A Hierarchical Model for Photovoltaic System Performance Analysis

by

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(ABSTRACT)

The advent of new technology and ever escalating fuel prices would make alternate energy sources increasingly important in coming years. This study is aimed to develop the tools required to analyse the feasibility of alternate energy sources. Although the study refers specifically to solar energy, the methodology is good for any alternate energy source.

Four models are used to analyse complete performance of a photovoltaic(PV) system. The SOLAR model estimates the total radiation at a site. The PVPM model calculates the PV output for this total radiation. The PRODCOST and LIFECC models analyse the economic performance of the photovoltaic system.

This works as a complete package which by itself will help to make preliminary analysis of various sites before making a further indepth study for a selected few. The model is intended to be a part of a larger model, which will be a complete planning tool for power system expansion in developing countries. The efforts towards this direction can be continued further by developing various models, each analysing a special task. The models can be integrated to form a hierarchical structure which completely model the power system in developing countries.

ACKNOWLEDGEMENTS

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1.0 INTRODUCTION

Many independent studies have been done to find the feasibility of integrating alternate energy sources with the electrical grid. Most of these studies are however of a general nature. With the ever increasing demand for electricity and diminishing supply of conventional energy sources, the requirement for alternate energy sources is inevitable within the next few decades. The strong opposition to nuclear energy will also help the growth of these sources. Wind energy in the form of wind farms is already commercially used in California.

The studies carried out so far can be broadly classified into two types.

- Use of microcomputers in power system planning
- Use of alternate energy sources in developing countries

The present study tries to integrate both these aspects and focusses specifically on use of microcomputer in photovoltaic system planning in developing countries.

1.1 BACKGROUND INFORMATION:

Ramakumar[1] analyses various models for integration of alternate sources with the electrical grid. The economies of renewable sources are also discussed in the paper.

Munson J. et al.[2] discusses in depth the use of microcomputers in energy system planning for developing countries. Various planning strategies and common pitfalls are also discussed in the report.

Meier and Mubayi[12] discuss the problems of national energy system planning by breaking it down to regional planning. As the data has more significance at smaller level this helps to improve the planning process.

Meier[4] discusses the network, economical and other models required for the energy system analysis for developing countries. Various models are discussed in detail with examples.

Rahman[11] discusses the use of hierarchical structure in deciding the national policy for power system planning. The hierarchy helps to break down the problem into smaller problems which can be tackled independently.

The present study develops a hierarchical structure for photovoltaic(PV) system performance evaluation. The complete modelling can be done on microcomputers and thus can be easily adopted for developing countries. The entire model can be broken down into four smaller models as shown in Figure 1 on page 3.

The first model finds the total global radiation for a chosen site on clear sky days. The radiation is used as an input to the next stage, the photovoltaic performance model(PVPM). This model evaluates the per-

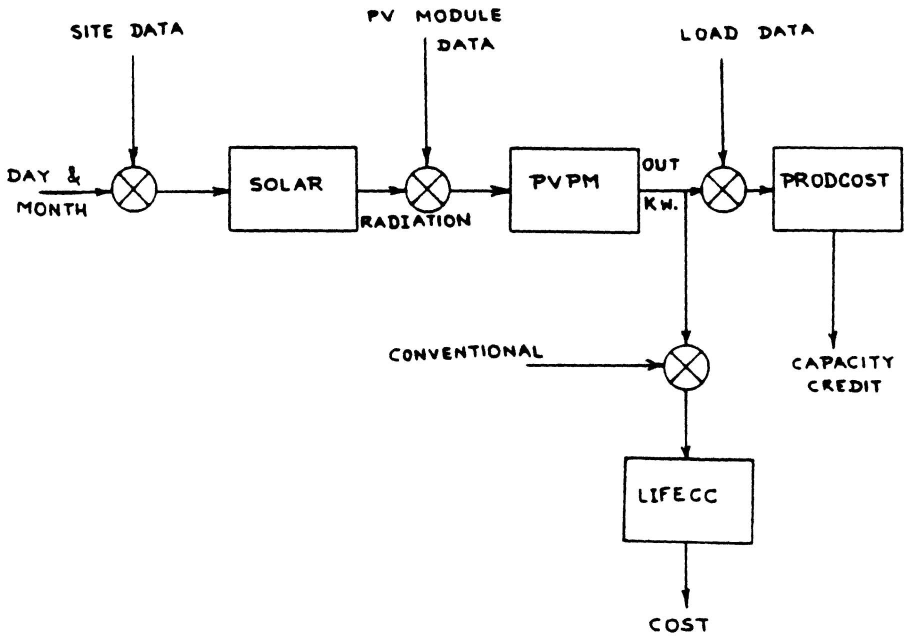

Figure 1. Flowchart for the PV System Performance Evaluation

formance of the chosen PV system for the radiation found in the first stage. The output of this model is in the form of total energy generated in KWH. This is used as input to the next model, the PRODCOST model which estimates the production cost for a specified load and a set of generators. This model also gives the loss of load probability(LOLP) for the specified load and generation. This model is used to determine the amount of conventional generation the PV system would replace without appreciable change in system performance. The capacity to be replaced is called capacity credit of the system.

Another model the LIFECC model is used to compare the cost of PV and grid energy. This model helps to determine the economic viability of the PV system. This model is quite elaborate and uses various indices to find the PV system electricity cost. This model can be used in an iterative process to find the lowest possible cost of solar energy.

The chosen site for the PV system was Raleigh in North Carolina. The site was chosen due to availability of required data at the site. The load profile used is a weighted composite system load for Carolina Power and Light(CP&L). The generation is the actual set of generators in the CP&L system. The load was represented by a load duration curve in the form of a fifth order polynomial with unity Y intercept. The polynomial was found on IBM-3084 using available Statistical Analysis System(SAS) routines for curve fitting. The function can also be done on a microcomputer. The PRODCOST routine was used to find capacity credit for a 500 MW PV system assuming a load growth rate of 3%. The LIFECC model is used to compare the electricity cost for a 1 MW PV system, with the grid electricity cost.

The first model to find total global radiation at a site, on a given day was developed by the author. It is a simple model which uses the standard equations to calculate the radiation value in KW/Sq.m. The next three models namely PVPM, PRODCOST and LIFECC are available as public domain software and were picked up for the present study. The models are easy to understand, do not require a lot of data and are compatible with IBM PC. The compatibility with PC helped in adopting the models for the present study. Each of these models and results obtained from them are discussed in detail in the following chapters.

Chapter 2 deals with calculating the amount of available radiation at the chosen site. It thus gives the potential of the site for a photvoltaic system. The model was developed by the author using standard equations giving total global radiation at a site. The model can also be used to maximise the incident radiation by tilting the collector.

Chapter 3 deals with calculating the output of the chosen photovoltaic system for the radiation estimated in chapter 2. The module for the photovoltaic system chosen is the one actually used at the CP&L test facility in Raleigh. The number of modules to be used is determined according to the desired system size. To calculate capacity credit a system size of 500MW is used, while for economic analysis a system size of 1MW is used. The model thus gives the actual amount of energy available from the photovoltaic system, in KWH.

Chapter 4 deals with one of the cost aspects of the system. It calculates the amount of conventional generation that can be replaced due to the photovoltaic system without altering the performance of the system. The loss of load probability is the performance index used in this case.

It also gives the amount of money saved in $ from fuel cost due to the photovoltaic system. This along with the constructional cost of PV and conventional generators can be used for further detailed cost analysis.

Chapter 5 deals with a direct aspect of cost analysis. It actually calculates the comparative cost of photovoltaic and conventional energy over the life period of the photovoltaic system. Various options are analysed here for the photovoltaic system to find the best possible alternative. This gives us the idea about feasibility of the photovoltaic system in near future.

The last chapter discusses the conclusions drawn from the study and shows how this model can be integrated as a part of a larger model. The larger model will serve as a planning tool for the developing countries.

2.0 MODEL FOR TOTAL RADIATION

The basic step in analyzing the feasibility of a photovoltaic system is to find the potential for such a system at a site. This involves estimation of total radiation available at the site, throughout the year. It is easy to estimate total global radiation on a clear sky day, however it is difficult to account for cloud cover and other climatic effects on the radiation value.

To overcome this difficulty, one alternative is to use typical meteorological data for the site. However such data is not available for most of the potential sites for a PV system. This is especially true in developing countries where the efforts to collect such data are minimal. Another approach is to use clear sky radiation for such a site and then account for cloud cover on a percentage basis.

