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Solar Milk Cooling: Smallholder Dairy Farmer Experience in Kenya

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Abstract

The USAID Photovoltaics for Sustainable Milk for Africa through Refrigeration Technology *(PV-SMART)* project is a new and creative concept of providing on-farm solar milk refrigeration for off-grid dairy farmers in Kenya. It uses a modified off the shelf direct drive photovoltaic refrigerator (PVR) technology, coupled with innovative cooling and energy storage approaches to chill evening milk on the farm for later transport the next morning to dairy collection centers. The battery-free PVR unit is designed to work optimally in locations with at least 4 average peak sun-hours per day. Farmers can receive a premium price for providing higher quality, refrigerated evening milk to dairy processors that would otherwise spoil. Dairy processors can also charge a premium for better quality and tasting dairy products from better quality milk that is maintained chilled from farm to factory. These solar farm milk coolers (FMC) are the first of their kind anywhere in the world and are a unique refrigeration system that uses thermal ice storage in lieu of electrochemical batteries and can operate directly on dc power from a PV module powering a variable speed dc compressor. The initial 40 pilot Solar FMC units have performed well in Kenya and lab and field assessments are discussed.

Keywords: *photovoltaics, direct drive solar refrigeration, milk chilling, Kenya*

1. Kenyan Dairy Sector

The ***Photovoltaics for Sustainable Milk for Africa through Refrigeration Technology (PV-SMART)*** project aims to tackle off-grid milk cooling under the United States Agency for International Development (USAID) Powering Agriculture Energy Grand Challenge Program (PAEGC). In collaboration with Winrock International (WI), SunDanzer Refrigeration Inc. (SDZR), a leading US solar refrigeration technology company, was awarded a highly competitive USAID grant to implement the project. The 3-year project began in 2014 and is implemented in collaboration with the County Governments and Agriculture Ministries of Baringo and Nakuru, and the Department of Dairy and Food Science and Technology at Egerton University located at Njoro, and various partner dairy cooperatives all in Kenya

There are over 850,000 small holder dairy farmers in Kenya, about 85 percent of whom do not have access to the national electric power grid. Diesel fuel is expensive and logistics difficult to deliver to small rural dairy farmers. Thus, there has not been an economical method available for on-farm milk chilling for the vast majority small holder dairy farmers in Kenya and other less developed regions globally. The typical Kenyan dairy farmer has about 3 to 5 cows, producing an average of about 8 liters per day of milk per cow (typically ~60% as morning milk and ~40% as evening milk). Dairy cooperatives have an organized morning milk collection system, but normally do not accept evening milk since by morning it has a high bacteriological count. Due to the lack of on-farm refrigeration, evening milk for which there is no milk collection has to be

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either forced consumed, sold cheaply to nearby neighbors or hawkers, or is lost. In Kenya, only about 40% of milk produced is processed nationally.

This failing in upstream milk production causes milk spoilage and lost farm earnings. It also causes poor quality milk and further losses in earnings along the downstream dairy value chain. Of the milk that does arrive, much of it still has a high bacterial count due to lack of refrigeration, resulting in poor quality dairy products. Farmers could receive a premium price for better quality, refrigerated milk; dairy processors could charge a premium for better quality products if milk can be kept cool all the way from cow to consumer; especially during the all-important first four hours after milking that determine quality.

In order to enhance the value of milk from remote producers, *PV-SMART* has developed an affordable solar powered farm milk cooler (FMC) so these producers can deliver cool milk rather than warm to the central collection stations. The farmers also use FMCs on the farm to preserve other produce such as eggs, meat, fruits and vegetables. Besides demonstrating the technology proof of concept, *PV-SMART* is also working with stakeholders to open up financing for solar technologies like PVRs that can increase on-farm productivity and increase incomes. Farmers need access to technology and credit on reasonable terms to finance the initial purchase of solar power systems, which have higher capital costs but lower operating costs when compared to traditional remote generation energy technologies like diesel gen-sets.

PV-SMART has a three-phase implementation strategy for developing, disseminating, and financing FMCs in Kenya as follows:

- **Pilot Phase 1 (Year 1):** Develop a FMC by enhancing an established off the shelf PVR model adapted as a Solar FMC and field tested on 40 farms in Baringo and Nyandarua Counties, and at Egerton University. A small wire basket for perishable household food is included, as well as two 5V USB ports for daytime cell phone charging.

