

# PVSOFT99 - PHOTOVOLTAIC (PV) SYSTEM SIZING AND SIMULATION SOFTWARE

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## ABSTRACT

*A computer program (PVSOFT99) has been developed for sizing and simulation of stand-alone photovoltaic (PV) systems. Two distinct PV sizing algorithms, one based on the worst case and the other on the reliability concept, have been incorporated in the program. The reliability concept is generalized in that variation of irradiation, temperature and load profile are all taken into consideration for the sizing process. The program is capable of performing both technical and economical analysis with comparative output of the PV system with diesel generation and grid extension.*

## INTRODUCTION

By PV system sizing, is meant determination of the appropriate ratings of the various components of the system (array, power conditioning system, and storage medium and other application specific sub systems) such that a given load is satisfactorily operated. An oversized system is expensive in terms of the initial cost. An undersized system, on the other hand, will not deliver the power required with the desired regularity and may also lead to shortened battery life (for systems with battery storage). Accurate system sizing is therefore very important for proper utilization of the PV technology.

The sizing problem is compounded by the fact that the energy source, the solar radiation, is a variable source whose properties can not be precisely controlled. Thus a good sizing procedure is always accompanied by simulation in which all components of the system including the solar radiation are modelled with a computer program and hourly performance is studied to get an insight into the whole process. A number of approaches have been followed for simulation as well sizing of a PV system [1-5].

All sizing algorithms start with the weather profile in its simplest form (or frequency distribution form for statistical algorithms), module efficiency  $\eta_m$ , battery efficiency  $\eta_b$ , the allowable battery depth of

discharge  $D_x$  and sub systems (inverter, converter, .., etc.) efficiencies  $\eta_i$ , and load profile including the load voltage  $V_L$  and the maximum power  $P_x$ . The weather profile includes at least the global irradiation on the horizontal plane, and if possible the diffuse and/or direct (beam) irradiation.

For systems that do not track the position of the sun, the optimum tilt angle must be determined such that the maximum possible output is obtained over the application period.

The output of a sizing algorithm may be given in terms of the total array area in  $m^2$  and total battery capacity in watt-hour. Equivalently, it may be given in terms of the number of series and parallel connected modules and battery cells. If  $A_m$  denotes the module area,  $A_a$  the array area,  $C_{bc}$  the battery cell capacity, and  $C_b$  the total battery capacity, then the following equation hold true.

$$A_a = N_{ms} N_{mp} A_m \quad (1)$$

$$C_b = N_{bs} N_{bp} C_{bc} \quad (2)$$

$N_{ms}$  is the number of series connected modules per string,  $N_{mp}$  is the number of such strings connected in parallel,  $N_{bs}$  is the number of series connected battery cells, and  $N_{bp}$  is the number of groups of such cells connected in parallel.

$N_{ms}$  and  $N_{bs}$  are mainly dependent on the battery voltage level, the load operating voltage and the module output at maximum power, temperature effects and wire and protective diode drops taken into account. The rating of the power electronic interfaces (inverters and converters) is determined by the maximum load power.  $N_{pm}$  and  $N_{pb}$ , on the other hand, depend of the load current requirements and the current output from a single string of modules and batteries.

The total array area and the battery capacity are in general related to carefully selected parameters  $E_L$  and  $E_{Lb}$  such that,

$$A = \frac{E_L}{H \beta \eta_a \eta_i} \quad (3)$$

$$C_b = \frac{E_{Lb}}{\eta_b D_x} \quad (4)$$

where  $H_\beta$  is the plane of array (tilt) irradiation,  $E_L$  is the daily load and  $E_{Lb}$  is part of the load to be covered by the battery, taking daily and seasonal energy balance.  $\eta_a$  and  $\eta_i$  are the array and interface efficiencies respectively.

The ampere-hour load, the corrected module current, and the effective sunshine hours determine the number of strings of modules to be connected in parallel. The ampere-hour load, the ampere-hour capacity of the battery and the specified number of autonomous days determine the number of battery strings.

The difference between the various design algorithms lies in the selection of the tilt irradiation  $H_\beta$ , ambient temperature  $T_a$ , and load parameters  $E_{Lb}$  and  $E_L$  also in selection of the tilt angle.