The present study takes the latter approach. The model predicts total global radiation based on standard formulae, which calculate the radiation, given the value of solar angles. The program is written in FORTRAN and run on IBM-PC AT. A sample output from the program is shown in appendix A. The model is fairly easy to understand and adequate for the evaluation.

The model developed calculates total global radiation in KW/Sq.m. on a horizontal surface. Once a site to be analysed for the PV system is determined, the model calculates the total global radiation on any day of the year at the site, using geographical data about the site. The total radiation is then used as an input for the next stage, the PVPM model which generates the possible output of the particular PV system to be installed at the site. The output is then used for economic analysis.

The clear sky radiation from sun on any day, is given by equation 2.1.

2.1 AVAILABLE INSOLATION

The angle of declination is 23.45 on June 22 and -23.45 on December 22.

$$S = S(\mathrm{Sin}(\theta+\alpha)\mathrm{Cos}(\delta)\mathrm{Sin}(\phi)+\mathrm{Sin}(\delta)\mathrm{Cos}(\theta+\alpha)).$$

Where

S = Maximum total global radiation possible
δ = Angle of declination
θ = Angle accounting for latitude
ϕ = Angle accounting for time of the day
α = Tilt of the flat plate module

The angle of declination varies sinusoidally during this period. This angle on any day of the year is given by equation 2.2

$$\delta = 23.45 * \mathrm{Sin}(360*(284+n)/365) \quad \ldots\ldots \quad (2.2)$$

Where

δ = Angle of declination
n = Julian day

The angle θ takes care of variations due to locations and is given by equation 2.3, while ϕ is responsible for variations of the Sun angle during a day. Thus ϕ is the actual sun angle at the site at the chosen hour.

$$\theta = \pi / 2 - \text{Latitude} \quad \ldots\ldots\ldots \quad (2.3)$$

The maximum possible radiation depends on altitude, day of the year and climatic conditions. The maximum possible radiation at any site on earth on any day is 1.353 KW/Sq.m. (Solar Constant). . The program calculates the maximum possible radiation on the day based on these variables and uses it in equation 2.1 to calculate the actual radiation. The angle α gives the tilt of the flat plate module with the horizontal. This can be used to maximise output of the PV system at any particular time of the year, depending on the load profile of the system. In two axis tracking systems this is used to maximise the system output at every instance during the operation of the PV system.

2.2 INPUT TO THE MODEL:

The site chosen for the study is Raleigh in North Carolina. The site was chosen due to availability of field data at the site. The basic inputs to the model are data about the site and the day and month on which the radiation is to be calculated. The site data that is required is latitude, longitude and altitude of the site from sea level. The latitude and longitude are specified in degrees while the altitude is in meters. As a finer approximation the type of climate at the site is required. For this purpose the types of climates are divided into four broad classes namely tropical, mid latitude summer, mid latitude winter and subarctic summer. The site data required for the program is shown Figure 2 on page 11.

To make allowance for difference between clock and solar time the standard longitude for the particular site in question is needed. If the site is in the United States the program finds the required standard longitude. However, for any other site, it needs to be supplied. It is possible to program all standard longitudes and let the program find the standard longitude for any desired site.

The program is written for the IBM-PC and is user interactive. It prompts the user for various inputs and options. Thus no data file is required. The results are however written to a output file for later reference. The option to rerun the program several times for the same or different sites can be used effectively for comparison between different possible sites.

2.3 PROGRAM DEVELOPMENT:

The earth is divided into longitudes which run North-South and latitudes which run East-West. As the solar time at any site is determined by solar angles at the site, the solar time changes from longitudes to longitudes. While on a particular longitude the solar time is constant for all latitudes. The clock time on the other hand is the actual time

Site	**Raleigh North Carolina.**
Latitude	35° 47'
Longitude	78° 39'
Altutude	360 feet or 110 m above sea level.
Climate Type	Mid latitude Summer/Winter

Figure 2. Geographical data about the Site

shown by clocks at the site. The clock times are so adjusted that at all standard longitudes the solar time and clock time are identical. As the sun angles are constant for a particular solar time at standard longitudes, the azimuth angle of Sun at 6.00 a.m. is 0^o at all standard longitudes. The azimuth angle changes by $\pi/12$ for each hour. Thus the azimuth angle of Sun at all standard longitudes, at a particular clock time, which is also the solar time, is same. The program first initializes the Sun angle at hourly intervals assuming the location to be on standard longitude. The relation between solar and clock time at any location is given by equation 2.4.

$$\text{Solar time} = \text{Standard time} + 4(L_{stn} - L_{loc}) + E \quad .. \ (2.4)$$

where

$E = 9.87\mathrm{Sin}(2B) - 7.53\mathrm{Cos}(B) - 1.5\mathrm{Sin}(B)$

$B = 360(n-81)/364$

n = Julian day

L = Longitude Standard/Location

This gives the difference in minutes between solar and clock time. The difference in minutes is then converted into angle measure in radians. The correction applied to solar angle at standard longitude gives us the actual solar angle at the site chosen, at hourly intervals. These angles are used in equation 2.1 to calculate the total radiation, at each hour.

The angle of Sun at sunrise is given by equation 2.5.

$$\sin(\phi_m) = -\tan(\delta) / \tan(\theta+\alpha) \quad \dots (2.5)$$

Where

ϕ_m = Angle of sun at sunrise

δ = Angle of declination of sun

θ = Angle accounting for latitude

α = Tilt angle of collector

Thus knowing the sunrise angle and angle of sun at each hour of the day the sunrise time can be easily calculated. Except for the discrepancy between solar and clock time, the sunrise and sunset are symmetric about noon. Taking into account this discrepancy, the sunset hour can be easily found from the sunrise hour. The radiation from sun is then calculated at each hour between sunrise and sunset.

The maximum possible total global radiation at a site is determined from geographical data about the site. The maximum at any time, at any site on earth is 1.353 Kw/Sq.m. (Solar Constant) This is for perpendicular incidence of sun rays. The maximum at the site depends on latitude, altitude and climatic conditions at the site, as shown by equation 2.6.

$$\text{Cosz} = S_r/S \quad \dots (2.6)\text{a}$$

$$\text{TB} = (\text{A0*R0})+(\text{A1*R1})*\text{EXP}(-(\text{K*RK/Cosz})) \quad \dots (2.6)\text{b}$$

$$\text{Maximum}= 1.353(1+.033\text{Cos}(2*n*\pi /365))*\text{TB} \quad \dots (2.6)\text{c}$$

Where

A0,A1,R0,R1,K,RK = constants depending on climate type

n = Julian day

S_r = Maximum radiation at the site

S = Solar constant 1.353 KW/Sq.m.

Cosz varies continuously throughout the day and thus the maximum possible radiation is different at each hourly interval.

2.4 SUBROUTINES:

There are three subroutines used in the program, each with a specific task. The subroutines are integrated as discussed in the previous section. The function of each subroutine is discussed briefly below.

2.4.1 NUMDAY:

As the name suggests this routine calculates the day of the year on which total radiation is desired. As the year does not play any role in the calculation a non leap year is assumed. The results should not however differ to any appreciable extent for a leap year.

2.4.2 CORRECT:

This routine calculates the correction required to account for the difference between solar and clock time. The correction calculated in minutes is converted to angles in radians and is applied to solar angles at standard longitude to get solar angles at the site. This stores the corrected sun angles at hourly intervals, at the site which are actually used in equation 2.1.

2.4.3 PEAK:

This routine calculates the maximum possible total global radiation at the site. As mentioned earlier the maximum value changes continuously and hence is calculated at hourly intervals. Finer adjustment to the maximum is done depending on the climatic type and altitude at the site.

2.4.4 MAX:

This routine calculates the tilt angle required to maximise radiation at a particular time of the day. In the present study the radiation is maximised at 12 noon on 22nd of each month. Although the radiation is maximised at 12 noon it may be less than the flat plate case at other hours of the day. Thus it is possible that the total output for the day may decrease for tilted collector compared to zero tilt case. In such a case the collector should not be tilted for that month.

The working of the program and flow of control is shown by a flow chart in Figure 3 on page 16.

