**New Solar Battery Demonstration – Vietnam 2011 - Steve McCarney– April 29, 2011**
**FINAL REPORT: PATH RMS2 HIP 1389-02—02-26**

## Executive Summary

If Lithium Phosphate (Li) batteries can prove to provide a reliable service life of 10 or 20 years, then solar powered vaccine refrigerator designers could match the service life of selected refrigerators (i.e. 10 year or 20 year life) to Li battery life and offer a "lifetime" battery. If Li batteries have a 20 year service life then Li battery *life costs* are lower than comparable maintenance free lead acid batteries that also meet World Health Organizations (WHO) Performance, Quality and Safety (PQS) specifications.

Figure 1: Cat Ba solar vaccine refrigeration installation in progress (with Valence Li Battery)

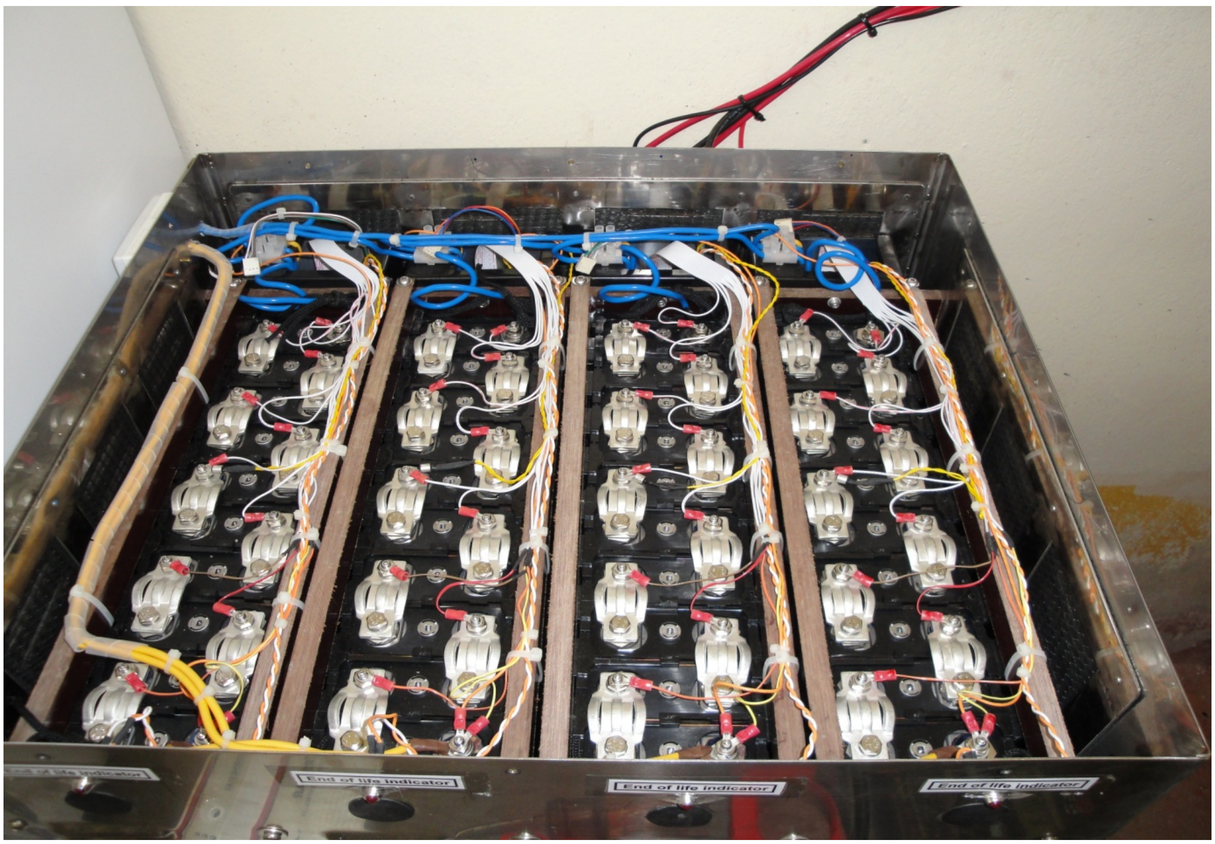
PATH commissioned a demonstration of two promising battery technologies for use in solar electric photovoltaic (PV) powered vaccine refrigerators. Lithium Phosphate ($LiFeMgPO_4$) and Nickel Metal Hydride (NiMH) were specified for solar application per the WHO PQS equipment standards. Presently, both battery manufacturers and the solar energy industry have little field experience in this application and neither provides established technical support for solar recharging applications of these types of batteries.

