Development of Design Practices for PV/Battery Remote Area Power Supplies

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Introduction

For many living in remote areas, there is no access to an electricity grid and virtually no possibility that grid electricity will be available in the future. If these people have electricity at all, it is likely being produced locally by a diesel generator. Quality of life in these remote areas would increase by the addition of remote area power supplies (RAPS) that utilize renewable energy resources with battery energy storage to provide power to individual homes, small communities, and villages. To help enable this it would be beneficial to develop design practices that would allow the selection, sizing, and testing of these storage batteries. This paper discusses the methodology and status of a project in which the needed design practice documents are identified and prepared.

Design Practices Development Methodology

There are several organizations throughout the world that are developing standards, design practices, or other similar instructional documents that discuss the manner in which storage systems for particular electricity generation installations should be selected, sized, tested, and generally handled. These documents are generally fairly specific for a particular area of the world, and emphasize conditions peculiar to that area.

In order to obtain information that would be more or less generic, we turned to the Institute of Electrical and Electronics Engineers (IEEE) Standards Coordinating Committee 21 (SCC21) Energy Storage Group. SCC21 is developing standards documents for remote systems using renewable solar photovoltaic (PV) energy as the principle resource, focusing on battery storage systems. There are two documents that SCC21 is developing that are directly applicable to the present project. One involves a stand-alone PV/battery storage system, while the second considers a PV/diesel hybrid with battery storage. These two systems define the types of RAPS systems that could likely supply electricity to single homes, small communities and villages that are cut off from any centralized grid. Therefore, as part of the current project, we are working with SCC21 to help develop these standards documents [PAR 1526, PAR 1561].

In order to best develop these documents, it was decided that actual data, both load and insolation, from remote sites around the world should be gathered. These data, load profiles and insolation profiles, could be mathematically converted to equations that could be used to aid in the sizing of RAPS systems. The remainder of this paper describes this effort.

Resource Profiles

In order to determine resource profiles (in this case, insolation profiles) for the regions where load profiles have been generated, a program called NSOL, developed by the Orion Energy Corporation, was utilized. NSOL uses insolation data gathered by the University of Massachusetts-Lowell and the National Renewable Energy Laboratory for sites around the world. The user can either input the name of the location or the latitude and longitude coordinates. The program outputs data for a year in addition to plots showing monthly insolation curves (based on average daily insolation) as well as twenty-four hour data.

When attempting to match insolation data with load data, NSOL in some instances provides insolation curves that are in the same location as the acquired load profiles. Some regions, however, can not be exactly matched in the database. In these cases, insolation profiles were estimated by choosing a region that was closest to an existing entry in the database. For instance, the NSOL database does not contain any data for cities in Bangladesh. However,

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Calcutta, India is reasonably close to the same latitude and longitude. Therefore, the load profile for Bangladesh can be matched with the resource profile of Calcutta. Figure 1 shows typical yearly insolation data for Calcutta, India while Figure 2 shows a typical daily insolation profile in July for the same region.

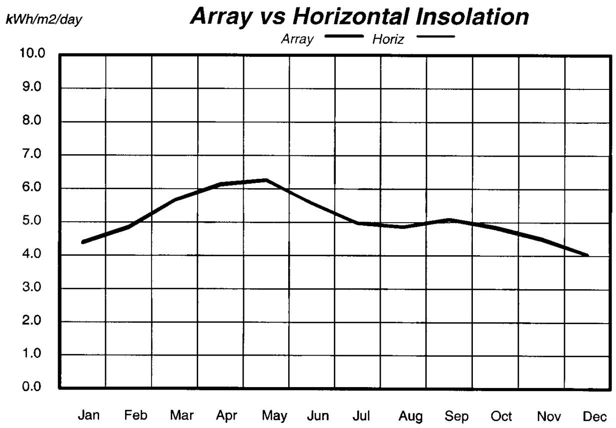

Figure 1. Yearly Insolation Profile for Calcutta, India

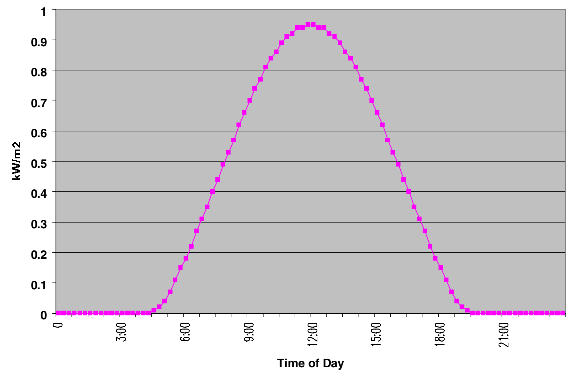

Figure 2. Daily Insolation Profile for Calcutta, India in July

Some of the insolation profiles follow typical seasonal changes. In several areas, however, this is not the case due to atypical weather conditions. For example, the yearly curve for Calcutta is not bell-shaped, likely due to the monsoon season occurring in June and July, giving it depressed solar energy for those months.

