Performance and Reliability of a PV Hybrid Ice-Making System

Robert Foster, Luis Estrada, Martín Romero
SW Technology Development Institute, College of Engineering, New Mexico State University
MSC 3 SOLAR, PO Box 30001, Las Cruces, New Mexico, 88003-8001 USA
E-mail: rfoster@nmsu.edu, lestrada@nmsu.edu

Sorn Stoll
Institute of Electrical Information Technology, Clausthal University of Technology
Leibnizstr. 28, 38678 Clausthal-Zellerfeld, GERMANY
Email: sorn@iei.tu-clausthal.de

Michael Ross, Charles Hanley
Sandia National Laboratories
PO Box 5800, MS-0752
Albuquerque, New Mexico, 87185 USA
Email: mpross@sandia.gov, cjhanle@sandia.gov

ABSTRACT
This paper describes the reliability and performance of the Chorreras photovoltaic (PV) hybrid ice-making system. The system is unique and is located near the fishing village of Chorreras, Chihuahua in northern Mexico. Information gathered from field visits and a continuous monitoring data acquisition system are reviewed to discuss system design and operation. The system has been working producing ice on a daily basis with occasional control problems and water line calcification that sometimes reduces ice production. The hybrid system provides a daily average of 8.9 kWh at 240 volts to the ice-maker. The system Coefficient of Performance (COP) is about 0.65 and a total of 97 percent of the energy has been supplied by the PV array, while only 3 percent has been supplied by the back-up propane-fueled generator. Production of ice varies slightly each month due to changes in insolation and ambient temperatures. Overall ice production fluctuates from 25 to 75 kg of ice per day depending on water line conditions. The actual load control of the ice-maker is a simple feed-forward control. With a fixed timer setting, the ice-maker is operated daily for about 3 hours except for Sunday. This is based on the assumption that the need of ice is the same every day and that at least the weekly PV energy generation covers the consumption of the ice-maker. By consideration of additional states of the system a more efficient automatic load control could be designed. A Fuzzy Logic control is a widespread method to deal exactly with this kind of problem which uses "experience" and empirical knowledge that is difficult to put into mathematical equations. This paper reviews ice-maker performance for the first 30 months of operation and energy balances. It also analyzes the strengths and weaknesses of the ice-maker control logic and how to further improve system performance.

1. INTRODUCTION

The world's first automatic commercial PV ice-making system was installed in March 1999 to serve the fishing community of Chorreras, Chihuahua in Mexico. The Chorreras ice-maker system was designed and installed by SunWize Technologies of Kingston, New York, with the assistance of Energía Solar de Ciudad Juárez (ENSO) of Chihuahua. This project was possible due to the support of developing high-value renewable energy applications provided by the New York State Energy Research and Development Authority (NYSERDA), which had teamed with Sandia National Laboratories (Sandia) the State of Chihuahua Dirección General de Desarrollo Rural and the Southwest Technology Development Institute (SWTDI) at New Mexico State University to develop, install, maintain, and monitor a PV hybrid ice-maker. The project was done in coordination and with cost-shared funding assistance from the Mexico Renewable Energy Program sponsored by the U.S. Agency for International Development (USAID) and the U.S. Department of Energy (DOE).

In the middle of the Chihuahuan desert lies the Luis Leon Reservoir formed from the waters of the Río Conchos as seen in Figure 1. For over a quarter century, fishermen from the nearby community of Chorreras have fished this man-made lake for bass, catfish, tilapia, sunfish, and carp. Today, there are about 70 fishermen who make a reasonable living from the lake. The community is not serviced by the conventional electric grid, and it is nearly a four-hour drive from the lake to Chihuahua City to get the fish to market. The fishermen have had to rely on Chihuahuan wholesale merchants to come and purchase fish from them.

Figure 1. The Luis Leon reservoir in the heart of the Chihuahuan desert with the Chorreras ice-house. The Chorreras community at the inauguration of their 2.4 kWp PV ice-making system in March, 1999. Everybody appreciates a little extra shade in the desert as well.