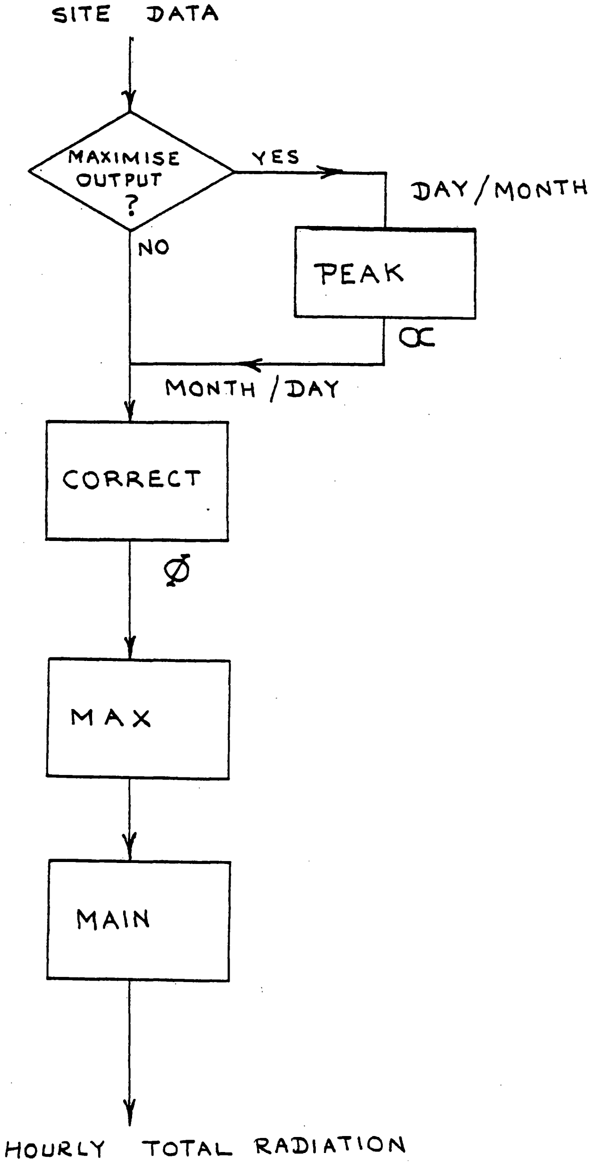

Figure 3. Flow-chart for the Solar Model.

2.5 OUTPUT FROM THE MODEL:

The program was written in FORTRAN and was run on IBM-PC AT. The output from the program is the value of total global radiation in Kw/Sq.m., at the chosen site, at hourly intervals, on the chosen day.

The value of total global radiation is as found on the hour. It is assumed to be constant during that hour. Thus sunrise between any two hours is shown at the following hour that is, if the sun rises anytime between 6 and 7, a nonzero output from the program is generated only at 7 a.m. This value is assumed to be constant for the following hour. The loss of radiation during the sunrise hour is then compensated by the positive effect at the sunset hour. These values of total radiation are used in the next stage, the PVPM model, to calculate the energy produced by the PV system during that hour.

To validate the model, field data from the site was used. The typical meteorological year (TMY) data was obtained on tape from the National Climatic Center[8] and was transferred to the IBM 3084 at Virginia Polytechnic Institute and State University. The data gives the amount of energy collected during that hour at the observation point and is in J/Sq. m. It was first converted to KW/Sq.m and was used to validate the model. Since the data was in J/Sq.m it takes into account the change in radiation during the hour. However the model predicts the radiation value on the hour. In spite of this discrepancy the model was found to be adequate. To account for this discrepancy, value of radiation at every half hour can be calculated, thus compensating the positive and negative effects of each half hour. The value can then be assumed constant for that hour.

The values of radiation found by the program were plotted against the field data for arbitrary days of the year. Since the program estimates clear sky radiation, only the days with clear sky were chosen for validation. The nature of the shape of the radiation vs. time curve gives an idea about the nature of sky. On a clear day the curve is symmetric in nature. The performance of the model on some of the arbitrarily chosen days is as shown by graphs in appendix B. To get an idea about the radiation values, the values from model and field data on a typical day are shown in Figure 4 on page 19. The graph for the day is shown in Figure 5 on page 20. Some more graphs comparing the estimated value with the field data are shown in appendix B.

The graphs give us a fair idea about the validity of the model on clear sky days. Except for the condition of clear sky the days chosen were at random. The model thus predicts the clear sky radiation to a reasonable extent. Although the graphs are shown only for a few days the model was analysed extensively and was found satisfactory. As the aim of the project was to find a relatively simple model to evaluate the performance of a PV system, the model fits the goal adequately.

The program has an option for tilting the collector to maximise the radiation on any particular day. The program by itself will calculate the required tilt angle. This will help to increase the incident radiation and thus will prove beneficial for the PV system. As mentioned earlier a single or double axis tracking system can be used for this purpose.

It was found that for the site chosen, the total radiation incident on the collector can be increased on an average by about 5%, by tilting

May 5

Time	Program Estimation	Tmy Data
1.0 - 5.0 a.m.	0.0	0.0
6.0 a.m.	0.0331	0.001
7.0 a.m.	0.1637	0.047
8.0 a.m.	0.3360	0.184
9.0 a.m.	0.5014	0.347
10.0 a.m.	0.6359	0.538
11.0 a.m.	0.7255	0.682
12.0 noon	0.7618	0.795
1.0 p.m.	0.7417	0.840
2.0 p.m.	0.6668	0.790
3.0 p.m.	0.5440	0.698
4.0 p.m.	0.3856	0.525
5.0 p.m.	0.2119	0.322
6.0 p.m.	0.0615	0.127
7.0 p.m.	0.0004	0.002
8.0 - 12.0 p.m.	0.0	0.0

Figure 4. Comparative radiation for a typical day

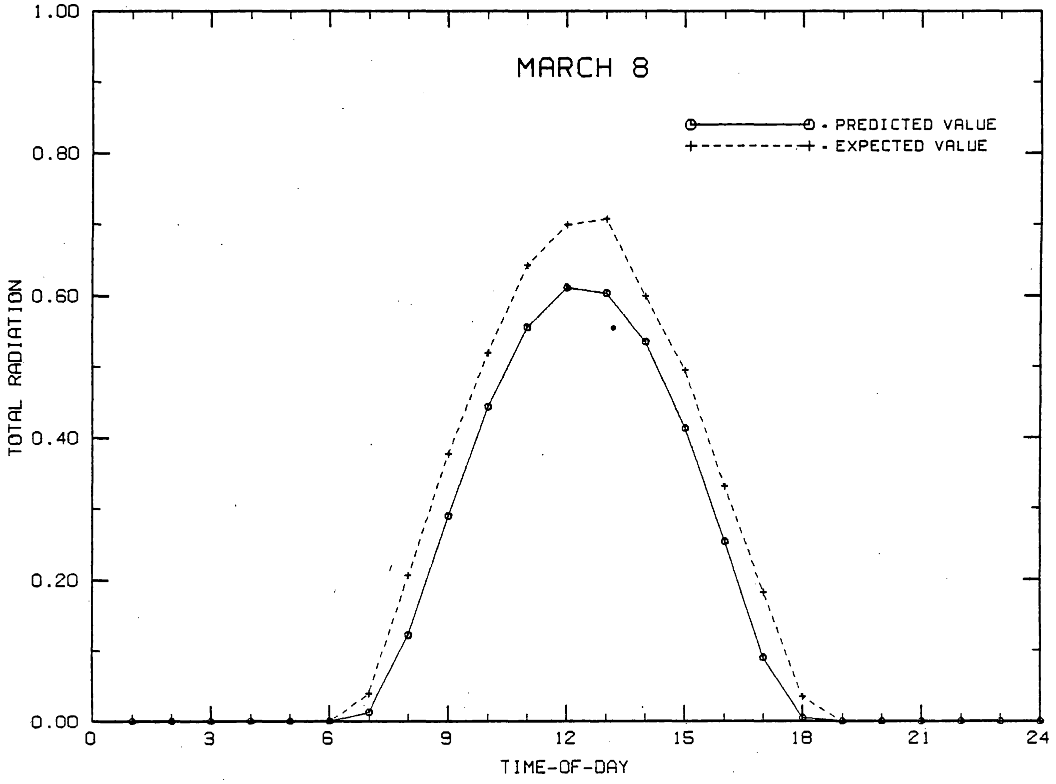

Figure 5. Graph for Comparative Radiation on a Typical Day.