The classical Loss of Power Probability (LPP) methods neglects variations in the load profile and ambient temperature. The most general (LPP) or its complement, reliability method has been incorporated in the computer program.

The generalized reliability,  $R$ , is defined as the long-term average joint frequency of occurrences such that the irradiation is less than, the ambient temperature is greater than, and the load is greater than the respective threshold (reliable) values. That is,

$$R = F(H < H_R, T > T_R, E_L > E_{LR}) \quad (5)$$

Thus the function is three-dimensional joint distribution of the irradiation, the ambient temperature and the load profile.

To use the reliability concept, the radiation data must be processed to get a working reliability database. The data should be in a form such that the combination ( $H_R, T_R, E_{LR}$ ) is extracted for any specification of  $R$ . The major input parameter for system design is the desired reliability  $R$  (%) and the program determines the number of autonomous days  $N_{AD}$ , satisfying the minimum life cycle cost criteria.

### SIMULATION MODELS

Simulation is a co-ordinated solution of a set of equations modelling each part of the system to be simulated. For a PV system, the array, the interface

and storage unit (if present), and other specific sub systems such as motor-pump unit are modelled by their equations with inputs of hourly weather and load profiles. The program will then compute, on hourly basis, all the desired system performance parameters.

A number of commercial packages are available to perform both sizing and simulation of PV systems. However, not all of them are suitable for a particular application due to the simplifying assumptions inherent to each program and the site specific nature of the underlying equations. Thus it is difficult to come up with sizing and simulation algorithm applicable to all conditions or locations.

### Weather Model

Meteorological parameters affecting the performance of a PV system are daily irradiation, the ambient temperature, wind speed and rainfall. PV systems perform better at low temperature and higher wind speed.

If there is a possibility to obtain random values of the weather parameters within a given limit (average and standard deviation), then the system performance is expected to represent the actual environment. In the program, the random sequence generator routine has been used to generate a variable weather data. Although the statistical properties of the computer generated random number are not identical to those of the actual weather, the sizing and simulation results are expected to be better than the results from fixed weather and load profiles.

The input weather data for the computer program consists of monthly averages and standard deviations of the global horizontal irradiation, (plus the diffuse component if available), the maximum and the minimum ambient temperature, and the rainfall. The later component is used to estimate the irrigation water requirement. While most of the available computer programs and algorithms rely on the average values, PVSOF99 combines the averages and the standard deviations to extract the weather parameters for sizing and simulation.

### PV Array Model

The most complete model of a PV cell requires that five parameters be known: the light generated current  $I_{ph}$ , the diode reverse saturation current  $I_0$ , the series resistance  $R_s$ , the shunt resistance  $R_{sh}$ , and the thermal voltage  $v_T$ . All of the five parameters may be functions of temperature, in

addition to  $I_{ph}$  being primarily dependent on irradiation. The PV array module is same as PV cell parameters with modification to take the number of series modules and parallel strings into account.

The shunt resistance of commercial modules is high compared to the series resistance. Practical models therefore neglect  $R_{sh}$  and use the remaining four parameters to characterize the module or array under variable irradiance and temperature conditions [9]. The PV module equation becomes,

$$I = I_{ph} - I_o \left( \exp \left( \frac{V + IR_s}{v_T} \right) - 1 \right) \quad (6)$$

Application of the three terminal conditions (short-circuit, open-circuit, and matched termination) the following useful relations among the common module parameters.

$$I_{ph} = I_o \exp \left( \frac{V_{oc}}{v_T} \right) \quad (7)$$

$$R_s = \left[ v_T \cdot \ln \left( 1 - \frac{I_m}{I_{ph}} \right) + V_{oc} - V_m \right] / I_m \quad (8)$$

Since module parameters are specified under standard weather, they must be transformed according to the actual temperature and irradiance values. To simplify the analysis the series resistance may be assumed to be independent of temperature. Under this assumption the effect of temperature on the other parameters will be as shown in the following equations.

$$v_T' = \frac{T_c'}{T_c} \cdot v_T \quad (9)$$

$$I_{sc}' = \frac{G'}{G} [I_{sc} + \alpha_I \cdot (T_c' - T_c)] \quad (10)$$

$$I_o' = I_o \left( \frac{T_c'}{T_c} \right)^3 \exp \left[ \frac{E_g N_{cs}}{v_T} \left( 1 - \frac{T_c}{T_c'} \right) \right] \quad (11)$$

where  $E_g$  is the material band gap energy (1.12 for silicon) and  $N_{cs}$  is the number of cells in series within a module.