Load Profiles

The methodology used to compile specific data for RAPS systems included searches at the Library of Congress and on the Internet for solar, wind, and other technologies used in remote area power. The literature on load profiles for remote sites is quite sparse. Much of it is based on approximations and assumptions rather than actual recorded data. Nevertheless, a database was built that includes approximately 70 sites that have used some form of renewable power. In several cases it was possible to generate load profiles. Where contact information was available, e-mails or phone calls were made to request more specific load information. The data from several sites were compiled including typical daily load profiles for several single-family homes, health clinics, schools, and villages.

For several projects, load data was available from a digital recorder. Load profiles for several small villages, homes, health clinics, and schools were plotted from these data. Combining these data enabled us to generate an average profile for a range of system sizes and functions. In other cases, however, load data versus the time of day was not readily available. RAPS project data often specified only the type of battery and PV array or wind unit used and how long the system had been in use. However, in the limited cases where load data were available, extrapolation was performed to estimate daily profiles. For instance, data collected from a PV system in Bangladesh indicated that a family used their 6-watt light, 15-watt black and white TV, 3-watt radio, and 6-watt cassette player for four hours per day. The total load is 120 watt-hours per day, seven days a week. Based on conversations with experts, we built a profile that showed a small load in the morning, which indicated only a light being used. A mid-day peak occurred around noon from TV usage, and in the evening the load profile generally spiked, since this is when most recreational activities take place.

Load data for several locations are discussed below.

<u>Single Family Homes</u>

a) Rio Negro, Argentina

Table 1 is a conglomerate of typical load conditions based on economic status and availability of power in the Rio Negro region of Argentina. Most profiles, regardless of economic status, showed that electricity was being used during two or three periods.

Table 1. Single Family Home Profiles by Economic Status in Rio Negro, Argentina

Profile	Economic Level (Pesos/month*)	Total Energy Used (Wh/day)	Load Type	Watts	Duration (hours/day)	Number in use
1	11	*160*	Light	15	4	2
			Radio	20	2	1
2	30	*635*	Light	15	6	5
			Radio	20	8	1
			Tape Recorder	25	1	1
3	45	*1250*	Light	15	12	6
			Radio	20	6	1
			Tape Recorder	25	2	1
4	60	*2030*	Light	15	16	7
			Radio	20	4	1
			Tape Recorder	25	0	0
			TV	60	3.5	1
			Video	40	1.5	1
5	75	*2760*	Light	15	16	7
			Radio	20	4	1
			Tape Recorder	25	0	0
			TV	60	10	1
			Video	40	10	1

* Represents the amount of money that a member of this profile group can pay per month. An Argentinean peso is worth about $1 US.

All profiles show morning and evening peaks while the more affluent homes showed mid-day peaks as well. In some cases, a non-zero baseload (using a radio all day, for instance) was also found. It was ascertained from conversations with experts in the field that if a family could afford it, they would "run lights and a TV all day." A basic profile would include only one to two lights and a small radio. Compact fluorescent lights (CFL) are used and typically draw five to twenty watts each. In a study conducted by the Transenergie-WBI group in May 1999, 66% of the villagers of the Rio Negro region of Argentina fell into Profile 1 of Table 1 [Transenergie WBI]. The Transenergie-WBI group used Graphical Information Systems to determine how many interviews were required to encompass a large enough sample size. Tape recorders, TVs, and VCRs are used in households that can afford to pay the utility costs. Twenty-seven percent of the villagers surveyed said that they could afford lights, radio, and a tape recorder, where only seven percent could afford a TV and VCR in addition to lights and a radio. It should be noted that these statistics vary depending on the region.

