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PERFORMANCE AND EFFICIENCY OF OFF-GRID APPLIANCES WITH POWER CONVERTERS

AUGUST 2020

PHASE 1 – SINGLE APPLIANCE TESTING OF REFRIGERATORS, TVS AND FANS

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. The phase 2 test results are provided in a separate report.

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GLOSSARY

AC	Alternating Current
DC	Direct Current
DI	Digital Inverter
EEI	Energy Efficiency Index
EPS	External Power Supply
Inverter	A power converter that receives DC power and outputs AC power
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) through the use of a power converter that provides the rated power of the appliance
PAYGo	Pay-As-You-Go financing
PSW	Pure Sine Wave
Rectifier	A power converter that receives AC power and outputs DC power
SERC	The Schatz Energy Research Center
SHS	Solar Home System
SPMS	Switching Mode Power Supply
SQW	Square wave
THD	Total Harmonic Distortion
TSC	Upfront Total System Cost
TV	Television

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 being used in off- and weak-grid areas, as observed by the Low Energy Inclusive Appliances (LEIA) programme 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 solar home system given unavailable DC appliances in their market. As a result of this mix of electrification approaches and appliance types, the 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 there is more to be learned on how appliance efficiency, performance and durability is affected by operation on different power supply options.

Appliances may be rated for use with direct current (DC) or alternating current (AC), and powered by the electrical AC grid, DC or AC mini-grids, or DC or AC 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 performs the reverse conversion of AC to DC. The use of a power converter adds additional power consumption, and typically increases the complexity of the system set-up, as well as adding cost and quality considerations. Effective support of the off- and weak-grid appliance market must consider the current state of this compatibility challenge as well as the future direction of AC and DC power supply.

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. For this study, 'native' mode was defined 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 through the use of 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 appliance in native mode	DC power supply *(DC SHS or DC mini-grid)*	DC appliance	None
2	AC appliance in non-native mode	DC power supply *(DC SHS or DC mini-grid)*	AC appliance	Inverter
3	AC appliance in native mode	AC power supply *(AC grid or AC mini-grid)*	AC appliance	None
4	DC appliance in non-native mode	AC power supply *(AC grid or AC mini-grid)*	DC appliance	Rectifier

Tests conducted

Laboratory tests aimed to replicate the products and conditions seen in off- and weak-grid settings, however, the number of tests possible and their length were limited by the scope of the project. Measurements were made in controlled conditions using standardised tests to estimate energy consumption and enable accurate comparisons between products. These estimates of energy use may differ from real-life conditions, where appliances are subject to highly variable environmental conditions and usage patterns.

Tests measured 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.

Current market trends suggest that in general, DC appliances such as refrigerators, TVs and fans may be more efficient, but have a higher purchase cost than their AC counterparts. The effect of this trade-off was tested with the use cases detailed above for DC and AC power supply options, as follows –

- Use case 1 and 2: Tests assessed whether a more expensive DC appliance running off a smaller PV system was more cost effective overall than an equivalent AC appliance with a lower upfront cost that required a larger PV system and an inverter.
- Use case 3 and 4: Tests assessed whether the combination of the higher upfront cost, but lower electricity cost expected for a DC appliance operating with a rectifier exceeded that of an AC appliance operating directly on an AC supply, over the appliance lifetime.

Use case 1 and 2

In order to compare the cost-effectiveness of use cases 1 and 2, the upfront total system cost (TSC) was estimated for the appliances running on an SHS. The TSC refers to the capital cost of the appliance plus the capital cost of a power system to run that appliance, i.e. an appropriately sized SHS (i.e. PV module, battery, charge controller, and balance-of-system components) and an appropriately sized inverter where the appliance is an AC appliance. Results of the study suggest that, in most cases, the most cost-effective appliance choice for SHSs are efficient, appropriately designed DC appliances, rather than AC appliances. This is due to the need for a larger, more costly SHS to both power less efficient AC appliances and cover conversion losses, combined with the added cost of the inverter. The use of an inverter also adds complexity, an additional point of failure, and potentially increases safety issues.

The difference in cost-effectiveness between use cases 1 and 2 was most salient in the case of refrigerators, where a larger difference in cost and energy use between AC and DC variants was observed compared to the TVs and fans tested in the study. This difference was due to the increased power needed by AC refrigerators compared to DC refrigerators, both in continuous operation and in the necessary in-rush current to start the compressor. The high in-rush currents for AC refrigerators were noted in tests to be significant, with three of the four AC refrigerators tested unable to be started using a 1.5kW DC power supply. However, some cases were seen where an AC refrigerator- which was both low cost and of relatively high efficiency, - was estimated to be more cost-effective than an equivalent DC refrigerator. Analysis of cost and energy data from the Equip Data[1] platform suggest that these cases were rare and only occurred where the DC refrigerator compared was on the upper end of the cost spectrum.

Quantifying the full cost of AC refrigerators used with DC supplies was valuable, as little data is available on size estimates for SHSs with inverters required to run these loads given their high in-rush currents. An AC refrigerator may be the only option for some households or businesses due to market availability or financial means. The market for DC refrigeration continues to develop alongside increasing DC supply options but current trends suggest that AC refrigeration will continue to be widespread in the coming years, particularly as grid extension continues to expand. The cost of DC refrigerators that are appropriately designed for off- and weak-grid contexts appears to be reducing but are still beyond the financial means of many households in these contexts. Analysis suggests that in order to increase uptake, DC refrigerator component costs need to fall further, while the production and distribution of DC refrigerators needs to scale up further to reduce the cost to consumers. VAT and custom duty exemptions may also play a role as DC appliances with higher upfront costs have higher VAT and custom duties applied to them, on an absolute basis, compared to AC appliances.

From the TV tests conducted, DC TVs were observed to be more cost-effective than AC TVs at the system level, mainly due to TVs being a DC-inherent product, with minimal upfront cost differences seen compared to AC TVs. From the results of the fan tests conducted, DC fans were observed to be a more cost-effective cooling option at the system level than AC fans, although tests and market assessment indicated that AC fans generally have higher air delivery capability, albeit at lower energy efficiency.

1 VeraSol Off-Grid Product Database (formerly Equip Data), https://verasol.org/

Use case 3 and 4

In order to compare the cost-effectiveness of use cases 3 and 4, simple lifecycle costs were estimated for the appliances running on an AC grid. The simple lifecycle cost refers to the capital cost of the appliance and rectifier, where needed, plus the electricity cost over the lifetime of the appliance. Results of the study suggest that AC appliances used 'natively' on an AC grid were more cost-effective than DC appliances used with a rectifier on an AC grid. This was due to the lower capital cost of AC appliances outweighing the electricity cost savings from more efficient DC appliances. However, it may be surprising to most that these overall cost differences were often not significant, suggesting that an efficient DC appliance can still be a viable option on an AC grid in the case that grid infrastructure is installed in an area where DC power supply and DC appliances are already available. This suggests that in areas where there are plans for the AC grid to be installed, it may still be economically rational to purchase a DC appliance with a DC power supply. Having an SHS already in place and adding an AC grid connection can bring a household a high measure of power security. The availability of dual power supplies provides users with a back-up to the AC grid in cases of power outages and can also reduce their AC utility bills. This hybrid approach is of increasing interest to households who can afford the investment and who value power security sufficiently to justify the investment, e.g. 63% of interviewees for the study *Peering into the future; India and the distributed standalone solar products market* (cKinetics, 2019) believed that a DC SHS has a role to play as a back-up system to the grid.

Power conversion

Whilst power conversion, from AC to DC or DC to AC, is a necessary step in some situations to improve electricity access, this always results in a 'sunk' power loss, which can vary according to the quality of the converter and how appropriately sized it is for the load. Conversion losses observed in this study were varied and, in some cases, significant. Inverters and rectifiers of a range of cost and quality were used, and in appliances' typical operating modes, conversion efficiencies were observed to be between 60%–90%. In low power modes, such as standby mode or periods when refrigerators were not cycling, conversions at under 5% efficiency were seen on some low-cost converters. This level of power consumption of the converter in low- and no-load conditions could have the effect of unexpectedly draining batteries or increasing electricity costs to the user, providing a further barrier to reliable and low-cost electricity access. Some low-cost power converters also performed poorly in other ways, e.g. not being able to provide rated power, failing to regulate input voltage, overheating and malfunctioning, or not including safety features such as cooling or grounding.

It is also important to understand the long-term performance of appliance and converter uses cases. This study was focused on shorter-term tests using a range of converters, including low-cost models. Low-cost inverters, for example, that use modified sinewave or square wave technology produce a lower-quality AC waveform that could damage appliances' components over time and shorten lifespan. In most of the shorter-term tests conducted in this study, however, AC appliances were able to operate on these inverters without issue.

Conclusions

This study aimed to assess the optimal combinations of appliance and power supply for the different use cases examined. Analysis has sought to quantify the cost differences between them and investigate some of the key issues that may be encountered when using power converters in relation to their quality and appropriate selection. There is little other similar research addressing power converters in off- and weak-grid settings, and further tests, including field testing may be valuable to learn more about the use cases simulated in laboratory tests in this study.

Various combinations of power supply and appliance have been identified as optimal in tests and subsequent cost analysis. A strong case is presented for utilising DC appliances natively on DC systems ahead of lower-cost AC appliances. However, policy and industry initiatives to reduce the upfront cost of DC appliances are still needed.

Projections suggest that a 'Hybrid AC/DC environment' is likely to develop in off- and weak-grid areas in the future. NGOs and practitioners have already raised concern about the scale of the existing compatibility challenge between power supply and appliance. Identification of the issues involved and effective strategies and policies to ameliorate them will be a key aspect of preparing for, and adapting to, future hybrid environments. Hybrid environments can be seen as an opportunity to improve energy access and preparation should be made for them. This can include further development of standards, codes, training and quality assurance initiatives. Additionally, more technical research can be directed towards appliances and associated devices that provide high compatibility across different supply options, to help ease this transition and realise the full benefits hybrid environments may bring.

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 of 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 through the use of 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 with a range of consequences for domestic life, work, education and healthcare, including the potential to damage appliances.[2]

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 (pManifold, 2019), in particular, where there are plans for the development of a 48V DC ecosystem and appliances.[3] Mini-grids currently account for a smaller share of off-grid power supply penetration compared to SHSs, having attracted around 15% of corporate investment in off-grid energy, compared to 80% for SHSs at the end of 2018.[4]

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. 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[5] 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

2 A. Botekar, "Voltage fluctuation damages 100 household appliances", The Times of India, 2020, https://timesofindia.indiatimes.com/city/nashik/voltage-fluctuation-damages-100-household-appliances/articleshow/73178858.cms
3 48V DC appliance range available from Cygni, https://www.cygni.com/products/48v-dc-appliances/
4 F. Sadouki, "The Land of Opportunity for Off-Grid Solar", Greentech Media, 2019, https://www.greentechmedia.com/articles/read/the-land-of-opportunity-for-off-grid-energy
5 International Energy Agency, Country report - Africa Energy Outlook, 2019, https://www.iea.org/reports/africa-energy-outlook-2019

access is AC grid extension and densification. Mini-grids are most viable for 30% of the population while stand-alone SHSs are most viable 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. This includes an 'AC domination' scenario where the AC grids expands 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.

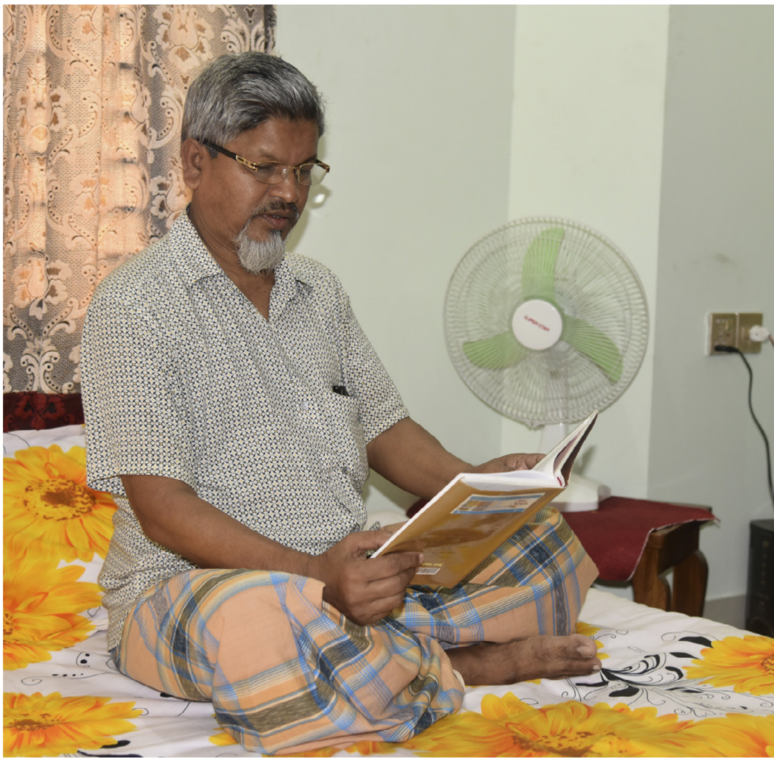
The market for off-grid appliances and power converters

AC appliances are more widely available in off-grid markets in sub-Saharan Africa and South Asia. For example, 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 the majority of refrigerators seen (67%) were small-volume AC models (Efficiency for Access Coalition, 2020).

DC appliances, such as fans that incorporate a brushless DC motor or refrigerators with variable speed 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 being 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, in particular, 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. Due to the 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 together 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.



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 widening access to efficient appliances at 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, 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. The phase 2 test results are provided in a separate phase 2 report.

Power converters tested

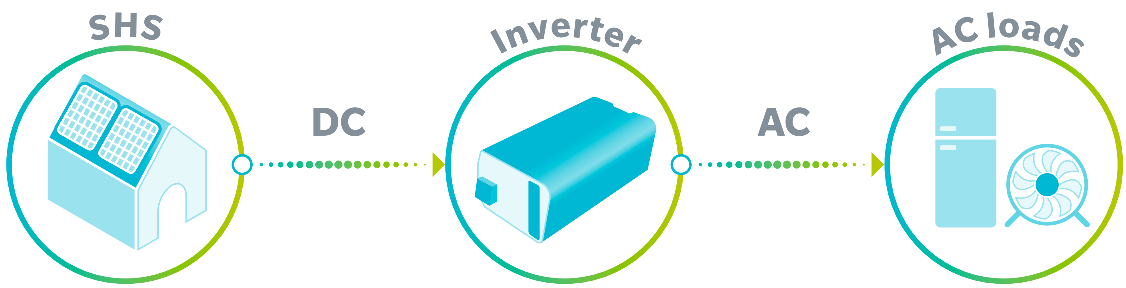
In the case of mini-grids, a power converter may be centralised at the powerhouse to provide one supply option to all households connected, or converters may be utilised at the single household level (one converter per household). A centralised power conversion at the origin is generally more efficient (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 that are considered typical 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 a commonly available product 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 these stores. Rectifiers identified included DIN rail-mounted and switching mode power supplies 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 appliance in native mode	DC power supply *(DC SHS or DC mini-grid)*	DC appliance	None
2	AC appliance in non-native mode	DC power supply *(DC SHS or DC mini-grid)*	AC appliance	Inverter
3	AC appliance in native mode	AC power supply *(AC grid or AC mini-grid)*	AC appliance	None
4	DC appliance in non-native mode	AC power supply *(AC grid or AC mini-grid)*	DC appliance	Rectifier

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



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 **Figure 2**. 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

Three 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.
- Square wave (SQW) – SQW inverters are the lowest cost inverter technology and provide the lowest quality AC waveform with the greatest harmonic distortion.

Their different waveforms are shown in **figure 3**.

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[8], and affect the ability of the motor to magnetise rotor and stator components. 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, but an AC sine waveform produced by a PSW inverter.

Figure 2a – Example of inverter efficiency curves[6]

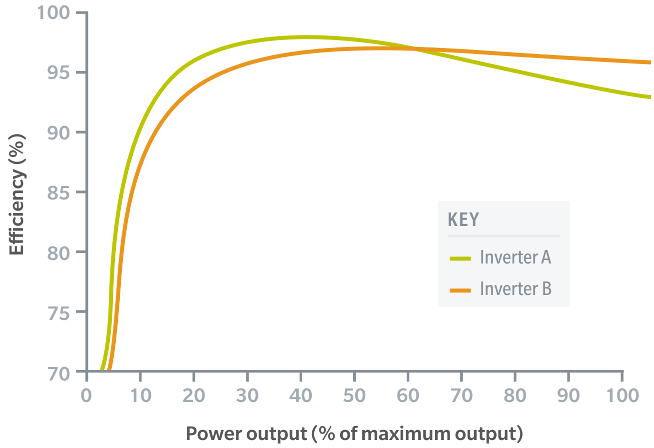


Figure 2b – Example of rectifier efficiency curves[7]

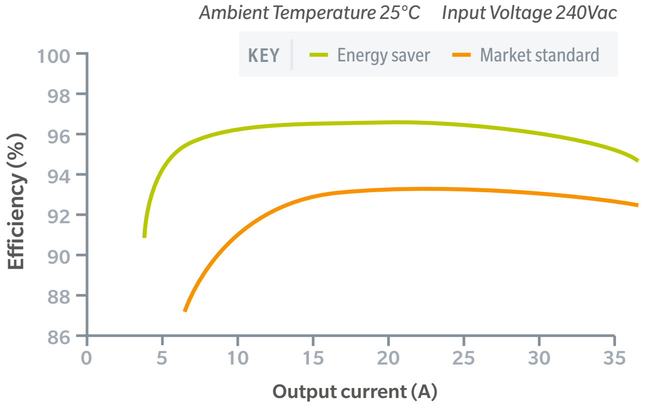
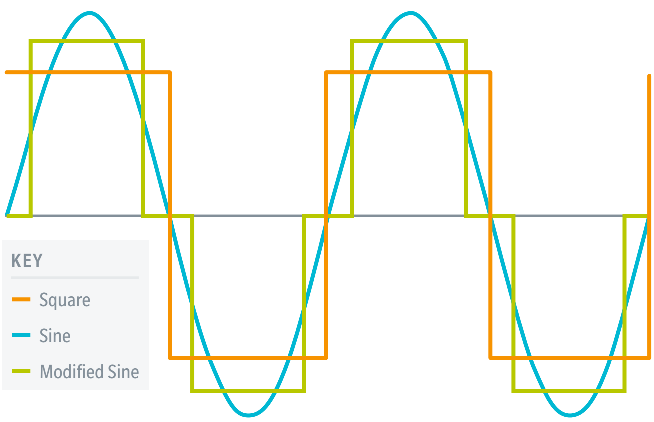


Figure 3 – Inverter waveforms



6 F. Peacock, "Two Reasons You Must Look At Efficiency Curves When Choosing Your Solar Inverter", Solarquotes, 2012, https://www.solarquotes.com.au/blog/two-reasons-you-must-look-at-efficiency-curves-when-choosing-your-solar-inverter/

7 Eaton – efficiency curve for market standard and energy saving rectifier, http://dcpower.eaton.com/3G/ESR-efficiency.asp

8 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

Figure 4 – Use case – AC loads running on DC mini-grid with inverter; and DC loads running on AC mini-grid with rectifier

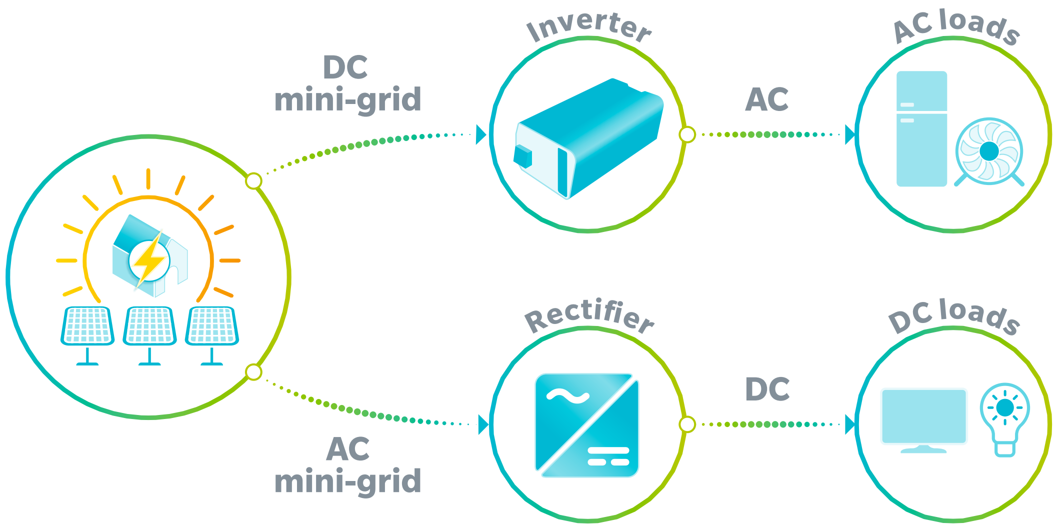
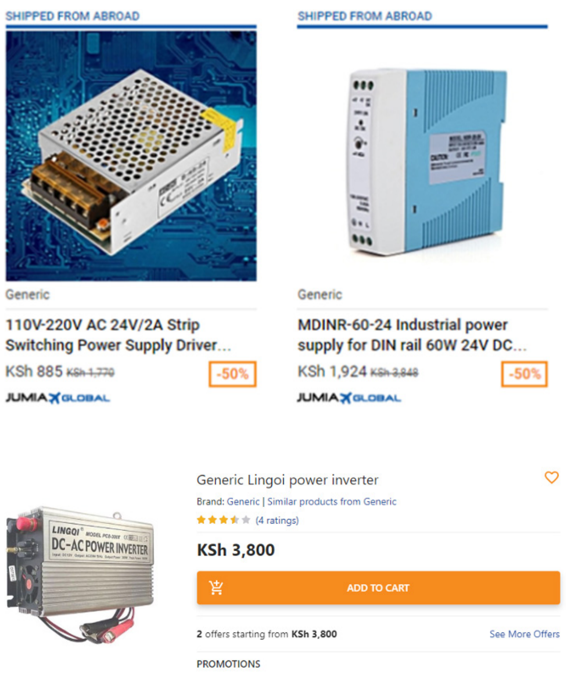


Figure 5 – Rectifiers (above) and Inverters (below) available in online retailers in Kenya



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 (i.e. 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[9] 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 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 rectifier, 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 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 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 as part of this study or the LEIA programme's market surveys and may have been subject to bargaining in some countries.

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

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 take into account pay-as-you-go (PAYGo) models. PAYGo is an increasingly popular distribution model to improve the affordability of SHSs and appliances for rural and lower-income households by allowing consumers to pay for systems and appliances over time, with payment packages typically designed around the incomes of their target users to increase affordability. PAYGo models, however, increase lifecycle costs as they include a financing cost.

E.g. Average rural incomes in Kenya were estimated as ranging between $124/month in the Mount Kenya region and $191/month in the Lake Naivasha region (Anker & Anker, 2017). Monthly payments for pay-as-you-go systems are set to be affordable to off-grid customers, and range from around $15 for a basic system over 14 months (e.g. the M-KOPA 5 system) 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)[10].

9 NL Lam, EW Wallach, Off-Grid Refrigeration System (OGReS) Cost Model (Version 1.0). Schatz Energy Research Center, 2020.
10 Solar home system and appliance packages from M-KOPA, http://www.m-kopa.com/products/

Sample selection and methodology

Six AC and DC refrigerators, typical of sizes and brands found in various off-grid markets, were sampled for testing, as per **Table 3**. The AC refrigerators sampled were generally low-cost, less efficient models, to establish if a low-cost AC model could be a more cost-effective refrigeration option when compared to a high efficiency, but usually more expensive, DC refrigerator. Three AC refrigerators sampled were under $200 and below 100-litre capacity. A fourth AC refrigerator sampled, the Ailipu BD/BC-258A, was a larger 213-litre chest cooler, capable of being run as either a fridge or freezer. This latter type of refrigerator is often used by businesses selling food or drink, and the appliance's manual provides details of the use of an inverter in case of power failure.

The two DC refrigerators sampled were of similar size to the smaller AC refrigerator samples to ensure comparability but were higher cost. The samples included the Hinnova HN67DC, an efficient model that was a finalist in the 2019 Global LEAP Awards, and the Pro Solar PS-SR120, a combination refrigerator-freezer model of more average efficiency from the Tanzanian market, which was previously tested for the Equip Data[11] platform. It was noted that the manual for one of the DC refrigerators specifically outlined operation on an AC supply with a rectifier as one of the viable use cases.

