EFFICIENCY FOR ACCESS

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OFF-GRID REFRIGERATION

TECHNOLOGY ROADMAP

June 2019

EFFICIENCY FOR ACCESS COALITION

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Acronyms and Abbreviations

AC	Alternating current
Autonomy	When an appliance is operating without external power input and draws on energy stored in its battery and/or thermal storage
DC	Direct current
EforA	Efficiency for Access Coalition
EPR	Extended Producer Responsibility (policy to address waste and other issues)
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
Global LEAP	Global Low Energy Appliances Program
GSM	Global System for Mobile communication (architecture for mobile communication)
GWP	Global Warming Potential (of refrigerants and other gases)
Holdover time	When an appliance is operating without external power input and without use of energy stored in its battery and/or thermal storage.
IEC	International Electro-technical Commission (standards body)
ISO	International Standards Organisation
LEIA	Low-Energy Inclusive Appliances Programme
MPP	Maximum power point (for power supplied by a PV array)
NGO	Non-governmental organisation
ODP	Ozone Depletion Potential (of refrigerants and other gases)
PAYG	Pay-as-you-go
PCM	Phase change material (for thermal storage)
PV	Photo Voltaic
PVC	Polyvinyl chloride (plastic material)
R290	International refrigerant designation for propane
R600a	International refrigerant designation for isobutane
SACCO	Savings and Credit Cooperative Organisation
SDD	Solar direct drive
SHS	Solar Home System
TWG	Technology Working Group
UNICEF	United Nations Children's Fund
WEEE	Waste electronic and electrical equipment
WHO	World Health Organisation
WHO PQS	WHO Performance, Quality and Safety (a programme supporting appliance procurement)

See also *Annex 1: Explanation of performance parameters for all types of appliance* for explanation of other terms.

Executive Summary

1.0 Introduction

Efficiency for Access (EforA) is a global coalition promoting energy efficiency as a potent catalyst in clean energy access efforts. Coalition programmes aim to scale up markets and reduce prices for super-efficient, off- and weak-grid appropriate products, support technological innovation, and improve sector coordination. Efficiency for Access introduced a new UKaid funded research and innovation program in early 2017, Low-Energy Inclusive Appliances (LEIA) program, with the goal to double the efficiency and halve the cost of a suite of appliances that are well-suited for energy access contexts.

Refrigerators were selected as a LEIA focus technology due to growth in consumer demand for off-grid cooling in the household, commercial, and agricultural sectors and the potential to drive significant economic growth[1]. If efficient, appropriately-priced refrigerators become accessible to commercial and household users then major strides could be taken to reduce food wastage, improve food security and reduce food-related illness. At the same time, this builds new business opportunities for suppliers of cooling related equipment & services and increases revenue for businesses making use of cooling.

A Technology Roadmap is a tool to identify and coordinate the activities, resources, and technology investments needed to develop or improve a product. It is best thought of as a consensus-based planning process carried out with stakeholders rather than a fixed outcome. This Roadmap was drawn up through consultation with a voluntary Technical Working Group (TWG) of varied experts convened by the LEIA programme in a one-year process starting May 2018, with further feedback encouraged.

The Roadmap preparation process started with an assessment of the products known to be sold into the off-grid and weak grid refrigerating appliance market, to develop a vocabulary and definitions of the types of product and their uses. It then considered the performance requirements of the appliances and how they vary by usage scenarios. Since price of refrigerating appliances is a major concern along with a need for internationally recognized test methodology, a sub-group of the TWG examined the economics of supply while another sub-group developed a specification for a future test method. All of the TWG group and subgroups' insights were collated and reviewed to identify technology needs and R&D investment opportunities, as well as other market support initiatives to accelerate commercial uptake.

Most technology roadmaps start with a focus on market needs and then develop the critical linkages to the products, technologies, and necessary R&D activities. Product requirements and performance targets are normally designated to be needed by a particular date and the associated technology options are then evaluated ahead of that date to inform any trade-offs necessary to achieve the desired performance, taking into account cost, availability, and other factors. This Roadmap is typical insofar as it has been prepared via consultation with a broad array of stakeholders in order to provide an industry-wide perspective on the off-grid and weak grid refrigerated appliance market. However, it became evident early on in the process that there was no single market need for refrigerated appliances, but in fact a diverse set of markets and market conditions.

As a result, this document has a broader scope than a typical technology roadmap, since it aims not just to identify technology and product improvement opportunities, but to consolidate market insight and identify activities that will assist market development as well. The trade-off arising from this breadth is that it provides less precise information on required product performance and timelines. It is thus an early stage roadmap – a tool for gaining understanding of markets and technologies rather than one that offers a clear pathway to achieving specific product performance objectives, as shown in the figure below. Nonetheless, all market operators should benefit from this Roadmap and all are invited to provide comments to help shape the ongoing programme. Implementation of the Roadmap begins in 2019 by informing the Efficiency for Access Coalition's R&D calls in coming years.

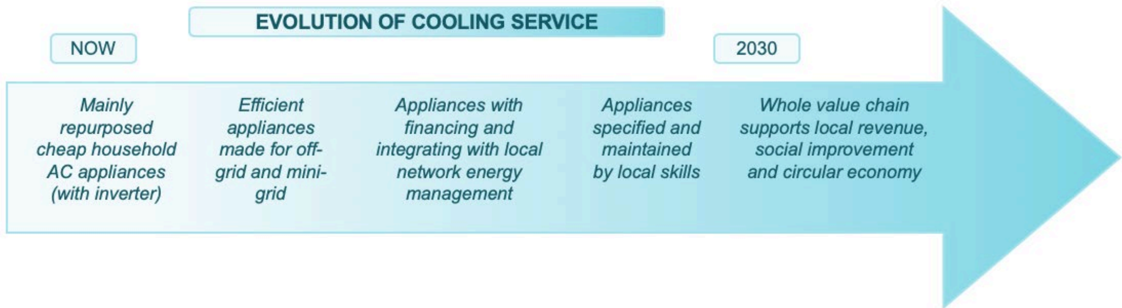

Figure 1: Evolution of cooling service.

2.0 Technology and Market Scope

This Roadmap is focused on:

> Refrigerating appliances with one or more compartments that are suitable for household or small commercial use for the storage of foodstuff or generation of ice, in off-grid and weak-grid communities. It prioritises rural and peri-urban, low resource communities. More specifically, it covers refrigerators and freezers with an indicative gross storage volume up to 80 litres for household and up to 180 litres for small commercial that can be powered by any of a wide range of power input options including AC, DC and solar direct drive.

Three market segments have been examined in depth:

1. Household refrigerators for food storage.
2. Small commercial refrigerators for community or retail, such as bottle coolers.
3. Small commercial ice-makers for agricultural or other commercial applications.

Besides these, there is a well-established market for off grid vaccine refrigerators (high performance and high value appliances) which have synergies and opportunities for technology transfer. There could be interdependencies with potential markets for milk coolers for dairy farms and for walk-in coolers, but those technologies are outside the scope of this roadmap.

Household Refrigerator Market

The majority of current household refrigerating appliance sales for off-grid and weak grid use are conventional, low price AC grid household refrigerators models, which require inverters and/or charge controllers when used in off-grid situations. Most cost around five times the combined value of all other appliances in the typical solar home system and are uneconomic to users and system suppliers. Furthermore, their power demand exceeds what most currently installed solar home systems (SHS) can deliver, leading to extremely low penetration of refrigerators into the solar home system market. This roadmap finds that expansion of household refrigerator sales into the mini-grid and weak-grid market is more likely than into the SHS market. Preliminary analysis suggests an indicative economically viable household refrigerator specification for 2020 of around 50 litres internal volume costing US$300 with less than 40W power demand, though it remains to be seen if this is technically and commercially viable. Market growth is currently constrained by a number of market development barriers including high product cost, high energy consumption and incompatible integration and systems controls. To make the economic case under long payback periods, reliability and reparability will be crucial.

Steps identified to develop the household market are:

1. Resolve PAYG compatibility, suitable system controls, and improved reliability.
2. Develop financing solutions through micro-finance and PAYG contracts in mini-grid and micro-grid markets.
3. Provide after-sales technical support and means to deliver appliances to remote regions.

Small Commercial Refrigerator Market
The opportunity to use refrigerators and freezers to generate income is being exploited in some regions, despite the large gap between theoretical needs and market realities. There is strong demand amongst roadside kiosks and small grocery stores, for example, in addition to fishermen using ice to preserve and transport their catch. However, the small commercial refrigerator market remains largely unexploited. Commercial cooling, including ice making (see commercial ice-maker market) as well as dairy and agricultural storage, could be important to improving food security as well as supporting economic development. Small businesses generally use repurposed household appliances with inadequate cooling capacity for the task and around one third are second hand.[2] Increasing sales would require designs tailored to the field conditions, trusted and relevant performance information and improved reliability to underpin the economic case for up to 10-year investments via leasing and other financing mechanisms. Since refrigeration can increase commercial revenues to cover the cost of its relatively high electricity consumption, commercial refrigeration could make micro-grids and mini-grids more economically viable overall – this symbiosis should be explored, as well as working with local and regional farming and retail SACCO's (Savings and Credit Cooperative Organisations).

Steps identified to develop the small commercial market are:
1. Encourage development of appliances, specifically for target markets and facilitate suppliers to work with business associations and SACCO's.
2. Develop financial case templates for entrepreneurs and encourage financing packages with mini-grid and micro-grid suppliers using refrigeration to justify power upgrades.
3. Develop means to provide after-sales technical support.

Commercial ice-Maker Market
There is evidence of strong economic and food security benefits from ice and thermal pack cooling systems that enable small farmers, fishermen, and other food producers to preserve and transport produce. The economic benefits of commercial appliances apply also to ice making with a very wide variety of applications, although the very high-power demand could make the economics challenging for some environments. The commercial case can be made for financing once reliable and efficient appliances and transportation systems are available. Steps to development of the ice maker market are the same as those for small commercial market, but targeted at different suppliers, users and technical specifications.

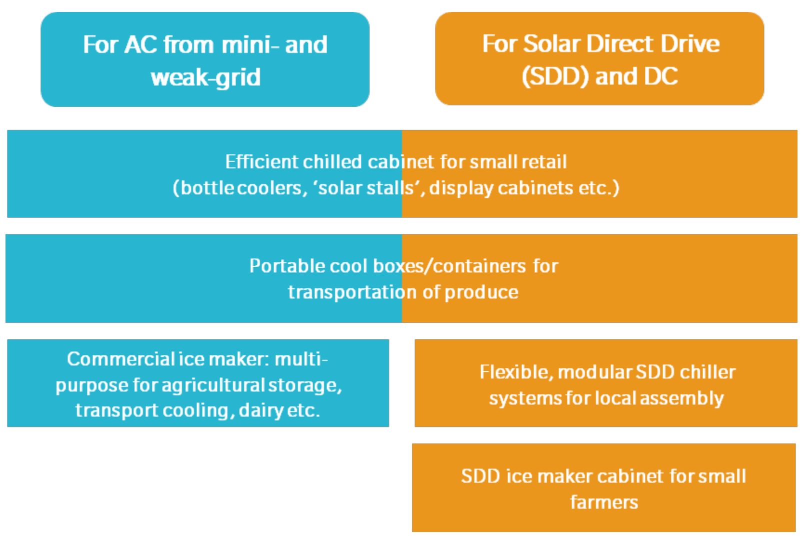

Figure 2: Refrigerating appliances needed.

3.0 Prioritised Market Needs, Products and Services
Stakeholder feedback and desk research has identified the following priority market needs from cooling appliances in the off-grid and weak grid sector:
1. Refrigerated storage
2. Ice making
3. Chilled transportation of foodstuff

The details provided by stakeholders suggest that the following priority products would be required by the target markets to address the above needs:

1. Small commercial refrigerating appliances to store and/or display drinks and foodstuff in retail stores and markets.
2. Small commercial refrigerating appliances for storage of produce in the food supply chain (e.g. agriculture, dairy, meat, fish).
3. Small commercial ice makers producing ice for food cooling in many applications.
4. Small volume insulated or refrigerated containers for transportation of perishable foodstuff in the food and drink supply chain.
5. Refrigerators and freezers for storage of foodstuff in community buildings and homes.
6. Modular chiller components and subsystems to be driven by solar direct drive, for local assembly as needed to suit varied applications.

4.0 Technical Requirements for Appliances

Off- and weak-grid appliances could and should be fundamentally different from conventional appliances due to their differing needs and priorities. Important requirements common to all off- and weak-grid refrigeration equipment are:

- Effective cooling at high ambient temperatures.
- Affordability (considering the full value proposition and life cycle cost).
- Good 'holdover time' (holding temperature without power input or using stored energy).
- Good electrical resilience and survivability (perform at over- and under-voltage).
- Appliance robustness (resist mechanical shock & drops, robust controls).
- Long service life.
- Good energy efficiency.
- Ease of maintenance and reparability.
- Ease of transportation (to place of use).
- Meet environmental impact expectations.
- Inclusive design (consider gender, disability, etc.).

Other requirements vary in relative importance by type of appliance and electrical input system and include: having low in-rush current (as appliance starts up), the ability to maintain cooling with low power input, and high cooling capacity.

While 'reduction of appliance cost' is a commonly heard challenge, the broader consideration of 'affordability' is more important, since the cost of components accounts for under half of the price charged to the end user. Key factors are:

- economies of scale in manufacturing;
- profit margins of supply chain players (and their number);
- revenue and running costs for appliances in productive use;
- competition between suppliers;
- shipping costs, tariffs/taxes;
- cost of financing;
- financial incentives.

Research is therefore needed into the relative importance of these key and other factors, as well as into the capital and running costs paid and revenues received in order to focus effort most effectively to improve affordability.

Improving energy efficiency is important to most systems for the following reasons: (1) the cost of the energy system (e.g. solar PV and battery) can be as much or even more than the cost of the cooling appliance; (2) cooling appliances require more energy than most common off-grid appliances (LED lamps, TV, fan); and (3) many users, especially on mini-grid or weak grid, may struggle to afford the power to run an appliance as demanding as a refrigerator. Highly efficient cooling appliances will require investment in better insulation, more efficient compressors and better controllers.

The circular economy (i.e. life cycle thinking, reduction of embodied impacts, extended appliance lifetime, reparability, reduced residual waste etc.) is highly important for the off-grid market. Circular economy issues can be addressed economically and fully if they are factored into the appliance specification at the outset (such as design for robustness, reparability, simplification and fewer material types and reclaiming appliances after use).

5.0 Technology Options to Improve Appliances and Expand the Market

Priority technologies identified to deliver improved appliances are summarised below.

Compressors and controllers to exploit variable speed operation

The efficiency and control advantages of variable speed compressor appliances are not yet exploited as more models are needed to cover a wider range of capacities and compatibility with hydrocarbon refrigerants (R290 and R600a). Controllers with excellent interoperability are also needed to enhance system efficiency and capability. Options such as aggregated procurement could be considered.

Cooling system modular designs for ease of transport, local assembly and high reparability

Refrigerators cannot generally be transported by motorbike and their fragility often leads to damage. An alternative is to transport only a robustly designed modular condensing unit and key components such as controls and evaporator, using local assembly of the insulated container or other application to ease transportation, reduce costs of shipping and tariffs, and stimulate the local economy.

Control systems to manage energy storage across solar energy systems

A refrigerator more than doubles the typical solar home power demand and yet cooling is a flexible load that can be switched in and out as needed and offers built-in thermal energy storage. A new generation of system controllers is needed to manage the challenges and capitalise on the advantages to enhance the economic case for cooling.

Selection and specification software for technical sales

It is complex to match an appliance to a particular power supply situation for a given level of service with many factors to take into account. Dealerships, suppliers and specifiers would benefit from an 'expert system' to lead them through questions and data to collect to ensure systems can deliver the service required. Solutions could include well-designed guidance as well as bespoke software.

6.0 Non-Technology Supporting Initiatives

These technologies would be most effectively deployed when supported by a range of coordinated non-technology initiatives.

Market support priorities are:

- Internationally recognized test methodologies to enable a fair competitive market and set the development direction for designers by covering performance parameters to specify appliances, assessing their compatibility with power systems and environmental and economic sustainability.
- Employment opportunities to build networks of trained and equipped refrigeration maintenance technicians to help specify, install, maintain, and repair appliances.
- Expanded financing plans, especially for mini-grids and PAYG (requires technical compatibility developments as well as commercial financing options backed up by published economic analysis of case studies).
- An appliance certification and quality programme that builds on the Lighting Global Quality Assurance system as a basis for financial incentives and high quality standards.
- Technical, policy and infrastructure developments to address circular economy issues regarding better materials, appliance design, recovery and reuse (must be factored into appliance specifications at the outset).
- Increase in user education and awareness including pictograms on appliance set up and usage, troubleshooting instructions and training for supply chain players.
- Support for testing facilities setup and accreditation, appliance testing by suppliers and publication of performance benchmarks to facilitate best products to the market.
- Market surveillance to control counterfeit and poor-quality appliances to improve appliance reliability and reparability including performance metrics, market research on failure modes and mitigation strategies.
- Mitigation of market risks and unintended consequences including economic, social, environmental and health risks, protection for local food businesses against external competition, appliance disposal challenges.

