LED lamps, phone charging and a radio (e.g. M-KOPA 600)[20].

18 Suri et al, Tegemeo Institute of Agricultural Policy and Development, Rural Incomes, Inequality and Poverty Dynamics in Kenya, 2008, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.161.8241&rep=rep1&type=pdf

19 Jacobs Foundation, Getting an education in rural Kenya: Findings based on the Kenya Financial Diaries, 2015, https://s3-eu-central-1.amazonaws.com/fsd-circle/wp-content/uploads/2015/07/30094306/Education-Funding-in-Kenya_JF-V0.4.pdf

20 Solar PV system and appliance packages from M-KOPA, http://www.m-kopa.com/products/

Phase 1 tests – single appliances using power converters

In the Phase 1 tests, laboratory tests were conducted to measure the energy consumption of refrigerators, TVs and fans operating in the different use cases. This enabled an estimate of the associated size and cost of the solar PV system required (for DC supply), or the electricity cost from a grid or mini-grid (for AC supply). The effect of the power converter on appliance performance was also observed, in order to consider longer-term operational issues and costs to the user. Cost estimates were compared to identify the optimal use case of appliance and power supply for the different scenarios. The main conclusions from the testing were as follows:

- **Single DC appliances run natively on SHSs are generally more cost effective than AC appliances run with inverters on SHSs** – Based on the test results and subsequent analysis, running a single DC appliance natively on an SHS was found, in most cases, to be more cost-effective than running a single AC appliance on an SHS with a dedicated inverter.
- **Converter quality and cost is highly variable** – Increases in energy use from the power conversion ranged from under 10% to over 50% in standard operating modes, with losses of over 90% observed in standby and no-load conditions. Tests showed that the performance, quality and cost of inverters is highly varied, and that a PSW inverter is likely required to ensure proper functioning of appliances and maximise their lifetime. The lower purchase cost of an MSW inverter might appear favourable in the short term, but may not be cost-effective in the long term.
- **Use of rectifiers to power off-grid DC appliances on AC supply appears viable, but quality issues may be encountered** – DC appliances were found to be a cost-effective option to run on an AC supply with a rectifier, if needed, as a result of their higher efficiency. Few compatibility issues were seen in the operation of DC appliances in this use case, and in most cases, the rectifiers tested produced a stable DC power output that was able to power appliances without issue.
- **Hybrid and efficient AC technologies are viable options for off-grid appliances**
- **Further cost reduction in DC appliances is necessary to gain the full benefits of their efficiency** – DC appliances were in general found to be more efficient but most costly on an upfront basis than AC appliances, and lower upfront cost is a strong driver of a user's choice of appliance.

The Phase 1 report can be found on the Efficiency for Access website **here**.

Phase 2 tests – multiple appliances using power converters

The Phase 2 tests built on Phase 1 by testing multiple AC appliances running simultaneously on an inverter, and multiple DC appliances running simultaneously on a rectifier. This simulated the usage pattern of a household or business that owns multiple appliances to assess the optimal appliance choices for this use case. As in Phase 1, tests were conducted in the laboratory to simulate the real-life use cases of off-grid and weak-grid users.

The scenarios explored in the Phase 2 tests simulate a level of energy access at around the tier 3 or 4 level[21], as defined by the ESMAP multi-tier framework. At this level of energy access, the household or business has relatively higher-powered appliances with power consumption between around 200-1500W each, e.g. a refrigerator, food processor, water pump or handheld power tools. A scenario of this type is more typical of a middle-income household or a small business, more likely from an urban or peri-urban area than a lower-income, rural location. A mix of AC and DC supply options is already seen in some urban and peri-urban areas where AC grid infrastructure is in place, but other power sources are used as a back-up for an unreliable grid. As previously mentioned, the SOGAM report (Efficiency for Access Coalition, 2019) projects further emergence of 'Hybrid AC/DC' environments where mini-grids and SHS are utilised in the same location as the grid.

Phase 2 tests explored the following use cases with multiple appliances:

- Use case 2 – DC electricity used to power multiple AC appliances through an inverter.
- Use case 4 – AC electricity used to power multiple DC appliances through a rectifier.

Tests were conducted to measure the energy consumption of sets of appliances for the different use cases. This enabled an estimate of the associated size and cost of the solar PV system required, or the electricity cost from a mini-grid. The effect of the power converter on appliance performance was also observed in order to consider longer-term operational issues and costs to the user. Cost estimates were compared to identify the optimal use case of appliance and power supply for the different scenarios.

21 Multi-tier framework for measuring energy access: https://www.usaid.gov/energy/mini-grids/economics/cost-effectiveness/tiers-of-service/

Phase 2 tests – testing of a refrigerator with inverter compressor technology

Refrigerators designed for AC grid supply have traditionally used single-speed compressors. However, this technology uses a significant amount of power intermittently and is usually not the most appropriate technology for use on a solar PV system, as concluded in the Phase 1 testing. DC refrigeration utilises a variable speed compressor, which runs more often but at lower power, and uses less energy overall to provide the same cooling service.

A newer AC refrigerator technology, known as inverter compressor technology, has become more widely available in recent years. The term 'inverter compressor' describes a variable capacity compressor that can match its pumping capacity to the varying cooling requirements of the refrigerator. It is used colloquially to describe any variable capacity compressor, not all of which may use an inverter to adjust its capacity. While there are a number of possible approaches, the most common configuration in household refrigerators is to:

- Rectify the mains AC supply to DC power.
- The DC power is supplied to a BLDC motor connected to the compressor pump.
- A small amount of the DC power is also supplied to an inverter, which generates a 3-phase variable frequency AC voltage. This AC frequency is used as a control signal to control the speed of the BLDC motor. The AC power from the inverter does not power the BLDC motor directly.

This technology has improved efficiency compared to typical single-speed compressor AC refrigerators, which must be either on or off, and run at a fixed speed.

Inverter compressor technology has been observed for sale online in East Africa , and its launch in India was reported in the media with marketing materials specifically promoting the technology's use with an external inverter on DC in the event of a power cut . However, the LEIA programme's market surveys in India and Africa did not observe strong market penetration of this technology, with largely AC single speed models and some DC variants seen. Refrigerators using inverter compressor technology have not been tested previously by the LEIA programme, as tests have largely focused on efficient DC models, as well as market average DC and AC models to establish performance baselines.

An inverter compressor refrigerator from India was tested in this study to explore the performance of the technology, both operating on its native AC supply and using an external inverter to simulate an off-grid case. This allowed total system cost estimates to be made.

All Phase 2 testing was conducted at the laboratory, Re/genT, in the Netherlands in 2020.

22 Samsung Newsroom, - How the Digital Inverter Compressor Has Transformed the Modern Refrigerator, 2015, https://news.samsung.com/global/how-the-digital-inverter-compressor-has-transformed-the-modern-refrigerator

23 Product listing for Hitachi RH330 inverter compressor refrigerator on Jumia Uganda. Accessed 13/8/2020. https://www.jumia.ug/appliances-fridges-freezers/

24 Samsung Newsroom India, Samsung Rolls Out India's First Digital Inverter Compressor and Smart Connect Inverter Series in Single Door Direct Cool Category, 2016 https://news.samsung.com/in/samsung-rolls-out-indias-first-digital-inverter-compressor-and-smart-connect-inverter-series-in-single-door-direct-cool-category

25 Samsung refrigerator purchase link. Accessed 13/8/2020, https://www.amazon.in/Samsung-Inverter-Refrigerator-RR20T172YU2-HL/dp/B08346J6SR/

Sample selection and methodology

A set of AC appliances were sourced that were considered typical of the sizes and brands found in off-grid and weak-grid markets. To represent typical domestic products, a refrigerator, fan, TV, LED lights and a mobile phone charger were sourced. The following productive use appliances were also sourced for the test: an AC-rated drill, hair clipper and sewing machine. Some samples were sourced from the UK but were of brands and sizes that were observed in African online retailers.

Energy consumption measurements were made of the multiple AC appliance set-up, operating in combination on a 12V DC supply through both a pure sine wave (PSW) and modified sinewave (MSW) inverter. Any performance issues or other pertinent observations from operating multiple loads with an inverter were also recorded.

Table 3: AC appliance test samples

APPLIANCE	APPLIANCE SPECIFICATIONS	RATED POWER	SOURCED FROM	WARRANTY	COST (US $)
 **Von Hotpoint HRD-071S refrigerator (70L)**	AC refrigerator with ice box **Compressor:** GMCC SZ55C1J, single speed, RSIR, 85W cooling capacity **Refrigerant:** R600a	60W	Kenya	12 months	157
 **JSK 24HD television**	24" LCD-LED TV **Rating:** AC input, rated 100-240 VAC	40W	Sierra Leone	None	117
 **Tesco LED classic ES light bulbs**		7W	UK	No information available	20 (for four bulbs) (approximate cost of similar product in off-grid market is $13, based on similar model found on Jumia Kenya)
 **Changli Crown pedestal fan**	Used in test with PSW inverter. In test with the MSW inverter, an issue with overheating occurred and it was replaced by the fan model below for the MSW test. **Diameter:** 16"	40W	Uganda	No information available	28
 **Handson Statiefventilator pedestal fan**	Used in test with MSW inverter **Diameter:** 16"	50W	Netherlands, by test laboratory	No information available	N/A
 **Brother LS14 sewing machine**		50W	UK	3 years	100 (approximate cost in off-grid market is $185, based on similar models found on Dukatech Kenya[27])
 **Bosch Easy Impact 550 hammer drill**	**Output power (max):** 370W **Rated torque:** 1.2 Nm	550W	Netherlands, by test laboratory	2 years	60 (approximate cost in off-grid market, based on similar model found on Jumia Kenya[28])

26 Product listing for Generic 220-240V LED Light Bulbs 7W on Jumia Kenya. Accessed 13/8/2020. https://www.jumia.co.ke
27 Dukatech, accessed 13/8/2020, https://dukatech.co.ke/product/brother-1430s-l14-white-sewing-machine/
28 Product listing for Bosch Impact Drill GSB 550 on Jumia Kenya. Accessed 13/8/2020. https://www.jumia.co.ke

Table 3: AC appliance test samples (continued)

APPLIANCE		APPLIANCE SPECIFICATIONS	RATED POWER	SOURCED FROM	WARRANTY	COST (US $)
	**Wahl Vogue hair clipper**		No information available	UK	3 years	28 (approximate cost in off-grid market is $40, based on similar model found on Jumia Kenya[29])
	**Mobile phone charger**	Alcatel PA-5V550mA-006	2.75W DC output (5V, 550mA)	Netherlands, by test laboratory	No information available	N/A – assumed for calculations that phone is already owned by user

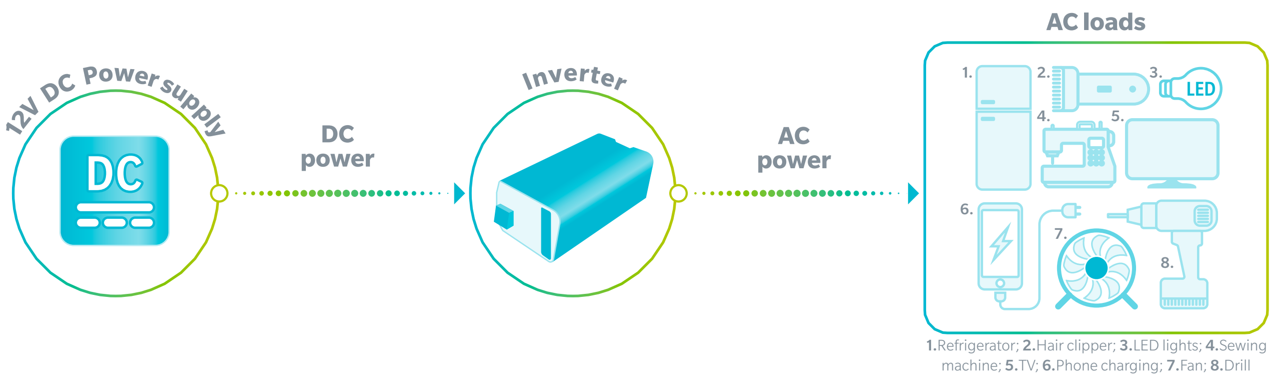
Testing was run over a 24-hour period at ambient laboratory conditions at temperatures of approximately 18 – 20˚C. The AC appliances were set up as in Figure 6.

A battery system, which was run using an external charger, was used to provide 12V DC power to the inverter. Measurements were taken before the inverter of the full load power consumption as input DC power, as well as after the inverter as AC power consumed by each individual load.

A load profile, as shown in Table 4, was created to replicate appliance usage at different times of the day. Hour 1 (in Table 4) represented midday, and use patterns aimed to replicate morning, afternoon, evening and night time use of the appliances. It was not fully intended to replicate an average off-grid user's load profile, as it was designed in part to observe the power consumption of each individual load, as well as observe the combined power draw of certain combinations of appliances, in order to assess whether there may be issues with their interplay. For example, high in-rush currents were expected to be seen from the refrigerator and drill, so periods of operating these two loads together were included, as well as a period where all loads were in operation together (hour 10). Key aspects of the load profile were as follows:

- The refrigerator was run constantly, with a usage pattern involving opening the door and removing cans during the simulated afternoon and evening hours, and with the door shut at other times of the day. More frequent compressor cycles were expected whilst the door was being opened, and this condition of higher power use alongside that of the productive use appliances was observed.
- The fan was run at high speed during the period simulating the warmest period of the day, and at lower speed in the simulated evening, night and early morning hours.
- The TV was in on-mode for a total of 3 hours to reflect typical usage, and in standby mode at other times during the day and at night time to simulate it being left in standby mode. It was also disconnected for a period of the day.
- The simulated afternoon period replicated a period of peak power demand. During this period, the TV was in on-mode and the productive use appliances were run alongside the already running fan and refrigerator. This aimed to determine the maximum power requirement of the set of appliances and observe how well the appliances and inverter performed in this condition. It also aimed to observe any issues where power demand was less constant and more sporadic, with high demand for short periods. This was done in order to see whether power could be provided effectively by the inverter in these cases, or if any appliances failed to operate, or the inverter shut down from overload.
- Each productive use appliance was also run on its own at some point, over the baseline loads of the refrigerator and fan.