An additional independent equation can be obtained by equating the experimental current and voltage temperature coefficients,  $\alpha_I$  and  $\beta_V$  respectively, to the derivatives of the analytical equation with respect to temperature.

Differentiating Equation (7) with respect to temperature and manipulation of variables results in the following equation.

$$v_T = \frac{\beta_V \cdot T_c - V_{oc} + E_g \cdot N_{cs}}{\frac{\alpha_I \cdot T_c}{I_{sc}} - 3} \quad (12)$$

The complete solution of the current and voltage depends on the load characteristics. There are two possibilities to load the PV source: either directly to the load or through a maximum power tracker unit. For direct connection, the current  $I$  and the voltage  $V$ , in Equation (6), are related by the load impedance, normally obtained the load profile. For interfaced system, however, the pair  $(V_m, I_m)$  corresponding to the maximum possible power at each irradiance and temperature condition must be solved. Mathematically, the derivative of the power expression is set to zero which is equivalent to the relation,

$$\frac{dV}{dI} = - \frac{V}{I} \quad (13)$$

In both cases the resulting non-linear equation must be solved using one of the root finding algorithms of computational methods. This completes the simulation model of the PV module and hence the PV array utilized in the computer program.

**Battery Model**

For a lead-acid battery, which is the most common type of storage system, the voltage  $v_b$  at a discharge current  $i_b$  is given by,

$$v_b = E_b - R_i i_b \quad (14)$$

where  $E_b$  is the battery emf and  $R_i$  is its internal resistance. Simulation algorithms with results of battery voltage and current rely on the above or similar terminal characteristics. Different suggestions have been made to model the internal resistance, charge-discharge current and terminal voltage of a battery [8,9].

In energy simulation, one is interested in hourly values of the state of charge of the battery (measure of the stored energy as percentage of the battery capacity), the energy flow into and out of the battery, the array energy wasted, and the load energy not served by the system. Thus the only parameters needed for battery simulation are the range of allowable state of charge and the battery capacity. It is this later approach followed in developing the computer program.

### Interface Model

Possible interface (inverter or converter) models include linear models based on the interface no-load demand and nominal efficiency or higher order polynomial models extracted from measured values of the interface input and output values. The polynomial model requires determination of the  $n+1$  constants in the equation,

$$P_o = c_0 + c_1 P_i + \dots + c_n P_i^n \quad (15)$$

There are two ways to provide data regarding the model: the coefficient array ( $c_0, c_1, \dots, c_n$ ) directly or measured values of input and output power values over the complete range of operation from which the coefficients can be determined.

Experience has shown that a single model performs differently for different parts of operating region. To ensure fairly uniform modelling accuracy over all parts of the operating curve, a piece-wise linear model has also been suggested. The piece-wise model is also based on values of the efficiency  $\eta_i$  as a function of the power input.

### Motor-Pump Model

The motor-pump unit is a cascade of an electric motor and a mechanical pump. The motor converts the input electric energy to mechanical energy and the pump converts the mechanical energy into useful hydraulic energy utilized to lift the water. Very much similar to interface unit, the motor-pump is represented by its efficiency that is assumed to be constant. Then,

$$E_h = \frac{\eta_{mp} \eta_i}{10000} E_a \quad (16)$$

where  $E_h$  is the hydraulic energy (output energy of the motor-pump),  $E_a$  is the array energy,  $\eta_i$  is interface efficiency (both efficiencies expressed in percent).

### Load Model

The load model for electrification systems is a profile of load power for each hourly interval since simulation is invariably an hourly computation. The hourly load profile can be given for each day, for each month or simply for the whole simulation period.

For water pumping systems, however, the load model is derived from the water demand profile coupled with water source characteristics. The latter is important if the water source behaviour

such as water level, draw down and flow rate are to be monitored.