Table 3 - AC and DC refrigerators tested

			CAPACITY (L)	REFRIGERANT	COMPRESSOR	SOURCED FROM	WARRANTY	COST (US $)
	**Haier HR-8K**	AC refrigerator with ice box	73	R134a	LG NS30LAEG, RSIR, 63W cooling capacity, 81W input power	Kenya	1 year	188
	**Midea HS-65L**	AC refrigerator with ice box	73	R600a	GMCC SZ55C1J, RSIR, 85W cooling capacity, 60W input power	Nigeria	1 year	92
	**Von VAR-08DMW**	AC refrigerator with ice box	92	R600a	Huayi L35CL, RSIR compressor, 55W cooling capacity, 60W input power	Kenya	1 year	153
	**Ailipu BD/ BC-258A**	AC chest cooler	213	R134a	Huaguang ASD53K, RSIR, 144W cooling capacity, 120W input power	Uganda	1 year	221
	**Hinnova HN67DC**	DC refrigerator with ice box	80	R134a	HuaJun ZH25G variable speed DC	China	2 years	724
	**Pro Solar PS-SR120**	DC combination 12-24V refrigerator-freezer	110	R134a	No information available	Tanzania	1 year	418

11 VeraSol Off-Grid Product Database (formerly Equip Data), https://verasol.org/

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

The four AC refrigerators were tested in July 2019 at the UK laboratory, RD&T, using the Global LEAP Awards Refrigeration test method[12].

To establish a baseline in native mode, the steady-state energy consumption of the AC refrigerators was measured on a 230V AC supply at an ambient temperature of 32°C. Each refrigerator incorporated a single-speed compressor, which uses significant power for a very short amount of time when the compressor cycles on. This is known as its 'in-rush current' and was also measured. The results are displayed in **Table 4**.

To size an inverter to run a refrigerator, it is necessary to know both the continuous and surge power draw. Surge power was estimated by multiplying the measured in-rush current by the input voltage and applying a correction for power factor (a value of 0.8 is appropriate for an inductive load such a refrigerator). Continuous power was estimated from observing the typical power draw when a compressor is on, after the initial in-rush current.

Figure 6 – Inverter information provided with the Ailipu AC chest cooler

Figure 7 – Information provided with the Pro Solar DC refrigerator on the use of a rectifier for operation on AC

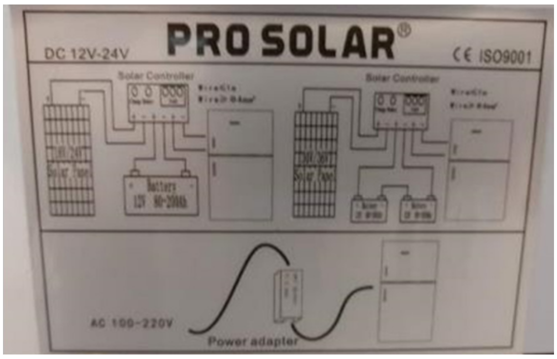
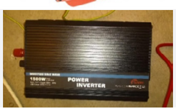
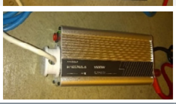


Table 4 – AC refrigerator native mode energy consumption and in-rush current

REFRIGERATOR	DAILY ENERGY CONSUMPTION AT 32°C AMBIENT (KWH/24H)	ESTIMATED CONTINUOUS POWER REQUIREMENT (W)	MAXIMUM MEASURED IN-RUSH CURRENT (A)	ESTIMATED SURGE POWER REQUIRED TO PROVIDE IN-RUSH CURRENT (W)
Haier	1.227	<110	12.3	2362
Ailipu	0.626	<150	15.8	3037
Von	0.562	<75	8.7	1661
Midea	0.597	<90	12.2	2344

Testing of AC refrigerators on a 12V DC power supply with inverters

Table 5 – Details of the inverters used for testing

		TYPE	RATED CONTINUOUS POWER/ SURGE POWER (VA)	MAXIMUM RATED EFFICIENCY (%)	WARRANTY	COST (US $)
	**Victron Phoenix 12/1200**	PSW	1200/2400	92	5 years (standard company warranty)	464
	**Mercury IMS-1500**	MSW	1500/3000	>80	1 year	231
	**Sunshine Solar CAR1.5K**	MSW	1500/3000	>88	No information available	269
	**Ansell H16576S-6 1500W**	MSW	1500/3000	>90	No information available	26

12 Efficiency for Access Coalition, Global LEAP Awards refrigerator test method, 2019, https://storage.googleapis.com/leap-assets/Global-LEAP-Off-Grid-Refrigerator-Test-Method-Version-2.pdf

Test results: sizing power supply and inverters

Tests were conducted to explore the performance of the AC refrigerators running on inverters using a 12V DC supply to simulate an SHS. The following PSW and MSW inverters were selected for testing due to their continuous and surge power ratings being well matched to the refrigerators. Inverters of varying cost and quality were included in the testing.

Each inverter was tested using some initial trial-and-error tests to see how well they could power the refrigerators. The Victron PSW inverter provided very reliable performance throughout and the Mercury MSW inverter operated the best out of the three MSW inverters. The Mercury, Sunshine and the very low-cost Ansell MSW inverters all had the same continuous and surge power ratings but showed very different performance. The Ansell inverter initially was able to power up the compressor of the Von refrigerator, but this then cut out after around 10 seconds. Measurements of the Ansell inverter's Total Harmonic Distortion (THD) could also not be taken for sufficient time or with a high level of reliability, but those made were over 40%, which would categorise this inverter closer to a square wave inverter than an MSW.

Other tests found that the Mercury inverter had a greater power output capacity than the Sunshine inverter, which suggests the Sunshine inverter may have been incorrectly rated. As a result, it was deemed that the Mercury inverter was the most appropriate MSW inverter to run further tests on.

The in-rush current measurements in native mode, as well as the initial trial-and-error tests, were used to establish the power supply requirement for running the refrigerators with inverters. Initially, a 600W 12V DC power supply was trialed to see if it could provide sufficient in-rush current to power the refrigerators through the Victron PSW inverter. The power supply was found to be unable to provide sufficient in-rush current for any of the refrigerators.

Next, a single 1.5kW 12V DC power supply was trialed, but only the Von appliance could operate on this supply through the Victron inverter. None of the other refrigerators were able to operate on this supply due to their high in-rush currents. The inability to start three of the four refrigerators on a 1.5kW supply emphasised just how much surge power an SHS with an inverter would need to supply to run a typical AC refrigerator.

It was determined that a total DC power supply of 3kW was needed to proceed with further testing, which was provided by wiring two 1.5kW DC power supplies together in parallel.

Figure 8 – Set up of two DC power supplies wired in parallel, totalling 3kW, connected to a PSW invertercurrent

Figure 9 – Midea AC refrigerator being tested

Figure 10 – Set up of the Ansell inverter (left) next to the Sunshine Solar inverter (right).

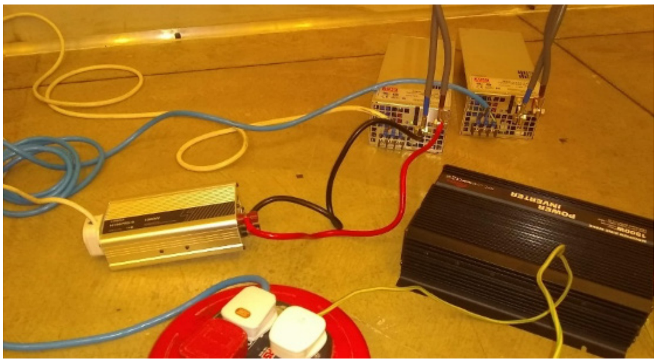


Table 6 – Energy and power consumption of AC refrigerators running on inverters (percentage differences from native mode expressed in brackets)

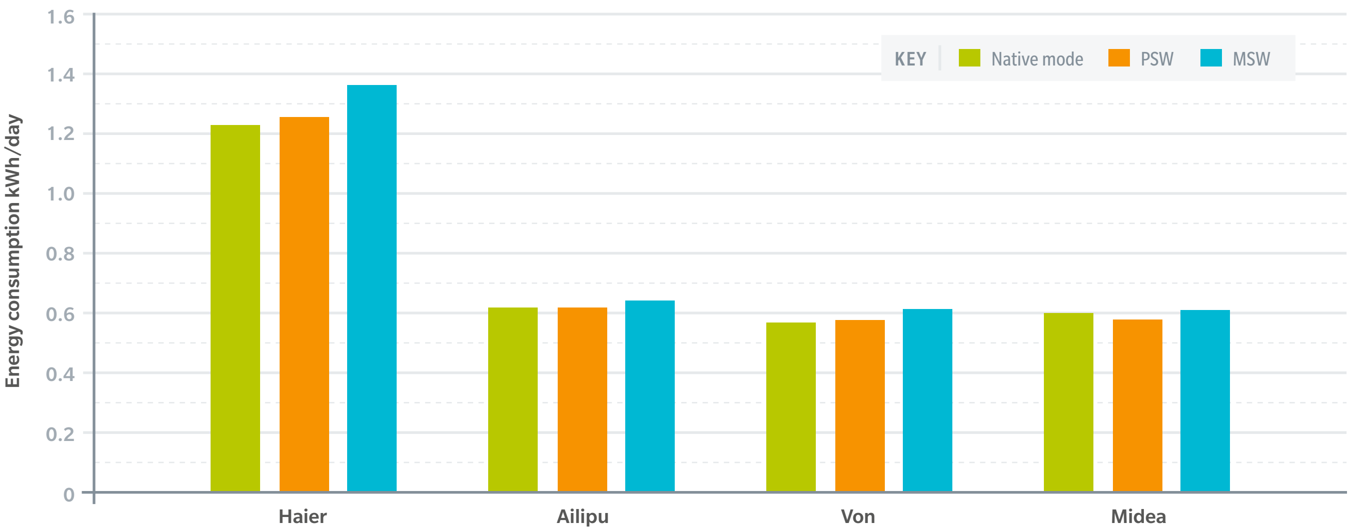
REFRIGERATOR	REFRIGERATOR NATIVE MODE ENERGY CONSUMPTION (kWh/24h)	WITH VICTRON 1200VA PSW INVERTER		WITH MERCURY 1500VA MSW INVERTER	
		Refrigerator energy consumption (kWh/24h)	Estimated refrigerator + inverter energy consumption, (kWh/24h)[13]	Refrigerator energy consumption (kWh/24h)	Estimated refrigerator + inverter energy consumption, (kWh/24h)
Haier	1.227	1.264 (+3.0%)	1.487 (+21%)	1.361 (+10.9%)	1.701 (+39%)
Ailipu	0.626	0.628 (+0.3%)	0.739 (+18%)	0.659 (+8.2%)	0.824 (+32%)
Von	0.562	0.567 (+0.9%)	0.667 (+19%)	0.608 (+5.3%)	0.760 (+35%)
Midea	0.597	0.573 (-4.0%)	0.674 (+13%)	0.611 (+2.3%)	0.764 (+28%)

Test results: steady-state energy and power consumption

The steady-state energy consumption test at 32°C was run on the AC refrigerators using the DC power supply in combination with either the Victron PSW or Mercury MSW inverter. The measurements for this test were taken at the AC power output from the inverter and are provided in **Table 6**. Measurement equipment for DC power was not available for this test to measure the DC input to the inverter, and thus the power consumption of the inverter itself.

Estimates for conversion efficiency from refrigerator tests conducted in the Phase 2 tests (85% for the PSW inverter and 80% for the MSW inverter) were applied in **Table 6** to provide an estimate of the full daily energy consumption from the combined refrigerator and inverter system. A higher figure for energy consumption was measured for the refrigerator operating on the MSW inverter, compared to the native mode results; this was over 5% for three of the four refrigerators, and as much as 10.9% for the Haier model. Energy consumption measurements on the PSW inverter were more consistent compared to the native mode results.

Figure 11 – Energy consumption per day for the four AC refrigerators measured in native mode compared to operation on PSW and MSW inverters



13 Using the PSW conversion efficiency estimate of 85% and the MSW conversion efficiency estimate of 80%.

For the Ailipu refrigerator, little difference was seen in the compressor cycle rate and duration between its native mode and when it was operated on the inverters. However, for the other refrigerators, each cycle appeared to require more power when operated on the inverters and reached a higher peak. The plots of power consumption over time for each refrigerator tested are provided as follows.

Figure 12a - Steady-state power consumption in native mode and with inverters (Haier)

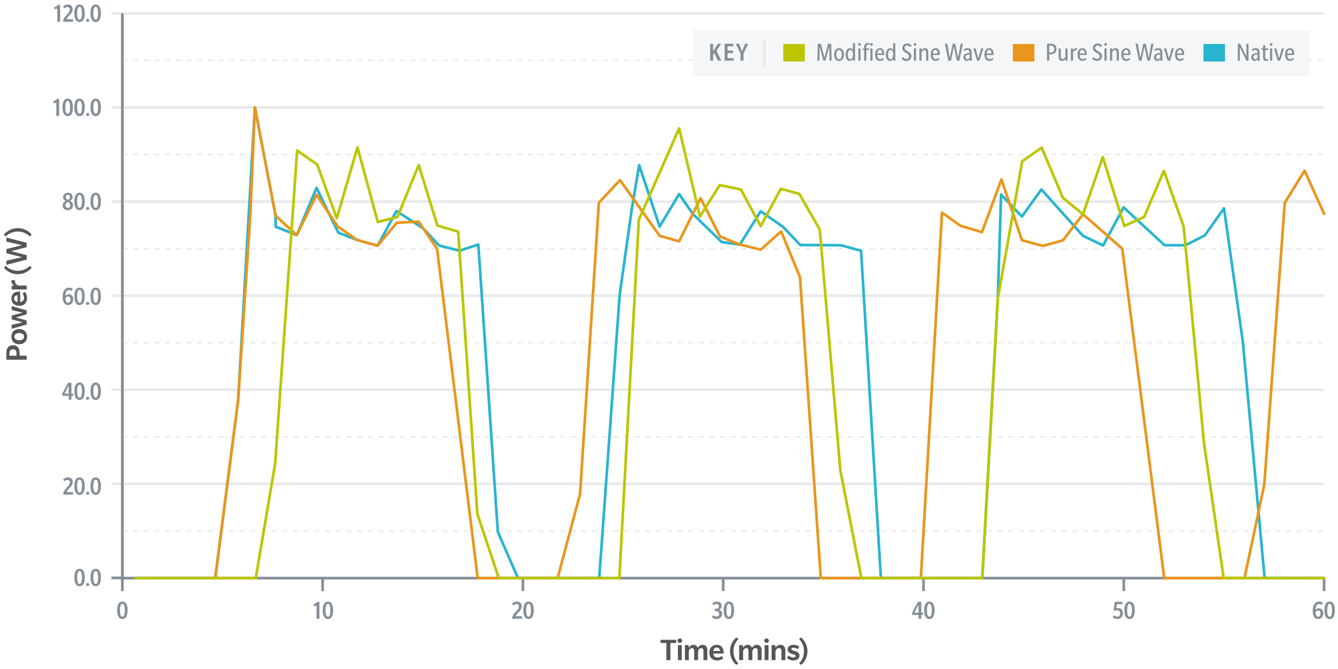


Figure 12b - Steady-state power consumption in native mode and with inverters (Ailipu)

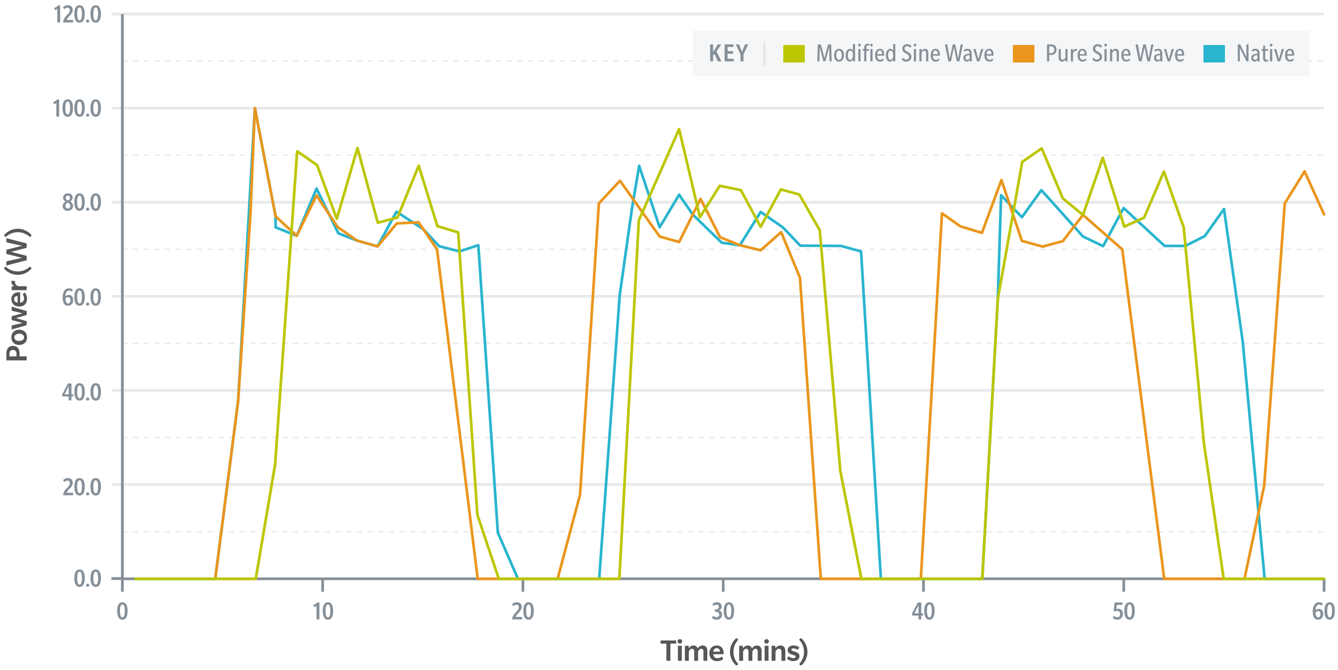


Figure 12c – Steady-state power consumption in native mode and with inverters (Midea)

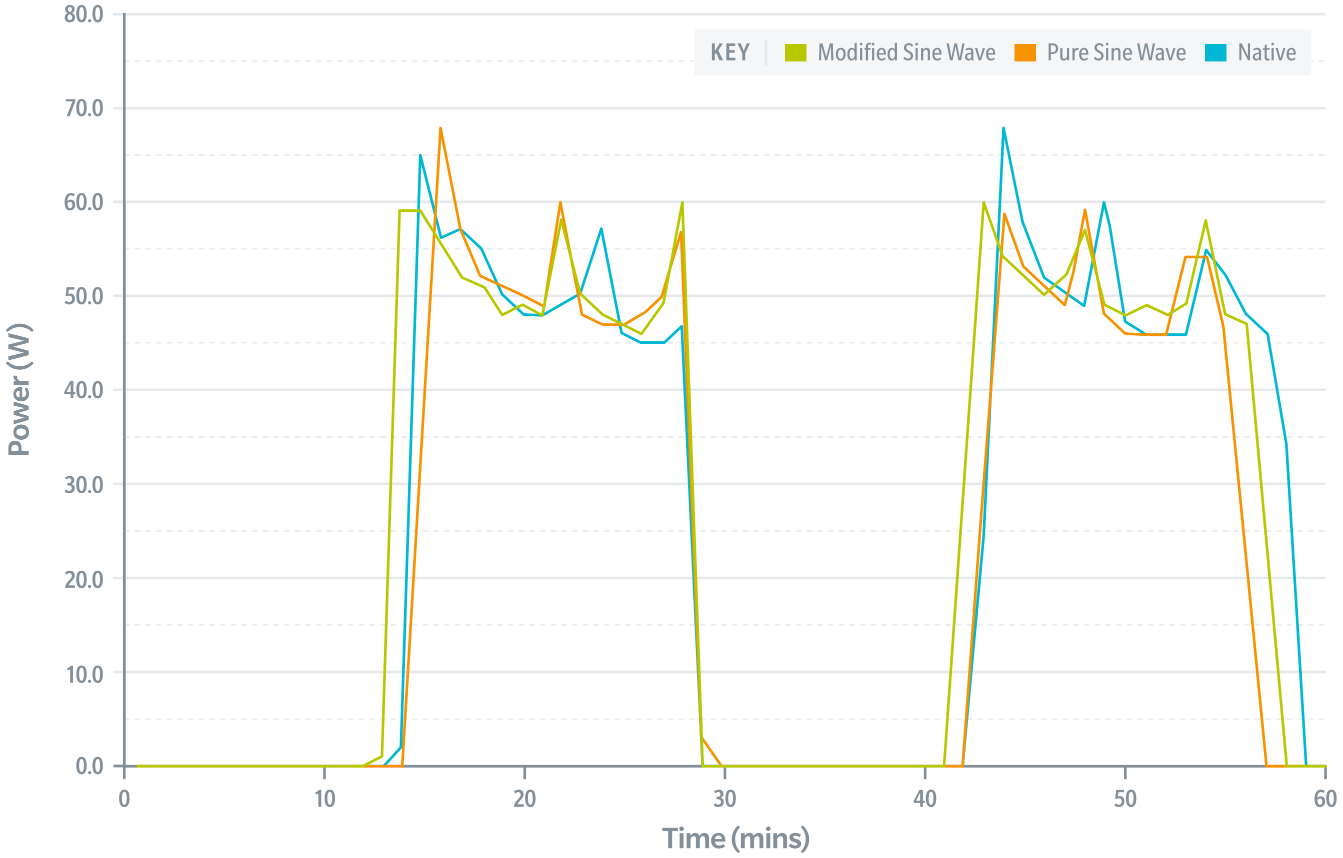


Figure 12d – Steady-state power consumption in native mode and with inverters (Von)

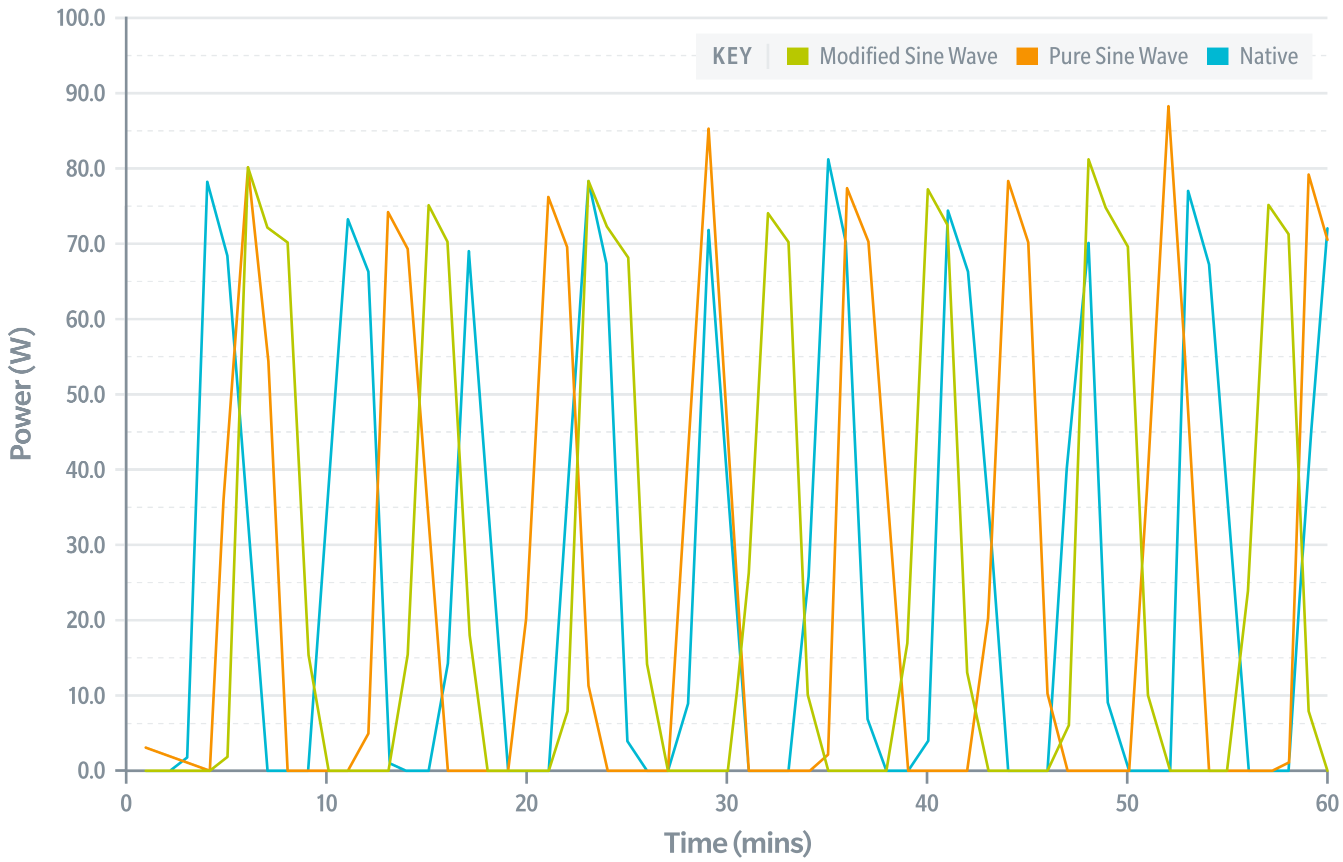


Table 7 – Over- and under-voltage energy consumption at 20°C ambient temperature

VOLTAGE CONDITION	ENERGY CONSUMPTION OF HAIER REFRIGERATOR (KWH/DAY)	
	With Victron 1200VA PSW inverter	With Mercury 1500VA MSW inverter
Under-voltage *	0.472	0.458
Over-voltage (13.8V)	0.470	0.583

**Under voltage condition was 10.8V for the PSW inverter and 11.2V for the MSW inverter*

Test results: over-voltage and under-voltage conditions

Voltage fluctuations and surges may be encountered on an SHS or DC mini-grid, potentially affecting appliance performance. Tests were run to see how over-voltage and under-voltage variations in the source DC power supply affected the refrigerators operating on inverters. A steady state power consumption test of the Haier refrigerator was run on both the Victron PSW and Mercury MSW inverters at 20°C ambient temperature. The DC voltages tested were 13.8V (115% of 12V) and 10.8V (90% of 12V), which were achieved on the Victron inverter but the minimum voltage that the Mercury inverter could operate on was 11.2V.