Figure 3: An indicative sequence for key market support initiatives.

Priority market research topics are:

- Research on potential markets both geographically, by end use sector and by power supply options with mini-grid as a priority but also SDD.
- Research to define and quantify the value chains of selected and most promising end use markets for cooling appliances.
- Research on affordability and issues impacting economic viability of appliances and services.
- Research to identify the benefits of refrigerated appliances to the target communities in terms of food security and reducing food waste, carbon saving, climate change policy and economic/employment benefits.
- Research on risks and unintended consequences to develop mitigation plans and inform the specification of appliances and services.

1.0 Introduction

About the Efficiency for Access Coalition

Efficiency for Access (EforA) is a global coalition promoting energy efficiency as a potent catalyst in clean energy access efforts. Since its founding in 2015, Efficiency for Access has grown from a year-long call to action and collaborative effort under Global LEAP and Sustainable Energy for All to a coalition of 13 donor organizations. Coalition programmes aim to scale up markets and reduce prices for super-efficient, off- and weak-grid appropriate products, support technological innovation, and improve sector coordination. Efficiency for Access introduced a new UKaid funded research and innovation program in early 2017, Low-Energy Inclusive Appliances (LEIA) program, with the goal to double the efficiency and halve the cost of a suite of appliances that are well-suited for energy access contexts.

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2.0 Scope of Appliances Included within the Roadmap

The definition of appliances addressed by this Roadmap was agreed in its early stages as[4]:

> *"An insulated cabinet with one or more compartments that are controlled within specific temperature range(s) and suitable for household or small commercial use for the storage of foodstuff and/or generation of ice in off-grid and weak-grid communities, prioritising rural and peri-urban low resource environments"*

The full detail of technical parameters and their options necessary to define the various types of household and small commercial refrigerator are tabulated in *Annex 2: Technical parameters that define categories of off-grid or weak grid refrigerating appliances and their basic specification, for household and small commercial applications*.

In summary, the Roadmap covers appliances with the following characteristics:

- Appliance types included are refrigerator, freezer and refrigerator-freezer.
- Gross storage volume of up to around 80 litres for household use and up to 180 litres for small commercial use (larger appliances will also find market niches).
- Appliance power options within scope (one or more may apply):
  - Battery (usually 12V or 24V) or Solar Direct Drive (10V to 45V);
  - AC (110V or 230V; assumed compatible with 50Hz and 60Hz unless otherwise stated);
  - Integrated thermal storage (thermal pack(s)) and/or ice packs;
  - Integrated electrical storage (battery and/or capacitor) supplied with the appliance;
  - Solar direct drive (SDD) cooling (usually has integrated energy storage[5]);
  - Thermally driven, e.g. solar thermal driven absorption cooling;

Cooling technology types:

- Priority on vapour compression (electrical compressor) based appliances anticipated to meet the majority of market need, which have fixed speed compressors or variable speed compressors.
- Acknowledging market presence and supplementary role of passive cooling approaches such as proactive shading, thermal chimney designs and evaporative cooling.
- Also acknowledging potential future role of other technologies such as thermoelectric cooling.[6]

Note: units burning propane gas, kerosene or other fossil fuels (e.g. to drive absorption or adsorption type systems) are excluded due to carbon impact as well as fire and carbon monoxide poisoning risks.

3.0 Current Markets and Routes to Develop Appliances

Six target market segments are considered. The first, about the first market for such appliances, is an introduction for context only. The fifth and sixth are out of scope of this roadmap.

1. (For context/information only: Vaccine refrigerators for preserving batches of vaccines at the necessary temperatures to enable their distribution and use in communities far from the electrical grid or with only weak grid access.).
2. Household refrigerating appliances (refrigerators and freezers) with standard cooling capacity for food storage (as opposed to the rapid cooling associated with commercial applications). Associated with this, a smaller market for household freezers.
3. Small commercial refrigerating appliances for community or retail usage such as bottle coolers (also a smaller market for commercial freezers) with a need for higher cooling capacity than household appliances, to achieve more rapid temperature pull-down for turnover of stock.
4. Small commercial ice-makers specifically for making ice or freezing thermal packs for agricultural or other commercial applications, requiring high freezing capacity.
5. (Out of scope: Milk coolers for dairy farms and smallholdings which receive, chill, often stir and preserve milk between milking the animal(s) and decanting for transfer or sale. The existence of this (potential) market is noted.)
6. (Out of scope: Walk in coolers (chilled or frozen) for storage of agriculture, dairy, fisheries, medical goods and for mortuaries. The existence of this market is noted.).

To provide insight into these and other markets, the LEIA programme has commissioned a market study in 2019 on off-grid and weak grid refrigeration use-case segmentation. The desk study includes research on usage patterns and its results will inform future iterations of this Roadmap. Figure 4 shows a simplified vision for current status and future development of these markets and appliances.

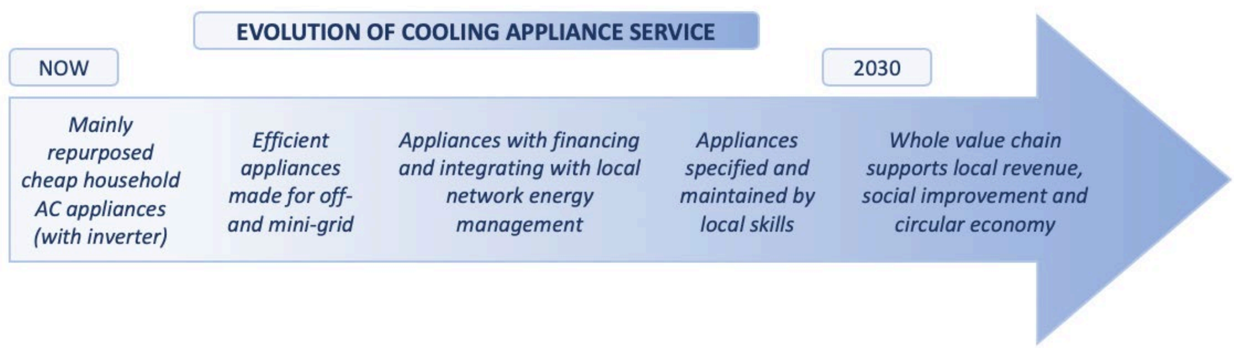

Figure 4: A vision for the future evolution of cooling service appliances in off-, weak- and mini-grid situations.

Vaccine Refrigerators Market

Market Status

There is a steady ongoing market for vaccine refrigerators for use in weak grid and off-grid communities that has become well established over the past 30 years or more. It consists of high-performance appliances with typical price being an order of magnitude higher than that of a viable household off grid appliance. The market operates to a highly evolved set of appliance testing protocols[7], quality assurance / registration scheme with catalogue and technical guides to specifying the equipment[8] and rigorous procurement support and processes that are formalised by the WHO/UNICEF.[9] There is a technical network for immunization professionals that includes forum for refrigerators and freezers with comprehensive technical resources.[10] The WHO 'PQS' prequalification registration scheme includes 77 refrigerators and freezers at January 2019 (including 38 for mains power; 28 solar direct drive; 9 with solar charged battery or ancillary battery; gross volumes from 26L to 340L). The appliances store vaccines within temperature constraints and holdover times that are highly demanding, given the ambient conditions and lack of reliable power supply: no typical household refrigerator would be able to preserve the vaccines under the required conditions. The typical price tag, upwards of US$2.000[11], is viable since the vaccines they protect are worth several times that amount and bring life-saving health benefits to hard-to-access locations. The appliances are likely to be batch produced (not mass-produced) and are bespoke products for this particular market and application. Whilst many of the designs and technologies used could be adapted to function very well as household refrigerators, their performance and price far exceed what is justifiable for a household market.

Suppliers

Vaccine refrigerators are made in modest quantities primarily by specialized companies, sub-divisions of a few major refrigeration equipment manufacturers or medical equipment companies. There are eight manufacturers listed in the 2018 WHO PQS/Technet-21 refrigerators and freezers catalogues.[12]

Household Refrigerator Market for Off- and Weak-Grid Applications

Market Status

The penetration of household refrigerators into the solar home system market is extremely low, but some distributors continue to seek off-grid appropriate suppliers and ways to offer a service. Low household penetration is a result of high product cost and power demand exceeding what home systems can provide. There is also little evidence of any significant penetration into the mini-grid market, although this may be a more viable market due to adequate power availability and higher running hours. Preliminary analysis noted that "steep prices and energy requirements mean that even households with diesel generators can rarely purchase and use refrigerators."[13] Roadmap stakeholders confirm that the majority of current sales are conventional grid AC household refrigerators used in weak- and mini-grids. Some come with solar generation systems that need multiple components such as inverters and charge controls. Users only gain partial benefits since most appliances run for a portion of time – "2-4 hours per day"- and are not designed for long holdover time.[14] Intermittent refrigeration is also not effective for food preservation or significant reduction of food waste.

Suppliers

Some manufacturers of vaccine refrigerators also offer appliances suitable for household use at a lower price point, but the majority of products, conventional or slightly off-grid adapted AC appliances, are sourced from Chinese or other manufacturers. No major multinational appliance manufacturers have invested significantly in off-grid refrigerators, though Haier has shown initial interest.[15] DC refrigerators are available for the off-grid market, but their price point tends to eliminate them as an option. Anecdotal evidence suggests that only a tiny proportion of refrigerators sold into the household market are served through solar or off-grid distributors, with most through self-sourced or other appliance markets.

Market Development Barriers

Preliminary analysis suggests a significant latent market, with potential sales worth US$220 million based on estimated potential spending power and full availability of best in class appliances, such as a 50 litre off grid refrigerator costing US$300.[16]

However, the following market development barriers currently exist:

- Appliance availability: Distributors of refrigerators for the household market face severe challenges on suitability of market products, product price, performance and reliability. Of these challenges, 'price' is arguably the most important and it effectively rules out development of the off-grid household refrigerator market at present (at least if based on currently available types of appliance, performance and financing mechanisms). Both price and efficiency must improve in order to reduce lifetime cost. A price point of $200 with a power rating of less than 40W have been suggested as economic viability targets for rural off-grid customers as shown in Figure 5, but the affordability of such units requires more investigation and is suggested as a market research priority.

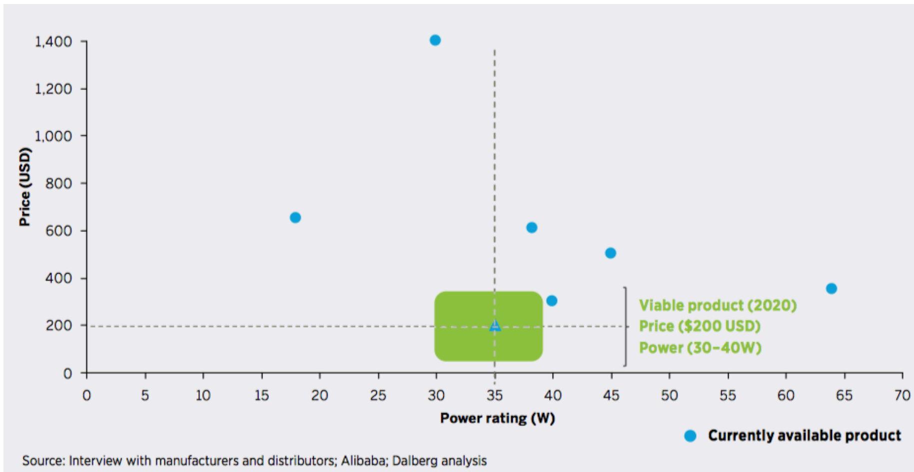

Figure 5: Comparison of price vs. power rating for currently available off-grid refrigerators.[17]

- Price: The refrigerator is by far the most expensive appliance currently envisaged for typical solar home and mini-grid systems.[18] A 19" screen TV cost around US$85 and a table fan US$12[19] whereas a currently available refrigerator that is not optimized starts around US$400 and does not include a PV system (inferred from the WHO *Performance, Quality and Safety* (WHO PQS) programme, and anecdotal evidence). Adding a refrigerator therefore requires around five times the total asset value compared to a previous 'comprehensive' solar home system, meaning that price and financing is a major challenge for consumers and PAYG suppliers.

- High energy consumption: As illustrated in Figure 6, a refrigerator running only 10 hours per day at around 100W would more than double daily consumption of a comprehensive home system with phone charging (3W), lamp (1W), TV (30W) and table fan (40W). This represents a doubling of daily ongoing cost of grid power, or investment in a much larger solar array (though anecdotal evidence suggests that the marginal cost of that is not prohibitive, especially if included from the outset). Appliances with lower power demand than those depicted in Figure 6 are available on the market, but overall power balance is highly dependent on solar irradiance, ambient temperature etc.[20] Figure 7 shows measured consumption data for refrigerators under various ambient temperature conditions, showing how consumption rises steeply with ambient temperature. If running costs are not kept low, customers may regularly switch off the refrigerator and run-hours could fall so low that the refrigerator becomes a 'stranded asset,' generating no value use for the system supplier (via electricity bills) and possibly having a high cost of retrieval due to its remote location.

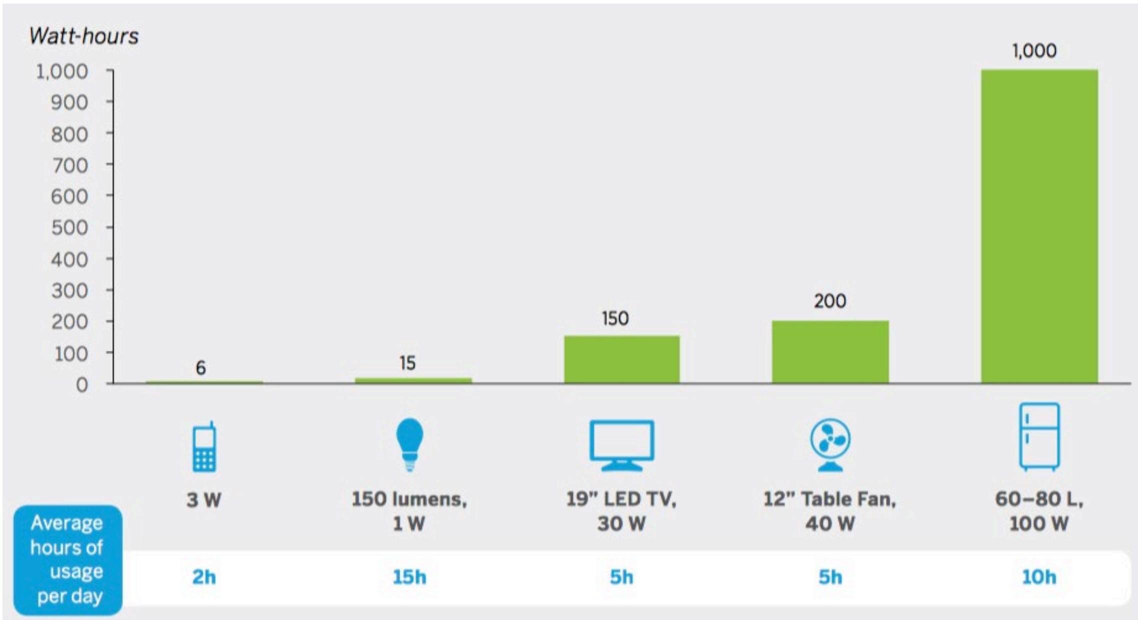

Figure 6: Average energy consumption of household appliances, adjusted for average hours of use.[21]

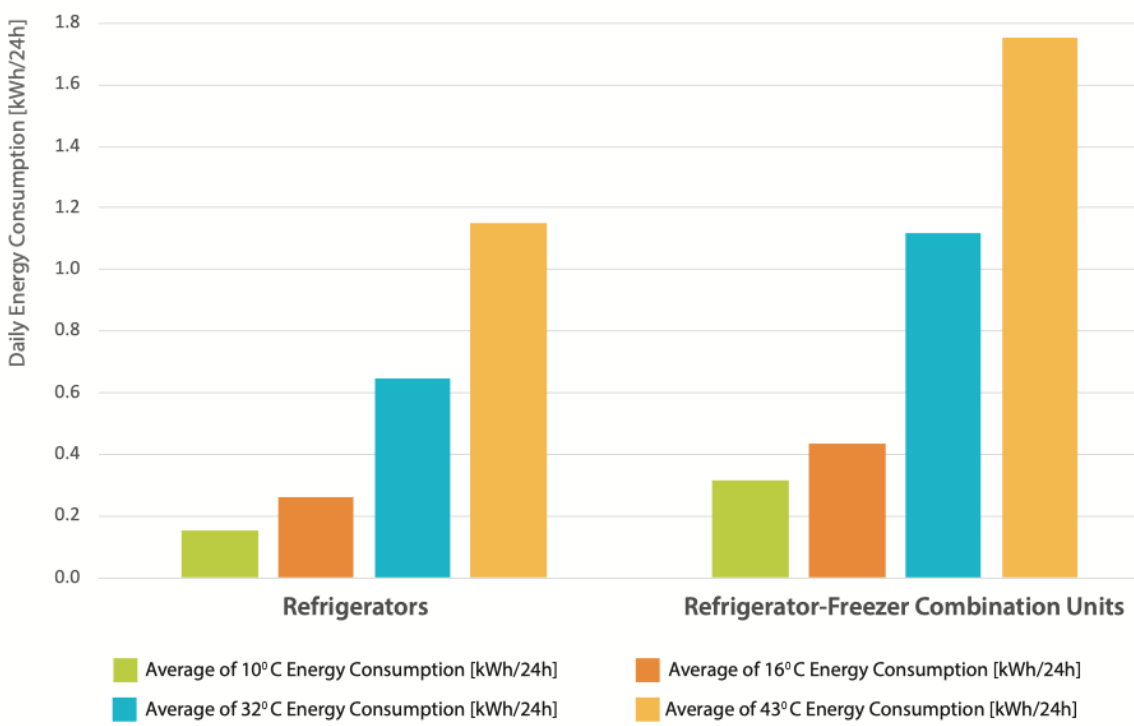

Figure 7: Average daily energy consumption by refrigerator type at various ambient temperatures.[22]

- **PAYG and system compatibility:** To access this particular type of market, refrigerators would need to be compatible with PAYG platforms (although other lease/financing methods are also available), but none are yet known to be available.

