Reliability Study on a Small-Scale Photovoltaic Refrigeration System

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ABSTRACT

The primary concern in designing photovoltaic (PV) systems is to optimize the PV array size and battery capacity of the system. The problem encountered in any attempt to size a PV system is to find the combination of PV array size and battery capacity to give a chosen reliability. The term "reliability" in the context of a PV system means the "assurance of energy supply" under stochastically varying weather conditions and it differs from the general meaning of physical reliability related to the functioning and quality of the components. The computer simulation technique can be used to obtain the reliability of a PV system for a given load profile and meteorological conditions. In this study, an experimentally verified simulation program for a PV refrigeration system is used to investigate the long-term behavior of the PV refrigeration system in terms of reliability. Simulated solar radiation and ambient temperature data were used for the year long simulation to calculate the Loss of Load Probability (LOLP) of the system under different PV array size-battery capacity combinations. The reliability-PV array size-battery capacity relationship established by multiple execution of the simulation program provides a useful information base for economic trade-off in the design optimization of PV systems.

1. INTRODUCTION

A photovoltaic (PV) system can be unreliable due to two types of reasons. Firstly, a PV system may fail to render its intended purpose due to lack of energy under poor weather conditions. Secondly, there may be system outages due to failure of its physical components. The latter is related to the quality of the system components while the former is related to the size of components. The unreliability caused by inappropriate component sizes is a problem often experienced in PV systems and therefore at the focus of attention of PV system designers. Although the word reliability generally means the physical reliability related to the functioning and quality of the components, the term "reliability" in this paper strictly mean the "assurance of energy supply" under the stochastically varying weather conditions (solar radiation, ambient temperature, wind), and it differs from the "physical reliability". The primary concern in designing any photovoltaic system with battery storage is to determine the optimum sizes for the PV array and the storage battery bank for assured electricity supply. Because a PV system with perfect reliability is oversized to meet a relatively low time percentage of peak load and cloudy days, to size a PV system to have a perfect assurance of supply is usually more expensive than to add a backup power which may cover the energy shortage due to unavailability of sunshine.

Ultimately, the problem of sizing is to make a trade-off between the system cost and reliability and the outage cost, which may be either the cost of running a backup power during the system outage or any other form of costs incurred due to loss of load.

The first task of sizing a PV system is to find the combination of PV array size and battery capacity to give a chosen reliability. It is generally inadequate to use monthly or daily average insolation and estimated number of continuous "no sun" days to determine array and battery capacities, because the dynamic behavior of PV system and the stochastic nature of solar radiation also significantly influence the required array and storage capacity. Computer simulation using meteorological data and load requirements to simulate the energy flow in the PV system and predict system reliability under assumed array and battery sizes, provides a solution to this problem. Multiple execution of the simulation exercise thus provides the reliability-array size-battery capacity relationship for a given load and meteorological conditions. This relationship can then be conveniently used in the economic trade-off between the system cost and outage cost.

The study based for this paper consisted of three steps: (i) development of a simulation model for a small-scale PV refrigeration system, (ii) experimental validation of the developed simulation model and (iii) the utilization of the validated simulation model to investigate the system reliability under natural conditions. However, the discussion in this paper is limited only to the use of a verified computer simulation model for evaluating the reliability of a photovoltaic refrigeration system which is specially designed for vaccine storage. The details of the simulation model and experimental validation can be found in Rajapakse and Chungpaibulpatana [1].

The simulation program developed was used to simulate the performance of a PV powered refrigeration system. The duration of the simulation covered a year long period. The objective of the simulation was to demonstrate the use of the simulation program to establish the reliability-PV array size-battery capacity relationship for the PV refrigeration system under study and to investigate the effect of the different combinations of array size and battery capacity on the performance of the refrigeration system. Moreover, the applicability of the simulation program to investigate the effects of system components other than the PV array and battery was also demonstrated.

2. PHOTOVOLTAIC REFRIGERATION SYSTEM

A stand-alone PV refrigeration system is schematically shown in Fig. 1 and it basically consists of a photovoltaic array, a controller, a storage battery and a refrigerator. The PV array, which generally consists of several PV modules, produces DC electricity when exposed to sunlight. This electricity is then transmitted to the controller via electrical cables. The controller, which is an electronic device, protects the battery by preventing it from being excessively charged or discharged. The storage battery is used to store the excess energy produced during sunshine periods and to maintain a nearly constant voltage system. This stored energy is used to run the refrigerator when solar radiation is not available. The refrigerator produces the cooling effect by running a vapor compression refrigeration cycle, which mostly uses a hermetically sealed 12V DC compressor.

The basic PV refrigeration system used for the development of the simulation model was located in the Energy Park of the Asian Institute of Technology, Bangkok, Thailand. Its PV array included two different types of PV modules: four ARCO SOLAR M75 (47 Wp) modules and four PHOTOWATT BPX47402 (40 Wp) modules. This system used two BP Solar PVSTORE 6P207 (6V, 207 Ah) lead acid batteries connected in series to make a system voltage of 12V. The controller of the system was a SCI charger model 1, 12V regulator manufactured by Specialty Concepts Incorporation, U.S.A. The