In the over-voltage condition, the refrigerator used 24% more energy when operated on the MSW inverter than on the PSW inverter. Much higher peaks of power consumption were also seen on the MSW inverter, in some cases reaching over 200W. Power consumption on the PSW inverter did not exceed 120W at any point during the tests.

Figure 13 – Comparison of energy consumption of the Haier appliance operated on the PSW and MSW inverters in over- and under-voltage conditions

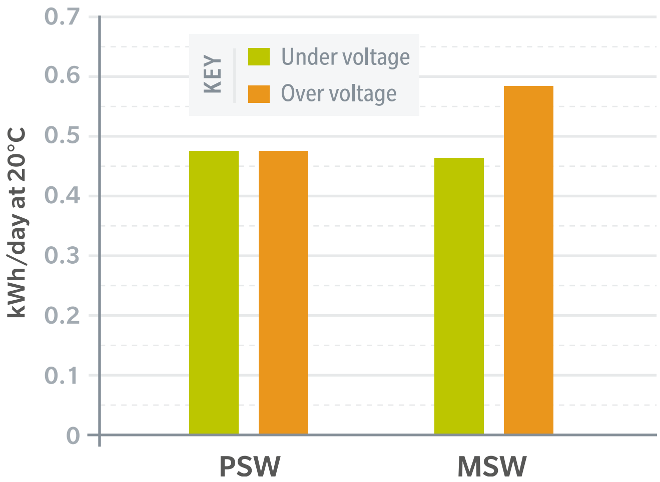
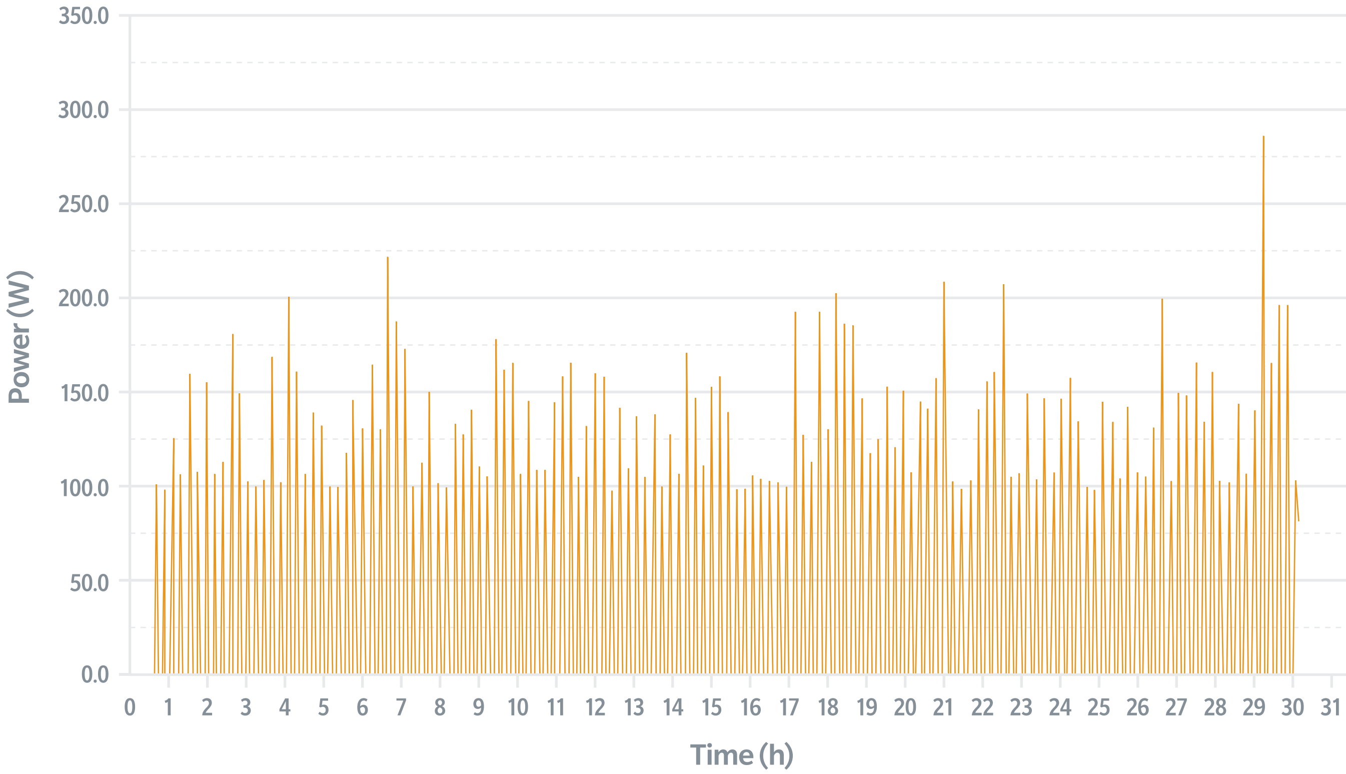


Figure 14 – Power measurements in over-voltage condition on the Haier appliance reached higher and more variable power levels running on the MSW inverter (top) compared to the PSW inverter (bottom) (note the different axis scales for power)



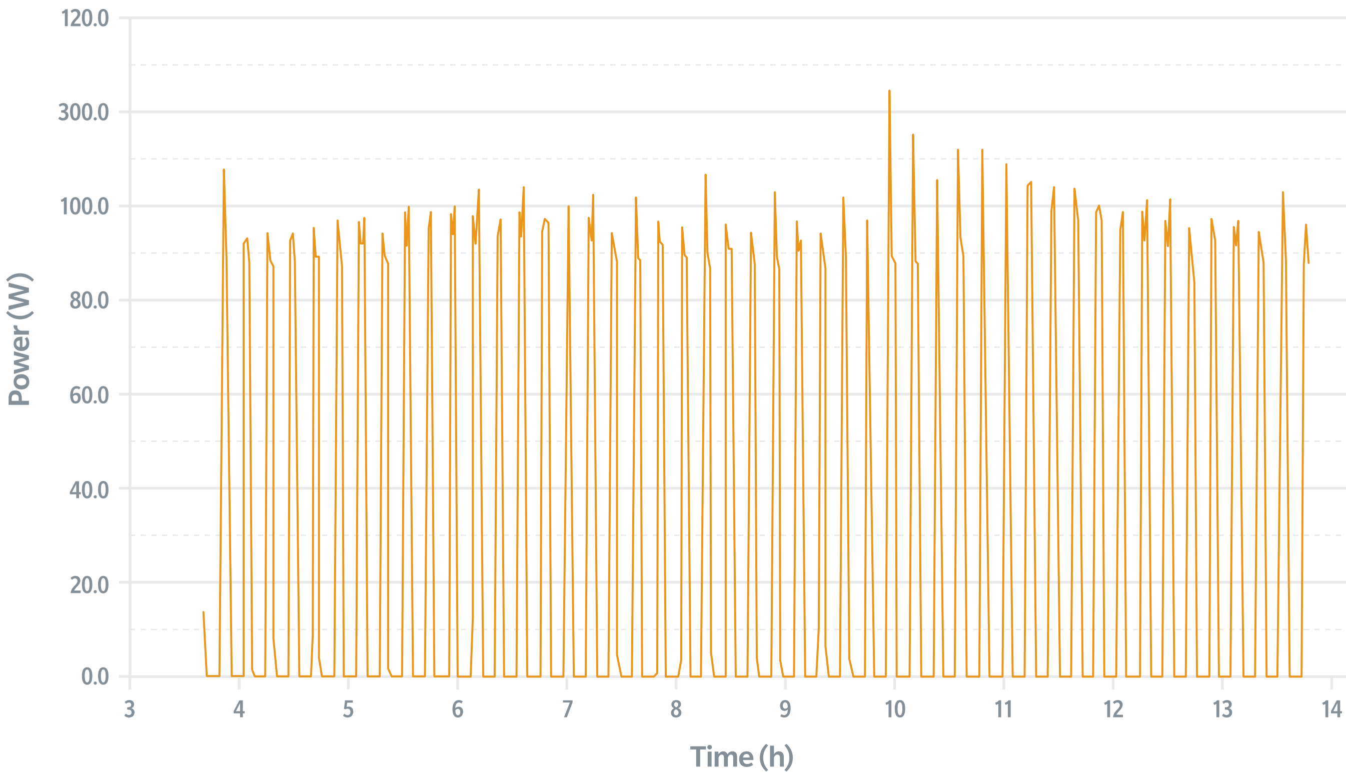


Table 8 – Inverter performance in steady-state energy consumption tests

REFRIGERATOR	OUTPUT VOLTAGE (VAC)		THD (%)		FREQUENCY (HZ)	
	Victron 1200VA PSW inverter	Mercury 1500VA MSW inverter	Victron 1200VA PSW inverter	Mercury 1500VA MSW inverter	Victron 1200VA PSW inverter	Mercury 1500VA MSW inverter
Haier	229.0	225.8	1.1	25.9	50.0	50.0
Von	229.1	224.5	1.1	24.6	50.0	49.8
Ailipu	229.0	224.5	1.0	25.6	50.0	49.8
Midea	229.0	225.8	1.4	25.1	50.0	50.0

Test results: inverter performance

The Victron PSW inverter provided AC power with very low THD, as well as a power factor (PF) and frequency similar to that of a good quality main grid supply. The AC produced by the Mercury MSW inverter had high THD, although typical of what would be expected for this technology. Its THD averaged over 25% for each test, and its output voltage was also measured to be lower than that of the Victron, although there were issues seen with accuracy of voltage measurements of the modified sinewave. Despite this, there were no issues seen with the performance of any of the refrigerators on the Mercury inverter, with temperature stabilisation able to be achieved.

Some performance issues were seen with the Mercury inverter in the over and under voltage tests. As mentioned above, it was unable to function at the under-voltage level of 10.8V. Power could be initially provided to the refrigerator at this under-voltage level when the compressor was off, but the inverter shut down when the compressor activated, and the minimum voltage it could operate at was 11.2V.

Additionally, the energy consumption was significantly higher in the over-voltage condition, consuming 21% more energy than at the under-voltage level of 11.2V, with much higher THD, measured at 42.7% - around the level that might be observed with a square wave inverter. The refrigerator appeared to operate without issue, but with a much more varied pattern of power consumption compared to operation on the PSW inverter.

No issues were seen with the Victron PSW inverter in over- and under-voltage conditions. It was able to operate at the under-voltage level of 10.8V. THD was measured at just over 1% for each test and energy consumption measurements between the over- and under-voltage condition differed by only 0.4%.

Table 9 – Inverter performance in under and over-voltage tests of the Haier refrigerator

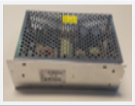
VOLTAGE CONDITION	OUTPUT VOLTAGE (VAC)		THD (%)		FREQUENCY (HZ)	
	Victron 1200VA PSW inverter	Mercury 1500VA MSW inverter	Victron 1200VA PSW inverter	Mercury 1500VA MSW inverter	Victron 1200VA PSW inverter	Mercury 1500VA MSW inverter
Under voltage[14]	228.6	221.8	1.2	21.9	50.0	50.0
Over voltage (13.8V)	228.7	223.3	1.1	42.7	50.0	50.0

14 Under voltage condition was 10.8V for the PSW inverter and 11.2V for the MSW inverter.

Testing of DC refrigerators on a 230V AC power supply with rectifiers

DC refrigerators often use a variable speed compressor which can typically maintain a cooling cycle at lower power than for an AC model. Native mode data was already held for the two sample DC refrigerators, the Pro Solar and Hinnova refrigerators, as they had previously been tested by the Netherlands-based laboratory, Re/genT, for the 2019 Global LEAP Awards[15] and the Equip Data platform. Further tests were conducted on the DC refrigerators using rectifiers at Re/genT during the second half of 2019 to simulate their operation on an AC grid or AC mini-grid. Three rectifier samples of a range of cost and efficiency were obtained online from trade suppliers. The specifications of the rectifiers were as follows.

Table 10 – Rectifiers used in testing of DC refrigerators

		TYPE	RATED POWER (W)	MAXIMUM RATED IN-RUSH CURRENT AT 230V (A)	RATED EFFICIENCY (%)	WARRANTY	COST (US $)
	Mean Well WDR-120-12	DIN rail power supply	120	50	89.5	3 years	66
	Hengfu HF120W	DIN rail power supply	120	40	83	5 years (limited)	25
	Hengfu HF150W-S-12	Switching mode power supply (SMPS)	150	40	79	5 years (limited)	18

Test results: steady-state energy consumption

Steady-state energy consumption tests at 32˚C were run on the DC refrigerators using the rectifiers on a 230V AC supply. Energy consumption from the previous native mode tests are detailed in **Table 11**. The measured energy consumption using the rectifiers was seen to be higher, in some cases significantly so, ranging between 7% and 56% higher. It was observed that the Pro Solar model used more energy than the Hinnova in its native mode, but its energy consumption did not increase as significantly when run on either rectifier. This was likely due to the rectifiers being better sized for the higher-power consuming Pro Solar refrigerator.

It was observed that the Hengfu rectifiers drew significant power when the refrigerator compressor was not running, whereas native mode tests showed the input power returning to near zero when the compressor cycled off. This no-load power draw of the rectifiers was significant, with an average of 5.5W and 4.6W measured from the two Hengfu rectifiers when no function was being performed by the refrigerator. A lower average power draw of 1.0W was seen on the more expensive MeanWell rectifier when the compressor was not running.

Table 11 – DC refrigerator energy consumption in native mode and with rectifiers

SAMPLE	REFRIGERATOR NATIVE MODE ENERGY CONSUMPTION (KWH/DAY)	REFRIGERATOR + RECTIFIER ENERGY CONSUMPTION MEASURED (KWH/DAY) (INCREASED ENERGY CONSUMPTION VS NATIVE MODE)		
		Refrigerator + Meanwell 120W rectifier	Refrigerator + Hengfu 120W rectifier	Refrigerator + Hengfu 150W rectifier
Pro Solar DC refrigerator	1.413	1.510 (+7%)	1.642 (+16%)	1.653 (+17%)
Hinnova DC refrigerator	0.526	0.724 (+38%)	Test not run	0.821 (+56%)

Table 12 – No-load power measurements

DC REFRIGERATOR	REFRIGERATOR NO-LOAD POWER MEASURED FROM APPLIANCE (W)	REFRIGERATOR + RECTIFIER NO-LOAD POWER (W)		
		Refrigerator + Meanwell 120W rectifier	Refrigerator + Hengfu 120W rectifier	Refrigerator + Hengfu 150W rectifier
Pro Solar	0.2	1.0	5.5	4.6
Hinnova	0.2	1.0	Test not run	4.6

15 Efficiency for Access Coalition, Global LEAP Awards – refrigerator competition, 2019, https://globalleapawards.org/refrigerators

Test results: over-voltage and under-voltage conditions

To simulate AC grid or AC mini-grid voltage fluctuations, steady-state power consumption tests at 207V (90% of the rectifiers' rating plate voltage) and 275V (120% of rating plate voltage), as well as reference measurements at 230V, were conducted on the Pro Solar refrigerator, using the Hengfu 120W and 150W rectifiers at 32˚C ambient. The results, in **Table 13**, suggest that the AC to DC power conversion is not significantly affected by voltage fluctuation. Only a slight increase in energy consumption was seen in the over-voltage condition, and a slight decrease in the under-voltage condition. Compared to some of the variation observed in the output voltage and energy consumption from the similar tests on inverters, the rectifiers' AC to DC conversion appears to be a more straightforward operation.

Table 13 – Over- and under-voltage energy consumption for the Pro Solar DC refrigerator with rectifiers

RECTIFIER	INPUT VOLTAGE (VAC)	AVERAGE DC OUTPUT VOLTAGE (VDC)	AC ENERGY CONSUMPTION BY CONVERTER AND APPLIANCE (KWH/DAY)	DC ENERGY CONSUMPTION BY APPLIANCE (KWH/DAY)	INCREASE IN ENERGY VS REFERENCE (%)
Hengfu 120W	229.8 (reference)	12.0	1.352	1.101	n/a
	206.7	12.0	1.306	1.081	-3.4
	275.0	12.0	1.352	1.083	0.0
Hengfu 150W	229.8 (reference)	12.0	1.246	1.043	n/a
	207.8	12.0	1.285	1.023	-3.0
	275.0	12.0	1.294	1.032	0.7

Test results: temperature pull-down

The pull-down test measures the energy consumption of the refrigerator in order for it to bring its internal temperature down from 32°C to 10°C. This simulates a typical use case where the refrigerator is switched on for the first time and has to initially achieve a low temperature setting in high ambient temperature conditions. This test was run on the Pro Solar refrigerator and was initially attempted using the Hengfu 120W rectifier. Steady-state power consumption tests had previously been run using this refrigerator and rectifier without issue, however, the pull-down test required more power and the refrigerator would not start with the Hengfu 120W rectifier. The Hengfu 150W rectifier was used in its place in order to run the test. The results are provided as follows.

Table 14 – Pull-down test times for the Pro Solar DC refrigerator

TEST	PULL-DOWN TIME TO 10°C (HOURS)
Native mode on 12V supply	8.6
On 230V AC supply with Hengfu 150W rectifier	8.6

The pull-down test was completed in a similar time to the one run in native mode, suggesting no effect from the power conversion in running this test, apart from an increase in energy consumption from the power conversion. The conversion efficiency of the rectifier was measured at an average of 85% during this test.

Figure 15 – Comparison of the Pro Solar DC refrigerator's ability to pull temperature down from 32°C to 10°C, in native mode (left) compared to when run on a rectifier (right).

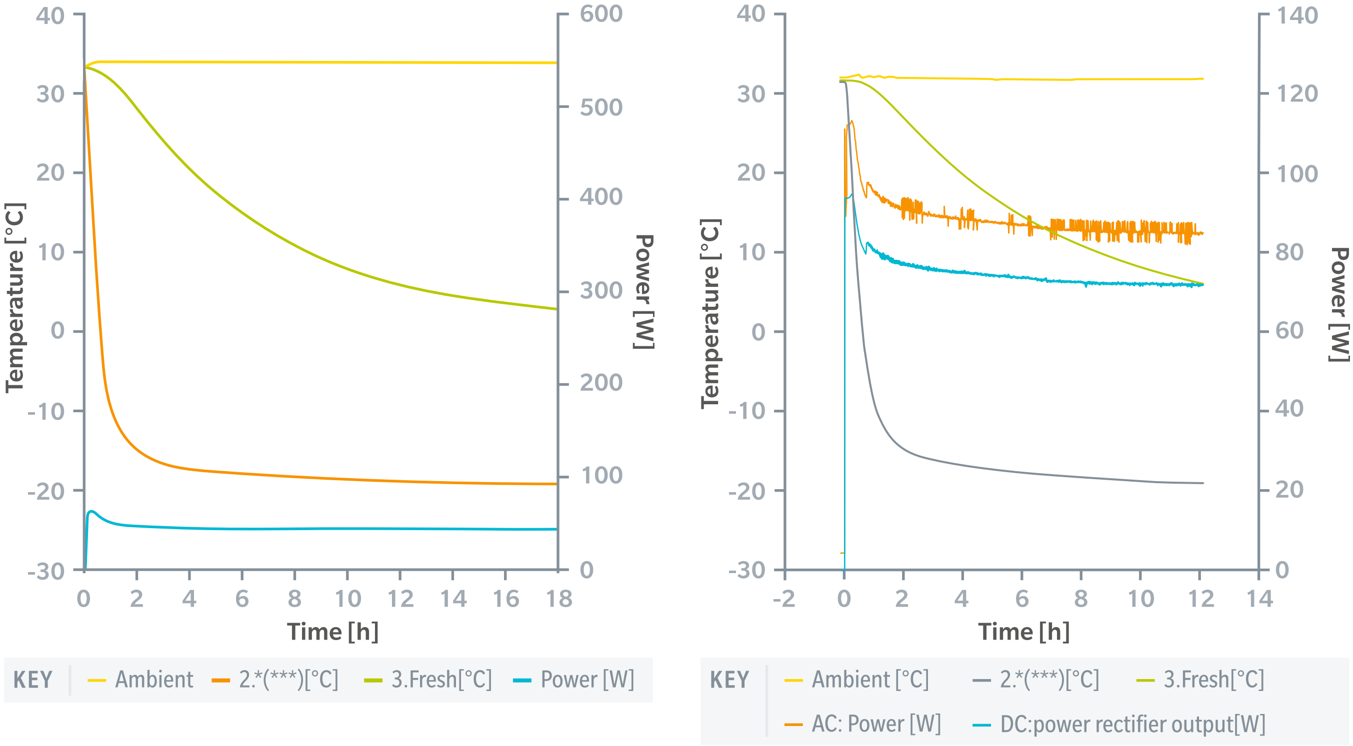


Table 15 – Rectifier conversion efficiency with the Pro Solar DC refrigerator

RECTIFIER	TEST VOLTAGE (INPUT TO RECTIFIER – VAC)	CONVERSION EFFICIENCY (%)	
		Measured	Rated
Meanwell 120W	230 – average during steady-state test	89.9	89.5
	230 – compressor off phase	20.0	N/A
Hengfu 120W	207	82.8	83.0
	275	80.1	
	230 – average during steady-state test	83.0	
	230 – compressor off phase	3.6	N/A
Hengfu 150W	207	82.1	79.0
	275	79.8	
	230 – average during steady-state test	83.2	
	230 – compressor off phase	4.3	N/A

Table 16 – Rectifier conversion efficiency with the Hinnova DC refrigerator

RECTIFIER	TEST VOLTAGE (INPUT TO RECTIFIER – VAC)	CONVERSION EFFICIENCY (%)	
		Measured	Rated
Meanwell 120W	230 – average during steady-state test	88.0	89.5
	230 – compressor off phase	20.0	N/A
Hengfu 150W	230 – average during steady-state test	76.7	79.0
	230 – compressor off phase	4.3	N/A

Test results: rectifier performance

The conversion efficiency of the rectifiers was determined from the DC power out of the rectifier divided by the AC power in. Measured efficiency during the steady-state energy consumption tests was relatively consistent across all tests run and approximately in line with the rated values of the rectifiers. The more expensive MeanWell was observed to have the highest efficiency.

The DC refrigerators appeared to operate without issue using rectifiers, achieving temperature stabilisation, which suggests that this use case on an AC grid or mini-grid supply is viable. However, the extra power consumption from using a rectifier was in some cases significant. This could be reduced by using a better-quality rectifier, such as the MeanWell rectifier. Conversion efficiencies during periods where the compressor was not running were much lower than for normal operation, as would be expected at low load. However, at low load, the MeanWell rectifier was over four times more efficient than the Hengfu rectifiers. Many similar generic rectifiers to the Hengfu rectifiers were observed to be available in online retailers, although these are not typically marketed towards the off-grid market.

Analysis: refrigerator results

Cost-comparison: AC refrigerators with inverter versus DC refrigerators in native mode

Using the system sizing and cost model calculator developed by SERC, the upfront total system cost (TSC) for the four AC refrigerators was estimated. The size of inverters needed for the systems was estimated from test data, with cost estimates taken from available source data.