Solar power systems were designed for a 20 year service life with no battery replacement. Both battery types were significantly more expensive initially than industrial quality tubular plate lead acid batteries. However, tubular lead acid batteries would require three to four battery replacements in a 20 year timeframe.

The batteries were installed with identical systems and in similar climate conditions on Cat Ba and Cat Hai islands in Vietnam. Installation was simplified when compared to flooded lead acid batteries with the WHO PQS requirement to add liquid electrolyte during installation. However, the local installation team was unfamiliar with the new battery technologies and their need for specific control set points.

The NiMH battery system failed entirely and was replaced with a lead acid battery after the battery manufacturer could not identify the cause of failure and could not provide suitable and safe troubleshooting procedures for non-technical staff or for solar technicians. The complex, factory installed battery management system can be seen in Figure 2.

Figure 2: GoldPeak NiMH batteries, enclosure and factory installed battery management system




The Li batteries are presently operating satisfactorily. However, the Li battery system's integral control system automatically shut down battery operation twice during June and July 2010. With support of the battery manufacturer it was determined that overheating had caused the shutdown and also that one of the four batteries failed. The battery was replaced by non solar technicians after ventilation was added to the battery enclosure and no additional shutdowns were recorded.

Extensive monitoring was installed that included: refrigerator temperature (2 places), room temperature, outdoor temperature, solar radiation, solar power system voltage, current and refrigerator current. Monitoring of refrigerator temperatures shows that when the vaccine refrigerator is provided power it will produce acceptable vaccine storage temperatures. Monitoring indicates the solar power system operated as expected and performs satisfactorily in producing power adequate for the refrigerator. Monitoring also provided valuable information in diagnosing the NiMH battery failure.

Users were happy with the temperature performance of the refrigerator. They had two main concerns that came out during interviews. First they were concerned about the size and configuration of the refrigerator compartments. For the vaccine compartment, they felt it would not be large enough to store the vaccine in the District health center, and they noted that the compartment was very deep, making it difficult to reach vaccines in the back. The freezer compartment was also considered too small given the needs for freezing icepacks at the District health center. Their second concern was in reaction to the system disruptions that occurred during the project. They attributed the problems to imperfect installation, and suggested as a lesson learned that installation should be very carefully managed in order to ensure smooth running of the refrigerators in the long term.

The following attributes would support the eventual substitution of Li batteries for lead acid batteries in solar vaccine refrigeration. These attributes are broadly described as:

1.) *Reliability and Safety*: Li batteries will need to exhibit reliability and safety equal to lead acid batteries;
2.) *Longer Service Life*: Li batteries will need to demonstrate the extent to which Li battery service life exceeds that of lead acid batteries and provide increased warranty;
3.) *Technical Support*: Improved technical support must be provided by both battery makers and solar industry specifically for standalone solar power recharging applications; and
4.) *Cost:* Although a 20 year Li battery has a life cycle cost advantage the initial cost of Li batteries likely will need to decline to establish market penetration.

**Acknowledgements**

The PATH Health Innovation Portfolio (HIP), funded by USAID, sponsored this demonstration project. PATH staff created and managed this field demonstration. PATH Hanoi worked closely with our supportive partners in Vietnam including the Hai Phong Medical University and National Expanded Program for Immunization (NEPI) officials. Project Optimize, a collaboration between WHO and PATH designed to address the future direction of vaccine logistics, provided ongoing technical support.