The fish buyers often bring some ice when they purchase fish and often barter the value of ice for fish. However, the buyers do not always show up when they say they will, and the fishermen of Chorreras often have lost fish to spoilage due to lack of ice. The fishermen also end up paying relatively high rates for the trucked-in block ice from Chihuahua when it does show up. The fishing cooperative annually harvests about 80,000 kg of fish. However, with no local ice source, they have had to put off fishing or take their chances that ice will arrive on time. The lack of ice also limited their ability to independently sell their fish, particularly during the high demand season of Lent in the spring.

The State of Chihuahua and Sandia joined forces to install a renewable energy powered ice-making system. The goal was to install an on-site ice-maker that could help meet some of the ice needs. Significant technical hurdles had to be overcome to develop a viable ice-making system that was energy efficient. A successful PV ice-making system was developed and installed in Chorreras. Most ice-making is done with the PV system and the propane generator is used only sparingly.

A data acquisition system (DAS) was designed, built, and installed by SWTDI for Sandia National Labs and SunWize to monitor system performance. The DAS was installed in March, 1999 and uses a GOES-based satellite communication system for the remote site. The DAS consists of a Campbell Scientific CR-10X datalogger, electronic transducers, and an assortment of other sensors.

Figure 2. End-user training on the Chorreras PV hybrid ice-making system in Chihuahua, Mexico.

2. ICE-MAKING SYSTEM DESIGN

The Chihuahuan desert is characterized by high solar insolation and high summer ambient temperatures, as well as winter temperatures well below freezing, which is an abusive environment for batteries. These considerations led to some interesting design and operational challenges for the ice-making system. Finding an acceptable freshwater source was another challenge since the fishermen wanted to be able to use the ice for personal use as well. This desire eventually resulted in the community building a 7 km gravity flow aqueduct across the rocky desert ground from a clean spring water source. The PV hybrid system is built on a galvanized steel frame bolted on a concrete platform and consists of the following major components:

- 2.4 kW PV array (fixed 30º array tilt) with 32 Siemens SP75 solar modules;
- Ananda Power Technologies (APT) Power Center;
- 24 Vdc 2200 Ah battery bank with 2 V cells;
- Two Trace Engineering 3.6 kW modified sinewave inverters provide 240 Vac electricity; and,
- One Kohler 6.3 kW propane fueled generator.

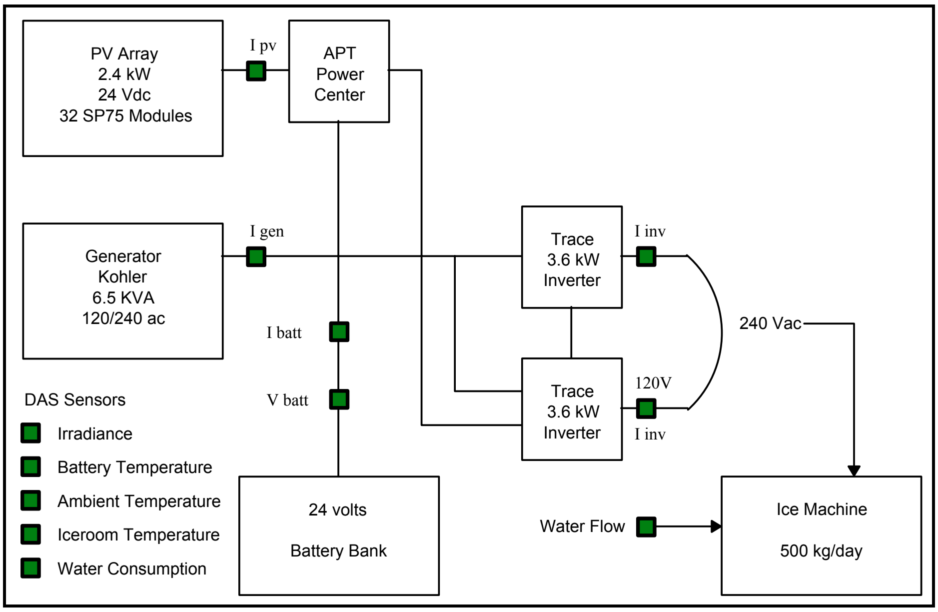

Figure 3. System one-line diagram. The square markers indicate sensors for measurements