Table 17 – Inverter sizing estimates for AC refrigerators

AC REFRIGERATOR	IN-RUSH CURRENT (A)	SURGE POWER REQUIREMENT (W)	ESTIMATED INVERTER SIZE REQUIRED (CONTINUOUS/SURGE POWER, W)	ESTIMATED INVERTER COST (US $)	
				PSW	MSW
Haier	12.3	2362	1200/2400	500	200
Ailipu	15.8	3037	1500/3000	750	300
Von	8.7	1661	1000/2000	300	100
Midea	12.2	2344	1200/2400	500	200

AC refrigerator TSC estimates were compared with TSC estimates for similarly sized DC refrigerators using test and cost data for 32 DC refrigerators from Equip Data. These DC refrigerators included both typical refrigerators available on the market and high-performing models previously submitted to the Global LEAP Awards. The breakdown of the cost of system components is presented in the figures below for four size categories. Each figure contains estimates for the TSC of one AC refrigerator using both the PSW and MSW inverters. These estimates were calculated using the energy consumption measurements from the tests above combined with the estimated conversion efficiency for the inverters. This is compared with the average TSC for DC refrigerators in the same size category running in native mode. Refrigerators used in comparisons include models that had capacity to provide a freezing function (such as an ice box or separate compartment) as well as those that only incorporated a fresh food compartment. The range in TSC for the DC refrigerators is also shown.

Figure 16 – Total system cost of Midea AC refrigerator with MSW and PSW inverters compared to the average of similarly sized DC refrigerators in native mode (capacity 30-50 litres) inverters compared to the average of similarly sized DC refrigerators in native mode (capacity 30-50 litres)

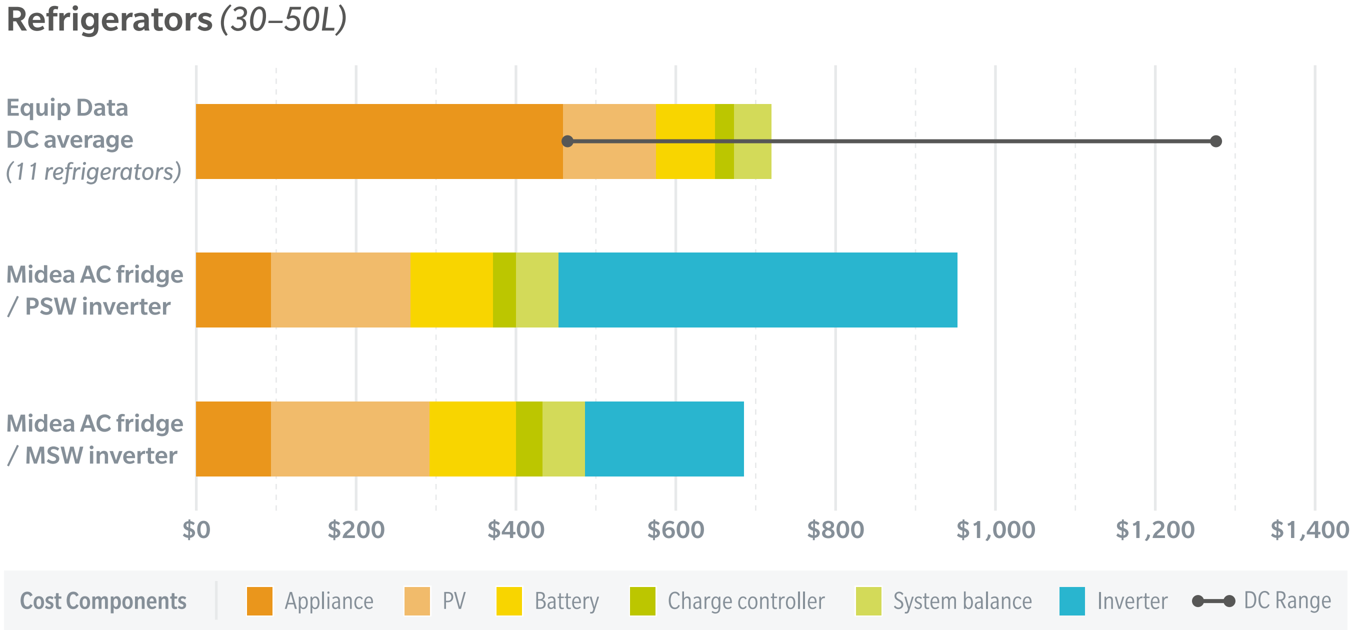


Figure 17 – Total system cost of Haier AC refrigerator with MSW and PSW inverters compared to the average of similarly sized DC refrigerators in native mode (capacity 70-90 litres)

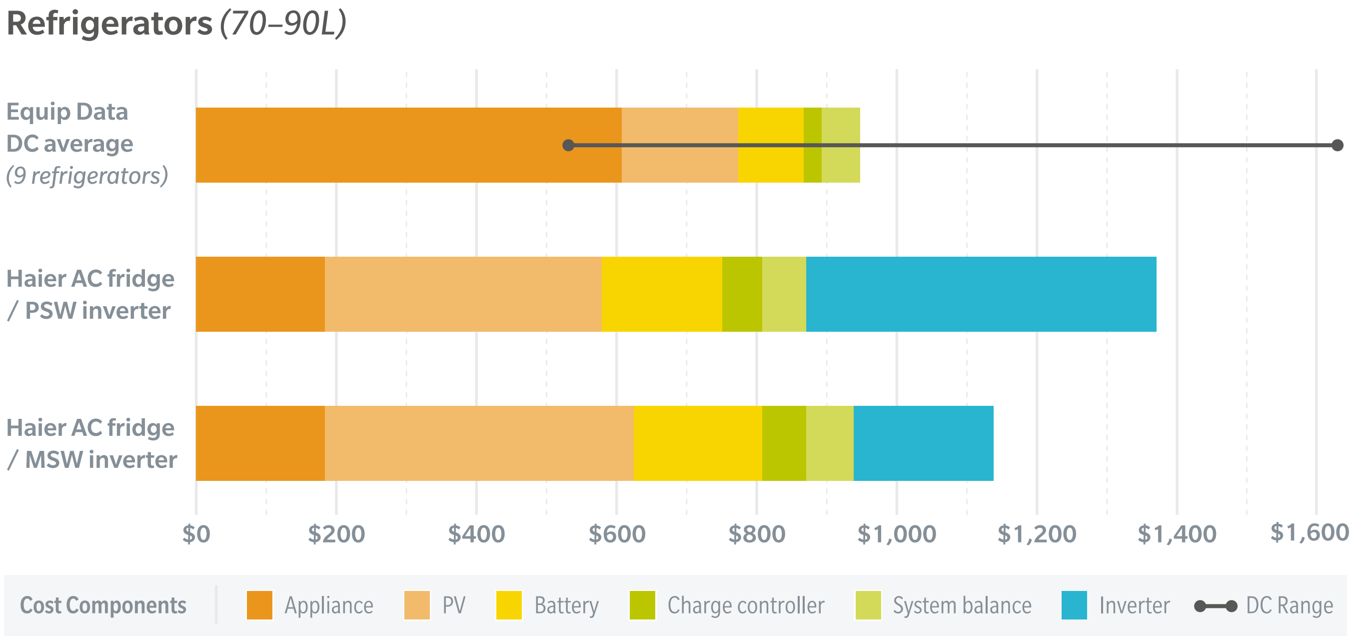


Figure 18 – Total system cost of Von AC refrigerator with MSW and PSW inverters compared to the average of similarly sized DC refrigerators in native mode (capacity 90-120 litres)

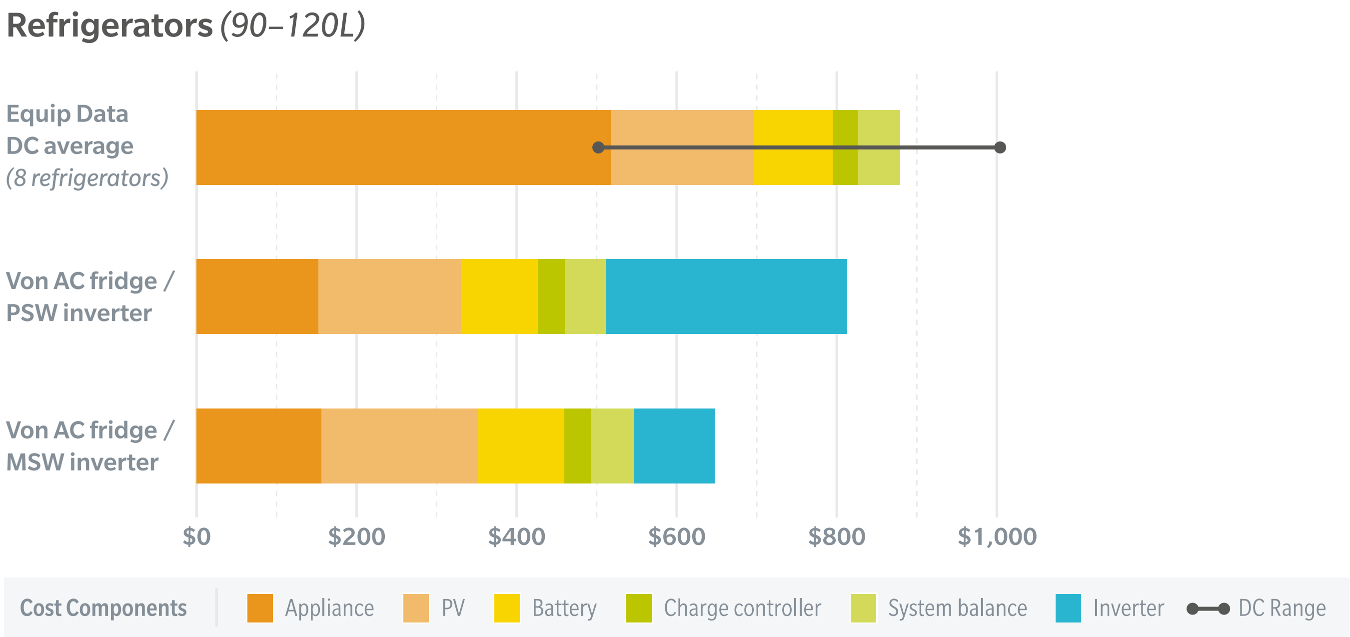
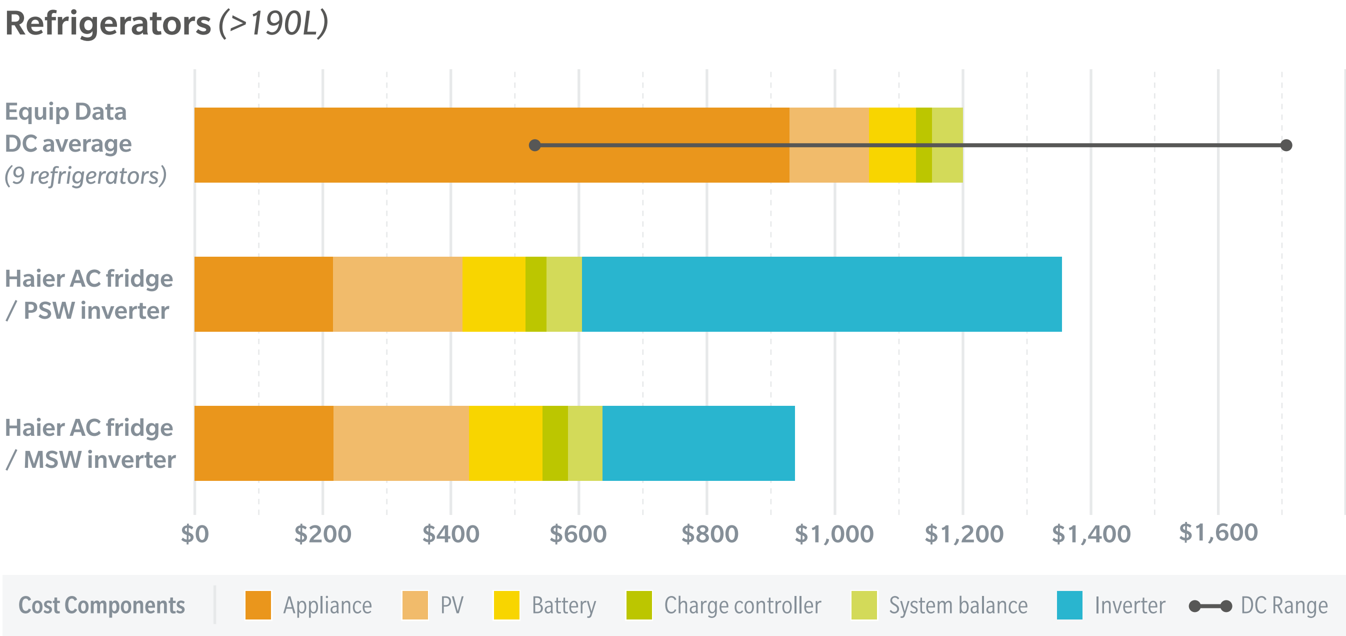


Figure 19 – Total system cost of Ailipu AC refrigerator with MSW and PSW inverters compared to similarly sized DC refrigerators in native mode (capacity >190 litres)



The AC refrigerator systems with inverters were generally seen to have a greater TSC than the DC refrigerators in native mode, with some exceptions. The Von AC refrigerator had the lowest energy consumption of the AC refrigerators tested and had a relatively low cost, resulting in an estimated TSC that was lower than six of the eight DC refrigerators in native mode compared. The purchase cost for each of these six DC refrigerators was over four times that of the Von AC refrigerator.

As mentioned earlier, PAYGo is becoming an increasingly popular option for consumers to purchase SHSs with appliances, as it allows consumers to pay for systems and appliances over time. For comparison of the total system cost of purchasing an SHS with a refrigerator in this way, the M-KOPA Solar Powered 100L Fridge package[16] is available in Kenya for a deposit of approximately $103, and payments at a daily rate of around $1.55 for 700 days, amounting to a total system cost of approximately $1,187. This is notably higher than the costs seen in **Figure 19** above, however, the package also includes a strip light, good after sales support, and a 2-year warranty. Warranties of less than 1 year (or none at all) were commonly observed in the LEIA programme's market surveys of refrigerators.

Findings from the data available in this study suggest that the price of DC refrigerators needs to reduce further to be truly cost-viable. DC refrigeration is an appropriate technology for off-grid applications, but more scale and market support to reduce purchase cost appears to be necessary to truly be competitive against inexpensive AC refrigerators as a viable option for cooling. It should be noted that full life cycle costs were not modelled and DC refrigerator systems running in native mode may potentially have better life cycle costs than AC refrigerator systems with inverters due to the following factors –

- AC systems have the additional component of an inverter, increasing the number of components with the potential to fail and have to be replaced.
- As stated previously, MSW inverters produce a lower quality AC waveform with high harmonic distortion that may lead to a build-up of excess waste heat in motors/compressors or affect the ability of the motor/compressor to magnetise rotor and stator components. This leads to earlier malfunctions and lower lifespans. As such, if AC systems are used with MSW inverters this could lead to higher life cycle costs.
- Brushless DC motors may have a longer lifespan than AC induction motors in some cases.

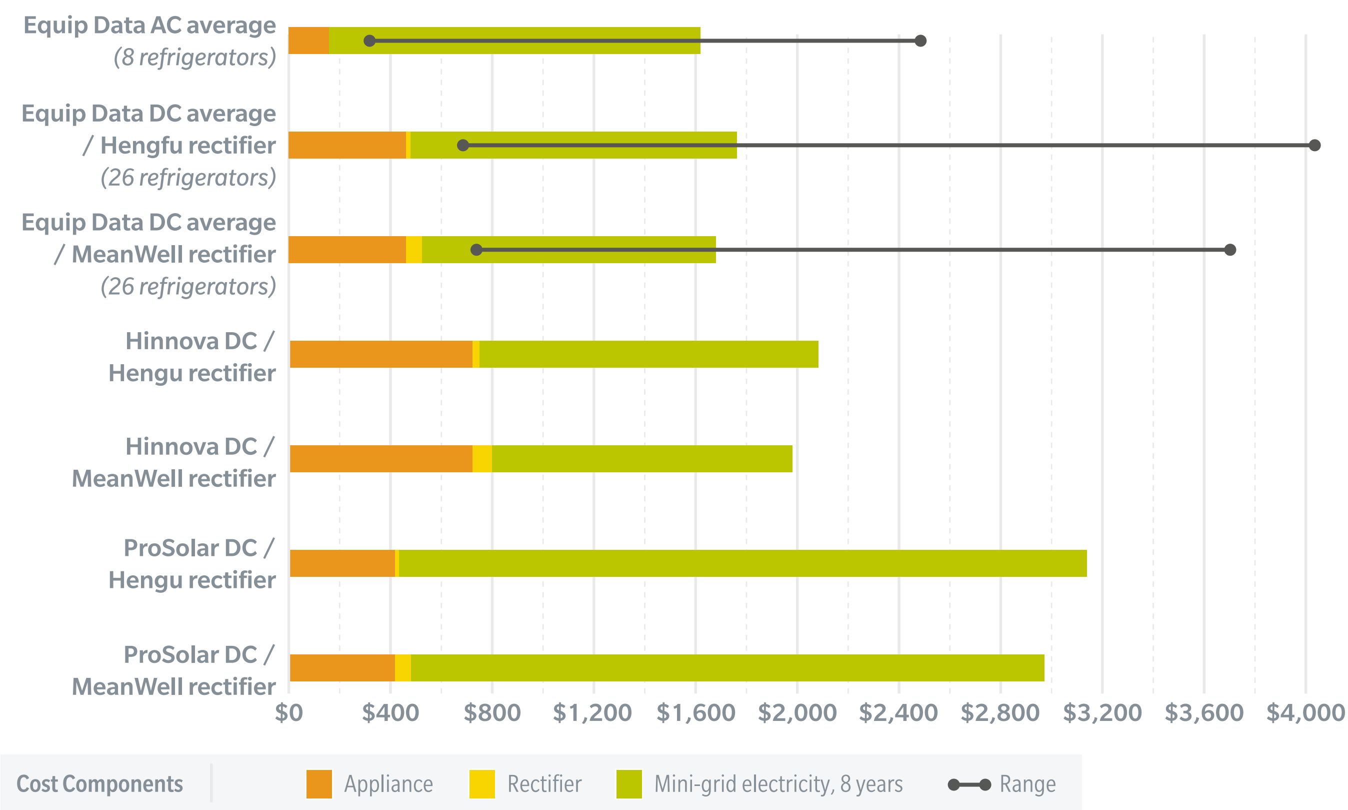
16 Solar home system and appliance packages from M-KOPA, http://www.m-kopa.com/products/

Cost-comparison: DC refrigerators with rectifier versus AC refrigerators in native mode

Simple lifecycle costs were estimated for running the two DC refrigerators on an AC grid or mini-grid using either the MeanWell 120W or Hengfu 150W rectifier. For comparison, simple lifecycle costs were also estimated for the 'average' DC refrigerator of similar size from Equip Data run on the MeanWell and Hengfu rectifiers, and the 'average' AC refrigerator of similar size from Equip Data operated in native mode. Models compared from Equip Data were all under 120 litres, and included appliances that were refrigerators only, and those that included a compartment providing freezing. The following assumptions were made in estimation of simple lifecycle costs –

- Electricity costs were modelled for Kenya, using $0.20/kWh for grid electricity and $0.56/kWh for mini-grid electricity.[17] Kenya was selected for this comparison due to its current mix of supply options, including AC and DC mini-grids and a large SHS sector.
- Costs are calculated over eight years, the expected lifetime of refrigerators.[18]

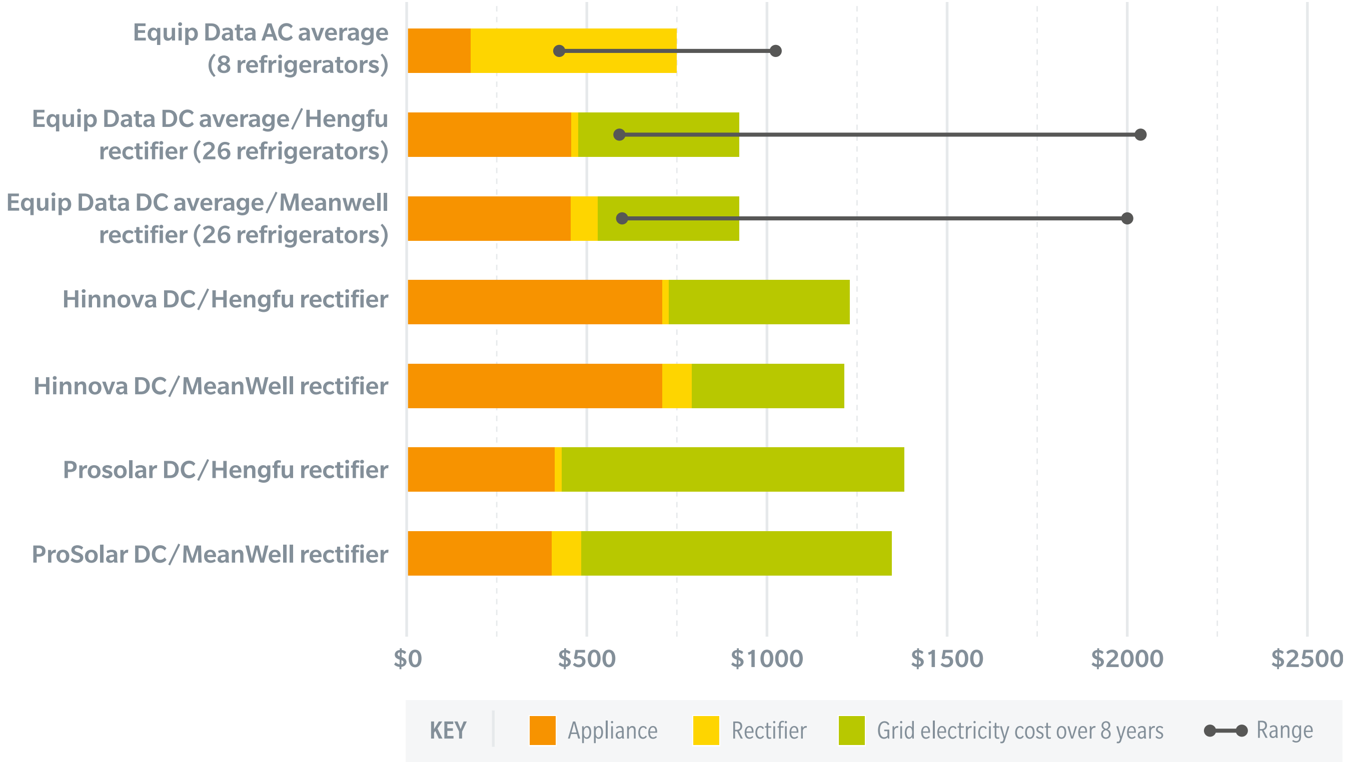
Figure 20 – Simple lifecycle cost of the tested DC refrigerators with rectifiers running on an AC grid, and comparison with average AC and DC models from Equip Data



17 The World Bank, Mini Grids in Kenya: A Case Study of a Market at a Turning Point, World Bank, 2017, https://openknowledge.worldbank.org/bitstream/handle/10986/29022/ESM-cKenyaMiniGridsCaseStudyConfEd-PUBLIC.pdf?sequence=1&isAllowed=y

18 Mr. Appliance Blog, "What is the Lifespan of your Refrigerator?", 2016, https://www.mrappliance.com/blog/2016/july/what-is-the-lifespan-of-your-refrigerator-/

Figure 21 – Simple lifecycle cost of the tested DC refrigerators with rectifiers running on an AC mini-grid, and comparison with average AC and DC models from Equip Data



For use on an AC grid supply, the comparison between the average models from Equip Data suggests that AC refrigeration is overall more cost-effective than DC equivalents with rectifiers, but not by a large margin. The 'average' AC refrigerator from Equip Data had a purchase cost of $163, over half that of the average DC model, which offset its higher running cost in the comparison with DC refrigerators. The cost of the rectifier did not make up a significant proportion of the running cost and use of a better-quality model would be expected to reduce electricity costs over time.

The Hinnova DC refrigerator had low energy consumption in tests, but this was seen to increase when run on a rectifier, and coupled with its relatively high purchase cost, was more expensive overall than the average AC model on a simple lifecycle cost basis. As a combination refrigerator-freezer, the Pro Solar DC model was observed to have higher energy consumption than some of the AC refrigerators tested, contributing to its higher simple lifecycle cost.