	MAY 22 Radiation(KW/Sq.m.)	
Time	Flat Plate	Collector Tilted
1.00a.m.- 6.00a.m.	0.0000	0.0000
7.00a.m.	0.0336	0.0517
8.00a.m.	0.1694	0.2536
9.00a.m.	0.3376	0.4833
10.00a.m.	0.4855	0.6796
11.00a.m.	0.5903	0.8170
12.00a.m.	0.6398	0.8817
1.00p.m.	0.6292	0.8679
2.00p.m.	0.5595	0.7768
3.00p.m.	0.4379	0.6168
4.00p.m.	0.2795	0.4050
5.00p.m.	0.1139	0.1744
6.00p.m.	0.0123	0.0162
7.00p.m.- 12.00p.m.	0.0000	0.0000

Figure 6. Effect of tilt on radiation.

the collector. The values of incident radiation for a flat plate and tilted collector on a typical day are as shown in Figure 6 on page 21. The latter chapters also analyse the effect of the collector tilt on PV output and cost of PV energy.

The graphs for the period between November 1 and April 1 show a discrepancy of an hour specially at the sunset. This is due to the daylight savings time during this period. The clocks are set an hour back on the last Sunday of each October and are reset on the last Sunday of each April, every year. The program however sees the correct solar time during this period. Thus during this period the difference between solar and clock time is increased by an hour. A sunset at solar time 7 p.m. will be shown by the graphs for field data at 6 p.m. This is due to the fact that field data, shows actual reading at each clock hour, will show the sunset at 6 p.m. However the program sees the sunset at correct solar time of 7 p.m. This discrepancy can be easily accommodated in the program. However since the potential of the site for a PV system is unaffected due to this discrepancy, it is neglected.

3.0 PVPM SYSTEM MODEL

The first module calculates total global radiation at the site of study. It thus gives potential of solar energy at the site. An equally important issue, however is to tap the available resource using PV cells. The photovoltaic performance model(PVPM) [1] module calculates the amount of energy that can be tapped from the available radiation using the photovoltaic cells.

The energy from sun is captured using Silicon or Galium Arsenide cells. As the technology for silicon cells is in developmental stage the efficiencies of these cells are low and the production cost is high. A crystalline silicon cell has an efficiency, at best of 20% while an amorphous silicon cell has an efficiency of at best of only 10%. The poor conversion efficiencies is a major drawback for commercial development of large scale PV systems.

To partly compensate for the poor conversion efficiency concentrators or tracking systems can be used. The concentrators focus the concentrated beam on the PV module. A single or double axis tracking system can be used to change the direction of the PV module such that it is always perpandicular to the direction of incidance of sun rays. A double axis tracking system follows the sun throughout the day and during seasons, while a single axis tracking system has only diurnal tracking. Obviously a double axis tracking increses the PV output more and is thus more costly

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[1] Developed by Electric Power Research Institute

than single axis tracking. As a compromise a single axis tracking with manual adjustments once a week, to account for seasonal changes can be used.

For the present study a PV system already installed at CP&L test facility at Raleigh was chosen. The modules are SX-38 ^{TM} from the Solarx corporation. Each module weighs 16 pounds and is 17.5'' X 38.25'' in dimension. The electrical characteristics of the module are shown Figure 9 on page 28. The typical peak power output of the module is 40 Watts. A panel is made up of number of such modules. Panels are commercially available in different ratings. The cost of a panel is usually specified in $/W and the approximate present day cost of a panel ranges from $5-10/W. Depending on the system capacity to be built a number of such panels will have to be integrated.

The PVPM module was used to calculate the output of these modules for the radiation estimated by the first module. The module output varies appreciably with temperature. As the module temperature goes up, the output goes down. The actual temperature data available from the site was used along with the estimated radiation data. The temperature data is for a typical meteriological year (TMY Data). Since efficiency of the PV cells is inversely proportional to temperature, within the operating range, the temperature affects the output of the module appreciably. Thus other factors being equal, a cooler place will be preferred for a PV system.

The inut data required for the PVPM module is shown in Figure 7 on page 25 and Figure 8 on page 26. Except for radiation

Variable	Unit	Description
APCONC	M ** 2	Area of concentrator Aperture
APMOD	M ** 2	Area of flat plate module
CK1 & CK2	%	Coefficients of Inverter efficiency equation
DCMAX	KW	Maximum input power rating of the inverter
EFFREF	%	Efficiency of module at reference temp.
ICOLCT		Indicator for type of Collector
ITRACK		Indicator for type of tracking system
NCONC		Number of Concentrator Units
NMOD		Number of Flat Plate Modules
OUTK		Factor accounting for miscellaneous losses
PLTLT		Angle between horizontal and array plane
SFAZM		Surface azimuth angle of flate plate array
TCK1 & TCK2		Coefficients of cell temperature equations
TEFFC	%	Loss of module efficiency/degree rise in temp.
TREF	C	Cell temperature ar referance

Figure 7. System Input Variables for PVPM Model.

Variable	**Unit**	**Description**
IHOUR	h	Hour of the day (0 to 23)
IMIN	min	Minute of the hour (0 to 59)
INDIANS		Indicator for type of insolation data
IYEAR	yr	Year of study e.g. 1984
LST	°	Longitude of local standard meridian
MALT	m	Altitude of the site
MDAY		Day of the month (0 to 31)
MONTH		Month of study (0 to 12)
TAMB	°C	Ambient temperature
TDN	KW/Sq.m.	Direct normal insolation intensity
TOTALR	KW/Sq.m.	Total horizontal insolation (direct + diffuse)
TPOA	KW/Sq.m.	Total plane of array insolation (direct + diffuse)
XLAT	°	Latitude (North positive)
XLONG	°	Longitude (0 to 360 starting at Greenwich)

Figure 8. Weather Input Variables for PVPM Model.

and temperature all other data is fixed once the site for analysis is chosen. This data can thus be directly incorporated in the source file. The program was modified to read temperature and radiation data for a 12 hour period at hourly intervals. Thus by repeated execution of the program the output for the entire day can be calculated in one run. The program can be modified further, by repeated execution in a DO loop to calculate the output of the PV system for the entire year.

3.1 PROGRAM DEVELOPMENT:

The program is available as a public domain software and it was adopted for IBM-PC with some modifications. The program is broken down into smaller subroutines, each with a specific function. This makes the program easy to understand and debug.

The program accepts input data about available radiation and type of PV cell to be used. It then calculates the amount of d.c. power available from this radiation. The losses in the inverter are separately accounted for in a subroutine, which gives the available a.c. output. The miscelleneous losses are then accounted for in a subroutine OUTK and this gives the actual a.c. power available for the given radiation. Due to the inverter model chosen, the inveter efficiency plays a very important role in this model, as explained later in this chapter. A flow chart for the photovoltaic performance model(PVPM) is shown in Figure 10 on page 29.

The program was run to get output for the chosen PV system for the estimated radiation. The output of the program was used for cost analysis by following modules. The program accepts as input the value of total

	12-volt	**6-volt**
Guranteed Minimum Peak power	38 W	38 W
Typical Peak Power	40 W	40 W
Voltage at Peak Power	16.2V	8.1V
Current at Peak Power	2.5A	5.0A
current at Specified Voltage	2.6A 15V	5.2A 7.5V
Short Circuit Current	2.8A	5.6A
Open Circuit Voltage	20.2V	10.1V
Temperature Coefficient of I	2.7mA/°C	5.4mA/°C
Temperature Coefficient of V	-79mV/°C	-40mV/°C

Figure 9. Typical Electrical Characteristics of SX-38 Module

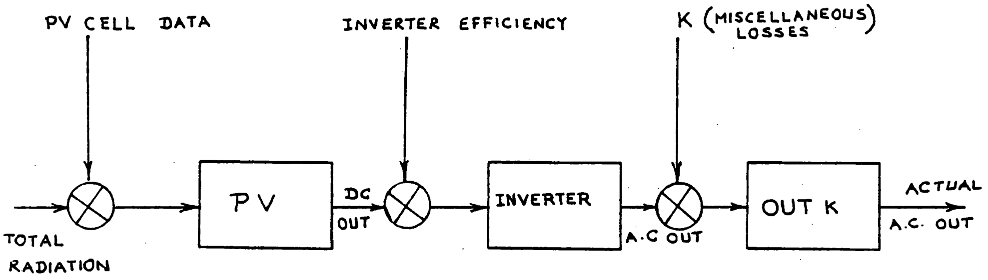

Figure 10. Flow Chart for the PVPM Model

global radiation in KW/Sq.m. as estimated by solar module and the temperature at the site obtained from a typical meteriological year data. These values along with the data about the site and data about the planned PV system are used to calculate the output of the PV system at the chosen site.