Figure 6: Schematic of multiple AC appliance set-up powered on a 12V DC supply through an inverter



29 Product listing for Wahl Balding Professional Hair Clipper on Jumia Kenya. Accessed 13/8/2020. https://www.jumia.co.ke

Table 4: Load profile used in AC appliance tests

HOUR	SIMULATED TIME OF DAY	REFRIGERATOR	FAN	SEWING MACHINE	DRILL	HAIR CLIPPER	TV	LED LIGHTS	MOBILE PHONE CHARGING
1	12:00	On-mode	Fan high speed mode	Off, load unplugged	Off, load unplugged	Off, load connected	Standby mode	Off, load connected	Off, load unplugged
2	13:00	On-mode with use pattern	Fan high speed mode	On-mode with use pattern	Off, load unplugged	Off, load connected	Standby mode	Off, load connected	Off, load unplugged
3	14:00	On-mode with use pattern	Fan high speed mode	Off, load connected	On-mode with use pattern	Off, load connected	Standby mode	Off, load connected	Off, load unplugged
4	15:00	On-mode with use pattern	Fan high speed mode	On-mode with use pattern	On-mode with use pattern	Off, load connected	Standby mode	Off, load connected	Off, load unplugged
5	16:00	On-mode with use pattern	Fan high speed mode	Off, load connected	Off, load unplugged	On-mode with use pattern	Standby mode	Off, load connected	Off, load unplugged
6	17:00	On-mode with use pattern	Fan high speed mode	Off, load connected	Off, load unplugged	Off, load connected	On-mode	Off, load connected	Off, load unplugged
7	18:00	On-mode with use pattern	Fan high speed mode	Off, load connected	Off, load unplugged	Off, load connected	Standby mode	On-mode	Off, load unplugged
8	19:00	On-mode with use pattern	Fan high speed mode	On-mode with use pattern	On-mode with use pattern	On-mode with use pattern	On-mode	On-mode	Off, load unplugged
9	20:00	On-mode with use pattern	Fan high speed mode	Off, load connected	Off, load unplugged	Off, load connected	Standby mode	Off, load connected	Off, load unplugged
10	21:00	On-mode with use pattern	Fan high speed mode	On-mode with use pattern	On-mode with use pattern	On-mode with use pattern	On-mode	On-mode	Charging mode
11	22:00	On-mode	Fan low speed mode	Off, load unplugged	Off, load unplugged	Off, load unplugged	Standby mode	Off, load unplugged	Charging mode
12	23:00	On-mode	Fan low speed mode	Off, load unplugged	Off, load unplugged	Off, load unplugged	Standby mode	Off, load unplugged	Charging mode
13	00:00	On-mode	Fan low speed mode	Off, load unplugged	Off, load unplugged	Off, load unplugged	Standby mode	Off, load unplugged	Charging mode
14	01:00	On-mode	Fan low speed mode	Off, load unplugged	Off, load unplugged	Off, load unplugged	Standby mode	Off, load unplugged	Charging mode
15	02:00	On-mode	Fan low speed mode	Off, load unplugged	Off, load unplugged	Off, load unplugged	Standby mode	Off, load unplugged	Charging mode
16	03:00	On-mode	Fan low speed mode	Off, load unplugged	Off, load unplugged	Off, load unplugged	Standby mode	Off, load unplugged	Charging mode
17	04:00	On-mode	Fan low speed mode	Off, load unplugged	Off, load unplugged	Off, load unplugged	Standby mode	Off, load unplugged	Charging mode
18	05:00	On-mode	Fan low speed mode	Off, load unplugged	Off, load unplugged	Off, load unplugged	Standby mode	Off, load unplugged	Charging mode
19	06:00	On-mode	Fan low speed mode	Off, load unplugged	Off, load unplugged	Off, load unplugged	Standby mode	Off, load unplugged	Charging mode
20	07:00	On-mode	Fan low speed mode	Off, load unplugged	Off, load unplugged	Off, load unplugged	Standby mode	Off, load unplugged	Charging mode
21	08:00	On-mode	Fan low speed mode	Off, load unplugged	Off, load unplugged	Off, load unplugged	Standby mode	Off, load unplugged	Charging mode
22	09:00	On-mode	Fan low speed mode	Off, load unplugged	Off, load unplugged	Off, load unplugged	Standby mode	Off, load unplugged	Charging mode
23	10:00	On-mode	Fan low speed mode	Off, load unplugged	Off, load unplugged	Off, load unplugged	Standby mode	Off, load unplugged	Charging mode
24	11:00	On-mode	Fan low speed mode	Off, load unplugged	Off, load unplugged	Off, load unplugged	Standby mode	Off, load unplugged	Charging mode

Legend 1: Power modes used in AC appliance tests

- On-mode
- On-mode with use pattern[30]
- Fan high speed mode
- Fan low speed mode
- Standby mode
- Charging mode
- Off, load connected
- Off, load unplugged

Inverters were selected with appropriate continuous and surge power ratings to supply the necessary power. Sizing an inverter for multiple appliances requires estimation of the maximum combined power draw when all loads are running continuously, as well as consideration of inverter surge power requirements for very short time periods to deliver in-rush currents. For example, during hour 10, when all eight loads were run at the same time, high in-rush currents may be required to start the refrigerator compressor or drill motor at the same time as other loads running, potentially requiring significant surge power from the inverter on top of a high continuous load.

30 Details of 'On-mode with use pattern':

- Refrigerator: Appliance filled with 24 drinks cans and temperature stability achieved prior to beginning the test. Door opened and one can removed at the start of each hour period and at 30 minutes past the hour. (On-mode, in green cells represents refrigerator running but with door closed)
- Sewing machine, drill, hair clipper: Four 15-minute usage patterns were run during each hour period. Each consisted of 5 minutes off, operation at full power for 5 minutes, 5 minutes off. Loads were left connected to the power source during these 'off' periods.

When estimating the surge power requirement for most loads other than motors, a rule of thumb is to double the continuous power consumption. Inverter surge and continuous power ratings are also typically specified in this ratio.

Various industry guides estimate surge power for loads incorporating induction motors, such as refrigerators and drills, to be three to seven times the continuous power[31]. In the Phase 1 tests, the surge power consumption from some of the refrigerators tested was found to be around 10 times that of their continuous power consumption. Estimates were made in Table 5 of the continuous and surge power requirements of each appliance. Note: the total inverter surge power required in the table is equal to the highest individual surge power requirement added to the total continuous power, as it is unlikely that two appliances would require start-up current at the exact same time.

Table 5: Estimated power requirements of the AC appliances

APPLIANCE	ESTIMATED CONTINUOUS POWER (W)	ESTIMATED SURGE POWER (W)
Refrigerator	100	1000
Fan	30	90
TV	25	50
Sewing machine	20	150
Drill	100	700
Hair clipper	5	15
LED lights	7	15
Phone charger	1	2
Inverter total requirement	**288**	>1300

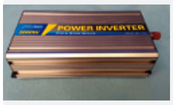
The Mercury IMS-1500 MSW inverter, rated at 1500W was observed in Phase 1 testing to be able to reliably provide the continuous and surge power required to run a refrigerator and was selected as a suitable MSW inverter to perform the tests with.

For the PSW inverter selection, a model made by SUG was procured. Phase 1 tests using PSW inverters employed a Victron brand inverter, which showed good performance, but is a more expensive model that may be outside of the financial means of lower-income households. (The Victron model used for Phase 1 refrigerator tests was rated at 1200VA for continuous power and cost around $460). As the performance of a lower-cost PSW inverter was not explored in Phase 1 of the study, a lower-cost model was procured for Phase 2 and the SUG PSW inverter (rated at 2000W continuous power and costing $290) was deemed suitable from this perspective. At the time of sampling, a lower cost, PSW inverter of the same power rating as the Mercury MSW inverter could not be found, so one of the next size rating up was procured.

The MSW and PSW inverter used would be considered oversized for the combination of appliances run, and a direct comparison cannot be made between the two given their different size ratings. However, they were not considered unreasonably oversized for the multiple appliance set-up. Both were deemed feasible options for an off-grid or weak-grid user wanting to ensure enough power can be provided, and to subsequently buy and run further appliances.

31 Don Rowe, Power Inverter FAQ, https://www.donrowe.com/power-inverter-faq-a/258.htm

Table 6: Inverters used in the multi-appliance tests

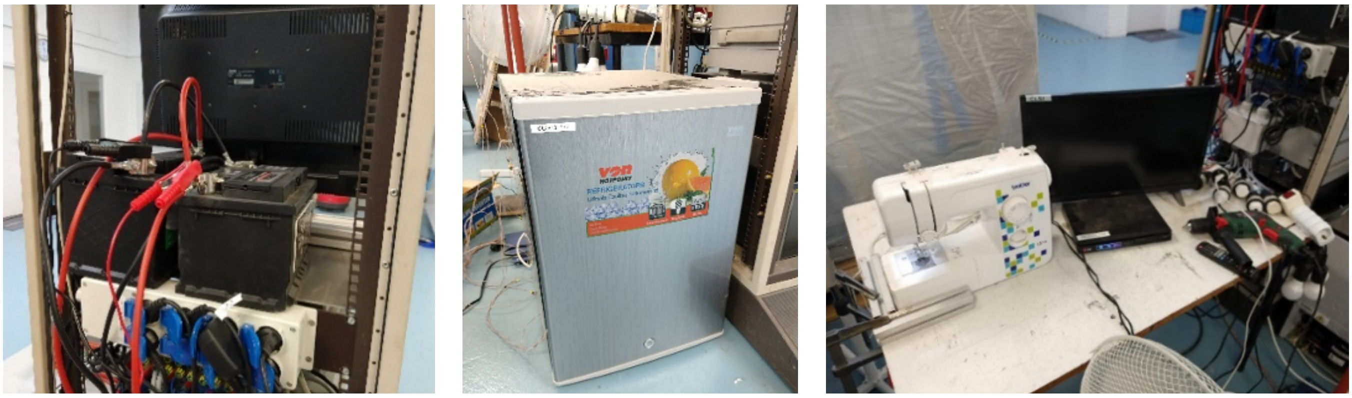
APPLIANCE	INVERTERS	TYPE	RATED CONTINUOUS POWER/SURGE POWER	MAXIMUM RATED EFFICIENCY	WARRANTY	COST (US$)
	**SUG 2000W**	Pure Sine Wave	2000W/4000W	94%	2 years	290
	**Mercury IMS-1500**	Modified Sine Wave	1500/3000VA	>80%	1 year	231

Initial trials of the test set-up using the MSW inverter showed an issue with the operation of the Changli Crown fan. A high frequency sound was produced when it operated, and the motor appeared to increase in temperature. As this test was to be run overnight, for safety reasons it was decided to replace the initial fan selected with the Handson fan, which had a similar input power rating. A similar, but much less pronounced effect was seen with the replacement fan, but it was deemed safe to run. Following resolution of the fan issue, the appliances could run for the 24-hour period using the MSW inverter without issue. The potential issue of running motor-based appliances on an MSW inverter were explored in the Phase 1 report. Higher harmonic distortion in the MSW AC waveform can cause core loss in motors, leading to a build-up of excess waste heat[32]. This instance may have been an example of this effect.

No similar issues were seen with the Changli Crown fan or any of the other appliances when the test was run on the PSW inverter. Enough power could be provided during periods of both high and low load on both inverters.

It was also noted that charging of the battery at times increased the voltage to both inverters, which appeared to increase the AC output voltage. Voltage fluctuations are expected from SHSs and mini-grids, and as such this was deemed an appropriate test condition. An output battery voltage of over 13V was seen for long periods in this test, which may be encountered in real-life conditions when a battery powering loads is also being charged by the PV array. No issues were seen with the performance of any individual appliance, or the combined loads, as a result of this higher input voltage.

Figure 7: Set up of AC multi-appliance tests. DC power supply to inverter (left), refrigerator (centre), sewing machine, TV, lights, drill and fan (right)



32 Associated Power Technologies - Total Harmonic Distortion and Effects in Electrical Power Systems, https://www.aptsources.com/wp-content/uploads/pdfs/Total-Harmonic-Distortion-and-Effects-in-Electrical-Power-Systems.pdf

Test results: energy consumption of multiple AC appliances running on an inverter

Energy measurements were taken for each hour period and aggregated over the full 24-hour period. Power draw of individual loads, and overall, from the combined set-up, were seen to be broadly similar on both inverters. Over the full 24-hour period, energy consumption from all loads combined was approximately 5% higher on the MSW inverter.

Some differences were noted in energy consumption between the two inverters. Higher energy consumption was seen on the PSW inverter for the sewing machine, hair clipper, and most significantly for the drill, which used 12% less energy on the MSW inverter over the full measurement period. Measurements were not taken of the service delivery of the appliances, but it may have been the case that the MSW inverter, as a result of its poorer quality AC output, was not able to provide as much power for the motor-driven loads as the PSW inverter. As discussed in the Phase 1 report, MSW inverters are generally not recommended for motor-driven loads as their high harmonic content can affect the ability to magnetise the rotor and stator components[33].

Differences in energy consumption were observed between the two inverters during periods of higher and lower load. The energy consumption using the PSW inverter was higher than the MSW inverter during hours 3, 4, 8 and 10, when more of the appliances were operating. Between hours 11 and 24, when only the refrigerator, fan, phone charger and TV (in standby mode) were operating, higher power consumption was measured on the MSW inverter.