Figure 3 is a one-line diagram of the complete PV hybrid ice-making system. The propane-fueled generator was included in the design to provide backup battery charging and boost ice production when needed for larger fish hauls and/or cloudy weather. Operation is controlled automatically through inverter set points. The batteries absorb high current transients and allow for load shifting to nighttime for more efficient summertime ice production when cool ambient temperatures are favorable for maximum ice production. The battery bank is thermally insulated and uses dc fans for cooling and hydrogen venting. Two Trace modified sinewave inverters are stacked together to deliver 60 Hz, 240 Vac single-phase power for the ice-maker.

Figure 4 shows the system power center and inverters. The inverters provide power to the ice-maker. The ice-maker is a vertical-evaporator compression-cycle unit installed on the roof of the fish storage building. It was designed for low maintenance and high reliability. For this specific application, modifications were made to the Chorreras ice-maker to reduce power consumption. A smaller compressor and condenser heater was modified resulting in a reduced current from approximately 22 to 11.5 amps at 240 Vac, thus reducing power requirements by about 40 percent. A 7 km aqueduct was installed by the Chorreras community to the fish storage facility to provide high-quality water. The polypropylene pipeline was buried 0.3 m in the hard desert rock soil to help provide lower water supply temperatures. Approximately 1.5 km from the ice-maker stands a 10,000-liter storage tank on top of a hill that provides consistent gravity water flow with sufficient pressure for the ice-maker. The water that runs into the ice-maker was filtered in March 2001 to help reduce contaminants in the water line to the ice-maker. Coils were also added to further cool the water line going into the ice-maker.

Figure 4. System Trace DR series inverters and APT power center with disconnects.

The ice-maker is set to run a dozen or so 15-minute automatic ice-making cycles each day (about 3 hours a day). The system freezes the water, a crusher breaks the ice into convenient flakes, and the ice falls via gravity into a cold storage room. The PV system is designed to produce about 75 kg of flake ice per day. However, production of ice can be increased by manual operation of the generator allowing a maximum ice production capacity of more than 400 kg/day. The timer is set to provide no ice on Sundays (a day with minimal fishing) to allow the PV array to fully charge the battery bank and help equalize the batteries each week.

The electrical energy production of the PV-hybrid system is reliable and the system functions as designed. The PV produces a maximum current of about 70Adc while the load (ice-maker) uses about 140Adc during operation. The system is designed to have the load run at night (summer operation) or during the day (winter operation). So in operation during the day, the PV can supply up to half of the energy to the load directly, but cannot recharge the batteries at the same time. At night, the load draws all 140Adc out of a 1400Ah Battery. Ideally, all energy produced during a day (less losses) can be drawn by the load at night (summer operation mode).

3. ENERGY NEEDS FOR ICE PRODUCTION

For the production of ice, energy is needed to cool down the water from approximately ambient temperature T_a to $T_0 = 0°C$ then to convert the water to ice and then to cool down the ice to its final temperature T_i (temperatures are given in $°C$).

The total energy E need to freeze the amount m of water from T_a to T_i is calculated by:

$$E = P \bullet t = \left(c_{p\text{-}water} \bullet (T_a - T_O) + h + c_{p\text{-}ice} \bullet (T_0 - T_i)\right) \bullet m$$

using the heat capacity of water: $c_{p-water} = 2.09 \frac{kJ}{kgK}$,

the heat capacity of ice: $c_{p-ice} = 4.2 \frac{kJ}{kgK}$,

and the enthalpy to freeze water: $h = 335 \frac{kJ}{kg}$

Given the power consumption of the ice maker that is measured to be about $P = 3.2\ kW$, it can be calculated how many kilograms of ice ($T_i = -5°C$) could theoretically be produced out of water ($T_a = 20°C$) in the time $t = 3\ h$, which is a realistic scenario for this application:

$$M = \frac{P \bullet t}{C_{p\text{-}water} \bullet (T_a - T_O) + h + C_{p\text{-}ice} \bullet (T_O - T_i)} E$$

