SUPPORTING INFORMATION ANNEX

MODEL QUALITY AND PERFORMANCE GUIDELINES FOR OFF-GRID REFRIGERATING APPLIANCES

Model Quality and Performance Guidelines for Off-Grid Refrigerating Appliances

Supporting Information Annex

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ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
AEC	Annual Energy Consumption
AEC_{max}	Maximum Annual Energy Consumption
CFC	Chlorofluorocarbon
DC	Direct Current
EEI	Energy Efficiency Index, AEC divided by AECmax
EPR	Extended Producer Responsibility
e-waste	Electrical and electronic equipment waste
GWP	Global Warming Potential
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
IEC	International Electrotechnical Commission
LEAP	Lighting and Energy Access Partnership
ODP	Ozone Depletion Potential
ODS	Ozone-depleting Substances
PV	Photovoltaic
R	AEC_{max} divided by AEC
WHO	World Health Organization

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ABOUT UNITED FOR EFFICIENCY

U4E (united4efficiency.org) is a global initiative led by UNEP, supported by leading companies and organizations with a shared interest in transforming markets for lighting, appliances and equipment, by encouraging countries to implement an integrated policy approach to energy-efficient products so as to bring about a lasting, sustainable and cost-effective market transformation.

The approach focuses on the end-user market and targets the five main components of the value chain for an energy-efficient market:

- Standards and regulations.
- Supporting policies, including education, information and training.
- Market monitoring, verification and enforcement.
- Finance and financial delivery mechanisms, including incentives and public procurement.
- Environmentally sound management and health.

U4E provides countries with tailored technical support through its in-house international experts and specialized partners, to get the most out of countries' electricity by accelerating the widespread adoption of energy-efficient products, allowing monetary savings on consumer electricity bills, helping businesses thrive through greater productivity, enabling power utilities to meet growing demands for electricity and assisting governments in reaching their economic and environmental ambitions. The initiative is present in more than 30 countries worldwide.

Based on each country's circumstances, U4E works with any of the following products: Lighting, Refrigerators, Room Air Conditioners, Electric Motors and Distribution Power Transformers – the five products that together consume more than half of the world's electricity. Such support is available at three levels: global, regional and national; providing tools and resources and supporting multiple stakeholders on international best practices, regional policy roadmaps and harmonization process recommendations through guidelines and publications, such as energy efficiency Policy Guides, Global Model Regulations Guidelines, Model Public Procurement Specifications and Financing Guidelines.

In addition, the initiative provides capacity-building and education, policy tools and technical resources, which include Country Savings Assessments completed for more than 156 countries showing the significant available financial, environmental, energy and societal benefits that are possible with a full transition to more energy-efficient electrical products. This growing suite of tools and resources equips policymakers to understand the significant opportunities and the steps needed to start transforming their markets to eco-efficient appliances and equipment.

EXECUTIVE SUMMARY

This annex provides context for the rationale underpinning the U4E Model Quality and Performance Guidelines for Off-Grid Refrigerating Appliances[1], which is voluntary guidance intended to inform market transformation efforts in developing and emerging economies that support the adoption of new off-grid refrigerating appliances with recommended parameters for quality assurance, energy efficiency, and use of refrigerants and foam-blowing agents with a lower global warming potential (GWP) than typical legacy refrigerants.

The Guidelines apply to refrigerating appliances intended for use on and/or compatible with off-grid energy systems – including those with thermal storage and solar direct drive products but excluding walk-in cold rooms – that are commonly used in residential and light commercial applications in off-grid regions. The Guidelines align with the VeraSol certification of refrigerators, which refers to the Global Lighting and Energy Access Partnership (LEAP) Award Off- and Weak-Grid Refrigerator Test Method. The Guidelines focus mainly on effective and efficient cooling (i.e., energy performance) at high ambient temperatures; meeting environmental impact expectations in GWP and ozone depletion potential (ODP) of the refrigerant and blowing agent for the insulating foam; proper functionalities in maintaining temperature without using energy storage; and providing information on key specifications, maintenance and reparability.

The recommended requirements for energy performance have been determined based on the performance of refrigerating appliances tested by the Global LEAP Awards and VeraSol. Of the 57 off-grid refrigerator models currently available and with suitable data for analyses, 25 meet the Guidelines' Intermediate requirements and 15 meet the High requirements. The Global LEAP Award-winning products (2016-17/2019) meet the Guidelines High requirements and are the most efficient designs analysed by a prior study. Performance data for off-grid refrigerator-freezers and freezers are very limited. Although only a few off-grid refrigerator-freezer models meet the Guidelines' Intermediate and High requirements based on the data analysed in this study, energy-efficient direct current (DC) products are expected to have similar or lower energy consumption than similar grid-connected products.

The suggested upper value for refrigerant GWP is 20. There are concerns about potential challenges in attempting to make this transition in the nascent, small-volume off-grid refrigerator market, where prices are already considered high and where lower-GWP refrigerants (including related technical capacity and infrastructure) are not well developed. However, studies find that low-GWP refrigerants such as R600a and R290 (GWP 3) are already penetrating this market.

Affordability is one of the biggest challenges prohibiting refrigerators from reaching off-grid consumers at a greater scale. This document highlights studies showing that energy-efficient designs offer a significant opportunity to reduce the initial purchase price of solar home systems, while other trends in the off-grid market offer avenues for improving durability and longevity, further reducing life-cycle costs.

The Guidelines provide initial considerations on repair and refurbishment options applicable to malfunctioning or broken products, as well as packaging characteristics. This document recaps recent discussions on circular economy opportunities, including the ability to repair a product and prolong its life, ahead of refurbishment and recycling.

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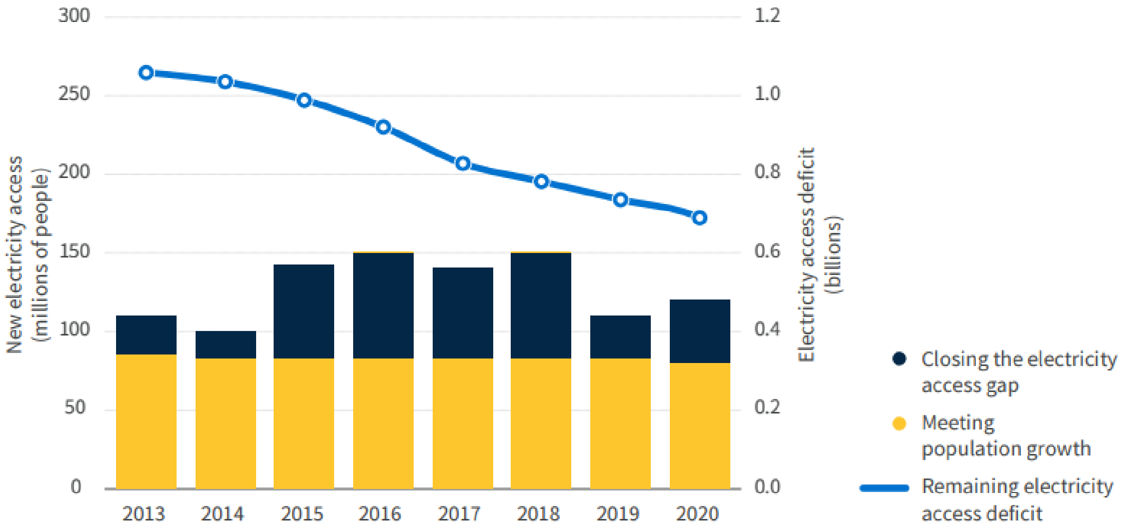
[1] Available at: https://united4efficiency.org/resources/model-quality-and-performance-guidelines-for-off-grid-refrigerating-appliances/

1 OVERVIEW: MARKET AND TECHNOLOGY TRENDS

As of 2022, 775 million people worldwide still lacked access to electricity, of which more than 80 per cent were in rural areas. Sub-Saharan Africa accounts for 77 per cent of the current gap in electricity access. While this number has steadily fallen in previous years (Figure 1), it increased in 2022 according to IEA commentary[2]. At the current rate of progress, it would still take many years to provide everyone with access to electricity at "Tier 1" levels (i.e., more than four hours of electricity supply) (Lighting Global / Energy Sector Management Assistance Program [ESMAP] *et al.* 2022).

Figure 1: Estimated number of people without electricity access, 2013-2020



Source: Lighting Global / ESMAP *et al.* (2022).

While there is a substantial market opportunity for off-grid refrigerating appliances, the penetration of household refrigerators in developing and emerging economies remains very low (e.g., 30 per cent in India and 17 per cent in sub-Saharan Africa) due to several barriers (Efficiency for Access 2019a). These include the lack of affordable products and access to financing, the high cost of energy supply, the difficulty of last-mile delivery, user hesitancy due to concerns about product failure, and a lack of after-sales service and maintenance, among others.

Studies show slower adoption rates for household refrigerating appliances than for small electronic devices and appliances such as lights, mobile phones, and fans, in part because households delay purchasing refrigerating appliances until incomes support it (Gertler *et al.* 2016; Richmond and Urpelainen 2019). In Bangladesh, rural electrification drove increased refrigerator adoption from 2.5 per cent in 2007 to more than 12 per cent in 2014, while mobile phone adoption increased from 2 per cent to nearly 90 per cent, and television usage doubled between 2004 and 2014 (Batteiger and Rotter 2018). Nonetheless, there is a positive relationship between the extent of electrification and refrigerator ownership (Barkat *et al.* 2002).

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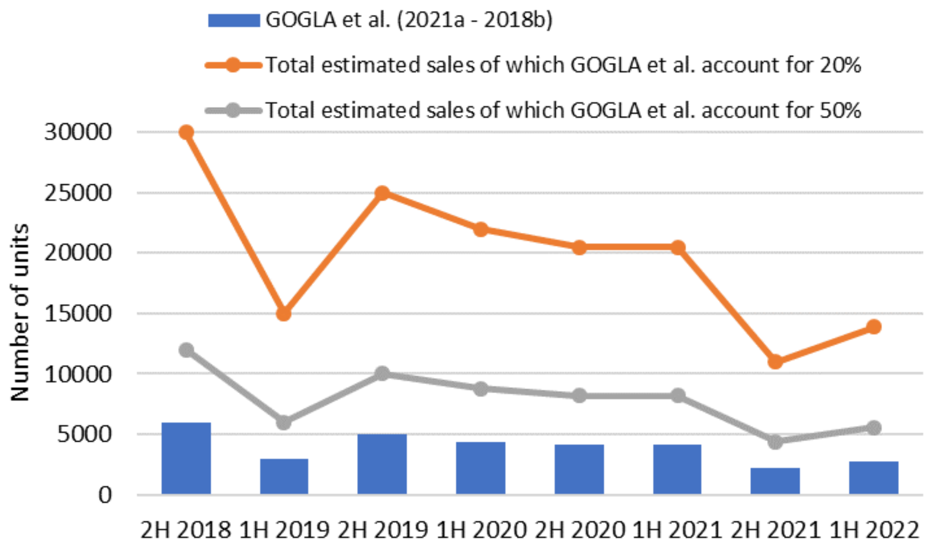
[2] https://www.iea.org/commentaries/for-the-first-time-in-decades-the-number-of-people-without-access-to-electricity-is-set-to-increase-in-2022

Every six months, the Global Off-Grid Lighting Association (GOGLA) with support from Lighting Global, the Efficiency for Access coalition and Berenschot collect data from companies through an online survey. Participating companies share data on product specifications and volumes sold per product and per country for the past half-year. Products surveyed include solar energy kits and energy-efficient electric appliances (e.g., televisions, fans, refrigeration units and solar water pumps) (GOGLA *et al.* 2022). Sales of off-grid refrigeration products between the second half of 2018 and the first half of 2021 were around 3,000 to 6,000 units. Despite remaining stable in the first half of 2021, sales dropped to around 2,200-2,800 units in the second half of 2021 and the first half of 2022 (GOGLA *et al.* 2018; GOGLA *et al.* 2021a)[3].

Lighting Global / ESMAP *et al.* (2022) provided more comprehensive data on the off-grid appliance market and estimated that a total of 5 million units (fans, televisions, solar water pumps and refrigerating appliances) were sold in 2021. It is estimated that the surveyed sales data from GOGLA *et al.* between 2018 and 2021 accounted for roughly between 20 per cent and 50 per cent of total appliance market sales (Lighting Global / ESMAP *et al.* 2022). Based on assumptions from Lighting Global / ESMAP *et al.* (2022), the annual sales of off-grid refrigerating appliances in 2021 were between 12,600 and 31,500 units (see Figure 2). While this is a rough estimate, the market size for off-grid refrigerating appliances is unquestionably far smaller than for grid-connected units, of which around 200 million were sold worldwide during the same time period (Statista 2021).

Figure 2: Estimated global sales off-grid refrigerating appliances, 2018-2021



Based on GOGLA *et al.* (2018; 2019a; 2019b; 2020a; 2020b; 2021a; 2021b) and Lighting Global / ESMAP *et al.* (2022).