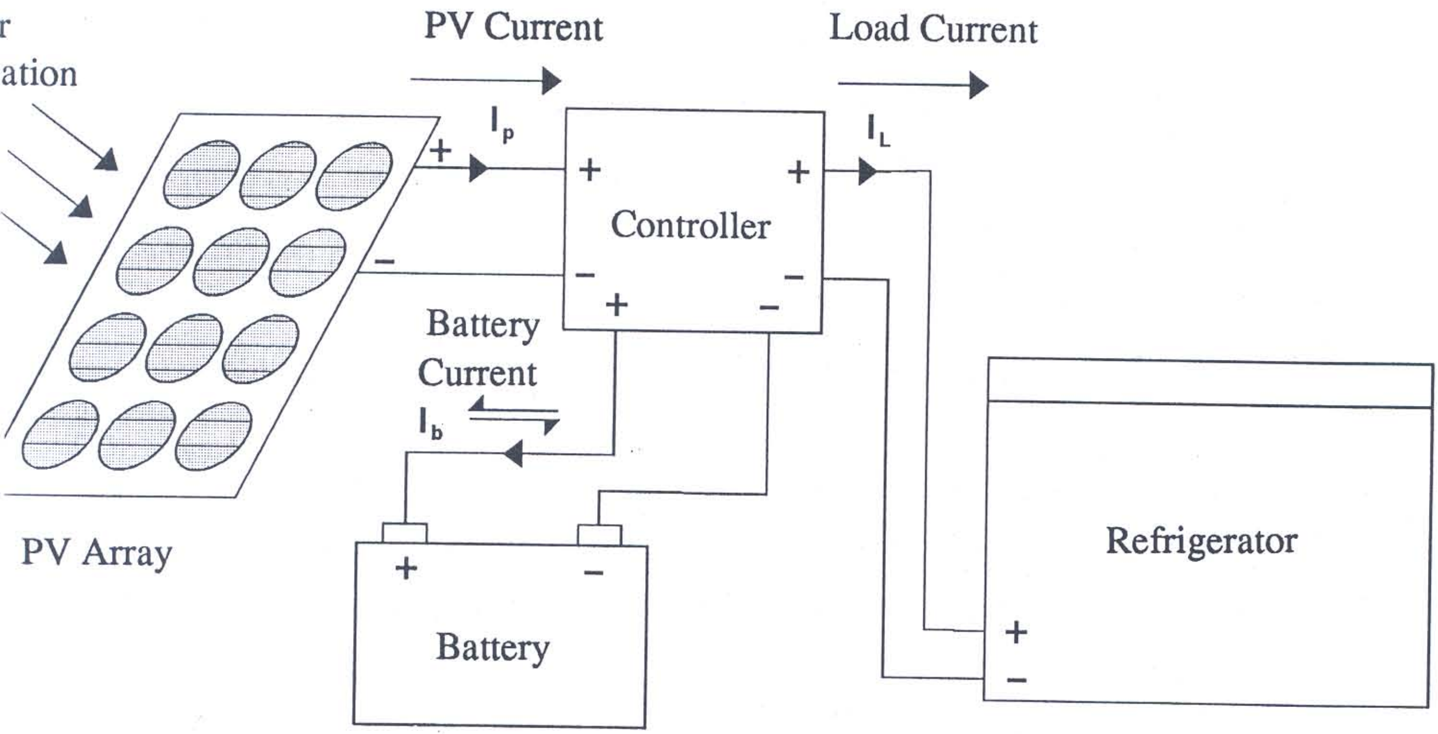


Fig. 1. Schematic diagram of a PV refrigeration system.

SHOWA ARCO model SASFE refrigerator used in the system has two separate compartments: one for vaccine storage (25.8-liter capacity) and the other for ice-pack freezing(10.9-liter capacity). Two hermetically sealed DANFOSS model BD2.5 compressors run two separate refrigeration circuits to cool these two compartments. The electricity consumption of the refrigerator varied with the operating conditions. At an ambient temperature of 32 °C and with 2.5 kg icepack freezing, the consumption was approximately 0.64 kWh per 24-hour operation.

This refrigerator has been manufactured to comply with the World Health Organization (WHO) specifications for solar PV vaccine refrigerators. According to these standards, the refrigerator should be capable of maintaining the vaccine temperature within the range 0-8°C, over the ambient temperature range 15-43°C, provided that the power supply to the refrigerator is not interrupted. Further, it must be capable of freezing 2 kg of ice within 24 hours under the same conditions. Ice-packs are required for vaccine transportation. Usually, vaccines are stored in cold boxes cooled by the frozen ice-packs during their transportation from the health center to remote places for the vaccination programs executed outside the health centers.

3. FUNCTION OF THE CONTROLLER IN A PV SYSTEM

In reliability analysis, the operation of the charge-discharge controller is of great importance and should be carefully understood. The primary function of the controller in a PV system is the efficient use of the photovoltaic energy while providing protection for the expensive batteries. Hence the controller has two main duties: charge regulation, which regulates the charging current and prevents the over charging of the battery by PV panels; and discharge regulation, which prevents the excessive discharge of the battery by disconnecting the load under low battery state of charge (SOC).

The controller senses the battery state of charge by continuously monitoring the battery voltage. When the battery SOC is low, for example at the sunrise, the charging relay of the controller energizes and connects the PV array directly to the battery. The battery will accept as much current as the array will provide and the battery voltage will rise. This operation is usually referred to as the Boost Charge Mode (BCM). Some controllers have an additional charging mode called the Float Charge Mode (FCM) for extending battery life, where the battery voltage and the charging current are kept below some specified Maximum Float Voltage (MFV) and Maximum Float Current (MFC). When the battery reaches the maximum float voltage, the current ceases preventing further charging of the battery. This is called the charge regulation function.

When there is no electricity generated from the array or the array current is not sufficient to meet the load, as at night or during cloudy days, stored electricity in the batteries is used, hence reducing the battery SOC. If the refrigerator operation is prolonged during a cloudy period, the battery SOC could drop to an unacceptable level, which would cause damage to the battery. Therefore the controller activates its discharge regulation function if any excessive battery discharge is detected. The discharge regulator prevents the battery from excessive discharging by disconnecting the load whenever the battery voltage goes below the low voltage disconnect threshold. This is referred to as Low Voltage Disconnect (LVD) mode. The load will be automatically re-connected when the battery voltage reaches the Load Re-connect threshold after being recharged by the PV array. Typical values for low voltage disconnect threshold are around 11.5 V and for load re-connect threshold around 13.0 V for a 12 V system.

Disconnection of the load (the refrigerator in this case), in the low voltage disconnect mode will halt the operation of compressors. This may result in excessive temperatures in the refrigerator (with subsequent loss of vaccines as vaccines must be maintained within the specified range of temperature, 0-8°C), or it may start the backup power system, if available.

4. RELIABILITY INDEX

The basis for sizing procedures of PV systems is the expected reliability. The system reliability should therefore be expressed in a manner useful for the process of design optimization. There are several ways to express the reliability of a PV system and the usual practice is to define a reliability index. In this study, Loss of Load Probability (LOLP) is selected as the reliability index, as it can be conveniently applied in the economic optimization.

The method of computation of LOLP can be described using the loss of load event function. In this case, only those loss of load events due to the disconnection of compressors from the power supply in the low voltage disconnect mode are considered. Therefore, the loss of load event function equals the low voltage disconnect function, LVD[t], (which is a time variable function) defined in the following manner.

LVD [*t*] equals "1" whenever the load is disconnected due to the operation of low voltage disconnect relay. Otherwise it is "0".

Then, the duration within which the power demand by the refrigerator compressor is not supplied can be calculated by performing the following integration.

$$LOLD\ [t] = \int_{t'=0}^{t} LVD\ [t']\ dt' \tag{1}$$

where *LVD[t]* = value of *LVD* at time *t* (0 or 1)
and *LOLD[t]* = loss of load duration from time 0 up to time t.

The above concept is graphically illustrated in Fig.2. At the end of simulation run, LOLP is computed as:

$$LOLP = \frac{LOLD\,[T]}{T} \tag{2}$$

where T = total duration of the simulation (should be sufficiently long to give an accurate representation of the system reliability, for example 1 year) and *LOLD[T]* = loss of load duration from time 0 up to time *T*.

The same value of LOLP can be from large number of short outages, as well as from few long failures. Therefore, high loss of load probability may imply more failures to supply electricity to the compressors or alternatively, long outages when a failure occurs. This implies that the system components may be undersized: either the PV array or battery capacity, or both. Zero LOLP indicates a perfectly reliable system and generally in this case the components are oversized.

It should also be noted that the reliability expressed by the above index in this study is used to describe the system unavailability due only to the lack of energy supply. It does not account for any loss of load events due to system component failures.

