Evaluation of Energy Harvest Control Systems Used with Solar Direct Drive Vaccine Refrigerators and Freezers in Senegal

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Introduction

Powering vaccine cold chain equipment in health facilities remains a challenge in low- and middle-income countries, where many locations lack reliable grid electricity.\(^1,2,3\) Most vaccines can withstand only limited excursions from the recommended transport and storage temperature of +2ºC to +8ºC, so uninterrupted power must be provided for mains-powered vaccine refrigerators in clinics and health facilities. An alternative to mains-powered refrigeration is solar direct drive (SDD) technology, which uses solar energy to freeze water or other phase change material in the appliance. The frozen phase change material keeps the vaccine compartment in the acceptable temperature range at night and on cloudy days. The dedicated solar arrays installed with the SDD refrigerator typically produce more electricity than the refrigerator needs for cooling. The excess power produced could be used for other key health and health system needs, provided there is no risk to the refrigerator performing its primary function of keeping vaccines in the acceptable temperature range; using this excess power is termed energy harvesting.

Some SDD refrigerators have been fitted with energy harvest controls (EHCs), devices that meet World Health Organization (WHO) Performance, Quality and Safety (PQS) standards to ensure that the power requirements of the vaccine refrigerators are prioritized over any other use of the solar array while allowing use of surplus energy for secondary purposes such as powering lights or medical equipment.\(^4\) Some EHCs are built into an SDD refrigerator, while other EHCs are separate devices that connect to the solar array and refrigerator. EHCs come with a variety of port types to access the surplus energy, including USB, 12 V bayonetted style (e.g., “automotive” cigarette lighter), barrel connectors, and proprietary ports.

We conducted an evaluation of SDD refrigerators fitted with EHCs in Senegal to determine whether the units performed in the field according to WHO PQS specifications,\(^5\) were acceptable and useful to end users, and had any notable positive or negative effects on the health system.

Materials and Methods

Study review and approvals

The Senegal Ministry of Health and Social Action (MOHSA) reviewed and approved the study design, ensuring compliance with local regulations. A review of the proposed work by PATH’s internal research determination committee determined that the proposed work did not qualify as human subject research and did not require review by an institutional review board. Verbal consent was obtained from study participants and documented on forms signed by the PATH representative obtaining consent.

Site selection

PATH’s past work conducting similar studies in Senegal\(^2\) and the presence of experienced local PATH staff contributed to the selection of Senegal for the current study. Sites were selected based on several criteria, including the following: approval by the Senegal MOHSA; presence of staff who provide regular immunization services; facility need for a vaccine refrigerator; facility was off-grid or connected to a weak grid where backup power was needed; mobile phone service was available; facility had minimal security risks; staff had use for the power provided by the EHC; and facility did not require major repairs, such as to the roof or foundation. Taking these criteria into account, 4 sites out of 12 visited were selected.
Study design

After an installation period of 1 to 2 days per site, a commissioning period of approximately 3 weeks ensued in December 2018. Users were instructed not to connect any electrical devices or use the equipment during this time, in order to accomplish two goals: 1) ensure that the refrigerator, EHC, dump loads, and monitoring equipment were functioning as expected; and 2) gather baseline data on the power available through the EHCs. For the second goal, “dump loads” intended to draw the maximum power possible through the available ports were used to estimate the energy that could generally be expected from the EHCs. The dump loads consisted of two 10,000-mAh lithium battery banks (Power Bank 2 PLM02ZM or Power Bank Pro PLM01ZM, Mi) for each USB port or 12 V bayonet style (e.g., “automotive” cigarette lighter) socket measured. Each pair of battery banks was continuously drained by a single power resistor capable of sinking the maximum current the USB port could deliver to the battery banks. The power delivered to the battery banks was logged.