The Efficiency for Access coalition and GOGLA have studied the relative market share of off-grid solar refrigerating appliances with and without thermal storage (Efficiency for Access and GOGLA 2022). The survey does not include all companies, but regular participants include established brands such as Global Ice Tech from Germany, Koolboks from Nigeria, SunDanzer from the United States, SureChill from the

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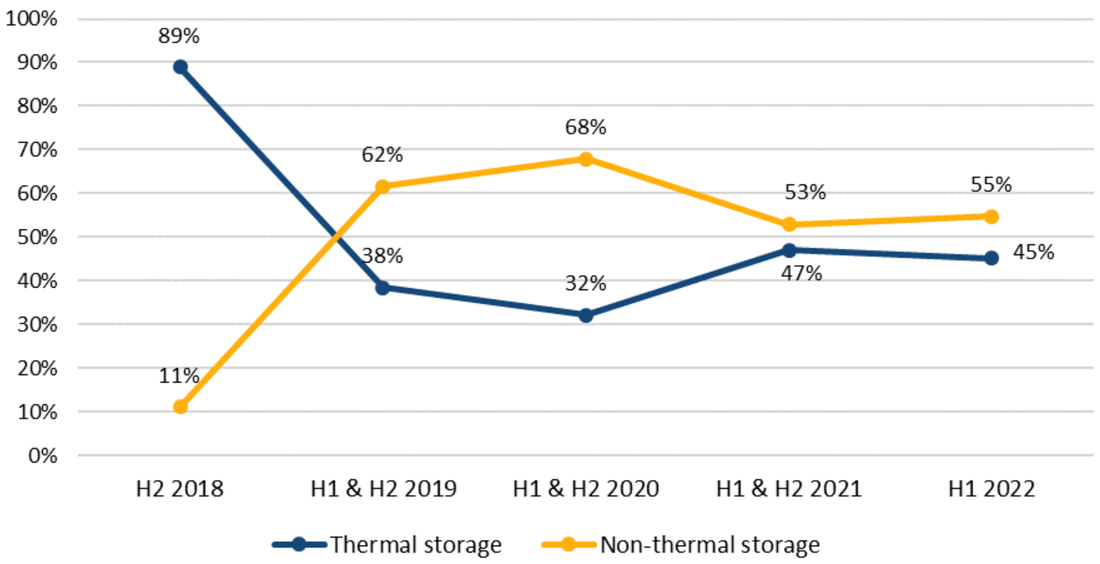
[3] These data are based on the most comprehensive third-party voluntary off-grid solar and appliance market data collection known to exist, which covers the last four years of sales from companies that are either GOGLA members or are affiliated with the Efficiency for Access and Low-Energy Inclusive Appliances (LEIA) programme activities.

United Kingdom, as well as factories that focus largely on production with branding by others. Figure 3 shows the relative sales over time, indicating that around 50 per cent of the off-grid refrigerating appliances reported to Efficiency for Access and GOGLA use thermal storage technologies that have been adapted from the vaccine refrigerator sector.

Figure 3: Market share of off-grid refrigerating appliances sold, by thermal and non-thermal storage, 2018-2022

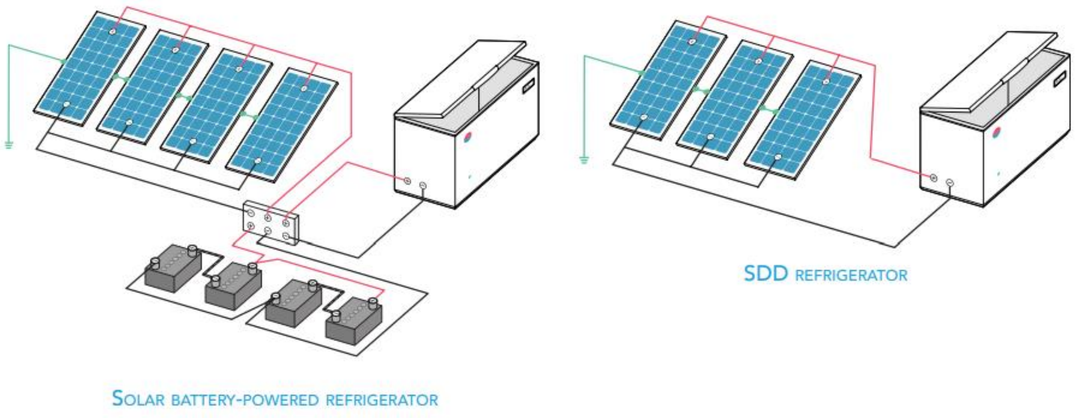


Source: Efficiency for Access and GOGLA (2022).

Although refrigerators with battery storage were introduced in the 1980s, battery technologies were not mature enough at that time to support sustained operation. Solar direct drive refrigerators connect directly to a photovoltaic (PV) energy system without an electric battery (or with a small batter for lights and auxiliary features), using PV-generated energy to freeze water (or another phase-change material) to form an “ice bank” that keeps the refrigerator cold (see Figure 4; World Health Organization [WHO] 2017, PATH and WHO 2013). This technology has been used for storing vaccines, mainly because solar direct drive refrigerators are available with an autonomy time of at least 72 hours (when tested at a constant ambient temperature above 43 degrees Celsius [°C]), and usually much longer. However, PV modules tend to be too large (i.e., oversized) for solar direct drive to meet energy requirements during poor solar irradiation.

Energy harvest controls can be applied to use surplus electricity to power additional devices such as temperature monitoring and mobile phones, and to provide lighting and other local needs. The WHO has prequalified more than 30 energy harvest systems proven to be safely coupled to vaccine refrigerators. According to the WHO Performance, Quality, and Safety (PQS) Catalog E007 for cold chain accessories (WHO n.d.), some energy harvest strategies provide around 500 Watt-hours per day of useful electricity while sustaining refrigeration needs. Solar direct drive refrigerating appliances are typically not connected to an electrical grid and would benefit from having access to excess electricity for other purposes. Energy harvest controls are designed to explore the opportunity to allow end users to use the excess electricity produced by solar direct drive refrigerators without impacting refrigeration performance.

Figure 4: Schematic of battery-powered and solar direct drive refrigerators



Source: WHO (2017).

To date, many appliances used in off-grid applications are repurposed appliances intended for stable, electricity-grid connections. Where the power supply and appliances are not directly compatible, an inverter [direct current (DC) to alternating current (AC)] or a rectifier (AC to DC) is required (Efficiency for Access 2020a). Power converters add components and associated reliability risks, increase power consumption due to efficiency loss, and add cost and quality considerations due to different surge power requirements of refrigerators (Efficiency for Access. 2020a).

The innovative use of wireless communication technology is revolutionizing the marketing, sales and financing of off-grid solar systems in some markets. Large gains in connectivity and digital access have occurred globally, including in developing countries. One increasingly popular mobile technology is pay-as-you-go (PAYGO) digital financing. PAYGO extends micro-finance to previously unbanked buyers using embedded systems that can electronically enforce repayment without the need for loan servicing agents (Phadke *et al.* 2015; Lighting Global / ESMAP 2022). Market and policy developments are needed to keep pace with technical advancements such as these.

The commercial (or “productive use”) sector currently presents a larger market opportunity than the residential sector[4]. In the commercial market, the purchase cost is offset against the revenue stream from increased sales of drinks or ice, fish or other produce as well as reduced loss and waste and the ability to sell a more extensive selection of goods preserved for longer and at a higher quality. Currently, the largest commercial market for off-grid refrigeration units is the medicine and vaccine refrigeration cold chain, which is dominated by bulk purchases for institutional use. Vaccine refrigerators are designed to provide precise and stable temperature control within a narrow temperature range, typically between 2°C and 8°C, and typically equipped with temperature monitoring and alarm systems to ensure that temperature deviations are detected and promptly addressed. In addition, off-grid vaccine applications are required to have more robust autonomy performance when the primary power is not supplied. The “productive use of energy,” or the ability to generate income using refrigerators and freezers, helps justify appliance purchases in micro, small or medium enterprise contexts (Efficiency for Access. 2019b).

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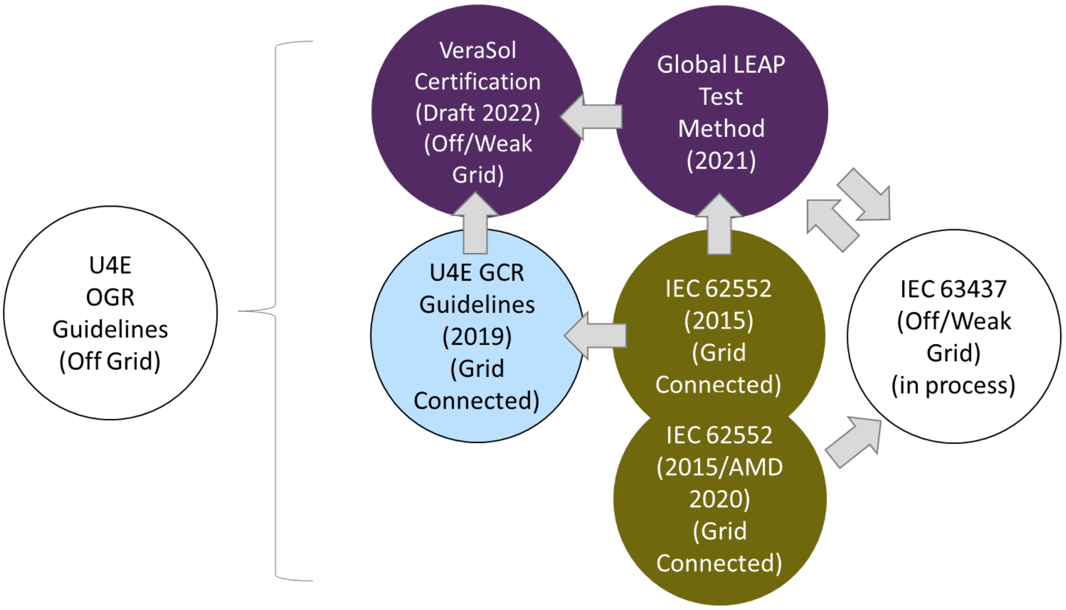
[4] According to interviews with 172 micro-enterprises in Uganda, around 70 per cent use grid-connected refrigeration units to sell cold drinks, nearly 15 per cent for ice cream and 10 per cent for other food items (Energy4Impact 2017).

2 GUIDELINES: SCOPE AND PRODUCT CATEGORIES

The product scope of the U4E Model Quality and Performance Guidelines for Off-Grid Refrigerating Appliances (OGR Guidelines) aligns with VeraSol certification of refrigerators,[5] which refers to the Global Lighting and Energy Access Partnership (LEAP) Award Off- and Weak-Grid Refrigerator Test Method[6] (VeraSol 2022). During the development of the U4E OGR Guidelines, the new International Electrotechnical Commission (IEC) standard (IEC 63437 Off- and Weak-Grid Refrigerating Appliances – Characteristics and Test Methods) was simultaneously under development (IEC 2022). Hence the U4E OGR Guidelines, Global LEAP Award test method (Global LEAP 2021) and VeraSol certification requirements are expected to be updated once the IEC 63437 standard is released.

Figure 5: Schematic of the U4E OGR Guidelines aligned with existing standards



a. The VeraSol Certification refers to the Global LEAP Test Method for performance tests and U4E Model Regulation Guidelines for Energy Efficiency and Climate Friendly Refrigerating Appliances (U4E GCR Guidelines – which address grid-connected products) for minimum energy performance requirements.
b. The current version of the Global LEAP Test Method refers to IEC 62552: 2015 and initial input to IEC 63437 and will be updated once the IEC 63437 standard is released.
c. The U4E GCR Guidelines refers to IEC 62552: 2015.

Source: Authors' work.

The U4E OGR Guidelines apply to refrigerating appliances intended for use on and/or compatible with off-grid energy systems and offered for sale or installed in any application. Table 1 shows the scope of the U4E Model Regulation Guidelines for grid-connected refrigerating appliances (UNEP 2019), commercial refrigeration equipment (UNEP 2021a) and off-grid refrigerating appliances (UNEP 2023). Table 2 and Table 3 show the product coverages of the Guidelines, VeraSol certification and the Global LEAP Award Test Method.

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[5] Draft Version 0.1 as of June 2022 (VeraSol 2022).
[6] Version 3, July 15, 2021 (Global LEAP 2021).

Table 1: Scope of U4E Model Guidelines for refrigeration equipment and appliances

	Grid-Connected Refrigerating Appliances (U4E GCR Guidelines)	Commercial Refrigeration Equipment (U4E CRE Guidelines)	Off-Grid Refrigerating Appliances (U4E OGR Guidelines)
Mains connected	• Connected to AC grid[a]	• Connected to AC grid[a]	• Not connected to AC grid (off grid)
Scope	• Refrigerators • Refrigerator-freezers • Freezers	• Refrigerated display cabinets • Refrigerated storage cabinets • Beverage coolers • Scooping cabinets • Ice cream freezers • Refrigerated vending machines	• Refrigerating appliances[b] for use with a photovoltaic module, a solar home system - Refrigerators - Refrigerator-freezers - Freezers
Energy efficiency	• Focuses on standards and labels, referring to best practices and best available technologies • Largely aligns with EU 2021/2024, India, Mexico and the United States	• Focuses on standards and labels, referring to best practices and best available technologies • Largely aligns with Australian 2021 and EU 2021 standards	• Largely aligns with the VeraSol certification standard (draft version 0.1) • Refers to international practices, e.g., Global LEAP Awards
Reference test/safety standards	• IEC 62552: 2015 • IEC 60335-2-24 2010/AMD: 2017	• ISO 23953: 2015 • ISO 22041: 2019 • ISO 22043: 2020 • ISO 22044: 2021 • IEC 63252: 2020 • EN 16838: 2016 • IEC 60335-2-89: 2019 • IEC 60335-2-75: 2012/AMD2: 2018	• Draft working document of IEC 63437 standard • Global LEAP Awards Test Methods (v3, 2021) (referenced IEC 62552: 2015) • VeraSol certification standard • IEC 60335-1, IEC 60335-2-24 (or -2-75, or -2-89)
Efficiency metrics	• Annual energy consumption (24°C, 20°C or 32°C)	• Annual energy consumption (25°C)	• Annual energy consumption (32°C)
Refrigerants	• GWP 20 or less • ODP 0	• GWP 150 or less • ODP 0	• GWP 1 500 or less / 20 or less • ODP 0

a. Implies a typical electricity grid that meets the quality requirements of IEC TS 62749: 2020 Assessment of power quality – Characteristics of electricity supplied by public networks. This standard sets out expected characteristics of electricity at the supply terminals of low-, medium- and high-voltage, 50 Hertz (Hz) or 60 Hz public networks.

b. Solar direct drive types are included along with the development of IEC 63437 standard and VeraSol certification standard.

Sources: UNEP (2019); UNEP (2021a); UNEP (2023).