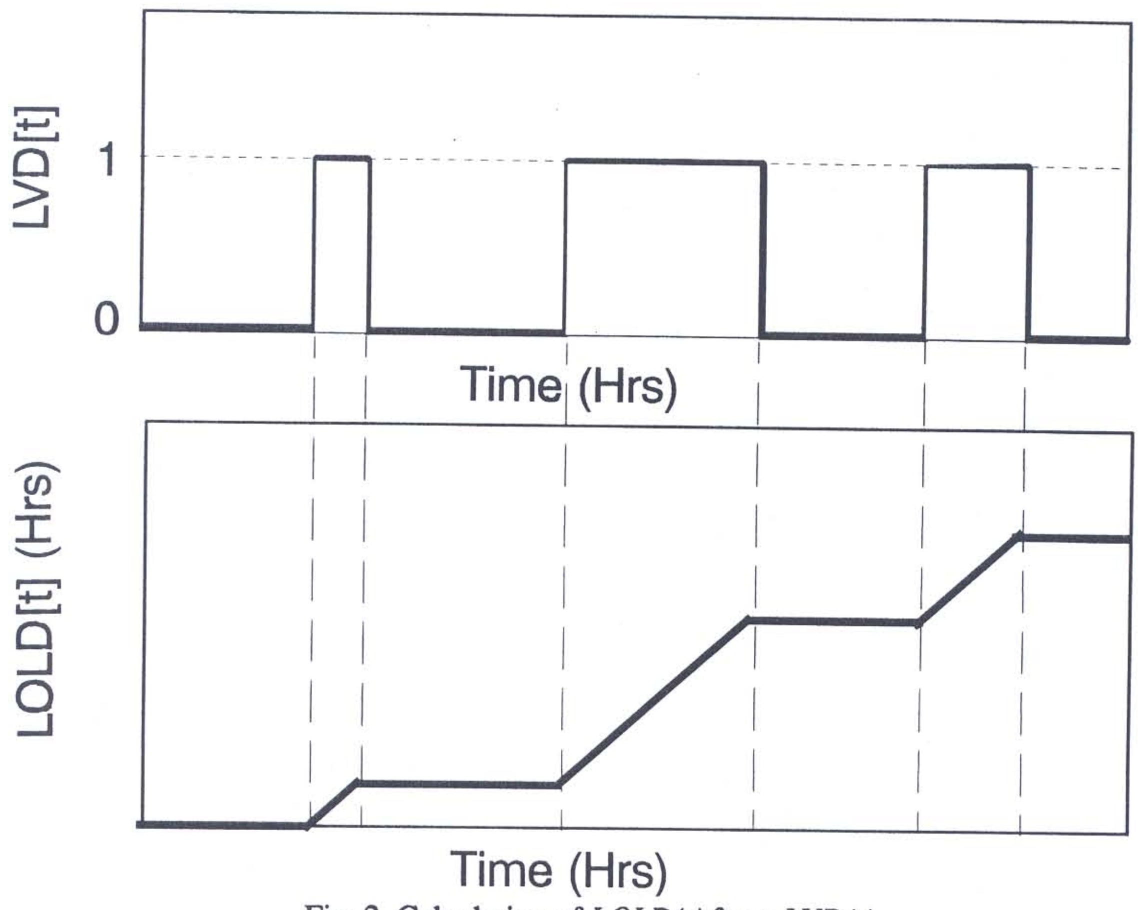


Fig. 2. Calculation of *LOLD(t)* from *LVD(t)*.

5. SIMULATION PROGRAM

The purpose of the simulation model is to determine the LOLP of the PV refrigeration system for a given system configuration and load profile under given climatic conditions. Therefore, the inputs to the simulation program include the information on system configuration such as PV array size, battery capacity, etc.; information on load profile such as frequency of ice-pack freezing; and the data on climatic conditions such as solar radiation, ambient temperature and room temperature data. The system simulation model comprises mathematical models for each of the main system components; those are the PV array, the battery, the controller and the refrigerator. The model is capable of dynamically simulating the interactions among the meteorological conditions and system components (e.g. solar radiation-ambient temperature-PV array, room temperature-refrigerator) as well as the interactions among the components of the system (PV array-controller-battery-refrigerator). Fig. 3 shows the block diagram representation of the system simulation model.

It was observed from the power consumption and temperature measurements of the refrigerator that the freezer compartment compressor undergoes ON-OFF cycles with a period of around 40 minutes, which may be slightly longer or shorter depending on the room temperature. The period of the ON-OFF cycles of refrigerator compartment compressor was around 300 minutes. Therefore, considering the corresponding fast temperature variations inside the freezer compartment, a 5-minute simulation time step was selected in this study in order to accurately simulate the system's dynamic behavior. The selected duration of the simulation is one year. In addition to computing the LOLP, the simulation program is capable to provide other output information such as temperature variation inside the refrigerator, battery voltage and state of charge variation, array current variation, power consumption of compressors, etc.. Figs. 4 and 5 present some examples of the output information from the simulation program. Fig. 4 shows the energy consumption details of the two compressors. It also shows the energy deficit during a period with low voltage disconnection. Fig. 5 shows the vaccine and ice-pack temperature variation during the same time period.

6. SOLAR RADIATION DATA

Five-minute data of solar radiation fluxes falling on the PV array over the reference year was required as an input to the simulation. Although there were computer programs to calculate hourly solar radiation fluxes, there was no such software available for computing five minute solar radiation data. Therefore, the computer program developed by Exell [2] for calculating hourly solar radiation in tropical climates was used with slight modification to generate simulated five-minute solar radiation data.

The above program consisted essentially of a collection of subroutines that can be used for calculation of solar positions and simulation of daily totals of solar radiation and hourly radiation fluxes. In the model [3] on which the above program is based, the global solar radiation G_h at a particular hour of the day was specified in terms of the clearness factor for that hour K_h, defined by

$$K_h = \frac{G_h}{G_{ch}} \tag{3}$$

where G_{ch} = Clear sky radiation at that particular hour (W/m²).