The dump loads were removed after the commissioning period, and Phase 1 was initiated for the period from January to mid-March 2019. During this phase, some of the power generated by SDD refrigerators was diverted by the EHC for use by staff to power other devices, benefitting the health facilities and staff. The refrigerators were not used for vaccine storage during Phase 1 as this was considered a safety testing period for the refrigerator. Phase 2 was conducted from mid-March to November 2019, and during this time, actively used vaccines were stored in the refrigerators while users accessed the additional power available via the EHCs. The study included both evaluation of the technical performance of the SDD refrigerator/EHC units and assessment of the acceptability of the technology by users at the health facilities.

Solar direct drive and energy harvest control equipment

Due to site limitations and the prioritization process, only devices that had already obtained and passed the laboratory test criteria for WHO PQS prequalification were included. At the time of study initiation, two EHCs had been prequalified by WHO, so these were selected for the evaluation. The equipment was installed at four sites from December 11 to 18, 2018. An in-country servicing firm contracted by the equipment manufacturer installed the solar array, SDD refrigerator, EHC (if separate from the SDD refrigerator), and all necessary electrical cables, grounding, and hardware.

Sites 1 and 2 received the same SDD refrigerator (Model A), which contained an integrated EHC, also known as a basic EHC. The basic EHCs each had two USB ports for powering electrical devices that could deliver a maximum of 1 A at 5 V from each port or 2 A at 5 V from a single port. Sites 3 and 4 received another SDD refrigerator (Model B); however, the SDD refrigerator at Site 4 also had an integrated ice-pack freezer. In addition, Sites 3 and 4 received an identical, standalone EHC, also known as an energy harvest kit (EH kit). The EH kit charged an internal battery, which provided power for devices after dark or during periods of low insolation. The EH kit had two portable, rechargeable lights and a small ceiling fan powered via a cable connected to the EHC. Power was delivered to other devices from a 12 V socket (with a maximum 2 A output current) and two USB ports that could deliver a maximum of 1 A at 5 V from each port or 2 A at 5 V from a single port.

Electrical devices provided to sites

Site personnel were asked for suggestions for equipment they needed that could be powered by surplus energy from the EHCs, in addition to the lights and ceiling fan that accompanied the EH kits. We also consulted documents from global health agencies to curate a list of potential electrical devices to provide at each site. Selected devices were submitted to the MOHSA National Expanded Programme on Immunization (EPI) Coordinator for approval before purchase. Portability, durability, staff training and experience, and power requirements were other key factors that influenced these decisions.

Sites that did not receive an EH kit were supplied with two fans (LYSB01GZMMH7K-CMPTRACCS, Keynice), while the sites that received an EH kit were supplied with one fan, for a total of two fans at each site. Each
site received one headlamp (B01MZDW5LU, Petzl Actik), one fetal Doppler (B Baby Activity & Heartbeat Monitor, Sonoline), and one otoscope (4th Generation, Dr. Mom). MOHSA approved the use of these devices in the study. Each of these devices was powered through USB ports or the rechargeable AA or AAA batteries. USB-recharged lithium battery banks (Power Bank 2 PLM02ZM, Mi) and AA/AAA battery chargers (B0777X81LZ, SunJack USB Battery Charger) were also provided, with each site receiving two battery banks per USB fan. The portable battery banks allowed use of devices at night or in rooms other than those with the EHCs.

**Staff training**

Early in Phase 1, facility staff were trained and instructed to begin use of the power available through the EHCs. Training covered the following topics: safety; details of the study and protocols; electrical equipment and their use; general solar power information; hands-on demonstrations of solar module shading, soiling, and cleaning; and maintenance of the equipment. Each participant was given the opportunity to practice connecting and operating the electric equipment and encouraged to use them. The trainings were conducted in small groups (usually three people from the health facility), which enabled every participant to have hands-on experiences with each device and the appliance. To ensure the key content was absorbed, instructors involved all participants in each hands-on activity and posed questions to each. Baseline interviews with the primary staff at each site were also conducted at this time.