Under the PAYG model, important ethical and practical decisions must be taken into consideration on how to grant or deny cooling access. The facility to remotely provide a yes or no signal is well established and for refrigerators, this may cut the power (food warms up with food safety implications) or, probably less viably, the door locks and the food stays cool but inaccessible.[23] There are further implications for storage of essential medicines and how to manage a need to plug into an alternative power supply if solar fails. Note that technical compatibility is not the only issue here: economic viability of refrigerators in such situations must also be addressed.[24]

- **Integration and system control:** The refrigerator for the household market must be suitable for electrical integration into the SHS or other supply environment. While basics integration such as electrical connectors can be easily sorted, arrangements for electrical grounding and voltage are more complex. Controls must be more than just compatible, but also strategically integrated into the system's energy storage to avoid system failure and leverage additional resilience; in-rush current on start-up must be managed or a DC port and/or charge controller with higher than usual current rating must be provided.[25] The refrigerator is a major power drain, but it also has potential for load shifting by switching off or running warmer when needed and over-cooling using surplus power to reduce later demand. These and other related topics are being addressed under a separate LEIA Technology Working Group and Roadmap on Interoperability.
- **The logistics of delivery:** Due to physical size and the fragility of components, the logistics delivery of refrigerators are particularly challenging and costly as they regularly result in damage. Delivery generally needs a 4-wheeled vehicle, whereas a motorcycle is often the only vehicle available.[26]
- **Lack of after sales support:** There are very few qualified solar fridges technicians and due to current low sales volumes compared to other SHS appliances, it would be very expensive for manufacturers to provide this.

Possible Routes to Future Market Development

The economic challenges to developing a substantial household refrigerator market in a sustainable way are currently prohibitive. Even though preliminary analysis suggests that the household refrigerator market could grow to just over US$1 billion within a few years, driven by price decrease, efficiency increases, population rise and increased spending power - this projection now seems credible only if it includes commercial usage (commercial and agricultural applications are not separately analysed.[27] Due to long running hours compared to other home appliances, the viability of household refrigerator appears strongest in a mini-grid or even weak grid situation more than for off-grid. Mini-grid opportunities have not been adequately represented in Roadmap consultations so far and should be further explored.

Discussions within the TWG suggest that outright purchase is not economically feasible for most household users; pay per use is not applicable and subsidies are short term and competitive. This leaves one route forward for the household market as PAYG via SHS, although this is also highly challenging. Under PAYG, customers could establish a track record for reliable payment through a contract for lights, TV or other cheaper appliances over months and if or when suppliers have confidence, they could grant addition of a refrigerator, which will quadruple the value of installed assets. Payback with current refrigerating technologies appears likely to take around 10 years of use, which is too long for commercial viability of almost all business models .[28] This results in the often-quoted priority of cost reduction for the household market, although this must be balanced with the need for reliability. Reparability will be crucial, as well as low running costs for grid-connected appliances to ensure users can afford reasonable running hours of usage.

Microfinance is possible in countries with less mobile money penetration and a strong self-help group network. For example, there is a lack of PAYG in South Asia, but proven models of microfinance exist elsewhere. In addition, refrigerators for the household market would have a big social impact and could attract grants and market development facilitation based on food preservation, cutting food waste, reducing food-related illness etc.

Small Commercial Refrigerator Market

Market Status and Potential

User and supplier surveys, anecdotal evidence and research papers suggest that 'productive use of energy,' or the ability to generate income using refrigerators and freezers, is being well used to justify appliance purchases. The box below presents insights on a 2017 study by Energy4Impact of 172 micro-enterprises on productive use applications for refrigerating appliances.

Findings from the 2017 Energy4Impact study on productive use applications for refrigerating appliances, based on interviews with 172 micro-enterprises in Uganda. [29]

- 80% of interviewees are small family retailers;
- Refrigerated appliance purchases very closely followed a grid connection;
- Concluded that solar (and DC) refrigerators are currently unaffordable;
- The typical appliances in the Uganda study were 80-300L refrigerating appliances costing $250, 40% were fridge-freezers; 40% refrigerators and 20% freezers;
- One third of appliances were bought second hand;
- Electricity costs were US$12 per month;
- 70% were used for selling cold drinks; nearly 15% used for ice creams and 10% for other food items;
- The most valued characteristics being energy efficiency and autonomy.

This and other studies have shown that there is undoubtedly a big gap between theoretical needs and market realities for small businesses. [30] Consensus is that demand is strong, even if it is stubbornly latent right now. Retail/catering refrigeration appliances were rated third amongst 20 electrical product categories for both consumer demand and impact potential in the Efficiency for Access coalition survey of 'productive use' users in 2018, while solar water pumps took the top spot. [31] Roadside kiosks and small grocery stores often sell chilled water, milk, soft drinks and chocolate in India; sellers of drinkable yoghurt driving sales of refrigerating appliances in Bangladesh (although numbers in Bangladesh are not at significant scale),and also fishermen preserving their catch to get to market. [32] TU Delft market studies have identified portable solar-powered refrigeration as a potentially significant technology to improve food security when applied to retail situations. [33] TU Delft studies in West Africa and the Philippines highlight the 'Solar Stall' with a refrigerated compartment for use at open air markets for fish and meat retailers, based on potential impact on food security, profitability and environmental sustainability. Similar portable coolers could also be used by street vendors for cold drinks and fresh fruit, etc. This remains a largely unexploited market. [34]

Suppliers

Anecdotal evidence suggests that small businesses in off grid and weak grid areas are mostly using household appliances, with small diesel generators, for their kiosks, stores and kitchens. It is possible that commercial appliance suppliers may operate in cities, but prices and delivery logistics would be prohibitive in rural areas. Therefore, the appliances used now are highly unlikely to be capable of delivering the needed cooling capacity, with an example quoted of freezer appliances being used to chill drinks in stores but rarely able to actually freeze the drinks. Using a freezer in this way is inefficient in terms of electrical efficiency, but is attractive due to higher cooling capacity than a similarly sized refrigerator and a freezer with a top opening retains the cold air even when the lid is open. Note that an appliance with lower cooling capacity may be adequate if drinks/food can be cooled overnight and if reserve stock is kept cool under wet cloths. However, in situations with a solar direct drive, a weak grid connection or high stock turnover, this may not be attractive or even viable.

Market Development Barriers

Commercial market certainly has economic viability. Purchase cost is offset against the revenue stream from (increased) sales of drinks or ices and increased revenue by a wider choice of goods preserved for longer and to a higher serving quality. However, as noted above, many appliances used to date in this market are repurposed household appliances. Specifiers and local suppliers are unlikely to have the insight or equipped with information by manufacturers to differentiate high cooling capacity from standard cooling capacity appliances (that are capable of cooling drinks quickly for commercial purposes). Anecdotal evidence from Uganda and Kenya suggests that many commercial end-users and dealers are running out of patience with poor quality, unreliable and inverter-driven appliances . [35] Although household appliances will suffice for some applications, the lack of technical awareness and information is a barrier that effectively rules out the purchase of the more reliable (and expensive) appliances that are specifically designed for commercial use. Other market development barriers are similar with those faced in household market such as price and running costs sufficiently low to enable sufficient running hours.

Possible Routes to Future Market Development

Further investigation is need into appliances such as the portable refrigerating compartment 'Solar Stall' (see Section 2) which can offer increased revenues for micro-businesses and help national food security through reducing food wastage. For wider applications, modification of established appliance designs is needed and can be generally straightforward with increased cooling capacity, compartment dividers and transparent display doors. Increased sales would require more comprehensive and reliable performance information along with improved reliability of appliances to underpin the case for investments with long paybacks. Leasing and other financing routes are feasible for commercial situations, though outright purchase is also a possibility for some businesses. However, more research is needed on the economic case, particularly on the comparison between on-grid and off-grid options. The commercial case can be made for financing of productive use applications. This is easier with use of template revenue and lifetime cost models which can be tailored to the appliance and application. Since refrigeration of goods can increase commercial revenues to cover the cost of its relatively high electricity consumption, commercial refrigeration could make mini-grids more economically viable overall and this symbiosis should be explored. In addition, the economics and business opportunities of appliances should also be explored with local and regional farming and retail SACCO's (Savings and Credit Cooperative Organisations). A separate market is already well under development by major drinks manufacturers through expansion of distribution networks for which branded appliances are provided – this is noted in the Energy4Impact Uganda study along with business comments and this market exploitation model also raises social and health risks (displacing local produce, diet/health impacts etc.).[36]

Commercial Ice-Maker Market

Market Status

As with small commercial applications above, there is evidence of strong market need but very low exploitation of ice packs used to keep food produce cool in storage, during transportation and on display for sale. Agricultural/cold chain cooling equipment was rated second amongst 20 electrical product categories for both consumer demand and impact potential in the 2018 Efficiency for Access coalition survey of 'productive use' users.[37] There are to date very good examples of commercial ice-maker businesses. Mini-grid system supplier JUMEME is operating a fish freezing and cold chain distribution operation from Ukara Island in Lake Victoria into Dar Es Salaam.[38] The University of Hohenheim has developed an ice-based cooling system to enable small farmers to sell milk into local cooperatives with pilots in Kenya, Tunisia and Colombia.[39] However, anecdotal evidence, along with the Efficiency for Access market survey suggests that this is another largely unexploited market (with the caveat that the survey may not have accessed the suppliers of this type of equipment).

Suppliers

The manufacture of commercial and industrial on-grid ice makers is a very well-established industry, but it is not known which, if any, of those manufacturers are supplying into off-grid or weak-grid markets. Anecdotal evidence suggests that there are at least a few commercial DC-rated ice makers on the market. But some users simply have household or off-grid freezer appliances that may or may not be modified in some way for the particular application.

Market Development Barriers

Feedback suggests that ice-making can have such a large cooling (and power) demand that the costs of a sufficiently large off-grid system can outweigh the revenue generation stream. The University of Hohenheim team experience confirms that price is playing part in slowing down progress in addition to very important socio-economic factors (as often found for the introduction of a new technology) such as inadequate understanding of market factors and underestimation of the importance of maintenance and post-installation servicing. Local technology suppliers must often adopt imported solutions rather than their own innovations to keep their business models feasible.

Possible Routes to Future Market Development

The ice maker market has economic viability where a revenue stream can be presented as increasing shelf life of produce, raising sales value through better quality, and enabling access to larger and more distant markets by preservation through longer journeys. In addition, the sale of ice itself has a very viable market. As with small commercial refrigerators, the commercial case can be made for financing and this is easier with use of template revenue and lifetime cost models which can be tailored to the appliance and application. Once a system prototype is available, a pitch could be made to SHS and mini-grid system suppliers to incorporate it in their business plans for which the high refrigeration electrical load provides an economically viable boost for suppliers of the electrical systems (as implemented for fish freezing systems by JUMEME, above). Experience suggests that technologies should be evaluated not only based on sustainability and affordability, but also for their social acceptance and adaptability to the local market. End user's requirements should be integrated in at an early stage as shown in Figure 8. Remaining ice used for transportation could even be sold as a product along with the foodstuff.

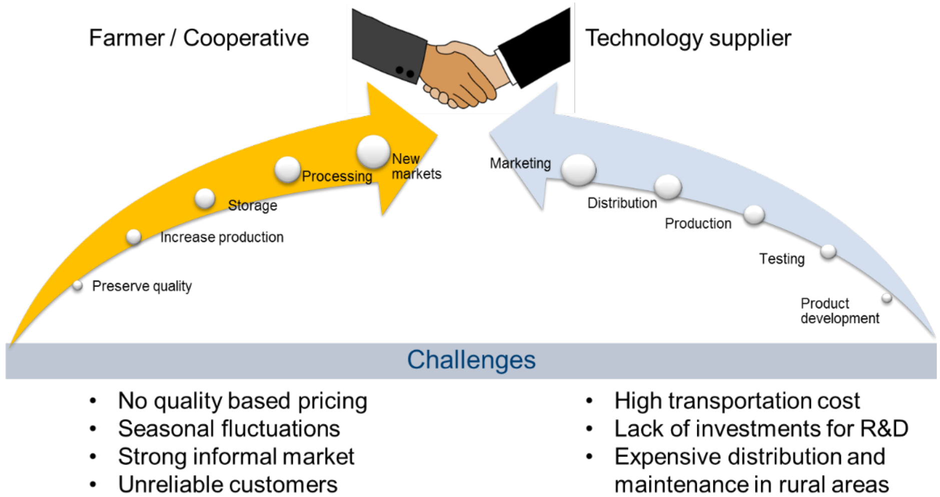

Figure 8: Schematic for challenges related to the introduction of business models for solar cooling of agricultural products.[40]

Milk Cooler Market

Milk chilling units were ranked fairly highly in the 2018 Efficiency for Access market survey: respondents gave them a comparative ranking of 5th out of 20 electrical equipment types for business/productive use impact potential (after LED lighting and in front of food grinding mills); and 6th place for consumer demand (after mobile/smart phone and in front of televisions).[41] No specific technical data, market development barriers or supplier related evidence has been identified for milk coolers. The existence of this potential market is noted, but out of scope for the current roadmap.

Walk-In Cold Rooms Market

The existence of walk-in cold rooms market is noted, but it is currently outside of the scope of this Roadmap. They will be important to complement the cooling markets described in this Roadmap. Suppliers have successfully deployed these coolers in many pilot applications.

4.0 Critical System Requirements

This section sets out a list of off- and weak-grid refrigerating appliances performance characteristics that the TWG stakeholders consider as most important for future appliances. The list was discussed and developed by the TWG, along with appliance affordability and energy consumption factors highlighted later in this section. The relative priority of the requirements will vary by application and by system type as set out in section. Performance requirement parameters are further set out in Table 1 and defined in *Annex 1: Explanation of Performance Parameters.*

Overview of System Requirements

High importance requirements common to all appliance types include (TWG stakeholders were consulted on relative importance of parameters):

- Effective cooling at high ambient temperatures.
- Affordability.
- Good 'holdover time' (meaning maintaining reduced temperature without use of energy storage)[42].
- Good electrical resilience (ability to withstand electrical disturbances in supply such as voltage spikes and drops).
- Appliance durability, such as: resilience to mechanical shock, drop and handling, especially of controls; long service life, backed up by warranty provision.
- Ease of maintenance and reparability (may also be provided via after sales service).
- Ease of transportation to and installation at usage location(s).
- Meet environmental impact expectations (in addition to low carbon / energy efficiency) including circular economy provisions; global warming potential (GWP) and Ozone Depletion Potential (ODP) of the refrigerant and blowing agent for the insulating foam; end of life (waste) provisions.
- Accessible design, with regards to gender and disability.
- Functional design: having appropriate compartments and dividers; glass door for retail display.

The other main requirements vary in relative importance by type of appliance and electrical input system:

- Good 'autonomy,' meaning maintaining reduced temperature whilst using energy storage: electrical or thermal (Note: this will be a much higher priority if energy supply is intermittent).
- Low in-rush current.
- Ability to maintain cooling with low power input and low starting current.
- Suitability of design for local manufacturing or assembly, scalability of the design for production in suitable numbers and also possibility to be adapted to local requirements including sizing.
- PAYG compatibility.
- Coping with high humidity (automatic defrost control or easy manual defrost).
- Good energy efficiency and/or low energy operational mode(s) and/or control strategies to reduce consumption.
- Accurate maintenance of temperature set by the user.
- High cooling capacity.

Whilst some of the performance requirements are already met by established technologies (but may not have been applied to the off-grid and weak-grid sector for economic or other reasons), other requirements will need to be addressed by new technologies. The priority of technology aspects is identified and addressed in Section 6.0 *Technology Options to Meet Performance Requirements and Market Needs*. Aspects relating to other market issues that must be addressed are identified in Section 7.0 *Non-Technology Initiatives and Competences Needed*.