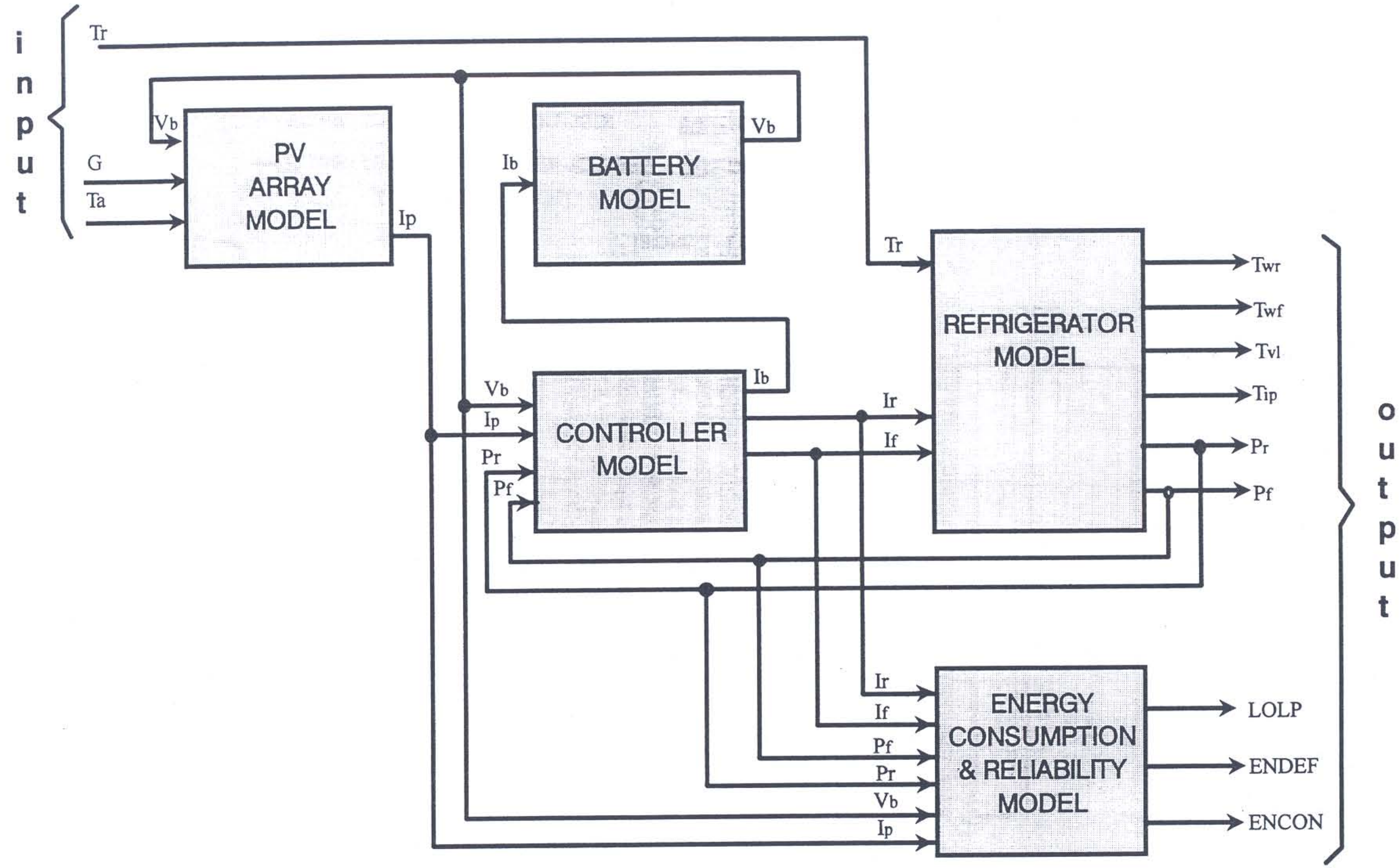


Fig. 3. Block diagram of the PV refrigeration system simulation program.

(Notation: T_r = Room temperature, G = Global solar radiation on the PV array, T_a = ambient temperature, I_p = PV array current, V_b = Battery voltage = PV array voltage, I_b = Battery current, I_f = Freezer compressor current, I_r = Refrigerator compressor current, P_f = Power to freezer compresor, P_r = Power to refrigerator compressor, T_{wr} = Wall temperature of refrigerator compartment, T_{wf} = Wall temperature of refrigerator compartment, T_{vl} = Vaccine temperature, T_{ip} = Ice-pack temperature, *LOLP* = Loss of load probability, *ENDEF* = Energy deficit, *ENCON* = Energy consumption)

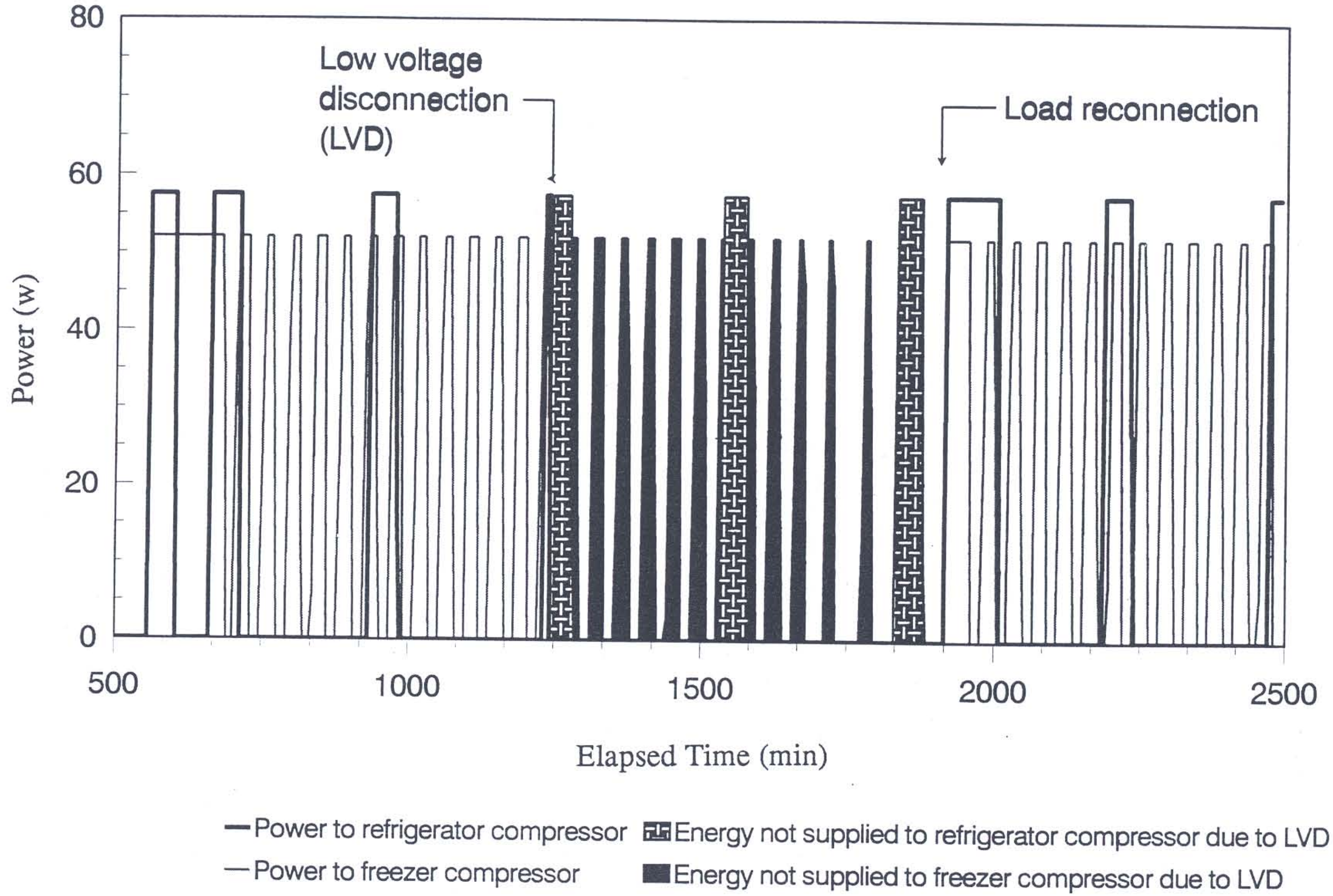


Fig. 4. A sample output of simulation program - energy consumption of refrigerator and freezer compressors. The period shown included a low voltage disconnect event.