Table 2: Scope of off-grid refrigerating appliances in the U4E OGR Guidelines, VeraSol, and Global LEAP Award Test Method, by power source and user context

Power Source / User Context		Device Power Input	Power Conversion	VeraSol[a]	Global LEAP[a]	U4E OGR Guidelines
Solar home system kit	12/24 VDC	DC	Not needed	🟩	🟩	🟩
		AC	DC-AC inverter	b	🟩	
Mini-grid	24/48 VDC	DC	Not needed	🟩	🟩	🟩
		AC	DC-AC inverter	🟩	🟩	🟩
	110-230 VAC	DC	AC-DC converter	🟩	🟩	🟩
		AC	Not needed	🟩	🟩	🟩
Weak grid	110-230 VAC	DC	AC-DC converter		🟩	
		AC	Not needed	🟩	🟩	

Green cells indicate that the product type is covered.

a. VeraSol Certification Draft v0.1 (VeraSol 2022); Global LEAP Award Test Method v3 (Global LEAP 2021).
b. Certifying Solar Home System kits by VeraSol do not currently cover AC outputs but may when the scope is expanded in the future.
c. Stand-alone AC-powered refrigerators are generally covered by the U4E GCR Guidelines (UNEP 2019); however, the U4E OGR Guidelines do not have provisions for their operation with inverters or with mini- and weak grids.

Table 3: Scope of off-grid refrigerating appliances in the U4E OGR Guidelines, VeraSol, and Global LEAP Award Test Method, by technology type or application

	VeraSol	Global LEAP	U4E OGR Guidelines
Refrigerators with ice-making compartment	a	a	🟩
Refrigerating appliances with auto defrost			
Ice-pack or water-pack refrigerators	🟩	🟩	🟩
Solar direct drive refrigerators	🟩	🟩	🟩
Vaccine refrigerators[b]			
Walk-in cold rooms[c]			

a. Not explicitly specified. Refrigerators with an ice-making compartment and manual defrost may be included, while those with an automatic defrost frozen compartment will not.
b. Excluding those used in a vaccine cold chain, as those should be managed through the WHO PQS system.
c. Excluding those, as the International Institute of Refrigeration (IIR) and others are working on this.

Weak-grid refrigerating appliances are not included in the U4E OGR Guidelines, in part because no formal or internationally recognized definition of what constitutes a “weak grid” has been identified yet. Although it could loosely be defined as a grid that does not meet the quality requirements of IEC TS 62749 in several aspects (e.g., through intermittency, voltage brown-outs, frequency variation, voltage surges, spikes, etc.), characteristics of weak-grid refrigerating appliances need to be further investigated. The majority of grids in developing countries have “weak-grid” characteristics at some point, especially with regard to the risks associated with appliance damage due to power fluctuations and surges from brown- or blackouts.

2.1 Reference standards

The U4E OGR Guidelines use definitions largely consistent with the existing standards (see Table 4). While the U4E OGR Guidelines refer to Global LEAP (2021) and IEC (2015a; 2020), there are differences, particularly in the definitions of refrigerators and freezers. Global LEAP (2021) defines refrigerators and freezers as unfrozen and frozen compartments, respectively, while IEC (2015a; 2020) and UNEP (2019) define them as fresh food and freezer compartments.

For solar direct drive cold chain refrigeration equipment (e.g., compression-cycle solar direct drive without battery storage), the WHO PQS has published equipment specifications and verification protocols for testing and field evaluation, as well as guidelines for manufacturers of solar power systems and energy harvest controls. There are two performance test methods for other solar direct drive applications: The Global LEAP Off- and Weak-Grid Refrigerator Test Method (v3) and a method developed by the Danish Technological Institute (DTI). As both methods are based on WHO/PQS/E003/RF05-VP.4 (solar direct drive refrigerator and freezer) and IEC 62552-2:2015 (on-grid refrigerating appliances), the energy consumption test conditions are largely consistent but the individual test methods have differences. For example, the DTI method uses light load (at 4.5 kilograms per 100 litres), while the Global LEAP method does not. If IEC 63437 includes a test procedure for evaluating energy consumption in solar direct drive refrigerators, the U4E OGR Guidelines will be updated to refer to it.

Table 4: Comparison of selected terms and definitions in the U4E OGR Guidelines and key references

Term	Global LEAP	IEC 62552-1: 2015 (and AMD1: 2020)	U4E OGR Guidelines
Unfrozen compartment	Compartment for the storage and preservation of unfrozen products where the storage compartment reference temperature is above 0°C.	Any of the following compartment types; zero-star (≤0°C)[a], chill, fresh food, cellar, wine storage or pantry.	Compartment for the storage and preservation of unfrozen products where the storage compartment reference temperature is above 0°C and zero-star compartments, i.e., any of the following compartment types: zero-star, 8°C, fresh food and cellar.
Fresh food compartment	Compartment for the storage and preservation of unfrozen food, where the reference temperature is 4.0°C.	Compartment for the storage and preservation of unfrozen foodstuff, where the reference temperature is 4.0°C.	Compartment for the storage and preservation of unfrozen food, where the reference temperature is 4.0°C.
8°C compartment	Not defined.	Compartment primarily designed for food and beverages to be stored at a reference temperature of 8.0°C.	Compartment primarily designed for food and beverages to be stored at a reference temperature of 8.0°C.
Cellar compartment	Compartment for the storage of foodstuff at a temperature that is warmer than that of a fresh food compartment.	Compartment primarily designed for food and beverages to be stored at a reference temperature of 12.0°C.	Compartment primarily designed for food and beverages to be stored at a reference temperature of 12.0°C.
Frozen compartment	Compartment for the storage and preservation of frozen products where the storage compartment reference temperature is equal or below 0°C.	Any of the following compartment types: one-star (-6°C) two-star (-12°C) three-star (-18°C) four-star (-18°C)[b]	Compartment for the storage and preservation of frozen products where the storage compartment reference temperature is equal to or below 0°C, i.e., any of the following compartment types: one-star, two-star, three-star, four-star.

Term	Global LEAP	IEC 62552-1: 2015 (and AMD1: 2020)	U4E OGR Guidelines
Freezer compartment	Not defined.	Three-star (-18°C), four-star (-18°C).	Compartment that meets three-star or four-star requirements. (In certain instances, two-star sections and/or sub-compartments are permitted within the compartment.)
Refrigerator	One or more unfrozen compartments.	At least one fresh food compartment (unfrozen foodstuff).	Refrigerating appliance intended for the storage of foodstuff, with at least one fresh food compartment.
Multi- or variable temperature refrigerator	Operated either as an unfrozen compartment or as a frozen compartment.	Intended for use as two (or more) alternative compartment types (e.g., a compartment that can be either a fresh food compartment or freezer compartment).	Refrigerating appliance that has one compartment with a multi or variable temperature that can be operated either as unfrozen or as frozen.
Refrigerator-freezer	At least one unfrozen compartment and at least one frozen compartment.	One fresh food compartment and at least one freezer compartment.	Refrigerating appliance having at least one fresh food compartment and at least one frozen compartment, excluding zero-star compartment.
Freezer	One or more frozen compartments.	Only frozen compartments, at least one of which is a freezer compartment.	Refrigerating appliance having one or more frozen compartments.

a. Although ice-making compartments and zero-star compartments operate below zero, they are configured as unfrozen compartments for energy and performance tests in IEC 62552.

b. One-star, two-star and three-star compartments are those where the storage temperature is not warmer than -6°C, -12°C, and -18°C, respectively. A four-star compartment is one where the storage temperature meets three-star conditions and where the minimum freezing capacity meets the requirements of Clause 8 of IEC 62552-2: 2015 / AMD 1: 2020.

Source: IEC (2015a); Global LEAP (2019); IEC (2020); UNEP (2023).

3 ENERGY PERFORMANCE AND MARKET AVAILABILITY

Given the unique and various characteristics of these appliances and the early-stage nature of the market, the U4E OGR Guidelines focus mainly on the following:

a) Effective and efficient cooling at high ambient temperatures
b) Meeting environmental impact expectations (e.g., energy efficiency, GWP and ODP of the refrigerant and blowing agent for the insulating foam, packaging, etc.)
c) Good “holdover” or “autonomy” time (i.e., maintaining reduced temperature without using energy storage)
d) Good electrical resilience (i.e., ability to withstand disturbances in electrical supply)
e) Ease of maintenance and reparability (may also be provided via after-sales service)
f) Functional design (e.g., appropriate compartment temperature)

3.1 Energy performance

Energy consumption values are obtained from test standards. While the standard for measuring refrigerator energy consumption is broadly similar across countries, a number of factors can drive variations in energy consumption values (e.g., Watt-hours per day or kilowatt-hours per year), in particular different specifications for ambient temperature, compartments’ internal temperature, and additional features in the test procedure. The differences in test conditions and/or use of the test results lead to different energy consumption values, making it difficult to compare across regions (UNEP 2019).

For on-grid refrigerating appliances, many parameters or features are considered in evaluating energy performance. A streamlined approach, similar to UNEP (2019), provides some useful indicators for evaluating off-grid refrigerating appliances. The maximum energy consumption requirements are stipulated for refrigerating appliances within three broad product categories – refrigerators, refrigerator-freezers and freezers – that can be adjusted in accordance with country- or region-specific market characteristics.

Refrigerating appliances for household and light commercial use are typically designed for an ambient temperature of 16°C or greater. National standards that adopt IEC 62552 for on-grid refrigerators (IEC 2015a; IEC 2015b; IEC 2015c; IEC 2020) are based on energy performance at 16°C and 32°C. The U4E OGR Guidelines are aligned with a working draft of IEC 63437, the U4E GCR Guidelines and the VeraSol Certification draft standard. Table 5 and Figure 6 show the energy performance requirements of the U4E OGR and GCR Guidelines.

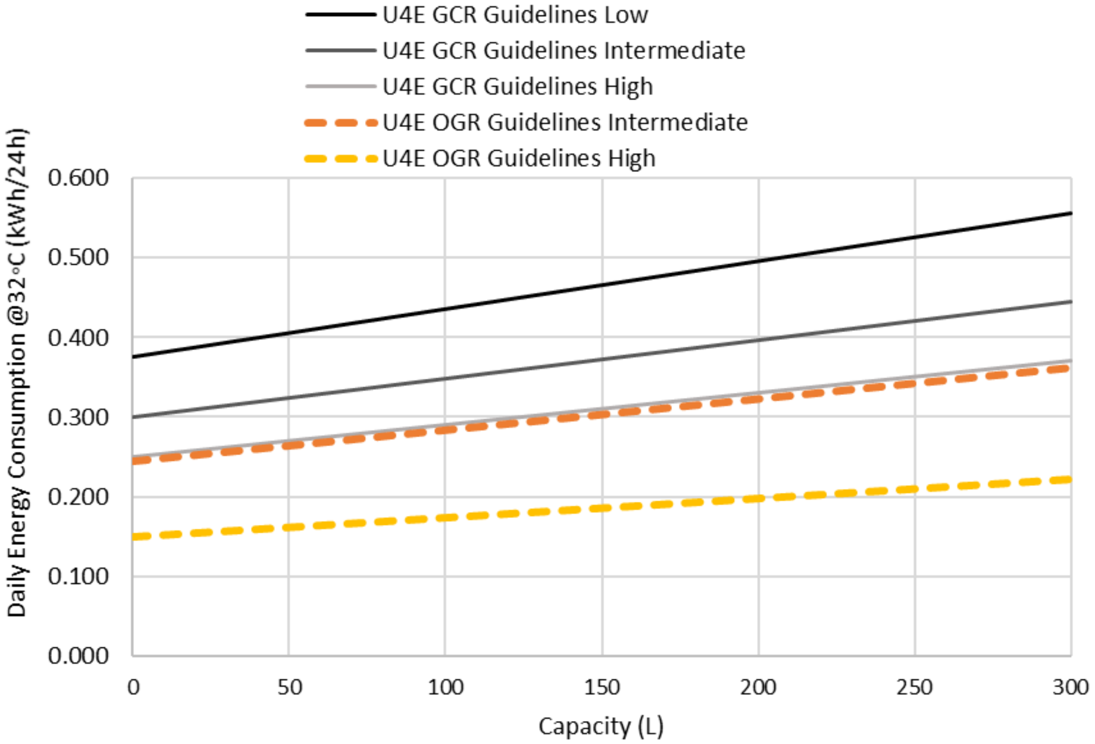
The U4E GCR Guidelines (UNEP 2019) define an energy performance index R as maximum annual energy consumption (AEC_{max}) divided by AEC, in a reverse form of the energy efficiency index (EEI), defined as AEC over AEC_{max} used in other programmes. The Guidelines provide energy performance requirements in both metrics (Table 5).