Prioritising Affordability Rather than Cost Reductions

'Reduction of appliance cost' is one of the most commonly heard challenges from TWG stakeholders. But the outcome of any economic decision of whether to purchase, or the result of a financing application, bears only some relation to the cost of components in the appliance. The manufacturing costs (i.e. components / technologies and assembly labour) usually accounts for well under half of the value charged to the end user. The concept of affordability takes into account many more factors affecting the net cost to owners over the appliance lifetime and must be considered here if best outcomes are to be achieved.

Other cost elements important for the buyer and user are:

- Total profit margins of all supply chain (and value chain) players, especially those that are active in rural areas.
- Fluctuations in raw material and component prices.
- Quantities in which the appliances are made (batch vs. mass produced).
- Purchase quantity.
- Shipping costs.
- Import tariffs and sales taxes.
- Financial transaction fees (loans, subsidies).
- Running costs, such as price per kWh of power consumed and maintenance.
- Value of the whole package with which it is sold (hardware and services).
- Any financial support or incentive initiatives (governmental, NGO or supplier led).

More research into the relative sizes of these cost/benefit elements is needed to properly focus attention on the most important aspects. In addition, affordability for any 'productive use' applications (commercial, agricultural) must relate to any revenue streams that the appliance enables.

Factors that could be as, if not more, influential on the financial attractiveness of affordable future appliances, when compared with cost reduction R&D for certain components, include:

- Economies of scale as the market grows (also exploiting synergies with refrigeration for motorhome and recreation markets).
- Programmes to facilitate aggregated purchase.
- Subsidies.
- Extending the life of the appliance (through better design and reparability).
- Increased fair competition between suppliers based on robust and relevant performance information and a level playing field.
- A stable or at least predictable regulatory environment within which market operators can develop their business models and operations and secure investment with higher confidence.
- Encouragement and incentives for the market to supply appliances that meet higher standards of performance, environmental impacts (waste; recyclability), social or other benefits.

Research priorities for better understanding of the economics of these systems are:

- Price per kWh of power delivered under different scenarios.
- Energy required per day for systems of various types, including, for example, input kWh per kg of ice produced; input kWh per [40] soft drink bottles cooled from [35ºC to 12ºC].
- Cost of a given cooling service with respect to daily revenue achieved, using a few illustrative example goods such as: bottles of drink per day, litres of milk or dairy goods sold at market etc.
- Relative importance and end price impact of the principle stages in the value chain from manufacturer to end user (as listed in section).
- Cost of solar system per kWh power output capacity.

Affordability must therefore take the whole value chain into account as well as quality, functionality and reliability of the appliance and the whole service experienced by the end user. It has given rise to some technology proposals (Section 5.0) and also several non-technology proposals (Section 6.0).

Energy Consumption and Efficiency Factors

For the majority of solar home systems currently in use in developing country communities, electrical power is stretched to cover a TV, lighting and fan. Energy efficiency is therefore very important for those appliances to ensure adequate service can be sustained on poor days with (for example) only 2 hours a day of good solar input. As shown in Figure 5 in Section 3.0, much higher power capacity home systems are needed to accommodate a refrigerator. Although it may seem more cost-effective over the system life to buy bigger solar panels than to invest in a more efficient appliance due to the falling cost of solar panels, higher efficiency is needed to truly minimize purchase cost of the system. It remains important from environmental impact considerations to have good efficiency in order to reduce resource extraction usage and emissions associated with manufacturing and waste of the power supply equipment (solar panels, larger batteries etc.). In the case of paid grid connections charged by a kWh rate, higher efficiency translates into an affordable mean to run the appliance for longer each day. Unfortunately for many, the cheapest and available appliances are poorly inefficient appliances and inverters. They compromise the vast majority of appliances used despite their poor medium and long-term economics. Purchase price is often a more dominant factor but a reasonable level of energy efficiency is a major driving factor in some usage situations and is clearly necessary.

Circular Economy Considerations

The circular economy incorporates life cycle modelling and design. It requires reduction of embodied impacts, extended appliance lifetime, reparability, reduced residual waste and more. Circular economy is guided by the hierarchy of prevention, minimisation, reuse, recycling, energy recovery, and disposal. Successful implementation will need better materials and product design, new business models, global reverse networks (including product reclaim and reuse) as well as much improved enabling conditions (policy and incentives).

Anecdotal evidence from TWG stakeholders suggests that circular economy issues are not yet given prominence in the supply chain considerations of many off- and weak - grid appliance manufacturers and suppliers. Fortunately, some are starting to develop appliance collection programmes for spares or repair at end of PAYG/lease contracts and GOGLA, the global association for the off-grid solar energy industry, has convened an e-waste Working Group[43] to develop an e-waste toolkit.[44] Another promising development is the USAID and UKaid supported Global LEAP Solar E-Waste Challenge for innovations in solar e-waste management in sub-Saharan Africa[45]. The program will support innovations in e-waste management for the off-grid sector, and in doing so, catalyse broader and longer-term action to address the e-waste challenge. While circular economy thinking and design is starting to gain prominence in on-grid appliance and policy initiatives for developed economies,[46] it is arguably far more important to the off-grid market and where perhaps it could first become 'mainstream'.

It is a challenging transition for conventional and for off-grid appliances, to break through conservative approaches and expectations that costs could be higher through circular economy design. Circular economy issues can be addressed most economically and fully if they are factored into the specification at the outset and built into new designs so that marginal costs are more manageable. Off-grid appliances could be fundamentally different to conventional appliances as needs and priorities differ and each sector can learn from the other. Practical first steps include designing for robustness, reparability, simplification and with fewer material types (especially plastics). If the design is appropriate and well-specified at an early stage, then economies of scale could result in similar overall cost. A full and robust specification must be embedded into procurement by buyers and underpin deployment campaigns by NGOs, donors, and other stakeholders.

In the case of refrigerators insulated with polyurethane foam, there is a balance to be struck between reparability/ease of disassembly at end of life, versus efficiency and structural integrity. Polyurethane insulating foam can account for 15% of appliance weight and is hard to recover.[47] Advice from experienced specialists suggests that end of life recycling concerns should not be allowed to unduly impact design of efficient appliances as recycling facilities will be established in due course.[48, 49] To achieve appliance recovery (reduce waste), 'Track and Trace' is a possibility for higher value appliances with a leasing supply model. Other policy possibilities include Extended Producer Responsibility and requirements modelled on EU WEEE regulations, which are being developed now in Africa, Asia and Latin America. Appliance waste can also be reduced through cash-back schemes for appliance replacement, feeding waste appliances into responsible, government-backed recycling schemes, such as the recycling plant already established in Rwanda.[50] Refrigerators have relatively high intrinsic value of their metals and components although handling and treatment costs usually result in a net cost for disposal. In the EU, material values vary between 40-80 €/tonne (sometimes up to 150 €/tonne) depending on the value of Fe, Cu, Al, and plastics[51], with total net cost after treatment of 40-50 €/tonne. Disassembly can be manual under controlled circumstances, but full treatment of insulating foam with safe disposal of any harmful foaming gases requires costly specialist plant.

Examples of circular economy policy requirements that can be appropriately adapted for the off-grid sector are:

- Resource efficiency requirements have been built into EU ecodesign regulations for commercial refrigeration equipment which cover availability and delivery of spare parts;[52] access to repair and maintenance information; requirements for ease of dismantling and recovery of hazardous components.
- Requirements for proper End-of-Life treatment are consolidated for Europe in the technical annexes of WEEELABEX standards.[53]

Details of Performance Requirements and how Importance varies by Appliance Type

Performance Requirement parameters are defined in *Annex 1: Explanation of Performance Parameters.* Relative importance is assessed indicatively as one of four levels of importance to the market:

H: High Importance
M: Medium Importance
L: Low Importance
N/A: Not Applicable or Zero Importance

Table 1. Relative importance of performance parameters for the different types of appliance.

Performance Requirement	Used on off-grid (solar PV)			Used on weak grid (also mini-grid)			Vaccine refrigerator (for reference only)	Comments
	Household refrigerator	Commercial refrigerated storage or transportation	Ice maker	Household refrigerator	Small Commercial refrigerator	Ice maker		
Effective cooling at high ambient temperatures	H	H	H	H	H	H	H	Technically challenging and really is about increasing cooling capacity and temperature lift; innovation needed; economic challenge too.
Affordability	H	H	H	H	H	H	M	Complex, many factors on top of technology: profit, tariffs, service, supply chain and financing to be addressed.
Good 'holdover time' (without use of energy storage[54])	H	H	H	H	H	H	H	Straightforward to resolve (insulation; thermal breaks; gaskets)
Good electrical resilience	H	H	H	H	H	H	H	Straightforward to resolve, some innovation useful
Appliance durability (mechanical resilience and long service life)	H	H	H	H	H	H	H	Complex, many factors in design, technical and service related. Metrics and assessment techniques needed. Plus, failure mode analysis.
Ease of maintenance and reparability	H	H	H	H	H	H	H	Complex, many factors. Metrics and assessment techniques needed foremost.

Performance Requirement	Used on off-grid (solar PV)			Used on weak grid (also mini-grid)			Vaccine refrigerator (for reference only)	Comments
	Household refrigerator	Commercial refrigerated storage or transportation	Ice maker	Household refrigerator	Small Commercial refrigerator	Ice maker		
Ease of transportation and installation	H	H	H	H	H	H	H	Innovation needed, complex challenge.
Meet environmental impact expectations	H	H	H	H	H	H	H	Straightforward but several design aspects to be combined. Needs suitable incentives and/or compulsion to ensure it is addressed.
Accessible design appliances (gender, disability)	H	H	H	H	H	H	H	Need to better understand the challenge – hardly scratched surface of this field yet. Improvements decided as important in this could have profound impact on appliance design and cost.
Good energy efficiency	H	H	H	H	H	H	H	Many aspects to this and relative importance does vary by usage situation (see section 4.3), but engineering can resolve once metrics and benchmarks are agreed; innovation also needed.
Low in-rush current	H	H	H	M	M	M	H	Should be straightforward to resolve (motor design, controls and electrical storage) but needs easy and low-cost implementation. Whether this is a real problem or not depends on the system, but refrigerators are unlikely to be compatible with most existing systems.
Ability to maintain cooling with low power input and low starting current	H	H	H	M	M	M	H	Innovation needed, such as control of variable speed compressors.

Performance Requirement	Used on off-grid (solar PV)			Used on weak grid (also mini-grid)			Vaccine refrigerato r (for reference only)	Comments
	Household refrigerator	Commercial refrigerated storage or transportation	Ice maker	Household refrigerator	Small Commercial refrigerator	Ice maker		
Suitability of design for local manufacturing or assembly	M	M	M	M	M	M	L	Innovation and local partners needed; scope for significant change in concept to meet many objectives including environmental and cost. Medium term objective.
PAYG compatibility	H	M	M	H	M	M	N/A	Interoperability essential, cross-platform solution. Innovation and industry cooperation needed. Technical and important ethical considerations to be addressed.
Coping with high humidity (automatic defrost control or easy manual defrost).	M	M	H	M	M	H	M	Should be straightforward to manage, but innovation needed.
Good 'autonomy' (using energy storage)	M	M	M	H	H	H	H	Should be straightforward but innovation needed on integration with SHS and optimal energy management.
Accurately maintain temperature	L	M	M	L	M	M	H	Various solutions, straightforward.
High cooling capacity	L	H*	H	L	H	H	L	Economic rather than strictly technical challenge (design to acceptable price); innovation needed. *Cooling capacity is not required for transportation boxes

5.0 Prioritised Market Needs, Products, and Services

TWG and stakeholder feedback, in addition of desk research, has identified the following priority market needs for cooling appliances in the off-grid and weak grid sector:

1. Refrigerated storage
2. Ice making
3. Chilled transportation of foodstuff

The details provided by stakeholders suggest that the following priority products would be required by the target markets to address the above needs:

1. Small commercial refrigerating appliances to store and/or display drinks and foodstuff in retail and at markets
2. Small commercial refrigerating appliances for storage of produce in the food supply chain, for example in agriculture, dairy, meat, fish
3. Small commercial ice makers producing ice for food cooling in very many applications
4. Small volume insulated or refrigerated containers for transportation of perishable foodstuff in the food and drink supply chain
5. Refrigerators and freezers for storage of foodstuff in community buildings and homes
6. Modular chiller components and subsystems to be driven by solar direct drive, for local assembly as needed to suit varied applications

Figure 9 (below) presents the main appliance types that stakeholder feedback suggests are needed in the targeted parts of the market.

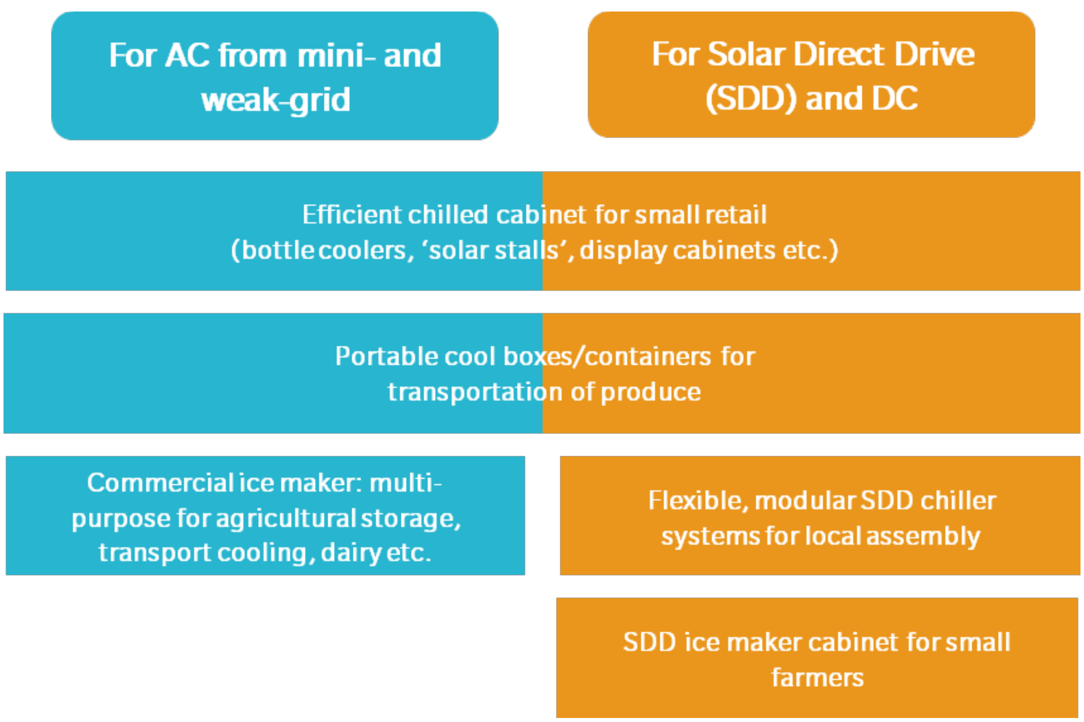

Figure 9: Overview of main appliance types needed to serve the targeted parts of the market for cooling appliances.

Products required for refrigerated storage are described simply in Figure 9, with more detail given below. The products required for ice making, for transportation and the modular cooling systems are less commonly familiar and some additional information has been collated to define them as below.

Appliances for Refrigerated Storage

These products provide a cooled space inside an insulated box with size, shape and temperature varying by application, as well as the necessary cooling capacity and design of door(s). The Roadmap appliance scope has already provided much of the necessary definition for these units, see Section 2. Household refrigerators for this market would have small storage volumes of around 80 litres, with commercial units having up to around 180 litres. For storage of produce in the food supply chain, these products would fulfil the needs of small producers and require storage in the range of a few hundreds of litres up to a couple of cubic metres. Products with a volume of more than two cubic metres are more like walk-in coolers and are not considered under this Roadmap.

Appliances for Efficient Production of Ice

Ice provides one of the most interesting but also demanding applications, with almost endless usage possibilities. Ice facilitates storage of thermal energy for cooling and can be used for:

- Load management, such as meeting peak demand using an ice bank for rapid cooling which can be built up over many hours using a small cooling system
- Storing/using surplus PV energy
- Cooling insulated transportation boxes for produce or milk
- Packing with foods for transportation, such as flaked ice for fish
- For sale as ice, for any use that a customer has for it

Through enabling the purchase of ice, those who cannot directly access or afford a refrigerator can get access to the benefits of cooling. The ice enables storage and transportation of foodstuff in cheap insulated containers, so that farmers and food producers increase revenues by reaching a wider selection of customers and getting best prices for their produce. It also reduces wastage including storage overnight for sale next day.

The end user may need ice in the form of block or flakes and in thermal packs or prescribed ice shape for other equipment in some applications. However, the experience of companies developing ice makers for off grid use suggests that block form is the most versatile as blocks last longer (than flake or smaller shapes) after production and can be transported and broken up by the user as needed. Each type of ice form has specific equipment needs to produce it most efficiently.

The needed appliances to produce ice can be defined as:

- General purpose stand-alone batch ice-making appliance with a compartment able to freeze various types of thermal pack or water container. Example technical specification is quoted here as a starting point, but other specifications would be needed that would vary by capacity of equipment: [at -10 ºC], with cooling capacity to produce [16 kg] of ice per 24 hours under solar irradiation of [5 kWh/day] and average daily temperature of [25°C] at an efficiency of at least [95 Wh/kg].[55]
- Very high cooling capacity system that is resistant against liquid refrigerant intake during harvesting cycles.
- Conversion kits with inverter and energy storage to enable suitable commercial on-grid units to be used off-grid or on mini-grid should also be considered.