- **Prototype field testing Phase 2 (Year 2):** A second generation prototype Solar FMC will be further tested on another 40 farms and with milk transporter-collectors and other potential dairy users.
- **Commercial roll-out Phase 3 (Year 3):** Based on feedback from field testing the final prototype design will be: (i) adapted, (ii) a local dealer network established and (iii) the Solar FMC commercially launched on to the Kenyan market and other countries in the region; and further afield.

PV-SMART initial pilots are underway with the Mogotio and Ngorika Dairy Cooperatives near Nakuru working in collaboration with a local Kenyan dairy processor experimenting with a milk quality payment system for the very first time in Kenya.

The project is also collaborating with established financial service associations such as the Savings and Credit Cooperative Societys (SACCOS) that already work with dairy cooperatives. The SACCOS can easily provide affordable financing for farmers for solar FMC systems. The estimated return on investment for the dairy farmer is from 1 to 3 years, depending on farm milk production levels. In March, 2015, the first 40 pilot units were deployed to the dairy cooperatives, as well as with the Egerton university dairy research unit. Performance of these units and farmer feedback on the early pilot systems are being used to make further design refinements.

2.0 Direct Drive Photovoltaic Refrigeration

The PVR has thermal storage (ice storage) instead of electro-chemical battery storage, and a direct connection is made between the cooling system and the PV panel. The embodied technologies were originally developed in support of NASA's future planetary mission's refrigeration requirements about a decade ago (Foster et al., 2001). This is accomplished by integrating water as a phase-change material into a well-insulated refrigerator cabinet and by developing a microprocessor-based control system that allows direct connection of a PV panel to a variable-speed dc compressor. By storing ice in the walls of the refrigerator, it eliminaes the needs of battery storage. The refrigerator uses a vapor compression cooling cycle with an integral thermal storage liner, PV modules, and a controller. The refrigerator employs a variable-speed dc compressor.

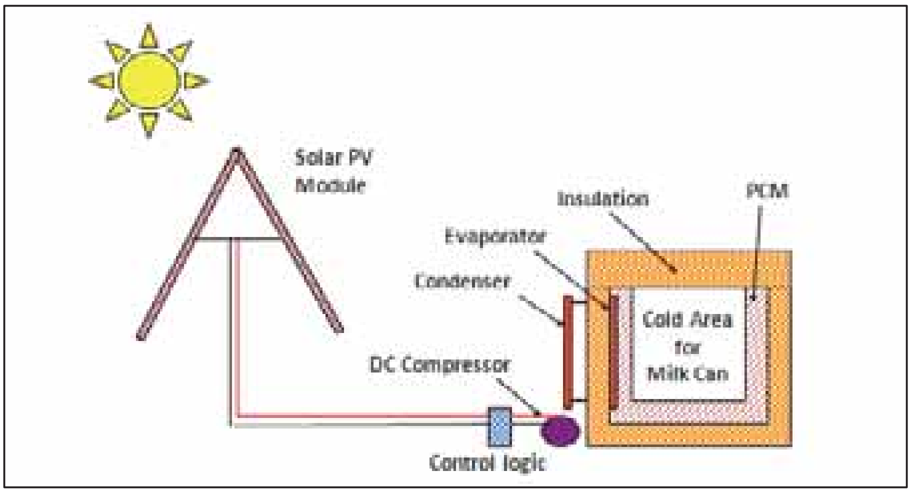

Fig. 1: Solar direct drive refrigerator with variable speed DC compressor and E-W "fixed tracking" array.

The PVR uses a fixed axis East-West tracker. This allows the variable speed dc compressor to start to spin earlier and until much later in the day, providing additional hours of refrigeration over a traditional equatorial facing fixed array. PV prices have come down sufficiently that "fixed tracking" is a viable economic option over tracking without the future maintenance concerns. This type of approach works especially well in lower latitudes like Kenya. This innovative simple approach provides superior performance.