An AC mini-grid supply generally has a higher cost per kWh than an AC grid supply. As a result, the electricity costs account for a higher share of the total lifecycle cost than in the comparison on an AC grid, which makes the case for use of efficient DC appliances in non-native mode slightly better. Simple lifecycle cost for the average DC refrigerator was estimated closer to the average AC refrigerator than for the grid comparison. Whilst DC refrigeration does not demonstrate an advantage overall against AC refrigeration in this context at the current price levels, this comparison does suggest that use of a DC refrigerator with a rectifier would be a viable option in a 'hybrid' scenario – for example, if the appliance was initially bought to operate on DC, but then AC mini-grid infrastructure was put in place. The choice of rectifier is an important factor, as tests showed that this conversion can significantly increase energy use.

In real-life cases, if an AC supply option is present, or planned, a user may perceive that investing in a more expensive DC refrigerator will have a 'lock-in' effect and may want to keep upfront expenditure as low as possible by purchasing an AC model. However, the comparison above suggests that DC refrigeration appears to have cost viability on both DC and AC supply options, should the further development of 'hybrid' environments of AC/DC infrastructure occur.

Summary of refrigerator results

- In tests on a DC supply, replicating a SHS, the in-rush current required to start the compressor of the AC refrigerators was observed to be significant, with three of the four refrigerators unable to be started with a 1.5kW DC power supply unit. The ability to provide this in-rush current needs to be factored into the design of a PV system, generally by correct specification of the inverter's surge power rating and the battery's discharge current. This, along with the generally higher continuous power requirements of single-speed compressor AC refrigerators, results in efficient DC refrigerators being more cost effective on an upfront total system cost basis.
- MSW inverters are not generally recommended to power refrigerators, but despite this, users may still choose this technology where cost reductions are desired. Short-term operation of the refrigerators on one of the MSW inverters tested did not show any major performance issues, but two other MSW inverter samples trialled could not power the refrigerators adequately. Several aspects of the tests suggest that subsequent problems may be encountered if using an MSW inverter, such as increased energy consumption, damage to the appliance's motor due to heat build-up, and irregular current draw patterns.
- Tests showed that operating a DC refrigerator on an AC power supply with a rectifier is viable with no performance or reliability issues encountered. However, the extra energy required for the power conversion can be significant if the rectifier is of low quality, or not appropriately sized.
- Measurements were taken over a shorter period of time, and as such, longer-term tests are recommended to fully establish the long-term performance of refrigerators with converters.

Sample selection and methodology

Two AC TVs and one DC TV were selected for testing. All three were 24″ models, a common screen size for off-grid use. One TV was sourced from Kenya and two from Sierra Leone. A 2018 market survey in Sierra Leone showed the TV market to consist almost entirely of AC models. This reflects the higher degree of AC infrastructure present in Sierra Leone concentrated in urban areas, and low development of an off-grid market. It is estimated that 80% of the rural population in Sierra Leone are off-grid, and only 2% of rural households own a TV (Efficiency for Access Coalition, 2019). TV testing took place at the laboratory Re/genT, in 2019.

Table 18 – AC TVs used in tests

		TYPE	RATING	SOURCED FROM	RATED EFFICIENCY (%)	WARRANTY	COST (US $)
	**Haier LE24K6000T**	24″ LCD-LED TV	AC input, rated 100-240 VAC	Kenya	89.5	1 year	158
	**JSK 24HD**	24″ LCD-LED TV	AC input, rated 110-240 VAC	Sierra Leone	83	None	117
	**Jiepak 24T5** *Provided with DC cable and AC mains adaptor*	20″ LCD-LED TV	Dual input, rated both 12 VDC and 110-240 VAC	Sierra Leone	79	1 month	195

Test results: native mode power consumption and over- and under-voltage conditions

Initial power consumption measurements were made in native mode for the three TVs. The TVs were also run in over- and under-voltage conditions at ±15% of their rated voltage, to simulate power fluctuation. Tests were run using the test clip from IEC 62087 'Methods of measurement for the power consumption of audio, video and related equipment'. The test clip is a standardised 10-minute loop representing visual content of average power consumption for 24 hours. This provides the 'on-mode' power consumption measurement for the TV. In testing, the on-mode power consumption was found to be generally lower than the figure on the TV's rating plate. For the over- and under-voltage test, minimal change was observed in the average power consumption, except for a drop in the Haier AC TV's power consumption in the under-voltage condition.

Although these measurements were considered 'native mode', TV electronics run internally on DC power. As such, for the AC TVs, there is a power conversion taking place through the AC adaptor provided, which is a rectifier. For the Jiepak DC TV, no power conversion took place when it was tested in DC.

Table 19 – Native mode and over- and under-voltage power consumption for TVs

MAKE/MODEL	RATED POWER (W)	TEST VOLTAGE	AVERAGE MEASURED ON-MODE POWER CONSUMPTION (W)
Haier AC TV	25	230 VAC (native)	18.0
		85 VAC	16.6
		276 VAC	18.0
JSK AC TV	40	230 VAC (native)	27.6
		85 VAC	27.8
		276 VAC	27.8
Jiepak DC TV	15-36	12.0 VDC (native)	18.0
		10.2 VDC	18.0
		13.8 VDC	18.0

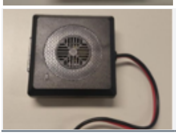
Testing of AC TVs run on a 12V DC power supply with inverters

The rating plates for the Haier and JSK TVs specified AC use only. The retail packaging for these TVs included a supplied AC adaptor and did not include an option for direct DC connection. Testing aimed to establish whether use of the inverters increased the overall energy consumption and if there were any performance issues. Operation of an AC TV on an MSW inverter would not be expected to result in some of the issues expected for an appliance with an AC motor. However, industry guides[19] and anecdotal experiences from off-grid internet forums have suggested that using an MSW inverter may result in a background buzzing sound and the appearance of lines on the display.

The on-mode power consumption of the TVs was tested on a 12V supply using PSW and MSW inverters of varying cost and quality. It should be noted that few inverters were available in continuous power ratings of below 250W, and as such, the inverters selected were sized much larger than the TVs' energy power consumption, as their continuous power ratings were in some cases over ten times the on-mode power draw of the TVs. As stated earlier, the conversion efficiency of inverters is higher when they are converting at a greater proportion of their maximum rated power. As such, test conditions could be considered sub-optimal for maximum inverter efficiency but are a viable use case that may be seen if an off-grid user only has an AC compatible TV.

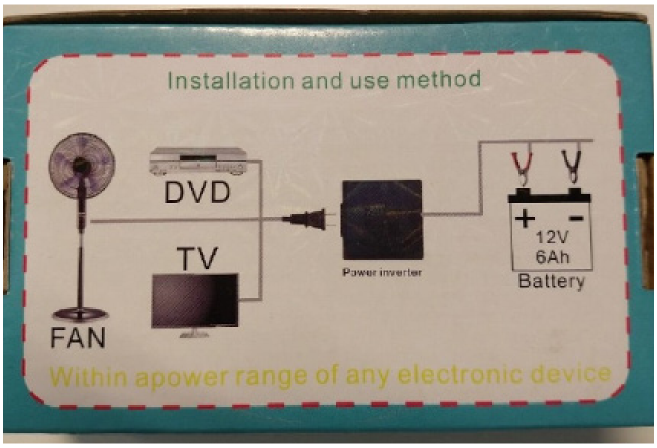
Three of the inverters were sourced from Kenya and Uganda. A market survey showed that the Victron brand is widely seen in markets in Africa, but the sample of this inverter was sourced from the UK for greater convenience. The lowest cost inverter sourced was a Jiepak model, which had the lowest continuous power rating of the inverters sourced, at 70W. It was sourced from a Ugandan online retailer at an equivalent cost of $19, and advertised as appropriate to run AC TVs, fans and stereos from a battery source.

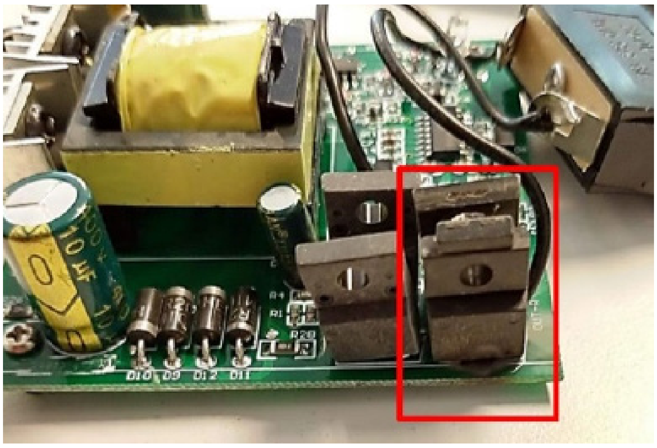
Table 20 - Inverters used in TV tests

		TYPE	RATED CONTINUOUS POWER (W)	MAXIMUM RATED EFFICIENCY (%)	SOURCED FROM	WARRANTY	COST (US $)
	**Victron Phoenix 12/250**	PSW	250	87	UK	5 years (standard company warranty)	115
	**Samlex 300W**	MSW	300	>90	Uganda	No information provided	65
	**I-Power SSK300**	MSW	300	>90	Kenya	No information provided	26
	**Jiepak 70W inverter**	MSW	70	Not stated	Uganda	No information provided	19

19 Select Solar – Guide to Inverters, https://www.selectsolar.co.uk/cat/202/guide-to-inverters

Figure 22 – Packaging of the lower cost Jiepak MSW inverter used in tests (left), and the exploded component following overheating of the device (right).





Power measurements were taken of the combined TV and inverter, as well as between the inverter and the TV, enabling the conversion efficiency to be determined and the AC voltage and THD to be measured. Both AC TVs were initially tested with the Jiepak MSW inverter, but during each of these tests the inverter components' temperature increased, and with no active cooling present in the product, such as a fan, a component overheated and exploded. As both samples of the Jiepak inverter experienced the same outcome, further tests with this inverter were abandoned.

Test results: on-mode power consumption

The on-mode power consumption test results of the two AC TVs with each inverter were as follows.

Table 21 – Power consumption of inverters with Haier AC TV

INVERTER	INVERTER TYPE	OUTPUT VOLTAGE (VAC)	AVERAGE INPUT POWER CONSUMPTION (W)		CHANGE IN POWER CONSUMPTION (%)
			TV only	inverter + TV	
Victron 250W	PSW	227.8	16.8	22.2	23
Samlex 300W	MSW	224.3	16.2	22.1	23
I-Power 300W	MSW	216.4	16.2	21.0	17
Native mode		**230.0**	**18.0**		

Table 22 – Power consumption of inverters with JSK AC TV

INVERTER	INVERTER TYPE	OUTPUT VOLTAGE (VAC)	AVERAGE INPUT POWER CONSUMPTION (W)		CHANGE IN POWER CONSUMPTION (%)
			TV only	Inverter + TV	
Victron 250W	PSW	227.4	24.0	34.8	26
Samlex 300W	MSW	223.3	27.3	33.1	20
I-Power 300W	MSW	215.2	24.0	32.3	17
Native mode		**230.0**	**27.6**		

Using an inverter with the AC TVs increased the power consumption of the total system by between 17% and 26% compared to native mode. The highest energy consumption was seen on the PSW inverter, although this may have been a function of the output voltage, which was higher than the output from the MSW inverters and closest to the TVs' rated voltage of 230V. Power consumption measured after the inverter to the TV was slightly lower than in the native mode in each case. Operating an AC TV through an adaptor connected to an inverter essentially means that two power conversions are taking place, which is reflected in the increased consumption seen.

Test results: over-voltage and under-voltage conditions

To simulate SHS or DC mini-grid voltage fluctuation, tests were run at 10.2V and 13.8V (±15% of 12V) for the AC TVs with each inverter. The power consumption of the full system was in all cases higher than the native mode consumption, with the largest increase seen with the Haier TV running on the I-Power MSW inverter at 13.8V input – a power draw 33% higher than in native mode. The results were as follows.

Table 23 – Over- and under-voltage power consumption of inverters with the Haier AC TV

INVERTER	INPUT VOLTAGE (VDC)	OUTPUT VOLTAGE INVERTER (VAC)	AVERAGE INPUT POWER CONSUMPTION (W)		CHANGE IN POWER CONSUMPTION (SYSTEM VS NATIVE MODE) (%)
			TV only	Inverter + TV	
Victron 250W PSW	10.2	226.7	16.8	21.0	17
	13.8	227.9	18.1	23.5	31
Samlex 300W MSW	11.4	217.7	12.0	19.8	10
	13.8	238.4	18.1	23.5	31
I-Power 300W MSW	10.2	206.5	16.5	21.6	20
	13.8	225.3	16.8	23.9	33
Native mode		**230.0**	**18.0**		

Table 24 – Over- and under-voltage power consumption of inverters with the JSK AC TV

INVERTER	INPUT VOLTAGE (VDC)	OUTPUT VOLTAGE INVERTER (VAC)	AVERAGE INPUT POWER CONSUMPTION (W)		CHANGE IN POWER CONSUMPTION (SYSTEM VS NATIVE MODE) (%)
			TV only	Inverter + TV	
Victron 250W PSW	10.2	225.9	24.0	33.0	20
	13.8	227.7	30.0	36.0	30
Samlex 300W MSW	11.4	216.8	24.0	31.3	13
	13.8	237.4	30.0	34.1	24
I-Power 300W MSW	10.2	205.9	27.3	32.6	18
	13.8	223.8	27.5	34.9	26
Native mode		**230.0**	**18.0**		

Test results: inverter performance

Some variation in the performance of the inverters was observed. The Victron PSW inverter was the only inverter to consistently regulate the output close to 230V at all input voltages, with much greater variation seen on the MSW inverters. On the I-Power MSW inverter, output voltage dropped to a minimum of 215.2VAC with 12VDC input, and as low as 205.9VAC with 10.2VDC input. On the Samlex MSW inverter, an output voltage of 238.4VAC was reached with 13.8VDC input, which was likely to have been the reason for the increased power consumption observed with the inverter in the over-voltage condition.

In under-voltage conditions, the Victron PSW inverter would not initially start the TV at 10.2VDC, but the TV would run when starting at a higher voltage and then reducing to 10.2VDC. The Samlex MSW inverter would not operate at all at 10.2VDC. The lowest voltage it could run the TV at was 11.4VDC, despite a minimum value of 10.5VDC stated in its manual.

Conversion efficiencies seen were lower than the inverters' rated values in all tests, with all measurements except one under 80%. This is likely due to the relatively low loads being run on the inverters compared to their power ratings. Conversion efficiency measurements were highly varied. For example, conversion efficiencies on the Samlex MSW inverter were between 60.6% and 87.7%. The Victron PSW inverter generally produced higher conversion efficiencies than the MSW inverters, with lower THD. Despite this, no issues were seen in any of the tests with the picture or sound, although tests were only run for 24 hours, which is not necessarily long enough to determine if long term operation on a high-THD AC supply could shorten the TV's lifespan.

Table 25 – Inverter performance with Haier AC TV

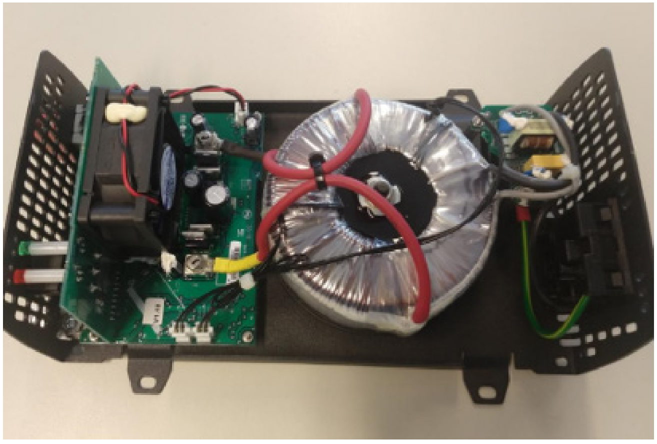
INVERTER	INPUT VOLTAGE (VDC)	OUTPUT VOLTAGE INVERTER (VAC)	CONVERSION EFFICIENCY (%)	THD (%)
Victron 250W PSW	10.2	225.9	72.7	12.5
	12.0	227.4	69.0	10.1
	13.8	227.7	83.3	9.3
Samlex 300W MSW	11.4	216.8	83.7	31.3
	12.0	223.3	82.6	29.3
	13.8	237.4	78.8	28.0
I-Power 300W MSW	10.2	205.9	76.9	37.0
	12.0	215.2	74.1	27.3
	13.8	223.8	87.7	33.0

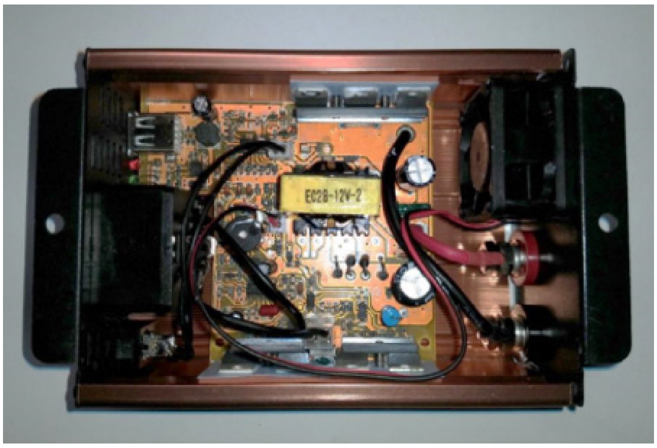
Table 26 – Inverter performance with JSK AC TV

INVERTER	INPUT VOLTAGE (VDC)	OUTPUT VOLTAGE INVERTER (VAC)	CONVERSION EFFICIENCY (%)	THD (%)
Victron 250W PSW	10.2	225.9	72.7	12.5
	12.0	227.4	69.0	10.1
	13.8	227.7	83.3	9.3
Samlex 300W MSW	11.4	216.8	83.7	31.3
	12.0	223.3	82.6	29.3
	13.8	237.4	78.8	28.0
I-Power 300W MSW	10.2	205.9	76.9	37.0
	12.0	215.2	74.1	27.3
	13.8	223.8	87.7	33.0

Quality inspections were also carried out on the inverters to observe the product build, safety features, certifications and information provided in the user manual. The Victron PSW and Samlex MSW inverters were CE marked, but the Victron inverter was the only product that also included information on conformity to EN standards in its manual. All three inverters did appear to have protection features for overheating, overload and short circuiting, but the Victron PSW inverter was the only one to also have a grounding mechanism present.

Figure 23 – Internal components of the Victron PSW (left) and Samlex MSW (right) inverters

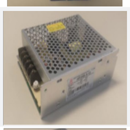




Testing of a DC TV run on an AC power supply with rectifiers

The Jiepak DC TV was tested on a 230V AC supply in on-mode and standby mode, and in over- and under-voltage conditions, using rectifiers of varying cost and efficiency. Rectifiers included a TDK 50W rectifier, a more expensive rectifier purchased online from a European distributor, and two Hengfu 35W and 50W rectifiers, which were lower cost, generic products bought online from distributors in China. Tests were also run using the Jiepak DC TV's included AC adaptor (external power supply or EPS) for comparison to the selected rectifiers.

Table 27 - Rectifiers used in DC TV tests

		TYPE	RATED CONTINUOUS POWER (W)	MAXIMUM RATED EFFICIENCY (%)	WARRANTY	COST (US $)
	**TDK DRB50-12-1**	DIN rail power supply	50	90	3 years	66
	**Hengfu HF35W-S-12**	Switching mode power supply	35	79	5 years limited	10
	**Hengfu HF55W-S-12**	Switching mode power supply	50	78	5 years limited	11
	**Jiepak AC adaptor - external power supply (EPS)**	No information provided	36 (12V, 4A)	Not stated	No information provided	No information provided

Test results: on-mode power consumption

The on-mode power consumption measurements were as follows.

Table 28 – Power consumption of Jiepak DC TV using rectifiers and in native mode

INVERTER	INPUT VOLTAGE (VAC)	OUTPUT VOLTAGE OF RECTIFIER (VDC)	POWER CONSUMPTION OF TV ONLY (W)	POWER CONSUMPTION OF RECTIFIER + TV (W)	INCREASED POWER CONSUMPTION OF RECTIFIER + TV COMPARED TO NATIVE MODE (%)
TDK 50W	195	12.0	17.5	20.3	13
	230	12.0	17.5	20.6	14
	265	12.0	17.3	20.5	14
Hengfu 35W	195	12.0	17.8	24.6	37
	230	12.0	17.9	25.5	42
	265	12.0	17.9	25.9	44
Hengfu 55W	195	11.9	17.8	23.9	33
	230	12.2	17.9	24.1	34
	265	12.2	17.8	24.2	34
Jiepak 36W EPS	195	12.0	18.0	21.2	18
	230	12.0	18.0	21.3	18
	265	12.0	18.0	21.3	18
Jiepak DC TV native mode	Input voltage (V)		Power consumption of TV in native mode (W)		
	12.0		18.0		
	10.2		18.0		
	13.8		18.0		

The total power consumption of the TV and rectifier combination was in some cases a significant increase compared to the native mode test. The average power consumption for the TV run on the Hengfu 35W rectifier was measured at 25.5W – an increase of 42% compared to the 18.0W measured in native mode.

Test results: standby power consumption

Previous tests for Equip Data[20] measured the Jiepak DC TV drawing 1.07W when run in standby mode on a 12V DC power supply, which is slightly above the limit of 1W that would be seen for a TV subject to European MEPS. When tested with the Hengfu 35W rectifier at 230V, the combined set-up was measured to have an average power consumption of 5.7W in standby mode, and 6.1W in the over-voltage condition – 4.7 times higher than in native mode.

Table 29 – Standby power consumption of the Jiepak DC TV using rectifiers

RECTIFIER	INPUT VOLTAGE (VAC)	OUTPUT VOLTAGE (VDC)	STANDBY POWER CONSUMPTION		INCREASED POWER CONSUMPTION (%)
			TV only (W)	Rectifier + TV (W)	
Hengfu 35W	195	12.2	1.0	4.9	358
	230	12.2	1.0	5.7	433
	265	12.2	0.9	6.1	470

20 VeraSol Off-Grid Product Database (formerly Equip Data), https://verasol.org/

Test results: rectifier performance

Compared to the previous inverter tests, minimal change in the output voltage from the rectifiers was observed. In most cases, the output voltage from the rectifiers was regulated close to 12.0V DC and the power delivered to the TV was similar to the native mode tests.

However, conversion efficiencies were higher for the TDK 50W rectifier and the Jiepak supplied 36W EPS, at over 80%, compared to the Hengfu products, which were between 69 – 75% in on-mode. In standby-mode, the 35W Hengfu rectifier measured very low efficiencies between 14% and 21%. Information to the user on no-load power draw of this rectifier was not available online and no operation manual was provided.