$$= \frac{3.2kW \bullet 3h}{2.09 \frac{kJ}{kgK} \bullet 20K + 335 \frac{kJ}{kg} + 4.2 \frac{kJ}{kgK} \bullet 5K}$$

$$= \frac{3.2 \frac{kJ}{s}\ 3 \bullet 3600s}{41.8 \frac{kJ}{kgK} \bullet 20K + 335 \frac{kJ}{kg} + 21 \frac{kJ}{kgK}}$$

$$= 87\text{kg}$$

This amount of ice can not be reached because of different loss mechanisms. The cooling cycle itself has losses between the electric supply and the refrigerant cooling the cylinders for the ice-production, e.g. non-ideal heat transfer in the heat exchanger, heat flow through the isolation, etc. as well as additional electric appliances like a water pump. The sum of losses is significant but difficult to quantify.

Furthermore, the cooling cycle is reversed for about 30 seconds at the end of each cooling cycle to remove the ice from the surface. This means that the production is effectively at most 14½ out of 15 minutes run time which amounts to 3.5% loss or 3kg. If the entry temperature of the water rises, more energy is needed to cool it down and accordingly less ice can be produced. E.g. if the temperature of the water entering the ice-maker is 40°C as we measured in the summer instead of 20°C, about 8kg of ice less is produced (about 10% loss).

While in this ideal state about 7 kg of ice could be produced in one 15 minute cycle, the typical production lies around 4 kg of ice in one cycle. The energy use of the ice-maker during the cycle is about 0.8 kWh that splits primarily into the conversion of water into ice (0.09 kWh/kg), the cooling of water (about 0.01kWh/(kg*10°C)) and losses. After the ice is produced, it falls into an uncovered ice storage bin in the ice-room, which represent losses of only a few Watts per hour.

4. SYSTEM RELIABILITY

The ice-maker is set to operate during the cool, late-night hours during the summer since high ambient and water temperatures reduce system ice-making efficiency. The load is driven solely by the batteries at night while the PV array replaces the consumed energy during the day. This nighttime operation results in deep-battery discharge cycles and increases ice production. In the winter, the system is used to produce ice during the daylight hours, allowing the PV array to provide some energy, directly minimizing battery roundtrip efficiency losses and extending battery lifetime due to decreased cycling.

The system has successfully operated in an unattended mode since its installation in March, 1999. While the system has typically operated on most of the scheduled days, there has been some small variation of ice production due to control system instability during the shifting of the ice-maker from ice production to ice harvesting cycles. During the first few months of production, ice making cycles were inconsistent yielding only a daily average of about 50 kg of ice. Adjustments to the compressor and modifications on the control timer corrected the inconsistency resulting in a daily average of 75 kg. In addition, the load surge currents, normally handled by an electric grid, resulted in failures of some control components and system shutdown for approximately 20 days in July, 1999. Daily, weekly, and seasonal weather differences results in variations in the generator run time. During the longer summer days, generator operation is more infrequent.