Table 5: The U4E OGR Guidelines' energy performance requirements for off-grid refrigerating appliances

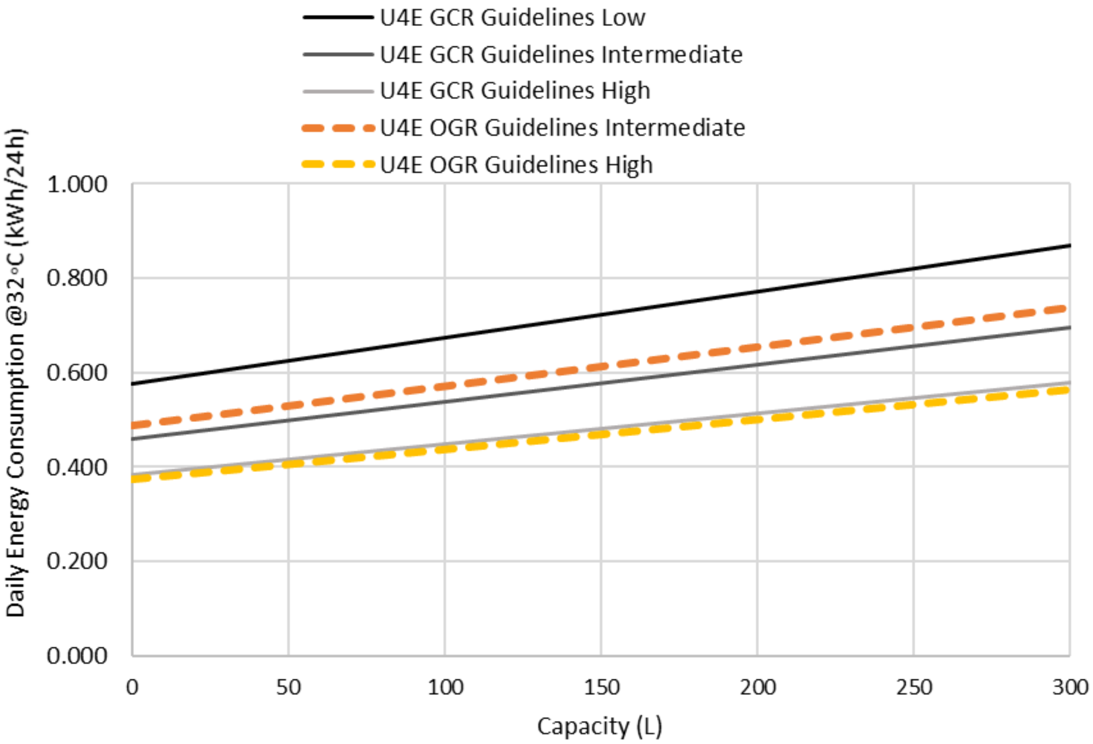
	Maximum Annual Energy Consumption (AEC_{max}) at Reference Ambient Temperature 32°C (kWh/y)	R = AEC_{max}/AEC EEI = AEC/AEC_{max}		
		Index	Intermediate	High
Refrigerators	0.220×AV+137	R	1.54	2.50
		EEI	0.65	0.40
Refrigerator-freezers	0.288×AV+210	R	1.17	1.54
		EEI	0.85	0.60
Freezers	0.268×AV+247	R	1.17	1.54
		EEI	0.85	0.60

Figure 6: The U4E OGR Guidelines' energy performance requirements compared to U4E GCR requirements for on-grid refrigerating appliances

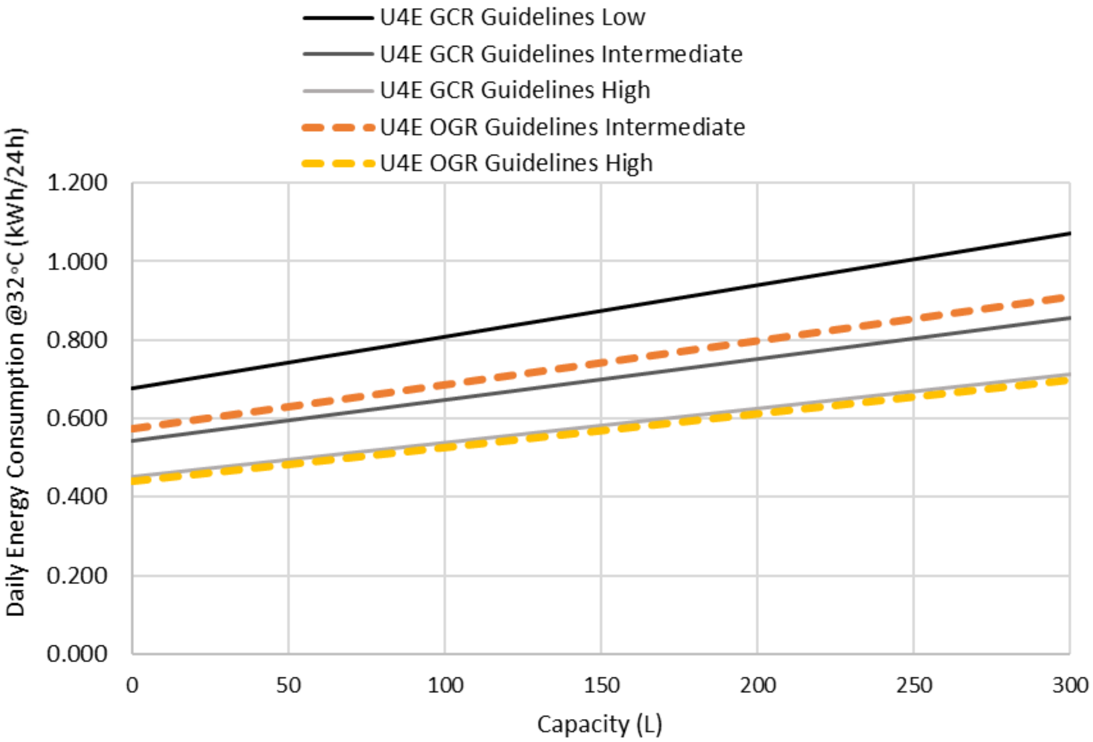
(a) Refrigerators



(b) Refrigerator-freezers

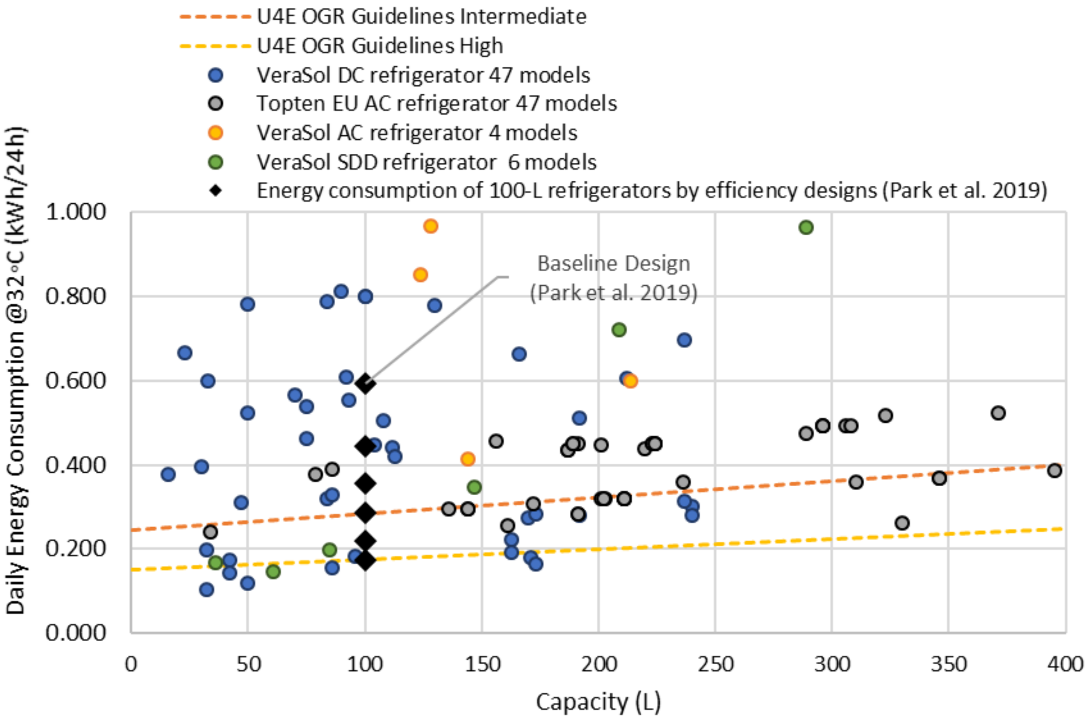


(c) Freezers



The energy performance requirements have been determined based on the performance of refrigerating appliances tested by the Global LEAP Awards and the VeraSol programme. Of 57 off-grid refrigerator models currently available on the market, 25 meet the U4E OGR Guidelines' Intermediate requirements and 15 meet the Guidelines' High requirements. For 100-litre refrigerators, the U4E OGR Guidelines' energy consumption requirements are close to the energy consumption by efficient design sets analysed by Park *et al.* (2019) (see Figure 7 and Figure 14). The Global LEAP Award-winning products (2016-17/2019) meet the U4E OGR Guidelines' High requirements, as does the most efficient design analysed by Park *et al.* (2019) (see Figure 8). If the energy consumption of the 57 off-grid refrigerator models is normalized to 100-litre capacity, 18 (32%) are estimated to meet the U4E OGR Guidelines' Intermediate requirements and 10 (18%) meet the Guidelines' High requirements (see Figure 9).

Figure 7: The U4E OGR Guidelines' energy performance requirements and performance of off-grid refrigerators

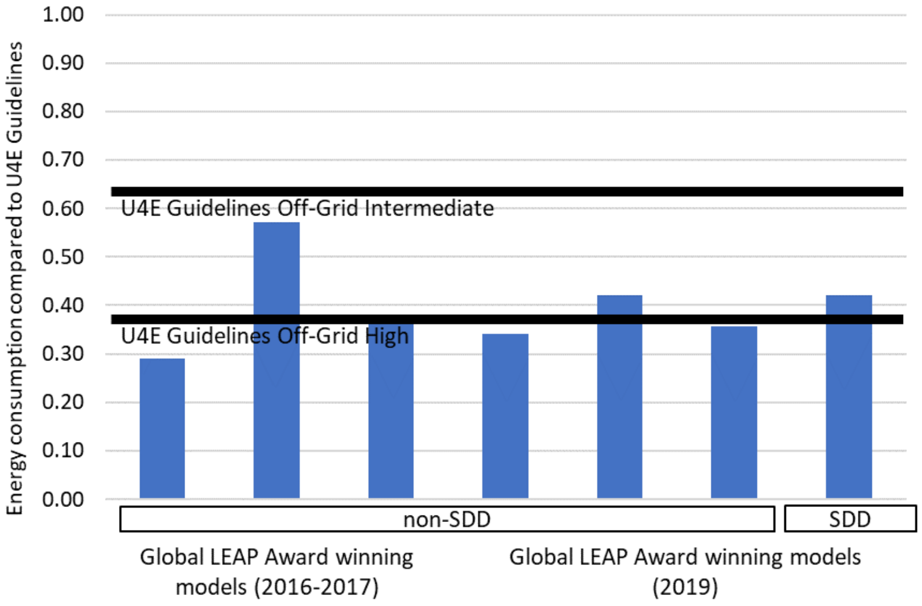


Note: Given that the European Union standard is based on an ambient temperature of 24°C, we used an adjustment factor in which energy consumption at 32°C = 1.44 x energy consumption (24°C). The adjustment factor 1.44 is the authors' assumption based on performance data.

See Figure 12 for efficiency designs analysed by Park *et al.* (2019).

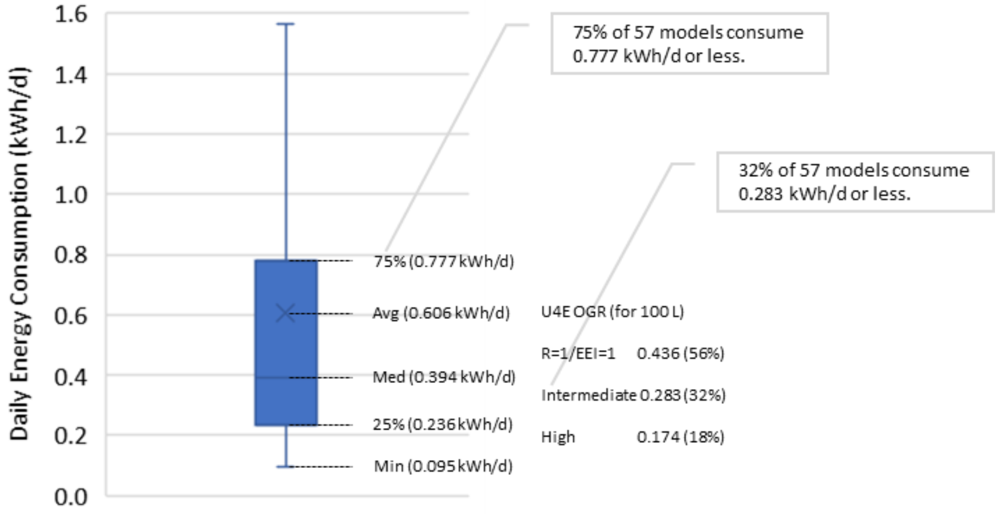
Source: Authors' work.

Figure 8: The U4E OGR Guidelines' energy performance requirements and best available off-grid refrigeration appliances as exemplified by Global LEAP Award-winning refrigerators



Source: Authors' work.

Figure 9: Energy consumption of 57 models, normalized to 100-litre capacity

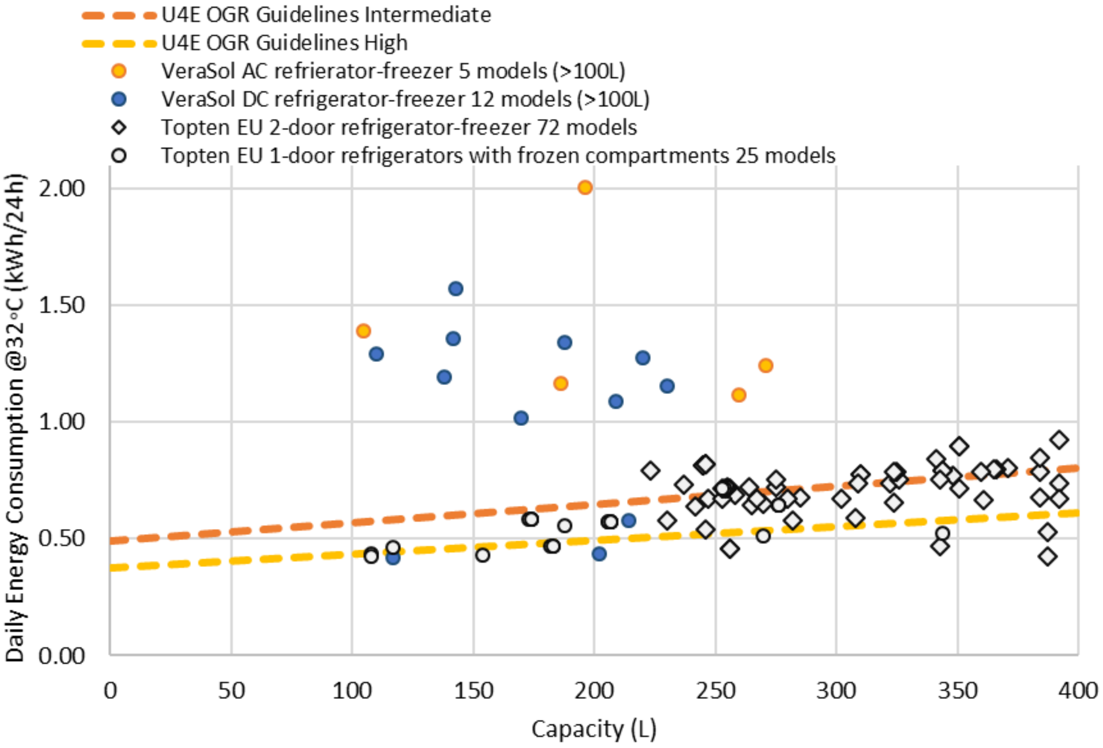


Note that four models whose energy consumption exceeds 1.6 kWh per day were excluded from this chart.