Systems for Chilled Transportation of Small Volumes of Produce

Farmers and food producers can expand their customer base and get better prices if produce quality and freshness is maintained during transportation through longer distances. Access to affordable technologies that enable local producers to sell into a growing cold chain will be crucial to maintaining local production, skills and employment and compete with imported chilled produce that may otherwise replace local foods.

The products needed for chilled transportation of small volume produce can be defined as:

- Lightweight insulated containers with which small farmers can transport products of various types making use of off-grid energy to produce cooling, either through integral cooling or using ice from other appliances. Containers should be suitable for containing [10kg to 30kg] produce loads of any or a mix (at different times) such as fish, milk, dairy products, meat, vegetables, and fruit. They should be Ideally suitable for local manufacture or assembly and able to take advantage of mixed mode transportation (on foot; bicycle/hand-cart; motorbike; car; pick-up; van). Example of a milk system is shown in Figure 10.

Figure 10: Insulated milk-cans with integrated ice-compartment for cold transport of milk[56]

Cooling System Modular Design

The delivery logistics to remote communities are challenging for refrigerators due to their physical size and has become an obstacle limiting growth. Delivery generally requires a 4-wheeled vehicle and cannot be transported by motorbike, which is often the only vehicle available in remote communities. Experience shows that refrigerator's fragility leads to damage on very rough roads, thereby making transportation of larger commercial equipment even more challenging. Repair is also challenging to organise, especially when it requires special tools and training. Furthermore, refrigerating appliances for a specific need on a farm or business may be extremely hard to identify or get hold of from the wider market, if they exist at all. Therefore, a system could be built to meet the specific need if local skills and components or subsystems are available, with suitable guidance and assured component compatibility.

Most of the transported volume of a conventional refrigerator is empty space. An alternative is to transport only the condensing unit and key components which could be set out on a self-contained frame ready to install in a locally made or repurposed insulated cabinet. For bespoke systems, components can either be purchased for local assembly or locally manufactured of the insulated cabinet or whatever is to be cooled. This would ease transportation, reduce costs and duties/tariffs, as well as engage local technicians to benefit the local economy and help make the industry sustainable. This could include locally produced insulation material with options for organic materials with very low environmental and waste impact (outer dimensions may not be closely constrained but significant compromise on properties would be needed[57]); frame and construction using commonly available engineering materials; guidance for robust and effective design. This approach would also ensure the widest scope for repurposing sub-systems and components at end of life as well as substitution of components from locally available stock for repairs (fan, compressor, evaporator, condenser, internal lamp etc). Example systems are shown in Figure 11.

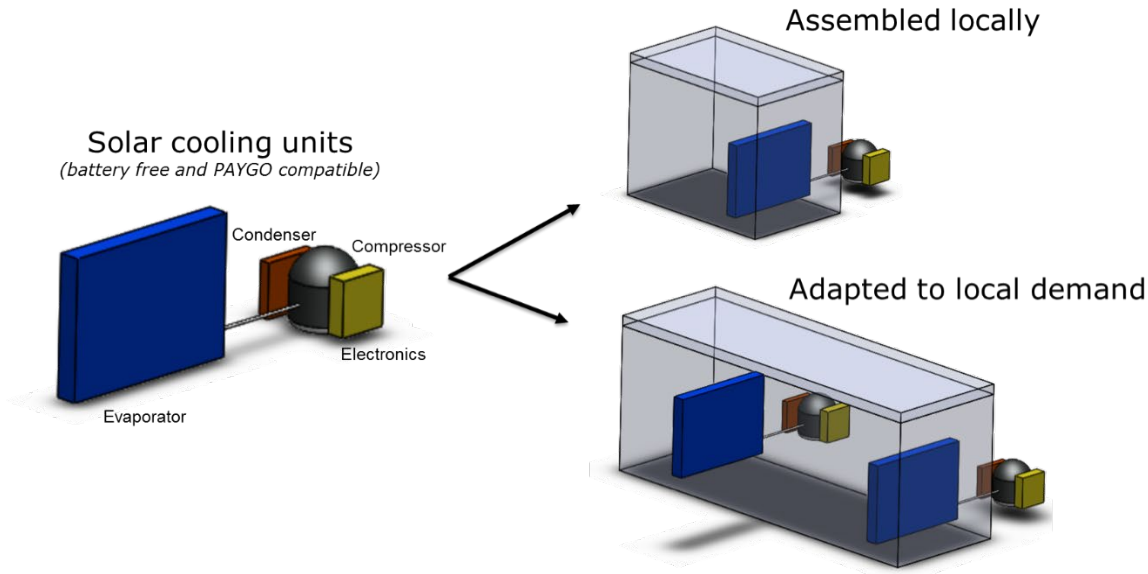

Figure 11: Schematic for 'Do It Yourself solar cooling units.[58]

6.0 Technology Options to Meet Performance Requirements and Market Needs

This section focuses on a list of priority technologies selected by TWG stakeholders (a longer list of technology options is presented in Table 2 of Annex 2). The following technologies are selected as they address more than one need, open up new markets, offer cost reductions and/or address other critical requirements. These technologies are explained in an indicative descending order of priority based on stakeholder feedback:

1. Compressors and controllers to fully exploit technology advantages.
2. Cooling system modular designs for ease of transport to place of use, local assembly and high reparability.
3. Control systems with smart algorithms to manage energy storage across solar energy systems, with good interoperability.
4. Selection/specification software to support technical sales, regarding compatibility of appliance and an electrical power system.
5. Simple technology solutions to increase cooling capacity at times of high ambient temperature and cope with high humidity.
6. Peltier cooling (e.g. for cool-boxes).

In addition to applying these technologies to develop the appliance market, appliances are needed that:

- Embrace the circular economy.
- Improve appliance reliability and reparability.
- Achieve PAYG compatibility.

Compressors and Controllers

Context

If the rotational speed and cooling capacity of refrigerator compressor can be varied, then cooling can be matched to demand at that point in time. Advantages of variable speed system compared with a fixed speed system include:

- Lower inrush current (through controlled slow start).
- One compressor size can serve a wider range of applications, increasing economies of scale and reducing unit cost.
- Lower noise levels when at lower speed.
- Cooling available during periods of low power availability (compressor can be started and run at lower power level than a fixed speed compressor).
- Higher overall energy efficiency over a daily and seasonal cycle.
- The included smart electronic control system can be applied in many ways:
  - User selectable ‘economy modes,’ e.g. to run at 50% or 25% of full capacity, advantageous for weak grid and off-grid applications; also, to extend operational time when users cannot afford 24/7 service (also secures additional revenue for system supplier serving low resource households);
  - More flexibility to inherently handle wide range of electrical input types (DC and AC inputs due to its inbuilt speed controller);
  - More flexible integration and energy management using energy storage and smart home controllers.

Anecdotal evidence suggests that not all suppliers utilize the variable speed functionality, even though it is included in the most widely used compressor for off-grid applications, and none yet exploit all of the potential advantages noted above.[59] Flexible controllers with excellent interoperability could greatly enhance overall system efficiency and capability.

The choice of DC compressors serving the off-grid market is extremely limited. The availability of additional variable speed compressor types and sizes would help the market to move ahead as it grows. Synergies are possible on DC refrigeration with the motorhome and recreation market in some developed countries, which could help drive some technology development and cost control measures until demand in off-grid markets takes off. Stakeholders have indicated that unit sales over 10,000 and possibly in excess of a million may be required to justify the significant development investment needed by manufacturers. Aggregated procurement options could be also considered.

Note: The variable speed motor control systems are largely the same as those applied to pumps, fans or other motorised systems, with some adaptation. Technology transfer both ways could be relevant: for example, technologies already well-established for solar water pumps such as small inverters incorporating maximum power point (MPP) trackers which are fully adapted for solar driven applications.

Technology Specification (the need)

1. Wider choice of variable speed DC compressors on the market that are compatible with R290 and other hydrocarbon refrigerants, and serving capacities from around 20W up to 300W or higher with key features, for example: soft start; wide speed and capacity range; maximum power point tracker etc. Cooling capacity range will vary depending on the application type (household or commercial) and is capped via an upper refrigerant charge size for class 3 (highly flammable including HC) refrigerants by the requirements of IEC 60335-2-89.[60] The limit set by the standard as of May 2018 is 150g which allows adequate cooling capacity for all household appliances and the vast majority of small commercial cabinets. However, a positive vote within IEC in April 2019 on the new version of IEC 60335-2-89 increases the class 3 charge limit to 500g[61]. This higher limit, once the standard is published, opens up a larger cooling capacity range for integral appliances to safely use flammable refrigerants. It will make it permissible, for example, to build large commercial chilled food retail display cabinets with full head height and a width of 3.5m.[62]
2. Separately available variable speed drive and compressor controller unit that is compatible with various compressors (often a compressor controller is required in addition to the speed controller, adding to total costs). Key features include user selectable 'economy modes,' compatibility with various electrical inputs (DC and AC), ability to drive various compressors, and flexible integration with smart solar home system controllers.

Anticipated Market Impacts

- Increased appliance and home system energy efficiency
- Elimination of system damage from inrush currents
- Expansion of energy storage options for home systems
- Expansion of viable market

Timelines and Milestones (speculative, for development of technology demonstration models)

- 3 Months: Basic controller specification plus enhanced options
- 9 Months: Pilot controller technology for a selected system
- 18 Months: Potential market for compressors used in off-grid and weak grid identified and quantified in terms of sales, with robust published market research
- 2 Years: Market-ready controller unit with some flexibility of applications
- 3 Years: Formal field trial for new designs of variable speed compressor, leading to aggregated purchase orders
- 3-5 Years: Sector-wide agreement on communication protocols and interface types
- 5 Years: New range(s) of variable speed compressors launched for this market
- 5-7 Years: Versatile universal controller

Optimizing Modular Design

Context

The context for this technology is described in Section 5 and results in a need for condensing units with key components that are set out on a self-contained frame, evaporators and other key components selected for mutual compatibility and local assembly in flexible modular ways to suit a specific local cooling need.

Technology Specification (the need)

- Versatile and modular condensing unit with controls and any other key components necessary to construct a cooling unit in an easy to assemble format, designed for flexibility on purpose and ease of maintenance using local skills and easily available tools. Schematic shown in Figure 11 of Section 5.
- Options: adequately effective, long lasting and low environmental impact insulation material suitable for local manufacture and/or assembly; designs using locally sourced low impact insulation materials, perhaps organic in origin (e.g. coir, textile, chaff etc.).

- Methodology and calculation aids to assist designers/specifiers through the process of assessing their cooling need, deciding if it can be met by the modular system, specifying their system and drawing up the plans for its assembly.
- Modular key components that are compatible with other components bought from local engineering/technical dealers and viable for stock/sale in sustainable quantities. Assumes basic engineering technician training, familiarity with how a fridge system works and basic assembly techniques.

Anticipated Market Impacts

- Stimulate local economy and build skills through ensuring full ownership of the technology and its future
- Potential to fulfil current and future cooling needs locally by adapting the equipment
- Make use of economy of scale by implementing the same key-components (e.g. Solar cooling units, insulation, fan, pumps etc.) for different applications as household refrigerators, freezers, ice-makers or ice-storage system for milk or vegetables cooling.

Timelines and Milestones

- 6 Months: Specification of most prevalent types of local need then specification for equipment
- 1 Year: System designed, components sourced and sub-assemblies designed and tested ready for field trials
- 2 Years: Field trials completed with feedback for adapting designs
- Modular selection of components available to order along with a design flowchart to assist design process by specifier.

Control Systems to Manage Energy Storage

Context

Solar energy systems, including for homes, businesses and small communities are well-established with associated controls, but adding refrigerating appliance to the system brings challenges as well as important opportunities that a new generation of controllers need to meet. Adding a refrigerator can easily more than double the power demand of a home system (see Section 3) and could quadruple its cost, as well as adding a risk from a high in-rush current when some types of refrigerator compressor start up. Conversely, cooling is a flexible load that can be switched in and out and offers built-in energy storage by sub-cooling of stored foods and/or of ice packs during energy surplus to provide cooling during time of low power (though some foods are damaged by lower temperatures). Controllers can also help with monitoring and predictive maintenance of the refrigeration.

Technology Specification (the need)

Integrated or modular controller compatible with solar home systems and certain refrigerators with functionality that could include:

- Energy storage protocols to switch on or off cooling, control compressor(s), control sub-cooling or production of ice or release of thermal storage based on energy availability and demands, economic and system technical data, avoidance of peak grid charges, load shifting, maximise harvesting of solar energy using mixed mode energy storage etc.
- Live user interface to monitor running cost and energy management where better user information can enable economic decisions, for commercial systems (not useful for households).
- Low-loss power supply conversion (DC-AC etc.; characterize losses; develop target efficiency) with protection against motor inrush current.
- PAYG compatible – which requires some technical and several important ethical and commercial liability considerations to be resolved such as regarding food safety; storage of important medicines; use of alternative power sources when needed etc.
- Offer economy modes for reduced running costs (e.g., 100%, 60% and 30% of full cooling capacity).
- Modular, replaceable unit.
- Flexible platform, high compatibility with existing systems, compartment temperatures and cooling capacities.
- Common industry standard communication protocol.
- Integrated remote monitoring for predictive maintenance via cellular coverage for PAYG systems (may only be economically feasible for larger commercial equipment). Many systems already have remote monitoring of other equipment, but cooling equipment must be integrated (link with Interoperability TWG).
- A standard application programming interface (API) for communication between power supply and loads, with an adaptive control system: as discussed by the Interoperability TWG. Also scalable for multiple refrigerating appliances across a mini-grid serving several or many homes.

Anticipated Market Impacts

- Users and system suppliers exploit load management for cooling equipment to make it more cost effective and provide better service for users.

Timelines and Milestones

- 6 Months: Controller specification with prioritised functionality
- 1-2 Years: Functional controller for certain systems
- 3-5 Years: Sector-wide agreement on communication protocols and interface types
- 5-7 Years: Versatile universal controller

Selection Software to Support Technical Sales

Context

It is complex to decide whether a given appliance is usable in a particular SHS or other power situation, or for a certain refrigerator to decide what the power requirements would be for a given level of service. There are many factors to take into account, not only for the technical aspects, but also for the economics. An 'expert system' would greatly aid other system supplier businesses and those involved in that process at dealerships, including some users, by leading them through the necessary technical and economic questions to ask and data to amass. Then a software aid to advise whether a given system can provide the power needed for the refrigerator to meet a minimum service level (or an ideal level), or what minimum power supply a refrigerator would need. An open source version must be made available early on, but more refined and accurate bespoke and proprietary systems will also be important in due course.

Technology Specification (the need)

- Open source guidance for those specifying refrigerating appliances for use with existing or new home and small commercial power systems, in both solar and weak grid power situations with two main components:
  a) An 'expert system' to lead them through the necessary technical questions to ask and data to find that is important to make an appropriate selection. Should include and address issues such as ambient temperatures, equipment geographical location, immediate environment (indoors/outdoors, sun shading etc.), usage scenario (indication of minimum ad ideal service required), electrical characteristics of the appliance and the power system, other load demands on the system, cost issues, AC versus DC systems, cost efficiency and suitability of ice-storage, geographical location (for solar cycle) or power supply profile per day and seasonally, and other factors as necessary.
  b) Software or other means to calculate whether the given appliance will deliver minimum necessary refrigeration service whilst sustaining acceptable service from the other loads on the system. This could include calculating system supply and demand energy profile(s), assess impact of energy storage etc.
- Suggested to be tackled at two levels of complexity: 1) a simple go/no-go indication based on short PDF/paper guidance including look-up tables and a flowchart for scenarios or similar diagram; and 2) a bespoke technical assessment using software.
- Outputs would include ensuring that suppliers of appliances and power supply systems fully understand the specification data needed from them and what data and look up tables will be needed to characterise weak grid scenarios.

Anticipated Market Impacts (in conjunction with other technologies/products)

- Good decisions made about compatibility of appliances in given power situations leading to satisfied customers and protecting the reputation of cooling services in this market
- Better overview of final system cost, including PV panels, batteries, ice-storage and cooling system.
- Better financial outcomes for users, appliance and system suppliers – and for the industry as a whole

Timelines and Milestones

- 1 Year: Specification for the concept with content and outputs needed from the guidance; at the simple level and at the technical analysis level, as tested and refined with stakeholders; specification of data inputs, data outputs and assessment/calculation algorithms to be used agreed with diverse expert panel.
- 1 Year: System performance and autonomy data on dependence of ambient temperature and solar radiation made available.
- 1 Year: Proprietary software with basic functionality available from some suppliers for their system/appliances.
- 2 Years: Necessary data specifications made available by appliance and power system suppliers; look-up tables of assumptions for solar and weak grid scenarios available.
- 3 Years: Open source software working as Beta after adequate field testing.