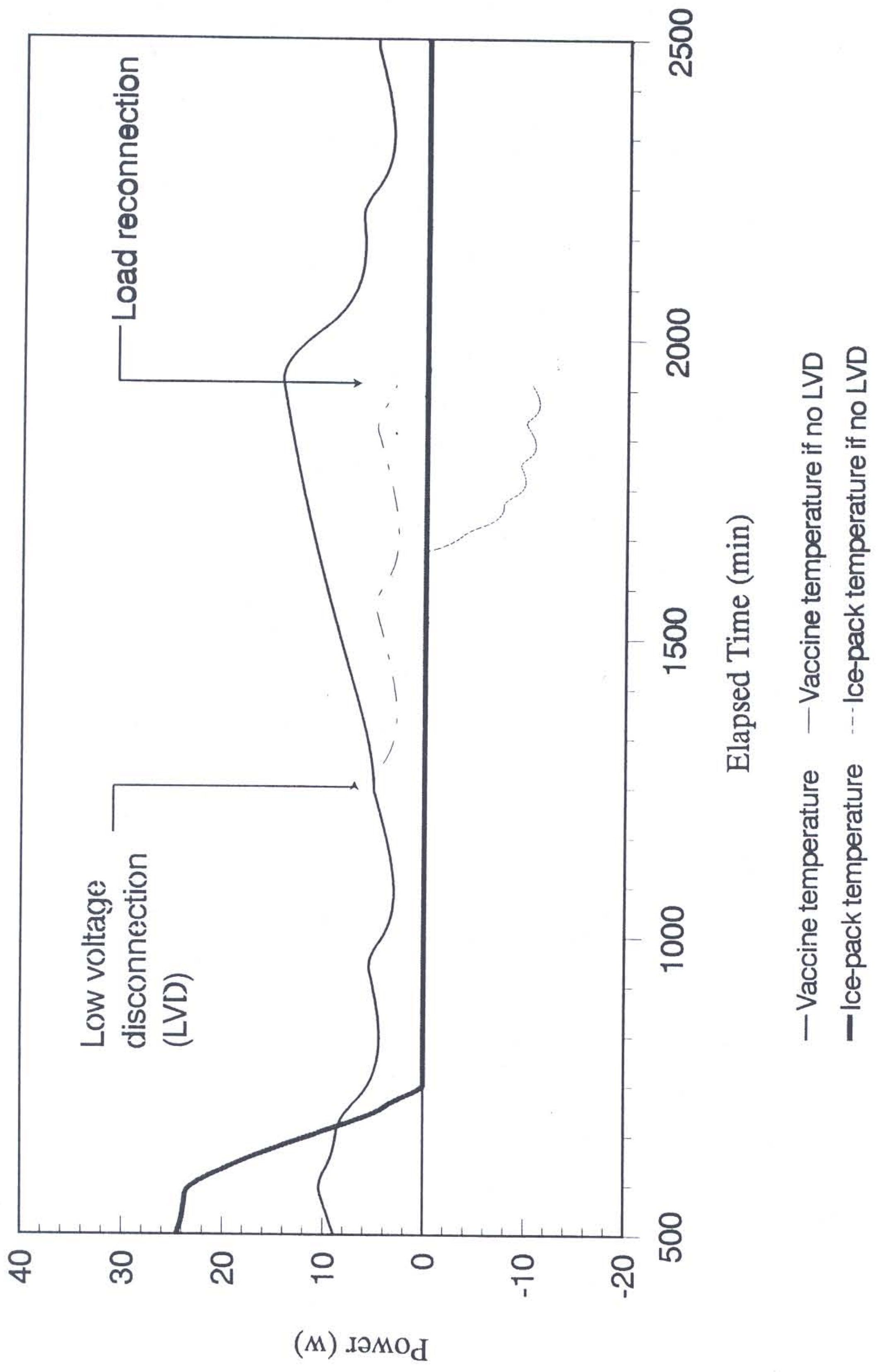


Fig. 5. A sample output of simulation program - Vaccine and ice-pack temperature variation.
The period shown includes a low voltage disconnect event.

Using the subroutines in the program, G_{ch} at a given time in a given day in the year could be calculated. Hourly clearness factors were assumed random and follow a binomial distribution with a mean equal to the mean clearness factor of the day. The program contained the subroutines to compute daily mean clearness factors.

In order to compute five-minute solar radiation fluxes, the solar radiation at the ith five minute interval of the day, G_i, was expressed as

$$G_i = K_i\, G_{ci} \tag{4}$$

where K_i = Clearness factor for the ith five-minute interval of the day
and G_{ci} = Clear sky radiation at the ith five-minute interval of the day (W/m²).

The same relationship was used in the model presented by Skartveit and Olseth [4] for calculation of intrahour solar radiation fluxes, to define 5-minute values of global clearness factor. The existing subroutines gave 13 hourly clearness factors for a day at 6, 7, 8, ... and 18 h. Once these hourly clearness factors were found, the mean clearness factor for the hth hour was calculated as

$$\overline{K}_h = \frac{\left(K_h + K_{h+1}\right)}{2} \; for\; h = 6, 7, 8, ..., 17 \tag{5}$$

Then a binomial distribution of the form given in Eq.(6) with a mean equal to the value calculated from Eq.(5) was assumed for the distribution of five-minute clearness factors in the hour. Hence, in the calculation, each five-minute clearness factor, K_i, in the hour was assigned a value at random in accordance with the percentage probabilities given by

$$P\,(K_i) = 100 \binom{10}{S} \left(\overline{K}_h\right)^s \left(1 - \overline{K}_h\right)^{10\,-\,S} \tag{6}$$

where $\binom{10}{S}$ = 10! / S! (10 -S)!
and S = 0, 1, ..., 9, 10 for the values of K_i in the set {0, 0.1, ..., 0.9, 1.0}.

A subroutine was added to the program to randomly calculate a further 11 K_i values for each of the hour in a day (i.e. total 12 K_i values per hour), resulting in total of 145 clearness factors for a day. Using the above K_i values, global solar radiation flux on a plane tilted 15° to the south could be computed using the other subroutines available in the program. A sample of solar radiation fluxes obtained from the above described computer program is shown in Fig. 6.

