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Review

Using solar-powered refrigeration for vaccine storage where other sources of reliable electricity are inadequate or costly☆

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ABSTRACT

Large areas of many developing countries have no grid electricity. This is a serious challenge that threatens the continuity of the vaccine cold chain. The main alternatives to electrically powered refrigerators available for many years—kerosene- and gas-driven refrigerators—are plagued by problems with gas supply interruptions, low efficiency, poor temperature control, and frequent maintenance needs. There are currently no kerosene- or gas-driven refrigerators that qualify under the minimum standards established by the World Health Organization (WHO) Performance, Quality, and Safety (PQS) system.

Solar refrigeration was a promising development in the early 1980s, providing an alternative to absorption technology to meet cold chain needs in remote areas. Devices generally had strong laboratory performance data; however, experience in the field over the years has been mixed. Traditional solar refrigerators relied on relatively expensive battery systems, which have demonstrated short lives compared to the refrigerator. There are now alternatives to the battery-based systems and a clear understanding that solar refrigerator systems need to be designed, installed, and maintained by technicians with the necessary knowledge and training. Thus, the technology is now poised to be the refrigeration method of choice for the cold chain in areas with no electricity or extremely unreliable electricity (less than 4 h per average day) and sufficient sunlight.

This paper highlights some lessons learned with solar-powered refrigeration, and discusses some critical factors for successful introduction of solar units into immunization programs in the future including:

- Sustainable financing mechanisms and incentives for health workers and technicians are in place to support long-term maintenance, repair, and replacement parts.
- System design is carried out by qualified solar refrigerator professionals taking into account the conditions at installation sites.
- Installation and repair are conducted by well-trained technicians.
- Temperature performance is continuously monitored and protocols are in place to act on data that indicate problems.

Abbreviations: PATH, Program for Appropriate Technology in Health; PQS, Performance Quality and Safety; UNICEF, United Nations Children's Fund; WHO, World Health Organization.

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Contents

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1. Introduction

Large areas of many developing countries have no grid electricity. The International Energy Agency estimates that 1.3 billion people lacked access to electricity in 2010, more than one-fifth of the world's population [1]. Some 85 percent of those without electricity live in rural areas, mainly in sub-Saharan Africa and South Asia where there is no distribution grid for electricity, nor prospects of the grid reaching them in the near future [2] (see Fig. 1). Even in areas with grid power, the demand growth for electricity has outpaced supply growth resulting in unreliable electricity, insufficient for continuous refrigeration [3]. This is a serious challenge that threatens the continuity of the vaccine cold chain. Alternatives to electrically powered refrigerators have been available for many years, but kerosene- and gas-driven "absorption" refrigerators have not kept up with the new, more stringent WHO PQS requirements while solar-powered electric compression-type refrigerators have continued to innovate and do meet standards established under the WHO PQS system.

For the last 35 years, areas with insufficient power supply for electric refrigerators have been mostly supplied with absorption-type refrigerators, the majority of which burn kerosene or bottled liquid petroleum gas to drive the cooling cycle. These fuels are polluting and suffer from supply interruptions due to numerous reasons including poor planning, fuel shortages, diversion for other uses, and theft.

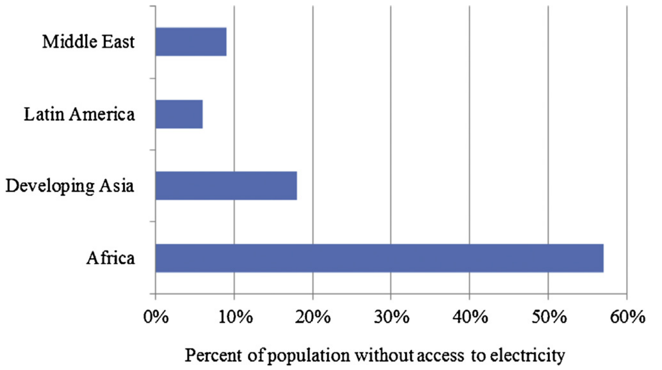

Fig. 1. Share of developing-country populations without access to electricity, 2010. Figure adapted from: The Organization for Economic Co-operation and Development (OECD)/International Energy Agency (IEA), World Energy Outlook, 2012, available at: http://www.worldenergyoutlook.org/media/weowebsite/energydevelopment/2012updates/Measuringprogresstowardsenergyforall_WEO2012.pdf.

