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When are solar refrigerators less costly than on-grid refrigerators: A simulation modeling study ☆

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ABSTRACT

Background: Gavi recommends solar refrigerators for vaccine storage in areas with less than eight hours of electricity per day, and WHO guidelines are more conservative. The question remains: Can solar refrigerators provide value where electrical outages are less frequent?

Methods: Using a HERMES-generated computational model of the Mozambique routine immunization supply chain, we simulated the use of solar versus electric mains-powered refrigerators (hereafter referred to as "electric refrigerators") at different locations in the supply chain under various circumstances.

Results: At their current price premium, the annual cost of each solar refrigerator is 132% more than each electric refrigerator at the district level and 241% more at health facilities. Solar refrigerators provided savings over electric refrigerators when one-day electrical outages occurred more than five times per year at either the district level or the health facilities, even when the electric refrigerator holdover time exceeded the duration of the outage. Two-day outages occurring more than three times per year at the district level or more than twice per year at the health facilities also caused solar refrigerators to be cost saving. Lowering the annual cost of a solar refrigerator to 75% more than an electric refrigerator allowed solar refrigerators to be cost saving at either level when one-day outages occurred more than once per year, or when two-day outages occurred more than once per year at the district level or even once per year at the health facilities.

Conclusion: Our study supports WHO and Gavi guidelines. In fact, solar refrigerators may provide savings in total cost per dose administered over electrical refrigerators when electrical outages are less frequent. Our study identified the frequency and duration at which electrical outages need to occur for solar refrigerators to provide savings in total cost per dose administered over electric refrigerators at different solar refrigerator prices.

1. Introduction

To effectively maintain an adequate supply of life-saving vaccines in low and middle income countries, where electricity supplies can be capricious [1], the World Health Organization (WHO) currently recommends solar refrigerators for regions with less than four hours of electricity per day, on average, and electric mains-powered ice-lined refrigerators (ILRs) for areas with more reliable electricity [2]. Gavi recommends solar refrigerators for locations with fewer than eight hours of electricity per day or power outages that last more than 48 h [3]. The question remains: Do these thresholds identify all locations where solar refrigerators provide value, or can solar refrigerators be a more effective and efficient means of vaccine storage than ILRs in areas with more reliable electricity? To identify additional settings where solar technologies may offer benefits that outweigh their higher price, further evidence is needed.

Efforts to develop and implement new vaccine storage technologies that reduce reliance on the electrical grid have been challenged by the added cost of many new devices, which can be difficult to justify without better understanding their potential

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value. Though solar direct-drive refrigerators (SDDs) avoid many of the problems associated with the earlier generation of solar refrigerators that require batteries [4], the purchase prices of SDDs remain higher than those of ILRs [5], and uncertainties persist around the useful lifetime of SDDs due to currently insufficient field data [6]. Barriers to proper, timely, and affordable maintenance for SDDs have included limited availability of technicians with the expertise needed to diagnose and repair solar devices in remote regions, as well as lack of personnel willing to climb onto roofs to clean solar panels [4,7]. At the same time, progress has been made in ILR technologies. Newer ILRs can maintain vaccine storage temperatures for over 10 days without electricity [2].

Understanding how unreliable electricity must be in order for solar devices to be favorable over electric mains-powered refrigerators (i.e. on-grid refrigerators, hereafter referred to as "electric refrigerators") in various settings is important for decision makers to select the most appropriate cold chain equipment for their situation. Computational modeling can help elucidate the potential system-wide implications of changing one or more components in a supply chain prior to deciding whether to invest the resources necessary for implementation [8]. We used simulation modeling to evaluate the impact of SDDs on vaccine supply chain performance and costs under a range of circumstances and to determine the conditions necessary for solar powered storage equipment to be favorable over ILRs.

2. Methods

2.1. HERMES model of the Mozambique vaccine supply chain

Using our HERMES (Highly Extensible Resource for Modeling Event-driven Supply Chains) software platform, our team developed a discrete-event simulation model of the supply chain for WHO Expanded Program on Immunization (EPI) vaccines in Mozambique. As described in previous publications [9–11], HERMES-generated models include virtual representations of every storage and immunization location, storage device, transport route, vehicle, and personnel in the supply chain, as well as each vaccine vial flowing through the system. We populated the model using data from the Mozambique Ministry of Health, the comprehensive multi-year plan, and WHO and UNICEF databases for vaccines and equipment [2,5,12–14]. Supply chain operations follow ordering and shipping policies observed in Mozambique.