7. AMBIENT TEMPERATURE DATA

The usual sinusoidal representation of the daily ambient temperature variation considerably deviates from the actual variation. Therefore, the following distorted form of the sinusoidal variation was used to obtain the daily ambient temperature variation:

$$T_o\,(t) = T_{mean} + T_1 \sin\left(\frac{2\pi\,(t - 9)}{24}\right) + T_2 \cos\left(\frac{4\pi\,(t - 9)}{24}\right) \tag{7}$$

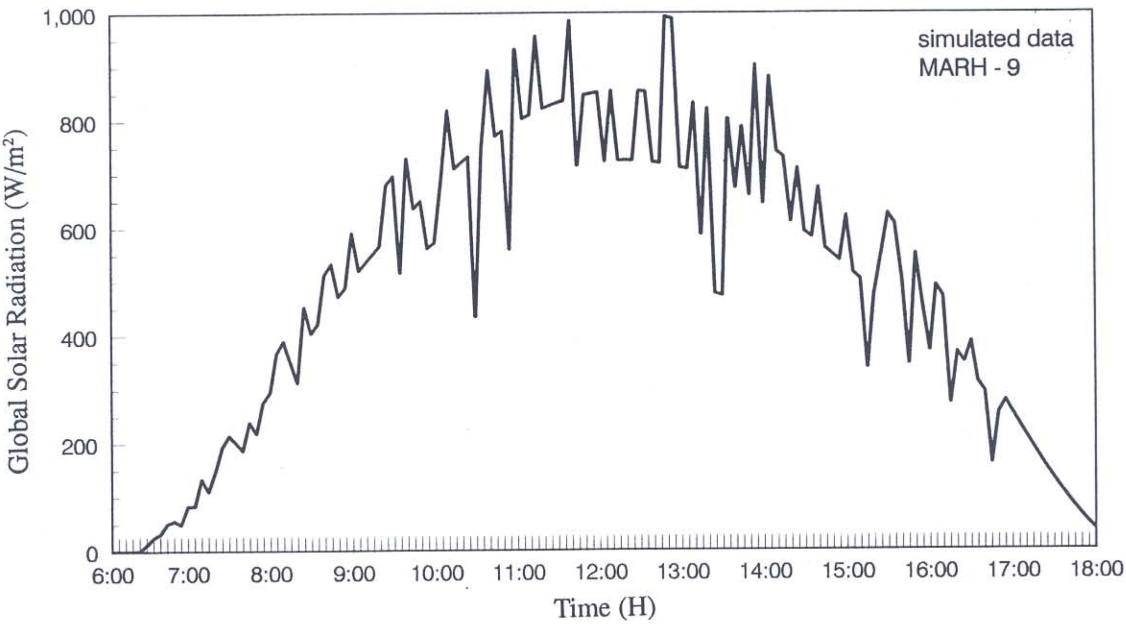


Fig. 6. A sample of solar radiation data computed from the solar radiation simulator.

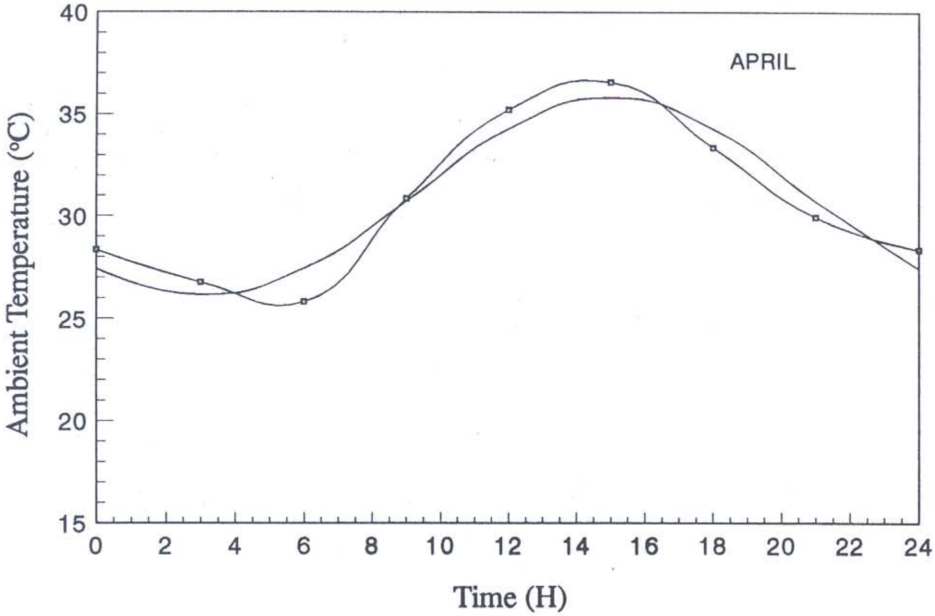
where t = Time of the day (hours)
$T_0(t)$ = Ambient temperature at time t (°C)
T_{mean} = Mean temperature of the day (°C)
and T_1, T_2 are constants to be found by fitting measured data.

A year was divided into 12 seasons corresponding to each month, and 12 sets of values for T_{mean}, T_1 and T_2 were estimated using the ambient temperature data for a whole year. The year 1992, during which the more or less average weather conditions prevailed in Bangkok, was selected for the purpose of demonstration in this study. The data collected by the Energy Technology meteorological station of AIT was used in the estimations. A sample of computed variation of the ambient temperature in a day using the above model is depicted in Fig. 7.

The simulation program required five-minute data of the temperature of the room where the refrigerator was kept in as well. In this example, it was assumed that the room temperature was equal to the mean ambient temperature of the day. Note that the ambient temperature was also required for the calculation of the performance of the photovoltaic modules.

8. LOADING PROFILE

A weekly cycle with one outreach immunization activity per week was assumed for the loading profile. Each outreach immunization activity required 2.4 kg of ice-packs to use in the vaccine cold boxes and it was carried out on the 3rd day of the week. According to the cycle, at 9:00 hrs on the 1st day of the week the freezer was switched on after loading 2.4 kg of ice-packs at room temperature.



(b) Ambient temperature variation - April

Fig. 7. A sample of ambient temperature data computed from the ambient temperature model.

These ice-packs were replaced by new ice-packs at ambient temperature at 9:00 hrs on the 3rd day. At 16:00 hrs on the 5th day the freezer was switched off and allowed to remain off until the beginning of the next week. The refrigerator was switched on throughout the whole simulation. Loading and unloading of vaccine was not considered, assuming it is a gradual process. Further, the increase of cooling load of the refrigerator due to introducing new vaccine packs is not significant because they are usually pre-cooled to the safe temperature range.

9. PRESENTATION AND DISCUSSION OF SIMULATION RESULTS

A support database was created using the data generated as described in Sections 6 and 7. This database consisted of 12 parts, each part containing global solar radiation, ambient temperature and room temperature data for a period of one month. Using these data the operation of the PV refrigeration system was simulated for 24 different combinations of PV array size (in terms of Peak Watt) and battery capacity (in terms of Ampere-Hour). These 24 combinations are given in Table 1.

Table 1. PV array - battery size combinations for the simulation.