Joanie Robertson, PATH Hanoi, provided guidance throughout the HIP process and field support in Vietnam. Lien Tran Thi Huong, PATH Hanoi, provided field support. Kien Vu, PATH Hanoi has grown to become a solar technician through troubleshooting and repairing both systems in Cat Ba and Cat Hai. Shawn McGuire, PATH Seattle, was responsible for the monitoring design and supervised the installations in Vietnam and provided the photos. Tina Lorenson conducted life cost analysis. SELCO, Ho Chi Minh City, installed the equipment. Conor Malloy, and the Valence Battery engineering staff of Belfast, N. Ireland provided technical support throughout the project. Morningstar, USA, provided and supported the solar controls. Sunfrost, Arcata, California USA sold the solar power system and vaccine refrigerators. GoldPeak, Hong Kong sold the NiMH battery.

**Background**

Solar vaccine refrigerators are most often used in remote health posts and clinics lacking reliable electricity. Current practice is to permanently install a solar photovoltaic (PV) power array to recharge a lead acid battery to power the refrigerator. Lead acid batteries have a service life of three to five years with rare reports of life of ten years. Lead acid battery life is significantly less than the 20+ year service life of solar PV modules and refrigerators with service life of 10 to 20 years. When a battery needs to be replaced it is especially problematic for small, remote facilities. This is because replacing lead acid batteries is expensive, requires a trained technician, will have complicated logistics and high quality batteries may not be readily available in country. Battery replacement must be planned at the onset of a solar vaccine refrigeration projects and funds must be available prior to the need for battery replacement.

In 2009 this project was approved, designs were created and equipment purchased. Site visits and staff training were carried out in January 2010. In March 2010 the equipment was installed at two sites in Vietnam on the nearby islands of Cat Ba and Cat Hai. Cat Ba used Li batteries while Cat Hai used NiMH batteries. One year of monitored data was recorded and analyzed. User acceptance and experiences were gathered through a series of three interviews throughout the project.

The Li battery has performed well after an initial shutdown condition was corrected by adding adequate ventilation to battery enclosure. The NiMH battery failed after 30 days and could not be repaired and it was replaced with a sealed, lead acid battery. Both the Li and NiMH battery manufacturers did not have specific guidelines for design, installation and troubleshooting of their batteries when used in solar PV electric recharging applications. The PV industry does not make specific controls for these batteries and has very little experience with either Li or NiMH batteries.

**Reliability and Safety**:

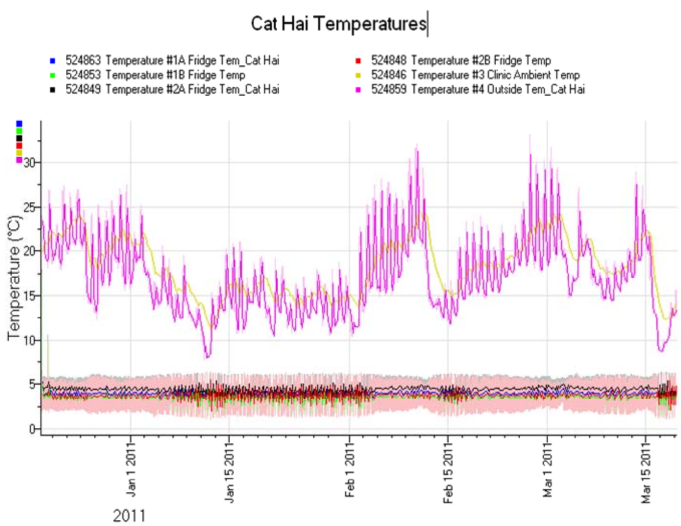
After 30 days the Gold Peak NiMH battery failed when voltage rose to extremely high levels indicating a control failure.