### PROGRAM DESCRIPTION

The purpose of the computer program is to provide a user-friendly tool to perform initial system sizing, configuration studies and performance prediction for a stand-alone system. The program was written in Visual Basic. The flowchart of the program is shown in Figure 1.

The program interface consists of a number forms and parameter entry/display screens. The major ones are MAIN, SUB-MAIN, LOCATION-APPLICATION, SUB SYSTEMS, and PROJECT. MAIN allows selection of general system options such as the application type and interfacing requirement, and design method.

In Figure 1-2, MAIN with one possible option (Single-Phase AC Electrification system design with Reliability method) is shown. If *Water Pumping* is selected two more default options (Water Supply system from a Ground Water source) become visible.

SUB MAIN, following Next on MAIN leads to selection of the surrounding type, the operating load voltage, interface input voltage (if interface based system is chosen), the number of autonomous days, and the application period. The screen also consists of command buttons that lead to LOCATION-APPLICATION and SUB-SYSTEMS that appear after operating voltages are entered.

An option to analyse an existing PV system (*User Supplied*) is provided in addition to the default option *New Design*. Figures 1-4a and 1-4b show the data entry screens resulting from a click on **Location & Application**. The monthly average and standard deviation of the weather data is necessary for both *Worst Case* design and *Reliability* design. The data is entered on the entry/display form obtained using Weather Data on LOCATION-APPLICATION and consists of monthly averages of the global (and diffuse if available) irradiation, ambient temperature, and rainfall. The rainfall data is necessary to estimate water requirements for irrigation only.

On MONTHLY AVERAGE WEATHER, it is possible to enter either global irradiation only (as dictated by many of the available solar irradiation data) or both the global and the diffuse irradiations. There is also an option to choose from units  $\text{Wh/m}^2$  or Langleys and from °Celsius or °Fahrenheit. Upon confirmation of the data, the program computes

the tilt irradiation using the Liu and Jordan method [10]. In cases where the diffuse irradiation is unavailable, the program estimates the values using the monthly average clearness index [11].

**Electrical Load** on **LOCATION-APPLICATION** displays data entry/display for hourly electrical load profile. Either typical or monthly average profiles can be entered and the program determines the monthly average daily total load including the night-time load component. The later, if computed to be greater than zero, activates **Battery** on **SUB SYSTEMS**.

**Water Source, Pump Set Data, and Water Demand** are similar to **Electrical Load** but for *Water Pumping* option. **Water Demand** is useful to enter the number of persons and/or livestock to determine the gross daily water demand. It also allows entry of basic irrigation data such as command (irrigated) area in hectares, crop type, etc., for irrigation option. Again the program estimates the daily water requirement on the field, taking the monthly average rainfall into consideration. In both cases the water volumes and the expected lift are combined to determine the equivalent load to the PV system in Wh. After all the selections are made, **Next** on **LOCATION-APPLICATION** enables **Sub Systems** on the parent screen, **SUB-MAIN**.

The sequence of activities in the design as well as the simulation process is under the control of program avoiding inadvertent selections and erroneous sequences. The program takes care of improper sequence or selection by disabling or hiding all buttons and options except the right ones. On **SUB-SYSTEMS** and **LOCATION-APPLICATION**, the command buttons and entry boxes valid for the general option setting on **MAIN** will be available for the user. For instance, if *Direct DC Water Pumping* is chosen on **MAIN**, **Battery** will be unavailable **SUB SYSTEMS** (storage is assumed to be with a water tank) and **Water Source** with **Water Demand** will be active on **LOCATION-APPLICATION**.

Furthermore, unless the required parameters for the active buttons are properly entered the next step or selection will not be available and the user will be prompted to complete the missing steps. This helps to avoid raising computational error conditions such as divide-by-zero.

**Battery** on **SUB SYSTEMS** will be visible when a non-zero night load is specified for electrification. The effect of the number of autonomous days in

water pumping application is the presence and absence of a water tank.

After entry of the array-battery information is completed, **Next** on **SUB MAIN** will be available to initiate the computation of array-battery size and interface rating and the output data is shown on **PROJECT**.

For new design, **Save Project** must be clicked get access to the output data. The output data available from **Technical (Main)**, and **Technical (Additional)**.