PV array (Wp)	Battery Capacity (AH)						
268	36.2	51.7	103.5	155.25	207	258.75	414
308	36.2	51.7	103.5	-	207	-	414
348	36.2	51.7	103.5	155.25	207	258.75	414
388	36.2	51.7	103.5	-	207	-	414

Since the simulation gives loss of load probability value corresponding to a specified battery capacity and array size combination, the loss of load probability (LOLP)-PV array size (Wp)-battery capacity (BC) relationship can be found by multiple execution of the simulation program. The relationship is expressed taking array size and battery capacity as the independent variables and LOLP as the dependent variable. Results of the simulation are presented in Figs. 8, 9 and 10. According to the outcome of the simulation, the LOLP-Wp-BC relationship for the PV refrigeration system was established (Fig. 8). As expected, LOLP decreases with the increase of array size and battery capacity. The improvement of LOLP due to the addition of unit battery capacity at a particular array size diminishes gradually with the decrease of LOLP. The same is true for the addition of PV panels at a fixed battery capacity. Therefore, achieving improved reliability demands more and more PV panels and batteries. This indicates the importance of optimization of the system design rather than designing to meet the worst case conditions. The impact of the battery capacity and array size on the energy deficit, ENDEF, is shown in Fig. 9. It can be seen that there is one to one correspondence between LOLP-Wp-BC and ENDEF-Wp-BC relationships.

A similar study was reported in the Solar Photovoltaic Handbook by Lasnier et. al. [5], where the reliability was expressed by Loss of Load Hours (LOLH). In their study, the load was assumed uniform throughout the time and a very similar relationship was obtained for LOLP-Wp-BC as a result of hourly simulation.

Another simulation was carried out to find the effect of wire resistance (Rw) of the cable connecting the PV array and the other system components on the system performance. The existing system used two cables; the cable connecting four ARCO SOLAR PV modules with a resistance of

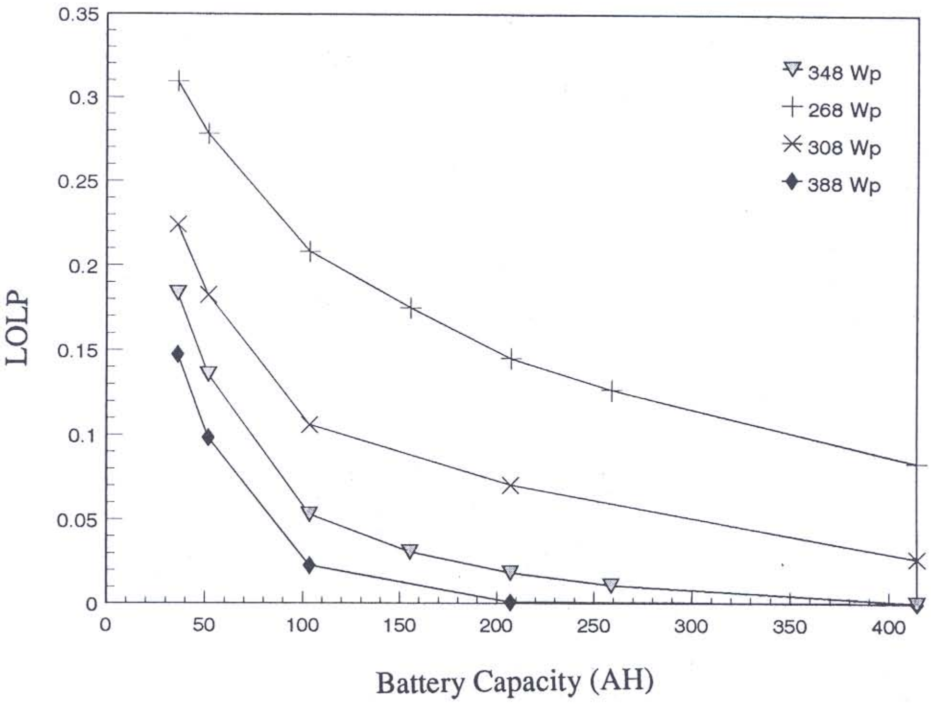


Fig. 8. Simulation results -- LOLP-PV array size-battery capacity relationship for the PV refrigeration system.

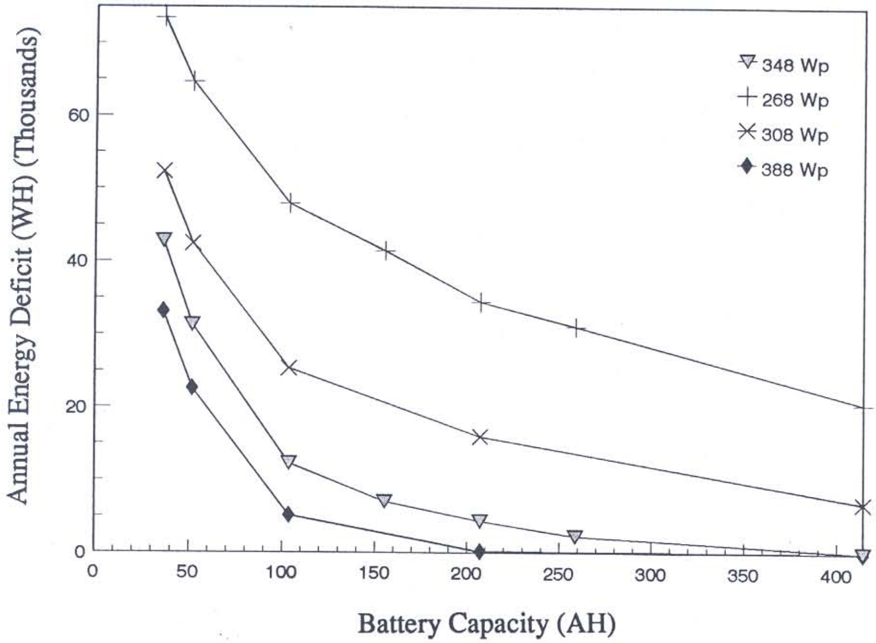


Fig. 9. Simulation results- energy deficit- PV array size - battery capacity relationship for the PV refrigeration system.

0.300Ω, and the cable connecting four PHOTOWATT PV modules with a resistance of 0.205Ω. The simulation result (Fig. 10) shows that the reliability improvement due to the reduction of both these resistances to 0.1Ω is equivalent to the addition of one PHOTOWATT PV module (which is 40 Wp). Therefore having lower resistance cables, means that less number of PV panels need to be used. This result indicates that the importance of using properly sized wires for achieving the maximum use of the PV array.

By using the same approach, the influence of the other factors such as increased thermal insulation of the refrigerator cabinet, controller thresholds, etc., on the performance of the refrigeration system can also be investigated. An economic analysis may also be required in the investigation for the justification of those improvements or modifications.

10. OPTIMIZATION OF PV SYSTEM DESIGNS

It is clear that a high degree of reliability requires high investment in PV array and batteries, but on the other hand, a lower degree of reliability results in higher outage cost (i.e. cost arising from malfunction of the system which in this study means the cost arising from lack of energy supply to the system). Accordingly, the trade-off between system investment and outage cost must be evaluated to determine the optimum reliability (i.e. the optimum value of LOLP). In the case of PV refrigeration systems for vaccine storage, the cost associated with loss of vaccine during the down-time of the refrigerator would reflect the outage cost, unless there is a backup power system.