Table 30 – Rectifier performance with the Jiepak DC TV

RECTIFIER / TEST	INPUT VOLTAGE (VAC)	OUTPUT VOLTAGE (VDC)	INCREASED POWER CONSUMPTION (%)
TDK 50W/on-mode	195	12.0	86
	230	12.0	85
	265	12.0	84
Hengfu 35W/on-mode	195	12.0	73
	230	12.0	70
	265	12.0	69
Hengfu 35W/standby-mode	195	12.2	21
	230	12.2	18
	265	12.2	14
Hengfu 55W/on-mode	195	11.9	75
	230	12.2	75
	265	12.2	74
Jiepak 36W EPS/on-mode	195	12.0	85
	230	12.0	85
	265	12.0	85

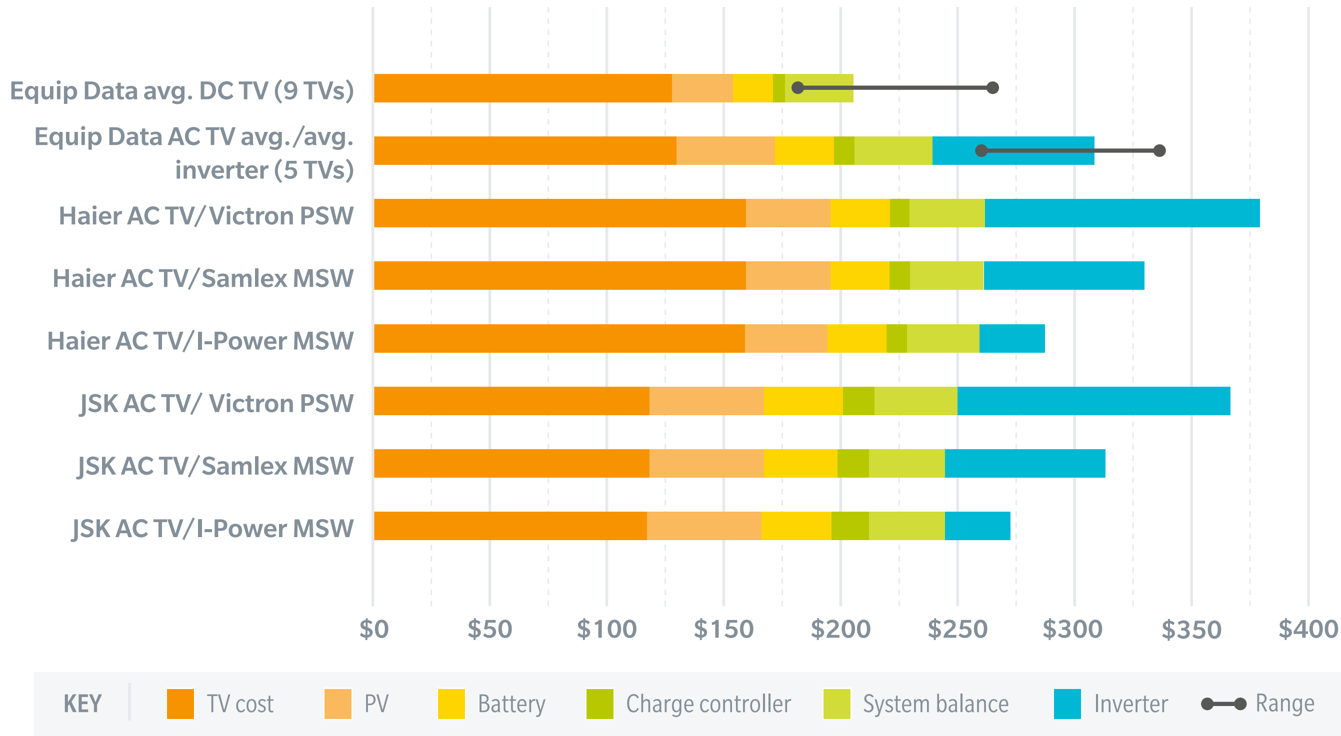
Analysis: television results

Cost comparison: AC TVs with inverter versus DC TVs in native mode

Using the system sizing and cost model calculator developed by SERC, the upfront total system cost (TSC) for the tested AC TVs was estimated. This was compared with TSC estimates for AC and DC TVs of a similar size where energy consumption and cost data were available from Equip Data. From the test data, a kWh/day figure was estimated by assuming the TVs are used in on-mode for four hours and in standby mode for two hours per day. The breakdown of the cost of system components is presented in **Figure 24** along with the range in TSC for the Equip Data DC and AC TVs. DC TVs are in some cases more expensive than AC TVs, but the cost data from Equip Data and the LEIA programme's market surveys showed that this difference is not significant (for example, compared to the scale of difference seen between AC and DC refrigerators). (Anker & Anker, 2017)

The AC TV systems were estimated to have a higher upfront system cost, due to their higher power requirement, with average PV module size calculated as 49Wp. The estimated average PV module size needed for the DC TVs was 29 Wp – this is similar to what is seen in some SHS packages available. For example, the M-KOPA Solar 600 package[21] offers a 30W solar panel with its 24" TV (as well as other smaller loads such as a radio, phone charging and lights). Other DC TVs tested by the LEIA programme were not included above as sample cost data was not available but had even lower power requirements. For example, a Niwa 23.6" DC TV tested had an on-mode power consumption of 11.7W[22], for which a PV module of under 20Wp could potentially be used to provide power. This supports the findings of Park and Phadke (2015) that the power requirements for DC TVs are significantly lower than for AC TVs.

Figure 24 – Total system cost of AC TVs tested with inverters, compared to the average of same-sized AC and DC TVs



21 Solar home system and appliance packages from M-KOPA, http://www.m-kopa.com/products/
22 Test data for Niwa off-grid television VeraSol Off-Grid Product Database (formerly EquipData), https://data.verasol.org/products/tv/niwa100?viewall=true

Cost comparison: DC TVs with rectifier versus AC TVs in native mode

The tests results showed the extent of inefficiency experienced when using a rectifier to run a DC TV, which could result in increased and unexpected costs to the user. A rectifier is needed to run TVs on the grid as TVs are natively DC and the AC grid power must be converted to DC for use by the TV. However, an off-grid user may also have a DC TV without an EPS, and have to purchase a third-party rectifier separately when an AC grid or mini-grid becomes available.

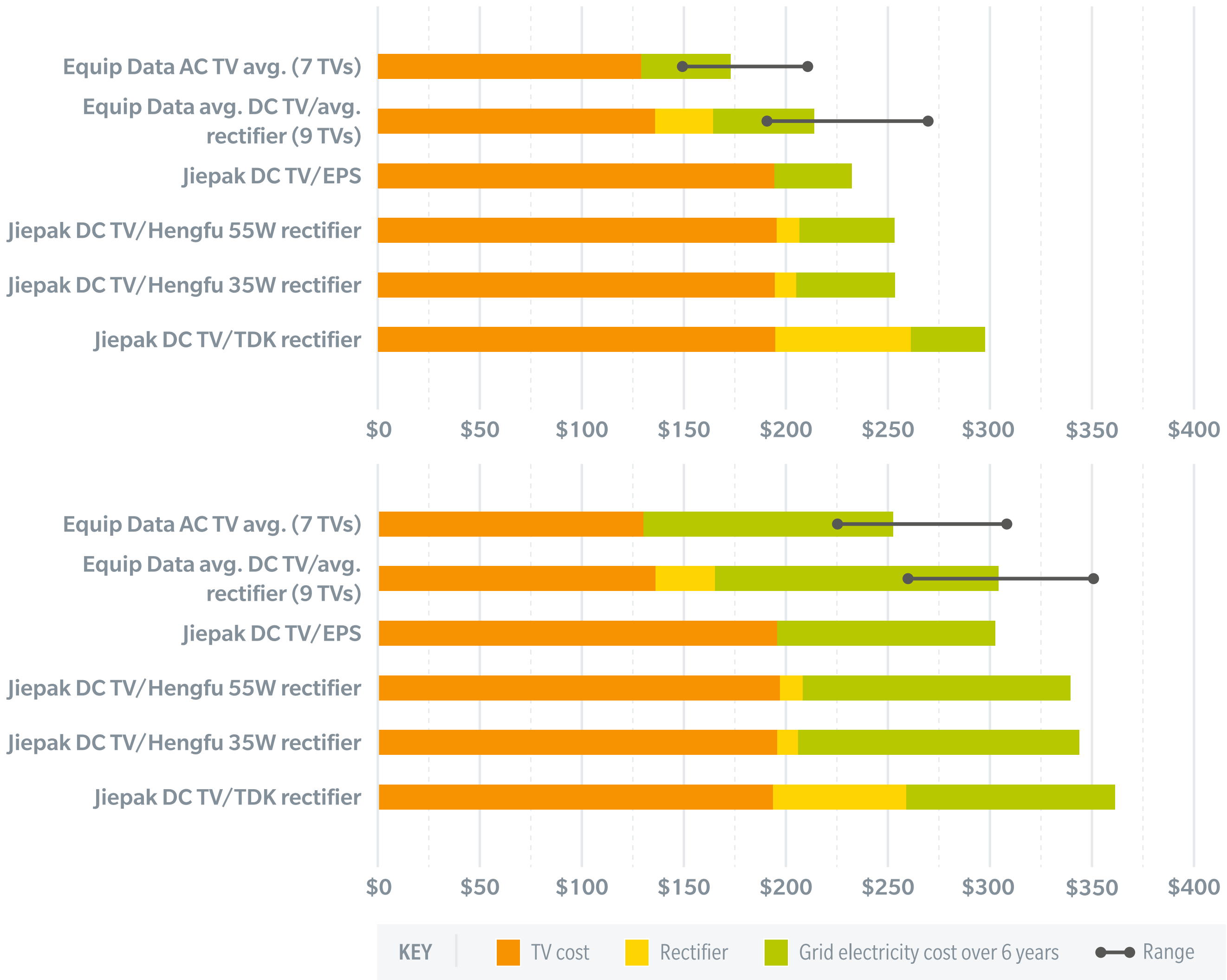
The figures below show the estimated simple lifecycle cost of running the Jiepak DC TV for six hours per day (four hours in on-mode, two in standby) on an AC grid and mini-grid with the rectifiers and EPS tested.

This is compared with the estimated simple lifecycle cost of the average of nine DC TVs and seven AC TVs for which energy and cost data was available from Equip Data. The following assumptions were made in estimation of simple lifecycle costs–

- Electricity costs are modelled for Kenya, using $0.20/kWh for grid electricity and $0.56/kWh for mini-grid electricity.[23] Kenya was selected for this comparison due to its current mix of supply options, including AC and DC mini-grids and a large SHS sector.
- Electricity costs are shown for six years, the typical lifetime of a TV.[24]

The cost breakdown shows that use of a rectifier could significantly increase the running cost for the TV. Running costs particularly increase when using a lower quality rectifier, such as the Hengfu model, eroding some of the efficiency gains of

Figure 25 – Simple lifecycle cost of the Jiepak DC TV with rectifiers on a grid (top) and AC mini-grid (bottom), compared to average AC and DC TVs from Equip Data



23 The World Bank, Mini Grids in Kenya: A Case Study of a Market at a Turning Point, World Bank, 2017, https://openknowledge.worldbank.org/bitstream/handle/10986/29022/ESM-cKenyaMiniGridsCaseStudyConfEd-PUBLIC.pdf?sequence=1&isAllowed=y

24 Reviewed – How Long Should Your TV Last?, https://www.reviewed.com/televisions/features/how-long-should-a-tv-last

using a DC TV, while use of a higher quality rectifier such as the TDK model would increase the upfront capital costs. None of the combinations of the Jiepak DC TV with rectifiers was more cost effective than running an 'average' AC TV with an EPS. From the data available, the Jiepak model was found to be of above average cost for a DC TV, but even for the 'average' DC TV the simple lifecycle cost was still above that for an 'average' AC TV due to the extra rectifier cost and electricity costs.

The EPS supplied with the Jiepak DC TV had a fairly high conversion efficiency of over 84%. This was at a similar level to the TDK rectifier, and outperformed the two Hengfu rectifiers, and was the most cost-effective way of operating the Jiepak TV on an AC supply. However, not all EPSs available may be as efficient – without MEPS in place in the TV's country of purchase, there remains a possibility for inefficient EPSs to be 'dumped' in off-grid markets, which may unexpectedly increase costs.

Summary of television results

- No major issues were observed when powering an AC TV on a DC power supply with an inverter, and there was little difference between the performance of the PSW and MSW inverters in the testing conducted. However, as a TV is an inherently DC appliance, extra, unnecessary energy consumption is required in this configuration, with two power conversions take place. Where a DC supply is available, a direct DC input to the TV is always the optimal means of providing power to the TV.
- The tests conducted with rectifiers also showed no issues, however the extra power needed to power both the rectifier and TV was relatively high, particularly in standby mode, which could result in unexpectedly high electricity costs to the user. The benefit of including a good quality, efficient rectifier (EPS) with a TV was observed, and efforts are recommended to ensure these are available to avoid the use of third-party rectifiers.
- A hybrid, dual-input option appears to be the optimal TV configuration where the user may use either AC or DC supply. A TV that provides a direct DC input provides the lowest power consumption and avoids some of the issues observed in the inverter tests. However, to also enable its use on an AC supply, a good quality rectifier (EPS) should also be included.

Sample selection and methodology

All fans and power converters for the fan tests were sourced from the Indian market, either from online retailers or local stores. India is known for having a well-developed market for both off-grid AC and DC fans, with well-established national manufacturing capacity. Fan samples were a mix of pedestal, table and ceiling fans, covering DC fans specifically designed for off-grid application and AC fans that would primarily be intended for use on the grid but could also be used with an inverter on a DC supply. Fans defined as operational on either AC or DC supplies are commonly seen in off-grid markets and one AC/DC fan sample was also included. Power ratings were available in some cases on the nameplate or in the advertised specifications, with AC fans generally having a higher power rating than similarly sized DC fans. The fans sampled and their specifications are provided below.

The DC fans all had a rated input power of under 30W. The Atomberg Technologies AC fan, incorporating a three-phase, variable speed AC motor was rated at 30W, lower than other AC-rated fans.

Table 31 – AC Fans used in tests

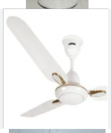
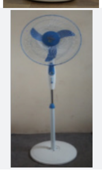
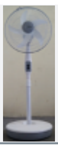
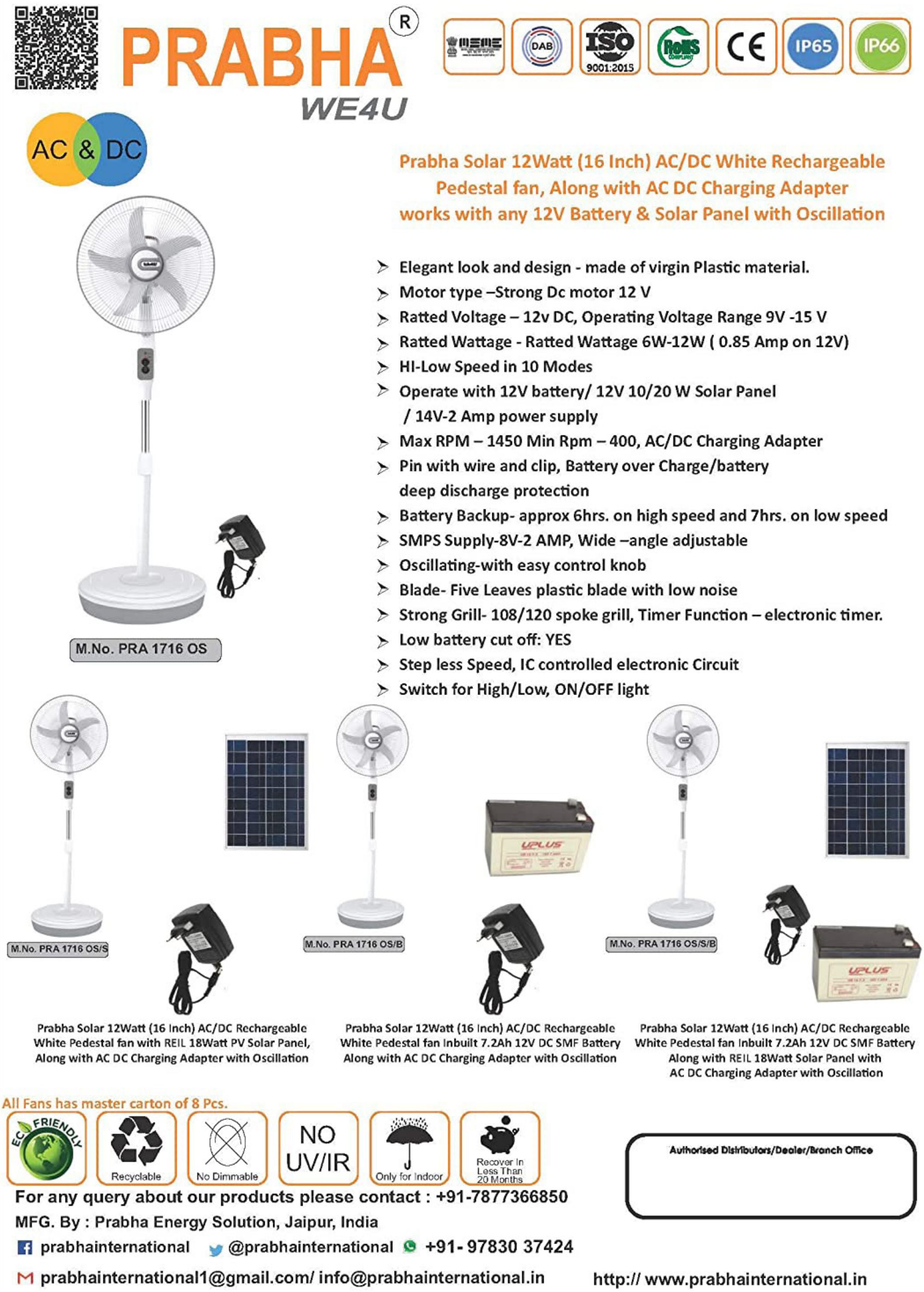
		POWER SUPPLY	MOTOR TYPE	RATED POWER (W)	SOURCED FROM	RETAIL COST (US $)
	**BuyFeb Seema 300mm Multi-Purpose Table Fan**	AC	AC	55	India	15
	**Atomberg Gorilla 3 Blade 400mm Energy Efficient Pedestal fan**	AC	3-phase AC	30	India	47
	**Usha Maxx Air 400mm, Pedestal fan**	AC	AC	60	India	33
	**Luminous Dhoom 1200, Ceiling fan**	AC	AC	70	India	22
	**Maa Solar Table fan**	DC	Brushless DC	12	India	13
	**REMI All Season 400 mm Solar Pedestal DC Fan**	DC	Brushed DC	22	India	22
	**Saish 12V Ceiling fan**	DC	Brushless DC	24	India	40
	**Prabha (16-inch) AC/DC Metal Rechargeable Pedestal fan**	Dual-input AC/DC	DC	15	India	44

Figure 26 – Online marketing information for the Prabha AC/DC fan. A 20W solar panel and 7.5Ah battery are specified for its operation in DC mode.



The most expensive products seen were the Prabha AC/DC and Atomberg AC fan. The Saish DC ceiling fan was more expensive than the similarly sized Luminous AC ceiling fan. The cost difference between AC and DC fans is not considered significant in established fan markets such as India, although a higher price trend for DC fans has been observed in some African markets.

Testing was carried out at the laboratory, Bharat Test House, in India in the second half of 2019 and early 2020. Measurements of air delivery and power consumption were conducted as per the Global LEAP fan test method .

Fans were first tested in native mode at their rating plate voltage. An Energy Efficiency Index (EEI) denoting the volume of air delivered per minute per watt of input power was determined for each fan. The fans were then tested using inverters and rectifiers in non-native modes.

Test results: native mode power consumption and air delivery

The results from native mode tests are provided in the table below. The Prabha AC/DC fan was tested both on a 14V DC supply directly through a DC cable, and with the supplied 250V AC adaptor. The energy consumption of the Prabha AC/DC fan was 8% higher on the AC supply but delivered 11% more air compared to when it was run on a DC supply using its supplied AC adaptor.

Table 32 – Fan native mode power consumption and air delivery

FAN	TEST VOLTAGE	POWER INPUT AT MAX SPEED (W)	HIGHEST REGULATED SPEED (RPM)	AIR DELIVERY (M^3/MIN)	EEI (M^3/MIN/W)
BuyFeb table	230 VAC	80.1	2272	59.5	0.74
Usha pedestal	230 VAC	53.5	1285	54.0	1.01
Atomberg pedestal	230 VAC	32.5	1270	53.7	1.65
Luminous ceiling	230 VAC	79.1	386	219.3	2.77
Maa Solar table	12 VDC	12.6	1340	29.1	2.31
REMI pedestal	12 VDC	22.1	1380	31.9	1.45
Saish ceiling	12 VDC	23.4	325	148.6	6.38
Prabha AC/DC pedestal	14 VDC	19.1	1306	28.7	1.50
	250 VAC	20.7	1320	31.9	1.54

25 Global LEAP Fan test method, https://storage.googleapis.com/leap-assets/Global-LEAP-Off-Grid-Fan-Test-Method-Version-1.2-Jan-2020.pdf

Testing of AC fans on a DC power supply with inverters

Both PSW and MSW inverters were used in fan testing, including models that also operated as an uninterruptible power supply (UPS). Input power for such products might be expected to be higher than for a standard inverter, as the combination inverter and UPS product may also be carrying out a charging function at times. Market research also determined that square wave (SQW) inverters were a common option used with SHSs in South Asia and were widely available. As such, a combination SQW inverter and UPS was also sourced for testing.

Table 33 – Inverters used for testing

		TYPE	RATED CONTINUOUS POWER AT 25°C	RETAIL COST (US $)
	**Exide Home 650VA Combination Inverter and UPS**	PSW	650 VA	66
	**Microtek 700VA Combination Inverter and UPS**	PSW	700 VA	37
	**Vantro 200W Inverter**	MSW	200W	29
	**Bestek 500W Inverter**	MSW	500W	34
	**Luminous EcoWatt+350 Combination Inverter and UPS**	SQW	350W	30

Test results: power consumption and air delivery

Due to the extent of the project scope, not all combinations of fan and inverter could be tested, but each AC fan was tested with at least two inverters. Measurements were taken of the power into and out of the inverter to determine conversion efficiency. Additionally, the no-load power draw, in-rush current to start up the fan motor, THD, power factor and frequency of the produced AC was also measured in each test.

An initial finding was that the Vantro MSW inverter, rated for 200W of continuous power, was unable to provide sufficient current to start the BuyFeb AC fan, despite the fan having a measured on-mode power consumption of around 80W. As a result, the Vantro MSW inverter was replaced by the Bestek MSW inverter for the testing.

The results measured were as follows.

Table 34 – BuyFeb AC table fan measurements

INVERTER/TYPE	INPUT POWER TO INVERTER (W) (% CHANGE VS NATIVE MODE)	OUTPUT POWER TO FAN (W)	HIGHEST REGULATED SPEED (RPM)	AIR DELIVERY (M^3/MIN)	EEI (M^3/MIN/W)	MAX. IN-RUSH CURRENT (A)	STANDBY POWER USING INVERTER (W)
Exide 650VA PSW/UPS	115.3 (44%)	77.0	2238	59.5	0.52	9.6	1.6
Bestek 500W MSW	85.3 (6%)	67.9	2025	56.5	0.66	7.5	3.7
Native mode at 230V		80.1	2272	59.5	0.74	Not measured	Not measured

Table 35 – Usha AC table fan measurements

INVERTER/TYPE	INPUT POWER TO INVERTER (W) (% CHANGE VS NATIVE MODE)	OUTPUT POWER TO FAN (W)	HIGHEST REGULATED SPEED (RPM)	AIR DELIVERY (M^3/MIN)	EEI (M^3/MIN/W)	MAX. IN-RUSH CURRENT (A)	STANDBY POWER USING INVERTER (W)
Microtek 700VA PSW/UPS	67.2 (26%)	56.6	1326	55.6	0.83	5.9	10.8
Bestek 500W MSW	56.2 (5%)	49.4	1309	54.1	0.96	5.0	3.7
Luminous 350W SQW/UPS	64.5 (21%)	57.2	1332	55.9	0.87	5.4	4.8
Native mode at 230V		53.5	1285	54.0	1.01	Not measured	Not measured

Table 36 – Atomberg AC Pedestal fan measurements

INVERTER/TYPE	INPUT POWER TO INVERTER (W) (% CHANGE VS NATIVE MODE)	OUTPUT POWER TO FAN (W)	HIGHEST REGULATED SPEED (RPM)	AIR DELIVERY (M^3/MIN)	EEI (M^3/MIN/W)	MAX. IN-RUSH CURRENT (A)	STANDBY POWER USING INVERTER (W)
Luminous 350W SQW/UPS	39.4 (21%)	36.8	1287	54.0	1.37	3.7	6.0
Bestek 500W MSW	45.9 (41%)	36.0	1284	52.6	1.15	3.9	3.8
Native mode at 230V		32.5	1270	53.7	1.65	Not measured	Not measured

Table 37 – Prabha AC/DC Pedestal fan measurements

INVERTER/TYPE	INPUT POWER TO INVERTER (W) (% CHANGE VS NATIVE MODE)	OUTPUT POWER TO FAN (W)	HIGHEST REGULATED SPEED (RPM)	AIR DELIVERY (M^3/MIN)	EEI (M^3/MIN/W)	MAX. IN-RUSH CURRENT (A)	STANDBY POWER USING INVERTER (W)
Luminous 350W SQW/UPS	26.3 (27%)	20.2	1325	29.4	1.12	2.6	4.8
Native mode at 250V		20.7	1320	31.9	1.54	Not measured	Not measured

Figure 27 – Testing of the AC fans with inverters

Table 38 – Luminous AC ceiling fan measurements

INVERTER/TYPE	INPUT POWER TO INVERTER (W) (% CHANGE VS NATIVE MODE)	OUTPUT POWER TO FAN (W)	HIGHEST REGULATED SPEED (RPM)	AIR DELIVERY (M^3/MIN)	EEI (M^3/MIN/W)	MAX. IN-RUSH CURRENT (A)	STANDBY POWER USING INVERTER (W)
Exide 650VA PSW/UPS	99.3 (26%)	84.3	395	222.8	2.24	8.3	1.6
Bestek 500W MSW	89.3 (13%)	73.7	388	218.3	2.44	7.9	3.6
Luminous 350W SQW/UPS	98.5 (25%)	79.1	379	214.7	2.18	8.6	4.8
Native mode at 230V		79.1	386	219.3	2.77	Not measured	Not measured

Significantly more power was required to run several of the fans on inverters. On average, the power consumption with the inverter was 23% higher than in native mode. The highest increase in power consumption observed was 44% for the Exide inverter/UPS to power the BuyFeb AC fan, which had a native mode power that was already relatively high at around 80W. The Atomberg AC fan was marketed as an efficient product and had the highest EEI of the table and pedestal AC fans in native mode. However, some of these efficiency gains appeared to be eroded when the Atomberg fan was operated on the inverters; input power to the inverters was measured 41% higher than native mode using the Bestek MSW inverter and 21% higher using the Luminous SQW inverter. It appeared that more power was required to drive the Atomberg fan 3-phase AC motor effectively when using a poorer quality AC waveform with higher harmonic distortion that reduces the ability to effectively magnetise copper and iron in the motor's stator and rotor.