The technical data contains the number of modules, the array tilt angle, the battery capacity, interface rating,....etc.) and the economic data (the capital and recurrent cost) is obtained using the life-cycle costing method. The array area and the battery capacity (if any) are available from **Technical (Main)**. **Technical (Additional)** will be active if an interface unit is part of the system or if the system is a water pumping system.

**ECONOMIC ANALYSIS** has entry boxes for the primary economic variables, discount rate, inflation rate, import tax,....etc. and separate buttons for each component - **Capital** and **Recurrent**. **Summary** has the purpose of displaying the economic data including the annualized life cycle cost and unit cost of output. Life cycle cost comparison of the designed system with either a diesel generator or with grid extension option is also available from **Summary**. **Cash Flow** lists down the cash flow over the financial life of the system, with or without loan.

Next, **PROJECT**, leads to interface data entry routine (for interface based system) and an optional simulation routine which involves computation of the hourly values of some performance parameters.

If chosen, the simulation period and initial condition (initial state of charge for battery based electrification system or initial water level for water pumping system) are required. The output being mainly in graphical form, numerical values of the array utilization and load coverage factors are also provided as a measure of source-end and load-end performance respectively.

## CONCLUSION

PVSOFT99 is a computer program that implements the generalized reliability sizing algorithm with life cycle cost analysis result. Furthermore, the program allows comparison of PV with alternative energy options - grid extension and diesel generation.

The computer program deals with non-tracking stand-alone system that is a typical configuration suitable for a rural area in a developing country. Improvements can be made to handle options for grid connected system and/or one or more types of sun tracking systems.

#### ACKNOWLEDGEMENT

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APPENDIX A – Flowchart of PVSOF99