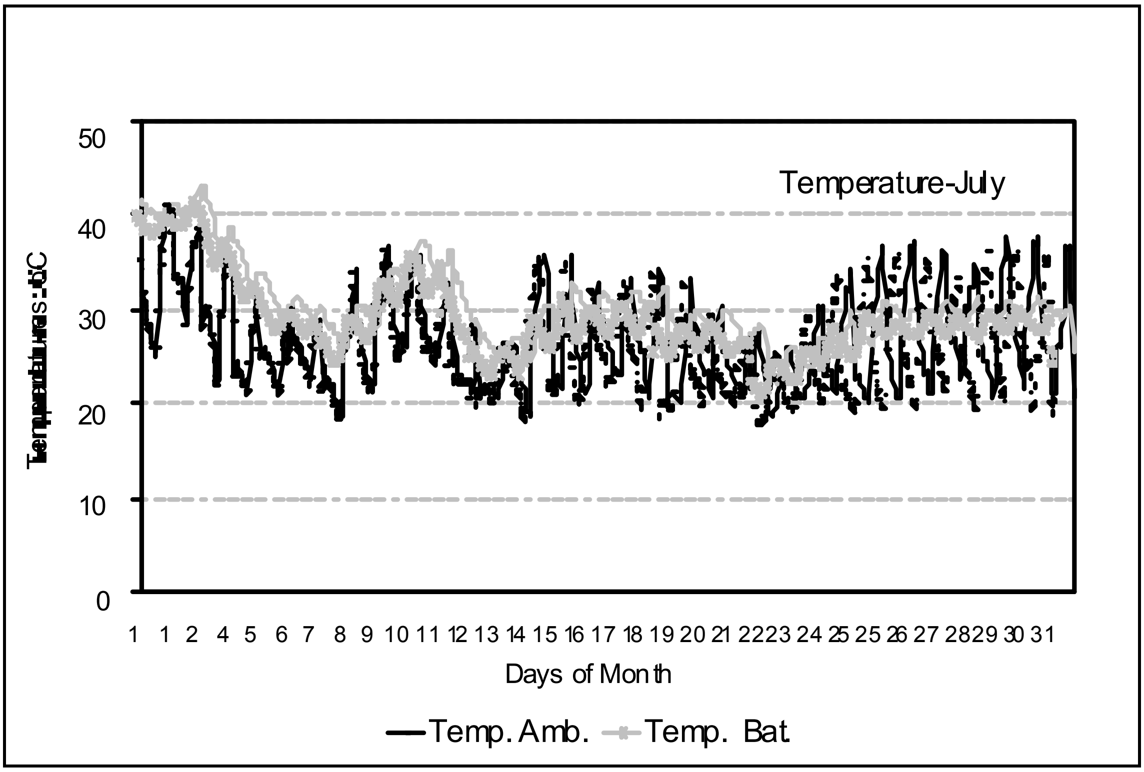

Figure 5. Ambient and battery bank temperatures for July 1999. Note how the battery temperature dropped from over 40°C to about 30°C when additional venting was added to alleviate high battery bank temperatures in July

The batteries are enclosed in a thick-walled, insulated industrial plastic enclosure filled with water and baking soda; however, temperatures in excess of 45° C (hourly average) were recorded while the batteries were being charged. The original passive cooling vents and a small hydrogen vent fan were not cooling the batteries sufficiently after installation. However, a dc cooling fan was added in July, 1999 to the battery container which remedied high battery temperatures and kept the battery bank below 40º C (Estrada, 1999).

5. SYSTEM PERFORMANCE

The energy performance for the first 30 months of the system from April 1999 - September 2001 is shown in Figure 6 below. The PV array generated a total of 7691 kWh (256 kWh monthly average) of energy for the battery bank. The community has barely used the propane generator to augment ice production since system installation (less than 100 hours) and the system has been producing ice entirely with PV. The ac load (ice-maker) has consumed a total of 4045 kWh allowing for an overall PV system efficiency (energy-out/energy-in) of 53 percent, including all load downtimes. In better months, system efficiencies have topped 60 percent, while they have dropped below 40 percent during more inefficient months and a few months when ice was not consistently produced when the ice-maker was not operated. Both inverters run continuously, while supplying power to the ac load and the DAS.