Fig. 11 presents a graphical interpretation of this situation. Investment cost, i.e. cost of PV panels and batteries, increases with the decrease of LOLP. But the cost of outages decreases with the decrease of LOLP. The total cost of the system is given by

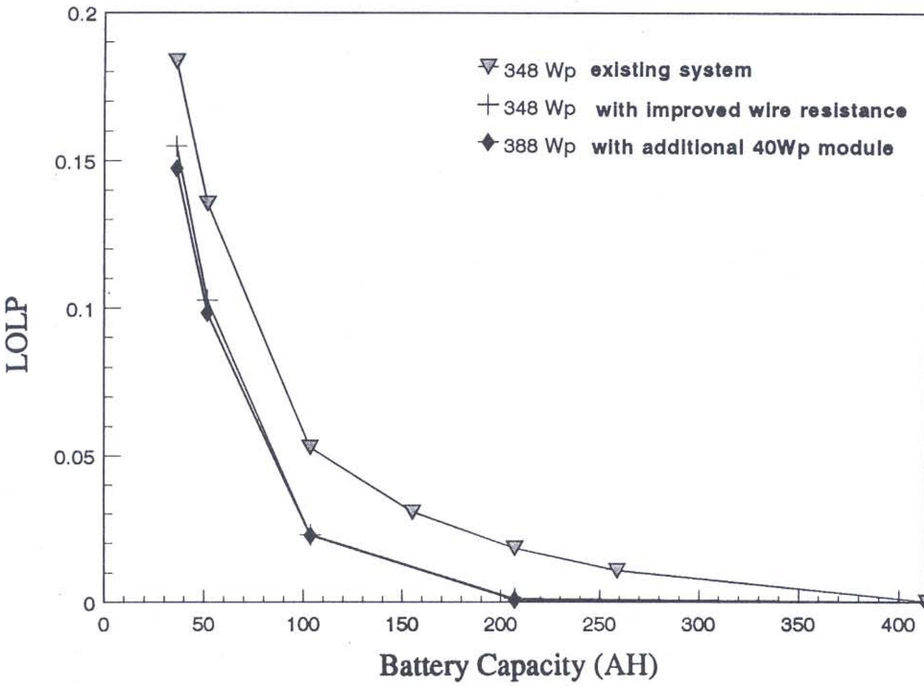


Fig. 10. The effect of wire resistance on the system reliability.

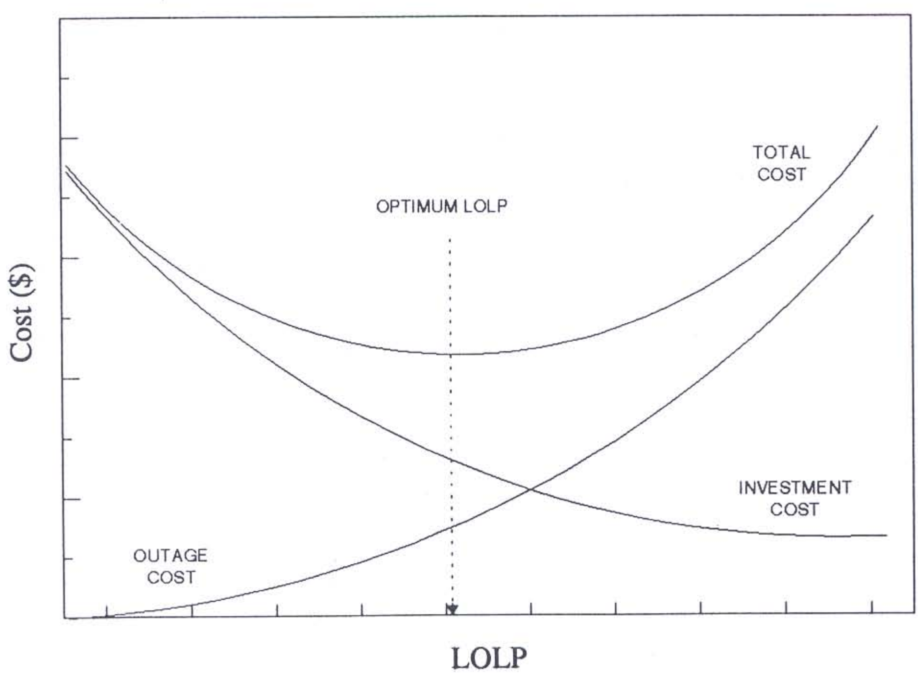


Fig. 11. Typical cost-reliability relationship.

$$\textit{Total cost} = \textit{Investment cost} + \textit{Operating cost} + \textit{Outage cost}.$$

However, the operating cost of a PV system without back-up can be assumed zero if battery replacement is not considered. In the typical situations, the total cost function has a minimum (Fig. 11). The optimum LOLP corresponds to the minimum point on the total cost curve, where the marginal cost of increasing the reliability is zero.

Therefore, once the relationships of LOLP with the investment cost and the outage cost are established, the above analysis can be carried out. But in the actual situations, the procedure becomes a little more complicated due to the existence of a number of Wp-BC combinations which would lead to the same LOLP. In this situation, the Wp-BC combination leading to the minimum cost has to be found before establishing the relationship between LOLP and investment cost. Detailed discussion of the optimization procedures is beyond the scope of this study. However, a description and mathematical formulation of the problem of optimization of the design of PV power systems can be found in the Photovoltaic Handbook prepared by Lasnier et al. [5] and the special study project report made by Wang [6].

The choice of LOLP as the reliability index however has the disadvantage that it does not give any idea about the frequency and the duration of the outages. For example, one long outage in a specific time period is much more serious than many short outages. The thermal capacity of the refrigerator and its contents keep the temperature low during short outages, preventing vaccine losses. Also, a long outage is likely to be more serious for the health of the battery. Therefore, it is useful to have a reliability index which reflects some knowledge about the frequency and the duration of the outages. However, the above short coming cannot be over come by simply selecting one of the other possible reliability indices. They also suffer from their own disadvantages. For example, an index such as "Frequency of Loss of Load Events" will not give any idea about the duration of outages. Similarly, "Average Duration of Outages" will not indicate how often the outages occur. Perhaps, a combination of those two indices would give a better picture of the system reliability, but in such a case it is necessary to develop a methodology to use those two indices (probably conflicting with each other) in the selection of the optimum sizes of PV array and storage battery. The authors recommend this problem for further investigation.

11. CONCLUSION

In the study presented in this paper, a computer simulation program was used to evaluate a reliability index (LOLP) for a PV powered refrigeration system. The duration of the simulation covered a year long period. By multiple execution of the simulation program for different PV array size and battery capacity combinations, the reliability-PV array size-battery capacity relationship for the PV refrigeration system under study was established. This relationship provides a valuable base for subsequent system design optimization. The simulation program can be further used to investigate the effects of system components other than the PV array and battery as demonstrated in the study.

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