There were instances observed where the output power from the inverter to the fan was lower than the native mode power draw, resulting in reduced fan speed. The largest reduction in fan speed was for the BuyFeb AC fan running on the Bestek MSW inverter. Input power to this inverter was 6% higher than native mode, but following the conversion, the output power to the fan was reduced to 68W, compared to 80W in native mode. As a result, the maximum fan speed was lower by 11% compared to native mode.

The Prabha AC/DC fan was able to run on either AC or DC, but only included an AC adaptor in its packaging – a DC cable had to be sourced for the native mode test at 14V DC. Operating this AC/DC fan on a DC supply through both an inverter and the included AC adaptor essentially involves two power conversions as the fan uses a DC motor, but this may be unavoidable if a DC cable is not available. Power consumption measured in this configuration was 26.3W, 27% higher than the power consumption measured for the fan run with the AC adaptor on an AC supply, and 38% higher than when the fan was run directly on a DC supply with no inverter or AC adaptor.

Some relatively high measurements of standby power were also seen. The Exide inverter/UPS had a low standby draw at 1.6W, but the other three inverters had standby power measurements of over 3.5W, with the Microtek inverter/UPS inverter having a standby power of over 10W with the fan connected but not running.

Test results: inverter performance

The performance of the inverters tested varied. Conversion efficiencies were measured between 67% and 93%, and the PSW inverters appeared no more efficient than the MSW or SQW inverters. This is likely in part because the PSW inverters were oversized. Few low power PSW inverter models were observed on the market, and the two PSW inverters tested were also UPSs that likely carried out concurrent charging functions of their internal battery.

As such, direct comparisons of conversion efficiency between fans with different rated power on the same inverter are not fully valid, as the conversion improves at higher points on the conversion efficiency curve. However, the inverters selected to operate the fans were considered viable representations of real-life selections from the market and show the range of conversion efficiency that can be seen by different products on the same inverter.

THD, power factor, and frequency measurements were measured for each inverter. AC output from all of the inverters had similar frequency measurements, close to 50 Hz, and power factors were all measured between 0.9 and 1.0. THD measurements were characteristic of the inverter technology, at <5% for the PSW models, 42.5% for the Bestek MSW inverter, and just under 55% for the Luminous SQW inverter. However, despite the high THD measurements for MSW and SQW inverters, no operational issues were observed with either the MSW or SQW inverters. As the tests were not conducted over a long period of time, it is not clear whether the long-term performance of the fan motors might be affected by the use of MSW or SQW inverters.

Table 39 – Inverter performance and conversion efficiency

INVERTER	POWER FACTOR	FREQUENCY (HZ)	THD (%)	FANS TESTED WITH	CONVERSION EFFICIENCY (%)
Exide 650VA PSW/UPS	0.99	50.4	2.7	BuyFeb AC	67
				Luminous AC	85
Microtek 700VA PSW/UPS	0.90	49.8	4.6	Usha AC	84
Bestek 500W MSW	0.96	50.1	42.5	BuyFeb AC	80
				Usha AC	88
				Atomberg AC	79
				Luminous AC	83
Luminous 350W SQW/UPS	0.98	49.9	54.9	Usha AC	89
				Prabha AC/DC	77
				Luminous AC	80

Testing of DC fans on an AC power supply with rectifiers

Rectifiers of varying cost and quality were sourced from online vendors in India and were similar to those used for the TV tests, with DIN rail and switching mode power supplies the most common types available.

Table 40 – Rectifiers used in testing

	RECTIFIER	TYPE	RATED POWER (W)	MAXIMUM RATED EFFICIENCY (%)	RETAIL COST (US $)
	MeanWell LRS-35-12	Switching mode power supply	35	86	9
	MeanWell DR-60-12	DIN rail power supply	60	82	17
	Shavision G31-60-12	DIN rail power supply	60	70-75	20
	Hilite ONS HL06FS-350	Switching mode power supply	60	no information available	6

Figure 28 – Testing of DC fans with rectifiers

Test results: power consumption and air delivery

Results for the DC fan tests on an AC power supply with rectifiers were as follows.

Table 41 – REMI DC pedestal fan measurements

RECTIFIER	INPUT POWER TO RECTIFIER (W) (% change vs native mode)	INPUT POWER TO FAN (W)	HIGHEST REGULATED SPEED (RPM)	AIR DELIVERY (M^3/MIN)	EEI (M^3/MIN/W)	MAX. IN-RUSH CURRENT (A)	STANDBY POWER USING INVERTER (W)
MeanWell 35W	25.0 (13%)	21.2	1379	31.4	1.26	0.28	0.0
Hilite 60W	24.9 (13%)	21.2	1372	30.3	1.22	0.26	0.8
Native mode		22.1	1380	31.9	1.45	Not measured	Not measured

Table 42 – Saish DC ceiling fan measurements

RECTIFIER	INPUT POWER TO RECTIFIER (W) (% change vs native mode)	INPUT POWER TO FAN (W)	HIGHEST REGULATED SPEED (RPM)	AIR DELIVERY (M^3/MIN)	EEI (M^3/MIN/W)	MAX. IN-RUSH CURRENT (A)	STANDBY POWER USING INVERTER (W)
MeanWell 60W	28.9 (24%)	19.9	302	143.2	4.95	0.20	1.4
Shavision 60W	29.1 (24%)	21.4	309	144.1	4.95	0.20	3.3
Native mode		23.4	325	148.6	6.38	Not measured	Not measured

Table 43 – Prabha AC/DC pedestal fan measurements

RECTIFIER	INPUT POWER TO RECTIFIER (W) (% change vs native mode)	INPUT POWER TO FAN (W)	HIGHEST REGULATED SPEED (RPM)	AIR DELIVERY (M^3/MIN)	EEI (M^3/MIN/W)	MAX. IN-RUSH CURRENT (A)	STANDBY POWER USING INVERTER (W)
MeanWell 60W	17.2 (-10%)	14.9	1276	26.2	1.52	0.18	0.5
Hilite 60W	17.5 (-8%)	14.3	1261	26.6	1.52	0.19	1.1
Native mode (14VDC)		19.1	1306	28.7	1.50	Not measured	Not measured

The results show that when the REMI DC pedestal fan was used with the rectifiers, energy consumption increased by 13%, for a similar level of performance to native mode. When the Saish DC ceiling fan was used with the rectifiers, energy consumption increased by 24% compared to native mode while the maximum speed and air delivery dropped slightly compared to native mode. The Prabha AC/DC pedestal fan was observed to use less energy when running on both rectifiers compared to its native mode. The rectifier output voltage to the Prabha fan was around 12.3V in each test, compared to its native mode DC voltage of 14V, reducing the input power to the fan to under 15W, compared to 20.7W on the AC supply. However, the speed and air delivery were also reduced.

Test results: rectifier performance

The MeanWell 60W rectifier had a relatively high mean output voltage of 13.5V, which may potentially have led to a higher output power. The no-load power consumption of the Shavision rectifier was considered high at 3.3W, however, the no-load power consumption of the three other rectifiers was not excessive.

Table 44 – Rectifier performance

RECTIFIER	MEAN OUTPUT VOLTAGE (V)	FANS TESTED WITH	CONVERSION EFFICIENCY (%)
MeanWell 60W	13.5	Saish	69
Shavision 60W	12.1	Saish	74
MeanWell 35W	12.3	REMI	85
	12.3	Prabha	86
Hilite 60W	12.4	REMI	85
	12.4	Prabha	82

Analysis: fan results

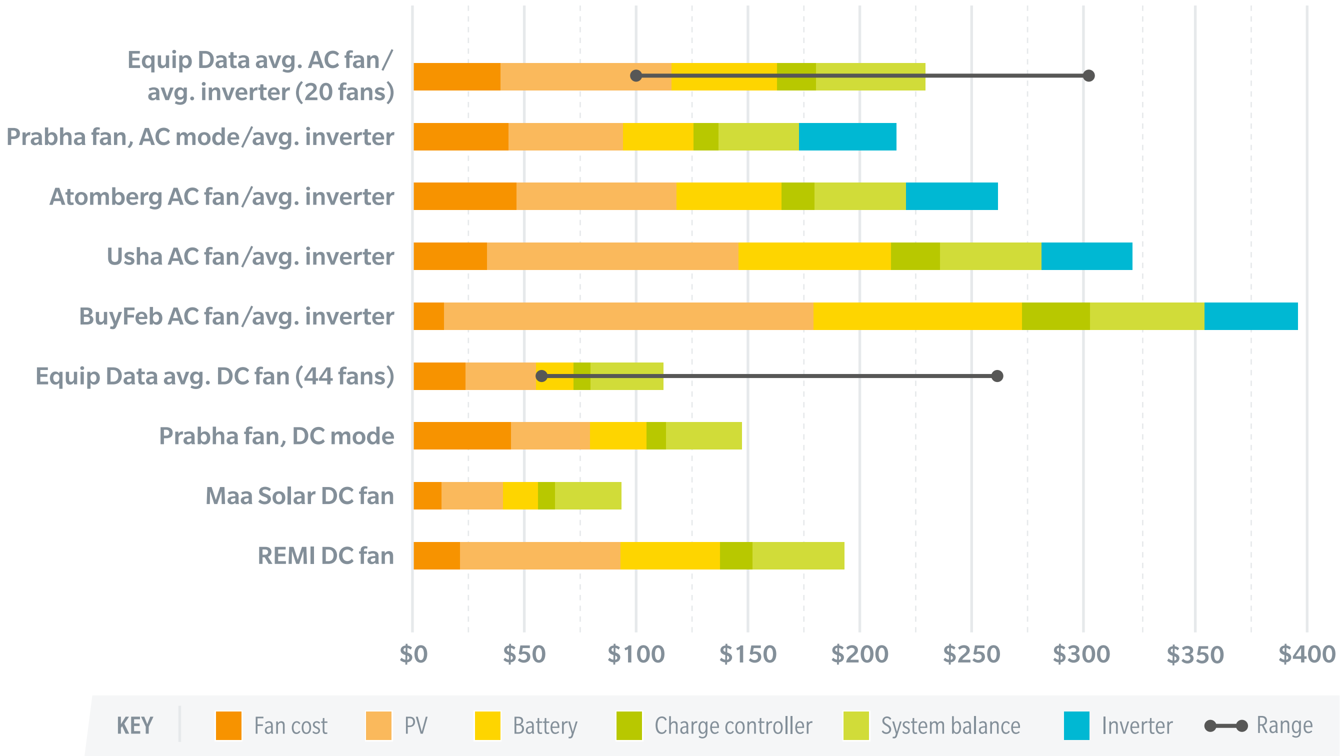
Cost comparison: AC fans with inverter versus DC fans in native mode

Using the system sizing and cost model calculator developed by SERC, the upfront total system cost (TSC) for the tested DC fans and AC fans operating with inverters was estimated. These were compared with TSC estimates for 21 AC and 44 DC fans where energy consumption and cost data were available from Equip Data[26]. For this calculation, it was assumed that the fans operate at maximum speed for 6 hours per day, are in standby mode for 6 hours and are disconnected for 12 hours. The average conversion efficiency observed from all of the inverter tests was 81%. This was rounded to 80% to estimate the extra power consumption required to run the Equip Data AC fans run with inverters. An average of the four tested inverters was also used to estimate standby power consumption and inverter cost. The breakdown of the cost of system components is presented in the figure below along with the range in TSC for the Equip Data DC and AC fans.

The TSC estimates show that AC fans have on average a higher power consumption, requiring larger PV module and battery capacity than DC fans. Factoring in the inverter further increases the TSC of AC fans. This comparison held for both AC and DC fans tested in this study, and for fans from Equip Data. The comparison between the fan's purchase cost and the PV system cost to run it shows the false economy of a cheap, but inefficient fan such as the BuyFeb AC fan, where the fan purchase cost of $15 makes up only around 4% of the TSC. Purchase costs of AC and DC fans varied, but overall, no strong trend was seen that DC fans were significantly more expensive.

The test data also indicated that although DC fans are generally more efficient, the AC fans had a higher air delivery which may be preferable to some users. The average air delivery figure from the AC fans from Equip Data was 41 m^3/minute, compared to 32 m^3/minute for the DC fans. This trend was also reflected in the models tested in this study, i.e. 49 m^3/min for AC fans, compared to 29 m^3/min for DC fans.

Figure 29 – Total system cost for AC pedestal and table fans with inverters, compared to DC fans, and average of AC and DC fans from Equip Data



26 VeraSol (formerly Equip Data) fan test database, https://data.verasol.org/products/fan

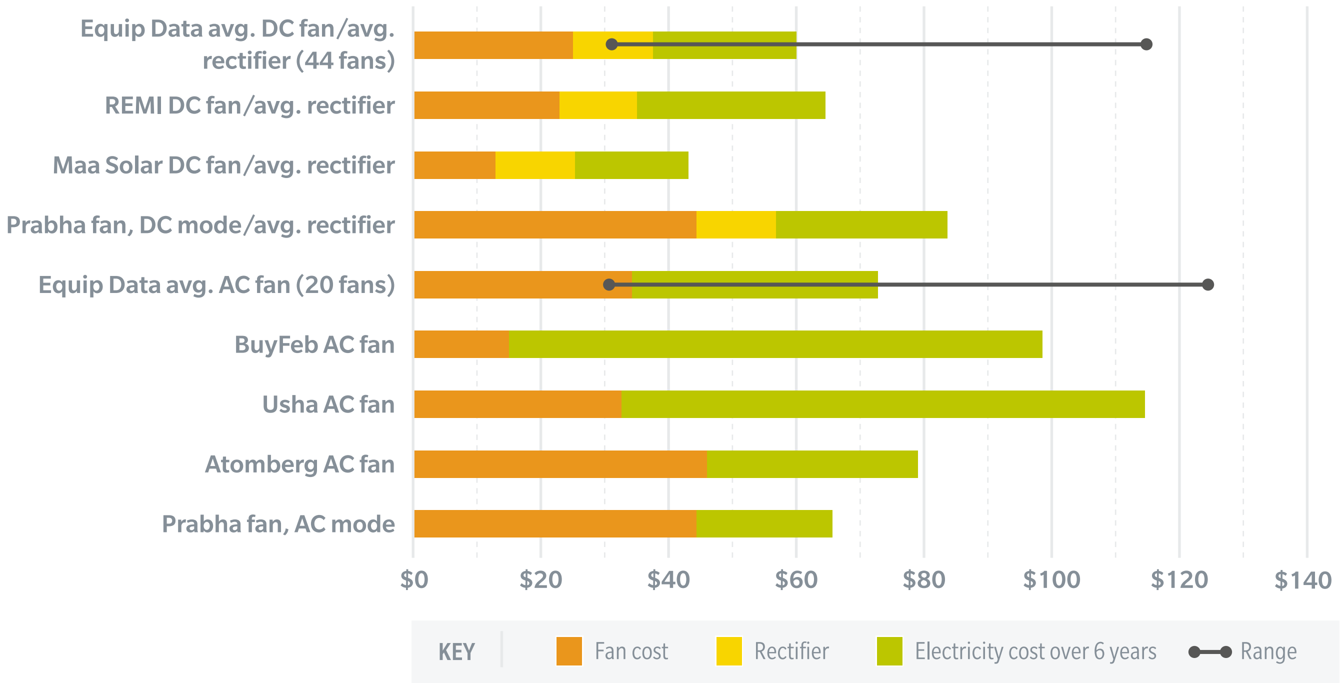
Cost comparison: DC fans with rectifier versus AC fans in native mode

The figures below show the estimated simple lifecycle cost of table and pedestal fans run on an AC grid and mini-grid supply. The following assumptions were made in estimation of simple lifecycle costs –

- The fans are in on-mode for 6 hours per day and standby mode for 6 hours per day.
- The cost, standby consumption and conversion efficiency of the rectifier modelled is the average of the rectifiers tested.
- The lifetime of fans was estimated to be 10 years in the EU Ecodesign preparatory study for fans[27], and around 8 years by Delta Fan[28]. However, this is expected to be lower in an off-grid setting. The GOGLA Standardised Impact Metrics for the Off-Grid Solar Energy Sector[29] takes average solar product lifetimes to be 1.5 times the warranty period, which is typically no more than one year for fans (and often less, or not in place). A nominal figure of 6 years was assumed for the lifetime of fans in these cost comparisons.
- The grid electricity cost was assumed to be an average tariff for India of $0.08/kWh[30] (using the average exchange rate at the date of the average tariff of 1 INR to 0.014 USD[31]). The retail mini-grid electricity price in India was taken as $0.41/kWh, which was estimated by taking the average of figures reported by the Rockefeller Foundation[32], Stanford University[33] and the World Bank[34] (the World Bank source cites that this figure would require subsidy).

Simple lifecycle costs were estimated for the tested REMI, Maa Solar and Prabha fan in DC mode, as well as for the average DC fan from Equip Data. DC fan estimates are compared with AC fans, operating in native mode, including the tested BuyFeb, Usha, Atomberg and Prabha fans in AC mode, and the average AC fan from Equip Data.

Figure 30 – Simple lifecycle costs of DC pedestal and table fans running on an AC grid tested with rectifiers, compared to AC fans, and average AC and DC fans from Equip Data



27 ARMINES, Université de Liège, idmec, AEA, BRE, IASA, Study on Comfort Fans – final report, Preparatory study on the environmental performance of residential room conditioning appliances (airco and ventilation), 2008, https://www.eup-network.de/fileadmin/user_upload/Produktgruppen/Study_on_comfort_fans.pdf

28 Delta Electronics, DC Fan Life Experiment Report, 2001, https://www.delta-fan.com/Download/MTBF/MTBF-EFB0512LA.pdf

29 Global Association for the Off-Grid Solar Energy Industry (GOGLA), Standardized Impact Metrics for the Off-Grid Solar Energy Sector, GOGLA, 2018, https://www.gogla.org/sites/default/files/resource_docs/gogla_impact_metrics.pdf

30 Statista - Average cost of state electricity supply across India from financial year 2009 to 2016, 2020, https://www.statista.com/statistics/808201/india-cost-of-state-electricity-supply/

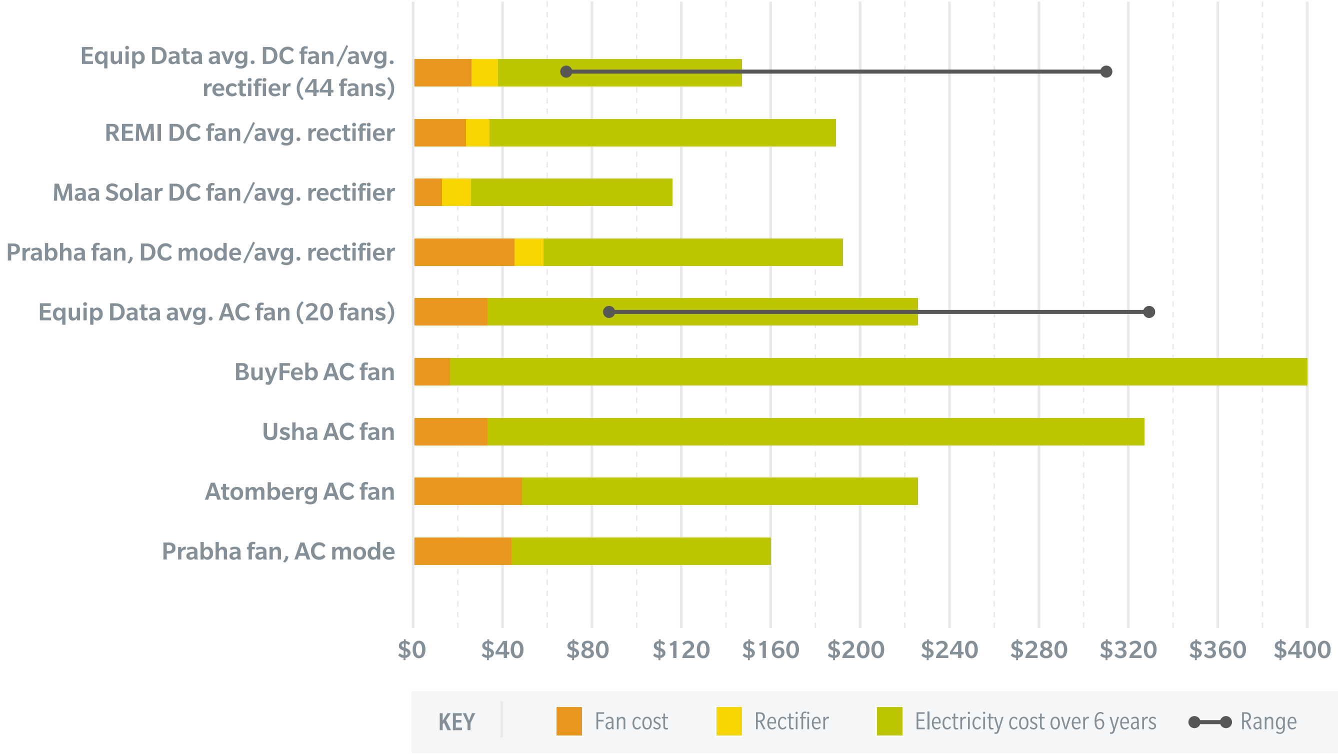
31 Exchange Rates - US Dollar to Indian Rupee Spot Exchange Rates for 2016, https://www.exchangerates.org.uk/USD-INR-spot-exchange-rates-history-2016.html

32 Institute for Transformative Technologies, Achieving universal electrification in India; A roadmap for rural solar mini-grids, Rockefeller Foundation, 2016, https://www.rockefellerfoundation.org/wp-content/uploads/Achieving-Universal-Electrification-in-India.ITTReport.April2016.pdf

33 S. Comello, S.J. Reichelstein, A. Sahoo, T.S. Schmidt, Enabling Mini-grid Development in Rural India, Stanford Graduate School of Business, 2015, https://www-cdn.law.stanford.edu/wp-content/uploads/2016/04/Enabling-Mini-Grid-Development-in-Rural-India.pdf

34 ESMAP, Mini Grids in Uttar Pradesh – A Case Study of a Success Story, The World Bank Group, 2017, http://documents1.worldbank.org/curated/en/181781512395036596/pdf/ESM-fUttarPradeshMiniGridsCaseStudyConfEd-PUBLIC.pdf

Figure 31 – Simple lifecycle costs of DC pedestal and table fans running on an AC mini-grid tested with rectifiers, compared to AC fans, and average AC and DC fans from Equip Data



For both the AC grid and mini-grids scenarios, DC fans used with a rectifier are cost competitive with AC fans as a result of their lower running costs and the minimal difference in the fan purchase cost. This again demonstrates the false economy of some cheaper and less efficient AC fans. The simple lifecycle cost differences between AC and DC fans on an AC grid are less marked than the above comparison of the TSC of AC and DC fans operated on SHSs.

Summary of fan results

- Operation of fans outside of their native mode was generally seen to be viable for both power conversions of DC to AC and AC to DC. The fans tested in this study, and those observed through prior testing and market surveys, show a wide range of power consumption and efficiency figures. Sizing of converters relative to the fan is a key aspect of maintaining a high level of energy efficiency. No major issues were seen in the ability of power converters to provide in-rush current, although an inverter rated for 200W continuous power was found to be unable to start up an AC fan that used 80W of continuous power when operating.
- No major issues were observed in fans operating on MSW and SQW inverters. However, only shorter-term tests were conducted and longer-term testing to explore the effect of these types of inverters on performance and lifetime are recommended. The performance of AC fans on these inverters was better than expected, given the nature of AC induction motors. Operation on MSW and SQW inverters, however, did appear to reduce the efficiency of the Atomberg fan, which incorporates a three-phase, variable speed AC motor that is more efficient than standard AC models.
- The fan market is not subject to the same price conditions as the refrigerator market, where AC refrigerators are generally much lower cost than DC refrigerators. The smaller upfront purchase cost difference between AC and DC fans reduces the potentially perceived economic advantage of purchasing a cheaper AC fan. As a result, the case for direct use of DC fans on SHSs and DC mini-grids is compelling. Tests and existing data show that DC fans have a strong advantage over AC fans in providing cooling at very low power levels, and that some AC fans available, such as low-cost models tested in this study, can result in a high false economy when operated with inverters on a DC supply.
- Hybrid, dual-input fans may be an excellent choice where both AC and DC power supply are available. It is important to ensure that hybrid fans can be used in their optimal modes, however, through the inclusion of cables, connectors, and a quality, appropriately sized converter (whether internal or external).