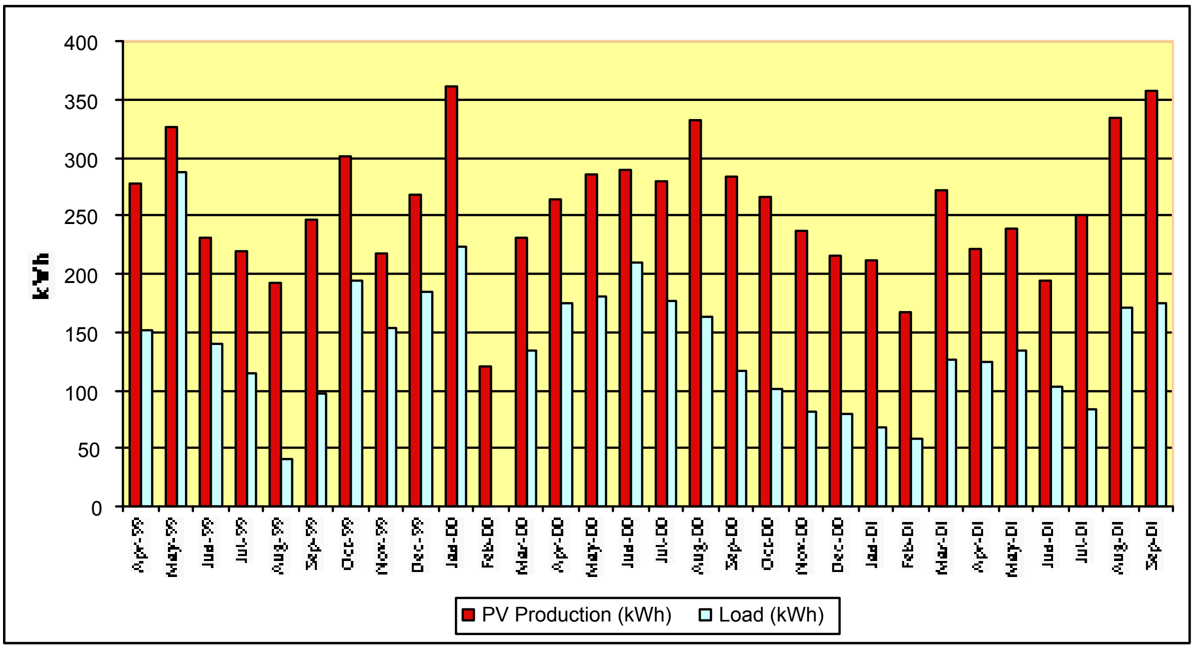

Figure 6. Overall Chorreras PV ice-maker system energy performance (first 30 months)

From April to October 2001, the ice-maker has produced nearly 48,000 kg of ice which has yielded an average daily ice production of 54 kg per day, almost entirely from solar energy. Gradual calcification of the ice-maker water pipes eventually caused one of the nozzles to become clogged to the point of spraying some water throughout the ice-maker cabinet, which caused one of the two-evaporator contactors to start to hum. The noise concerned the users who shut down the system in February, 2000. A mechanical cleaning of the system identified and corrected the problem and the system was brought back to normal operation and the noisy relay replaced. A simple (acidic) rinse provided the chemical cleaning necessary for the pipes. The project partners must continue to conduct a vinegar rinse on a regular basis to maintain optimal ice-making performance (recommended about once every nine months).

The sump and lines where the water is collected becomes calcified after about nine months. The large content of carbonate in the water leads to partial or complete ice-maker nozzle plugging which eventually reduces ice production to a low of about 25 kg/day due to insufficient water distribution (as compared to nearly 75 kg/day during the best months). The pump that pumps the water through the nozzles doesn´t have enough power to ensure even water distribution on the cylinders when nozzles are partially clogged. Water drops down without touching the cylinder surface, thus reducing ice production. This situation is resolved by regular cleaning of the ice-maker (every six to nine months).

The water temperature varies greatly over a day. As the water is drawn from a storage reservoir that provides sufficient operational water pressure via gravity over a large distance (~1 km) through a black polypropylene tube just below the desert surface. The water reaches the ice-maker with a fairly high temperature (approximately 35°C during the daytime in the summer). Not only does the water have to be cooled down before it is turned to ice, the warm water melts some of the ice on the cylinder surface. Thus, in summertime, the unit is best operated in the early morning hours before sunrise when the water is coolest and the air temperature is at its lowest for the air-cooled condenser.

The ice-maker is controlled by a timer that is set to operate a fixed time-period every day (except Sunday when the unit rests). In winter production mode the unit starts at 10 am and operates for about 3 hours using 7 kWh. On a sunny day, the PV array can produce about 11 kWh daily in the winter and significantly more in the summer. In the summer, the unit is operated just before sunrise when temperatures are at their coolest. Some solar energy is lost on some days when the charge controller disconnects the PV from the already fully charged batteries on a daily basis.