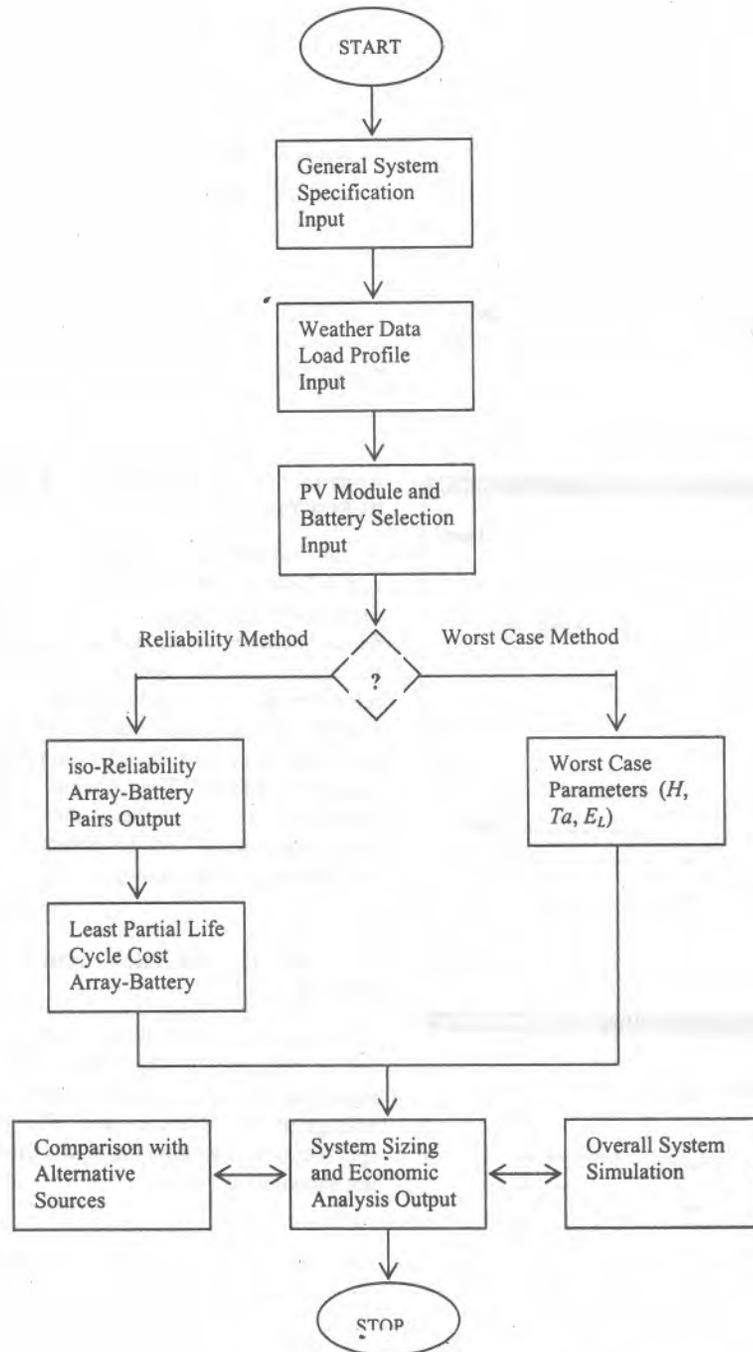


Figure 1-1 PVSOF99 Flow-Chart

## APPENDIX B- Major PVSOFT99 Forms

Figure 1-2 MAIN - PVSOFT99

Figure 1-4b LOCATION-APPLICATION for  
*Electrification*

Figure 1-3 SUB MAIN - PVSOFT99

Figure 1-4a LOCATION-APPLICATION  
for *Water Pumping*Appendix C - Application Examples using  
PVSOFT99

As an illustration, hypothetical DC electrification and AC water supply systems are considered. Each illustration represents a class of application in which there are input and output data specific to the class. The DC system is designed using the reliability algorithm developed by the author and the AC system is an example of the worst case algorithm modified by the computer generated random numbers. The screens shown for the examples are only the major ones and the remaining screens can be observed by executing the program on the accompanying disk.

C1 - DC Electrification System - Reliability  
Method

This application example is located at Addis Ababa and is required for the whole year. Suppose an operating voltage of 120 V and an interface input voltage of 125 V are chosen. The general system specification is entered on MAIN and SUB MAIN, not shown here.

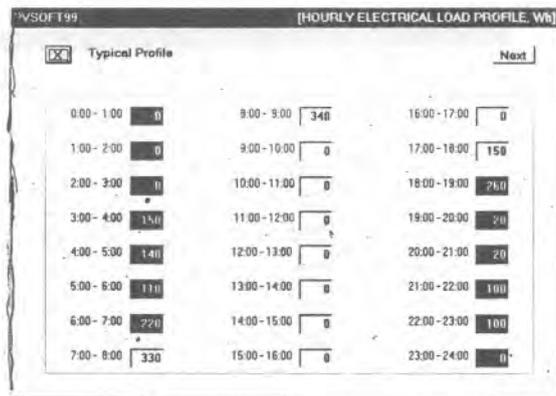


Figure 1-5 HOURLY LOAD PROFILE

An hourly load profile, shown in Fig. 1-5, is given such that daily total of 1940 Wh with night time component of 1120 Wh results in the design load computation. Thus the reliability is a function of only the irradiation and temperature. The following combinations of irradiation, temperature and number of autonomous days are obtained for a specified reliability of 90%.

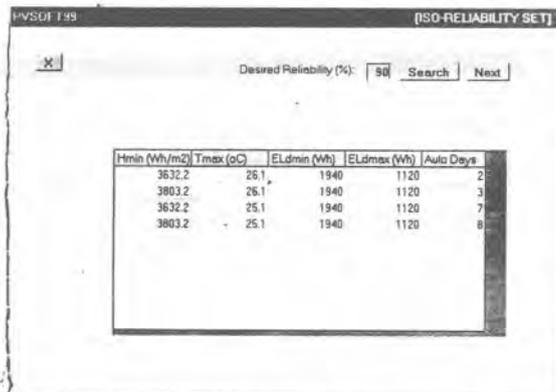


Figure 1-6 ISO-RELIABILITY SET

The temperature and irradiation values determine the array size where as the night load component and the number of autonomous days determine the corresponding battery size. The program performs a preliminary economic comparison of the options and displays the following data.