Absorption refrigerators also suffer from low efficiency, poor temperature control, frequent maintenance needs, and limited ice-making capacity [4]. In the early days of vaccine cold chain design in developing countries, absorption devices were widely used because there were no other readily available options at a similar cost, and countries anticipated that grid electricity would soon be distributed to rural areas, providing a reliable and affordable source of energy for compression-type refrigerators. However, given the low-population densities, minimal consumer loads, and steeply rising costs associated with rural electrification, it is often not an economically viable option. As a result, absorption refrigerators continue to be used today in more than 60 percent of vaccine storage locations (see Fig. 2) in spite of their shortcomings in providing safe and appropriate storage for vaccines.

However, the vaccine refrigerator market has changed. No kerosene or gas refrigerators have been approved by WHO PQS; thus, the United Nations Children's Fund (UNICEF) supplies these refrigerators only in rare circumstances [4]. Liquid petroleum gas

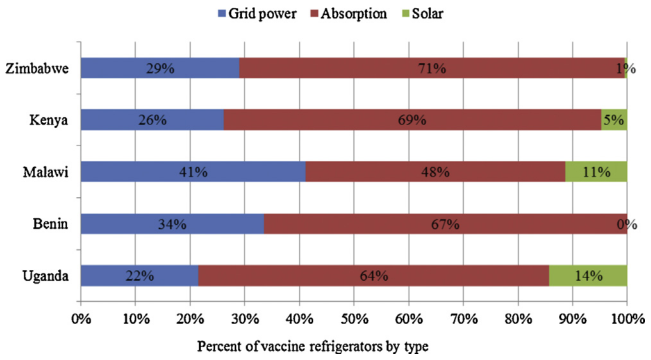

Fig. 2. Prevalence of grid-electric, solar, and absorption vaccine refrigerators. Figure adapted from: Dicko M. WHO/PATH Project Optimize internal report. Seattle: PATH, WHO; 2013.

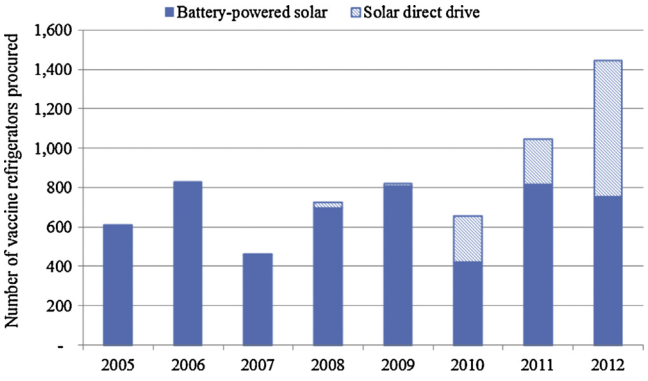

Fig. 3. Solar refrigerators supplied by UNICEF.

supplies remain irregular, are subject to theft, and are increasingly costly not only to acquire but also to transport to remote areas. Thus, the role of absorption refrigerators in the vaccine cold chain is anticipated to diminish in the future.