6. FUTURE SYSTEM DESIGN CONSIDERATIONS

Develop an automatic control based on a fixed timer or based on stored energy. A fixed daily runtime is set to operate the load, the ice-maker. Currently, the available energy is not taken into consideration when controlling the energy consumption by the load. Furthermore, the timers do not always work consistently, so that the load is not always operated as designed. Counting Ah or simply a voltage measurement when the load is running (which has the effect of a current compensation and leads to a fairly good accuracy) are easy ways to determine the approximate state of charge, which indicates the amount of stored energy. This information should be used to determine the runtime of the load.

Even a manual control that would allow the fisherman to make ice during the day in the summer when the batteries are fully charged would increase the output of ice. The fishermen can also produce more ice by running the generator in manual mode. The ice-maker is controlled by a timer that the fishermen cannot adjust. They only have the option to set the controller to automatic (= timer) control or off. The users could operate the system based on a voltage reading, e.g., by pressing a button that activates the ice-maker for a specific time-period.

The actual load control of the ice-maker is a simple feed-forward control. With a fixed timer setting, the ice-maker is being operated daily for about 3 hours except for Sunday. This is based on the assumption that the need of ice is the same every day and that at least the weekly PV energy generation covers the consumption of the ice-maker. By consideration of additional states of the system a much more efficient automatic load control could be designed. Useful information for the design of a more efficient load control are:

- The actual PV energy production (battery losses can be avoided by the direct use);
- The state of charge of the battery (e.g., considering the current compensated voltage as a model);
- The amount of ice needed;
- The availability of propane (for controllable additional energy production); and,
- Different temperatures (e.g., the temperature of the water entering the ice-maker).

The devices to be controlled would be the ice-maker and possibly the generator. By observing these inputs and outputs of the control, it is obvious, that a multi-variable time- and event-discrete problem with partially inaccurate information (e.g. battery state of charge) needs to be solved. Classic optimization algorithms may be able to find a solution but the design is complicated and very time consuming by itself, and the solutions that are gained using this type of design strategy are generally difficult to understand.

A Fuzzy Logic control is a widespread method to deal exactly with this kind of problem. In contrast to the classic analytical way of control design as described above, fuzzy logic uses "experience" and empirical knowledge that is difficult to put into mathematical equations. The first step is to take the inputs and determine in how far they belong to each of the appropriate fuzzy sets (e.g. temperature: low - medium - high) via membership functions. The so-called fuzzyfied inputs are set into relation with each other by a set of linguistic rules (e.g. IF water temperature = high AND battery state of charge = low THEN ice-maker = off). Next, the results of all rules are aggregated into a single fuzzy set for each output. Finally, these fuzzy sets are transformed into the real output value (defuzzification).

Already from this short description it can be seen, that a very transparent design of the control can be realized. Having some experience working with a fuzzy logic tool, the design can be done in a very short period of time. Giving the rules in an efficient manner and choosing the method of defuzzification may be a challenge but a decent first control design can be developed quickly. Any optimization may take place on basis of the knowledge gained by analyzing the performance of the current system. These advantages, as stated above, make the fuzzy logic controller the ideal tool for the load control of the Chorreras ice-maker.

7. SYSTEM ECONOMICS

The State Government of Chihuahua purchased the ice-making system for US$38,000 with funding assistance from Sandia and USAID to buy down the risk. In addition, the State of Chihuahua and the community of Chorreras pitched in additional funds to build the 7 km aqueduct and to rehabilitate the ice-room. NYSERDA funded engineering design and development for this novel system, and Sandia/DOE funded the DAS and follow-up system monitoring. Thus, the final cost for this project including aqueduct, ice-room renovation, monitoring, etc., was about US$150,000.