Vaccines enter the country supply chain at one national warehouse in the capital city of Maputo, which also serves as a provincial warehouse for Maputo province. Vaccines travel from Maputo to 10 other provincial warehouses by plane or truck. Two provinces supply vaccines directly from their provincial warehouses to all health facilities via monthly distribution loops, in which trucks deliver vaccines to several facilities in a single trip before returning to a warehouse. Seven provinces distribute vaccines monthly to district stores, from which vaccines are either delivered to health facilities or picked up by health workers from the facilities each month. The remaining two provinces use a combination of distribution loops from the provincial warehouses and distribution through intermediary district stores to move vaccines to health facilities. The 1377 health facilities across the country provide routine immunizations each weekday to target groups among the Mozambican population of 26,423,623 [15].

For a baseline comparison between electric and solar powered refrigerators at the district and health facility levels, we modified the supply chain model to relieve storage and transport constraints and assigned only one storage device model per level. The selected device at each level was currently WHO prequalified and had a vaccine storage capacity that most closely matched the storage needs of an average location at that level [2]. This allowed for a comparison between the most suitable ILRs and SDDs for the system, while sensitivity analyses varied characteristics of these devices (as described under Experiments) in order to assess how different devices or future technological developments may impact the results. Every location received a sufficient number of the assigned device to hold the quantities of vaccines needed with a 25% buffer stock, per EPI policy. In all scenarios, the national and provincial warehouses stored vaccines in electric cold rooms. At the lower levels, the baseline comparison assessed ILRs (217 Vestfrost MK 404 across all districts, 1691 Haier HBC 110 across all health facilities) and SDDs (218 Dulas VC 200 SDD across all districts, 1680 SunDanzer BFRV 55 across all health facilities). Table 1 summarizes the characteristics of these refrigerators at baseline and in the following experiments [2,3,5,6].

2.2. Experiments

To identify primary cost drivers of the systems modeled in the baseline comparison, sensitivity analyses compared the selected ILRs and SDDs with varying characteristics and under a broad range of conditions, without electrical outages, to measure the impact of potential changes in device characteristics, real-world deviations from baseline assumptions, and the extent to which cost savings may vary in different settings (for example, many Sub-Saharan African nations have higher costs of electricity than Mozambique [16]). These analyses varied the energy costs, purchase price, maintenance costs (for spare parts as well as labor required for repairs, defrosting and cleaning devices, and cleaning solar panels), and useful lifetime of each device.

Further analyses identified the necessary conditions for a solar refrigerator to offer savings over ILRs with varying holdover times, in scenarios introducing electrical outages of varying durations (one or two days) and frequencies (0–20 times per year). ILR holdover times (i.e. the length of time an electric-powered device can maintain vaccine storage temperatures during an electrical outage, during which the device cannot be opened) varied within the range for currently available ILRs of similar size (Table 1) [3]. Reported results for each scenario are the average over 10 iterations of one simulated year.

3. Results

3.1. Identifying cost drivers

Both systems in the baseline comparison achieved full demand fulfillment due to an absence of electrical outages, with similar non-storage costs ($1,039,751 in labor, $186,512 in building, $3,312,718 in transport for the entire system, on average). We therefore compared the two based on annual storage costs (energy, maintenance, and amortization for storage devices including power system) at the district and health facility levels. Using ILRs at these levels led to $74,066 in energy, $59,226 in maintenance, and $122,838 in amortization costs of storage equipment annually. SDDs at these levels incurred $284,464 in maintenance and $573,313 in amortization costs.

We calculated the annual storage cost savings provided by ILRs as the difference between the annual storage costs accrued when using electric devices at the district and health facility levels and those incurred when using solar refrigerators. Without electrical outages, using ILRs at the district and health facility levels cost $711,351 less in annual storage costs than SDDs ($334,822 as compared to $1,046,173, 2016 USD). In sensitivity analyses (Table 2), varying the purchase price or useful lifetime of solar devices had