Since cooking with electric stoves and hot plates is costly, propane, natural gas or wood burning grills were used in all of the single-family homes. Refrigeration proved to be cost prohibitive in many homes; restaurants and other large commercial facilities were the only establishments that could afford this luxury.

b) Puerto Plata, Dominican Republic

The small village of Puerto Plata in the Dominican Republic hosts an experimental PV array for a residential electrification project. The project was established in a home that was thought to represent a typical village home with four family members in the dwelling. Initially, designs were made to include a TV, which would be in use 3-4 hours per day, 1-2 lights used 4 hours a day, and radio used for most of the day. After the system was installed, it was discovered through remote monitoring that the TV was used far more than the original assumptions. Instead of the projected 3-4 hours per day, the TV was actually used 8-10 hours per day. One theory was that other villagers frequented the household since it had a TV, hence contributing to the increased usage. The single home load profile is shown in Figure 3.

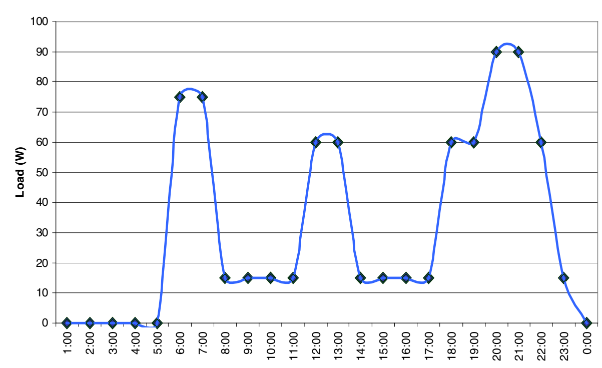

Figure 3. Puerto Plata Load Profiles

Village Loads

a) San Juanico, Baja California, Mexico

The village has three schools, two of which require little or no electricity. San Juanico has two restaurants or cantinas. Twenty-five of the homes have satellite dishes, reinforcing the importance of TV viewing. In several situations, TVs were used more frequently than originally anticipated. TV usage typically began early in the morning while the family was preparing for school and work. Load spikes in the middle of the day and evening were attributed to TV use. RAPS systems designed for 3-4 hours a day, were (similar to Puerto Plata) in some cases, used for 8-10 hours a day. During World Cup soccer games, up to 40 people may be present in a single home, watching the same ten-inch TV.

A survey conducted by the National Renewable Energy Laboratory's "Renewables for Sustainable Village Power" program [Jimenez] supports the notion that the load the household values most is the TV. A washing machine, radio and refrigerator were the next most necessary items for this village, respectively. It was found that families would conserve electricity by turning off the light just to have longer playing time for the TV.

A sample profile from a secondary school shows primarily light usage and occasional TV usage throughout the day. In some cases a radio may be used to receive some lesson topics. This particular school also serves as an adult education center at night. This distance-learning program receives a signal that has been broadcast from another center and the school's satellite transmits the signal to several TVs. The large spike in power at the end of the day can be attributed to this program, which uses lights, TV, and satellite.

There is a health clinic in San Juanico, which shows refrigeration equipment used around the clock with a baseline load of about 40 watts. (Refrigerators are generally 40-120 watts depending on size and efficiency.) The refrigerator is used to keep vaccines and other temperature-sensitive medicines from spoiling. Some small cantinas in the Baja California village of San Juanico found that even using a small glass case refrigerator was too expensive. Communication equipment such as a satellite or radio device can be used for emergencies when a clinic staff member needs to consult a specialist or to arrange for evacuation of a seriously ill or injured patient. As the workers arrived in the morning, several lights are turned on and as well as the TV. Each day the workers sterilize their instruments in an autoclave. This generally occurs near the end of the day, lasting for approximately 2 hours at around 125 watts. In the evening, there may be some additional TV usage and one to two lights may be used.

When designing remote area power supplies, perturbations to normal load profiles should be taken into account. In the case of San Juanico, for example, the famous biennial Baja off-road car race passes through the town, doubling its normal population of 400 people. This has a significant effect on power use. Restaurants generally are open longer and people are staying up later, using more lights and watching TV during these events.

b) <u>Alaminos, Philippines</u>

A load profile for the Alaminos, Philippines village can be found in Figure 4. This curve is similar to typical single-family home profiles, but, of course, on a larger scale. The Alaminos load profile data was taken from a PV mini-grid that powers 60 homes. The system averages out to approximately 2000 Wh/day per home, which is very similar to the Single Family Home Profile # 4 from Rio Negro, Argentina, shown in Table 1. This system is large enough to support several lights, a radio, tape recorder, TV and VCR [Navarro].