Increasing Cooling Capacity

For commercial and agricultural cooling systems (not relevant to household or small commercial appliances), it is expensive and wasteful to design systems that are inherently able to deliver cooling at times of peak demand and/or peak ambient temperatures. Many existing systems struggle to meet evolving needs. But simple technologies can boost cooling capacity, both as original components and retrofits. Examples include additional condenser (or evaporator) fans; water-spray assisted cooling of condensers; improved shading and cladding; improved insulation; and also, maintenance measures such as condenser cleaning, eliminating refrigerant leaks and ensuring correct amount of refrigerant is in the system. Coping with humidity would require automated door closure mechanisms, use of PVC transparent plastic strip curtains that reduce the amount of warm air and humidity going into a cooled space whilst still allowing access to people and goods, evaporator designs that are easy to defrost etc. Much of the equipment could be locally sourced - it would be the designs and step by step processes that are prepared and made available and adapted/implemented locally. The need is for designs and training for technology add-ons that can be incorporated into systems being built or retrofitted, with a view to local sourcing of the components and tools needed. This could be offered as part of a technician training initiative.

Exploit Peltier Cooling

Thermoelectric (Peltier) cooling generates a cold face (c.-30ºC) and a hot face (c.+200ºC) on opposite sides of a thin plate of special materials, by applying an electric current. To make a cool-box, each side of the plate can have a finned heat exchanger with a fan attached: cold side faces inside an insulated box, hot side faces outwards and then it can cool the box contents.

Whilst the technical feasibility is good for a cheap and reliable cool-box or household refrigerator, efficiency and cooling output are low with thermodynamic efficiency of 1%[63] compared with 14% for vapour compression. Another report suggests a coefficient of performance, a metric for refrigerating efficiency, of 0.7 for Peltier, 2.6 for vapour compression and 0.5 for absorption.[64] In addition, technical feasibility in high ambient temperatures is disputed. There are also major challenges to building such a market aimed at very low resource users who already cope very well without a refrigerator using (for example) a wet earthenware pot for cooling, using fresh food daily and boiling milk to store it longer.[65] Peltier cooling is unlikely to be suitable for commercial or agricultural applications due to low cooling capacity.

7.0 Non-Technology Initiatives and Competences Needed

This Roadmap is focused mainly on technology R&D needs, but stakeholders have made clear that the technologies cannot be successfully deployed without a range of coordinated supporting initiatives, competences and resources. This section briefly identifies necessary supporting initiatives that are not yet in place, with the priorities summarised in Figure 12.

Figure 12: Main market support deliverables identified to ensure a sustainable market.

Market support initiatives and competences identified to assure deployment of appropriate appliances are listed here:

- Establish recognised definitions, categories and performance metrics.
- International test methodology.
- Networks of trained and equipped refrigeration maintenance technicians.
- Expanded financing options.
- Appliance certification and quality programme.
- Address circular economy issues.
- Education and awareness raising for users and the supply chain.
- Support for manufacturers and system developers to get appliances tested.
- Technologies and approaches to improve appliance reliability and reparability.
- Helping suppliers to make informed decisions on appliance/service value & affordability.
- Evaluating and mitigating market risks and unintended consequences.

These requirements are described and explained below.

Establish Definitions, Categories, and Performance Metrics

Many refrigerator types are well defined in standards such as IEC 62552, WHO specifications and others. However, definitions and categories are not necessarily applicable in off- and weak-grid refrigerator market as suppliers do not operate within standard frameworks of test methods and product specifications, although Global LEAP has established a voluntary approach. Therefore, an established definitions and categories will have to be adapted. A breakout group of TWG stakeholders has made good progress, with their results shown in *Annex 3: Categorical Technical Parameters* and as previously mentioned, the LEIA programme has commissioned a market study on off-grid refrigerator use cases due to report in early 2019.

International Test Methodology

One or more internationally recognised test standards that cover all of the necessary performance parameters to properly specify refrigerating appliances, their compatibility with power systems, as well as other characteristics to assess appliances for environmental and economic sustainability, are needed. The standard should enable a functioning and fair competitive market, allowing fair comparison of performance for competing systems and technologies; and give a clear sense of technical direction to appliance and system designers. The standard must define metrics and test/assessment methods in a way that is representative users' experience. It should identify a set of typical PV-power profiles and associated ambient temperature profiles so that appliance performance can be compared under a manageable and recognised set of representative ambient environmental conditions. In due course the standard should be adopted under one of the international standards bodies (e.g. IEC) for official use by governments, national and international programmes to set performance benchmarks and encourage deployment of verifiably better appliances. Currently, a specification ('Standardisation request') for such a test standard is being developed by a breakout group of TWG stakeholders. A strategy is needed for a global harmonised standard or family of standards with a key priority on working towards a globally recognised and adopted standard so countries do not each opt for their own local standards, which could lead to stifle competition and technology transfer.

Trained Refrigeration Maintenance Technician Networks

Training of local supply and maintenance staff is considered a crucial enabler for the off-and weak-grid refrigerator market. Technicians will be needed to help specify and install units, ensure suitable power supply and connections as well as locations for use, inform users how to make good use of the equipment and repair appliances. Technicians will also be needed to design and construct bespoke cooling systems for small commercial and agricultural applications. This can build on existing initiatives to establish technician colleges for air conditioning systems or other allied industries in target regions and equip them with adequate tools and supply chains to do that job well. Suppliers should be encouraged to incorporate maintenance as a value-adding component of their service, both to end users and SHS, PAYG and mini-grid providers. Local maintenance service contracts bring employment opportunities, which could be attractive for government support. Technician training must address safety issues for flammable refrigerants including certification on local charging, assembly and maintenance, access to spare parts and the skills to adapt creatively to use components that are available locally, and to understand the efficiency and effectiveness implications of compatibility issues.

Expanded Financing Options

Based on stakeholder feedback, mini-grid systems may offer the most economically viable route to market for refrigerators, but this is largely unexplored to date. Synergies should be explored where revenue-earning commercial refrigeration appliances make expanded power capacity economically viable for mini-grids. In parallel, PAYG offers a possible route into the household market although this remains extremely challenging in terms of economics, power demand and compatibility. Refrigerators are not yet economically viable for most solar homes, though a small number of system suppliers are evaluating possibilities. Even basic technical PAYG compatibility issues have yet to be fully addressed. If the household market is to be developed, then technical compatibility with PAYG and mini-grid must be standardized. This requires technical compatibility progress (controls, higher power etc.) AND an attractive long term financing package based on reliable and easy to repair appliances (to ensure long term availability) that users can afford to run for a substantial proportion of the time. To enhance economic feasibility, the opportunities for earning revenue from the equipment must be explored/understood and complemented by other innovative financing options. As noted previously, enabling PAYG and other pay to access funding models require technical, ethical and potentially liability issues to be resolved (see Section 3).

For the small commercial market, leasing and other financing routes are feasible for refrigerating equipment, once the case for securing a revenue stream can be made – this makes deployment of refrigerators much more viable for small commercial applications. Reliability, reparability and assured performance to enable the income are crucial for a convincing case. Considerations include that the cost of the appliance should incorporate its 'service:' value added on reliability, delivery of maintenance and training, especially as local service contracts bring employment opportunities which could be attractive for government support. There is also a need for published economic analysis of case studies.

Appliance Certification and Quality Programme

Lighting Global established a comprehensive Quality Assurance system for LED lighting products and solar home system (SHS) kits which provides suppliers with internationally recognized equipment assessment standards.[66] At its simplest, it provides a level playing field on which to compare products. Furthermore, it provides a route to independent certification of products. Once formally certified, eligibility is opened up for financial incentive schemes run by major donors and NGOs. This approach may also be valuable for off-grid refrigeration to establish and uphold high quality standards that do not only benefit users and suppliers, but also protect the reputation of the fledgling industry.

Circular Economy Issues

Circular economy life cycle thinking is essential for the environmental as well as for the economic sustainability of these emerging markets. Non-technology aspects include establishing a policy framework to ensure it happens. Possible policy elements include: 'Track and Trace' to recover appliances and reduce waste is a possibility for higher value appliances with a leasing model of supply, along with Extended Producer Responsibility and requirements modelled on EU WEEE and similar regulations, as are being developed now in Africa, Asia and Latin America. See also Section 4 Circular Economy Considerations for other aspects.

Education and Awareness Raising

Household and commercial users in off-grid markets will need training and refrigerator user manuals in regional or local languages. They are unknown to many and in some regions, this is due to urban households having no need or desire for them. To enable this, tools such as IP-free pictograms for appliance usage instructions would be useful including simple "do's and don'ts," to help users understand good practice usage, loading to allow cold air circulation, when and how to defrost, maintenance of temperature control, and management of door opening (e.g. products at the top will usually stay warmest). For example, it has to be clear for SHS users that if they leave the fridge door open, then sooner or a little later their lights will go out. Once standardised and multi-lingual guidance is developed, suppliers could be encouraged to include it with their appliances, or even compelled to do so in some regions or under some schemes. An additional level of training is needed for supply chain players in how to specify, assess compatibility and interpret technical specifications of appliances.

Testing Support for Manufacturers and System Developers

Getting appliances tested is expensive – a full performance test of a household refrigerator to the IEC standard takes two weeks in a thermal chamber and costs around $6.000. The additional aspects of electrical resilience and stress testing of off-grid appliances could more than offset any relative simplicity in other respects. But rigorous, fair and consumer-relevant testing is essential for the design and development process for any supplier, though many of these suppliers are small businesses with limited resources. Getting the best products to market in the shortest time will require support to complete testing. In addition to agreeing a test method[67], the following support is needed:

- Helping suppliers to set up test facilities, perhaps financing options;
- Identifying the important basic issues for which they should test, such as over or under voltage, power interrupts and harmonics, temperature attainment);
- Facilitating improvement and accreditation of regional labs;
- Guidance and support for field trials;
- Making it easier for suppliers to get appliances tested in reputable labs;
- Independent testing to establish and publish performance benchmarks - especially on new metrics such as reparability (industry average performance; best practice etc.);
- A simplified test protocol for screening of design options.

Improved Reliability and Reparability

A reputation for reliability is crucial for individual suppliers and also for the industry as a whole, especially when trying to negotiate better financing packages and is a key element of achieving a circular economy. Opting for cheaper appliances has major risks if failure rates increase and cause reputation damage followed by departure of investors. Identifying ways to measure reliability is therefore very important as well as market research on failure mode analysis (electronics; corrosion; damage from current surges; failures through icing up or damage during 'mechanical defrost'). Market surveillance is needed to control entry of counterfeit and poor-quality appliances.

Mitigation strategies include:

- In-field monitoring of hardware during development and in real use.
- Algorithms to anticipate failure.
- Technologies to reduce corrosion.
- Effective appliance regulations and training of market surveillance authorities.

Closely associated is the need for design for reparability, simple and robust designs (recognising the trade off with energy efficiency), use of standardised components, consensus to use the same climate-friendly refrigerant(s). There is, unfortunately, a serious obstacle to reparability of appliances that use very low GWP and energy efficient refrigerants which are flammable hydrocarbons (R290, R600a), imposed by safety requirements such as within IEC 60335-2-89.[68] This includes that re-makeable joints are to be avoided due to risk of leakage (and such joints are expensive anyway) and fully brazed joints are highly recommended as they are leak tight (and mandatory for larger systems). Nevertheless, methodologies are already well advanced in EU and other policy circles on how to assess and quantify reparability – these could be adopted into off-grid and weak-grid appliance standards and schemes. The availability of spares and locally trained technicians are also important in improving reliability and reparability.[69]

Informing Suppliers on Service Value & Affordability

This is a far more complex decision than setting an appliance price. Market players must make complex judgements for their own specific markets, products and businesses. Cooperative initiatives can help market players to make the best decisions for their business through the following possible routes:

- To establish common definitions for product types, power supply situations and market segments, and to help suppliers plan product deployment accordingly.
- Gather evidence about economic models used in relevant market segments, statistics such as typical price of power as charged to users etc.
- Establish a balanced set of metrics and market benchmarks against which appliances can be assessed against their price (see Section 6.1).
- Gather information and good practice guidance on cost optimisation for appliance and system design, including optimising design parameters, quality of sensors and controls, methodologies to trade off initial cost, running cost and reliability; methodologies to optimize system efficiency against capacity of supply; trade-off between thermal storage, electrical storage and PV supply.

Evaluating and Mitigating Market Risks and Unintended Consequences

Off-grid and weak grid refrigerating appliances bring food cooling to remote communities, which undoubtedly have positive outcomes (reduced food wastage; increased trade routes for local producers; less food poisoning etc.). Possible negative impacts (potential economic, social, environmental and health risks) have to be also considered with mitigating measures put in place. These mitigation measures should include support and protection for local businesses, support networks for sustainable practices, environmental and health policies, circular economy issues. Planning for this requires an understanding of social transformations, monitoring impacts, demand management, research on wider sustainability impacts, proceeding carefully, paying attention to social inequalities and consulting widely with affected communities.[70]

8.0 Summary of Market Development Actions

The market development prospects and priority considerations for development that emerged from the Roadmap consultation and analysis process are summarised for each target market below.

To support development of all markets:

1. Develop suitable international test standards to enable suppliers and reviewers to publish robust and useful performance information characterising appliances.
2. Build capacity to get appliances properly tested and means for suppliers to access testing.
3. Publish research quantifying and characterizing the potential markets, regional opportunities and necessary products.
4. Exploit synergies of increased user business revenues and power demand for cooling with mini-grid suppliers.
5. Encourage development of local refrigeration skills for specification, installation, servicing and repair, also linked to local economic development policy priorities.
6. Build appliance quality certification and endorsement schemes, which can also underpin procurement programmes.
7. Work towards a circular economy through building capacity of suppliers, local services and infrastructure to improve appliance durability and reliability, minimize and address waste streams.

For the household refrigerator market:

- The economic challenges to developing a substantial household refrigerator market in a sustainable way are currently prohibitive.
- Barriers to development include availability of suitable appliances, price too high and power demand exceeding what is available in most off-grid situations.
- Viability appears strongest in a mini-grid situation due to higher power availability combined with longer running hours.

Steps to development:

1. Resolve PAYG compatibility, suitable system controls and improved reliability.
2. Develop financing solutions through micro-finance and PAYG contracts in mini-grid markets.
3. Provide after-sales technical support and means to deliver appliances to remote regions.

For the small commercial refrigerator market:

- Demand is strong for refrigerating appliances for 'productive uses' that earn revenue in shops and food service, with strong pioneering examples reported although the market is largely unexploited so far
- Barriers include lack of financing and lack of appliances specifically aimed at this market, early adopter entrepreneurs express dissatisfaction with often-unreliable, inverter-driven, repurposed household appliances.

Steps to development:

1. Encourage development of appliances specifically for target markets and facilitate suppliers to work with (for example) regional business associations and SACCO's. Examples include 'solar stalls' for markets and roadsides, soft drinks coolers for shops and transportable coolers for farmers and producers of fish, meat and dairy with a focus on reliability.
2. Develop financial case templates for entrepreneurs based on revenues and encourage suitable financing packages particularly with mini-grid suppliers, for whom the increased business revenues enabled by refrigeration could justify power upgrades.
3. Provide after-sales technical support.

For the commercial ice-maker market:

- There is evidence of strong market need, good pioneering examples but very low exploitation to date for ice packs used to keep food produce cool in storage, during transportation and on display for sale.
- Economic case is particularly sensitive to price of electricity due to very high power demand for ice making, although substantial increase of revenue is made possible through selling higher quality goods with longer shelf life, reduced wastage and reaching previously inaccessible markets.

Steps to development:

1. Encourage development of appliances specifically for target markets and facilitate suppliers to work with farmer cooperatives and other SACCO's. Examples include small agricultural, meat, fish and dairy storage and transportation systems.
2. Develop financial case templates for entrepreneurs based on revenues and encourage suitable financing packages particularly with mini-grid suppliers, for whom the increased business revenues enabled by refrigeration could justify power upgrades.
3. Develop means to provide after-sales technical support.

9.0 Summary of R&D and Market Research Priorities

This section describes topics for substantial market and technology R&D projects that emerged from the development of this Roadmap. The market needs and resultant recommendations to develop the market that were identified by stakeholders through the roadmap development process are summarised in Figure 13. Many other important topics for smaller initiatives and tasks are identified throughout the previous sections of this Roadmap. Note: Additional R&D activity relating to interoperability and system controls are covered by the Interoperability TWG.