Solar refrigeration was a promising development in the early 1980s, providing an alternative to absorption technology to meet cold chain needs in remote areas. Devices generally had strong laboratory performance data; however, experience in the field over the years has been mixed. Solar refrigerators bring a new element of complexity that requires technical expertise to maintain and repair—expertise that is not always available in the community prior to installation. In addition, traditional solar refrigerators relied on battery systems with relatively short lives compared to the refrigerator, often requiring replacement after several years and adding expense to lifetime operation of the refrigerator [4]. There are now alternatives to the battery-based systems and a clear understanding that solar refrigerator systems need to be designed, installed, and maintained by technicians with the necessary knowledge and training. Thus, the technology is now preferred by WHO and UNICEF as the refrigeration type of choice for the cold chain in areas with unreliable electricity and sufficient sunlight.

This paper highlights some lessons learned with solar-powered refrigeration, both challenges and benefits, and it discusses the critical factors for successful introduction of solar units into immunization programs in the future.

2. Review of in-country experience—challenges

Since 2005, UNICEF has supplied more than 6500 solar-powered vaccine refrigerators (6048 were battery based and 497 were direct drive), with the greatest number supplied to Africa (see Fig. 3).

There have been a number of challenges constraining the performance and reliability of solar vaccine refrigerators. Four challenges listed below are drawn from a review of in-country experience and are each discussed in the following sections:

- Inadequate system design and installation quality.
- Maintenance and spare parts supply not addressed.
- Inappropriate use.
- Lack of feedback on field performance.

2.1. Inadequate system design and installation quality

Most of the refrigerators supplied by UNICEF have been prequalified by WHO under the PQS standards. In addition to prequalifying refrigerators, the PQS division at WHO sets standards for solar power-generating systems and identifies qualified suppliers who are recommended to supply combined refrigerator and solar-power systems. Qualified suppliers must meet certain minimum levels of expertise and experience. This list of qualified suppliers is available from WHO and can be accessed by countries doing their own procurement. It is generally acknowledged among experts in the field that sometimes qualified suppliers are not used when procurement occurs outside of UNICEF channels, either because of lack of awareness of the qualified supplier list or because other priorities drive the procurement process.

Failures in Ghana
About 80 solar refrigerators were installed in Ghana in the late 1980s, but they experienced a high failure rate (about 50 percent) soon after installation. Several of the problems could possibly be traced back to inadequate installation quality, including faulty controllers, fire-damaged components (possibly not using high-quality components rated to the expected electric loads), deteriorated solar-support structures, faulty wiring, heat-damaged solar panels (due to poor positioning of panels on roof), and shaded solar panels [13].

According to reports from the field, some of the most common problems relating to system design and installations are:

- Designers lack data—when buyers do not provide suppliers with sufficient installation site data, including geographic location, solar radiation, and temperature to accurately design the system for optimal performance.
- Poor system sizing—when designers do not properly match the size of either the solar module and/or the battery bank with the solar radiation expected at the installation site and the power demands of the refrigerator.
- Poor installation—when installers orient and mount the solar array poorly by using inadequate structural support or not accounting for the sun path, provide insufficient protection for solar array and wiring, and/or use low-quality electrical equipment including automotive or other transportable battery types.

2.2. Maintenance and spare parts supply not addressed

Maintenance challenges have been mainly of three types:

- Failure of the users to properly care for the system, with simple maintenance tasks such as regular cleaning of the solar array and topping up battery cells with distilled water.
- Lack of local qualified electrical technicians to diagnose failures and to repair systems and funding for training over time.
- Lack of a plan or source of funding to purchase the correct spare parts, in particular to replace batteries as needed over the lifetime of the system.

Despite best-practice guidelines, the main cause of these solar refrigerator problems can be attributed to the lack of necessary budget and planning for long-term maintenance. Sustaining solar refrigerators requires setting up a specified equipment maintenance program that can incorporate either outsourced maintenance contracts or ministry-managed repair technicians supported with rigorous ongoing training. Dedicated and knowledgeable users can sustain solar power systems for more than 20 years. However, training of the users and maintenance technicians has too often been perfunctory and not repeated over time [5]. A mechanism for ensuring sustainable training and finances for proper installation and maintenance is needed.