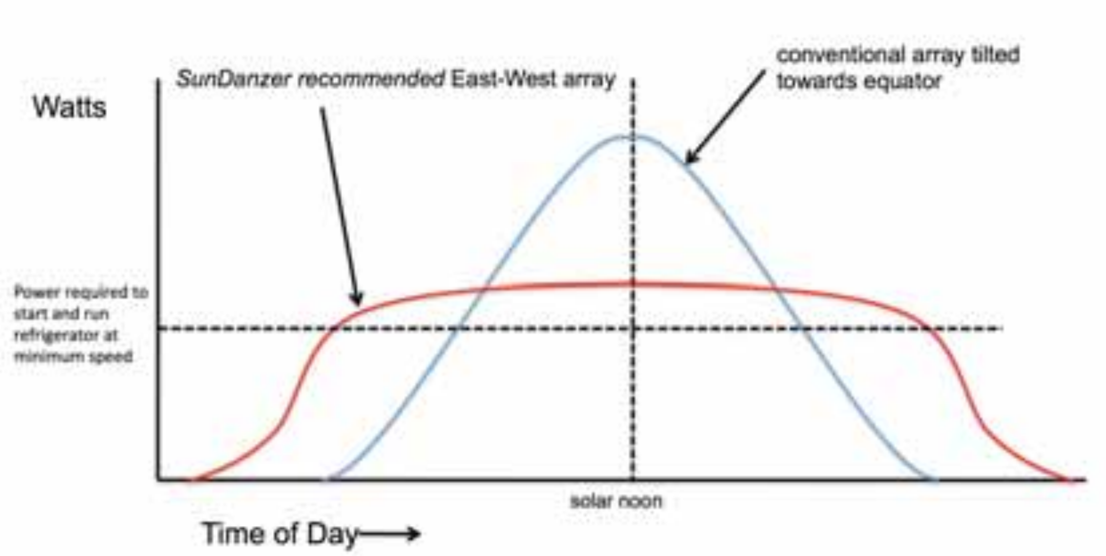

Fig. 2. E-W "fixed tracking" array designed to maximize compressor run time rather than energy capture.

With the compressor running most of the daylight hours due to the E-W "fixed tracking" array (the array is not actually moving like a conventional tracker, but is fixed with half the array facing East and the other half facing West to maximize daily compressor run time). Ice is formed and stored into the walls of the PVR. Thus, there is no need for expensive battery storage and replacements. Ice does not wear out. Testing at New Mexico State University for NASA and SDZR on an early prototype PVR with ice storage was successful for over a decade (Foster et al., 2001), which led to the development 5 years ago of direct drive vaccine PVRs using ice storage. The proven PVR technology is now expanded to FMCs.

In order to maximize heat transfer, the FMC incorporates brine bags which do not freeze at 0°C that are placed around the milk cans to increase heat transfer and cool milk quickly. As well as providing a complete and well-balanced diet for the newborn calf, kid or human baby, milk also contains antibacterial agents to protect the suckling young from potential infectious diseases; these antibacterial agents also slow bacteriological growth – the cause of milk souring. This effective natural protection is called the lactoperoxidase system, and has both bacteristatic and bactericidal effects against some milk spoilage microflora for about the first four hours after milking. Bacteriological growth is futher retarded when mik temperatures fall below 10°C and is essentially halted at 4°C. The FMC chills 25 liters of milk down to 10°C in a couple of hours, and the milk temperature in the morning is about 4°C as shown in Fig. 4.