During Phase 1, health workers were trained to open the SDD refrigerator for 3 minutes in the morning and in the afternoon to check temperatures and simulate vaccine removal and replacement. This simulated use as a vaccine refrigerator lasted approximately 2 months, with the nurse or midwife using the EHC features to power useful devices as well. As noted above, during Phase 2, refrigerators were opened as needed to use vaccines.

**Data collection and analysis**

**Temperature measurements**

Temperature loggers (TRIX-16, LogTag) were used to measure ambient temperatures near the appliance and temperatures inside the appliance. Loggers placed inside the upper and lower portions of the refrigerator compartment in each appliance measured temperatures in these two locations, while another was placed inside one of the ice-pack freezing compartments of the Model B SDD refrigerator at Site 4.

Temperature data were collected by a manufacturer’s sensor located inside the SDD refrigerator wall. Thermal protection of the sensor provided by the appliance wall made this sensor less responsive to temperature fluctuations than the LogTags.

**Measuring irradiance, energy harvested, and energy consumed**

Monitoring equipment was installed at each site to measure and record solar irradiance, energy consumed by the appliances, and energy harvested by the EHCs. Data were downloaded from monitoring devices during each visit by study staff. The following frequencies were used for quantitative data sampling: voltage and current: one measurement every minute; irradiance: one measurement every minute; and temperature: one measurement every 4 minutes.

For measuring irradiance, a pyranometer (80SPC, SolData) was installed on a vertical pole near the solar array with the same orientation and tilt as the array. The voltage signal produced by the pyranometer was recorded
by a voltage logger (Tinytag TGPR-1001, Gemini Data Loggers) and translated to an irradiance value based on the calibrated pyranometer response. The following equation was used to estimate the array power output:

\[
\text{Array power output} = \frac{\text{irradiance}}{1,000 \, \frac{W}{m^2}} \times (\text{module capacity at STC}) \times (4 \, \text{modules})
\]

The power available was likely slightly lower than the estimate provided by the calculation due to module efficiency losses caused by module temperature, soiling, and other factors.

The current supplied by the solar array to the EH kit, by the EH kit to the SDD refrigerator, or by the solar array to the SDD refrigerator was monitored by measuring the voltage drop across a shunt resistor (RS50-100, Riedon). The voltage drop signal was then amplified by an instrumentation amplifier (AD623, Analog Devices). A voltage logger (Tinytag TGPR-1001, Gemini Data Loggers) translated and recorded the resulting voltage signal as a current value based on the shunt resistance. The voltages supplied to the appliances or EH kit were measured and recorded using a voltage logger (Tinytag TGPR-0704, Gemini Data Loggers). Current supplied to the loads (devices or dump loads) connected to the Model A SDD refrigerator USB ports was measured using a current-sensing integrated circuit (MAX471, Maxim Integrated) that converted the measured current to a voltage signal. The resulting signal was recorded by a voltage logger (Tinytag TGPR-0704, Gemini Data Loggers). The same model voltage logger was used to record the voltage supplied by the USB ports to the loads.

Since a single USB port could deliver the same maximum current as two individual USB ports combined, the power and voltage from a single USB port were monitored before passing to a USB splitter that provided two USB ports for loads. The remaining unmonitored port on the Model A SDD refrigerator was blocked for the study period. Current and voltage supplied to loads attached to the EH kit were not monitored directly. Instead, the total energy harvested by the EH kit was estimated from the difference between the power entering and leaving the EH kit. Power consumed by the EH kit for running its internal circuitry was included in the total energy harvested estimate.

Staff interviews

After installation, the commissioning period, and training, study staff visited the sites approximately every 2 weeks. After the first visit, the researcher used an observational tool to record equipment use and adaptations. This was not administered as a deliberate interview; rather, observations and relevant information from conversations that occurred during the visit were recorded.