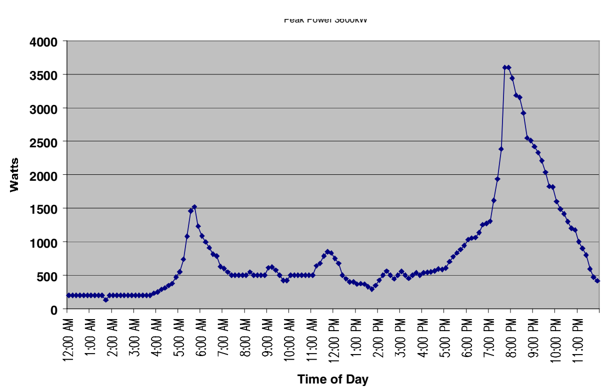

Figure 4. Load Profile of a Village in Alaminos, Philippines

In the GTZ Philippines solar project, monitoring was done to see if villagers followed the recommended practice of reducing the consumption; e.g. lesser TV viewing or using fewer lights for a shorter period, during rainy days. It was found that the households did not reduce consumption during rainy days as recommended. They experienced load disconnects from the controller when the cloudiness lasted for several days. This indicates that days of autonomy considerations in design practices must take this kind of behavior into account. . Under the conditions described here, the battery only lasted for two years. It was also of interest to find out if TV use increased on the weekends. It was found that weekend TV use was less when compared to weekdays when there were better shows. In homes where there was no TV, a radio was used for the majority of the day.

c) Hyderabad, India
A village load profile was created from data collected from Hyderabad, India [Urmee]. Several matters were taken into account before selection of this particular village for electrification. Preference was given to villages that had organized communities and townships. In addition, priority was given to villages whose per capita income could be increased through harnessing the electricity for agricultural and industrial purposes. Hyderabad has approximately 60 households and 300 people where the basic load profile includes private houses, streetlights, a community center, a health center and a water pump. The profile (Figure 5) reflects the general, morning, noon, and evening load seen in single home profiles.

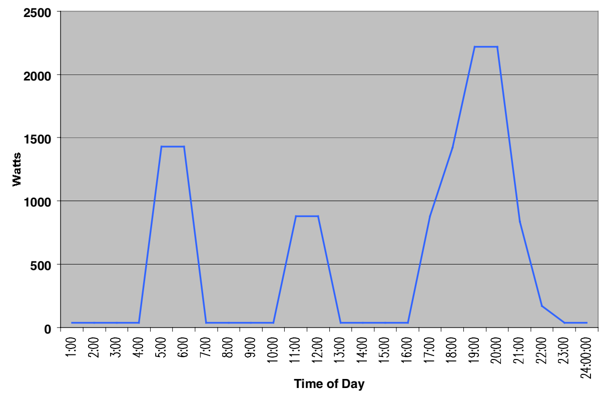

Figure 5. Hyderbad, India Load Profile

Load Profile Equations

Three years ago, an international team was formed by the International Lead Zinc Research Organization (ILZRO) with the support of Sandia National Laboratories (SNL). The team identified stand-alone homes, communities, and villages for RAPS applications, and defined several different sizes/power requirements for each. Based on this, the team devised a “strawman” series of load profiles and developed a preliminary equation for a generic load profile. The general premise was that electricity was used during three peak time periods: in the morning, afternoon, and evening. At other times, electricity usage was zero or near zero. This hypothesis appears to be borne out by the load profiles shown above. As a result, the load equations were built on the original assumptions.

To find the equation of a load profile, the method of **Divided Difference** is used to generate a polynomial **P(t)** that can estimate a village’s energy usage. In general, the single homes, community and village systems being studied serve loads in which the base load is small relative to peak loads that occur in the morning, mid-day and evening. In fact, if all of the appliances used in the village have no parasitic load, then the base load is equal to zero. Therefore, to generate a graph portraying a village’s power usage, the day is broken into six time slots:

- the morning peak between 5 AM and 10 AM with all appliances turned on
- the morning off-peak between 10 AM and 11 PM with all appliances turned off
- the afternoon peak between 11 PM and 4 PM with one or two appliances turned on
- the afternoon off-peak between 4 PM and 6 PM with all appliances turned off
- the evening peak between 6 PM and 11 PM with all appliances turned on
- the evening off-peak between 11 PM and 4 AM with all appliances turned off

Energy usage has been examined for nine villages around the globe during different seasons. Typical villages consist of approximately thirty homes, a clinic, a school, and a cottage industry. Each home may have a TV, some light bulbs and a radio. A school may have four to six light bulbs. A clinic uses light bulbs, a refrigerator, a TV, communication equipment, and an autoclave to sterilize instruments. The cottage industry generally has light bulbs and other equipment required by the industry. Because appliances are either turned on or off, there is no cycling load and during the off-peak slots, the load equals zero or the base load.