Various options such as use of concentrators, single or double axis tracking etc. can be analysed using the options offered by the program. Since the size of PV system desired was very large, a tracking system was thought to be too expensive and was not used. For the purpose of cost analysis, however the effect of tracking is analysed in chapter 5. The concentrator was not used due to the lack of exact data about the cost. This also leaves us with some margin in the results, as the output of the system would be much higher if concentrators were used. This would thus partly compensate for the favourable effect on PV system output, created due to the assumption of clear sky, alternatively the study can be performed by using typical meteriological year data and use of concentrators. However, such data is not available for all potential sites for a PV system, and collection of such data would require efforts of many years.

The program has options to use total horizontal, total fixed plane of array or direct normal insolation depending on the data available. If required the subroutine SPLIT divides total horizontal insolation into normal and diffuse components. Under clear sky conditions, the diffuse component has less energy compared to direct component. In this case total horizontal radiation is used. The subroutine SPLIT is based on the insolation split model developed by Aerospace Corporation and documented in aerospace report ART-81(7878)-1. The code has been slightly modified to fit into the PVPM model.

Depending on the type of insolation to be used, type of collector and tracking scheme only certain combinations of these are allowable. The program checks the compatibility of these indices and if required generates an error code. For each of these combinations the corresponding subroutine calculates the amount of usable insolation at apperture.

The usable insolation is then used to calculate power output of the entire module taking into account the number of modules, area of each module and efficiency of the module. This gives the actual output of the PV system. The losses in the power conditioning system (Commonly known as PCS), however are still unaccounted for. This output is then used in subroutine INVOUT to find a.c. output of the inverter for this d.c. power input. This also calculates the efficiency of the inverter depending on efficiency equation for the inverter, as given by equation 3.1.

$$\text{Inverter Efficiency} = CK1 - (CK2/\text{Inverter Power Input}) \quad ..(3.1)$$

where

CK1 and CK2 = Coefficients of efficiency equation

The efficiency is proportional to the d.c. input power. It increases with increase in d.c. power generated by the PV cells. This gives the a.c. output of the system. Various miscellaneous losses in the system are then accounted for in the subroutine OUTSYS and this gives the actual a.c. power available from the PV system.

As mentioned earlier the efficiency and hence output of a PV cell varies appreciably with temperature. To account for this, the subroutine SCTEMP calculates cell temperature depending on ambient temperature and power output using equation 3.2.

$$\text{Cell temperature} = T1 + TCK1(TPINSL) + TCK2 \qquad \ldots \quad (3.2)$$

where

T1 = Ambient temperature

TPINSL = Insolation intensity at module aperture

TCK1, TCK2 = Coefficients of cell temperature equation.

The program was run using the actual data available about the PV module, known data about the site, and estimated radiation by the solar model. The results obtained during various runs are discussed in detail in the following section.

3.2 PROGRAM OUTPUT:

This model is the main link in the entire PV system performance evaluation. The analysis of feasibility of the PV system in the following two chapters is dependant entirely on the output of this model.

The output of the model is in the form of amount of KW generated due to incident radiation at hourly intervals. The value in KW at an hour is the amount of power generated on the hour by the PV system. This KW amount is assumed to be constant for the following hour and hence it is also numerically equal to the KWH generated by the PV system during the hour.

The total energy generated during a day can then be calculated by summing up the hourly output at each hour.

As mentioned earlier the data about the module is the actual data, as given in Figure 9 on page 28. Thus the output of this model can be validated against the field data obtained by the system.

In order to obtain a consistent method of comparison, capacity factor of the system is used as an index for validation. Capacity factor for any system is given by equation 3.3

$$\text{Capacity Factor} = \frac{\text{Total energy generated in time T}}{\text{T} * \text{(Rated power of the system)}} \quad ..(3.3)$$

Thus it is clear that the capacity factor is independent of size of the system and thus has a distinct advantage over the actual output, as an index of comparison, while comparing systems of different sizes.

The field data in the form of capacity factor was obtained from the actual system. The PVPM model calculates the output in KW for the given system. Since the data is available at hourly intervals, dividing the actual KWH output by the rated capacity gives the estimated capacity factor at hourly intervals for the system.

Three different sizes of PV systems were used for the complete analysis. For the purpose of finding the capacity credit of the PV system, a size of 500MW was used. Due to the intermittent nature of solar energy, the capacity credit for a PV system is approximately about 30% of the rated power. The smallness of the capacity credit was the incentive to use such a large system size.

To validate the model against field data and for economical analysis of the system of 1MW size was used. This is a practical size of a commercial PV systems and was found suitable for the analysis. Thus chapter 4 uses a 500MW system while chapter 5 uses a 1MW system. The size of the system should not however play any important role in the actual analysis.

The model was thus validated for a 1MW system using capacity factor as an index of comparison. Again as in the case of solar model, only the days with clear sky were chosen for comparison. The actual capacity factor and estimated capacity factor were plotted against time. The graphs obtained are shown in appendix C. The model was analysed extensively for various days. Except for the condition of clear sky the days were chosen arbitrarily and the model was found to be satisfactory. To get an idea about the values of capacity factors, the actual capacity factor and the one found by model for a typical day are shown in Figure 11 on page 35. On most days there is a sudden drop in capacity factor during evening hours just before sunset. This is probably due to the fact that efficiency of inverter is very low at lower values of DC output and hence lower values of radiation. For the inverter model, used the efficiency is found to vary from 45% to 90% for a change in radiation from 0.2 to 0.9 KW/Sq.m. The temperatures during these hours are also high compared to morning hours of low radiation. This contributes to the lowering of efficiency of PV cells. Both these factors combine to cause the sudden drop in capacity factor during pre sunset hours. With availability of more data about inverter efficiency the model can be further improved.

Time	Capacity Factor Program	 Site Data
1.00a.m.- 5.00a.m.	0.0000	0.0000
6.00a.m.	0.0	0.001
7.00a.m.	0.0233	0.135
8.00a.m.	0.2578	0.235
9.00a.m.	0.6234	0.580
10.00a.m.	0.7789	0.758
11.00a.m.	0.8608	0.838
12.00a.m.	0.8865	0.874
1.00p.m.	0.8720	0.857
2.00p.m.	0.8189	0.805
3.00p.m.	0.7244	0.715
4.00p.m.	0.4604	0.543
5.00p.m.	0.0615	0.330
6.00p.m.	0.0091	0.125
7.00p.m.- 12.00p.m.	0.0	0.000

Figure 11. Comparative Capacity Factors

As seen in the previous chapter the incident radiation is dependent on the tilt of the collector. Maximising the incident radiation, by changing the tilt increases output of the PV system considerably. This is helped to a certain extent by improvement in inverter efficiency at this higher output. To get an idea about the increase in output due to tilt, output of the PV system with and without tilt are shown in Figure 12 on page 37. The tilt angle used, is so as to maximise the output on that day. The tilt was so as to maximise the output at noon on that day. it may however happen that output for other hours may be actually less for tilted collector compared to flat plate case. Thus if the total output for the day is less for tilted collector compared to flat plate, then we may be better off not tilting the collector during that month. We observe such a thing happens for June and July at the chosen site.

The effect of tilt of collector on the cost of PV energy is analysed in chapter 5. The increase in output due to tilt may be a major favourable factor for building a PV system.

Month	Output Flate Plate (KWH)	Tilted (KWH)
January	2955.9	17136.1
Februry	7811.1	17979.1
March	13050.9	18452.7
April	16610.7	18734.7
May	19304.1	19767.9
June	20090.1	19818.1
July	19611.9	19284.3
August	18224.7	18526.8
September	14247.3	17933.7
Octomber	9605.7	17124.7
November	3948.0	17027.1
December	2222.7	16753.1
Total	147683.	218538.5

Figure 12. Effect of Tilt on Output of PV system.

4.0 ESTIMATION OF CAPACITY CREDIT

Capacity credit for an alternate energy source gives the amount of conventional generation the alternate energy source would replace, without any appreciable change in system performance. The performance index used is the loss of load probability (LOLP) of the system[4].

The permitted LOLP for a power system is usually very small, of the order of 1 day in 10 years. The intermittent nature of alternate energy sources, and the small value of LOLP required for a power system combine to make the capacity credit of an alternate energy source considerably less than its rated output. It also makes it an important index in deciding the viability of the source.

The present chapter deals with the estimation of capacity credit for the chosen PV system, at the chosen site. The load data used is a weighted composite system load for the CP&L system. The analysis also gives the amount of money saved in dollars due to saving in fuel cost. The savings can be combined with the cost of conventional generation not built due to the PV system and the cost of PV system for a detailed cost analysis. In the following sections the method for estimating capacity credit and the results obtained from the study are discussed.