Semi-structured questionnaires were used to interview head nurses at the health facilities at the end of Phase 1 and Phase 2 about the performance, acceptability, and systems fit of the SDD refrigerator with EHC. In addition, health workers, maintenance agents, and EPI focal points were asked about the ease of use of the SDD refrigerator with the basic EHC or the EH kit. Qualitative interview and observational data were analyzed using Excel with the coding of themes derived from responses.
Results and Discussion

Performance of equipment

Due to unforeseen LogTag data collection issues, LogTag temperature data were not collected during several time periods. With manufacturer permission, we used the temperature data collected by the on-board SDD refrigerator control system to fill in the gaps.

Mean refrigerator temperatures for the duration of Phase 1 were between +3.2°C and +5.3°C for all four sites between December 18, 2018, and March 19, 2019. Mean refrigerator temperatures for the duration of Phase 2 (similarly measured) were between +3.2°C and +5.4°C for all sites between March 19, 2019, and September 14, 2019.

The EHC-SDD refrigerator systems all provided power for the user devices, covering at least some of the power needs of the facilities in addition to powering the vaccine refrigerators. Overall system performance was acceptable, with some exceptions. One site with an EH kit had a faulty battery charging system, which was replaced and then performed acceptably. The two USB ports that comprised the user interface with the basic EHC became nonfunctional at one site and were not repaired during the study due to logistical issues obtaining parts and service.

Temperature analysis

Fig 1 displays refrigerator and ambient temperatures measured at a single site, Site 3, during the commissioning period and Phase 1. The large, short-duration increases in temperature in the upper and lower portions of the refrigeration compartment data occurred when LogTags were removed to download logged data or during door openings. The equipment at Sites 1 and 2 had similar refrigerator performance (see data availability section below). The equipment at Site 4, which also included a freezer, had similar refrigerator data for the period of December 18, 2018, to January 29, 2019, (see data availability section below). There was data collection gap between January 29, 2019, and the start of Phase 2 on March 19, 2019. The temperature data demonstrate that the SDD refrigerators were able to maintain the appropriate temperature range despite the EHCs diverting excess power to loads, whether the loads were dump loads that came close to drawing the maximum power from the EHC or user-selected devices.

Fig 1. Temperature data from Site 3. Temperatures measured inside the refrigerator (upper and lower portions of the vaccine compartment), in the cabinet wall, and at an external location (ambient temperature) throughout the commissioning period and Phase 1.
Fig 2 displays the refrigerator and freezer temperature data at Site 4 for Phase 2 and is representative of the equipment at other sites for Phase 2 (see data availability section below; freezer data was only at Site 4). The large, short-duration increases in temperature in the upper and lower compartment data occurred when LogTags were removed to download logged data or during door openings. Again, the temperature data show that the refrigerators could maintain the correct temperature range with the EHCs diverting power to user-selected devices and while being used for vaccine storage.

Fig 2. Temperature data from Site 4. Temperatures measured inside the refrigerator (upper and lower portions of the vaccine compartment), in the cabinet wall, in the freezer slot, and at an external location (ambient temperature) during Phase 2.

Note: Between 4/8/2019 and 5/20/2019 the freezer data were not recorded due to LogTag programming errors.