Indonesia experience

A 1998 assessment team in Indonesia reviewed data available on the status of 520 solar refrigerators installed in 1991. Reports indicated a lack of spare parts and technical know-how as major constraints [5].

2.3. Inappropriate use

Three abuses of the system remain the most problematic. First, solar modules are susceptible to theft [6]. Although features exist to combat theft, such as mounting modules on tall poles, fastening them with theft-deterrent hardware, and/or integrating them into the roof structure, not all solar systems include these security features. Theft deterrent fasteners are required by PQS, but more effective theft proofing such as roof integration is typically expensive except in the case of new construction, and poles are not usually procured with a system as they add cost and transport bulk. Second, refrigerators have been used for personal purposes (e.g., storing food and drinks). Introduction of additional thermal mass affects the internal temperatures of the refrigerator, which may negatively affect the integrity of the vaccines stored inside [7]. Finally, power has been diverted from batteries for other uses (e.g., lights in the facility or televisions in nearby homes). These additional uses are extra loads that will strain the solar electric power system that was designed to produce power sufficient only for the vaccine refrigerator.

2.4. Lack of feedback on field performance

An overarching challenge with both battery-based and direct-drive refrigerators has been the lack of funding and commitment to post-market surveillance of these products in the field. Without this information, manufacturers and other system designers cannot make improvements to their equipment that respond to the needs of users in the field. Field reports often describe only the first years of a program – there is very limited documentation on longer-term performance [8,11]. Such evidence might have led to more timely improvements in first-generation solar refrigerators.

3. Responding to challenges

3.1. Technology advances to improve performance

The first generation of solar refrigeration systems was designed to store energy in batteries to maintain refrigeration during the night and on days with reduced sunlight. A majority of published reports on solar-powered vaccine refrigerator failure have involved the battery system [9–12]. This reliance on costly, special-purpose, imported batteries that often have a service life of five years or less has presented a major parts replacement problem for countries. In addition, other major components of a typical PQS battery system such as a battery-charge regulator, electric cabling, lockable and vented battery enclosure, fusing or other over-current protection devices are also susceptible to failure. Efforts to substitute lithium-ion batteries intended for vehicles have not been successful either due to cost and limits to battery life. Less-common failures include refrigerator component failures [11,13,14]. The component least likely to fail is the solar module [13].

Northern Nigeria repairs

Only 25 of 74 refrigerators were working when inspected a few years after installation in the early 2000s. However, the program identified 32 solar refrigerator candidates for rehabilitation and was able to reinstate 28 of them. Seventy-five percent of the repairs needed were related either to the battery or the electronic battery controller [10].

Recognizing that the majority of equipment failure has centered on the battery system, in the last decade refrigerator manufacturers have developed second-generation solar refrigerators that store energy in the form of frozen water or other phase-change material rather than in batteries. Because direct-drive systems eliminate the need for batteries, they have several potential advantages over traditional solar systems, including simpler installation, fewer maintenance requirements, and lower operating costs. Unlike the battery-based systems that can be adjusted to a range of “autonomy” (number of days the refrigerator can provide cooling with low levels of sunlight), the direct-drive systems have a fixed autonomy determined by the size of their thermal storage bank and the impact of ambient temperature, usage, and climate conditions.

In 2001, the SolarChill Project was launched by collaborating partners from the United Nations and other public- and private-sector organizations [15]. The goal was to work toward the design and development of a battery-free solar refrigerator. Over a decade of development later, the first of a new generation of solar vaccine refrigerator systems received WHO PQS prequalification in 2010. Since then, five additional manufacturers have submitted direct-drive refrigerators that have been prequalified under the WHO PQS system, and more are in the pipeline.