When the ice-maker is properly maintained, ice production has been found to be about 11.5 kg per sun hour with an overall Coefficient of Performance (COP) of about 0.65. The system can produce over 25,000 kg of ice per year from the solar alone when properly maintained and operated. To date the average production has been about 19,700 kg/year of ice due to somewhat irregular maintenance. Assuming a value of US$0.30 per kg of ice (for this remote site where it must be hauled in), this implies a simple payback as currently operated of about seven years (with better operation and maintenance this could be reduced to about five years). Taking into account the value of reduced fish spoilage, actual payback is actually even less. Overall, it is anticipated that ice production over the system lifetime, with future battery replacements and system maintenance, should be less than US$0.15 per kg. Of course, having a reliable source of ice in the desert not only for fish storage but also for a cold drink has an intrinsic comfort value that is difficult to express simply in terms of dollars!

8. CONCLUSIONS

In the first thirty months of operation the ice-maker has performed adequately. A few relatively small changes in equipment and operation have resulted in more consistent ice production using solar energy. A simplified regular maintenance procedure for chemical cleaning to prevent calcification has to be conducted about every nine months. While the components function well, the whole system operates somewhat inefficiently and could be improved. Major energy losses on the way from PV-production to the ice are caused by the charge controller (that disconnects the PV from the battery when at full stage of charge), the battery roundtrip efficiency, the inverter (dc-ac conversion) and the ice-maker itself. Additional minor enhancements of the hardware and a different load control are possible retrofits in the future. The community could also further increase ice production by running the propane generator when needed.

It is important to include thermal consideration in the design of battery racks or containers. Even small thermal differences among batteries can contribute to battery decay in the long-run. A strict maintenance schedule and procedure is required for batteries that pays special attention to safety. This schedule includes adding water and monitoring battery temperature and voltage. In periods of low insolation (winter with short days, or cloudy seasons) consideration might be given to adjusting the inverter set points to allow longer generator run times. Manually initiated frequent (monthly) equalization periods are also recommended. Efforts continue to expand on the maintenance program to enable the system users to maximize the life and productivity of this unique system.

For any type of relatively complicated hybrid system, it is important to not only consider the technical side of the equation, but the institutional side as well. The system has proven that a properly designed, operated, and maintained system can indeed produce a significant and valuable resource, such as ice, even in the middle of the desert. Long-term commitment and follow-up by the Mexican project partners is required for continued project success. This project is a good example of using renewable energy as a tool to contribute to local economic development in a remote area. Based on the Chorreras pilot project, future ice-making systems can be further improved so that ice can be produced even more efficiently and with reduced installation costs. Future such systems are likely to also use variable speed direct drive dc compressors to eliminate battery and inverter inefficiencies.

9. REFERENCES

Estrada, L., R. Foster, A. D. Cota, L. Hoffstatter, M. Schiff, D. Panico, V. Meraz, "First-Year Performance of the Chorreras PV-Hybrid Ice-Making System in Chihuahua, Mexico," DSSA 09-03, Proceedings of the Millennium Solar Forum 2000, International Solar Energy Society, Asociación Nacional de Energía Solar, Mexico City, Mexico, September 17-22, 2000, p. 513-518.

Estrada, L., SWTDI Chorreras ice-maker site visit reports, Las Cruces, New Mexico, April and July 1999, and March 2000.

Foster, R., "Chihuahuan Site Visit Summary," for Sandia National Laboratories, Albuquerque, New Mexico, August, 1994.

Foster, R., "Photovoltaic Ice-making: Case Study of Chorreras, Chihuahua, Mexico," Seminar 15: Solar Energy Applications and Case Studies, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Winter Meeting, Dallas, Texas, February 6, 2000.

Hoffstatter, L., V. Meraz, One-year maintenance report, Sunwize Technologies & Energía Solar de Ciudad Juárez, October 1999, March 2000.

Hoffstatter, L. and M. Schiff, "Commercial Solar Electric Ice Plant - A First Year Report," Proceedings of the American Solar Energy Society, ASES 2000 Annual Conference, Madison, Wisconsin, June, 2000.

Southwest Technology Development Institute, "Chorreras System Monthly Performance Summaries," for Sandia National Laboratories, Las Cruces, New Mexico, April 1999 through September 2001.

Southwest Technology Development Institute, "Mexico Solar and Wind Resource Assessment Summary 1992-98," for Sandia National Laboratories, USAID, DOE, Las Cruces, New Mexico, February, 1999.