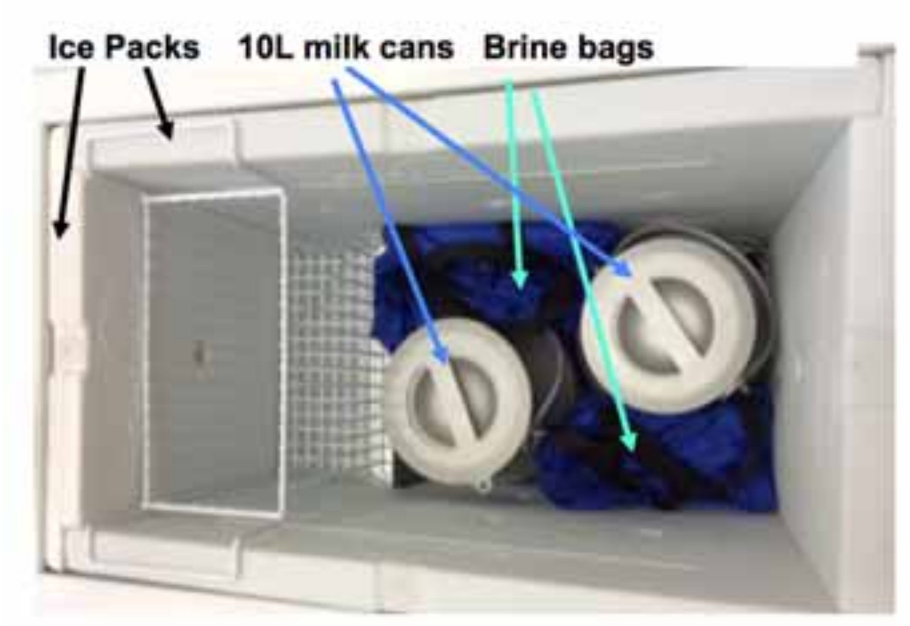

Fig. 3: PV using thermal ice storage and brine bags to chill evening milk.

Fig. 4: Solar milk chilling lab test temperature reduction results for 2 milk cans. Bacteriological growth in milk largely becomes inactive below about 7°C. There is about a 4 hour window before significant bacterial growth starts in milk. The FMC unit successfully meets this threshold for 25 liters of milk.

Fig. 5: Dairy farmer from Ngorika shown with his E-W fixed tracking array for a Solar FMC.

3.0 Preliminary FMC field Operational and Technical Findings

WI in collaboration with Egerton University (Kenya's leading agricultural university) has been monitoring and evaluating (M&E) the performance and benefits of the Solar FMCs installed on the Mogotio and Ngorika Cooperative dairy farms. The WI team developed a '*PVSMART* Milk Chillers User Satisfaction Survey' form that Egerton has been using to survey half of the farmers with FMCs as of Oct. 1, 2015 after 5 to 6 months of operation.

PV-SMART team is also monitoring solar irradiance at Ngorika and Egerton sites. A few selected milk cans have a Hobo data logger installed on them to monior milk can temperature data. The temperature probe is installed on the can with foam over it so that it measures true milk can temperature only, see Figure 6.

Fig. 6: Brian Jensen of SDZR and Bruce Knight of WI install a temperature probe and small datalogger on a 10 liter milk can at Egerton University Dairy Lab.

The preliminary findings are based on meetings with users, milk can temperature data, and field observations by the WI and Egerton University team. All solar milk chillers visited are functioning properly except one unit which had a refrigerant leak upon delivery probably due to some of the extremely rough roads traversed for delivery; easily repaired by a local refrigeration technician.

Fig. 7: Johnson Mwove of Egerton University dairy lab surveying a dairy farmer with a solar FMC near Mogotio.

Installation: The units are all very well-installed. However installation costs were somewhat high for the Phase 1 pilot and will decrease in subsequent phases with the normal learning curve.

User operation: No major issues were found with user operation. Most users were not cooling milk to full capacity (25 liters), while two farmers were exceeding capacity and successfully cooling 40 liters a night. There was one farm where the woman operator had no prior experience operating a refrigerator before and had misunderstood the sign on top of the refrigerator to keep the chest lid open when "not in use" as to leave the lid open during the day when there was no milk. Her misinterpretation was corrected and the unit now operates correctly.

Milk temperature: The FMCs work well to chill 25 liters of evening milk to 4^{O}C and lower. If some milk is not removed the next morning and left throughout the day, small quantities of milk can freeze, indicating the prototype FMC may have 'spare' cooling capacity for Kenya. Figure 8 below shows daily milk cooling cycle for one of the farmers, milk temperature is repeatedly cooled to about 5°C. Note that the farmer puts the milk can outside for drying after cleaning representing the daily peak temperatures.