Source: Authors' work.

Performance data for off-grid refrigerator-freezers and freezers are limited. In addition, one-door refrigerators with a frozen compartment are categorized as refrigerator-freezers in the Global LEAP Awards and the VeraSol database, but these are classified as refrigerators under IEC 62552. Regardless, they seem to be less efficient than similar products in energy-efficient grid-connected markets, where there are large commercial market demands combined with regulatory pressures for this level of performance and where highly efficient products exist. Although only a few off-grid refrigerator-freezer models meet the U4E OGR Guidelines' Intermediate and High requirements based on the data analysed in this study (see Figure 10), energy-efficient DC products are expected to have similar or lower energy consumption compared to similar grid-connected products, as shown in the case of off-grid refrigerators (see Figure 7).

Figure 10: The Guidelines' energy performance requirements and performance of off-grid refrigerator-freezers (> 100 litres)



Source: Authors' work.

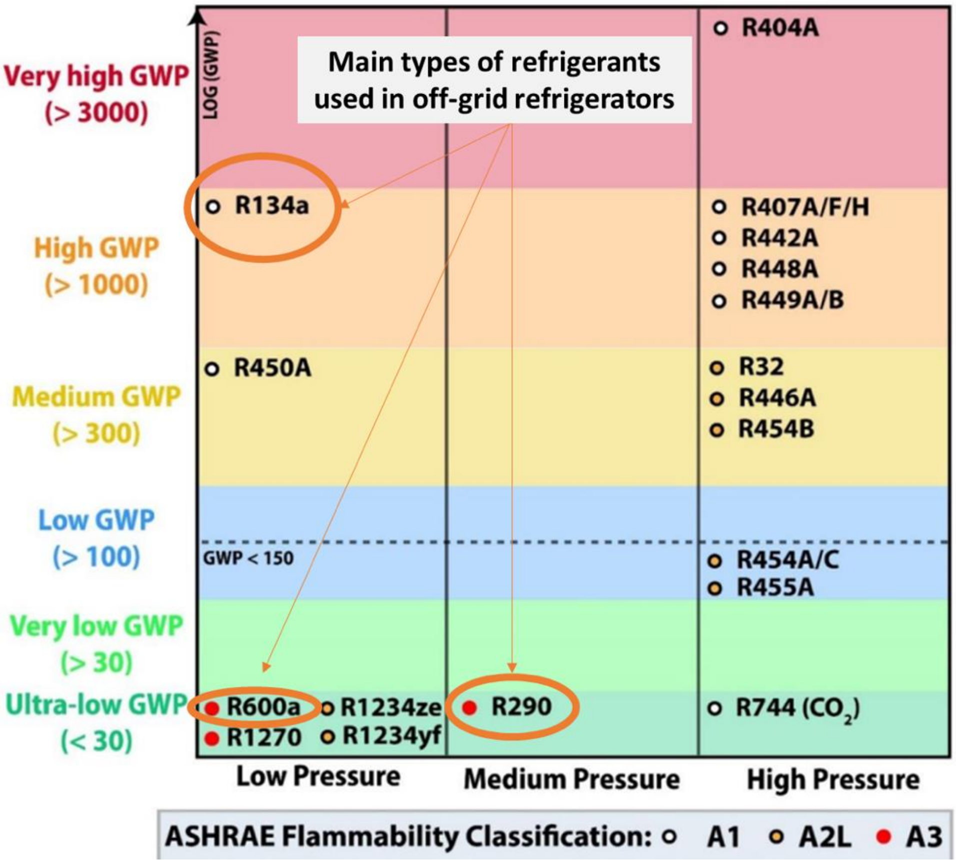
In general, testing appliances at standard test conditions may not be sufficient to determine performance in actual use-case conditions where commercial use typically adds further draws on power consumption by more frequent opening of the refrigerating appliances and re-stocking by adding warm contents. Abagi, Ireri and Lai (2019) assessed that the energy consumption difference between lab and field testing is significant, and field testing provides some useful insights on consumer preferences, behaviour, and usage patterns and how these variables affect the technical performance of refrigerators. Nevertheless, performance evaluated at standard test conditions provides useful information to end users when they make purchase decisions among similar products as they are tested in the same manner.

3.2 Lower-GWP refrigerant options

The Montreal Protocol on Substances that Deplete the Ozone Layer (the Montreal Protocol) was adopted in 1987 to regulate the production and consumption of nearly 100 ozone-depleting substances. While the Montreal Protocol originally focused on ozone layer protection, it also contributed to climate change mitigation by phasing out the use of ozone-depleting substances such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), both potent greenhouse gases, and by encouraging parties to promote alternatives that minimize impacts on climate and meet other health, safety and economic considerations (Park *et al.* 2021). There are concerns about the challenges faced by attempting to meet this transition in such nascent and small-volume off-grid refrigerator markets, where prices are already considered high and beyond the means of many who need them, and where lower-GWP refrigerants (including their associated technical capacity) are not well developed.

Efficiency for Action (2021) finds that the off-grid refrigerator market is dominated by the use of R134a and R600a (see Figure 12). When considering applying the U4E OGR Guidelines in a market transformation programme, it is encouraged to combine the transition towards higher efficiency with the transition towards lower-GWP refrigerants, whereby manufacturers exploit synergies in redesigning equipment and retooling manufacturing lines to pursue both opportunities simultaneously.

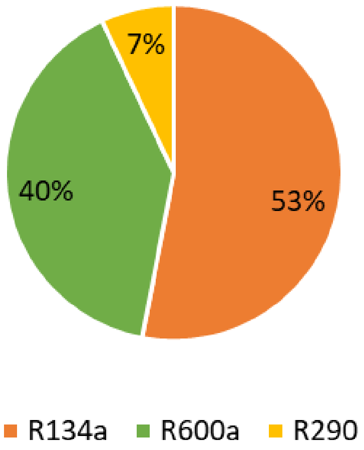
Figure 11: GWP values, flammability classifications, and operating pressures of the refrigerants used in refrigeration systems and the main types of refrigerants used in DC refrigerators in off-grid settings



Note: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Flammability Classification: A1 (No flame propagation); A2L (Lower flammability); A2 (Flammable); A3 (Higher flammability)

Source: Efficiency for Access (2021); UNEP (2021b).

Figure 12: Proportion of off-grid refrigerator companies using HFCs and natural refrigerants in sub-Saharan Africa and South Asia, by refrigerant type



Source: Efficiency for Access. (2021).

4 ENERGY-EFFICIENT DESIGNS, COSTS AND BENEFITS

Price sensitivity in off-grid rural areas of developing countries is a fundamental consideration for businesses, governments, and organizations aiming to provide sustainable energy solutions. High upfront costs for renewable energy systems or energy-efficient appliances can be a significant barrier to adoption in off-grid rural areas. Even if these technologies promise long-term savings, the initial investment can deter potential buyers. To expand adoption in off-grid markets, it is essential to offer affordable, accessible, and economically viable products and services that align with the financial realities and priorities of the local population. Table 6 shows the typical product capacity and price, as well as the percentage of rural households that own refrigerators, in eight selected countries, although the data refer to refrigerating appliances only (without solar home systems).

Table 6: Typical product capacity/price and household ownership of refrigerators in selected countries

Country	Typical Product Capacity (L)	Typical Product Price (US$)	Share of Rural Population that Owns Household Refrigerators (%)
Côte **d'I**voire	50-250	$200-1,300	4% (2011-2012)
Ethiopia	50-100	$700-900	0% (2016)
India	200-250	$525-825	16% (2015-2016)
Kenya	35-112	$500-800	2% (2015)
Myanmar	200-250	$525-825	6% (2015-2016)
Nigeria	42-250	$250-1,000	11% (2015)
Sierra Leone	50-250	$200-1,300	0% (2013)
Uganda	50-100	$700-900	2% (2016)

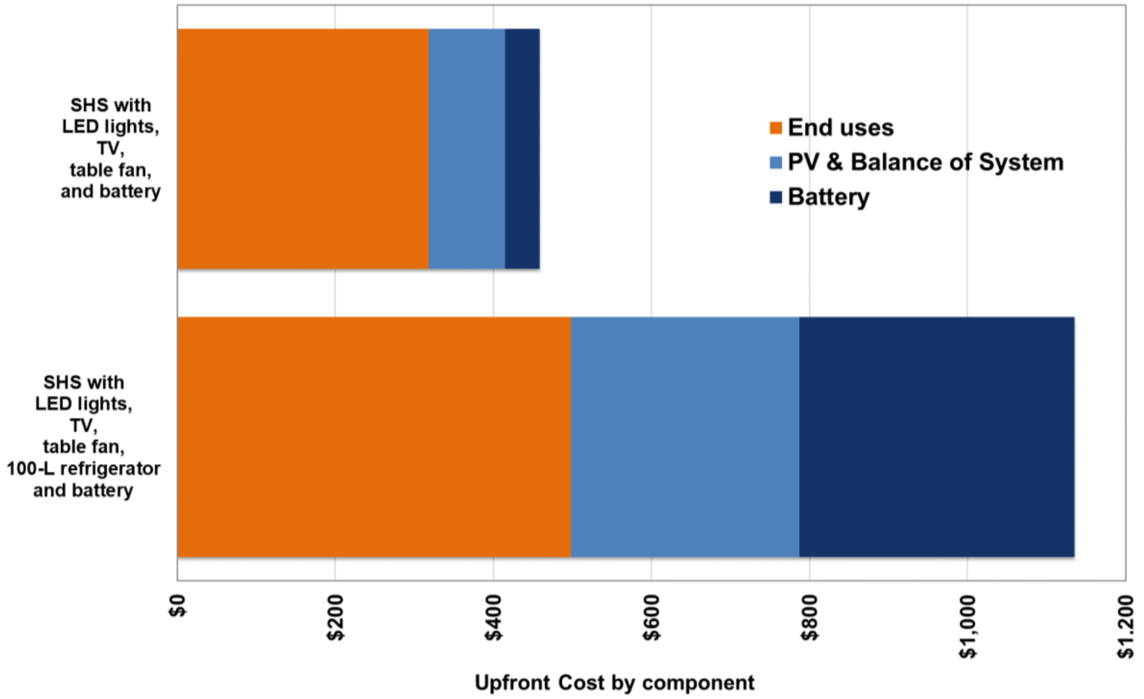
Note: Prices refer to refrigerating appliances only and can vary by energy performance and other features at the same size. The data do not specify AC- or DC-powered refrigerating appliances.

Source: Efficiency for Access (2019c).

Energy-efficient appliances offer a great opportunity to reduce the initial price of solar systems as the PV needs are down-sized, while other trends in the off-grid energy market offer avenues for improving durability and longevity, further reducing life-cycle costs. For example, system durability strongly influences the environmental and human development outcomes associated with using off-grid energy systems (Phadke *et al.* 2015; Efficiency for Access 2019d). However, highly efficient DC-powered refrigerators that require smaller solar home systems are currently expensive niche products that are unaffordable for most consumers.

A 100-litre refrigerator running 24 hours per day at 60 Watts rated power would roughly double the daily consumption of a solar home system with phone charging, two LED lamps, a television and a table fan. This addition represents doubling the upfront cost of investing in a much larger solar array (see Figure 13, which compares two cases). A price point of US$200 and a power rating of less than 40 Watts have been suggested as economically viable targets for many typical rural off-grid customers, although this varies widely depending on the local context (Efficiency for Access 2019b).

Figure 13: Estimated purchase prices for two solar home system cases



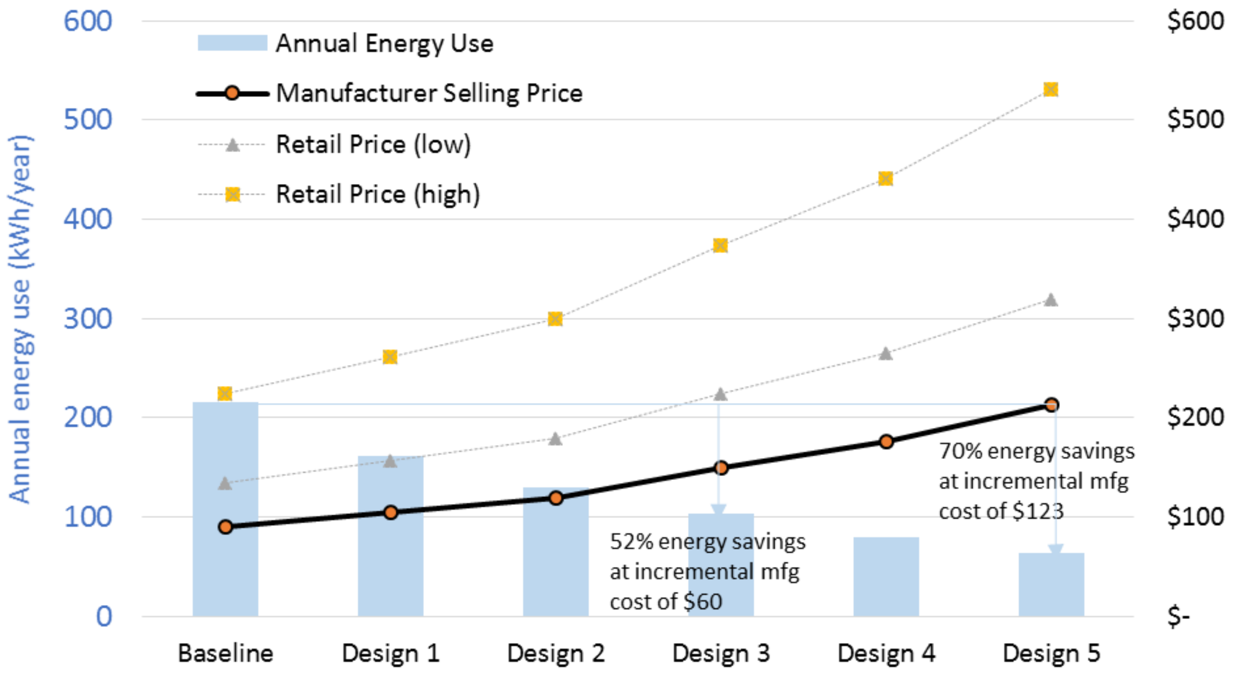
Assumptions: One mobile phone (2Wx2.5h), light bulbs (4Wx5h), one small table fan (8Wx4h), one television (12Wx4h) and one 100-litre refrigerator (60W, 592 Wh/24h). Note that the results are based on modelled data to show the difference between the two cases; actual system sizing and price would vary by practice since it would need to conform to available end uses and component sizes for PV modules and batteries.