Energy consumption measurements were seen to reach a peak in hours 8 and 10. Graphs of the power consumption of the appliances during hour 10 are shown below in Figure 9 (for the PSW inverter) and Figure 10 (for the MSW inverter). The difference between the DC power input to the inverter (light purple), and AC power output from it (grey) can be seen, with the size of the gap showing the loss due to the DC to AC conversion.

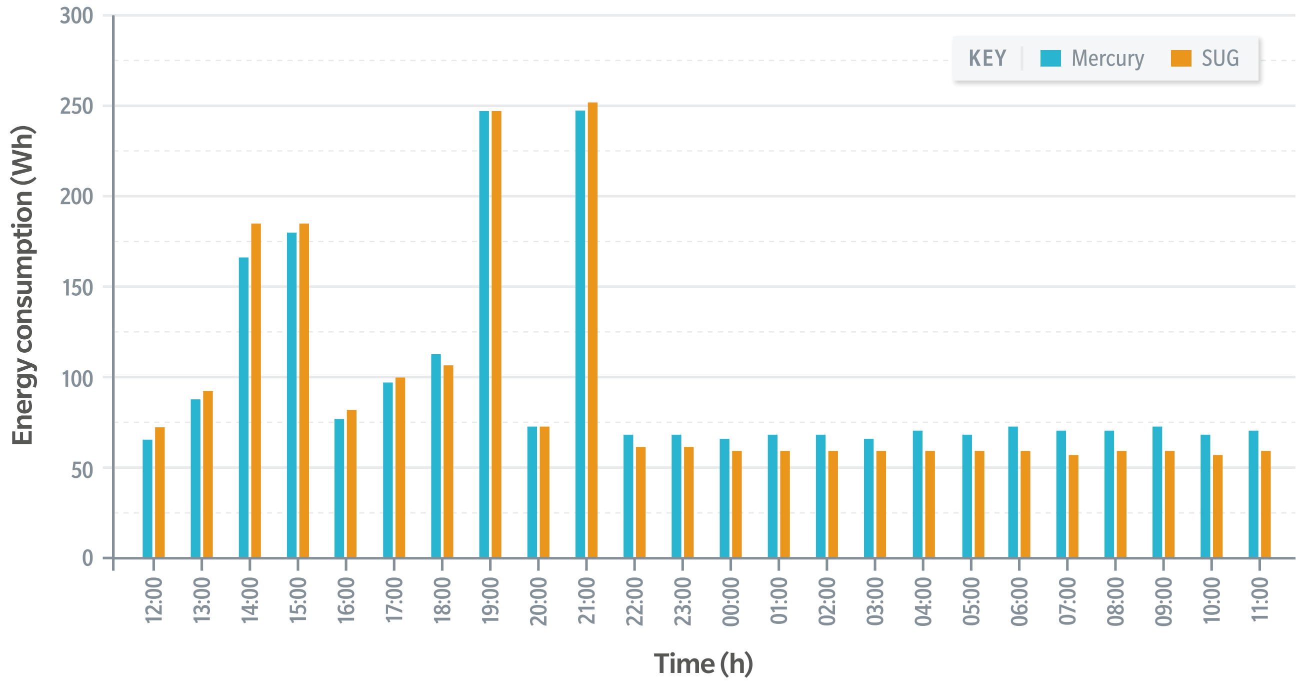
The maximum continuous power consumption from all loads combined during hour 10 was measured to be higher on the PSW inverter (647W) than the MSW inverter (534W). The lower power consumption measured from the MSW inverter may have been a result of the loads not running optimally on the MSW inverter, potentially delivering lower levels of service, e.g. the drill and sewing machine, which were operated in this hour segment. The surge power was also measured, but the time period was too small to be visible in the graphs.

Table 8: Energy consumption (kWh) measured over 24h by each appliance, and by all appliances combined

APPLIANCE	ENERGY CONSUMPTION OVER 24H (KWH)	
	PSW inverter	MSW inverter
Refrigerator	0.374	0.369
Fan	0.825	0.823
TV	0.084	0.083
Sewing machine	0.069	0.062
Drill	0.414	0.364
Hair clipper	0.015	0.009
LED lights	0.108	0.107
Phone charger	0.003	0.002
Total energy consumption of all appliances as AC power	**1.89**	**1.82**
Total energy consumption of inverter as DC power	**2.21**	**2.32**
Estimated PV panel capacity (Wp)	**737**	**772**
Estimated battery capacity (Ah)	**351**	**386**

33 N. Dyess, Motors@Work, 2018, https://www.motorsatwork.com/from-the-blog/troubleshooting-series-total-harmonic-distortion/

Figure 8: Energy consumption of all appliances combined during each hour period (Wh)



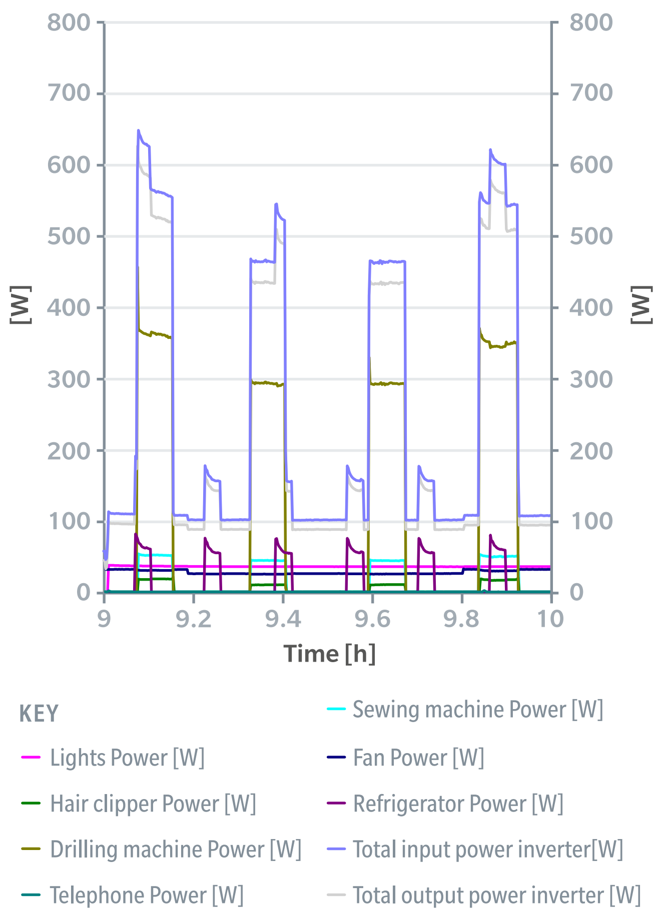
The highest surge power measured during the test to any one appliance was 1,394W AC power to the refrigerator on the PSW inverter (dark purple line). This was in comparison to its continuous power consumption of around 80W.

On the PSW inverter, the refrigerator can be seen to cycle on six times during hour 10, with the in-rush current / surge power occurring at the start of each cycle. At times, the refrigerator cycles took place between the operating periods of the drill, sewing machine and hair clipper, but the refrigerator did also cycle on at the same time as when these loads were also drawing power, resulting in a high combined power consumption. Surge power is only required for a very short period of time to start the refrigerator compressor, but when combined with the continuous power consumption of the other loads, the measured surge power of the refrigerator suggests that an inverter rated at over 2000W of surge power was needed for these loads. This was comfortably within the surge power rating of the inverters selected.

The drill (light green line) was observed to draw between 300-360W of power when operating, the sewing machine (light blue) drew around 40W, and the hair clipper (dark green) drew around 5W. Relatively steady power draw was observed from the four lights (pink) of around 35W from the fan (dark blue) of around 27W.

On the MSW inverter, the highest continuous power measurements were over 500W during periods when the drill was running, and the refrigerator cycled on. The drill was observed to draw less power in the tests on the MSW inverter compared to the PSW inverter, suggesting that it may not

Figure 9: Measured power consumption during hour 10, with all loads running on the SUG PSW inverter. The graph shows input DC power to the inverter, output AC power drawn by all loads combined, and the power draw of each individual appliance

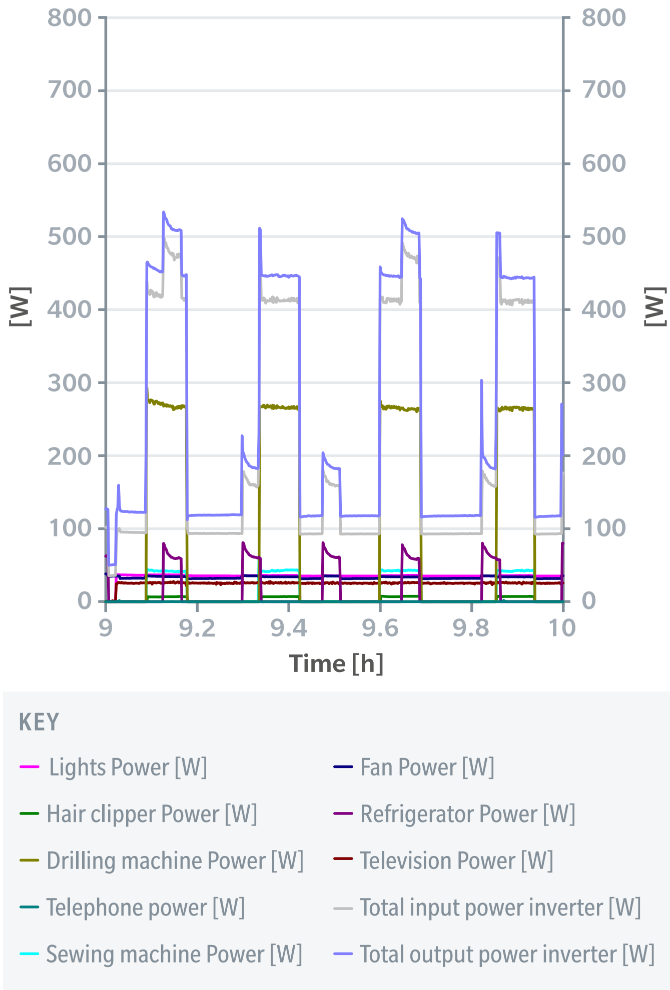


have functioned as effectively on a modified sinewave AC supply. However, the speed of the drill was not measured and compared when operating on the MSW inverter and PSW inverter, so the difference in energy consumption was not conclusive.

Test results: inverter performance

The conversion efficiency of the inverters was calculated as the ratio of output AC energy to input DC energy. This was calculated over the 24-hour period for each hour segment to observe how efficiency varied with the combined load. Over the 24-hour period, the average conversion efficiency for the MSW inverter was calculated as 79%, and for the PSW inverter it was calculated as 85%.

Figure 10: Measured power consumption during hour 10, with all loads running on the Mercury MSW inverter. The graph shows input DC power to the inverter, output AC power drawn by all appliances combined, and the power consumption of each individual appliance.



The conversion efficiency for each discrete hour period is shown in Figure 12 below. As discussed in the introduction, the efficiency of an inverter is dependent on the amount of power it is converting, following an efficiency curve. Generally, the efficiency of an inverter is close to its peak rated efficiency when it is outputting 20% to 100% of its rated power. As the output of a converter falls from 20% to 0% of its rated power, however, its conversion efficiency drops sharply towards 0%. The PSW inverter had a consistently higher conversion efficiency at over 90% during some periods of higher load. The MSW inverter had conversion efficiencies of over 85% in hours 3, 4, 8 and 10. During low load periods, as expected, the conversion efficiencies were lower on both inverters, but this fell below 70% on the MSW inverter in hours 20 and 24. In some periods, the conversion efficiency of the MSW inverter was more than 10% less than the PSW inverter.

As mentioned earlier, both inverters had power ratings much higher than the continuous power rating of the combined loads. This was more the case for the PSW inverter, which had a continuous power rating of 2000W as opposed to the MSW inverter's continuous power rating of 1500W. Despite this, the PSW inverter performed conversions at higher efficiency than the MSW inverter, and at over 90% in conditions of higher load.