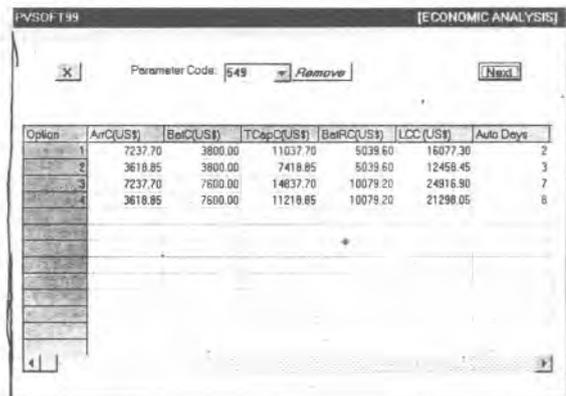


Figure 1-7 ISO-Reliability Set (Economic Analysis)

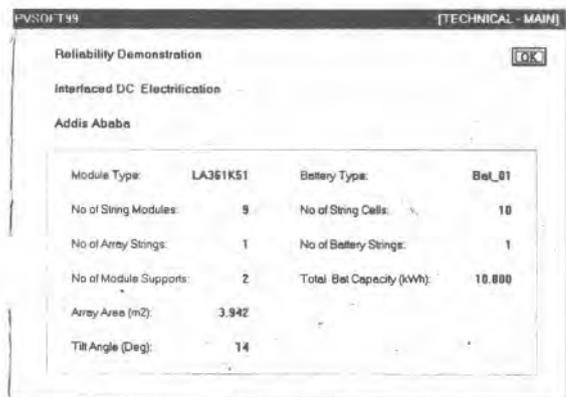


Figure 1-8 TECHNICAL - MAIN

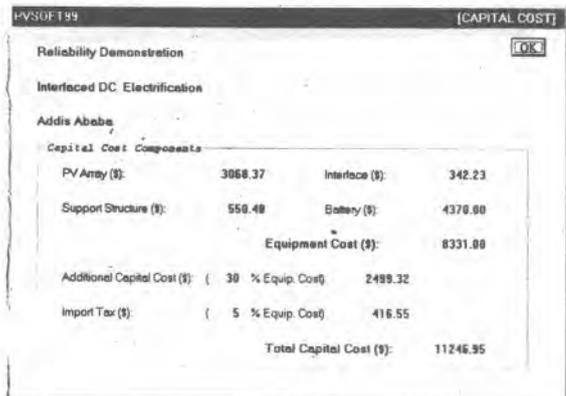


Figure 1-9. CAPITAL COST

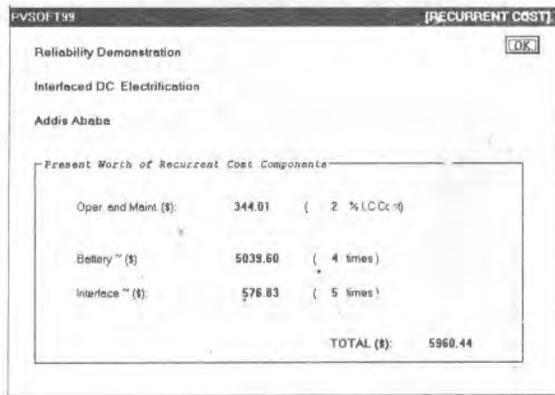


Figure 1-10 RECURRENT COST

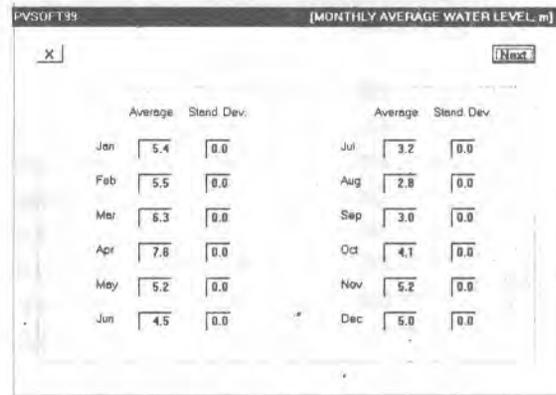


Figure 1-12 MONTHLY AVERAGE WATER LEVEL

The program selects the combination with the least life cycle cost and proceeds with the computation of the remaining technical and economic data to be available on PROJECT as shown in Figs. 1-7, 1-8 and 1-9.

**C2 - Direct DC Water Supply System - Worst Case Method**

Metema (12.95° N, 36.07° E), located at an altitude of 803 m above sea level, is chosen as an example for water pumping. The water is assumed to be pumped from a local well with parameters as shown on WATER SOURCE.