Source: Authors' work based on assumptions adjusted from Park *et al.* (2019) and Phadke *et al.* (2015).

Park *et al.* (2019) assessed the technical potential to reduce the energy consumption of small refrigerators using commercially available technology to determine whether refrigerators could be made more affordable for off-grid populations (i.e., both the cost of the refrigerator and the cost of a solar home system capable of powering a refrigerator). The study explains that the higher prices for off-grid DC refrigeration products are likely because of higher mark-ups, higher costs of efficient components (e.g., DC compressors) and a lack of economies of scale. Thus, the data currently available on the cost of small, efficient DC refrigerators likely do not accurately represent the cost of small, efficient refrigerators deployed at scale.

To evaluate whether energy-efficient refrigerators can reduce the cost of providing refrigeration service in off-grid settings, we need to know the cost of small, efficient refrigerators produced at scale, not just the current prices of efficient DC refrigerators. Park *et al.* (2019) found that improving the efficiency of small refrigerators can reduce their annual energy use and therefore reduce the size and cost of the solar home system required to power them by up to 70 per cent. Further, efficiency improvements can reduce the annualized consumer cost of refrigeration service by up to around 50 per cent, even with the extra up-front cost. Figure 14 shows the Park *et al.* (2019) estimated manufacturing cost, retail price and associated efficiency improvement over a 100-litre refrigerator baseline.

Figure 14: Estimated incremental cost versus efficiency improvement over the 100-litre baseline



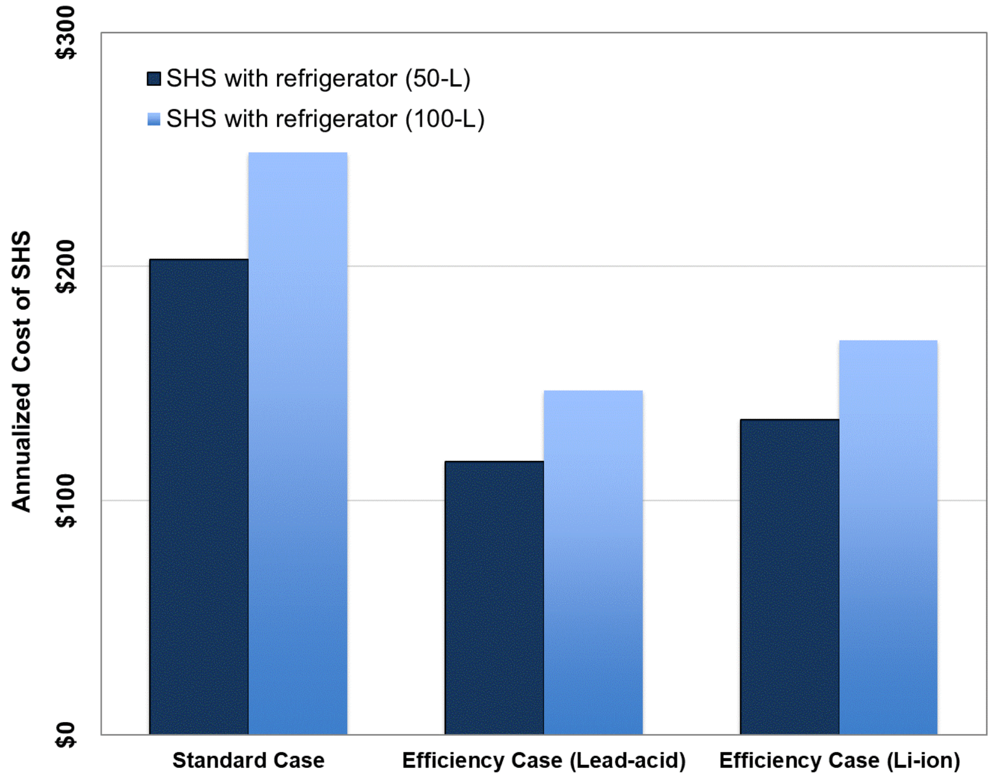
	kWh/year (at 32°C)	Energy Savings (%)	Manufacturing Cost ($)	Cost Increase (%)
Baseline (COP 1.4, insulation 3.8cm)	216	–	90	–
Design 1: Insulation thickness 5.8 cm	162	25	105	17
Design 2: Design 1 + Efficient compressor (COP 1.7)	130	40	120	33
Design 3: Efficient compressor (COP 1.7) + Insulation 9.8 cm	104	52	150	67
Design 4: Design 3 + DC VSD compressor	80	63	177	97
Design 5: Design 4 + VIPs	64	70	213	137

COP: coefficient of performance; VSD: variable-speed drive; VIP: vacuum insulation panel

Source: Park *et al.* (2019).

Figure 15 shows the annualized costs of solar home system design scenarios. The two efficiency cases reduce the annualized cost of the solar home system 30-42 per cent (compared with the cost of the standard baseline case) by reducing the required PV module and battery capacities 63-76 per cent.

Figure 15: Annualized costs of solar home systems by efficiency scenario and battery type



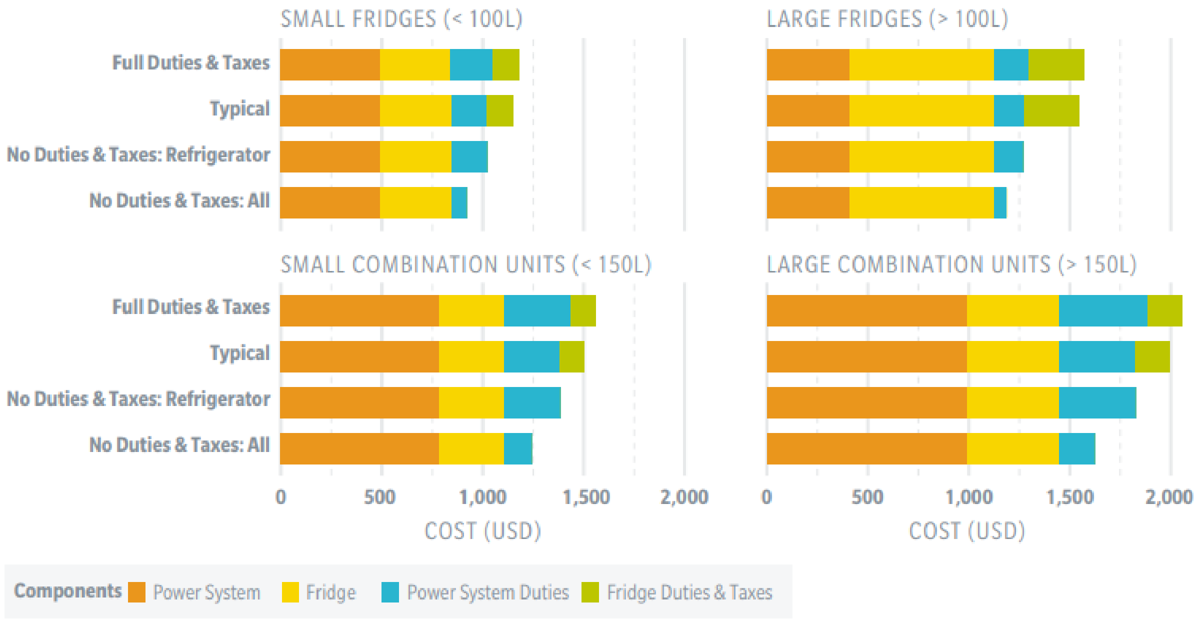
Scenario	Battery Type	Refrigerator	Capacity (L)	Total Daily Load (Wh/day)	Battery Storage (Ah)	PV Module Size (Wp)
Standard Case	Lead-acid	Standard (Baseline)	50	567	203	196
			100	592	211	205
Efficiency Case (Lead acid)	Lead-acid	Super-efficient (with Design 5 in Figure 12)	50	209	75	72
			100	176	63	61
Efficiency Case (Li-ion)	Li-ion	Super-efficient (with Design 5 in Figure 12)	50	209	58	64
			100	176	49	54

Note: Upfront costs estimated if sold at scale: 50L Standard Case ($647); Efficiency Case (Lead-acid, $563); Efficiency Case (Li-ion, $835)

Source: Park *et al.* (2019).

Lam *et al.* (2020) examined the economic potential for deploying refrigerators of less than 300 litres in off-grid settings, particularly in sub-Saharan Africa and India, and found sizable variation in off-grid refrigeration system costs, including duties and taxes, across geographies and use cases (see Figure 16).

Figure 16: Average refrigeration system costs under different duty and tax regimes

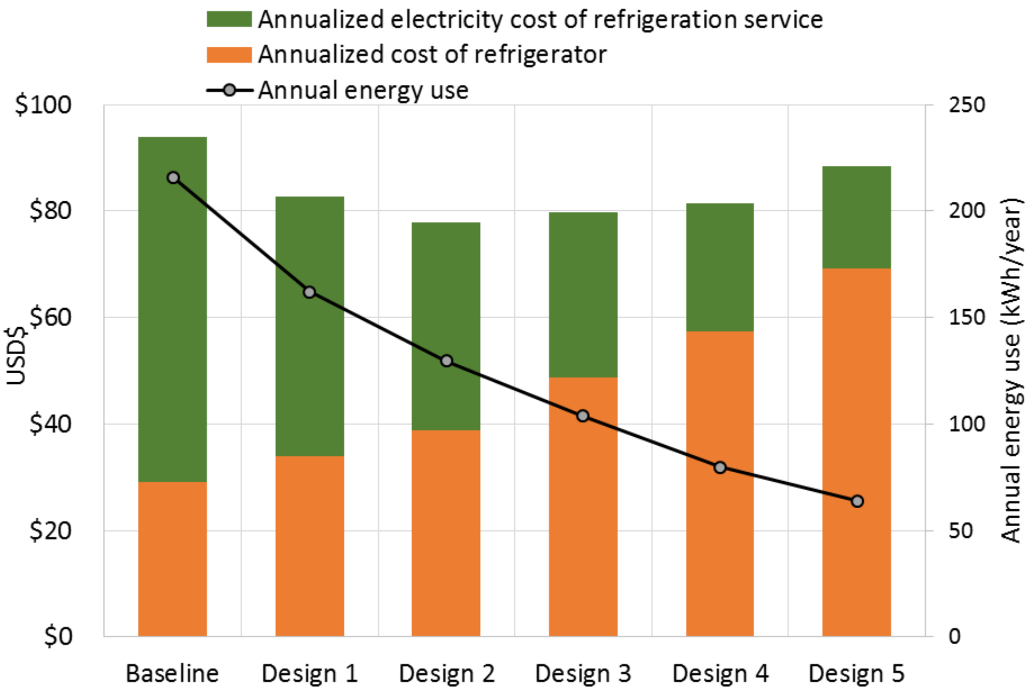


Note: Under “full duties and taxes,” taxes apply to all system components (i.e., there are no tax/duty exemptions for solar products). In some countries, duties on some solar power system components are reduced or eliminated to increase access, but similar reductions are usually not available for refrigeration equipment. The “typical” scenario uses average duty and tax rates in selected East and West African countries. “No duties and taxes: all” applies zero duties on all components, except batteries, as batteries rarely receive exemptions. Achievable reductions in individual countries will differ due to the variation in factors affecting system design and duty/tax rates.

Source: Lam *et al.* (2020).

Highly efficient small refrigerators can reduce the cost of refrigeration service in electricity access settings such as mini- or microgrids. Electricity tariffs for mini- or microgrids are significantly higher than those for the central grid (e.g., \$0.15 to \$0.45 per kWh for mini- or microgrids compared with \$0.07 to \$0.10 per kWh for central grids in India) (Park *et al.* 2019). A highly efficient refrigerator on a mini- or microgrid has the potential, despite its higher up-front cost, to reduce the annualized cost of refrigeration service (i.e., the annualized cost of the refrigerator plus the cost of electricity use) by up to 17-19 per cent (13-15 per cent on average), compared with the cost with an inefficient refrigerator (see Figure 17).

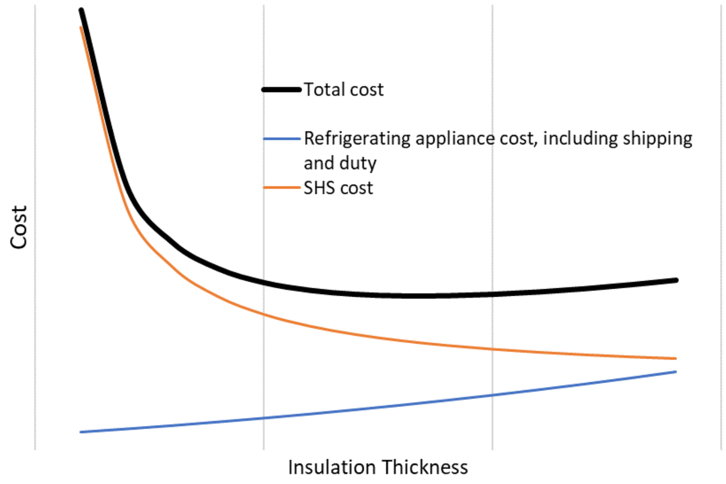
Figure 17: Annualized cost of refrigeration service with a 100-litre refrigerator on micro/mini-grids at various efficiency levels



Source: Park *et al.* (2019).

Designing a PV or solar home system that includes refrigerating appliances involves making decisions that balance total cost and efficiency. This balance becomes important when considering the relationship between the efficiency gains of the system and the reduction in the size of the PV components. Particularly, the choice of insulation thickness for refrigerating appliances has broader implications beyond just energy efficiency. Thicker insulation improves the appliances' ability to retain cold temperatures efficiently, reducing energy consumption. However, thicker insulation can lead to larger appliance sizes, potentially impacting the quantities of appliances that can be transported in shipping containers. This affects logistics and import duties, as larger shipments might incur higher costs, resulting in total cost increase (see Figure 18). While efficient appliances might allow for a smaller PV or SHS system, other considerations such as insulation thickness and its impact on logistics and import costs also play a role. It is important to optimize these factors to develop a system that is cost-effective, energy-efficient, and practical to implement.