4.1 METHOD OF ESTIMATION:

The alternate energy sources use natural resources to generate electrical energy. As their nature suggests they are dependent on natural resources like weather, environment etc. and have a cyclic pattern with random variation. The random and unpredictable nature of these sources makes it difficult to count them as firm generation. This also makes it impossible to include them in unit commitment. However due to their cheap availability, they will have highest dispatch whenever they are available.

To overcome this problem the alternate energy sources are treated as negative loads in power system analysis. Thus when the generators are producing some output, it helps to lessen the burden on conventional generators. When they are not producing any energy they are treated as unavailable and are neglected from the analysis.

This principle is used in the method to estimate capacity credit in the present study. The yearly load is divided into four seasons and the system performance for the load is evaluated using a production costing routine. The generation of the PV system for the period of study is then calculated using the SOLAR and PVPM models as already discussed. Treating this generation as negative load it is then subtracted from the actual 1984 load on an hourly basis. This gives us the new hourly load on the system, with a PV system in operation.

The production costing routine is run on this new reduced load and with the same sets of generators as in the original case. This represents the performance of the system including the PV arrays. As expected the total cost of generating electricity and the LOLP of the system decrease considerably. However since we are satisfied with the original LOLP value for the system, we can remove some of the generators and bring back the LOLP to the original value. This is an iterative process and by running the routine many times with different set of generators we come sufficiently close to the LOLP value for all four seasons. The amount of generation that can be dropped, with the introduction of PV in the system, without damaging the LOLP, gives the value of capacity credit for the PV system.

Another approach to the problem can also be tried. Assuming that the growth rate of all load in the system to be 3%, the new load for 1985 can be obtained. By addition of PV system the LOLP can be brought back to the original value. The amount of conventional generation that would have been neccessary to get the LOLP back to original value without the PV system gives the capacity credit for the PV system.

4.2 PRODCOST MODEL:

The production costing routine PRODCOST, used to calculate the cost of generating energy for a given set of load and generators, is also available as public domain software[5]. The routine was available on IBM 3084 and was transferred to IBM AT with certain modifications. The routine analyses the data extensively, to calculate the total cost of generating electricity, LOLP, total energy served , total unserved energy etc. The routine also gives the output of each generator in each of the period of study.

For the purpose of analysis the year can be divided on monthly or seasonal basis. The seasonal basis was used to facilitate comparison with another model, doing similar analysis on the same set of data. The model requires large amount of storage and this created some problem while transferring it to the IBM-PC. The model can analyse upto 400 generators in a system serving given load. It was transferred to the AT with little modifications required to fit it into IBM-PC AT memory. This however does not hamper the performance of the model in any way.

The model is written in Fortran and was compiled using microsoft fortran compiler version 3.2. Due to the large number of calculations involved the model takes about 70 seconds of execution time. When the updated version of the same fortran compiler was used, although the compilation was slower, the execution time decreased by 5 seconds. Since the model is run iteratively to estimate capacity credit, this proves to be a considerable improvement.

The model requires as an input the load data in the form of fifth order polynomial. The generators available, their fuel type, maintenance requirement and the heat rates. The program then schedules maintenance for the generators, after serving the load for the entire period of study. The cost of serving this load is also calculated. The program outputs the generation of each generator during every period of study The cost of total generation and loss of load probability annually and during each period of study is also calculated. Although the main aim of the program is to calculate the cost of generation, the values of LOLP calculated are mainly used in this study.

4.3 OUTPUT FROM THE MODEL:

The load data is available in the form of hourly load on the system, for the entire year. This is represented in the program in the form of a fifth order polynomial with unity Y intercept. The peak load for the period and number of hours in that period also need to be supplied. Residual load is obtained by subtracting the hourly PV output from hourly load. The residual load is also represented by a fifth order polynomial.

The polynomial fit for the load was done using SAS routine on IBM 3084. The load polynomials for reference and residual load for 1984 are shown in Figure 14 on page 44. The set of generators used was the actual set of generators in the CP&L system as shown in Figure 13 on page 43, with a total capacity of 7431MW. The program also gives total cost of generation and LOLP for each period of study and an annual value.

The program was run for residual and reference load. As expected the total cost and LOLP values decreased significantly for residual load due to addition of the PV system. The values of total cost, energy served, and peak load for each period is as shown in Figure 15 on page 45.

The LOLP was then increased by removing some conventional generation. The program was run several times on different set of generators, to get the values of LOLP sufficiently close to the original values, for all periods of study. The results obtained from some typical runs are shown in Figure 15 on page 45

4.4 DISCUSSION:

The total cost of generation shows a decrease of 18 million dollars annually, which is a considerable saving. With ever increasing prices of fuel and its inherent shortage, this amount would be much more significant in the next decade.

Unit	Number of Units	Capacity		Heat Rate		Availability
		Min	Max	Base	Peak	
1 NDYD	1	25.	220.	0.	0.	100.
2 ASHO	2	70.	196.	10633.	8943.	95.
3 CF34	2	12.	32.	14400.	10912.	97.
4 CF5	1	45.	143.	10684.	9194.	97.
5 CF6	1	50.	173.	13645.	9376.	99.
6 LE12	2	38.	78.	11560.	10678.	97.
7 LEE3	1	70.	252.	11228.	8337.	96.
8 ROB1	1	50.	174.	11321.	9069.	92.
9 ROX1	1	125.	385.	10276.	9186.	93.
10 ROX2	1	250.	670.	10076.	8750.	89.
11 RX3	1	250.	720.	10440.	8825.	86.
12 SUT1	1	35.	97.	11557.	10029.	96.
13 SUT2	1	35.	106.	10681.	8909.	98.
14 SUT3	1	125.	415.	10852.	9151.	84.
15 WP12	2	20.	49.	12132.	10765.	97.
16 WP3	1	33.	78.	10659.	9447.	97.
17 NROB	1	228.	665.	11080.	9969.	92.
18 NBRU	2	173.	790.	13580.	9270.	82.
19 IC29	9	15.	29.	13920.	13920.	92.
20 IC14	9	7.	14.	14800.	14800.	92.
21 IC52	11	26.	52.	12442.	12442.	92.
22 IC84	1	32.	84.	11446.	10289.	92.

Figure 13. Generator Data for the CP&L System

Reference Load

	Max.Load	X5	X4	X3	X2	X1
Fall	5890.0	-9.8936	26.0530	-25.6790	11.5671	-2.6510
Winter	5263.8	-13.7696	37.9146	-38.2089	16.9585	-3.5035
Summer	6200.0	-6.9263	18.6137	-18.4964	8.2757	-2.0866
Spring	5691.6	-13.3182	36.4086	-36.7648	16.5650	-3.5127

Residual Load

	Max.Load	X5	X4	X3	X2	X1
Fall	5889.9	-11.0464	21.1960	-28.8732	13.0649	-2.9542
Winter	5198.3	-13.2914	36.6471	-37.2398	16.9076	-3.6311
Summer	6133.4	-7.8014	60.6700	-20.2785	9.0499	-2.2610
Spring	5599.3	-12.1651	33.1987	-33.6619	15.4294	-3.4179

Figure 14. Polynomials for Reference and Residual Load Duration Curves.

	winter	spring	summer	fall	annual
Reference Load(MW)	5890.0	5263.8	6200.0	5691.6	6200.0
Energy Served (GWHr.)	8531.0	7238.0	8938.0	7987.0	32694.0
Oper. Cost (Mil. $)	100.7	88.2	130.2	102.1	421.3
Residual Load(MW)	5889.9	5198.3	6133.4	5599.3	6133.4
Energy Served (GWHr.)	8352.0	7010.0	8735.0	7795.0	31892.0
Oper. Cost (Mil $)	96.5	83.5	124.8	98.1	402.9

Figure 15. System Performance With & Without PV.

	winter	spring	summer	fall	annual
Reference Load	.025873	.005700	.09457	.010966	.033441
Residual Load & All Gen.	.019532	.004323	.075032	.008499	.027011
Residual Load & 106MW Out	.024801	.005591	.083544	.011235	.031470
Residual Load & 143MW Out	.026960	.006282	.089251	.011730	.033742
Residual Load & 104MW Out	.021263	.004855	.078535	.009384	.028679

Figure 16. Seasonal and Annual LOLP Values

The results shown in Figure 16 on page 46 show that removal of 106MW SUT2 unit or 104MW IC52 unit will maintain LOLP values lower than the base case. While removal of 143MW unit gets the LOLP values sufficiently close to the reference load LOLP values. Thus a capacity credit of about 150MW can be obtained from this PV system. In certain cases when more reliability and hence lower LOLP values are required a capacity credit of about 100MW can be obtained.