The time of failure coincided with a large regional thunderstorm and lightning was suspected as the contributing factor. The manufacturer could not determine the cause of failure from field information and data (see graphic) and indicated the fault was likely in other components. Several attempts were made to isolate the cause of failure through a process of elimination. After determining that the solar array was operating correctly and the refrigerator operated properly the Morningstar battery charge control was removed, replaced and sent to the factory where it was confirmed that it still operated correctly and had no evidence of lightning damage. Meanwhile, the system (with new, preset Morningstar solar charge control) was switched on and the system operated correctly for several hours before staff left the site. Within 24 hours it was reported the NiMH battery enclosure (metal) had become too hot to touch. The system was disconnected safely but Gold Peak could not provide satisfactory troubleshooting steps. Troubleshooting was hampered by the complex nature of the Gold Peak factory-installed internal battery control that could not be isolated from the battery. Gold Peak requested that entire battery, control and enclosure assembly be removed and returned to Gold Peak for internal lab test and report to PATH. The battery was received at Gold Peak in January 2011 but no report was received after repeated requests.

The Valence Li batteries overheated in the summer of 2010 and their internal control system automatically disconnected the batteries. Satisfactory troubleshooting steps and diagnostic equipment was provided by Valence. Non-solar staff were able to discover that one battery had failed and they were able to replace it. It was also discovered that the battery enclosure provided by Sunfrost did not meet WHO PQS specifications for ventilation since it had no ventilation provisions. Lack of venting is suspected to have caused the battery overheating. The manufacturer and the author determined a satisfactory ventilation retrofit for the enclosure, staff were able to carry out the retrofit in the field and the Valence batteries have functioned perfectly since.

The Evergreen solar modules and Morningstar controls correctly functioned. Monitoring has indicated that the Sunfrost solar vaccine refrigerators have operated within acceptable vaccine temperature range when solar power has been provided. See Figure 3 Cat Hai refrigerator and ambient air temperature data indicating stable internal temperatures within typical ambient temperature swings.

Figure 3: Cat Hai refrigerator and air temperatures




## <u>Service Life:</u>

Solar photovoltaic (PV) powered vaccine refrigeration systems consist of a vaccine refrigerator and solar power system. Vaccine refrigerators can provide a long service and at least one manufacturer now advertises a 20 year life expectancy. Solar modules carry a 20 to 25 year power warranty. Battery charge and discharge controls are warranted for 5 to 10 years.

Traditional industrial quality lead acid batteries typically are not warranted for more than 5 years in PV applications and the warranty is conditioned on use at +25C (with battery life roughly declining by 50% for each +10 C increase in temperature). Therefore lead acid battery failure is likely in the first 5 to 10 years in well designed systems and failure may occur in less than 5 years in poorly designed systems.

Valence data indicates the possibility of 10,000 cycles when discharging the Li battery by 50% of initial rated capacity. Some solar designers consider each day as one complete charge and discharge cycle. A 10,000 cycle life would equate to over 27 calendar years. Since the Li battery power capacity is slowly reducing over time this factor, sometimes called "irreversible loss of life", must be considered in order to attain an extended calendar life with adequate capacity. It is possible the internal electronic controls will fail before the battery itself. To obtain the most life from the battery Valence provides an optional Battery Discharge Indicator (see Figure 5).

According to Valence engineers the irreversible capacity loss at +23°C is about 2%/year. At +45°C, the irreversible capacity loss is about 13%/year. Assuming a logarithmic relationship between capacity loss and temperature, the capacity loss would be about 4-5%/year for +32°C