Figure 11: Energy consumption of all loads combined running on the MSW and PSW inverters, as input and output energy

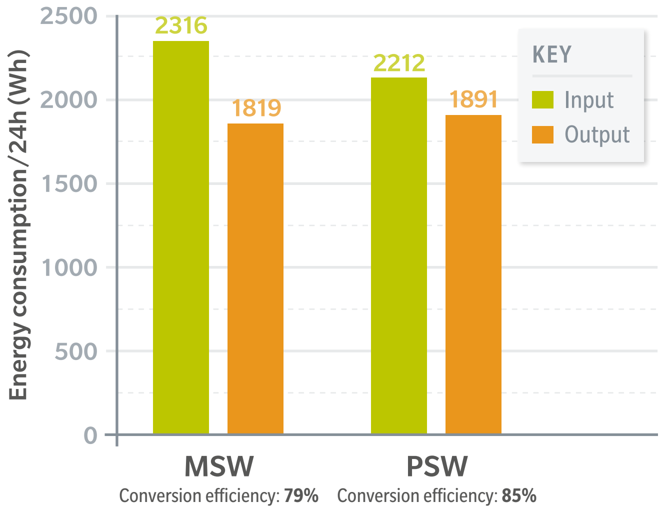
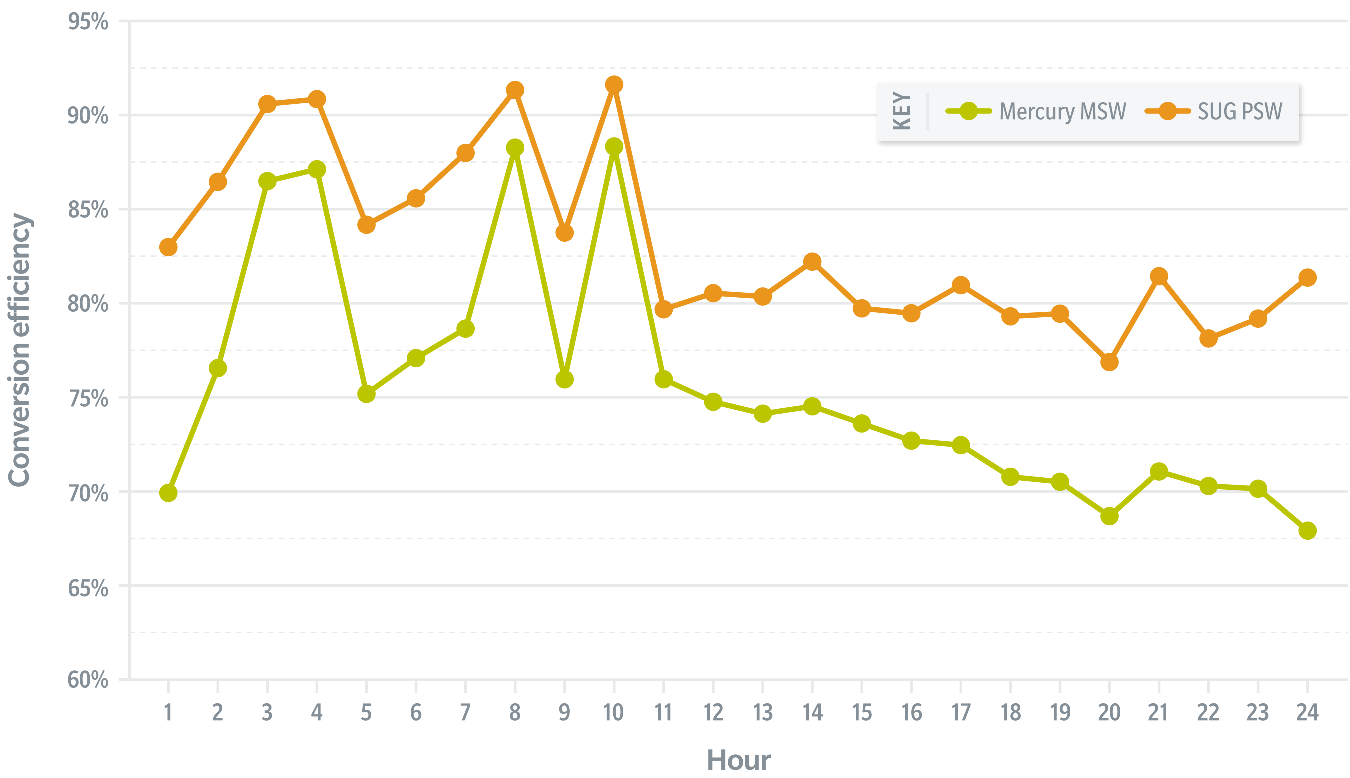


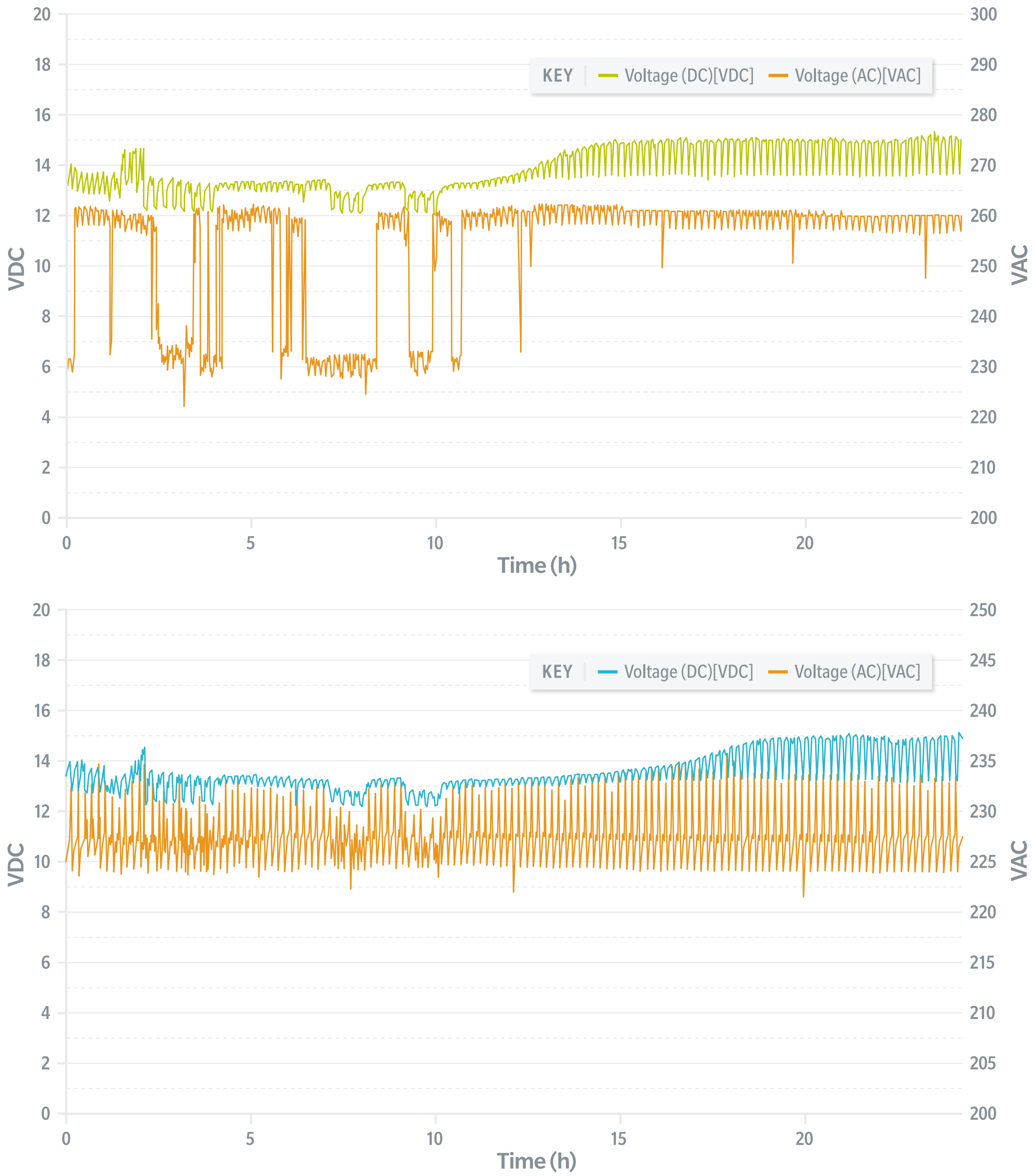
Figure 12: Conversion efficiency of the PSW and MSW inverter in each hour period



As mentioned earlier, input voltages from the battery to the inverter of over 12V were measured during test periods, as a result of the concurrent charging of the battery that took place. The output AC voltages from the two inverters also showed variation. The output AC voltage from the PSW inverter was over 250V on average, which may help to explain some of the higher power consumption observed at times on the PSW inverter. Larger voltage drops were also seen on the PSW inverter than the MSW inverter during periods of higher load.

In the prior Phase 1 tests that used a Victron 1200VA PSW inverter to operate refrigerators in over-voltage conditions (at 13.8V), an increased AC output voltage was not observed from the Victron PSW inverter (average output voltage of 228.6V was measured). The MSW inverter's average output voltage of 226.7W was similar to that measured in Phase 1 tests when running a refrigerator in over-voltage conditions (223.3V average output at 13.8V input).

Figure 13: Inverter output voltage variability of PSW inverter (top) and MSW inverter (bottom)



The high output voltage that was not regulated close to the rated output was likely a characteristic of the relatively low cost of the SUG PSW inverter ($290), when compared to the Victron used in previous tests. Consistently powering appliances above their rated voltage, as output by the SUG PSW inverter, can potentially increase the risk of damage to components and shorten the lifetime of the connected appliances.

Measurements of total harmonic distortion (THD) of the output AC from both inverters, going to each appliance, were also taken. The results were in line with expected values for PSW and MSW inverters. Such high THD values for the MSW inverter are likely to have some long-term negative effects on inductive loads such as motors, which has not been assessed in this report.

Cost comparison: multiple AC appliances with inverter versus multiple DC appliances in native mode

The upfront total system cost (TSC) for a solar PV system running multiple AC appliances tested was estimated using the sizing and cost model calculator[34] developed by SERC based on the daily energy consumption measured. This was estimated for the multiple AC appliance systems with PSW and MSW inverters and compared with the upfront TSC for running an equivalent DC appliance system.

Additionally, the simple lifecycle cost was estimated for AC appliances running with both inverters on a DC mini-grid. This was compared to equivalent DC appliances running natively on a DC mini-grid.

Table 8: Average input and output voltages measured from the inverters

INVERTER	AVERAGE INPUT VOLTAGE (VDC)	AVERAGE OUTPUT VOLTAGE (VAC)
SUG PSW	13.8	254.1
Mercury MSW	13.5	226.7

Table 9: Measurements of THD of AC power produced from the PSW and MSW inverters

LOAD	SUG PSW THD (%)	MERCURY MSW THD (%)
Refrigerator	0.4	35
TV	1.2	28
Fan	0.9	28
Sewing machine	0.6	28
Drill	0.8	32
Hair clipper	0.6	28
Lights	1.3	28
Phone charger	0.8	28

34 Lam NL, Wallach EW. (2020). Off-Grid Refrigeration System (OGReS) Cost Model (Version 1.0). Schatz Energy Research Center.

Cost comparison: operation on a solar PV system

Table 7, above, showed the energy consumption of the combined appliances measured 2.21 kWh per day on the PSW inverter and 2.32 kWh per day on the MSW inverter. Solar PV system power requirements were estimated as similar on both the PSW and MSW inverters. A PV array of around 730-780 Wp and a battery of at least 350 Ah were estimated as required to power both multiple appliance set-ups. The PSW inverter was more expensive than the MSW inverter, raising its TSC, but it would be expected to perform better over time and reduce the risk of appliance breakdown.

For the DC appliances compared, estimates of required PV system capacity and upfront purchase cost were derived from data for DC appliances from prior tests for the Equip Data platform[35] and the Global LEAP Awards[36]. Energy consumption assumptions made for the equivalent DC appliance set-up are detailed in Table 10 below.

Table 10: Estimates of daily power consumption for equivalent DC loads

DC APPLIANCE	ESTIMATED DAILY ENERGY CONSUMPTION (kWH)	ASSUMPTIONS
Refrigerator	0.203	• *The average of four 'best-in-class' efficient DC refrigerators previously tested.* • *The daily energy consumption figure from previous tests comes from steady state tests at 32˚C, whereas the multi-appliance test was run at laboratory ambient temperature (18-20˚C). As such, a conservative correction factor was applied based on the approximate ratio of power consumption from prior tests conducted at 16˚C and 32˚C for the LEIA programme. The correction factor of 75% of the energy consumption at 32˚C was assumed for this comparison.*
Fan	0.380	• *The average of 14 similarly sized DC fans previously tested.* • *The multi-appliance test had the fan running for 24h at two different speeds. A conservative estimate is applied for the kWh/day figure, derived from the average on-mode power draw of the DC fans and assuming the fan is in operation for 24 hours at maximum speed.*
TV	0.064	• *The average of 12 DC TVs where cost and energy data is held, where the daily energy consumption is estimated from on-mode and standby mode power measurements, using the same usage pattern as the multi-appliance test.*
LED lights	0.107	• *The energy consumption of DC rated lights was assumed to be similar the measured energy consumption for AC rated lights in the multi-appliance test.*
Drill	0.414	• *The energy consumption was assumed to be similar to the AC rated appliance as no data was available. This is a conservative estimate as a drill or sewing machine with a DC motor is likely more efficient than one with an AC motor.*
Sewing machine	0.062	
Hair clipper	0.015	
Phone charger	0.003	• *The energy consumption assumed is the same as the energy consumption from the multi-appliance test.*
Total	1.25	• *Estimated PV panel capacity: 416 Wp* • *Estimated battery capacity 198 Ah*

35 VeraSol Off-Grid Product Database (formerly Equip Data) https://data.verasol.org/
36 Global LEAP Awards website http://globalleap.org/

It was estimated that DC equivalents of the AC appliances tested would use around 1.25 kWh per day to operate. The improved efficiency of DC appliances modelled, and the avoidance of a power conversion, would be expected to reduce energy consumption significantly. As such, it was estimated that power for DC variants of the AC appliances tested could be provided with a PV array of under 420 Wp and battery of just under 200 Ah, as determined using the SERC system sizing and cost model calculator.