The unit IC52 is an internal combustion turbine, a peaking unit. Thus installation of a PV system has helped to replace a peaking unit, which is the aim of modern day load management. This should also give us higher savings in fuel cost, due to higher heat rate for the peaking unit.

The study of the load pattern and PV output shows that maximum of PV output occurs at nonpeak hours. The Figure 17 on page 48 gives the PV output at the time of peak load during each month. The maximum PV output at the time of system monthly peak is only 156MW, which is considerably less than the rated value of 500MW. During 6 months, which is half of the year it is even less than 50MW, while at the time of system peak which occurs in August it is only 138MW. This causes the capacity credit to decrease considerably. Since at most of the sites, the output pattern of the PV system should be similar, a system with compatible load curve shape would perform much better with this PV system. An alternative is to store solar energy during off peak hours and use it during system peak hours. This would, however, involve additional cost to the PV system and needs to be studied carefully.

Month	Peak		PV Output (MW)	
	MW	Time	At System Peak	Best for the Day
January	6080.0	0800	0.0	400 @ 1300
February	5759.8	0800	81.5	490 @ 1200
March	5009.6	0800	154.0	500 @ 1200
April	4209.8	0800	0.0	463 @ 1200
May	4650.0	0800	53.0	342 @ 1200
June	5263.8	1800	65.5	379 @ 1200
July	5983.0	1700	156.0	397 @ 1300
August	6200.0	1700	138.0	333 @ 1400
September	5412.6	1700	25.0	116 @ 1000
October	4767.8	0800	14.5	414 @ 1300
November	5220.0	0800	5.0	198 @ 1000
December	5691.6	0900	141.0	358 @ 1200

Figure 17. Monthly Peak Load and PV Output.

4.5 ALTERNATE APPROACH:

One of the important planning issues in the power system is its expansion plan. The expansion of generation capacity required is calculated based on the expected growth rate of the load on the system. The additional capacity required is such that the LOLP value for the new load is within the required constraint.

This was used as an alternate approach to find the capacity credit of the PV system. The growth rate for the weighted composite load was assumed to be 3%. For a more detailed analysis the growth rate can be found independently for the industrial, commercial and residential sectors respectively.

The new composite load was also represented as a fifth order polynomial with unit Y intercept. The PRODCOST routine, when run with this load and original set of generators gives the value of LOLP, total cost and energy served for the base case. The PV system output was then subtracted from the base case to get the residual load. The results of PRODCOST routine with this residual load are shown in Figure 18 on page 50.

To get this lower LOLP for the reference load from the conventional generators some generation will have to be added. As described earlier some trial runs with different sets of generators were carried out to find the LOLP values closest to the residual load LOLP. The results of some of the sample runs are shown in Figure 19 on page 51.

As in the previous case it was found that addition of 3 52MW units gets the LOLP closest to that of residual load. Thus this also gives the

	winter	spring	summer	fall	annual
Referance Load					
Energy Served (GWHr.)	8896.0	7552.0	9103.0	8244.0	33796.0
Oper. Cost (Mil. $)	108.7	83.9	148.4	97.6	438.6
Residual Load					
Energy Served (GWHr.)	8570.0	7252.0	8906.0	8027.0	32756.0
Oper. Cost (Mil $)	102.5	78.7	139.2	94.1	414.4
Capacity Expansion 3 52MW Gen Extra.					
Energy Served (GWHr.)	8901.0	7553.0	9118.0	8246.0	33818.0
Oper. Cost (Mil $)	109.4	84.0	150.3	97.92	441.7

Figure 18. System Performance With & Without PV.

	winter	spring	summer	fall	annual
Reference Load	.036236	.006426	.107060	.010978	.040095
Residual Load & All Gen.	.029861	.005104	.096747	.008815	.035131
Expansion 2 52MW Gen Extra	.032337	.005498	.100141	.009313	.036760
Expansion 3 52MW Gen Extra	.030476	.005042	.097023	.008779	.035257

Figure 19. Seasonal and Annual LOLP Values

capacity credit for the PV system to be 150MW, about 30% of the rated value. The value of capacity credit is slightly larger than average value of the capacity credit for an alternate energy source.

A similar analysis was done for the same site using another model, PVFORM[7] to predict the output of the PV system using the typical meteorological data for the site. The LOLP values were estimated using WASP model [2][9]. The results obtained were found similar to the present study. The matching of results in three cases points to the validity of the model.

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[2] Wien Automatic System Planning Model

5.0 ECONOMIC ANALYSIS

The success of any technical project depends on its technical feasibility and economic viability. Due to the advancements in the field of Silicon technology it has been amply demonstrated that large scale utilisation of solar energy is possible from technical point of view. This leaves us with the question of whether solar energy can compete with conventional energy on a commercial basis.

This chapter tries to answer this question and analyse various situations which would help to make solar energy more economically competitive with conventional generation. The model used for the analysis is the LIFECC model, which was developed at the Rocky Flats Facility[6]. The model was originally developed for economic analysis of wind turbine generators, however it is also applicable for solar panels and is used in this study as such.

5.1 METHODOLOGY OF ASSESSMENT:

The methodology has its base in life cycle costing taking into account the time value of money and effects of inflation on investment. Due to the time value of money concept it is possible to make a choice of products on a comparable economic basis. The product which gives maximum return on investment is usually selected.

Construction of a solar plant can be treated in the same manner. The plant would compete with conventional generation to minimise the cost of generation over the life period of the plant. Although the conventional generation may be cheaper today, due to the rising cost of fuel it may not be the case during entire life of the PV system. The program then computes the return on investment in solar energy and conventional generation. This gives the cost of solar energy and conventional generation over the life period of the PV system. If the investment in the PV system can reduce the operating expenses and thus can bring higher return on investment then it becomes an economically prudent decision to build the PV system.

5.2 INPUT DESCRIPTION:

There are mainly two costs associated with the PV system-the onetime construction cost and variable operation and maintanence cost. While there are indirect benefits from the PV system in the form of tax credits from the federal and state government and the revenue collected from the sale of electricity generated by the PV system. The inputs required for the program are shown in Figure 20 on page 55. The installed cost was calculated based on the value of $6800/KW, for PV.

It is expected, however, that with a higher demand and mass production this value would decrease significantly. The effect of decrease in the cost of panels on the cost of generated electricity was analysed and is discussed later in the report. As already mentioned earlier the system used for the analysis has a rated capacity of 1MW. The life of PV panels was taken, as suggested by the manufacturor, to be 30 years. During this period the availability of the plant is 98%. This is the time period for

```
-------------INITIAL VARIABLES----------------------------

SWECS INSTALLATION COST   =  $ 680000.0
YEARS OF SWECS LIFE       =    30

TOTAL AMOUNT OF LOAD      =  $ 580000.0
DOWN PAYMENT ON LOAD      =  $ 100000.0
LOAN TERM                 =    25. YRS
LOAN INTEREST RATE        =    .10

USER'S DISCOUNT RATE      = .10
USER'S TAX BRACKET        =
FIRST YEAR TAX LIABILITY(W/O PV) =  0
RESIDENTIAL USE FACTOR    =  1.0

UTILITY GRID COST FOR FIRST YEAR = $/KWH  .06
UTILITY GRID COST ESCALATION RATE = .14
UTILITY BUY BACK FACTOR           = 1.0


-------------FUTURE COSTS-----------------------------------

OPERATION AND MAINTENANCE COST FOR FIRST YEAR = $ 20,000
OPERATION AND MAINTENANCE COST ESCALATION RATE = .12

AVAILABILTY FACTOR  = 98%
TOTAL DIRECT USE FACTOR = .002
SALVAGE VALUE OF SWECS = $ 10,000
TOTAL FIRST YEAR TAX BENEFITS = $ 10,000

ANNUAL ENERGY YIELD =  BY MONTH FOR EACH CASE.
```

Figure 20. Input to the LIFECC Model

which the plant was available for generation, given sunshine availability. The operation and maintenance costs and the salvage value of the system were chosen arbitrarily as no data for the same was available.

The grid electricity cost was the average cost of electricity for a residential customer. The grid cost inflation rate of 14% was on a bit higher side. As the entire energy produced by the system would be available to the utility, direct use factor and utility buy back factors were unity.

The entire success of the project may be based on two main factors, the loan interest rate, period and tax considerations. For all other inputs, required data was available based on latest market price. The shortage of conventional fuel and environmental considerations may make these factors more favourable to the PV system. The interest rate was taken from the market value and the tax credit was chosen arbitrarily, at reasonable values. Any favourable effect on these factors would help to decrease the cost of PV energy.