3.2. Benefits of solar refrigeration

Solar-powered refrigeration has demonstrated four main benefits for the vaccine cold chain relative to absorption refrigeration fueled by kerosene and gas. First, laboratory testing has confirmed higher performance on several critical parameters, most importantly temperature control. Second, system reliability has been adequate where WHO PQS recommendations have been respected and regular maintenance and repair service have been sustained. Third, the lifetime cost of direct-drive solar remains lower than absorption refrigeration and is increasingly competitive with grid-powered systems. Finally, solar systems may be an environmental improvement over absorption refrigerators, eliminating the need to burn fossil fuels. In fact, absorption-cycle refrigeration is fundamentally less efficient than solar or grid-electric compression refrigeration, consuming more energy to provide the same cooling.

Success in Sierra Leone

After 8 years, 75 percent of more than 700 solar refrigerators installed to replace gas absorption refrigerators are still in working order. The keys to success included the use of WHO PQS-prequalified equipment supplied by qualified suppliers and installation by trained technicians. A system is in place to inspect and repair non-working devices, and there is budget allocated for ongoing long-term maintenance. In addition, there is an ongoing training program to ensure that new staff are trained and to allow more experienced staff to refresh their knowledge [14].

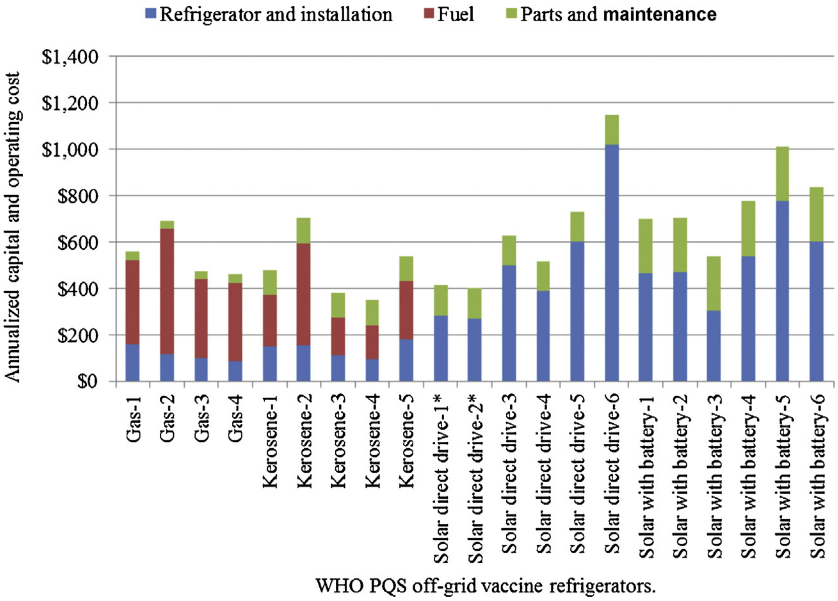

Fig. 4. Comparative annualized costs of different WHO PQS-approved vaccine refrigerators for use in areas with unreliable electricity. * Solar direct drive with ancillary battery.

Figure adapted from: Lorenson K. Cost comparison of refrigerator options. Seattle: PATH; 2011.

3.2.1. *Solar refrigerator temperature performance is superior*

Laboratory testing has shown that the standard of temperature control in solar compression refrigeration is higher than kerosene or gas absorption refrigeration (WHO unpublished confidential data). Control remains within a narrower temperature range and with fewer excursions outside the recommended range. With current PQS-qualified direct-drive solar refrigerators, during periods of low sun, the autonomy of the systems (the time that the refrigerator can continue to cool the vaccine compartment under poor solar conditions such as heavy cloud and rain) is at least three days and as long as ten days in some models—considerably better than the 5 h of cold life achieved by absorption systems when fuel is not available [4]. Among refrigerators that have been prequalified by WHO, solar models with ice-freezing capability produce more ice per 24 h than absorption models. Finally, and most important, all current PQS-prequalified solar refrigerators are designed to avoid accidental freezing of vaccines, a frequent problem for most absorption systems.