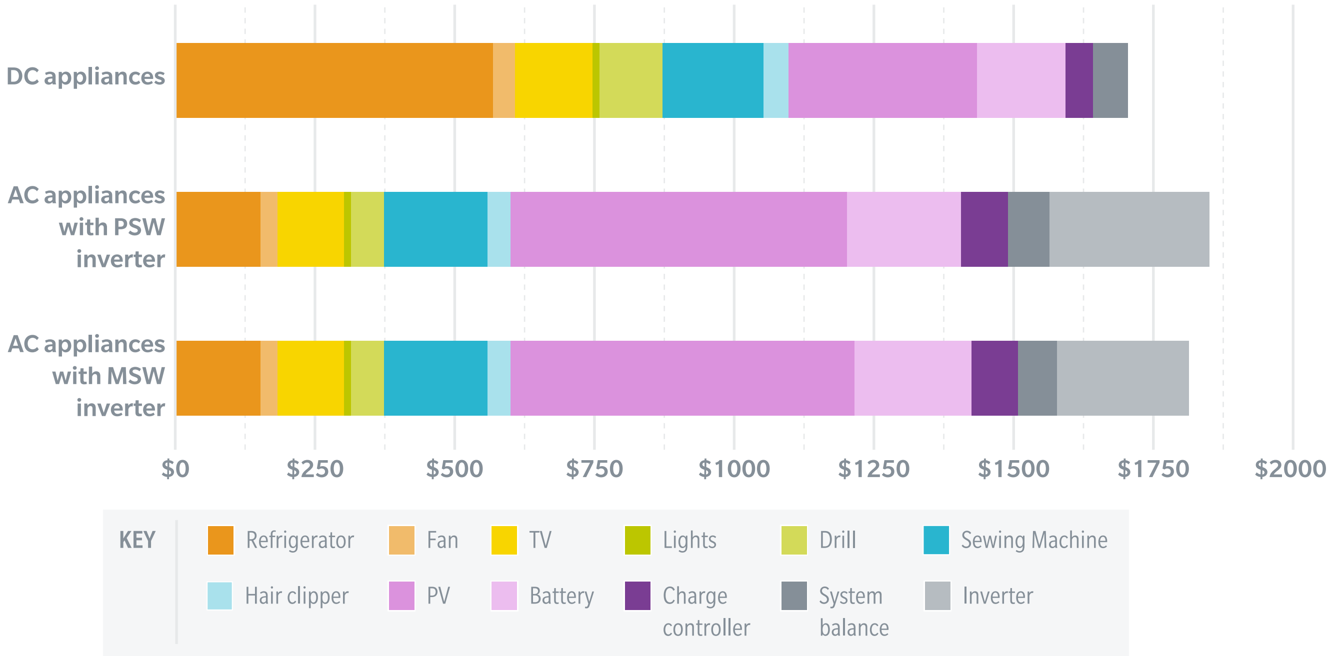
The cost assumptions derived from data held from Equip Data and the Global LEAP Awards, and sampled from online retailers, are detailed in Table 11 below. The data suggests that DC appliances are generally more expensive than AC appliances, and in some cases significantly so, for example, in the case of DC refrigerators. In this comparison, the DC refrigerator modelled is a highly efficient model, but one that is on the upper end of the cost spectrum.

The TSC of the natively DC system is estimated to be more cost-effective compared to the AC systems with inverters, as seen in Figure 14.

Table 11: Appliance cost estimates used for comparison

APPLIANCE	ESTIMATED COST (USD)		COST RATIO (DC/AC APPLIANCE)	ASSUMPTIONS
	DC APPLIANCE	AC APPLIANCE		
Refrigerator	$572	$157	3.6	• *AC: Cost of refrigerator used in multi-appliance test.* • *DC: Average of the 4 highly efficient DC refrigerators used for the DC daily energy consumption estimate.*
Fan	$35	$30	1.2	• *AC: The fan used in the MSW test was procured in Europe. The cost estimate used was the average of 21 similarly sized AC fans tested for Equip Data, and similar to the AC fan used in the PSW test ($28).* • *DC: Average cost of the 14 DC fans used for the DC energy consumption estimate.*
TV	$143	$117	1.2	• *AC: Cost of the TV used in multi-appliance test.* • *DC: Average cost of the 12 DC TVs used for the DC energy consumption estimate.*
LED lights	$13	$13	1	• *Cost of AC-rated lights sampled from Jumia Kenya and assumed similar to DC-rated lights.*
Drill	$107	$60	1.8	• *AC: Cost of a similar model to that used in the multi-appliance test found on Jumia Kenya* • *DC: Cost data for drills sampled from Jumia Kenya.*
Sewing machine	$185	$185	1	• *Cost data estimated from products sampled from Dukatech and Jumia Kenya.*
Hair clipper	$40	$40	1	
Phone charger	N/A	N/A	N/A	• *Cost of phone charger assumed negligible.*
Total	**$1,095**	**$602**		

Figure 14: Total system cost of PV systems with AC appliances and inverters compared to a system with equivalent DC appliances running in native mode



This is despite the increased total purchase cost estimate for DC appliances being significantly higher than for AC appliances (in large part due to the much greater DC refrigerator cost). This is the case as the higher PV system cost for the AC appliances, including the inverter, outweigh the higher capital cost of the DC appliances.

Cost comparison: operation on a DC mini-grid

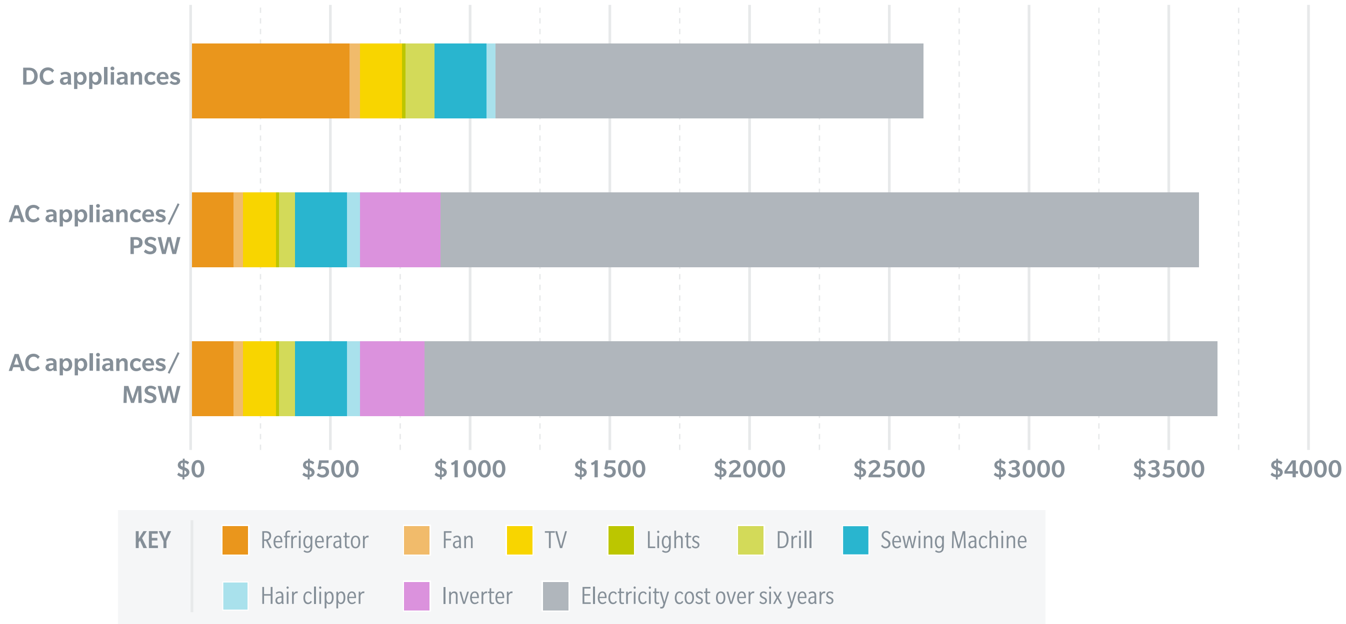
Simple lifecycle costs were estimated for the operation of the systems on a DC mini-grid, using the following assumptions:

- The electricity cost is taken as $0.56/kWh. This is the cost given for mini-grid electricity costs in Kenya from the World Bank report, Mini Grids in Kenya: A Case Study of a Market at a Turning Point.[37]
- Electricity costs are modelled over six years. This is based on the expected appliance lifetimes assumed in the calculations for the Phase 1 tests , i.e. six years for a TV and a fan and eight years for a refrigerator.[38]

37 The World Bank, Mini Grids in Kenya: A Case Study of a Market at a Turning Point, World Bank. 2017, http://documents1.worldbank.org/curated/en/792001512392701402/pdf/ESM-cKenyaMiniGridsCaseStudyConfEd-PUBLIC.pdf

38 Efficiency for Access Coalition, Performance and efficiency of off-grid appliances with power converters: Phase 1, 2020. https://storage.googleapis.com/e4a-website-assets/Performance-and-efficiency-of-off-grid-appliances-with-power-converters-phase-1-report.pdf

Figure 15: Estimated simple lifetime cost of operating multiple AC appliances with inverters on a DC mini-grid connection, versus operating DC appliances in native mode



From the simple lifecycle costs calculated, the use of AC appliances on a DC mini-grid over a six-year period was estimated to have a higher overall cost than the use of DC appliances. The lower running costs for the efficient DC appliances offset the higher upfront purchase costs over six years. This further supports the case for the use of efficient DC appliances in off- and weak-grid settings, as well as the case for avoiding power conversions where possible. This comparison would come out even more in favour of using DC appliances if an early failure of an AC appliance was seen. Anecdotal evidence and experiences reported from the field suggest that less expensive, lower quality AC appliances may fail within two to three years, and achieving six years' lifespan would not be expected in many cases. Additionally, inverters have been reported to undergo early failure in some studies (Formica, Khan, & Pecht, 2017) and may be another system component that may have to be replaced, potentially increasing the capital cost.

Encouraging the use of the most efficient appliances by customers is not always the highest priority for mini-grid developers, however. Mini-grid financing often becomes more cost-effective the more energy is used, and operators may offer a lower price per kWh beyond a level of energy use. For mini-grids to be more cost effective, higher energy use by end users is often encouraged.

Methodology and sample selection

Four DC appliances were procured for this test to simulate a user operating DC loads on an AC grid or mini-grid connection with a rectifier. The appliances sourced are detailed in Table 12, and were typical of those found in off- and weak-grid markets. A 112 litre DC refrigerator from a SHS supplier that was a finalist in the 2019 Global LEAP Awards was included in the samples, as well as a DC TV previously tested for the Equip Data platform. A DC pedestal fan was procured from a retailer in Uganda, and 12V DC LED spotlights were sourced from the UK, but were representative of lighting products found in off- and weak-grid markets.

Table 12: DC appliance test samples

APPLIANCE		APPLIANCE SPECIFICATIONS	RATED INPUT POWER	SOURCED FROM	WARRANTY	COST (US$)
	**Solar Now DC-112 (112L)**	**Compressor:** CK35DC variable speed DC **Refrigerant:** R134a	65W	Direct from supplier, as a previous entry sample to the 2019 Global LEAP Awards. Refrigerator is available in Uganda and Kenya	12 months	650
	**Jiepak 24T5**	20” LCD-LED TV	15-36W	Sierra Leone	1 month	195
	**Saachi NL-FN-1782DC pedestal fan**	**Diameter:** 16"	15W	Uganda	12 months	30
	**Greenandco MR16 GU5.3**	12V DC LED spotlights **Lumens:** 470	6W	UK	No information available	20

The multiple DC appliance set up was tested with a higher- and lower-cost rectifier on a 230V AC supply. The test was run for six hours at ambient laboratory conditions at temperatures of approximately 18-20˚C, to simulate a user having a segment of AC electricity access during the day. The equipment was set up as per the schematic in Figure 16. As with the inverter test, the full load AC power consumption was measured before the rectifier, and each individual load’s DC power consumption was measured after the rectifier.

Figure 16: Schematic of multiple DC appliances operating on a 230V AC supply through a rectifier

The use case of running DC appliances on an AC supply is considered to be less common than running AC appliances with an inverter on a SHS or mini-grid DC supply. With the current state of DC appliance market development, the DC appliances would most likely be acquired alongside a means of DC power provision, i.e. provided bundled in a package from a SHS provider. A user may then gain subsequent access to an AC supply and choose to operate the appliances on the AC supply. This test simulates a weak-grid scenario where a user has access to the grid for a short period of time and uses AC power as complementary to a DC power source such as a SHS. The chief aim of this test was to assess the viability of operating multiple loads on the rectifier, identify any performance issues, and determine whether the rectifiers were able to provide enough power to multiple loads operating at the same time. The load profile used for the tests was representative of a short period of use, rather than a full day's use. As such, a cost comparison has not been made with operating similar AC appliances on an AC supply.

The load profile used is provided in Table 13. The same refrigeration use pattern was applied as for the test on the inverters, with half-hourly removal of drink cans for the full six hours. The fan was run at two speeds and the TV in both on-mode and standby mode. The rectifiers used in the tests are listed in Table 14. Both were deemed suitably sized for the combined load.

Table 13: Load profile used in DC appliance tests

HOUR	REFRIGERATOR	FAN	TV	DC LED SPOTLIGHTS
1	On-mode with use pattern	On-mode	Standby mode	Off, load connected
2	On-mode with use pattern	On-mode	On-mode	Off, load connected
3	On-mode with use pattern	On-mode	On-mode	On-mode
4	On-mode with use pattern	Off, load connected	On-mode	On-mode
5	On-mode with use pattern	Off, load connected	On-mode	Off, load connected
6	On-mode with use pattern	Off, load connected	Standby mode	Off, load connected

Legend 2: Power modes used in DC appliance tests

On-mode | On-mode with use pattern | Standby mode | Off, load connected

Table 14: Rectifiers used in the tests

APPLIANCE		TYPE	MAXIMUM RATED IN-RUSH CURRENT AT 230V	RATED EFFICIENCY	WARRANTY	COST (US$)
	Mean Well WDR-120-12	DIN rail power supply	50A	89.5%	3 years	66
	Hengfu HF120W	DIN rail power supply	40A	83%	5 years (limited)	25

Test results: energy consumption of multiple DC appliances running on a rectifier

The test could be completed with both rectifiers without any performance issues observed from any of the appliances. As in the multi-appliance test with inverters, the refrigerator was filled with drinks cans, and allowed to stabilise, and run at ambient laboratory temperature (18-20˚C) before measuring energy consumption. However, in the test on the MeanWell rectifier, the DC refrigerator did not cycle on and no power measurement above 0.5W was recorded for the refrigerator during the 6-hour period. The drink cans appeared to hold the thermal load such that the refrigerator did not need to cycle on, but it was unclear why this was the case for only one of the rectifiers. Therefore, assessment of the full extent of the power requirement to operate all the appliances was only possible from the test on the Hengfu rectifier.