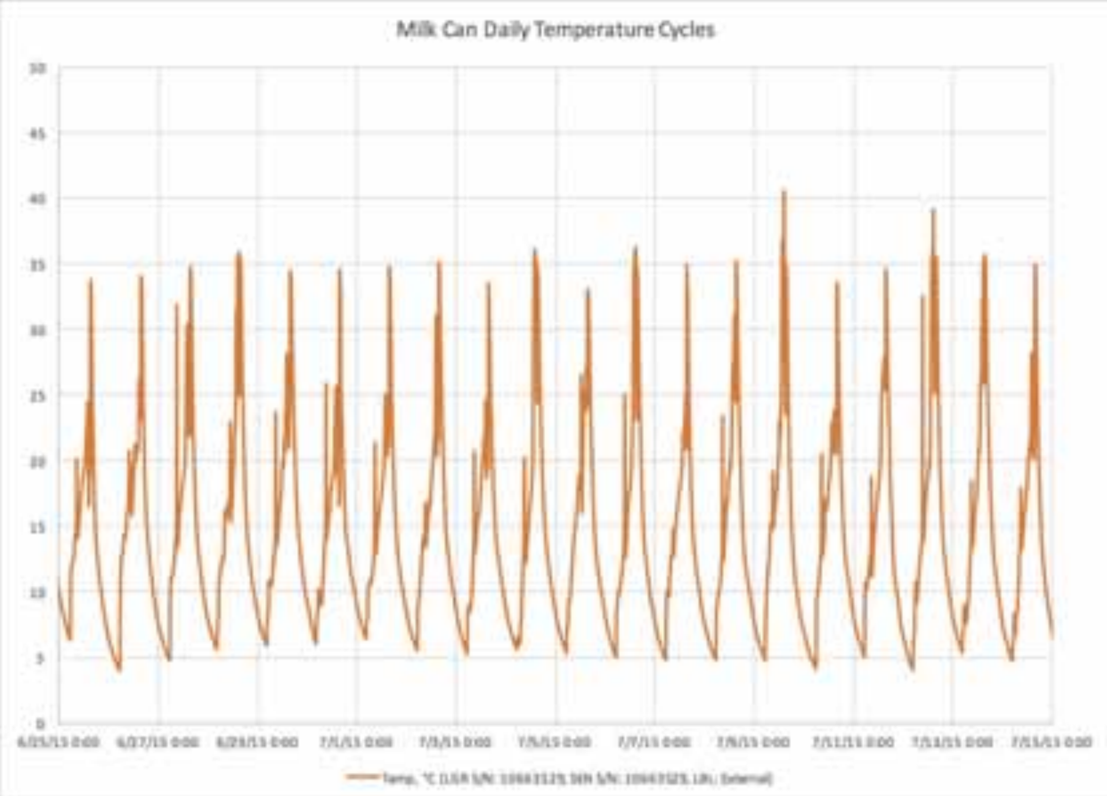

Fig. 8: Daily milk cooling cycles at a farmer's location: milk can temperatures. Note they clean and put the milk can outside in the sun to dry during the day.

Cooling Capacity: About half the users did not have enough evening milk to fill the pilot FMC. About ¼ of users utilize full capacity at 25 liters either from their own production or by also combining production with that of their neighbors, thus earning extra income for milk handling/bulking. Another user also earns extra income from charging cell phones from the two USB ports installed on the refrigeration unit, as much as US$1 per day (rate of US$0.10 per phone charge).

About ten percent of users have too much evening milk, i.e. more than 25 liters. These users and the cooperative managements want the FMC to be able to chill 50 liters milk in the standard 50 liters can. Some users are storing/cooling milk in plastic containers in the FMC and already exceeding the original design capacity. One cooler in Ngorika is chilling 40 liters milk in a food grade plastic water barrel, achieving overnight cooling to 'below 10^{O}C, indicating the potential of the unit to chill more milk adequately.

Other uses: Dairy value chain actors have been innovative in finding novel and remunerative uses for their prototype FMCs including:

- Standard cooling of evening milk by individual farmers;
- Bulk cooling of milk assembled from a number of local farmers by a farmer-collector;
- Bulk cooling of milk assembled from a number of local farmers by a collector-transporter;
- Keeping pasteurized milk chilled prior to sale in the immediate locality;
- Cold storage of perishable fresh foods; and,
- Cell phones charging.

3.1 Ngorika Dairy Association Observations

The Ngorika dairy farmers are overall satisfied with the cooling capacity of the FMCs and consider that the pilot project is going well. One farmer noted that small quantities of milk left in for longer time periods rather than just overnight sometimes might freeze. Since Ngorika is much higher (>2,500 meters above sea level) and thus much cooler due to the altitude, they have historically been able to sell some excess evening milk. The Ngorika farmers using the Solar FMCs have had no milk rejections whatsoever, so there is still an additional income increase due to quality. One farmer actually cools 40 liters of evening milk to $4^{O}C$ overnight in a 40 liter food grade plastic container rather than a traditional milk can. Their potential incremental gross earnings gain at current milk price was about KES51,300 (US$488) per month. This farmer produces more milk and is interested in increasing cooling capacity, or obtaining a second unit. Another farmer was found to have a potential incremental gross earnings gain at current milk price through the Solar FMC of about (US$564) per month (for own farm & farms serviced by collector).