Table 1 summarizes the LogTag data from the upper and lower portions of the vaccine compartment and the manufacturer's integrated temperature sensor inside the cabinet wall. The extreme and mean values in the table include short excursions above +8°C that, based on the review of available data, are very likely due to the door-open events performed by the health workers. These door-open events include the 3-minute vaccine removal and return simulations of Phase 1 and actual vaccine use in Phase 2. However, it does not include data-download events, when the LogTags were removed from the refrigerator. These data were discarded from calculations because the event included removal of the temperature measurement device from the refrigerator. No excursions below –0.5°C were recorded, average temperatures remained within the acceptable range, and the minor excursions above +8°C were shorter than WHO PQS alarm conditions of temperatures greater than +8°C for 10 or more consecutive hours. Maximum temperatures during Phase 2 were higher than during Phase 1, possibly due to longer and/or more frequent door openings during actual vaccine usage.
Table 1. Summarized, aggregated temperature data for the four sites over the combined pre-Phase 1 commissioning period and Phase 1, and Phase 2.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Site</th>
<th>Upper location</th>
<th></th>
<th>Lower location</th>
<th></th>
<th>Manufacturer's sensor</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Max. temp. (°C)</td>
<td>Min. temp. (°C)</td>
<td>Mean temp. (°C)</td>
<td>Max. temp. (°C)</td>
<td>Min. temp. (°C)</td>
<td>Mean temp. (°C)</td>
</tr>
<tr>
<td>Commissioning and Phase 1</td>
<td>1</td>
<td>9.5</td>
<td>2.6</td>
<td>3.7</td>
<td>7.1</td>
<td>2.4</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7.4</td>
<td>2.3</td>
<td>3.5</td>
<td>6.2</td>
<td>2.2</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>10.4</td>
<td>3.9</td>
<td>4.6</td>
<td>9.3</td>
<td>4.5</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>9.4</td>
<td>3.3</td>
<td>4.5</td>
<td>7.5</td>
<td>4.3</td>
<td>5.3</td>
</tr>
<tr>
<td>Phase 2</td>
<td>1</td>
<td>15.8</td>
<td>2.0</td>
<td>3.7</td>
<td>11.4</td>
<td>1.6</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>21.3</td>
<td>1.6</td>
<td>3.6</td>
<td>10.6</td>
<td>0.7</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>29.1</td>
<td>2.9</td>
<td>4.8</td>
<td>25.6</td>
<td>2.7</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>11.4</td>
<td>3.0</td>
<td>4.7</td>
<td>11.4</td>
<td>3.7</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Power analysis

The power data demonstrated that the EHCs were able to divert useful amounts of excess electricity to loads. Fig 3 shows the power going to the SDD refrigerator (Model A, basic EHC) from the solar array, the power going to the dump loads, and the estimated solar array power output for a mostly clear day at Site 1 during the commissioning period. The solar array power output was not measured directly but calculated as described in Materials and Methods.

Fig 3. Power production and usage for the solar direct drive (SDD) refrigerator (Model A, basic energy harvest control [EHC]) for an indicative, mostly clear day at Site 1.
Since the EHC is internal to the SDD refrigerator in this model, the “Solar array to SDD refrigerator” curve includes the power going to both the refrigerator components and the dump loads. The area under the “SDD refrigerator to load” curve is the total energy diverted to the dump loads. The area under the “Estimated array output” curve is the total estimated energy that could be supplied by the solar array over the entire day. The total energy consumed by the appliance components and the dump loads is far less than the total estimated available energy from the solar array due to the limited power output of the USB ports.

Daily power appliance and dump load curves for the SDD refrigerator at Site 2, which was also a Model A, were similar to those at Site 1 (see data availability section below). However, because of a malfunction in the sensing element of the pyranometer, little irradiance data were collected at Site 2.

More power was diverted to the loads at Site 3 and Site 4, where the SDD refrigerator was accompanied by an EH kit. This was primarily due to the EH kit having a rechargeable 12 V DC battery (120 Watt hours available when fully charged) coupled to the portable lights, fan, and a 12 V socket, in addition to the USB ports. Fig 4 shows the power data for a clear day at Site 3 while the dump loads were attached (commissioning period). As the power diverted to dump loads was not measured directly, the “Solar array to EH kit” power curve includes power going to charging the lights, running the fan, charging the internal EH kit battery, powering the dump loads, and running the internal functions of the EH kit as well as energy going to the refrigerator. The total energy used by the EH kit for all load and internal functions corresponds to the area between the “EH kit to SDD refrigerator” curve and the “Solar array to EH kit” curve.

Even on the day with the lowest estimated solar array output for each model, sufficient energy was available for the appliance, energy was diverted to the dump loads, and a substantial amount of excess energy remained unharvested as shown in Fig 5 for Site 1. Data for the other sites showed a similar underutilization of excess energy (see data availability section below).
The pyranometer at Site 4 failed in a similar manner as the pyranometer at Site 2, so an accurate estimate of the potential solar energy available to the refrigerator and EH kit could not be made until after the faulty equipment was replaced.