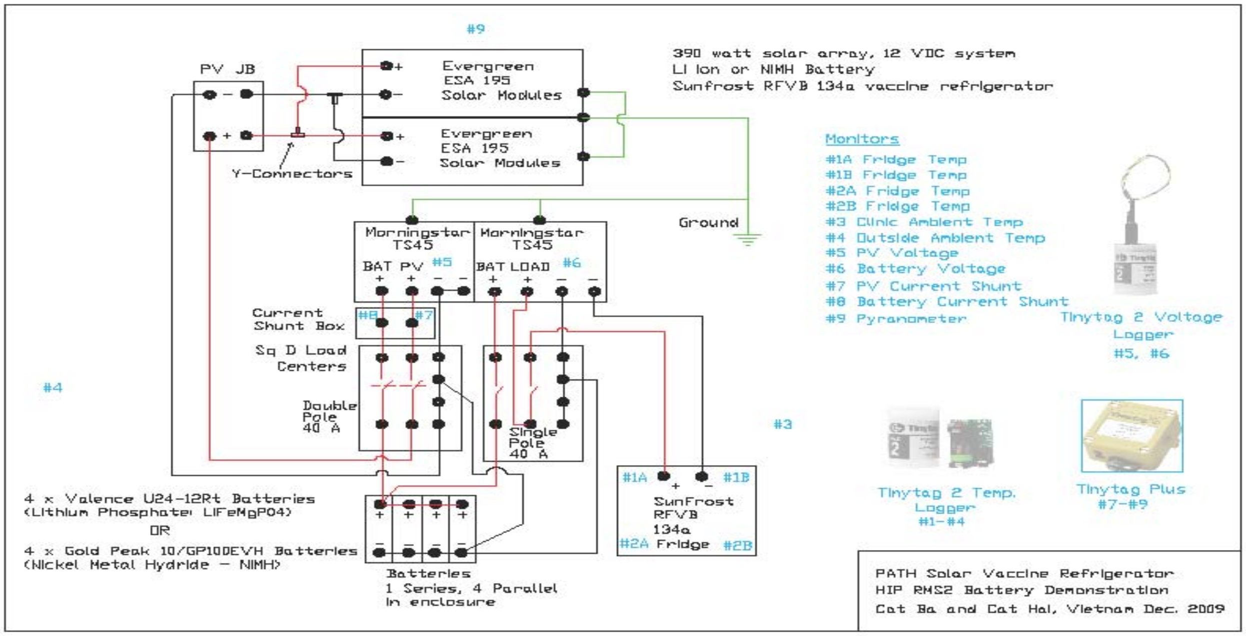
New battery options may offer a 15 to 20+ year battery life. Field reports from Hexagram of some small lithium thionyl chloride cells achieving over 20 years life when powering remote, wireless sensors. Hexagram states these batteries are reported to have 25% of their original capacity available after 24 years in field operation indicating the importance of understanding the irreversible loss of life factor for a specific applications and ambient temperature. SAFT provides a wide selection of Li batteries, some projecting a 15 year calendar life, some intended for solar and a variety of other demanding applications including space satellites.

**Technical Support:**

In an effort to reduce the negative impact of battery failure designs were established for maximum system service life targeted at 20 years. With the direct assistance of two battery manufacturers and a solar control manufacturer PATH created two system designs. One employs Lithium batteries and the second employs NiMH batteries. Each battery required slightly different set points for both charge and discharge termination. A system specification and wiring diagram was created and approved by the battery maker, Morningstar and PATH. See Figure 4.

A competitive bid was solicited from all WHO/UNICEF Qualified Suppliers of solar vaccine refrigeration systems. Sunfrost was selected to provide two of their RFVBB 134a vaccine refrigerators and a WHO PQS compliant solar power system kit complete with all equipment, wiring and hardware except for the batteries. A Li battery was provided directly by manufacturer Valence and a NiMH battery was provided directly by manufacturer Gold Peak. The systems were installed in March 2010 by SELCO, a Vietnamese solar contractor. Monitoring then commenced.

Figure 4 Monitoring and Wiring Diagram




***System Specifications***:

| | |
|---|---|
| *Load:* | Sunfrost RFVB 134a (design consumption of 380 Wh/day at +32°C)<br>(2 year warranty) |
| *Solar Array:* | Two (2) Evergreen ESA 205 Solar Modules (Array 410 Watt peak)<br>*(25 year warranty) Note:* due to availability constraints the ESA 205 was substituted for the ESA 195 originally specified |
| *Controls:* | Two (2) Morningstar TriStar TS 45 (adjusted to battery manufacturer's voltage set point recommendations for solar charging of battery and battery discharging to load)<br>*(5 year warranty)* |
| *Battery 1:* | Lithium Iron Magnesium Phosphate ($LiFeMgPO_4$) Battery<br>Four (4) Valence U24-12RT batteries in parallel<br>(12.8 volt, 110 amp hour x 4 = 440 ah)<br><br>High voltage cut off 14.6 Vdc<br>Low voltage cutoff 11.5 Vdc<br><br>Battery with integral control cost (2009) $ 1510 each<br>(2 year warranty)<br><br>Total cost per kWh ($ 1072/kWh) |