Today, the direct-drive system is the option of choice, but there are currently two conditions where battery systems may be a better choice. First, in areas where longer autonomy is required than a solar direct-drive refrigerator can provide, such as locations where there are several consecutive weeks of heavy cloud cover expected every year. Second, if ice packs must be prepared on site, currently only a limited selection of PQS-prequalified direct-drive solar devices have combined refrigerator and freezer capability. However, this number is likely to increase as manufacturers are responding to the need to make ice in the field.

3.2.2. *System reliability has been adequate*

Though there have been many challenges with solar equipment, on average these systems have performed adequately in the Expanded Program on Immunization system. The potential working life of solar refrigeration systems is ten years or longer. Given that there is no battery to replace, solar modules are generally warrantied for 20–25 years, and refrigerators can be made to last longer than ten years if well maintained. In the mid-1990s, experience in four countries had shown an average mean time between failures for solar refrigerators of 3.5 years. (This means that the solar refrigerators required some major maintenance every three and a half years on average.) At that time, WHO expressed that although 3.5 years between failures was a good result, they hoped that time between failures would increase given the high investment costs of these refrigerators [16].

A retrospective investigation in Senegal reported that the mean time between failures for a group of battery-based solar systems installed in 1994 was approximately four years and that the main failure was due to the battery [12]. Field reports from other countries indicated high rates of failure exceeding 33 percent of installed systems soon after installation [9,10,13]. On at least one occasion, 100 percent of installed systems failed [13]. According to written communication with experts in the field, Kamau S, Taqi G, and Rivera R (2010), some first-generation solar refrigeration systems sustained operation for more than ten years, but published reports of success are difficult to find.

Battery failure in Senegal

From 1993 to 2002, 34 villages in the Casamance Region of Senegal were equipped with photovoltaic systems in health centers. Nine of those installations included refrigerators. A system was put in place whereby each health center had to contribute a monthly stipend toward maintenance. The scheme did not provide enough funding to replace the batteries for the solar refrigerators, and all eventually failed [12].

Solar direct-drive refrigerators have not been in the field long enough to make a good assessment of their typical working life or the mean time between failures. Technical issues have occurred with early versions of some devices deployed to countries, and manufacturers are making adjustments to technical components and recommended conditions for storage and transport in response to these experiences [17]. The information gleaned from these experiences with the second-generation devices highlights the need for careful monitoring of early field use and the importance of ensuring that the information gets back to the manufacturer.