R&D Funding Call Topics

a) **New compressors:** To provide to the market ranges of DC variable speed compressors that are designed for high efficiency with R290, R600a or similar near-zero GWP and zero ODP refrigerants, compatible with multiple input Voltages and available with separately sold controls ready for integration into appliances and energy management systems. See Section 6 for controls aspects.

b) **Control units for small power supply networks:** Integrated or modular controllers that are specifically designed to manage the high demand challenges to accommodate refrigeration but also exploit its opportunities for thermal management, energy storage and temperature control across a network, proactively balancing cost with delivered service in light of variable input power, ambient temperature and other inputs. See Section 6.

c) **Modular cooling sub-systems and components:** Designed robust and compact for ease of transport to remote locations with local assembly, should facilitate design freedom to meet local needs for small agricultural and commercial usage. Make use of locally available inter-connections and components and designed for assembly with basic refrigeration toolkits. Guidance provided for system design and assembly, with parts lists and step-by-step instructions for a small range of basic systems. An important aspect is how the sub-assemblies are packed for protection and multi-mode transportation including manual handling, pick-up truck, motorbike, hand-cart etc. See Section 6.

d) **Specific technologies and design innovations**: to improve any or all of reparability, appliance reliability and maintenance of adequate cooling capacity at times of high ambient temperature. Innovations must not only be grounded on good market research for need and practicability, it must also serviceability using the tools and skills accessible to trained refrigeration technicians in the cities and towns of target countries. See Sections 6 and 7.

e) **Appliance and system selection software:** a software aid to advise whether a given system can provide the power needed for the refrigerator to meet a minimum service level (or an ideal level), or what minimum power supply a refrigerator would need. Designed for those specifying refrigerating appliances for use with existing or new home and small commercial power systems, in both solar and weak grid power situations. See Section 6.

Market Research Topics

Organisations can more cost-effectively and quickly develop appliances and systems if they have access to good market and technology insight. Therefore, these topics could be the most valuable to publish.

- **Research on potential markets both geographically, by end use sector and by power supply options** (SDD, mini-grid etc.). This would include usage scenarios, generic equipment types, basic economic factors and indicative key points on how the envisaged cooling service can enhance the activity to become economically sustainable for the end user and/or for the power system supplier. See Section 7.

- **Research to define and quantify the value chains of selected and most promising end use markets for cooling appliances.** This should provide input data to help suppliers evaluate feasibility of potential appliances or services as well as signposting key considerations and local stakeholders such as SACCOs. See Section 7

- **Research on affordability and issues impacting economic viability of appliances and services**, including price per kWh of power delivered under different scenarios, energy usage per day for systems of various types, daily revenues achieved from trading situations such as sale of soft drinks. See Section 7.

- **Research identifying the benefits of refrigerated appliances to the target communities** in terms of food security, reduction of food waste, carbon saving, climate change policy and economic/employment benefits, in order to ensure that activities are complementary to those objectives and that these policy links and sources of support are also exploited. Starting with a desk study of existing sources: in particular, food security is already a political priority and in developing economies, most food waste occurs on the production side where logistics and economics make it slightly easier to address than at the consumer side (as in Western economies).
- **Research to map out the consequences of large scale deployment of these appliances** in order to develop mitigation plans and inform the specification of appliances and services at an early stage. This would include environmental impacts, appliance end of life and waste issues, social and health impacts (from changed diet, food sources, working & socialising patterns etc.). This would necessarily include circular economy considerations. See Section 4.

Figure 13: Summary of the findings regarding market needs, technologies and competences, R&D programmes, products and necessary resources identified through the Roadmap development process.

Annex 1: Explanation of Performance Parameters

These are definitions and notes on the performance parameters for all Types of Appliances shown in Table 1.
Listed in alphabetical order:

- *Ability to maintain cooling with low power input and low starting current:* Ability to operate under low power conditions is mainly applicable to solar power direct drive systems.
- *Accessible design appliances:* appliance design without gender bias and accommodating those with performance limitation (principles of design are set out, for example, in ISO/TR 22411[71]).
- *Accurately maintain temperature:* maintaining the internal storage temperature within the limits as set out in the relevant temperature class requirements (yet to be defined).
- *Affordability:* put simply: 'to be available at a price within the financial means of buyers', but this is complex and many factors impact both the price, lifetime cost and the economic case.
- *Appliance durability (long service life):* Premature failure severely undermines economic performance and market development. Many design factors are relevant and must be balanced against price (degradation of insulation, corrosion, water penetration, battery life [cycles], resilience to mechanical damage of hinge, latch, switches etc.). Metrics include failure rate.
- *Coping with high humidity (automatic defrost control or easy manual defrost).*
- *Ease of maintenance and reparability:* This can be significantly improved by appliance design such as types of fasteners; standard components for easy replacement; no irreversible assembly stages (e.g. insulation foaming over key components); design for access to key components[72]; use of only basic tools and training. Also dependent upon information provision including parts list and fault-finding; after-sales parts service and support; warranty provisions; availability of local technicians.
- *Ease of transportation:* compact and light for transportation on small trucks or even motorbikes for remote areas and robust against damage. This could be addressed via local assembly. Note: assembled size in final location is rarely constrained (compared with highly normalised sizing of the majority of household refrigerating appliances).
- *Effective cooling at high ambient temperatures.* Technically this corresponds with adequate temperature lift (so able to dump heat at high ambient temperatures) and adequate cooling capacity (to keep contents cool despite heat loads through insulation and from door openings, loading products into the cooled space etc.).
- *Good 'autonomy.'* This is extending holdover time by energy storage within the appliance or system (thermal or electrical). The extended cooling time is crucial for vaccines or other medical applications but for others, electrical storage is attractive to supply inrush current.
- *Good 'holdover time'.* In situations of power failure[73], reduced power availability (cloudy days when solar driven) and when users cannot afford constant usage, food is better preserved by systems that allow only slow rise of temperature especially as this can extend to days at a time. This is mainly dependent on insulation thickness and effectiveness, quality of door seals and limiting thermal bridges.
- *Good electrical resilience:* could be defined as ability to withstand high voltage and current variation without damage; or as maintaining [x%] of cooling capacity at [TBD] voltage or current disparity from nominal. Another aspect is Voltage or current below which appliance will no longer start.
- *Good energy efficiency:* low energy consumption in kWh per day under certain defined conditions.
- *High cooling capacity, for bottle coolers and for ice makers*: this is the ability to rapidly and efficiently cool down foodstuff or thermal packs and is important for small commercial, ice making and agricultural type applications.

- *Low in-rush current:* conventional electric motors require a high instantaneous current during start-up to get them spinning – this can cause electrical over-current problems and even failure for some control and electrical supply systems.

- *Meet environmental impact expectations:* Must meet local regulations as well as good practice requirements of aid agencies or governments through procurement rules (to reduce legacy product disposal problems, hazards and costs. Expectations include:
    - Zero ozone depletion potential (ODP) for insulation foam and refrigerant (Montreal Protocol).
    - Low global warming potential (GWP) refrigerant and foaming agent [e.g. GWP <150 or natural/hydrocarbon refrigerant], in line with the Kigali Amendment.
    - No/low hazardous components [chemicals; batteries].
    - Good reparability.
    - Designed for ease of dis-assembly at end of life for repurposing or recycling, including clear identification and easy removal of all harmful components (e.g. battery, circuit boards).

- *PAYG compatibility:* PAYG compatibility is crucial and likely to be the only viable route into the household refrigerator market. Purchase is out of the question due to substantial costs as compared with lamps, a TV or fan.

- *Suitability of design for local manufacturing or assembly:* important for improved access to remote areas by shipping sub-assemblies rather than whole appliances; ensure less damage in transit through robust design and innovative packaging that also eases carrying.

Annex 2: Performance Requirements in need of Technology Development

Table 2 identifies the performance requirements that need technology development to resolve or make more accessible (derived from **Table 1** and presents an initial list of technology options to address them from which the technologies described in section 5.0 Technology Options to Improve Appliances and Expand the Market are derived.

Table 2. List of performance requirements for which technology development is needed and options for which technologies might address them.

Performance Requirement	Solution types or 'Technology Drivers' (and comments)	Alternatives within solution types (and comments)
Effective cooling at high ambient temperatures	Cascade cooling (cooling systems in series)	• Two or more vapour compression (VC) units working in a cascade series (each achieves part of the total temperature reduction) • Hybrid cascade making use of VC plus another cooling technology (possibly Peltier, although no viable demonstration has been identified of this) • Hybrid system using evaporative cooling + vapour compression (no commercial example yet identified)
	Condenser/evaporator design	• Compact heat exchanger design to increase capacity (may or may not improve efficiency) • Increased heat exchange efficiency and capacity through additional heat transfer surface or forced convection (large area condenser on sides and rear of unit) • Fan assisted condensers to increase capacity (though fan energy will increase consumption) • Water spray (evaporative assisted) condenser cooling – could be integrated or retrofit • Water cooled condenser (e.g. rain water reservoir)
	Compressor capacity	• DC / variable speed compressor
	Refrigeration cycle	• Liquid line heat exchanger • Sub-cooling
	Thermal energy storage (deplete store during high demand)	• On-board storage • Storage and controls integrated with SHS / wider system to load shift

Performance Requirement	Solution types or 'Technology Drivers' (and comments)	Alternatives within solution types (and comments)
Affordability *(reduce costs; increase income; easier financing – there are many solution types for this!)*	Conversion kit with inverter that enables mass produced AC refrigerators to be used with DC power supply.	• Either special inverter or use existing frequency-controlled appliances.
	Alternative cooling technology	• Thermoelectric (Peltier) cooling: low price but much higher consumption per kW of cooling; zero maintenance; extremely robust (except air ducting/fan, which are easily repaired or replaced)
	Cheaper components	• Material substitution
Ease of transport and installation	Modular and flat-pack design	• Combines well with high reparability • Feedback suggests that examples are already on the market from Mexico and also demonstration systems from University of Hohenheim
	Simple key component assembly with plug and play electrical connections; design for local assembly and installation	
	Weight reduction for transportation	• Lighter components mean lower cost and less drop damage
Low in-rush current	Controls/electrical supply that can deliver inrush demand	• Capacitors (super-capacitors) / battery and resilient electrical system • Compressor soft start (electronically controlled increase of speed) or special electronic starters • Electro-mechanical device/flywheel/Induction motor starter[74]
	Protect system from inrush damage	• Electrical surge protection
Maintain cooling during low power input (and low inrush)	Compressor (motor) type for high efficiency	• DC / variable speed compressor
	Hybrid cooling system	• Twin system with one low (baseload) cooling unit, plus second unit during high demand
	Clever controls	• Predictive controls to manage supply and demand, load shift etc
	Thermal energy storage (deplete store during low supply)	• Enable load shifting

Performance Requirement	Solution types or 'Technology Drivers' (and comments)	Alternatives within solution types (and comments)
Suitability for local manufacturing / assembly and maintenance	Promotion of key components instead of key systems System design and component selection that makes local assembly and local maintenance easier and viable for skills likely to be accessible	• Enable the adaptation of technologies to the local market based on similar key components (economy of scale) • Increase competitiveness of local manufacturers in comparison to imported systems • Increase access to refrigeration and facilitates maintenance in isolated rural areas
PAYG compatibility	Technical compatibility of communications between appliance/SHS and supplier and facility to grant/deny access to the service (refrigeration)	• Appliance has either keypad, GSM module, or another machine-to-machine interface with a PAYG management platform connected to means to grant/deny service
	Ensure appliance that users can afford to run for substantial proportion of the time, so that PAYG supplier can earn revenue from the appliance	• High energy efficiency (see below) • User controls offer 'Economy mode(s)' for reduced running costs (e.g., 100%, 60% and 30% of full cooling capacity)
Coping with high humidity (easy defrost)	Evaporator design	• Design for which effectiveness is less impacted by frost • Design that is easy to mechanically remove frost (e.g. plate evaporator)
	Effective defrost when its needed *especially* when (surplus) energy is available to both carry out the defrost and recover storage temperature	• Smart controls with frost detection or frost prediction ('defrost on demand') AND sensing energy availability • Automated defrost that uses available energy efficiently
Good energy efficiency	Higher efficiency compressor	• DC / variable speed compressor (allows to match energy consumption closely to demand) • High engagement of suppliers in design for testing, specification, refining design and specification
	More effective insulation	• Thicker insulation • Use insulation material with lower thermal conductivity • Reduce thermal bridges across insulation

Performance Requirement	Solution types or 'Technology Drivers' (and comments)	Alternatives within solution types (and comments)
	Whole system optimization (heat exchangers; pipework; expansion valve; refrigerant; refrigerant charge; controls etc.)	• Careful specification of components and design of features • System testing and optimization during development • Engagement with component suppliers in design • Reduce exchange of air when opening the door • Expansion device for this size of system is almost always a capillary tube for cost reasons, although seasonal performance could in theory be improved using a controlled valve
Control of system energy storage for best 'Autonomy'	Interoperability of control systems for appliance and SHS	• Communications protocols between appliance and system • Energy storage control protocols including assessing energy availability and demands, algorithms to evaluate options based on economic and technical data on energy in each format etc.

Annex 3: Categorical Technical Parameters

The technical parameters in the tables below define categories of off-grid or weak grid refrigerating appliances and their basic specification, for household and small commercial applications

Crucial Parameters for Specifying a Weak- or Off-Grid Refrigerating Appliance

Ref	Variable / Parameter	Technical options for that variable / parameter						
A	**Compatible input power option(s) depending upon whether grid / storage / direct drive etc)** (single option or combination, including those designed to integrate into a solar home system. Note: passive cooling type has no steady state energy input)	DC (12V / 24V)	AC (110V; 230V. 50Hz; 60Hz)	Integrated thermal storage (thermal pack(s) and/or ice with quantity in [$kWh_{thermal}$ or $kJ_{thermal}$])	Integrated electrical storage (battery, capacitor). Including WHO 'Type 1'; or 'UPS' with quantity in [$kWh_{electrical}$] and/or equivalent $kJ_{Thermal}$)[75]	Solar cooling direct drive(including WHO 'Type 2'; sold as complete kit)[76]	Heat driven (thermal/absorpti on type) *Note: carbon fuels not in scope of the roadmap*	Evaporative cooling (evaporation of water - no power input)
B	**Storage volume** (internal volume of compartment(s))	'Compact' Combined volume below [80] litres			'Standard' Combined volume [80] to [180] litres	'Large' Combined volume over [180] litres		
C	**Rated ambient climate class** (examples are given as per IEC 62552 but new specifications are needed based on temperatures with practical relevance to where off grid appliances are used)	10-32ºC = SN, 'extended temperate'			16-32ºC = N, 'temperate'	16-38ºC = ST, 'sub-tropical'	16-43ºC = T, 'tropical'	
D	**Type** (see also rated storage temperature classes)	Refrigerator (could be simple compartment; with frozen sub-compartment; with other sub-compartment(s))		Refrigerator-freezer (separate compartments; could include additional sub-compartments)	Freezer (could include additional sub-compartments)		Able to operate as refrigerated or frozen compartment(s) (variable temperature as per control setting)	
E	**Rated storage temperature classes** (examples only: appropriate classes to be developed in due course by a test standard working group)	**Chilled:** 0 to 4ºC	4 to 10ºC	*Other chilled at higher temperatures	**Frozen:** 0 to ≥-6C	-6 to ≥-12C (EU: 1 star)	-12 to ≥-18C (EU: 2 star)	≤-18C (EU: 3 star)

Ref	Variable / Parameter	Technical options for that variable / parameter					
F	**Cabinet configuration; also including number of doors (1, 2, 3 etc.)**	Upright (front opening)	Chest (top opening)	Under Counter (front opening and <1.05m high; may have hard top surface)	Refrigerator-freezer (side-by-side, front opening)	Freezer top/ Refrigerator bottom (front opening)	Refrigerator top/ Freezer bottom (front opening)
G	**Cooling / freezing capacity rating** (could also be characterised by end use: 'household use'; 'bottle cooler'; 'ice maker' etc.)	Standard capacity rating for household food *storage,* refrigerator or freezer (limited pull-down or freezing capability; does not meet the minimum capacity required for 'high capacity' rating)			High cooling capacity refrigerator (meets minimum threshold [TBD] pull-down capability, suitable for small commercial usage as bottle cooler or similar[77])	High cooling capacity freezer meets freezing capacity threshold [TBD], designed for small commercial ice making or demanding household use (for bulk ice, cool packs, high quantity of food freezing etc)[78]	
H	**Holdover/autonomy time[79]**	Extended holdover/autonomy capability (meets criteria [yet to be decided] that define extended holdover/autonomy time – possibly: highest temperature remains below [10]°C after 72 hours without external power input under tropical ambient conditions[80])			Standard holdover/autonomy capability (cannot meet the extended holdover/autonomy criteria). *Note: for off-grid systems with adequate capacity of battery to last the night and size of solar array to run cooling and charge the battery, there may be limited need for good holdover performance (as long as the power system has no malfunction).*		

Other Parameters Important to System Distributors

Ref	Variable / Parameter	Technical options for that variable / parameter		
*I	**Connectivity and controls (PAYG, other)**	Compatible with PAYG control system (i.e. function of appliance can be granted/denied: incorporates a keypad, GSM module, or another machine-to-machine interface with a PAYG management platform)[81]	Other local or remote-control interface (but not PAYG compatible)	No local control interface (other than standard thermostat)
J	**Electrical resilience rating** (suggested as 'high' and 'standard' – but could be graded 1, 2, 3 etc.)	High electrical resilience rating (could be defined as: ability to withstand [specified TBD] high voltage and current variation over [y hours TBD] without damage *and* maintain [x% TBD] of cooling capacity at [specified TBD] voltage/current disparity from nominal; and/or cut-out Voltage or current below which appliance will no longer start)	Standard electrical resilience (TBD - threshold defined similarly to high resilience rating but less demanding)	
K	**Designed for good reparability[82]**	High reparability: meets minimum score [threshold score TBD] in assessment to prEN 45554 *General methods for the assessment of the ability to repair, reuse and upgrade energy related products*	Standard reparability: does not meet minimum reparability threshold score	
L	**Additional features**	Hard top (work surface); Built-in design (for installation inside a cabinet); Ice cube maker; Water Cooler; Anti-condensate heaters; Condenser fan (for higher efficiency and capacity)		