At all sites, the energy harvested during the commissioning period by the dump loads exceeded the energy harvested during "normal" use once the dump loads were removed and the users began connecting other devices to the EHCs. This is because the dump loads were designed to continuously draw close to the maximum power output of the EHCs. By contrast, user-selected devices were not always connected to EHCs and usually drew less current than the dump loads.

Table 2 summarizes the average daily total energy harvested for each site during the commissioning phase, Phase 1, and Phase 2. The daily energy consumption of the refrigerators was consistent throughout this time. The SDD refrigerator at Site 4 (Model B, EH kit) consumed more energy on average than the SDD refrigerator at the other sites, likely because of its ice-pack freezing capability. The energy harvested by the Model A refrigerators (basic EHC) at Site 1 and Site 2 during the commissioning period was comparable to the manufacturer-specified maximum energy harvest of 50 Watt hours/day. The energy consumed by the EH kit was much less than the manufacturer-specified maximum daily energy harvest of 465 Watt hours/day. The EH kit at Site 3 consumed an average of 400 Watt hours/day during the period before the hypothesized completion of charging of the internal battery on December 31, 2018. Thereafter, the EH kit at Site 3 consumed only 283 Watt hours/day on average. These data suggest that the dump loads at Site 3 were not able to fully drain the EH kit internal battery overnight. The EH kit at Site 4, which lacked a functioning internal battery, consumed only 176 Watt hours/day during the commissioning period. This implies that a functional internal battery is necessary to maximize energy harvest by the EH kit. Another potential reason that the EH kit energy consumption was less than the manufacturer rating was that the rechargeable lights or fan on the EH kit were probably not used during the commissioning period, prior to the official user training in Phase 1.
Table 2. Average daily calculated estimate of energy available from the solar arrays and measured power used by the refrigerators and dump loads/devices. Dates of data analyzed are given for each site with exceptions detailed in table footnotes.

<table>
<thead>
<tr>
<th>Site</th>
<th>Commissioning</th>
<th>Phase 1</th>
<th>Phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Site 1: 12-18-2018 to 01-10-2019</td>
<td>Site 1: 01-11-2019 to 03-17-2019</td>
<td>Site 1: 03-21-2019 to 08-18-2019</td>
</tr>
<tr>
<td></td>
<td>Site 2: 12-20-2018 to 01-09-2019</td>
<td>Site 2: 01-10-2019 to 03-17-2019</td>
<td>Site 2: 03-20-2019 to 08-17-2019</td>
</tr>
<tr>
<td></td>
<td>Site 4: 12-20-2018 to 01-09-2019</td>
<td>Site 4: 01-12-2019 to 03-17-2019</td>
<td>Site 4: 03-19-2019 to 08-17-2019</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solar array</th>
<th>Refrigerator</th>
<th>Dump loads</th>
<th>Solar array</th>
<th>Refrigerator</th>
<th>Devices</th>
<th>Solar array</th>
<th>Refrigerator</th>
<th>Devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2,100 ± 400</td>
<td>266 ± 25</td>
<td>54 ± 12</td>
<td>2,320 ± 290²</td>
<td>237 ± 17³</td>
<td>25 ± 92</td>
<td>2,060 ± 260⁴</td>
<td>239 ± 13⁵</td>
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<tr>
<td>2</td>
<td>ND⁷</td>
<td>276 ± 18</td>
<td>57 ± 10</td>
<td>ND²</td>
<td>222 ± 14</td>
<td>12 ± 9</td>
<td>ND⁸</td>
<td>256 ± 21</td>
</tr>
<tr>
<td>3</td>
<td>2,320 ± 280</td>
<td>250 ± 14</td>
<td>400 ± 40/283 ± 16¹⁰</td>
<td>2,360 ± 240</td>
<td>231 ± 18</td>
<td>73 ± 22</td>
<td>2,100 ± 300¹¹</td>
<td>233 ± 19¹²</td>
</tr>
<tr>
<td>4</td>
<td>ND⁷</td>
<td>323 ± 17</td>
<td>176 ± 22</td>
<td>ND³</td>
<td>334 ± 19</td>
<td>60 ± 30¹³</td>
<td>2,000 ± 200¹⁴</td>
<td>348 ± 18</td>
</tr>
</tbody>
</table>

Abbreviation: ND, no data.