The Hengfu rectifier was able to provide enough continuous and surge power for all four appliances, including at peak demand. This was observed to be highest during hour 3 when all four appliances were running; the average AC input power to the Hengfu rectifier was measured as 118W (against the rectifier's continuous power rating of 120W), with a maximum recorded value of 142W. Output DC power was seen to peak at 117W and averaged 98W during hour 3. Overall energy consumption during the 6-hour period was measured as 361 Wh on the Hengfu rectifier.

Figure 17: Power measurements of the DC appliances running on a 230V AC supply through the Hengfu rectifier during the full six-hour period. Input AC power is shown in orange, output DC power shown in yellow. The refrigerator (purple) can be seen cycling on between hours 2 and 5 at a relatively consistent power consumption of around 45W. Power consumption was also observed to be relatively consistent for the fan (green), lights (blue) and the TV (grey).

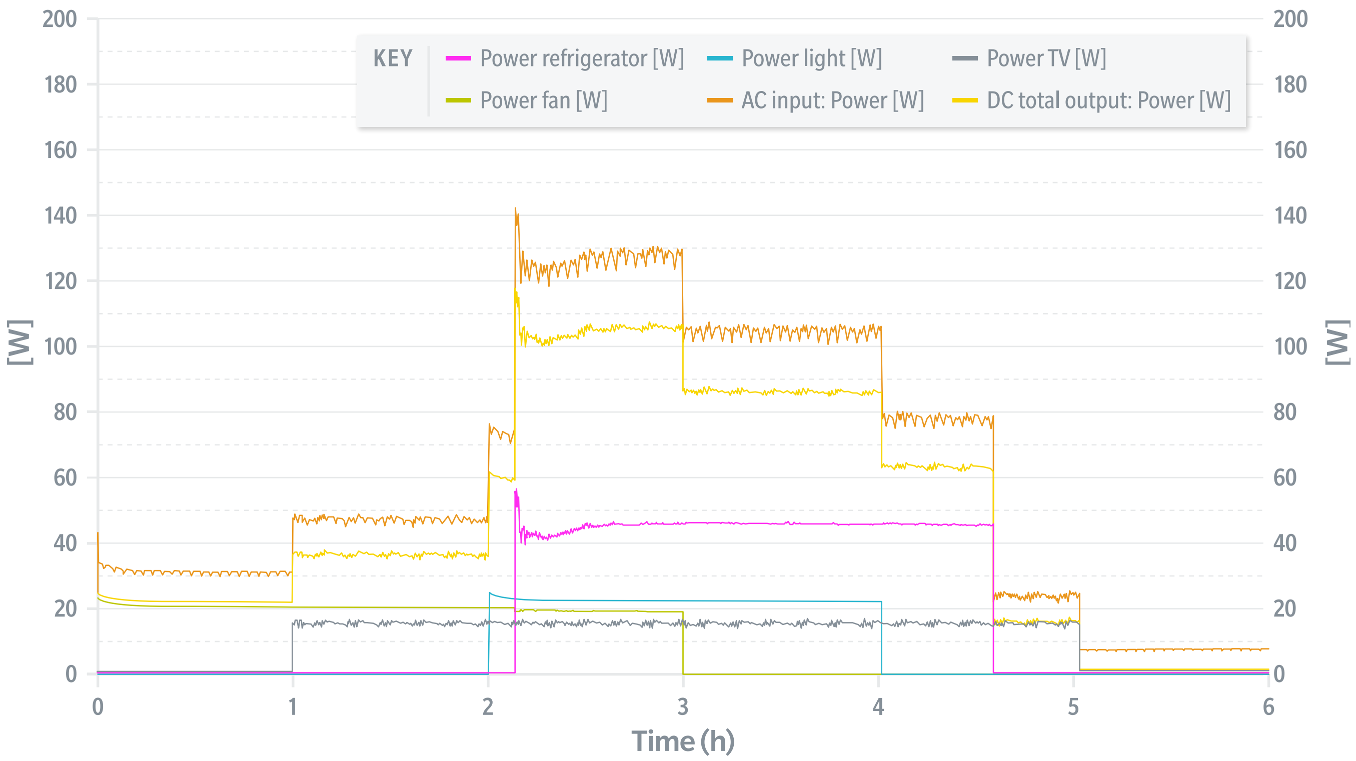
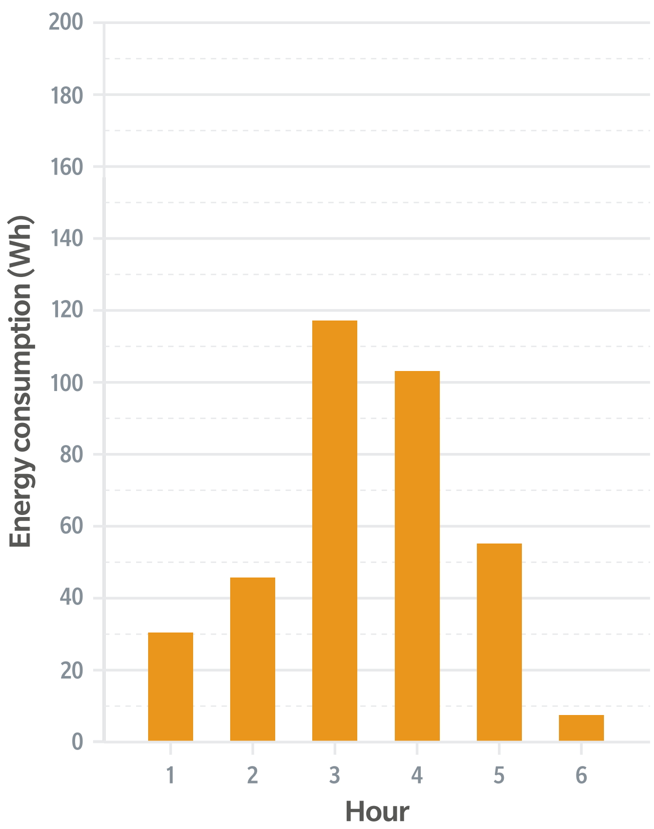


Figure 18: Combined energy consumption in each hour period for all loads on the Hengfu rectifier



Test results: rectifier performance

An exact comparison at higher load between the two rectifiers was not possible as there were no refrigerator cooling cycles observed during the test on the MeanWell rectifier, but a comparison of the overall conversion efficiency could still be made for both rectifiers. Conversion efficiency, as the ratio of output energy consumption to input energy consumption, measured in each hour period, was calculated as follows.

Figure 19: Conversion efficiency during each hour period on both the MeanWell (higher cost) and Hengfu (lower cost) rectifiers

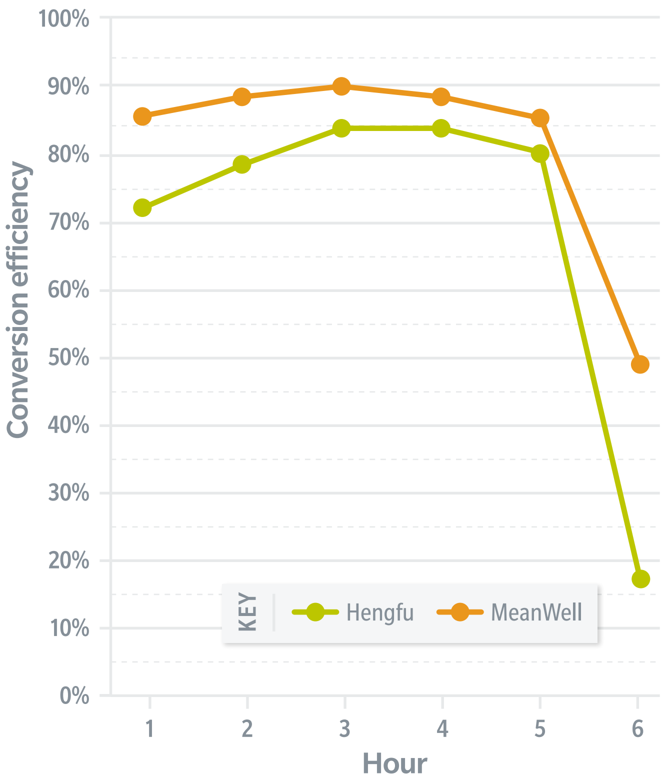
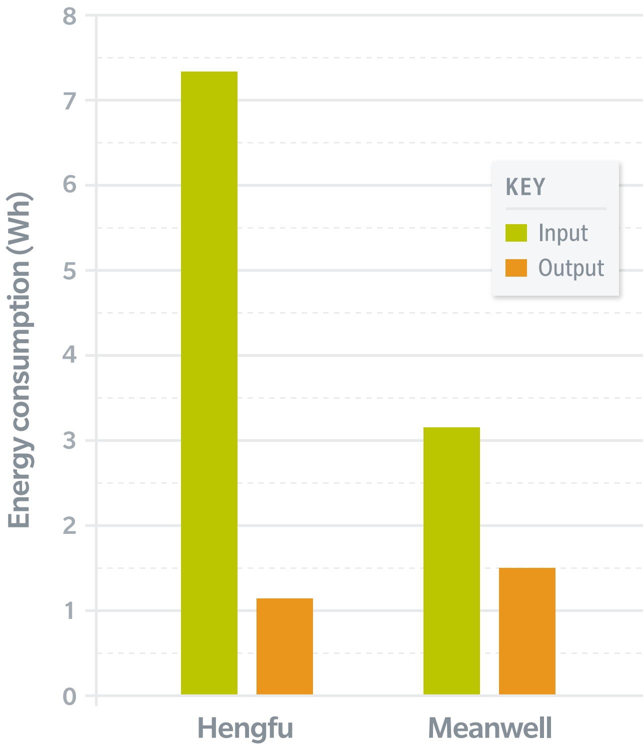


Figure 20: Energy consumption measured as input to and output from the Hengfu and MeanWell rectifiers during low-load conditions in hour 6



A pertinent observation was that the MeanWell rectifier provided a more efficient conversion than the Hengfu rectifier, even without the refrigerator contributing significantly to the overall load. Despite the reduced load, conversion efficiency on the MeanWell rectifier was over 80% during hours one to five and reached a peak value of 89% during hour 3. The Hengfu rectifier carried out conversions during hours one to five at between 72% and 83% conversion efficiency.

During hour 6, the refrigerator's compressor did not run on either rectifier, and the other appliances were in a low-load or no-load condition, enabling a comparison of the low-load performance of the rectifiers. In this hour period, 3.19 Wh energy consumption was measured from the MeanWell rectifier, with output energy consumption of 1.55 Wh to the appliances, giving a conversion efficiency of 49%. On the Hengfu however, the measured energy consumption of the rectifier was 7.37Wh, with 1.24Wh consumed by the appliances. This resulted in a low conversion efficiency of 17% for the Hengfu converter.

The output DC voltages from both rectifiers were averaged for the full test duration. These were observed to be fairly consistent throughout on both rectifiers, although a drop below 12V was observed on the Hengfu rectifier during periods of higher load and it averaged an output of 11.8V overall. During hour three, the average output voltage from the Hengfu to all loads was 11.6V, and the lowest voltage to any one appliance was 11.1V to the refrigerator. Output voltage on the MeanWell was seen as more consistent. These differences in output voltage drop with increased load are known to be due to differences in internal resistance (impedance) of the conversion equipment.

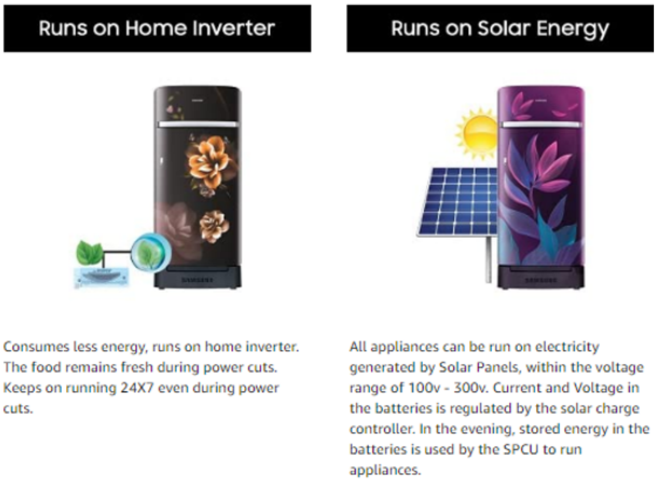
Table 15: Average input and output voltages on the MeanWell and Hengfu rectifiers

RECTIFIER	AVERAGE INPUT VOLTAGE (VAC)	AVERAGE OUTPUT VOLTAGE (VDC)
MeanWell	230.4	12.0
Hengfu	230.8	11.8

Sample selection and methodology

Inverter compressor refrigerators were not widely seen in off-grid market surveys in India and several African countries surveyed. However, anecdotal evidence suggests the technology is becoming more common generally, and mainstream in many higher-income countries.

Figure 21: Marketing material for the inverter compressor refrigerator tested, detailing use on a home inverter and solar PV systems



Inverter compressor refrigerators have several operating advantages: they are soft start (i.e. not requiring high in-rush current) and electronically controlled so the system can vary the speed to match the cooling requirement. They can be more efficient at part load conditions in which they tend to spend most of their operating life, as the flow of refrigerant can be reduced. In turn, this also reduces temperature gradients across the evaporator and condenser. It also means that on-off cycling, which occurs in single speed systems under most conditions, is reduced or eliminated, thus reducing compressor start-up losses. It is important to note that inverter systems and single speed systems may have similar efficiency at full load (no cycling of the compressor). However, there is a divergence between the two types in overall operating efficiency as cooling requirements reduce.