Figure 18: Costs of refrigerating appliance and SHS at various insulation thickness levels



Source: SunDanzer

Integrating advanced monitoring systems, enhancing serviceability, and adding multi-function support to refrigerating appliances for off-grid rural areas not only provide users with more control and convenience but also contribute to reliability, cost savings, and customer satisfaction.

In addition to energy-efficient designs discussed above, advanced monitoring systems can contribute to energy efficiency by allowing users to fine-tune appliance settings based on real-time data. This ensures that energy is used efficiently, which is critical in off-grid environments with limited power resources. Incorporating Bluetooth, cellular gateway, or IoT-based monitoring systems (which have come down in price and are readily available) provides real-time visibility into the performance of the refrigeration unit. This is particularly valuable in remote off-grid areas, where service technicians may not be readily available. Users can monitor temperature, system health, and other parameters, ensuring optimal operation. These systems can also enhance security by alerting users to unauthorized access or tampering with the appliance, reducing the risk of theft or spoilage of valuable contents.

Monitoring systems can predict maintenance needs based on performance data, ensuring that appliances receive timely service. This proactive approach increases reliability and prolongs the lifespan of the units. By minimizing unexpected breakdowns and optimizing maintenance schedules, integrated monitoring and serviceability features can lower the total cost of ownership over the appliance's lifecycle.

Adding multi-function support to refrigerating appliances, such as USB charging ports or additional storage compartments, enhances the usability and versatility of the appliance. This can be especially valuable in off-grid settings, where resources are limited. The ability to offer services beyond cooling, such as device charging or storage, aligns with the needs of off-grid users who may rely on a single appliance for various purposes. It maximizes the utility of the appliance, making it a more attractive investment.

As discussed in Section 1, leveraging excess energy from PV systems for other use cases in off-grid settings could be a valuable strategy to maximize the benefits of renewable energy and refrigeration system's energy efficiency, while reducing overall costs. While price is assessed to be the most important factor, these features align with the unique challenges and priorities of off-grid communities and can make such appliances more effective and appealing in these environments over their lifecycle.

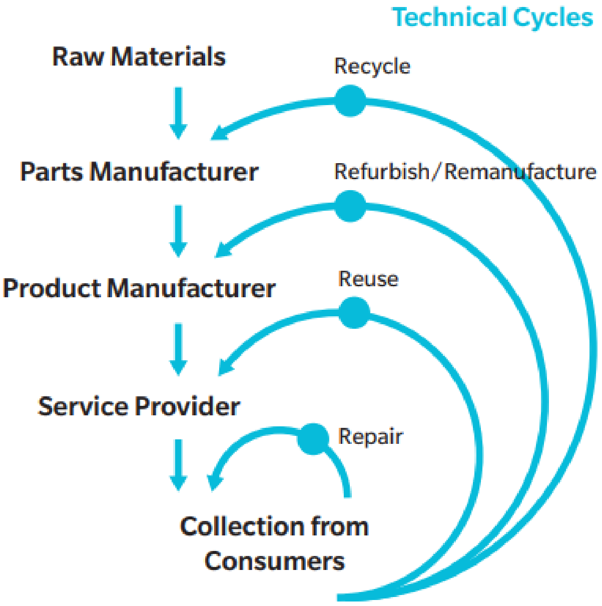
5 CIRCULAR ECONOMY

5.1 Overview

The U4E OGR Guidelines include basic content as a starting point for addressing repair and refurbishment options applicable to malfunctioning or broken products, as well as packaging characteristics that can be considered. Strategies for market growth and energy access in the global off-grid sector have largely relied on the logic of conventional, linear economies, where the ecological footprint and the consequences of products are not considered.

However, in recent discussions on a circular economy, the ability to repair (and maintain and prolong the life of a product) is a high-value outcome, ahead of refurbishment and recycling (Efficiency for Access 2020b). Efficiency for Access (2020b) also describes the benefits, impacts and barriers to increased repair rates for manufacturers and product users. At the same time, repair and refurbishment options should address malfunctioning or broken products that are still in their useful lifetime. The butterfly diagram of a circular economy in Figure 19 shows a hierarchy of strategies to preserve value and embodied energy.

Figure 19: Technical cycles of a circular economy



Source: Efficiency for Access (2020b).

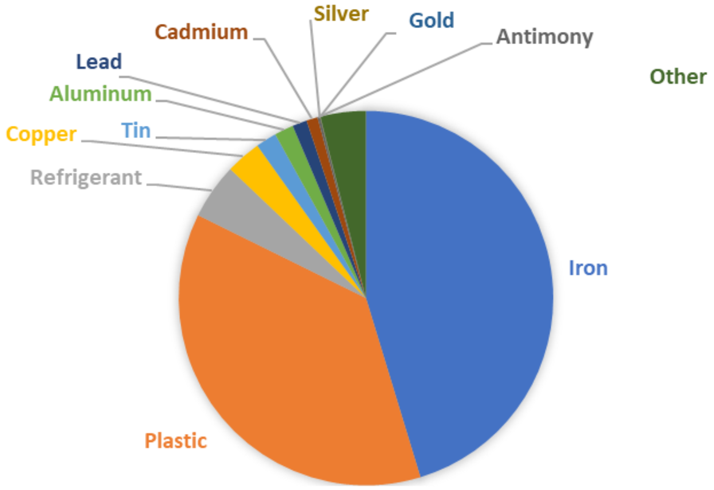
It is also useful to see how the cooling appliance service sector is evolving across the globe. Once a refrigerating appliance reaches its end of life, it becomes part of the electrical and electronic equipment waste (e-waste) stream, where refrigerating appliances fall into the category of "temperature exchange equipment" under the United Nations University KEY 0108 (Forti *et al.* 2020). Many refrigerating appliances are equipped with fluorinated gas (F-gas) refrigerants, which are short-lived climate pollutants that have high GWP. According to the California Air Resources Board (2017), around 80 per cent of the greenhouse gas emissions from refrigerants come from end-of-life leakage. The Investment Climate Facility (2018) projects that the United States could avoid 75 million tons of carbon dioxide (CO_2) equivalent (Mt CO_2e) annually from end-of-life products equipped with refrigerants, equal to the annual emissions from 16 million passenger vehicles or 19 coal-fired power plants. Similarly, the European Environmental Coalition on Standards (ECOS) (2019) estimates that two-thirds of waste refrigerators and air-conditioners do not reach legitimate recyclers, leading to an environmental impact equivalent to the CO_2 emissions of 6 million cars annually in the European Union. Forti *et al.* (2020) estimated that the greenhouse gas emission potential from undocumented wasted refrigerating appliances and air-conditioners in Africa in 2019 was 9.4 Mt CO_2e.

In addition to refrigerants, refrigerating appliances consist of many other toxic and carcinogenic materials such as mercury, antimony, cadmium, lead (in printed circuit boards and refrigerator light bulbs, and PV and solar home systems with lead-acid batteries), as well as polyvinyl chloride (PVC) plastics, flame retardants and foams. The toxic materials and substances contaminate soil and groundwater, put food supply systems and water sources at risk, and contribute to air pollution and climate change (Orisakwe *et al.* 2019; Liu *et al*. 2020).

Plastics and flame retardants require special consideration. Brominated flame retardants in plastics are extremely harmful to public health and the environment, especially when combusted. Hence, in the European Union, the recycling process (whether it is for reclaiming or decomposing resources) should follow the related standard, such as Regulation 2037/2000/EC, to completely recycle and monitor the process outputs (i.e., gas and liquid emissions) during treatment (Keri 2019). In addition, there are emissions from collecting, sorting, and transporting e-waste, which vary from case to case.

On the other hand, e-waste contains several precious metals (e.g., gold and silver), critical raw materials (e.g., neodymium, indium, palladium and cobalt), and other ferrous and non-ferrous metals (e.g., iron, aluminium and copper) (Huisman *et al.* 2017; Mathieux *et al.* 2017) that could be recovered. Figure 20 shows the details of materials used in refrigeration appliances.

Figure 20: Representative composition of various available resources within refrigeration appliances that can be recycled



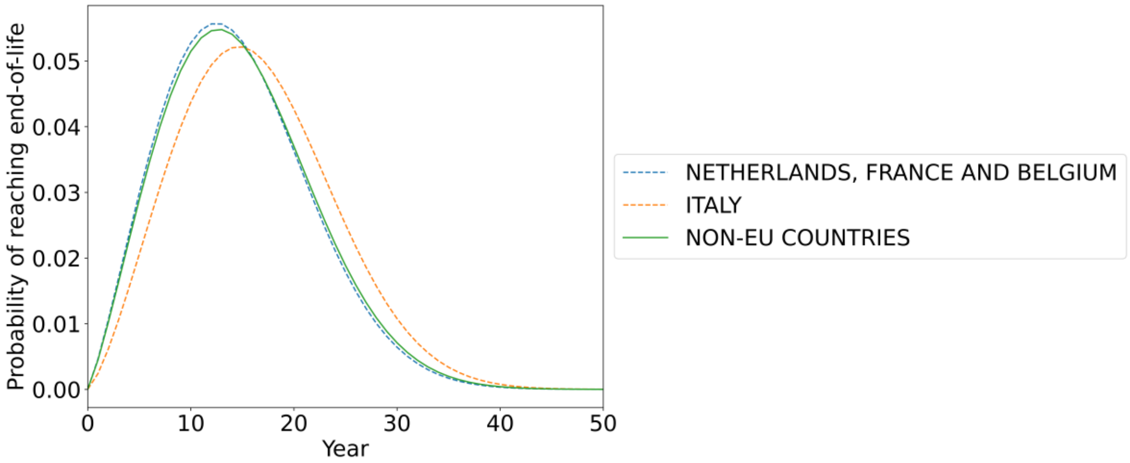
Source: Data extracted from Li, X. *et al*. (2019) and subject to change depending on model, manufacture, location, etc.

Circular economy strategies focusing on product life cycle are gaining momentum. For refrigerating appliances, a circular economy approach could mean the establishment of 1) robust collection frameworks, 2) refrigerant recovery mechanisms, and/or 3) recycling systems for the entire equipment.

While reuse and refurbishment are also important circular economy strategies, country-specific energy efficiency programmes continuously improve the energy efficiency of electrical and electronic products.

Figure 21 shows a representative plot of the probability of refrigerating appliances reaching their end of life, based on a Weibull prediction model reported by Forti, Baldé and Kuehr (2018). According to the model, most refrigerating appliances have life expectancies of between 10 and 20 years, which aligns well with other studies for refrigerating appliances in specific countries such as China and India (Dwivedy and Mittal 2012; Li, X. *et al*. 2019).

Figure 21: Representative plot showing the probability of reaching EOL end of life for refrigerating appliances based on Weibull parameters



Source: Forti, Baldé and Kuehr (2018).

5.2 Collection

Extended producer responsibility (EPR) is the common regulatory approach used to increase collection of e-waste. Conceptually, EPR is designed to make the manufacturers internalize the external costs associated with the end-of-life management of their products. However, its implementation suffers due to the absence of strong law enforcement and sufficiently compelling economic incentives (Ilankoon *et al*. 2018; Turaga *et al*. 2019).

EPR or similar structures could be supported with regulatory frameworks and financing mechanisms to establish a robust reverse-logistics chain. Digital technologies can support that structure by tracing the e-waste, components and materials and by making the resulting data securely accessible to all actors in the value chain. Monitoring of e-waste flow could also help measure the effectiveness of waste and refrigerant management regulations, help control illegal e-waste trade, and support international conventions such as the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal.

In addition, designing separate collection requirements for temperature exchange equipment would reduce contamination, increase refrigerant recovery and recycling efficiency, and guarantee that this product category is handled by trained technicians.

5.3 Refrigerant recovery

Although several pieces of legislation following the Montreal Protocol phased out the use of CFCs and HCFCs and phased down the use of hydrofluorocarbons (HFCs) (under the Kigali Amendment to the Montreal Protocol), appliances whose manufacture predated those requirements and still contain those substances must, once discarded, be treated adequately to contain the risks they pose to the environment and health.

Currently, reuse of recovered refrigerants is rare. The Environmental Investigation Agency (EIA) (2019) suggests that current rates of reclamation of used refrigerant in the United States were around 22 per cent in 2017, while Project Drawdown estimates that around 3.4 per cent of refrigerant banks were recovered globally in 2014. Most refrigerants are incinerated after collection to be disposed of due to economic reasons. In addition, mixed refrigerants are very difficult to separate because of the azeotropic form they have created. However, recently launched initiatives such as the Fluorocarbon Life-Cycle Management Initiative and the Climate Ozone Protection Alliance (COPA) aim to accelerate the mitigation measures needed to address accumulated amounts of ODS and HFCs in outdated, old and end-of-life refrigerant banks (ENV 2020; COPA 2022).

5.4 Recycling processes

Progress towards concepts such as design-for-disassembly and design-for-dismantling can increase the refrigerant recovery and recycling efficiency of products. Most electrical and electronic products, including refrigeration appliances, are rarely designed to be disassembled and recycled at the end of their useful lifetime.

Recyclers would generally first dismantle the device and, depending on local practice, sort out reusable components that do not require processing. Adequate recycling requires separating "controlled substances" from the refrigerating appliances for their destruction. Dismantling and treatment shall be performed in two steps:

- Step 1: extraction of "controlled substances" and oil out of the cooling circuits
- Step 2: removal of "controlled substances" from the insulation foam for destruction and the separation of recyclable and recoverable materials (e.g., metals, glass, plastics, cables, etc.).