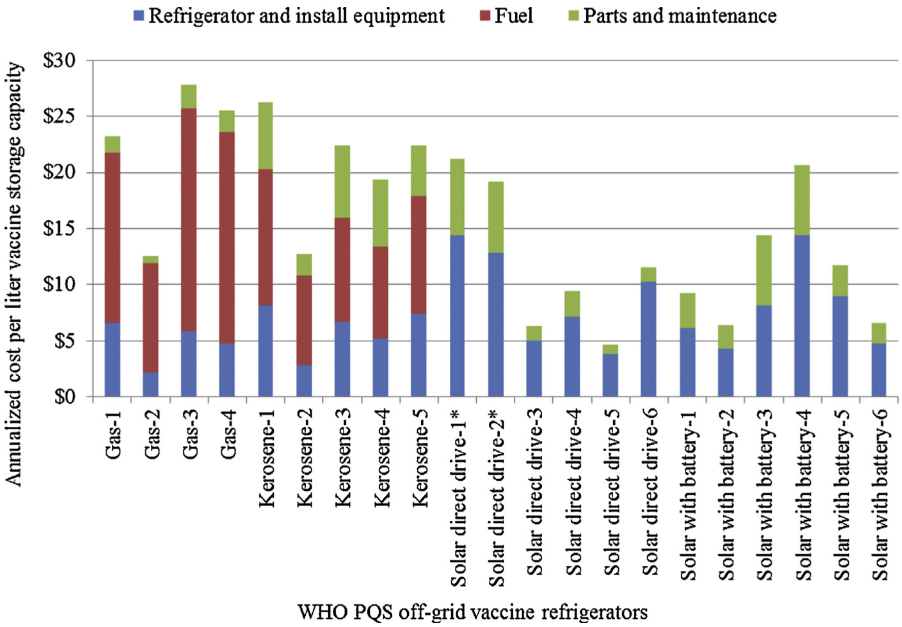

Fig. 5. Comparative annualized cost per liter vaccine capacity of different WHO PQS-approved vaccine refrigerators for use in areas with unreliable electricity. * Solar direct drive with ancillary battery.

3.2.3. *Annualized total cost is lower*

In addition to the development of solar direct-drive refrigerators, which eliminates the cost of the battery, solar refrigerator buyers are also benefitting from the global decrease in solar module price. Between 2008 and 2011, the average cost of solar modules, measured in price per Watt peak, decreased from approximately US$5.5 per watt to $2.3 per watt [18]. Fig. 4 presents comparative annualized costs of solar refrigerators, battery-based and direct-drive, and absorption refrigerators, both gas and kerosene powered. Kerosene and gas refrigerators are representative of models from the WHO Product Information Sheets (PIS) that preceded the WHO PQS system established in 2009. For solar refrigerators, data are included for individual refrigerators prequalified under WHO PQS as of June 2013. Fig. 4 shows that the total annualized capital and operative costs of a solar direct-drive system are similar to absorption refrigerators despite the comparatively higher purchase price of solar refrigerators. Assuming each unit is utilized to its full vaccine storage capacity, Fig. 5 depicts the estimated annualized cost per liter storage capacity of each WHO PQS-listed refrigerator brand used in areas with unreliable grid electricity. Over the long term, solar direct-drive refrigerators display estimated costs lower than the solar refrigerators with battery- or fuel-powered units if fully utilized. It is important to appropriately size a refrigerator for the population served and vaccines provided; however, even when not fully utilized, many solar direct-drive units may often have lower life costs when compared to smaller fuel-powered units.

Connecting to the community in Colombia

In Choco, Colombia, four remote rural communities installed photovoltaic systems to provide a range of electric applications including lighting, refrigerators, and equipment for health clinics, as well as a movie theater for income generation. In this example, community participation (through their use of the movie theater) was effective in generating funds to maintain photovoltaic systems for the health center [11].

The following assumptions were made in the cost comparison model:

- With typical maintenance and repair, all refrigeration units will last ten years. Total average purchase price, installation, operating, maintenance, and repair costs are amortized over ten years at a 3 percent discount rate.
- Average fuel commodity prices represent an average of prices obtained from Kenya, Malawi, and Mozambique in 2012.
- Kerosene: $0.85 per liter.
- Liquid petroleum gas: $1.83 per kilogram.
- Price per refrigerator is taken from the 2009 WHO PIS or from the 2013 WHO PQS list; pre-2013 prices are inflation adjusted at a rate of 3 percent per year to reflect the 2013 estimated price.
- Operating costs assume that a continuous energy supply is available per the WHO PQS definition.

4. Conclusion

There are strict conditions that must be adhered to for successful introduction of vaccine refrigerators and solar refrigerators in particular, given their relatively new introduction to the market. If these conditions are not met, countries will be at risk of large-scale failures reminiscent of early experiences with solar battery refrigeration.

The performance of solar refrigerators is sufficient for vaccine storage even in a very hot climate, given appropriate equipment selection and proper installation. The second-generation, solar direct-drive systems are more economical to purchase and operate and may be more reliable than their battery-based predecessors due to decreased technical complexity. Solar refrigeration is also already well aligned with future policies to provide solar electrification to rural communities and health facilities in a decentralized way [19]. As broader introduction of solar electrification gets under way, vaccine refrigerators could easily be connected straight into this new electric infrastructure. Thus, there are sound reasons to mainstream their use in the vaccine cold chain where there is no electricity or electricity cannot be reliably supplied.