*Battery 2-a*: Nickel Metal Hydride (NiMH) Battery
Four (4) Gold Peak 10GP100EVH batteries in parallel (12 volt, 100 amp hour x 4 = 400 amp hours)

High voltage cut off 14.5 Vdc
Low voltage cutoff 11.0 Vdc

Battery Cost (2009) $ 850 each ($ 708/kWh)
Battery Control Cost $ 400 total ($ 83/kWh)
(2 year warranty)

Total cost per kWh ($ 791/kWh)

*Battery 2-b*: Replacement Lead Acid Valve Regulated Battery*
Four (4) FIAMM Enerlite 12 SP 100 batteries in parallel (12 volt, 100 amp hour x 4 = 400 amp hours)

High voltage cut off 14.4 Vdc
Low voltage cutoff 11.6 Vdc

Cost (2010) = $ 148 each ($ 124/kWh)

Total cost per kWh ($ 124/kWh)
(warranty to be negotiated)

*battery does not comply with the WHO PQS life specifications

Neither the Li battery or the NiMH battery were actively marketed to the solar recharging market in 2009 but both companies provided evidence that expected service life would exceed 10 to 15 years. It was found that neither battery manufacturer would warrant even a 10 year life and that neither had extensive experience with solar recharging. The level of support for NiMH batteries in solar application is far less than found with the well known lead acid battery applications. The level of technical support from Valence for their Li battery was exceptional.

Both batteries are provided with a proprietary control system that balanced charge to the numerous individual cells. These controls did not serve the same function as a battery charge control and therefore a separate solar charge and discharge was required. Neither manufacturer would specify a solar control to use. A search of the solar control industry found no products specifically for large format Li or NiMH batteries.

To meet the specific voltage set point requirements defined by each manufacturer  a control that allowed for customization was needed. Morningstar controls were known to be reliably used for solar vaccine refrigeration system and some models allowed for customized set points. The Morningstar TriStar control was specified by PATH for both solar charge control and load discharge control. Although the controls were provided by Sunfrost, the refrigerator/solar power system supplier, Sunfrost asked that PATH be responsible for customizing the set points. PATH engineers customized the controls. Morningstar accepted the challenge to provide ongoing support for their TriStar controls and their after sales service was considered to be excellent.

Recent interviews indicate that there is at least one solar control maker (Steca) planning to develop a solar control for Li and possibly NiMH batteries. BYD, a manufacturer of both Lithium Iron (LiFe) batteries and PV modules, also provides fully integrated solar power systems including controls for remote, standalone applications similar to the application for vaccine refrigeration.

In order for Li batteries to be acceptable for use in solar vaccine refrigerators manufacturers must:

1.) *Establish solar power system design guidelines that:*
    a. Introduce the irreversible loss of life parameter for long term storage degradation estimation
    b. Provide capacity curves for various temperatures and discharge periods typical of standalone solar power systems
    c. Establish and publish charging and discharging limits and solar control set points
    d. Establish battery life expectancy under different temperature, charge and discharge profiles
    e. Define a warranty for batteries when installed in solar recharged systems

2.) *Establish solar installation guidelines that:*
    a. Specify the maximum number of parallel batteries
    b. Specify battery layout and spacing requirements
    c. Specify battery enclosure ventilation requirements
    d. Provide detailed troubleshooting procedures for solar applications

Figure 5: Valence Lithium Polymer batteries with Battery Discharge Indicators

**<u>Cost:</u>**

Lithium ion batteries are considered to be the most promising technology for solar applications by the French Institut National de L'Energie Solaire (INES). INES research presented at the Batteries 2008 Conference focused on SAFT Lithium ion batteries in solar applications and indicated that a 20 year life is possible with no maintenance. Present costs for power delivered over the life of a battery were shown to be the same for both Lithium ion batteries and the flooded tubular lead acid batteries that comply with the WHO PQS. Comparisons by INES are based on life cycle costs that also include a cost for maintenance. If cost reduction targets are met INES projects that Lithium ion batteries will cost 43% less than lead acid over a 20 year period. The key assumption of a 20 year maintenance free life is still untested. See Table One.