Fig. 9: Satisfied Ngorika dairy farmer is happy with the Solar FMC and is actually exceeding recommended design cooling capacity by successfully cooling 40 liters of evening milk overnight.

3.2 Mogotio Dairy Cooperative Observations

The Mogotio dairy farmers have 18 Solar FMCs, as well as one unit at the dairy cooperative headquarters. The Co-op considers the Solar pilot as 'going very well' and they are interested in more units. Mogotio farmers are seeing significant increased income by selling evening milk stored overnight in the Solar FMCs, more so than Ngorika. This is due to the much hotter climate. Some users are even buying their neighbors evening milk and refrigerating to sell the next morning. The Solar FMCs benefit farmers because they can: (i) sell more milk; (ii) boost farmer earnings by collecting milk from neighbors, (iii) charge a cooling fee;

and (iv) keep drinks and perishable food cool and fresh for longer periods. For example one farmer was able to sell an extra ~8.5 liters of milk daily. Another farmer, besides chillng milk, also charges cell phones for 10 neighbors daily at US$0.10 each; the earnings are used to hire a 'Boda-Boda' (motor-cycle taxi) to transport her 2 teenage daughters to and from school. Her potential incremental gross earnings gain at the current milk price is about US$125 per month (including cell phone charging). Other smaller dairy farmers not utilizing the Solar FMC to full capacity (e.g, 5 lpd) had a potential incremental gross earnings gain at current milk price as low as US$23 per month.

So hotter climates are better as far as payback. But everyone surveyed likes and wants the Solar FMCs. The neighboring dairy cooperative next to Mogotio now wants their own Solar FMCs after seeing the successful results of their neighbors.

Fig. 10: Mogotio dairy farmer with his fixed E-W tracking array powering the Solar FMC.

4.0 Cost Benefit

Milk quantity and potential incremental gross earnings gain at current milk prices is already quite good for these pilot units, with simple payback ranging anywhere from one to three years depending on user milk production. From the initial surveys users sell between 2 and 45 liters of extra evening milk each day, indicating gross incremental income gains ranging from US$23 to $650 per month. These figures factor in gains by users bulking milk or charging cell phones on behalf of neighbors.

A complete cost benefit analysis will be done after one year of operation during Phase 2 to determine an acceptable/optimum Solar FMC price for SDZR and farmers. For Phase 2, SDZR plans to distribute units with end user cost share; for the initial pilot, farmers were not asked to cost share the Solar FMC price (only their time and milk cans); USAID PAEGC funded the units to buy down the technology risk for demonstrating a completely new concept with relatively poor rural small holder dairy farmers.

5.0 Conclusions

The key technical and operational take aways from the preliminary assessment of the *PV-SMART* Phase 1 pilot PVR units are that Solar FMCs offer small off-grid dairy farmers and milk collector/transporters the affordable opportunity for a value adding route to market that delivers better quality milk attracting premium prices, especially for evening milk. All units are working well with no complaints from farmers. A couple of farmers already are chilling 40 liters of evening milk with success. Consideration may be given to increasing the cooling capacity to cool a 40 or 50 liter milk can. From the initial surveys users sell between 2 and 45 liters of extra evening milk each day, indicating gross incremental income gains ranging from US$23 to $650 per month with expected paybacks ranging from 1 to 3 years for the Solar FMCs. A cost benefit analysis will be done during Phase 2 to determine an acceptable/optimum Solar FMC price for users and SDZR. There is also huge market potential in other countries in Africa, Asia, and Latin America; there are from 3 to 5 million off-grid small dairy farmers in the African Tripartite Free Trade Area (TFTA). The project is now planning to leverage the technical and operational achievements achieved during first phase and apply lessons learned to the upcoming Phases 2 and 3.

6.0 References

Foster, R., L. Estrada, D. Bergeron, 2001. Photovoltaic Direct Drive Refrigerator with Ice Storage: Preliminary Monitoring Results, Presented at "ISES Solar World Congress," Adelaide, Australia.