The load profile of the village is obtained by summing the energy usage of its individual components (homes, school, clinic and industry) during every hour. Once the load has been determined for the whole day, the load data is broken into the six time periods shown above. To express each peak by an equation, the loads for each time period, t, (each hour in these cases) are entered into an Excel spreadsheet. The method of divided differences is then used to calculate the coefficients of the polynomial P(t) that accurately fits the load profile. The polynomial is then expressed as a series of calculated coefficients and time functions:

$P(t) = c_0 + c_1 (t-t_0) + c_2 (t-t_0)(t-t_1) + c_3 (t-t_0)(t-t_1)(t-t_2) + \ldots + c_n (t-t_0)(t-t_1)(t-t_2)\ldots(t-t_{(n-1)})$

where:

- t_0 is the time of peak initiation (for example, the morning peak is initiated at 5 AM, so $t_0 = 5$; the evening peak is initiated at 6 PM, so $t_0 = 18$),
- t_1, t_2, etc are the times one hour, two hours, etc., after peak initiation, and
- n is the number of hours covered by the peak.

The coefficients, calculated by the method of divided differences are:

c_0 = the load at time t_0 (which is L_0)
$c_1 = (L_1 - L_0) / (t_1 - t_0)$
$c_2 = [(L_2 - L_1)/(t_2 - t_1) - (L_1 - L_0) / (t_1 - t_0)] / (t_2 - t_0)$
$c_3 = [((L_3 - L_2)/(t_3 - t_2) - (L_2 - L_1) / (t_2 - t_1)) / (t_3 - t_1) -$
$((L_2 - L_1)/(t_2 - t_1) - (L_1 - L_0) / (t_1 - t_0)) / (t_2 - t_0)] / (t_3 - t_0)$
$c_4 = \{[((L_4 - L_3)/(t_4 - t_3) - (L_3 - L_2) / (t_3 - t_2)) / (t_4 - t_2) -$
$((L_3 - L_2)/(t_3 - t_2) - (L_2 - L_1)/(t_2 - t_1)) / (t_3 - t_1)] / (t_4 - t_1) -$
$[((L_3 - L_2)/(t_3 - t_2) - (L_2 - L_1) / (t_2 - t_1)) / (t_3 - t_1) -$
$((L_2 - L_1)/(t_2 - t_1) - (L_1 - L_0) / (t_1 - t_0)) / (t_2 - t_0)] / (t_3 - t_0)\}/ (t_4 - t_0) \ldots$ etc.

The coefficients for each peak are calculated using an Excel spreadsheet. One can express any of the load profiles identified or developed by similar sets of equations.

For example, for the single home in Puerto Plata, Dominican Republic (discussed above) that uses a 10-watt light bulb, a 60-watt TV, and a 5-watt radio, the load profile is shown in Figure 3. The load profile has three peaks:

- the morning peak during which some lights and the radio are used while preparing breakfast;
- the afternoon peak characterized by lunch preparation during which the radio may be used as well as the TV;
- the evening peak characterized by meal preparation and leisure activities after sunset with all lights, TV and radio turned on.

Using the appliance usage data, coefficients for the morning, afternoon and evening peaks were calculated, and a load profile curve was drawn that matches the actual Puerto Plata profile in Figure 3.

Conclusions and Future Work

While data on actual RAPS systems are limited, the data that do exist, and the profiles generated from these data as well as profiles extrapolated from more limited data, appear to fit the same general three-peak profile. The equations that can be generated from these profiles (as well as similar ones that can be generated from resource profiles) can be used to provide information for developing design practices information for RAPS. The group plans to continue gathering this type of information for use in design practices development, and extend the scope to include other types of remote systems (e.g., communications systems) and other resources (e.g., wind).

References

- P1526 "Draft Recommended Practice For Testing the Performance of Stand-Alone Photovoltaic Systems", IEEE, SCC21
- P1561 "Recommended Practice For Optimizing the Performance and Life of Lead-Acid Batteries in Hybrid Remote Area Power Supply (RAPS) Systems" (Draft), IEEE SCC21
- Transenergie WBI, Estudio de Factibilidad sobre la Concesion del Mercado, Rural Disperso, Resumen Ejecutivo del estudio de la Provincia de Rio Negro – May 1999
- Tony Jimenez, NREL, Personal communication, February 15, 2000
- Silver Navarro, Personal communication, May 12, 2000
- Tania P. Urmee Personal communication, December 20, 1999