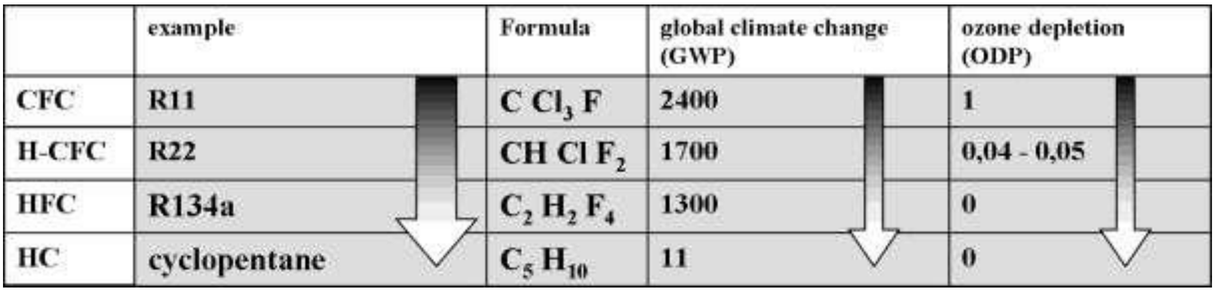
Other components undergo various size-reduction processes (such as pelletization, shredding and homogenization) to produce small pieces or powder forms for further physical separation. Physical separation processes include density separation to separate the heavy and light components and magnetic separation to sort out the magnetic components (Salhofer *et al.* 2007).

The non-metallic resources in refrigeration systems include plastics, refrigerants and insulating materials. The plastics stream could be used for energy conversion or conversion to reusable plastics for other applications. The refrigerants and insulating materials, if applicable, could be reclaimed by manufacturers or decomposed (Devotta, Asthana and Joshi 2004; Foelster *et al.* 2016). Recycling these streams requires careful consideration, as improper recycling can lead to environmental and public health concerns.

The use of CFCs in producing insulation foams and refrigerant circuits for cooling and freezing appliances was banned in the mid-1990s in many countries. Consequently, the producers of refrigerating appliances developed a new technology using pure hydrocarbons (HCs) such as butane, propane and pentane instead of CFCs as usable refrigerants. Cyclopentane continues to be used almost exclusively as the blowing agent of choice for polyurethane foam insulation.

One of the main characteristics of HCs, in comparison with CFCs, HCFCs and HFCs, is that HC has no ODP and a low GWP (see Figure 22).

Figure 22: Environmental impacts of blowing agents in PUR-polyurethane foam



	example	Formula	global climate change (GWP)	ozone depletion (ODP)
CFC	**R11**	$C\,Cl_3\,F$	**2400**	**1**
H-CFC	**R22**	$CH\,Cl\,F_2$	**1700**	**0,04 - 0,05**
HFC	**R134a**	$C_2\,H_2\,F_4$	**1300**	**0**
HC	**cyclopentane**	$C_5\,H_{10}$	**11**	**0**

Source: WEEEFORUM (2013).

However, the mechanical treatment of foam containing HCs may require special handling to avoid potential deflagration and fire hazards. Technical training for the manual separation and mechanical shredding of components should be provided in compliance with the technical standards set. More detailed guidance on manual e-waste recycling can be found in UK DEFRA (2006); WEEEFORUM (2013); GIZ (2016) and UNDP (2021).

Furthermore, it is recommended to select and/or develop clean recycling processes for recovery and recycling. For example, novel treatment processes, such as electrochemical or bio-extraction processes, are being developed in bench-scale settings and might be available soon (Chagnes *et al.* 2016; Işildar 2018; Li, Z. *et al*. 2019). However, it is important to ensure that the environmental impact of end-of-life waste management processes is lower compared to primary production.

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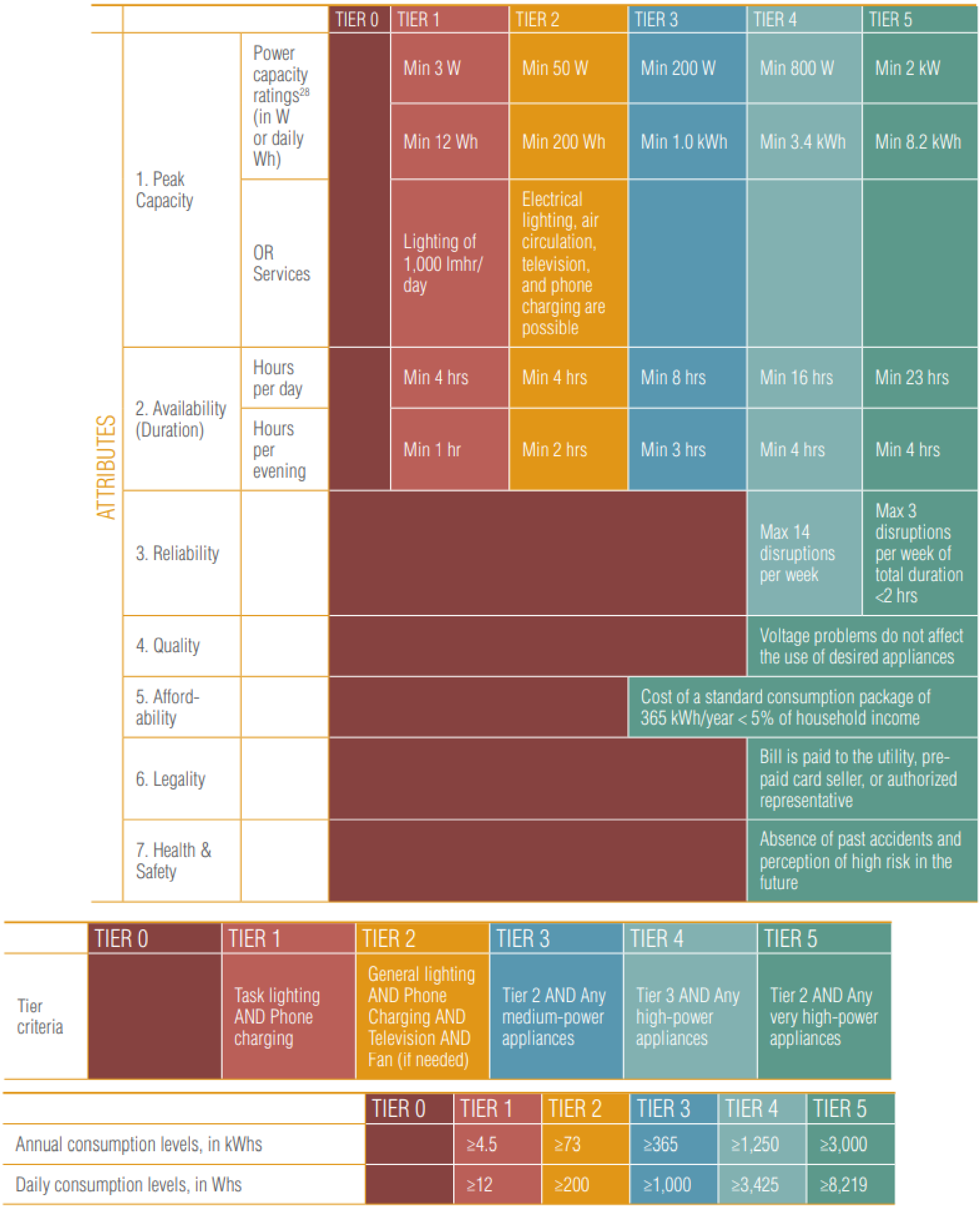
Annex A: Multi-Tier Matrix for Measuring Access to Electricity

Table A1: ESMAP's multi-tier matrix for measuring access to household electricity supply, electricity services, and electricity consumption



			TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
ATTRIBUTES	1. Peak Capacity	Power capacity ratings[28] (in W or daily Wh)		Min 3 W	Min 50 W	Min 200 W	Min 800 W	Min 2 kW
				Min 12 Wh	Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh
		OR Services		Lighting of 1,000 lmhr/ day	Electrical lighting, air circulation, television, and phone charging are possible			
	2. Availability (Duration)	Hours per day		Min 4 hrs	Min 4 hrs	Min 8 hrs	Min 16 hrs	Min 23 hrs
		Hours per evening		Min 1 hr	Min 2 hrs	Min 3 hrs	Min 4 hrs	Min 4 hrs
	3. Reliability						Max 14 disruptions per week	Max 3 disruptions per week of total duration <2 hrs
	4. Quality						Voltage problems do not affect the use of desired appliances	
	5. Afford-ability					Cost of a standard consumption package of 365 kWh/year < 5% of household income		
	6. Legality						Bill is paid to the utility, pre-paid card seller, or authorized representative	
	7. Health & Safety						Absence of past accidents and perception of high risk in the future	

	TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
Tier criteria		Task lighting AND Phone charging	General lighting AND Phone Charging AND Television AND Fan (if needed)	Tier 2 AND Any medium-power appliances	Tier 3 AND Any high-power appliances	Tier 2 AND Any very high-power appliances

	TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
Annual consumption levels, in kWhs		≥4.5	≥73	≥365	≥1,250	≥3,000
Daily consumption levels, in Whs		≥12	≥200	≥1,000	≥3,425	≥8,219

Source: Energy Sector Management Assistance Program (2015).

Annex B: Value of Sustaining Reliable and Quality Power in Weak-Grid Communities

The supply of reliable and quality power has become increasingly important for maintaining individual, economic and societal development. The costs of power interruptions consist of the costs of complete supply interruptions (i.e., blackouts), frequency and voltage reductions (i.e., brownouts), and sudden sharp fluctuations or surges in frequency and voltage (Munasinghe and Sanghvi 1988).

Since the "value of lost load" (VOLL) concept was proposed in reference to the costs associated with an interruption of electricity supply, many studies have assessed power interruption costs to electricity customers – either to specific customer segment(s) or to all customers. These studies measure non-residential customers' costs and savings from power interruptions or residential customers' willingness-to-pay to avoid (hypothetical) power interruptions. Some individual studies were aggregated to construct customer damage functions. The studies' results were used to estimate customer interruption costs of interruption attributes, customer characteristics, and environmental attributes and to justify future investments in reliability.

Noteworthy among these efforts is comparing the value of lost load estimates in emerging economies at different levels of development. Van Der Welle and Van Der Zwaan (2007) conducted a literature review of studies in different countries on the value of lost load. They reported that the value of lost load in developing countries is about 40 per cent of the value of lost load estimates in developed countries. Explanations of the difference include the higher dependency on electric power in developed countries, the differences in perceived reliability levels (Van Der Welle and Van Der Zwaan 2007), and income effects that mask a higher valuation of services (Baik *et al*. 2020).

A few studies tried to scale the value of lost load estimates under different settings for assessing the rural electrification value assessments (for instance, see Mandelli *et al.* 2016). However, this approach does not seem plausible as the underlying end uses, the electric appliances customers own and use, and electricity consumption profiles are fundamentally different from each other. In addition, many studies conducted in developed countries focused more on the costs of blackouts than brownouts, sharp fluctuations, or surges. In contrast, the costs of power quality events are more important for off- and weak-grid communities, particularly in rural areas. Thus, a simple scaling down of the value of lost load estimates assessed in other countries is not appropriate for assessing the value of reliable and quality power in off- and weak-grid regions. This caution applies especially to estimates of developed countries where most electricity customers are connected to the central grid and could receive reliable and high-quality services.

Other studies have estimated the value of electrification in rural communities. Kennedy, Mahajan and Urpelainen (2019) explored the relationship between the quality of electricity service and rural Indian households' willingness to pay to receive it. Graber *et al.* (2018) used choice experiments to assess the value of introducing solar microgrids in rural India. Harish, Morgan and Subrahmanian (2014) estimated interruption costs in rural India and compared the cost-effectiveness of five electrification options. However, most studies estimate the value of improved accessibility to electricity at the community level rather than assessing the value of securing electricity at the end-user level. Finally, these studies consider only the economic value of rural electrification. They do not consider the indirect benefits (e.g., broader community or economy-wide benefits) or non-monetary social benefits.

To date, few studies have assessed the value of refrigeration systems in weak-grid regions. Further, studies must separately assess the value of having more climate-friendly and energy-efficient refrigerators. These findings emphasize the need to assess the benefits and costs of having (or having more) efficient and climate-friendly refrigerators.

Assessing the benefits and costs associated with weak-grid refrigerating appliances

Several recent studies have recognized the importance of high-quality, efficient, and off- or weak-grid appropriate appliances (Hirmer and Guthriue 2017; Park *et al.* 2019; Phdake *et al.* 2019; Lai, Muir and Erboy Ruff 2020). However, the benefits and costs of sustaining critical electric appliances in weak grids have not been systematically measured.

Cost-benefit analysis is widely used in policy analysis and government decision-making to examine whether a specific policy is justified. There are three major inputs to the benefit-cost analysis:

1) An assessment by the community of the duration and quality of electrical power supply with the likely frequency and duration of future outages
2) The incremental cost of introducing a weak-grid refrigeration appliance programme
3) The benefits associated with the introduction of the programme.

Assuming that the outage frequency and duration scenarios can be generated from historical data, the costs and benefits associated with a programme would determine the justification of the investment. Costs and efficiency relationships of existing weak-grid appliances are collected and shared through several platforms, including Mangoo Marketplace and CLASP. While making the refrigerating appliances robust against power quality events incurs engineering costs, improving efficiency can reduce the energy consumption costs by 50 to 70 per cent (see Park *et al.* 2019). In addition, making the refrigerating appliances more resistant to power quality disturbances could reduce equipment failures, malfunctions, overheating, and damage to the equipment, thus reducing the replacement costs.

Benefits associated with the programme need to be assessed at different levels. At the individual household level, having a refrigerator or improving refrigerator efficiency (leading to longer use in limited electricity access) will decrease not only food spoilage but also the risk of food poisoning and enable a healthier diet (Hirmer and Guthrie 2017). At the industry level, accessing cold chain technology would decrease pre-market loss of food production in the developing world (Food and Agriculture Organization of the United Nations 2018) and expand the refrigerated/frozen food market. At the national/global level, implementing the programme reduces air pollution and greenhouse gas emissions (Haines *et al.* 2009).

Ideally, the incremental costs of introducing weak-grid refrigerating appliances would be justified by direct economic and social benefits associated with the programme. In some cases, incorporating externalities such as energy efficiency subsidy programmes or incentives may justify the costs of implementing the programme. Another consideration is the trade-off between making the grid more accessible, affordable, and reliable and making critical electric appliances more robust against power quality events and blackouts. We consider only the latter with the Guidelines' focus on refrigerating appliances. However, the former is critical for those equipped to conduct system-level analyses.

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