Values are average ± standard deviation.

Footnotes for data exceptions:
1. Data exclude energy consumption during initial cool-down.
2. Data for January 11, 2019, to March 7, 2019, due to data collection failure.
4. Data for May 24, 2019, to August 18, 2019, due to data collection failure.
5. Data for March 21, 2019, to April 11, 2019, and May 24, 2019, to August 18, 2019, due to problems with current sensor.
6. Device energy consumption could not be measured due to USB power monitor failure.
7. Solar array output could not be estimated due to faulty pyranometer output.
8. Only 3 days of pyranometer data collected due to data logger failure.
9. Data for March 20, 2019, to April 8, 2019, due to failure of current sensor.
10. Average daily energy calculated for periods before/after December 31, 2018, when internal battery is hypothesized to have finished charging.
11. Data for March 20, 2019, to April 9, 2019, and May 24, 2019, to July 2, 2019, due to data collection failure.
12. Data for March 20, 2019, to April 6, 2019, due to problem with current sensor.
13. Data for January 12, 2019, to February 18, 2019, due to replacement of faulty EH kit.
14. Data for July 5, 2019, to August 17, 2019, due to replacement of faulty pyranometer.
15. Data for March 27, 2019, to August 16, 2019, due to failure of solar array power monitor.
Acceptability evaluation

In general, EHC systems were well received, according to interviews and reports of conversations and observations. All health facility personnel responded that the EHC systems provided benefit to the facility. Head nurses commented that workers were able to use lighting powered by the EHC for women giving birth at night, rather than using light from candles, mobile phones, or flashlights. Others said that health workers felt less stress because they were able to charge mobile phones without paying or traveling long distances from the health facility. Teams were better able to screen patients with the fetal Doppler and otoscope powered by batteries recharged by the EHC. The use of both the fetal Doppler and otoscopes resulted in instances of patient referral to higher-level care.

At the end of Phase 1, the head nurse at each site was asked how their EHC model affected her or his ability to perform their jobs using a check-all-that-apply question format. Head nurse responses are shown in Table 3.

Table 3. Head nurse perceptions on how the energy harvest control (EHC) affected their job performance by health facility and appliance type, Phase 1. N = 4

<table>
<thead>
<tr>
<th>Site</th>
<th>EHC</th>
<th>Saved time</th>
<th>Able to provide new health services</th>
<th>Able to work more efficiently</th>
<th>Able to work more comfortably</th>
<th>Client/community happier</th>
<th>Had to keep clients/community from using to charge devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basic</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>2</td>
<td>Basic</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>EH kit</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>EH kit</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
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<td>3</td>
<td>4</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 4 presents other perceptions from head nurses describing how the EHCs affected their job performance during Phase 1.

Table 4. Head nurse responses on how the energy harvest control (EHC) affected community/client perceptions during Phase 1. N = 4

<table>
<thead>
<tr>
<th>Site</th>
<th>EHC</th>
<th>More positive attitudes toward health services</th>
<th>More health services used</th>
<th>Clients/community want to charge mobile phones</th>
<th>Clients/community support the new EHC system</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basic</td>
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<td>X</td>
<td>X</td>
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</tr>
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<td>2</td>
<td>Basic</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
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<tr>
<td>4</td>
<td>EH kit</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>
In Phase 2, all sites reported that the community/clients had more positive perceptions regarding their health services after using the EHC (Table 5), and none of the sites reported more negative perceptions.