**Table One: Battery Comparison: Lithium-ion Battery and Lead Acid Battery**

| Battery Technology | Li-ion (Today) | Lead Acid (tubular) | Li (5 year) |
|---|---|---|---|
| *Assumptions: 12 kWh battery, 5 days autonomy* | | | |
| Initial battery cost ($) | 13440 | 2520 | 7560 |
| Expected life (years) | 20 | 8 | 20 |
| Total number of cycles | 7300 | 2920 | 7300 |
| Total discharged kWh | 17520 | 7008 | 17520 |
| Cost of ownership ($/kWh) | 0.76 | 0.36 | 0.420 |
| Cost with maintenance ($/kWh) | 0.75 | 0.74 | 0.42 |

Source: INES, Batteries 2008 modified to USD at exchange rate of 1.4 USD per Euro

The 2009 cost of the maintenance free Valence Li batteries used in this project was $ 1072/kWh of full rated capacity. This battery would meet the WHO PQS equipment specifications. Since this battery is capable of repeated discharges to 100% then the cost of energy capacity available for use is also $ 1072/kWh.

The 2011 cost for a WHO PQS compliant maintenance free OPzV tubular lead acid battery is approximately $ 214 per kWh of full rated capacity. Many solar designers limit the depth of discharge of this type of battery to 50% to prolong battery life. Then the cost of energy capacity available for use is double or $ 428/kWh.

The 2011 cost for a WHO PQS compliant flooded OPzS tubular lead acid battery is approximately the same as OPzS when added shipping costs are considered (i.e. $214 per kWh of full rated capacity). Many solar designers limit the depth of discharge of this type of battery to 80% to prolong battery life. Then the cost of energy capacity available for use is $267/kWh.

The service life of a Li battery will be impacted by the temperature of the battery and depth of the discharging. Cooler temperatures and lower discharging depths will increase battery life. For a 20 year service life, the Li battery must be oversized initially to compensate for irreversible loss of life. (i.e. for the installation sites it was estimated at approximately 2.5 % per year at +25°C per Valence estimations of the system design used by PATH). This irreversible loss of life essentially results in a doubling of the initial capacity requirement simply to offset irreversible life loss. Lead acid battery designs typically do not attempt long service life and therefore this factor is ignored.

To compare the long term costs of the three WHO PQS compliant battery strategies the following minimum factors must be included:

1. Initial cost of battery system ($/kWh of available capacity);
2. Annual maintenance cost;
3. Number of battery replacements during service life; and
4. Costs for each battery replacement/disposal include battery, technician time and travel.

Sealed Li and sealed lead acid batteries are assumed to have similar transport costs, installation costs and maintenance costs. Flooded lead acid batteries will increase transport costs, installation risk and time, maintenance costs and may also impact disposal costs. Not considered in such a cost analysis is the cost of refrigerator failure. These costs include lost immunization opportunities, lost vaccines and indirect costs (e.g. immunization service credibility).

A simple life cost analysis of 20 years indicates that a maintenance free Li battery designed for 20 year life will have a lower life cost than the comparable maintenance free lead acid battery over 20 years.

The analysis shown below compares the life cost per kWh of three battery technologies for refrigerators offering 20-year and 10-year lives in the clinic. Major assumptions are:

1.) each type of lead acid battery will require replacement at 5 years;
2.) the flooded battery will require quarterly maintenance with 4 litres of distilled water per year (estimated $ 24/year);
3.) replacement batteries will cost the same as 2011 prices;
4.) technical time/travel costs are $ 150 per replacement ($ 40/day technician labor plus $ 110 travel costs);
5.) annual inflation rate 2%;
6.) *Lithium Phosphate Battery (Li)* first cost = 2 x $ 1072 = $ 2144/kWh (2009 price) or estimated $2,231 (2011 price equivalent), no battery replacements;
*7.)* *Sealed Lead Acid Battery (OPzV)* first cost = $ 428/kWh, and 3 battery replacements;
*8.)* *Flooded Lead Acid Battery (OPzS)* first cost = $ 267/kWh and 3 battery replacements; and
*9.) All batteries are sized appropriately for the intended kWh required*