Inverter compressor refrigerators offer several other attractive features for use in off-grid or weak-grid environments. Since they rectify AC to DC, these systems are relatively robust and largely unaffected by power quality or harmonics. This means that it should be possible to use many types of low-cost inverters without long term detrimental effects to the performance of an inverter compressor refrigerator. The other advantage of inverter compressor refrigerators is that most can cope with substantial variations in supply voltage without any significant adverse effects.

An AC inverter compressor refrigerator was sourced from India. At 192 litres capacity, this was a larger model than most observed for domestic use by lower-income households, but would be considered a typical purchase choice for middle-income households. The refrigerator was purchased online for 13,890 INR – approximately $188[39]. At a cost of $0.98 per litre capacity, this is a lower cost per unit of capacity than many of the DC refrigerators seen in market surveys. The AC refrigerators tested in Phase 1 testing were priced between $92 and $221 (for sizes between 46 L and 213 L). In terms of cost per litre, the lowest cost for these models tested was $1.00 per litre. The rest of the models ranged from $1.70 to $2.60 per litre of capacity.

39 Purchased for 13,990 INR on 10 March 2020, exchange rate on this date: 1 INR = 0.01342 USD. From OANDA, accessed 13/8/20.

Table 16: Specifications of the inverter compressor refrigerator sample

APPLIANCE		APPLIANCE SPECIFICATIONS	RATED INPUT POWER	SPECIFIED ENERGY CONSUMPTION	RATED VOLTAGE	SOURCED FROM	WARRANTY	COST (US$)
	**Samsung RR20T172YR2 /HL (192L)**	Single door refrigerator with ice box **Refrigerant:** R600a **Compressor:** Samsung NI34N9802AD	60W	162 kWh/YEAR	220 VAC	India	One year on product, 10 years on compressor	188

Test results: AC inverter compressor refrigerator native mode energy consumption and in-rush current.

The refrigerator was tested in July 2020 at the laboratory Re/genT in the Netherlands, using the Global LEAP Awards Refrigeration test method[40]. The steady-state energy consumption of the refrigerator was tested at an ambient temperature of 32°C. Tests were conducted at the refrigerator's rated voltage of 230 VAC, and under- and over-voltage conditions of 207 VAC and 275 VAC respectively, with results provided in Table 17. The daily energy consumption of the refrigerator was observed to be lower than for all the AC, single speed compressor refrigerators tested in Phase 1, the lowest of which was a 92 L refrigerator with ice box, that was measured at 0.562 kWh/day (also at 32°C). In the over- or under-voltage conditions, there was little change observed between energy consumption measurements.

Measurements were also taken of the average power draw during on-cycles of the compressor and off-cycles when the compressor was not running. In-rush current could not be measured during the native mode tests as the equipment available did not have the necessary sensitivity. As such, an estimation of the surge power required to run the refrigerator was not available.

Table 17: Test results of Samsung inverter compressor refrigerator at ambient temperature of 32°C

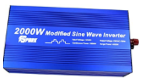
INPUT VOLTAGE (VAC)	DAILY ENERGY CONSUMPTION (kWH/DAY)	ON-CYCLE AVERAGE INPUT POWER (W)	OFF-CYCLE AVERAGE INPUT POWER (W)
207	0.458	38.6	0.2
230	0.469	39.2	0.2
275	0.483	40.6	0.3

Testing of AC inverter compressor refrigerator on a 12V DC power supply with inverters

Inverters of a similar power rating to those used for testing the AC refrigerators tested in Phase 1 testing were used. Tests were conducted to explore the performance of the refrigerator when operated on these inverters. Two inverters were tested: a Su-Vastika Solar (formerly Sukam Solar) PSW uninterruptible power supply (UPS) inverter purchased from India, and a lower cost Spark MSW inverter purchased from the UK.

40 Global LEAP refrigerator test method, 2019, https://storage.googleapis.com/leap-assets/Global-LEAP-Off-Grid-Refrigerator-Test-Method-Version-2.pdf

Table 18: Inverters used for testing

APPLIANCE		TYPE	RATED CONTINUOUS POWER	RATED PEAK POWER	RATED INPUT VOLTAGE	RATED OUTPUT VOLTAGE	MAXIMUM RATED EFFICIENCY	WARRANTY	COST (US$)
	**Su-Vastika Solar Falcon+ PSW 1100 VA Home UPS/ inverter**	PSW	1100 VA	3300 VA (300% of rated capacity)	12V	220 VAC	Not stated	1 year	104[41]
	**Spark 2000W MSW inverter**	MSW	2000W	4000W	12V	220-240 VAC	85%	1 year	123[42]

Test results: steady-state energy and power consumption

With the refrigerator running on a 12V DC supply through inverters, steady-state energy consumption tests were conducted at 32°C ambient temperature. Results are shown in table 19. The power consumption measurements were made at the DC input to the inverter and at the AC output from the inverter to the refrigerator to establish a conversion efficiency. Additionally, measurements were made of the input power to both the inverter and refrigerator when the compressor was both on and off. Native mode measurements are included for comparison.

As in previous tests, when the Su-Vastika Solar PSW UPS inverter was used, an increased voltage was seen from the battery used for the DC supply, as a result of it also being charged while supplying power. Input voltages of over 14V were seen in these tests. This was considered a condition typical of off-grid conditions when used with this type of inverter. Output voltage from the inverters in relation to this increased input voltage was also observed as per Table 21.

Table 19: Energy and power consumption of the AC inverter compressor refrigerator running on the inverters

INVERTER	DAILY ENERGY CONSUMPTION (kWH/DAY)		ON-CYCLE INPUT POWER (W)		OFF-CYCLE INPUT POWER (W)	
	REFRIGERATOR	REFRIGERATOR + INVERTER	REFRIGERATOR	REFRIGERATOR + INVERTER	REFRIGERATOR	REFRIGERATOR + INVERTER
Su-vastika (PSW)	0.454	0.958	38.6	59.7	0.1	20.6
Spark (MSW)	0.455	1.043	38.2	75.9	0.3	10.6
Native mode (230 VAC)	0.469	N/A	39.2	N/A	0.2	N/A

The energy consumption measured at the input to the inverter was relatively high compared to the native mode measurements. Daily energy consumption was measured to be around twice of the native mode test. Energy consumption by the refrigerator only (output from the inverter) was measured to be very similar to the native mode tests. The power consumption measured at the inverter during the compressor on-cycle was around 34% higher than that measured for the refrigerator in the native mode test at 230V. Power measured at the input to the inverter during the compressor off-cycle was also seen to be significant. This was measured at over 10W on the Spark MSW inverter, and at over 20W on the Su-vastika PSW inverter.

Various aspects should be taken into account when interpreting these results. The Su-vastika PSW inverter was a UPS/inverter, and the higher off-cycle power consumption of it compared to the MSW inverter was likely to be from it carrying out a charging function. This UPS inverter type was commonly observed during sample selection research of the inverter market in India, with fewer PSW inverters that did not also

41 Purchased for 7,750 INR on 10 March 2020, exchange rate on this date: 1 INR = 0.01342 USD. From OANDA, accessed 13/8/20.
42 Purchased for 99.99 GBP on 24 April 2020, exchange rate on this date: 1 GBP = 1.235 USD. From OANDA, accessed 13/8/20

provide UPS functionality. Both inverters were also oversized, to ensure they could provide sufficient in-rush current, which contributed to reduced conversion efficiency. However, the energy consumption increase from use of the inverters was higher than expected, and the increase may have been lower on a more optimally sized inverter. The relatively high power consumption from the inverter when the compressor was not running was also higher than expected.

A further inverter test was subsequently run to validate the measurements on the Su-vastika and Spark inverters. Using another PSW inverter, the Victron Phoenix 1200VA, with the refrigerator, measurements of the power consumption by the inverter and refrigerator during the on- and off-cycles were taken at laboratory ambient conditions of around 18-20°C, rather than 32°C ambient. Running the check test at a different ambient temperature did not allow for comparison of daily energy consumption figures with the other inverter tests at 32°C ambient, however, it enabled a sense check of the power draw when the compressor cycled on and off. Measurements from the Victron inverter check test are provided in Table 20.

Table 20: Check test of on- and off-cycle power consumption of the AC inverter compressor refrigerator running on the Victron Phoenix 1200VA PSW inverter

INVERTER	ON-CYCLE INPUT POWER (W)		OFF-CYCLE INPUT POWER (W)	
	REFRIGERATOR	REFRIGERATOR + INVERTER	REFRIGERATOR	REFRIGERATOR + INVERTER
Victron Phoenix 1200VA (PSW)	37.7	53.3	0.1	16.8

Power measurements on the Victron PSW inverter were largely in line with those seen on the Su-vastika PSW inverter. A relatively high off-cycle input power to the inverter of over 16W was again measured on the Victron PSW inverter. The on-cycle power measurement to the Victron PSW inverter was slightly lower than that measured at 32°C ambient on the Su-vastika PSW inverter, resulting in a slightly higher estimated conversion efficiency. Power consumption by the refrigerator alone (output from the inverter) on both the on- and off-cycle was similar to that seen in the native mode tests. The check test thus provided some validation of the results observed on the Su-vastika and Spark inverters.

Despite the increased power consumption observed, no performance issues were observed with the refrigerator's performance or with the inverters in any of the tests. Temperature stabilisation was able to be reached and the inverters were able to provide sufficient power at all times.

Test results: inverter efficiency and performance

Conversion efficiency was calculated as an overall figure from the overall daily energy consumption measurement, and for both the compressor on- and off- cycles. Average voltage and total harmonic distortion (THD) of the PSW and MSW inverter outputs were also measured. Conversion efficiency calculated from the on- and off-cycle check test measurements on the Victron PSW inverter have also been included for comparison.

Table 21: Efficiency and performance of inverters tested

INVERTER	AVERAGE VOLTAGE		CONVERSION EFFICIENCY (%)			THD (%)	
	INPUT (VDC)	OUTPUT (VAC)	OVERALL	ON-CYCLE	OFF-CYCLE	ON-CYCLE	OFF-CYCLE
Su-vastika (PSW)	14.3 (low setpoint) 14.2 (high setpoint)	232.9 (low setpoint) 232.5(high setpoint)	47.4%	64.7%	0.5%	5.5%	2.6%
Spark (MSW)	14.2 (low setpoint) 13.8 (high setpoint)	222.4 (low setpoint) 222.4 (high setpoint)	43.7%	50.4%	2.9%	27.5%	41.1%
Victron (PSW, check test)	N/A	N/A	N/A	70.7%	0.6%	N/A	N/A

Overall conversion efficiencies were observed to be low for both the Su-vastika and Spark inverters, with efficiencies of below 50%. This is thought to be mainly due to the oversizing of the inverters. However, an inverter of this size may realistically be used in a situation where a user is powering more loads beyond the refrigerator. Where this is the case, there will likely be times when the refrigerator is the only load being powered by an inverter, for example, at night time when other appliances are disconnected.

Conversion efficiencies calculated for the on-cycle power measurements were seen to be higher on the Su-vastika and Victron PSW inverters than the Spark MSW inverter, which is likely a function of their more appropriate sizing. Conversion efficiency during the off-cycle was observed to be higher on the Spark MSW inverter than for the Su-vastika inverter. However, this is likely in part to be due to the extra power consumption from the Su-vastika UPS functionality carrying out a charging function.

The comparison with the Victron PSW inverter during the off-cycle provided an interesting result. Whilst an exact comparison cannot be made due to the different temperatures of the tests, the off-cycle power consumption of the Victron inverter was measured to be higher than for the Spark inverter, resulting in a higher conversion efficiency on the Spark in this load condition.

Further tests would be needed to establish the optimal inverter size for the refrigerator tested. While the in-rush current could not be measured, there were no issues seen with the compressor starting. The fact that conversion efficiency was observed to be low on this inverter also suggests that an even smaller inverter could provide power for a refrigerator of this type.

Output voltage was observed to be consistent on both inverters, and in line with their voltage ratings. THD measurements were found to be around the levels typically seen for PSW and MSW inverters. It was noted that THD measured on the Spark inverter reached over 40% on average during off-cycles, which was significantly higher than the figure of 27.5% measured during the compressor on-cycle. As discussed previously, higher THD may affect the working of motor-driven loads and potentially damage components over time. However, inverter compressor refrigerators may be affected less by operation on higher THD waveforms. The initial internal power conversion from AC to DC is expected to remove harmonics from the waveform that would not be in place for single speed compressors driven directly by the higher THD waveform of an MSW inverter.