This study involved laboratory testing to assess the power consumption, efficiency, performance and costs of AC and DC appliances operated on different power supplies and converters, which were representative of common off- and weak-grid use cases. The study provides insight into which combinations of appliance and converter are viable or optimal for different power supply types, as well as which combinations are unsuitable for providing cost-effective, reliable and safe conditions to operate appliances. The main conclusions from the study 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 an inverter.

For refrigerators assessed in the 30-50 litre size bracket, 9 of 11 DC appliances had a lower total system cost than that of a low-cost AC appliance run on an inverter. For the 70-90 litre bracket, 7 of 9 DC refrigerators had a lower total system cost than the AC model tested. However, test results and cost comparisons also showed that there are some low-cost, efficient AC refrigerators that can be more cost-effective than equivalent size DC refrigerators.

Alongside the cost analysis, test results demonstrated the additional complexity of using inverters with AC refrigerators, particularly as a result of the high in-rush currents of single-speed AC compressor motors and the potential long-term issues resulting from the use of low-cost inverter types. This makes a strong case for the use of DC refrigerators with SHSs rather than AC refrigerators.

For TVs and fans, current market data shows minimal cost difference between AC and DC models. Analyses conducted found that the additional energy consumption of AC TVs and fans (compared to most DC TVs and fans), plus the inclusion of power conversion, almost always results in AC TVs and fans requiring a larger SHS to run. For TVs, a DC-inherent appliance, power conversion is an entirely unnecessary and avoidable step when run on a DC power supply, and the conversion was observed in some cases to increase overall energy consumption significantly.

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. The performance of some low-cost converters was better than expected, however, there were issues observed related to the ability of some low-cost converters to deliver their rated power and supply consistency (e.g. variations in output voltage from under- and over-voltage 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. Whilst in some cases MSW inverters powered appliances without issue, each one tested at some point was found to have an aspect of sub-optimal performance, e.g. extra energy consumption, not being able to provide rated power, failing to regulate input voltage, overheating and malfunctioning, or not including safety features such as cooling or grounding.

Cost analyses showed that the use of MSW inverters could decrease total system costs quite significantly compared to PSW inverters, particularly for higher powered loads such as refrigerators. However, measurements of the AC power produced from all of the MSW inverters showed high THD, which may lead to a build-up of excess waste heat in motors or affect the ability of the motor to magnetise rotor and stator components. This leads to earlier malfunctions and lower lifespans for motor-based appliances (Dyess, 2018) Longer term tests than those carried out in this study would be needed to provide a better indication of appliance issues and lifespan differences resulting from their operation on MSW inverters.

Research (Formica, Khan, & Pecht) has also suggested that failure of the inverter itself is a common aspect of PV system issues, with one example finding that 60% of failures logged over a 3-year period from 202 grid-connected solar PV systems in Taiwan, were attributed to the inverter. Various sources estimate inverters to have an average lifespan of around 10 years.[35]

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. The conversion appeared less subject to variation across products and less prone to fluctuation than with the DC to AC conversion performed by inverters.

This suggests that in areas where there are plans for the AC grid to be installed, it may still be economically rational to purchase a DC appliance with a DC power supply. Having a SHS already in place and adding an AC grid connection can bring a household a high measure of power security. The availability of dual power supplies provides users with a back-up to the AC grid in cases of power outages and can also reduce their AC utility bills.

Rectifier selection is a key consideration to ensure power is delivered as efficiently as possible. Rectifier sizing appeared to be less problematic than for inverter sizing as significant surge currents were not encountered in DC appliances, although some issues related to sizing were noted. A rectifier with a higher power rating (150W) was needed for the Pro Solar DC refrigerator to be able to pull temperature down from 32˚C to 10˚C, than was required for steady state cooling test at 32˚C (120W). Additionally, when the ProSolar and Hinnova DC refrigerators were tested on the same rectifiers, a greater increase in percentage energy consumption, versus native mode, was seen on the more efficient Hinnova refrigerator, as the rectifier's efficiency curve was more optimal for the ProSolar's power consumption.

Higher cost rectifiers generally performed with a conversion efficiency of over 80%, while low-cost rectifiers had a conversion efficiency in the 70-80% range. For the refrigerators tested, power draws of up to 5.5W were seen on low-cost rectifiers when the refrigerator itself was not consuming any power. For the DC TV tested, the standby mode power consumption with a rectifier was 5.7W, whereas in native mode the standby power consumption of a TV subject to MEPS would generally be less than 1W. This could unexpectedly increase costs for users. Overall, rectifiers from more well-known manufacturers were seen to perform better in conversion efficiency, and at low-load than generic products.

Hybrid and efficient AC technologies are viable options for off-grid appliances

As discussed previously, The IEA's 2019 Africa Energy Outlook[36] 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 most viable for 30% of the population, while stand-alone SHSs are most viable for around 25% of the population. The 2019 State of the Off-Grid Appliance Market (SOGAM) report (Efficiency for Access Coalition, 2019) identified that a 'Hybrid AC/DC environment' scenario is most likely to occur in the future. 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.

Current product data from Equip Data and the LEIA programme's market surveys suggest a low proportion of products are designed for true dual input use. Only 1 out of 70 refrigerators on Equip Data was defined as AC/DC, while 7 of 123 fans and 15 out of 148 TVs had dual inputs.

35 Solar Market, The Life Span Of A Solar Inverter, 2019, https://www.solarmarket.com.au/blog/the-lifespan-of-a-solar-inverter/
36 International Energy Agency, Africa Energy Outlook 2019, 2019, https://www.iea.org/reports/africa-energy-outlook-2019

Generally, dual-input, hybrid appliances are designed around an inherently AC or DC appliance and feature an internal or external power converter (an included adaptor), enabling the appliance to be used on either AC or DC supply, avoiding the 'lock-in' effect. A comparison of the non-native mode performance of both DC and AC appliances suggests that DC-inherent appliances are the more viable option for hybrid appliance design.

The AC/DC hybrid Jiepak TV and Prabha fan tested both performed well and were energy efficient. The Jiepak TV showed low power consumption appropriate for use on a SHS when powered directly on DC, and its included AC adaptor enabled use on AC for only a relatively small increase in power consumption. Similarly, the Prabha AC/DC fan had low power consumption when run on either a DC power supply or an AC power supply using its included AC adaptor. However, a DC cable was not included with the Prabha AC/DC fan, which could potentially result in extra power conversion if the user operates it through both its AC adaptor and an inverter. Improving the availability of associated hardware with hybrid appliances in an important consideration in fully realising the energy savings available.

Whilst the cost comparisons made in this study appear to favour the use of DC appliances natively, rather than incorporating power conversions, there are some developments in AC appliance technology that may change this in the future. This study tested an Atomberg AC fan that incorporates a three-phase, variable speed AC motor, which operates more efficiently than other AC fans. Digital Inverter (DI) compressor refrigeration is another AC-based technology which undergoes internal power conversions to enable variable compressor speeds using a 3-phase AC motor, improving efficiency. This technology has been available for several years in on-grid markets[37] but has yet to be deployed widely in off-grid markets, likely due to its greater cost as a new technology, and lack of specific use case for off-grid use.

The use of some older AC technology may also be efficient and cost effective. For example, the Von AC refrigerator, despite incorporating a single-speed compressor, performed fairly well in terms of efficiency. This refrigerator, which was on sale for $153 in Kenya, may be an example of where production scale can be achieved to reduce both purchase and running costs. Further market studies would need to be carried out to determine if there is a consistent and commercially viable supply of refrigerators with this cost and performance profile.

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 users' choice of appliance. One reason for this is that the DC appliance market cannot yet benefit from the higher production and distribution scale experienced by the more established AC appliance market. Another reason is the application of taxes and duties on DC appliances, which is much greater on an absolute basis compared to AC appliances, due to the higher upfront cost of DC appliances.

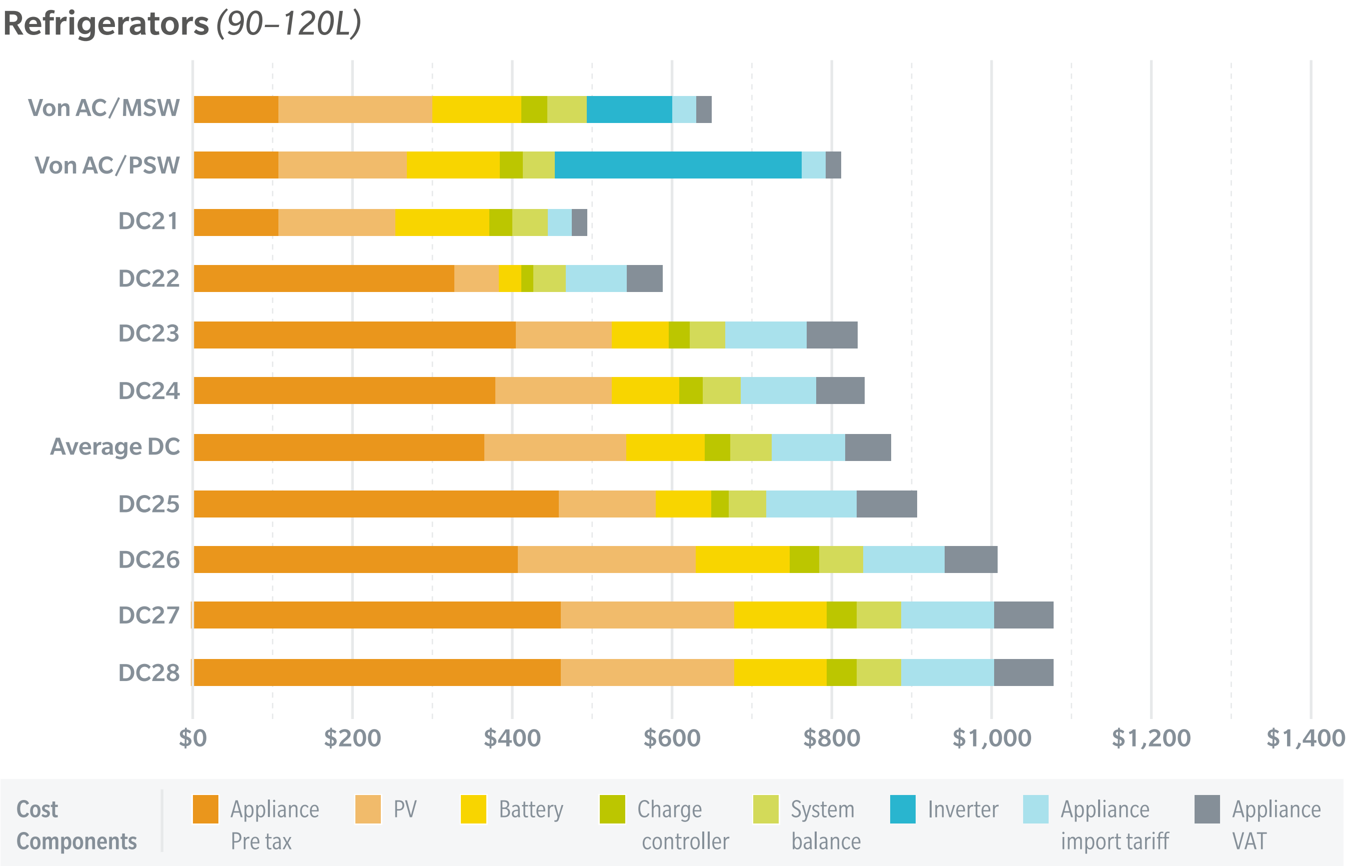
Efforts to provide tax exemptions are underway in Kenya, Ethiopia and Sierra Leone where the waiving or reduction of import duties and/or VAT on SHSs and solar appliances has been introduced (Efficiency for Access Coalition, 2019). However, reports from industry suggest that this policy is not being deployed consistently, and different import rules between these countries can be quite different, reducing the opportunity to scale distribution across a wider geography.

Figure 32 shows the upfront total system cost for the category of 90-120L refrigerators examined previously and incorporates the estimated proportion of VAT and import duty that is levied on a DC appliance in Kenya (16% for VAT and 25% for import duty)[38]. The Von AC refrigerator, with a low upfront cost of $153, has significantly lower VAT and import duty costs than seven of the eight DC refrigerators (for which data was held), which results in only two of the eight DC refrigerators in this size category being more cost effective than the Von AC refrigerator. Exemption of VAT and import duty would subsequently result in six of the eight DC refrigerators having a lower total system cost than the Von AC refrigerator operated on a PSW inverter.

37 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

38 OGRES Explorer, https://chih-weihsu.shinyapps.io/OGRES_explore/

Figure 32– Total system cost of Von AC refrigerator with MSW and PSW inverters compared to the average of similarly sized DC refrigerators in native mode (capacity 90-120 litres), inclusive of VAT and import duty



There are also further practical considerations that need to be taken into consideration when determining what will ultimately influence consumers' purchasing decisions and whether these can be significant enough to outweigh more technical performance issues. For example, consumers may recognise and aspire to own well-known AC branded appliances even if they live in an off-grid area. The payment terms underlying the purchase of an appliance are another important consideration.

Many DC Appliances are made available on a PAYGo basis when bundled with or bought after a PAYGo SHS, which is a major selling point compared to most AC appliances only being available on a cash basis. Additionally, it may be inferred that the growing availability of quality, appropriately designed off-grid DC appliances will automatically compete with the current dominance of AC appliances being used off-grid with a converter.

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.
   - Newer AC technologies, such as three-phase, variable speed AC motors and digital inverter compressor refrigeration, and their potential use in off- and weak-grid appliances.
   - Current AC refrigerators that are both efficient and low-cost, such as the Von AC refrigerator identified in this study.
   - How further cost reductions can be achieved with DC appliances, including incentives to drive these cost reductions.

2. **Policymakers should attempt to support optimal 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. The waiving of taxes and duties, as described above, is one method to do this.

3. **As a Hybrid AC/DC environment is expected to develop in off- and weak-grid areas, policymakers should develop standards in anticipation of this scenario, in order to address compatibility, safety and quality issues.** Minimum performance standards and quality assurance programmes for converters and appliances can be used to prevent poor quality products from being available in these markets. Information provision, awareness raising and training on the use of quality converters and appliances are additional options for policymakers.

4. **Policymakers and donors should support further research in the area of efficient appliances, converters, and business models for off- and weak-grid areas**, particularly in the context of the hybrid AC/DC scenario, e.g. further research into dual-input hybrid appliance, or hardware involved in power conversions, for example as was seen with the Google Little Box Challenge , which aimed to reduce the physical size of inverters.

5. **Policymakers should regulate to improve the provision of essential hardware for power conversions.** For example, recent developments in EU Ecodesign policy have put the onus on appliance manufacturers to provide spare parts for a specified length of time [40] and develop a common mobile phone charger [41]. A similar approach in off-grid markets could help increase provision of cables and connectors that are specifically intended for appliances to enable their optimal configurations, rather than leaving the user to acquire a third-party product.

6. **Manufacturers should design more flexible, dual-input appliances using good quality converters, coupled with reliable after-sales support on their use.** Providing appliances with compatibility across more than one power supply may provide market advantages in a future hybrid environment.

7. **Effective collaboration between SHS companies, mini-grid developers, utilities and governments is needed to ensure that the development of hybrid environments does not also result in further disorganisation of the appliance market, in relation to compatibility, and disadvantage to end users.** The Peering into the Future report (cKinetics, 2019) emphasises that for hybrid environments, standards must be developed and harmonised to ensure that this architecture emerges in a resilient manner. Whilst companies are acting in a competitive business environment, and may largely focus on one particular type of power supply, the most secure energy supply for a user may be where they have access to both AC and DC, which must be taken into account in planning.

   A good example of relevant industry collaboration with parallels to this situation is the development of the USB standard for low voltage power and data transfer. Regular dialogue between companies operating in the same space, and where possible the sharing of best practice, data, and awareness of key issues for users (such as avoiding 'lock-in' effects from a particular supply or appliance type) is beneficial. Further co-operative initiatives could be beneficial, such as voluntary agreements, and industry codes on compatibility. Collaboration could also include combined procurement activities for DC appliances to be offered in packages and help to increase order sizes, reducing costs to the end user.

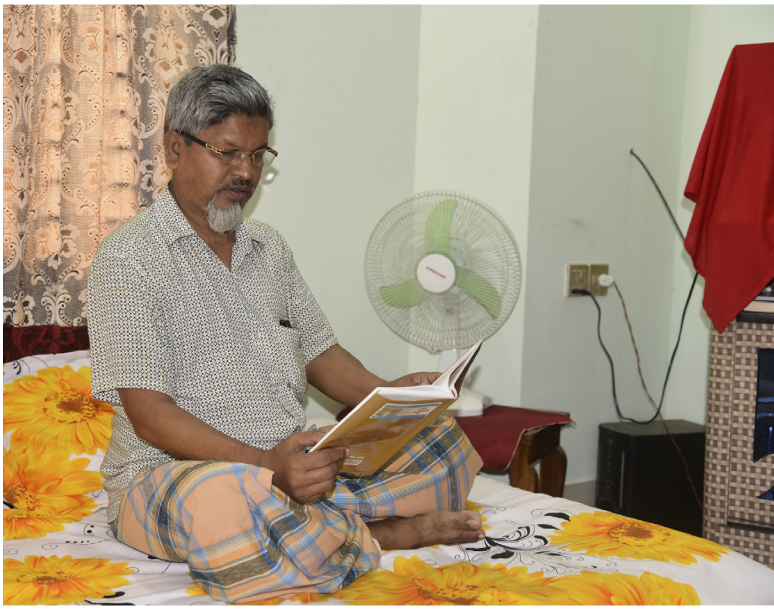
39 The Little Box Challenge presented by Google and the IEEE Power Electronics Society was an open competition to build a smaller power inverter, https://epc-co.com/epc/LittleBoxChallenge.aspx

40 European Commission, The new ecodesign measures explained, https://ec.europa.eu/commission/presscorner/detail/en/qanda_19_5889

41 European Commission, One mobile phone charger for all, 2019, https://ec.europa.eu/growth/sectors/electrical-engineering/red-directive/common-charger_en

8. **Mini-grid developers should involve themselves in appliance provision to ensure users have reliable, compatible appliances with a long lifetime.** This will ultimately provide a better return on the mini-grid investment and is a preferable situation to where the user has an appliance that is not well designed for the power supply, and may have to rely on low-quality, third-party converters and other hardware, which could result in less frequent and reliable use of the mini-grid, power surges, and shorter lifetime of the appliance.

9. **Product development and distribution planning for SHS companies should involve gaining a better understanding of the third-party AC and DC appliances and converters** available to their target end-users, as well as their appliance-type preferences – in order to provide compatible and optimal solutions for users.



REFERENCES

Anker, R. & Anker, M. "Living Wage Report, Kenya", Global Living Wage Coalition, 2017.

ARMINES, Université de Liège, idmec, AEA, BRE, IASA, "Study on Comfort Fans – final report, Preparatory study on the environmental performance of residential room conditioning appliances (airco and ventilation)", 2008, https://www.eup-network.de/fileadmin/user_upload/Produktgruppen/Study_on_comfort_fans.pdf

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

Botekar. A, "Voltage fluctuation damages 100 household appliances", The Times of India, 2020, https://timesofindia.indiatimes.com/city/nashik/voltage-fluctuation-damages-100-household-appliances/articleshow/73178858.cms

cKinetics, "Peering into the future - India and the Distributed Standalone Solar Products Market", 2019, https://www.gogla.org/sites/default/files/resource_docs/report_india_and_the_solar_standalone_market_sizing_in_india_web_opt.pdf

Comello, S., Reichelstein, S.J., Sahoo, A., Schmidt, T.S., "Enabling Mini-grid Development in Rural India, Stanford Graduate School of Business", 2015, https://www-cdn.law.stanford.edu/wp-content/uploads/2016/04/Enabling-Mini-Grid-Development-in-Rural-India.pdf

Dyers, N., "Motors at Work, Motors at Work", 2018, https://www.motorsatwork.com/from-theblog/troubleshooting-series-total-harmonic-distortion/

Efficiency for Access Coalition, "Country Profile - India", 2020, https://storage.googleapis.com/e4a-websiteassets/India_CountryProfile_Final.pdf

Efficiency for Access Coalition, "Global LEAP Awards – refrigerator competition", 2019, https://globalleapawards.org/refrigerators

Efficiency for Access Coalition, "State of the Off-Grid Appliance Market Report", 2019, https://assets.publishing.service.gov.uk media/5ddd51bf40f0b650da54c52e/Clasp-SOGAM-Report-final.pdf

ESMAP, "Mini Grids in Uttar Pradesh – A Case Study of a Success Story", The World Bank Group, 2017, http://documents1.worldbank.org/curated/en/181781512395036596/pdf/ESM-fUttarPradeshMiniGridsCaseStudyConfEd-PUBLIC.pdf

European Commission, "One mobile phone charger for all", 2019, https://ec.europa.eu/growth/sectors/electrical-engineering/red-directive/common-charger_en

European Commission, "The new ecodesign measures explained", https://ec.europa.eu/commission/presscorner/detail/en/qanda_19_5889

Formica, T., Khan, H. A., & Pecht, M. G., "The Effect of Inverter Failures on the Return on Investment of Solar Photovoltaic Systems", IEEE Access, 2017, https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8039151

Global Association for the Off-Grid Solar Energy Industry (GOGLA), "Standardized Impact Metrics for the Off-Grid Solar Energy Sector", GOGLA, 2018, https://www.gogla.org/sites/default/files/resource_docs/gogla_impact_metrics.pdf

International Energy Agency, "Africa Energy Outlook 2019", 2019, https://www.iea.org/reports/africa-energy-outlook-2019

International Energy Agency, "World Energy Outlook 2018", 2018, https://www.iea.org/reports/world-energy-outlook-2018

Institute for Transformative Technologies, "Achieving universal electrification in India; A roadmap for rural solar mini-grids", Rockefeller Foundation, 2016, https://www.rockefellerfoundation.org/wp-content/uploads/Achieving-Universal-Electrification-in-India.ITTReport.April2016.pdf

Lam, N., Wallach, E., "Off-Grid Refrigeration System (OGReS) Cost Model (Version 1.0)", Schatz Energy Research Center, 2020.

Lam, N., Wallach, E., Harrison, K., Khan, S., Sridhar, P. & Jacobson, A., "Use Cases and Cost Breakdown of Off-Grid Refrigeration Systems. Efficiency for Access Coalition", 2020, Efficiency for Access Coalition, https://efficiencyforaccess.org/publications/use-casesand-cost-breakdown-of-off-grid-refrigeration-systems

McKinsey, "Brighter Africa: The growth potential of the sub-Saharan electricity sector", 2015, https://www.mckinsey.com/~/media/McKinsey/dotcom/client_service/EPNG/PDFs/Brighter_Africa-The_growth_potential_of_the_sub-Saharan_electricity_sector.ashx

REFERENCES

Mr. Appliance Blog, “What is the Lifespan of your Refrigerator?”, 2016, https://www.mrappliance.com/blog/2016/july/what-is-the-lifespan-of-your-refrigerator-/

Opiyo, N. N., "A comparison of DC- versus AC based minigrids for cost-effective electrification of rural developing communities", Elselvier, 2019, https://www.sciencedirect.com/science/article/pii/S2352484719300617

Peacock, F., “Two Reasons You Must Look At Efficiency Curves When Choosing Your Solar Inverter”, Solarquotes, 2012, https://www.solarquotes.com.au/blog/two-reasons-you-must-look-at-efficiency-curves-when-choosing-your-solar-inverter/

Planas, E., Andreu, J., Garate, J., & Ibarra, E., "AC and DC technology in microgrids: A review". Renewable and Sustainable Energy Reviews, 2015, https://www.researchgate.net/publication/272381840_AC_and_DC_technology_in_microgrids_A_review

pManifold, "Integrating energy efficiency with energy access interventions. pManifold", 2019.

Sadouki, F., “The Land of Opportunity for Off-Grid Solar”, Greentech Media, 2019, https://www.greentechmedia.com/articles/read/the-land-of-opportunity-for-off-grid-energy

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

Solar Market, "The Life Span Of A Solar Inverter", 2019, https://www.solarmarket.com.au/blog/the-lifespan-of-a-solar-inverter/

The World Bank, "Mini Grids in Kenya: A Case Study of a Market at a Turning Point", World Bank, 2017, https://openknowledge.worldbank.org/bitstream/handle/10986/29022/ESM-cKenyaMiniGridsCaseStudyConfEd-PUBLIC.pdf?sequence=1&isAllowed=y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