Table Two: 20-year refrigerator with 20-year life LiFeMgPO4 battery and 5-year life lead acid batteries life-cost comparison

| | $LiFeMgPO_4$ battery* | Sealed OPzV lead acid battery | Flooded OPzS lead acid battery |
|---|---|---|---|
| Battery price per kWh | $1,115 | $214 | $214 |
| Required kWh adjustment factor | 2 | 2 | 1.2 |
| Battery cost per unit at required kWh | $2,231 | $428 | $257 |
| Intended life | 20 | 5 | 5 |
| Number of batteries over 20 years | 1 | 4 | 4 |
| Replacement charges over 20 years | 0 | 3 | 3 |
| Local maintenance over 20 years | 0 | 0 | 20 |
| Total** | $2,231 | $2,558 | $2,486 |

Table Three: 10-year refrigerator with 10-year life LiFeMgPO4 battery and 5-year life lead acid batteries life-cost comparison

| | $LiFeMgPO_4$ battery* | Sealed OPzV lead acid battery | Flooded OPzS lead acid battery |
|---|---|---|---|
| Battery price per kWh | $1,115 | $214 | $214 |
| Required kWh adjustment factor | 1.5 | 2.0 | 1.25 |
| Battery cost per unit at required kWh | $1,673 | $428 | $268 |
| Intended life | 10 | 5 | 5 |
| Number of batteries over 10 years | 1 | 2 | 2 |
| Replacement charges over 10 years | 0 | 1 | 1 |
| Local maintenance over 10 years | 0 | 0 | 10 |
| Total** | $1,673 | $1,067 | $1,099 |

*2009 battery price per kWh of $1,072 subjected to 2% compounded annual interest to reach 2011 illustrated price
**Total = [battery price per kWh in 2011 + battery price per kWh in 2016 + battery price per kWh in 2021 + battery price per kWh in 2026] + [# of times battery replacement is required over 20 years*average replacement charge over 20 year period] + [# of times local maintenance is required over 20 years*average maintenance charge over 20 year period]

Assumptions for Table Two and Table Three:

Installation costs related to technician support and travel time are equivalent across all batteries and therefore not included as a component of the life-cost comparison.
Annual interest rate: 2%

Technician time and travel costs are $ 150 per replacement ($ 40/day technician labor plus $ 110 travel costs).
Variable cost per battery replacement: $150

The flooded battery lead acid battery will require quarterly maintenance with 4 litres of distilled water per year
Annual maintenance cost: $24

The life cost analysis for a 20-year refrigerator life scenario based on the assumptions outlined above, indicates that Li batteries have the lowest life cost of three batteries that comply with the

WHO PQS. However, should a refrigerator with a 10-year life be preferred, the battery life-cost comparison indicates the Li battery will be the most expensive option of the 3 batteries assessed.

**<u>Conclusion:</u>**

If Li batteries can prove to provide a reliable service life of 10 to 20 years then solar powered vaccine refrigerator designers could match the service life of selected refrigerators (i.e. 10 year or 20 year life appliance) to battery life and offer a "lifetime" battery that is maintenance free.

The PATH field demonstration has shown that *reliability* issues prevented the NiMH battery from completing the one year demonstration. *Reliability* concerns remain for Li batteries where one of the five total batteries installed failed within four months of installation.

Additional solar application experience is needed by both the battery makers and the solar industry. Solar application specific *technical support* literature is needed and could be developed by both the battery manufacturer and the solar industry.

The limited time frame of this demonstration cannot determine if a 10 or 20 year *service life* will be realized but evidence indicates that Li batteries could outlast traditional lead acid batteries.

Comparing three battery types that meet the WHO PQS equipment specifications it was estimated that Li batteries have the highest *life cost* if their service life is 10 years. However, Li batteries have the lowest *life cost* if their service life is 20 years and irreversible capacity loss is limited to 50% over the 20 year life.