Technical Parameters (inside the 'black box' as seen by most users and distributors)

Ref	Variable / parameter	Technical options for that variable / parameter			
M	**Cooling Technology employed**	Vapour Compression (compressor driven)	Absorption (heat driven chemical process) (heat source: gas fuel, electrical heater, solid fuel; waste heat)	Passive cooled using ice or thermal packs	Passive cooled using evaporative cooling[83]
N	**Compressor type (control)** (has important efficiency and testing implications)	Fixed speed compressor		Variable speed compressor	
O	**Defrost control type**	None / Manual defrost		'Frost free' / automatic defrost (could be timing controlled, frost-detection or other control type)	
*P	**Ability to maintain cooling with low power input and low starting current** (Power input parameters should be quantified in the specification)	Ability to operate under low power conditions (threshold of Watts at which nominal or [x%] of cooling capacity can be maintained is to be defined; possibly combined with kWh per day and/or maximum starting (inrush) current threshold. Could simply be expressed as: 'minimum run-time per day to be effective')[84]		Standard power demand (i.e. unable to provide nominal cooling if available power is below a threshold to be decided or inrush current exceeds a threshold limit)	
Q	**Air circulation within storage volume**	Convection only for internal air circulation (static air – no fan circulation)		Fan assisted internal air circulation (associated with higher cooling/freezing capacity)	
R	**Temperature Control type**	Single Control (one temperature sensor, even if 2 or more compartments (EU: 'Type I'))	Dual (or multiple) Compartment Control (temperature sensor and cooling capacity operate independently for each compartment (EU: 'Type II'))		
S	**Flammability of refrigerant (ISO 5149)[85]**	Higher (ISO 5149 class 3)	Flammable (ISO 5149 class 2)	Lower (ISO 5149 class 2L)	Non-flammable (ISO 5149 class 1)

Ref	Variable / parameter	Technical options for that variable / parameter		
T	**Environmental impact of refrigerant GWP range (ODP must be zero!)**[86]	Negligible GWP (<5, e.g. propane, butane)	Low GWP (<150[87])	High GWP (>150)

Endnotes

[1] Efficiency for Access. (2018). Off-Grid Appliance Market Survey: Perceived Demand and Impact Potential of Household, Productive Use and Healthcare Technologies. Retrieved February 19, 2019, from https://storage.googleapis.com/e4a-website-assets/Market-Survey-2018.pdf.
[2] Energy4Impact. (2018).Grid Powered Refrigeration for Productive Use. https://www.energy4impact.org/file/1946/download?token=2Li0aJN0
[3] Efficiency for Access. (2018). Off-Grid Appliance Market Survey: Perceived Demand and Impact Potential of Household, Productive Use and Healthcare Technologies. Retrieved February 19, 2019, from https://storage.googleapis.com/e4a-website-assets/Market-Survey-2018.pdf.
[4] Note that during the roadmap development process, an additional priority of small refrigerated transportation boxes was identified and these are also addressed in the roadmap.
[5] Solar Direct Drive implies integrated energy storage – otherwise it would be referred to as simply 'solar powered'.
[6] Thermoelectric cooling is currently low efficiency but cheap and reliable and subject of work by Global Good and other market players including for vaccine solar cooling use. See Arktec solar driven cooling device, as described in this paper: *A SDD and PCM solution for vaccine storage and outreach*, Junshan Michael Li, Michael Friend, Andrew Miller, Shannon Stone, 2016 IEEE Global Humanitarian Technology Conference (GHTC), 13-16 Oct 2016. ISBN: 978-1-5090-2432-2.
[7] WHO cold chain equipment test protocols available from: http://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/catdocumentation.aspx?id_cat=17.
[8] See WHO PQS catalogue at http://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/index.aspx. Also UNICEF cold chain equipment supply catalogue (appears to be related to WHO PQS listing) at https://supply.unicef.org/unicef_b2c/app/displayApp/(cpgsize=5&layout=7.0-12_1_66_68_115_2&uiarea=2&carea=4F0BB633A0B90688E10000009E711453&cpgnum=1)/.do?rf=y.
[9] See WHO Cold chain support package at https://www.unicef.org/supply/index_68367.html.
[10] See Technet-21, refrigerator and freezer page at https://www.technet-21.org/en/forums/tags/pqs-e0033;
[11] WHO PQS database shows the lowest priced unit at US$410 ranging up to US$8.000 with average in excess of US$2.000.
[12] Suppliers listed at 7 January 2019: AUCMA Co Ltd; B Medical Systems Sarl; Dulas Ltd; Godrej & Boyce Mfg Co Ltd; Qingdao Haier Biomedical Ltd; Sundanzer Refrigeration Inc; Zero Appliances (Pty) Ltd. See: http://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/categorypage.aspx?id_cat=17.
[13] The State of the Global off-Grid appliance Market, Dalberg for Global LEAP (2016). Estimate extrapolated globally from economic analysis of ten developing economies.
[14] Dalberg Advisors, op. cit., pg. 35.
[15] Off-Grid Solar Market Trends Report 2018, January 2018, Dalberg Advisors and Lighting Global, page 102.
[16] Dalberg Advisors, op. cit.
[17] Ibid.
[18] These prices do not take into account import duties/tariffs, which vary widely: imported appliances in Bangladesh, for example, can attract duties of over 50%.
[19] The State of the Global off-Grid appliance Market, Dalberg for Global LEAP (2016). Estimate extrapolated globally from economic analysis of ten developing economies.
[20] The 2017 Global LEAP buyers guide for off grid fans and televisions includes a 16" TV at 7W measured consumption and table fans measured at 8 to 20W.
[21] The State of the Global off-Grid appliance Market, Dalberg for Global LEAP (2016). Estimate extrapolated globally from economic analysis of ten developing economies.
[22] Market Baseline Performance Testing for Off-Grid & Weak-Grid Refrigerators, May 2018, Ideas to Impact and Efficiency for Access, for UKaid
[23] Providers have their own bespoke communication platforms and protocols based on whether payment is approved online; the Interoperability TWG is examining the feasibility of a common platform for appliances to use.
[24] Feedback suggests, for example, that constrained households in India choose at times to run their fan rather than TV or even lights in the evening – a refrigerator would not be viable in such a situation.
[25] A refrigerator start-up current could be as high as 10A, compared with more usual LED light at 1-2A, TV at 3A.
[26] Field trials of refrigerators in Uganda by Efficiency4Impact showed that delivery was very challenging; trucks had to go very slowly and fridges got damaged.
[27] Dalberg Advisors, op. cit., pg. 35.
[28] For example: Energy4Impact 'productive use' study in Uganda shows a costing for a 139L DC refrigerator purchased at US$500 and using 1.2kWh/day would need at least a 300Wp system at a total cost of approx. $1,500; using the same

monthly instalment rate as local grid power electricity bills for a similar grid appliance of US$12 per month, it would take more than 10 years to pay back the system alone.
[29] Grid Powered Refrigeration for Productive Use, A Study of 172 Micro-Enterprises in Uganda to Understand the Case for Off-Grid Appliances, November 2017. Available from https://www.energy4impact.org/publications.
[30] OFF-GRID APPLIANCE MARKET SURVEY: Perceived Demand and Impact Potential of Household, Productive Use and Healthcare Technologies, Third Edition, September 2018, Efficiency for Access Coalition. Page 7.
[31] Ibid, page 20.
[32] Dalberg Advisors, op. cit., pg. 35.
[33] TU Delft studies include *Solar Cooling in West-Africa*, van der Meer, M, TU Delft Industrial Design Engineering, September 2017. Abstract at: https://repository.tudelft.nl/islandora/object/uuid:6d0333d8-1321-4cc7-a237-a934d6105387?collection=education.
[34] OFF-GRID APPLIANCE MARKET SURVEY, page 32, amongst 44 suppliers surveyed; radios, SWP and TVs jointly account for up to 90% of units sold.
[35] Personal communication following extensive field experience, March 2019.
[36] Energy4Impact. (2018).Grid Powered Refrigeration for Productive Use.
https://www.energy4impact.org/file/1946/download?token=2Li0aJN0
[37] Dalberg Advisors, op. cit., page 20.
[38] See https://www.seforall.org/content/jumeme-unique-mini-grid-model-gains-traction-tanzania.
[39] See https://energypedia.info/wiki/Solar_Milk_Cooling_with_Insulated_Milk_Cans and
https://youtu.be/ZI22h96RYv0.
[40] Source publication: *V. Torres-Toledo et al. / International Journal of Refrigeration 90 (2018) 22–31*
https://doi.org/10.1016/j.ijrefrig.2018.04.001.
[41] OFF-GRID APPLIANCE MARKET SURVEY: Perceived Demand and Impact Potential of Household, Productive Use and Healthcare Technologies, Third Edition, September 2018, Efficiency for Access Coalition. Page 20.
[42] Energy storage can be costly to purchase in the case of batteries; use of thicker insulation to increase holdover time may be unattractive for commercial users for whom space is limited.
[43] See GOGLA article: *Off-grid solar e-waste: the industry is growing responsible in waste management*, 28 March 2019, available at https://www.gogla.org/about-us/blogs/off-grid-solar-e-waste-the-industry-is-growing-responsible-in-waste-management?platform=hootsuite.
[44] The GOGLA E-waste toolkit is being published at https://www.gogla.org/e-waste – one of the three elements of the toolkit, the Introduction to Recycling, is available. 16 April 2019.
[45] Global Leap Solar E-Waste Challenge. 15 March 2019. https://globalleapawards.org/e-waste
[46] See BY THE NUMBERS: The Home Appliance Industry in Europe, 2017-2018, Applia Home Appliance Europe. Available from https://www.applia-europe.eu/key-data.
[47] See Management and Destruction of Existing Ozone Depleting Substances Banks, Guideline on the Manual Dismantling of Refrigerators and Air Conditioners, GIZ, Eschborn 2017. Available from
https://www.giz.de/expertise/downloads/giz2017-en-weee.pdf.
[48] Personal correspondence, February 2019, SOFIES.
[49] Sustainable Management of E-Waste in the Off-Grid Renewable Energy Sector in Rwanda, by Evidence on Demand through the UK Department for International Development (DFID), July 2017.
[50] Ibid.
[51] Personal correspondence, February 2019, SOFIES.
[52] Final draft: COMMISSION REGULATION (EU) …/… laying down ecodesign requirements for refrigerating appliances with a direct sales function pursuant to Directive 2009/125/EC, available from:
http://ec.europa.eu/transparency/regcomitology/index.cfm?do=search.documentdetail&Dos_ID=17154&DS_ID=60277&Version=2.
[53] See https://www.weeelabex.org/standards/.
[54] See 'autonomy' for performance using energy storage.
[55] Source and more information available from: *Design and performance of a small-scale solar ice-maker based on a DC-freezer and an adaptive control unit*, Solar Energy, Volume 139, 1 December 2016, Pages 433-443. Available from:
http://dx.doi.org/10.1016/j.solener.2016.10.022.
[56] Source publication: *V. Torres-Toledo et al. / International Journal of Refrigeration 90 (2018) 22–31*
https://doi.org/10.1016/j.ijrefrig.2018.04.001.
[57] It is not possible to match the combined mechanical, adhesive, thermal, water resistance, durability and cost properties of foamed polyurethane with any currently envisaged alternatives.
[58] Source publication: *V. Torres-Toledo et al. / International Journal of Refrigeration 90 (2018) 22–31*
https://doi.org/10.1016/j.ijrefrig.2018.04.001.
[59] One very widely used compressor is the Secop/Nidec BD35K compressor which includes variable speed capability and a basic controller which is clipped onto the compressor base. Technical data sheet available at

https://www.secop.com/fileadmin/user_upload/SEPS/datasheets/bd35k_101z0211_r600a_12-24vdc_05-2016_desd100g602.pdf.

[60] IEC 60335-2-89:2010+AMD1:2012+AMD2:2015 *Household and similar electrical appliances - Safety - Part 2-89: Particular requirements for commercial refrigerating appliances with an incorporated or remote refrigerant unit or compressor.*

[61] The IEC vote in April 2019 was initially counted to reject the amendment, but days later overturned to pass after reassessment of votes. See article https://www.coolingpost.com/world-news/flammable-refrigerant-limits-approved-in-recount/.

[62] Personal correspondence with natural refrigerant expert, 18 April 2019.

[63] Thermodynamic comparison of Peltier, Stirling, and vapor compression portable coolers, Christian J.L. Hermes, Jader R. Barbosa Jr., Applied Energy 91 (2012) 51–58. Available from: https://www.sciencedirect.com/science/article/pii/S0306261911005538?via%3Dihub.

[64] Comparative study of vapour compression, thermoelectric and absorption refrigerators, P. K. Bansal, R and A. Martin, Department of Mechanical Engineering, The University of Auckland, International Journal of Energy Research 2000; 24:93-107.

[65] An eye-opening review of a failed low-cost refrigerator for India is available at https://jtbd.info/when-you-define-competition-wrong-a5431d038f06.

[66] See https://www.lightingglobal.org/resource/solar-home-system-kit-quality-standards/.

[67] Dalberg Advisors, op. Cit., pg 37

[68] Appliances should meet the safety requirements of IEC 60335-2-89:2010+AMD1:2012+AMD2:2015 *Household and similar electrical appliances - Safety - Part 2-89: Particular requirements for commercial refrigerating appliances with an incorporated or remote refrigerant unit or compressor*.

[69] Dalberg Advisors, op. cit., pg. 38

[70] Source: Dr Rosie Day, Energy and Environmental Justice Specialist, School of Geography, Earth and Environmental Sciences, University of Birmingham.

[71] ISO/TR 22411:2008 *Ergonomics data and guidelines for the application of ISO/IEC Guide 71 to products and services to address the needs of older persons and persons with disabilities*. Also relevant: ISO/IEC Guide 71:2014 *Guide for addressing accessibility in standards* (available free of charge from https://www.iso.org/standard/57385.html).

[72] Design with the possibility to clean around compressor and other maintained components is desirable.

[73] A common metric for reliability of supply is the **Loss of Load Probability (LOLP) -** the probability that a system demand will exceed capacity during a given period (often the estimated number of days over a given period).

[74] System with a small motor spins up a flywheel; when compressor cuts in it works as a generator.

[75] UPS = 'Uninterruptible Power Supply'. This provides a level of guarantee of uninterrupted cooling capacity through a battery and/or alternative power supply (e.g. could be battery plus auto-start diesel generator); definition criteria could be developed if required.

[76] Solar Direct Drive generally implies input voltage of 30V or 32V for the appliance; can be 13V for some units.

[77] Definition of high pull-down capability could be: time to pull down the temperature of a calculated number of beverages (e.g. [50%] of full load) from the ambient temperature to the defined temperature class in less than [a threshold TBD (e.g. 12)] hours at a given ambient temperature class (based on EN 16902).

[78] Definition of high freezing capacity could be: freezing capacity of 10kg food packs per 100 litres of frozen storage volume from ambient to <=-18ºC within 24 hours at a [specified] ambient temperature class (based on IEC 62552).

[79] Extended holdover / autonomy is generally associated with higher cost.

[80] 'Holdover' applies when no energy storage is present; 'autonomy' includes use of energy from thermal or electrical storage.

[81] * Principle is that the system suppliers have some way to control access to the appliance service via machine-is locked out to prevent functioning unless it receives a correct code via machine-to-machine (M2M) communication. This may involve the user entering a code via keypad on the SHS power module or on their phone, or receipt of a signal directly by the power module via GSM. In any case, the appliance itself must have an M2M solution and a microcontroller if it is to be secured to work only when authorized. This could be a cable, IR, Bluetooth, Zigbee, etc. There are both technical and ethical issues to be resolved on this.

[82] Good reparability very likely to be associated with higher cost.

[83] Passive cooling using evaporative cooling presents significant challenges for a suitable test method – far more so than passive cooling using thermal packs, and so is proposed as a separate category.

[84] Example format: *"[x] Watt-hrs./day at 32°C and [y] Amp-hrs./day at 12V, 32°C"*.

[85] Appliances should meet the safety requirements of IEC 60335-2-89:2010+AMD1:2012+AMD2:2015 *Household and similar electrical appliances - Safety - Part 2-89: Particular requirements for commercial refrigerating appliances with an incorporated or remote refrigerant unit or compressor*. This includes a maximum charge size of 150g for class 3 (hydrocarbon) refrigerants, which is adequate for all household refrigerators and the majority of small commercial appliances.

[86] GWP = Global Warming Potential; ODP = Ozone Depletion Potential.

[87] GWP 150 is the threshold used by European air conditioner regulations for 'low GWP' performance bonus (see European Regulation 206/2012 *Ecodesign Requirements for Air conditioners and Comfort fans*).