Site 4 noted that the EHC had a positive impact on health care quality and that it created more comfortable conditions for patient care because of new appliances such as the fetal Doppler. Only Site 3 reported that clients had more access to health services. Three of the four sites found that the community wanted to charge their cell phones at the health facility. For example, Site 1 stated that the community was satisfied with the service improvements and the ability to charge their phones at the health facility.

Table 5. Head nurse responses on how the energy harvest control (EHC) affected community/client perceptions during Phase 2. N = 4

<table>
<thead>
<tr>
<th>Site</th>
<th>EHC</th>
<th>More positive attitudes toward health services</th>
<th>More health services used</th>
<th>Clients/community want to charge mobile phones</th>
<th>Clients/community support the new EHC system</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basic</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>Basic</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>3</td>
<td>EH kit</td>
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<td>4</td>
<td>EH kit</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

**Staff requirements and time**

Anecdotal evidence suggested that health workers had to spend less time traveling elsewhere to charge devices. For example, at the Site 3 health facility, health workers normally had to travel to the village’s drilling pump to charge their mobile phones. The other sites had separate solar panel installations at or near the health facilities. So, although they could charge their mobile phones previously from the solar panels already at the sites or nearby, they found this less convenient than charging from an EHC directly at the health facility.

**Limitations**

Our study had some limitations. First, this is a limited sample of only four sites. In addition, the monitoring equipment did not provide data on what devices were used or how much power each device used. The study evaluated how the EHCs performed, but it did not evaluate the devices themselves; for example, the team did not evaluate whether the otoscope was easy to use, or how well it performed its medical function, nor did it compare this device to other otoscopes. To date, the manufacturer has not diagnosed the initial EH kit battery charging system failure at Site 4 or the USB port failures at Site 1 due to logistical issues surrounding return of the failed equipment to the manufacturer for diagnosis.
Conclusions

This field study in Senegal confirmed that the SDD and EHC equipment works generally as intended. All temperature data from the vaccine refrigerators were acceptable, and no refrigerator functions were compromised by including the EHCs. The equipment safely provided power from the EHC-SDD refrigerator systems, but both pieces of equipment underutilized the power available from the solar array because of significant limits on the amount of power that can be supplied by the low-power ports and small number of ports.

In terms of acceptability, users generally appreciated the surplus power, used some of the study-provided devices, and charged additional devices such as mobile phones. The failures of the EH kit battery charging system and the USB ports on the basic EHC did not impact operation of the vaccine refrigerator attached to either EHC and demonstrated examples of “fail safe” operation of the vaccine refrigerator in the case of EHC failure. In general, the equipment saved the health workers time and allowed them to work more efficiently and more comfortably. It also allowed facilities to provide new health services. The efficiency and time gains may increase the health workers’ availability for health service delivery or improve work-life balance, but neither was confirmed in this study. All sites reported that the EHCs did not increase nor decrease client attendance at the facility; however, all sites reported that clients spent more time at the facility.

Overall, the study results demonstrate that EHCs can provide useful additional electrical power that is much appreciated by health care workers and clients without negatively impacting an SDD refrigerator’s ability to store vaccines in the appropriate temperature range. The energy data showed that there is room to expand the power supplied by the EHCs by expanding the number and capacity of the ports, potentially increasing the positive impacts that can be achieved from harvesting underutilized solar power at health facilities. As the number and types of EHCs deployed increase, additional studies on their impact on health facility operations and patient health outcomes would provide further evidence on the usefulness of EHCs.
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Under the grant conditions of the Bill & Melinda Gates Foundation, a Creative Commons Attribution 4.0 Generic License has already been assigned to the Author Accepted Manuscript version that might arise from this submission. The views expressed herein are solely those of the authors and do not necessarily reflect the views of Gavi or the Gates Foundation. The refrigerators and EHCs as well as international shipping costs were provided for the field study by the manufacturers.

Data availability

Data presented in this article are available from the online Data Archiving and Network Service (DANS) under the title “Energy harvest control systems Senegal study dataset” with digital object identifier 10.17026/dans-zws-ng3k.
References