The next section contains specific recommendations to help improve the chances for success with new solar refrigerator installation projects. They are based on lessons learned from years of the first-generation battery-based technology, as well as early experience with the second-generation direct-drive devices.

5. Recommendations

5.1. Plan initial and recurrent investment for the future

Today, introducing solar refrigeration is a long-term investment and a long-term recurrent cost commitment for the ministries of health and their partners. Refrigerator maintenance should be included in the national multi-year plan, and a budget commitment of at least ten years should be secured for maintenance and routine parts replacement. Another approach to offsetting solar power system maintenance and repair costs involves fee for service, income generated through the sale of essential medicines, or other income-generation schemes that use the benefits of solar electricity to provide services that are in demand and can be paid for [11,20]. These are beyond the scope of this report but offer interesting approaches to sustainability.

5.2. Accept only professional system design

Governments and donor partners should select only from the range of refrigerators that have been prequalified by WHO PQS and purchase from qualified suppliers or other suppliers that meet the criteria of the WHO PQS standards. Procurement mechanisms should be put in place that incentivize countries to consider solar systems over non-PQS-approved absorption systems. Systems should be designed specific to site conditions, including the vaccine storage capacity needs, the freezing capacity needs (if any), and the climate conditions including the ambient temperature and solar radiation received ensuring that direct-drive sites are not adversely shaded. Coordination is needed between WHO, UNICEF, and other global organizations involved in vaccine cold chain design and provision to ensure that clear guidelines are developed, communicated, and observed.

5.3. Plan for installation and repair services

Procurement contracts should address the need to train and/or supplement national technician teams for high-quality installation of systems. Installation budgets should include adequate transport and purchase of appropriate electrical hardware and supplies. Planning should include any training that is needed for users and repair technicians specific to the system. The buyer should:

- Establish system maintenance and repair services, either by outsourced contract or assignment within the buyer's organization (e.g., the ministry of health).
- Incorporate a monitoring and feedback process into a country's supply chain management system to ensure strong performance is recognized and problems are resolved.
- Commit funds and schedule regular technician maintenance visits (within one month of installation and then every three months for battery-based systems and every six months for direct-drive systems).
- Stock spare parts and schedule battery replacement according to the recommendation of the qualified supplier.

All power systems and all refrigerators will require maintenance and will occasionally fail. New solar equipment options are available that overcome a major weakness of battery solar equipment, but this will not eliminate the need for ongoing technical training and maintenance for long-term successful operation. Program managers at the global and national level should heed the lessons learned in the past and ensure that technical support is in place so that the new-generation solar vaccine refrigerators will meet with success.

5.4. Monitor temperature performance

All solar refrigerators should be monitored in use, and the necessary devices and standard operation procedures should be in place at the time of installation. Monitoring instrumentation exists to automatically record parameters such as temperature and power management and either to maintain the record for periodic downloading or to transmit the data in real time through the mobile communication network. In addition, 30-day temperature loggers with high and low alarms are standard products prequalified through the WHO PQS system for monitoring refrigerator temperatures on a daily basis. With support as needed from international organizations, countries should operationalize systems for monitoring vaccine refrigerators and acting upon the results. Unacceptable temperature performance data should prompt timely repair and maintenance activities. Furthermore, feedback on temperature performance should be fed back to the manufacturers so they can perform diagnostic analysis as appropriate to improve and to identify root causes and improve their technologies.

Authors' contributions

Steve McCarney is primary author of manuscript. Joanie Robertson, Juliette Arnaud, Kristina Lorenson, and John Lloyd are the secondary authors of manuscript. Significant contribution to content.

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Conflict of interests

All authors have no conflict of interests.

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