The users are villagers and a limited size of livestock. The program computes the daily water requirement using standard per capita figures recommended by WHO. 5 days of autonomy are considered enough to limit the size of the storage tank. An operating voltage of 100 V is chosen. The worst case method is assumed.

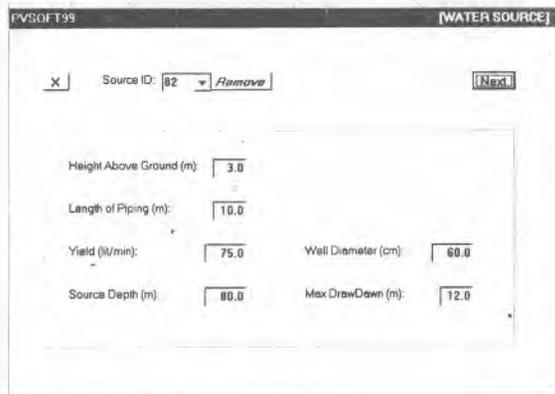


Figure 1-11 WATER SOURCE

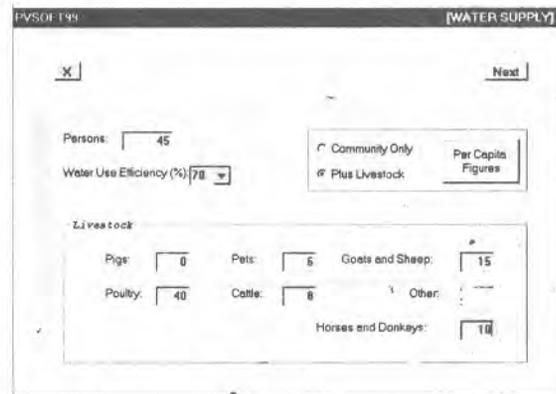


Figure 1-13 WATER SUPPLY

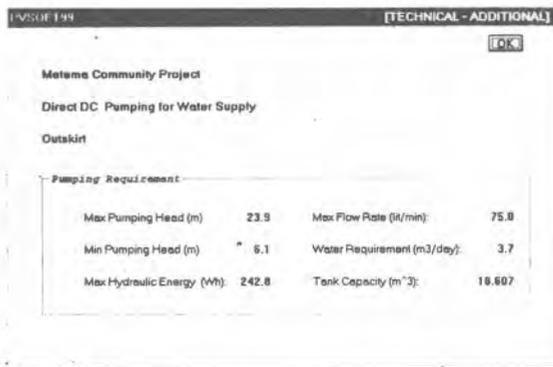


Figure 1-14 TECHNICAL - ADDITIONAL

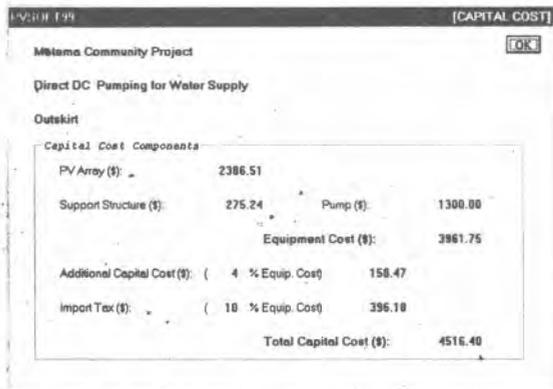


Figure 1-15 CAPITAL COST

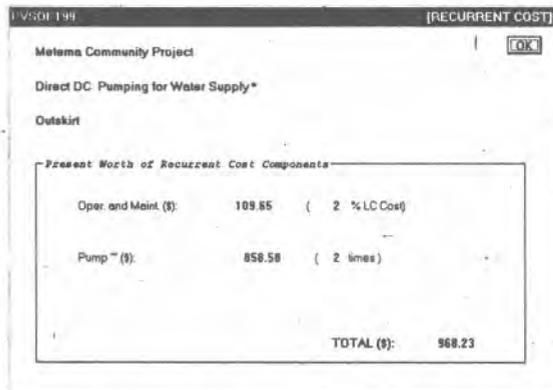


Figure 1-16 RECURRENT COST