Cost comparison

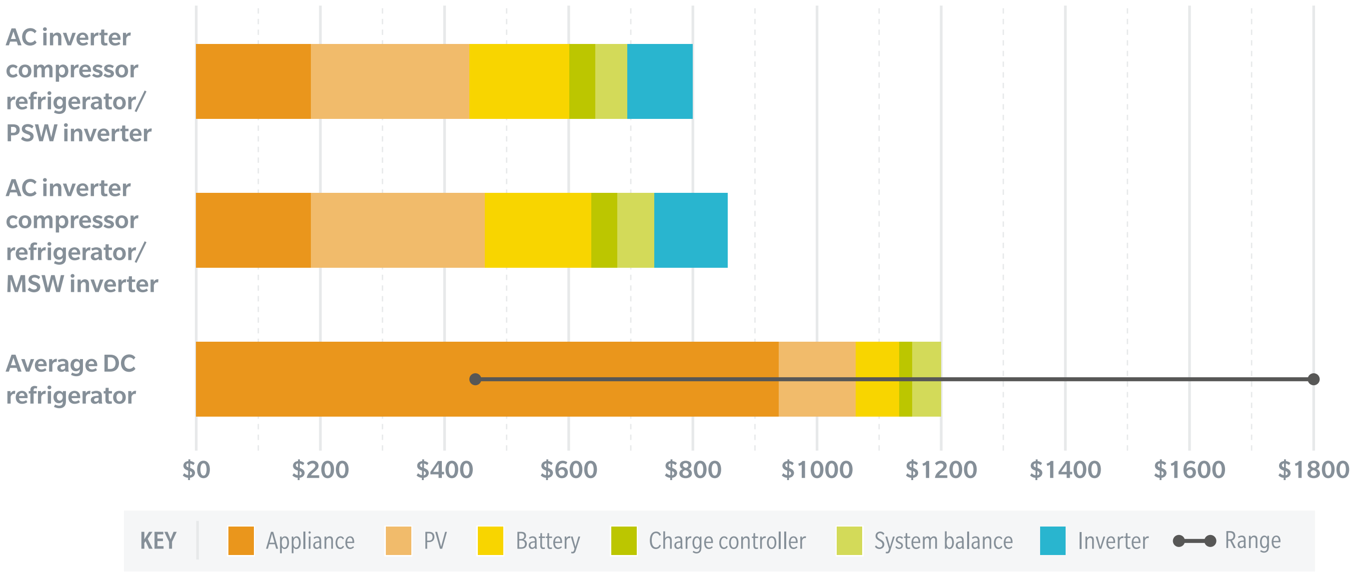
Using the SERC system sizing and cost model calculator, the PV system size required to operate the inverter compressor refrigerator with the inverters tested was determined to establish an estimated upfront total system cost (TSC). This was then compared with a TSC estimate for 12 DC refrigerators of a similar size, for which cost and energy consumption data were held. DC refrigerators used in the comparison were larger models with volumes ranging between 160 L and 240 L, and were a mix of refrigerators sold in off-grid markets of average efficiency and high performing models previously submitted to the Global LEAP Awards.

DC refrigerators in this size bracket had relatively high upfront costs, ranging between $362 and $1,437, with an average cost of $934 (see the 'Cost analysis assumptions' section in the Introduction for more detail on appliance cost figures used). Many of the DC refrigerators were previously measured to have low energy consumption, with eight of the twelve refrigerators having a lower daily energy consumption than the inverter compressor refrigerator in native mode (0.469 kWh/day). This would result in a smaller PV system needed for these DC refrigerators; the lowest energy consumption refrigerator being a 173 L model with daily energy consumption of 0.164 kWh/day, which would require a PV module of around 55 Wp in size and a battery size of around 26 Ah.

The energy consumption of the inverter compressor refrigerator, however, was seen to increase significantly when run on the inverters in these tests. As a result, an estimated PV array size of around 320 Wp is required for running the refrigerator with the PSW inverter tested, and an estimated PV array size of around 350 Wp is required for the refrigerator with the MSW inverter tested. Estimated battery size for these two cases was over 150 Ah.

The overall cost breakdown is shown in Figure 22. Whilst the PV system cost is considerably higher for the AC inverter compressor refrigerator run on inverters compared to the average DC refrigerators used in the comparison, this is outweighed by its much cheaper upfront purchase cost. As a result, the TSC estimate for the inverter compressor refrigerator run on inverters was lower than that for the average of the 12 similarly sized DC refrigerators compared.

Figure 22: Total system cost estimate of the AC inverter compressor refrigerator with MSW and PSW inverters compared to the average of similarly sized DC refrigerators in native mode (capacity 160-240L)



The TSC estimates for the AC inverter compressor refrigerator could be subject to variation; a higher cost inverter could be used which may last longer and provide better long-term operation of the refrigerator. For example, the Victron 1200VA inverter costs over $450, while the two inverters used in the tests were both just over $100. It is also possible that a more optimally sized inverter would result in reduced energy consumption compared to that observed in the tests and reduce the size of the PV system needed.

From online research conducted, the cost of inverter compressor refrigeration was seen to be quite variable, and not all available refrigerators in different markets were around the price of the model tested. For example, in Uganda, a 230L inverter compressor model was found[43] to cost just under 1,800,000 UGX (around $475). Online checks of Jumia Nigeria found over ten inverter compressor refrigerators of varying size available[44], with the lowest cost model being a 199L refrigerator priced at 124,000 NGN (around $325)[45]. As such, the price found for similar inverter compressor models in sub-Saharan Africa may not yet have reached the levels of the market in India.

43 Product listing for Hitachi RH330 inverter compressor refrigerator on Jumia Uganda. Accessed 13/8/2020. https://www.jumia.ug/appliances-fridges-freezers/

44 Online search of Jumia Nigeria of Inverter compressor refrigerators. Accessed 13/8/2020. https://www.jumia.com.ng/catalog/?q=inverter+compressor

45 Exchange rates from NGX and NGN to USD taken from xe.com, accessed 13/8/20.

Where solar PV systems are used to power multiple appliances, the use of DC appliances is more cost effective than the use of AC appliances

Based on the test results, the upfront total system cost (TSC) estimates of solar PV systems running multiple appliances showed that systems with DC appliances have a lower overall cost compared to systems with AC appliances and an inverter. The comparison made estimated that a set-up of similarly sized, highly efficient DC appliances would use around half the energy of the less efficient AC appliances tested in this study. The TSC reduction estimated for the DC appliances versus the AC appliances was more marginal, at under 10%.

The case for using DC appliances was further supported by estimates made for DC mini-grids running multiple DC appliances versus running multiple AC appliances with an inverter. The simple lifetime cost (over six years) of the AC appliances was estimated to be around 30% lower than for the DC appliances modelled.

This is in line with the findings from Phase 1 tests. The main reason for this result is that the reduced energy demand from highly efficient DC appliances results in a much smaller PV system required to run them, and reduced electricity costs in the case of DC mini-grids. Use of DC appliances in native mode also avoids the complications from running an AC appliance on an inverter, such as complexity in sizing, ensuring compatibility of cables and connectors, and potential issues with MSW inverters operating motor-driven loads.

For the set of appliances tested, the refrigerator contributed the largest share of the energy requirement. As such, for the modelled DC appliance set-up, the use of a highly efficient refrigerator significantly reduces the size of the PV system needed. For example, the Youmma NILO 100, which was the winner of the medium size category in the 2019 Global LEAP Awards[46], is estimated to require a PV module capacity of only 80Wp and a battery capacity of 22Ah to run. For the full set of DC appliances tested, it was estimated that the energy to run them could be provided with a PV array of around 420 Wp and battery capacity of around 200 Ah. For equivalent AC appliances (in terms of size), it was estimated that a PV array of around 750 Wp and battery capacity of around 350 Ah was required, in addition to the need for an inverter.

The estimated size of the system to run the AC appliances was also relatively conservative, as the Von refrigerator tested was one of the more efficient AC models available. It was measured as using 0.530 kWh per day in a separate steady-state energy consumption test at 32˚C, which is lower than most AC models tested in Phase 1 of this study and most lower-cost AC refrigerators featured on the Equip Data platform[47].

When selecting appliances for SHS and DC mini-grid deployment, market actors should consider DC appliances as the optimal appliance choice.

Operating multiple AC appliances improves the cost-effectiveness of inverter use compared with operating a single AC appliance, but the quality of inverters and appliances must be considered

Phase 1 testing with single DC appliances showed that PV systems were most cost-effective when run natively, compared to running single AC appliances with inverters. However, in Phase 2 it was found that a set of lower-cost AC appliances with an inverter may appear more cost-effective than DC appliances in the short term. Running multiple AC appliances enables more efficient use of available PV system power and more optimised loading for the inverter. This is especially evident when running a refrigerator. A single refrigerator would generally require disproportionate oversizing of the inverter to account for the refrigerator's high in-rush current. In a multi-appliance set-up, the same size inverter can be used, but the additional appliances mostly contribute to increasing the continuous power requirement.

46 Global LEAP Awards, 2019 Buyer's Guide for Outstanding Off-Grid Refrigerators, https://storage.googleapis.com/leap-assets/2019-Global-LEAP-Refrigerators-Buyers-Guide_final.pdf

47 VeraSol Off-Grid Product Database (formerly Equip Data), https://data.verasol.org/products/ref

This makes the system more cost-effective when more AC appliances are added, and results in a more efficient power conversion, due to a better match with the inverter's continuous power rating.

It is, however, important to consider that inverters have often been observed to be a source of PV system failure (as was found in several of the examples cited by (Formica, Khan, & Pecht, 2017)). The tests in this study showed that use of a PSW inverter is a safer and more reliable option for running appliances compared to the use of an MSW inverter – as observed from Phase 1 testing issues with MSW inverters, and from the overheating of a fan running on an MSW inverter in Phase 2.

The SUG PSW inverter used, which was of lower cost than the Victron PSW inverter used to power the refrigerators in Phase 1, appeared to perform well in Phase 2 tests. An inverter of this type could be a cost-effective option. However, the tests also uncovered some issues that may be seen on some PSW inverters – a high output voltage well above 230V was observed for long periods with the SUG PSW inverter, which could affect appliance lifetime in the long term. Future research is required to understand better the effects of long-term use of appliances with power converters, particularly low-cost converters such as MSW inverters.

While running multiple AC appliances with PV systems may be less expensive in the short-term, they may not be optimal in the long term if the lower-cost AC appliances are not off-grid appropriate and are likely to fail early. In addition, Phase 2 tests further demonstrated the complexity involved in selecting good quality power converters and appliances that are optimal for specific use cases. Selection and design guidelines can help buyers identify the optimal options and help prevent potential product failure.

AC inverter compressor refrigeration shows strong potential as a technology to provide efficient refrigeration at relatively low cost, but there are barriers to its wider uptake

Tests conducted on a 192 L AC inverter compressor refrigerator, purchased for an equivalent cost of $188, showed that this technology can provide energy access benefits. The model tested demonstrated lower energy consumption than single-speed compressor AC refrigerators and would appear to be an appropriate and cost-effective technology to operate on AC grids and mini-grids. Tests run on a DC supply with external inverters also showed that this refrigerator type could operate effectively in this configuration, and total system cost estimates suggested it would be more cost effective in this use case than older AC refrigeration technology, where DC infrastructure, or hybrid AC/DC environments are present.

However, while tests run on both PSW and MSW inverters did not present any performance issues, several instances in both phases of this study have shown that using an external inverter adds a layer of complexity in operating appliances. Inverter compressor refrigeration is expected to reduce this complication as they require lower in-rush currents, which should reduce the need for oversizing an inverter to the extent expected for single-speed AC refrigerators, enabling a more optimised continuous power loading. Inverter compressor refrigerators are also expected to work better than single-speed refrigerators on external inverters that provide a lower quality output AC, due to the internal conversion to DC that takes place. Tests conducted did not show any performance issues of inverter compressor refrigerators running on an MSW inverter compared to the PSW inverters, although energy consumption was increased on both inverter types. The scope of this testing allowed only preliminary measurements of this refrigerator type on inverters. Further tests of inverter compressor refrigerators, including specific testing with lower cost inverters, and over longer time periods, is recommended to establish a larger body of data.

While this technology could provide a more efficient and cost-effective refrigeration option for people in areas with weak AC grid and mini-grid infrastructure, previous market surveys, and online research identified that inverter compressor technology is not yet widespread in off-grid markets. Scaling the technology in these markets and dedicated research into adapting the technology for lower income users, for example with smaller refrigerators, could provide wide benefits.

While the cost of the model tested is relatively low compared to most off-grid refrigerators, it may still be outside the financial means of many off-grid households if the product is not offered as part of a PAYGo package to improve affordability. Industry and researchers may find benefit in pursuing further research into smaller refrigerators using inverter compressor technology with the aim to reach an affordable price point for off- and weak-grid users.

Recommendations

1. Further studies should be conducted to investigate:

- Longer term use of appliances with power converters, particularly low-cost converters such as MSW inverters.
- The performance and specific power requirements of AC and DC motor-based, productive use appliances, and options to best increase access to these appliances when faced with challenges of incompatibility of power supply and appliance.

2. Policymakers should attempt to support optimal and appropriate off-grid appliance types based on the power supply options common in their jurisdiction.

For example, where further SHS and DC mini-grid deployment is common or expected, DC appliances will be the optimal appliance choice and policy instruments should be employed to reduce their cost and disincentivise non-optimal appliance use cases. Phase 2 tests further suggested that there is scope for reduction in purchase costs of DC appliances, and that when multiple appliances are run on a DC supply, a set of lower-cost AC appliances with an inverter may appear more cost effective than DC appliances in the short term. However, they may not be optimal in the long term if the lower-cost AC appliances are not off-grid appropriate, are likely to fail early and will require use of an inverter, adding complexity.

3. Policymakers and donors should develop standards and support programmes in anticipation of the development of hybrid AC/DC environments.

Phase 2 tests further demonstrated the complexity involved in selecting good quality power converters that are optimal for specific use cases. Minimum performance standards and quality assurance programmes for converters and appliances can be used to prevent poor quality products from being available in off- and weak-grid markets. Information provision, awareness raising and training on the use of quality converters and appliances are additional options for policymakers.

4. Industry and researchers should further explore inverter compressor refrigeration technology, with the aim of enabling it to reach a more affordable price point in most off- and weak-grid markets.

This technology could provide a more efficient and cost-effective refrigeration option for people in areas with weak AC grid and mini-grid infrastructure. Scaling the technology in these markets and dedicated research into adapting the technology for lower income users, for example with smaller refrigerators, could provide wide benefits. Further research into the opportunity to use inverter compressor refrigeration on DC power supplies to expand upon testing conducted in this study is also recommended. This research could explore longer term operation on inverters to further assess viability, and optimal inverter specification around the power requirements of this technology.

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