5.3 COST ANALYSIS:

The inputs to the program are shown in Figure 20 on page 55. As mentioned earlier, actual data for most of the inputs was available from various sources. The data not available was chosen at a reasonable value.

The cost of PV energy is determined by each of the input variables. The variables most likely to change in future are the production cost and the energy generated by the PV system. The introduction of a new material may also help to lower the prices of PV system and increase its output.

	Efficiency	
Month	10% (KWH)	16% (KWH)
January	17136.1	28752.0
February	17979.1	29636.2
March	18452.7	30848.1
April	18734.7	31358.7
May	19767.9	33088.8
June	19818.1	33310.2
July	19284.3	32317.8
August	18526.8	30982.2
September	17933.7	30062.4
October	17124.7	29504.0
November	17027.1	28426.5
December	16753.1	28156.4
Total	218538.5	366443.3

Figure 21. Effect of Increase in Efficiency on Output.

	Loan Amount $ * 10000	Loan Term Years	Cost of PV Energy $/KWH
No Tilt	680	20	6.098
	600	20	5.393
	680	25	6.057
	600	25	5.356
Tilt to Maximise Output	680	20	4.306
	600	20	3.830
	680	25	4.272
	600	25	3.800
Efficiency 16% + Tilt	680	20	2.576
	600	20	2.291
	680	25	2.556
	600	25	2.273

Figure 22. Cost of PV Energy

The effect of these variables and the loan period on the cost of electricity was analysed using the LIFECC model. The results obtained are shown in Figure 22 on page 58.

5.4 DISCUSSION:

As expected the cost of PV panels and the output of PV system were found to have the strongest effect on the cost of PV energy as shown in Figure 22 on page 58. A decrease of $800/KW in cost of PV module showed a decrease of about $.70/KWH which is a moderate decrease. However it is not unlikely that the cost of PV panels may decrease by a greater amount within next few years.

The tilting of collector increases the energy generated significantly due to increase in incident radiation as shown in -- Figure id 'tiltout' unknown --. This makes a significant contribution to lowering the cost of PV energy. The increase in output due to increase in efficiency is even more significant as shown in Figure 21 on page 57. The decrease in cost obtained due to rise in efficiency of the module was even more encouraging. An increase of 6% in efficiency leads to almost halving the cost of PV energy. This clearly points to the fact that any increase in the efficiency of a PV cell will greatly help make PV energy competitive with the conventional generation.

Although the impact of all other factors would not be as significant as the cost and output of the PV system, a small favourable effect due to each may lead to significant decrease in cost of PV module.

6.0 CONCLUSIONS

The aim of the study was to develop a package which by itself can do preliminary analysis about the feasibility of a PV system at a site. The package consists of four independent models viz. SOLAR, PVPM, PRODCOST and LIFECC. Each of these models were seperately tested before their integration. For a more detailed analysis the individual models can be replaced by more sophisticated models. Specifically the SOLAR model which estimates the radiation only for a clear sky should be the major concern for a more advanced study.

The results obtained from SOLAR model for clear sky days are quite accurate for a preliminary analysis. Moreover since in most of the cases the estimated value is smaller than the typical value, it provides a margin of safety. The option to maximise the output at the site can be used effectively to increse the PV output.

The PVPM model has various options like the use of concentrators, single or double axis tracking etc. With more data available about the cost of concentrators and tracking system these can be included in the economic analysis. The use of either or both would help to increase the PV output and thus decrease the cost of PV energy. However a careful analysis about the cost of tracking and its effect on output should be made before going ahead with the decision of building a tracking system.

The capacity credit obtained from the PRODCOST model using two methods matched with each other and also matched with the capacity credit found in another study using PVFORM and WASP models[4]. The values of LOLP found from PRODCOST were slightly higher than those found using WASP model. This may be due to the difference in method of maintenance scheduling in the two models. The WASP model however is more advanced and can be taken as standard. It was however not used in the present study due to difficulty in transferring it to IBM-PC AT. Although the actual values of LOLP's differ in the two cases they follow a similar pattern for reference and residual loads. Since this descrepancy in no way affects the capacity credit of the PV system, which is our main concern, there is no cause of alarm.

Although the exact data about the tax credits and interest rate was not available, the results obtained from LIFECC model were quite encouraging. A substantial decrease in cell cost and an increase in cell efficiency would be required to make PV energy economically competitive with the conventional generation. With a better idea about tax credits, specifically federal tax credits and possible availability of lower interest rate loans, a better picture about the comparative costs can be drawn.

The model thus serves as a complete package for analysis of a PV system. Although it is not a very advanced model, it is recommended for preliminary analysis of various sites before proceeding with an indepth study of a chosen few. Due to its availability on a personal computer, it has no execution cost and thus can be used liberally for analysing many sites before a final decision is reached. Using the same methodology, but more advanced individual models, indepth study about the site can be performed. Thus the hierarchial nature of the methodology offers the flexibility to examine any part of the performance analysis to any extent desired.

6.1 SUGGESTIONS FOR FUTURE WORK:

Planning of power system expansion is a difficult process due to the inherent assumptions about the growth rate of load. Since building of a conventional generation facility takes anywhere from 5 to 10 years, a planning engineer has to plan well in advance for the required expansion of the generation capacity.

The planning process can however be simplified by breaking it down into smaller problems which can be tackled independently. Development of the package in the present study is one of such efforts to simplify the planning process. Using the same methodology similar models can be developed for wind, hydro and other alternate energy sources. The models required for representing conventional generation are already available in many forms as public domain software.

Once all such models are developed, an effort to integrate them can be done. For a large power system this integration can be done on a regional basis. Once the load-generation analysis for all regions is complete, the efforts for integrating the entire power system can begin. Due to the detail planning on regional basis, the transmission distribution required for the entire system can be easily modelled. The large scale use of alternate energy sources in different parts of the power system would complement each other and thus would give considerable capacity credit for the entire system of alternate sources.

Developing countries, which have abundance of alternate energy sources but minimal efforts towards planning of the power system, would benifit most from the planning process. Greater availability of electricity would also help them accelerate their economic and industrial development.

The present study was started with this goal in mind. It can thus be continued further to complete the entire model. It would require efforts of few years to complete the planning process. However due to the possibility of tackling smaller problems independently, the planning process can be accelerated considerably.

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APPENDIX A.

The SOLAR model is user-interactive and a sample output obtained from it is shown below. The program can maximise the value of the output on a particular day. The output shows the value of radiation for the vernal equinox. Both the maximised output and the output without any tilt are shown.

```
  This program evaluates potential of solar energy at a site.

  Type the latitude of site in degrees.(I3)

   38

 Enter the longitude of the location (I3)

   78

 Is the location in U.S. (Y/N) ?

Y

 TYPE ALTITUDE OF LOCATION IN M (I4)

 110

ENTER ONE OF THE CLIMATE TYPES...
 1) TROPICAL .............T
 2) MID LATITUDE SUMMER ... M
 3) SUBARTIC SUMMER ....... S
 4) MID LATITUDE WINTER.....W

   W
```

```
Do you want to Maximize output (Y/N)?

  Y

Type the month in which you want to calculate  energy

 3

Type the day on which you want to calculate  energy

  22

  DAY 22    MONTH 3

TIME  1 TOTALR .0000

TIME  2 TOTALR .0000

TIME  3 TOTALR .0000

TIME  4 TOTALR .0000

TIME  5 TOTALR .0000

TIME  6 TOTALR .0000

TIME  7 TOTALR .0517

TIME  8 TOTALR .2536

TIME  9 TOTALR .4833

TIME10 TOTALR .6796

TIME11 TOTALR .8170

TIME12 TOTALR .8817
```

```
TIME13 TOTALR .8679

TIME14 TOTALR .7768

TIME15 TOTALR .6168

TIME16 TOTALR .4050

TIME17 TOTALR .1744

TIME18 TOTALR .0162

TIME19 TOTALR .0000

TIME20 TOTALR .0000

TIME21 TOTALR .0000

TIME22 TOTALR .0000

TIME23 TOTALR .0000

TIME24 TOTALR .0000


Do you want to continue the analysis?


 Y


Do you want to analyse a different location?


 N


 ENTER ONE OF THE CLIMATE TYPES...
1) TROPICAL .............T
2) MID LATITUDE SUMMER ... M
3) SUBARTIC SUMMER ....... S
4) MID LATITUDE WINTER.....W
```

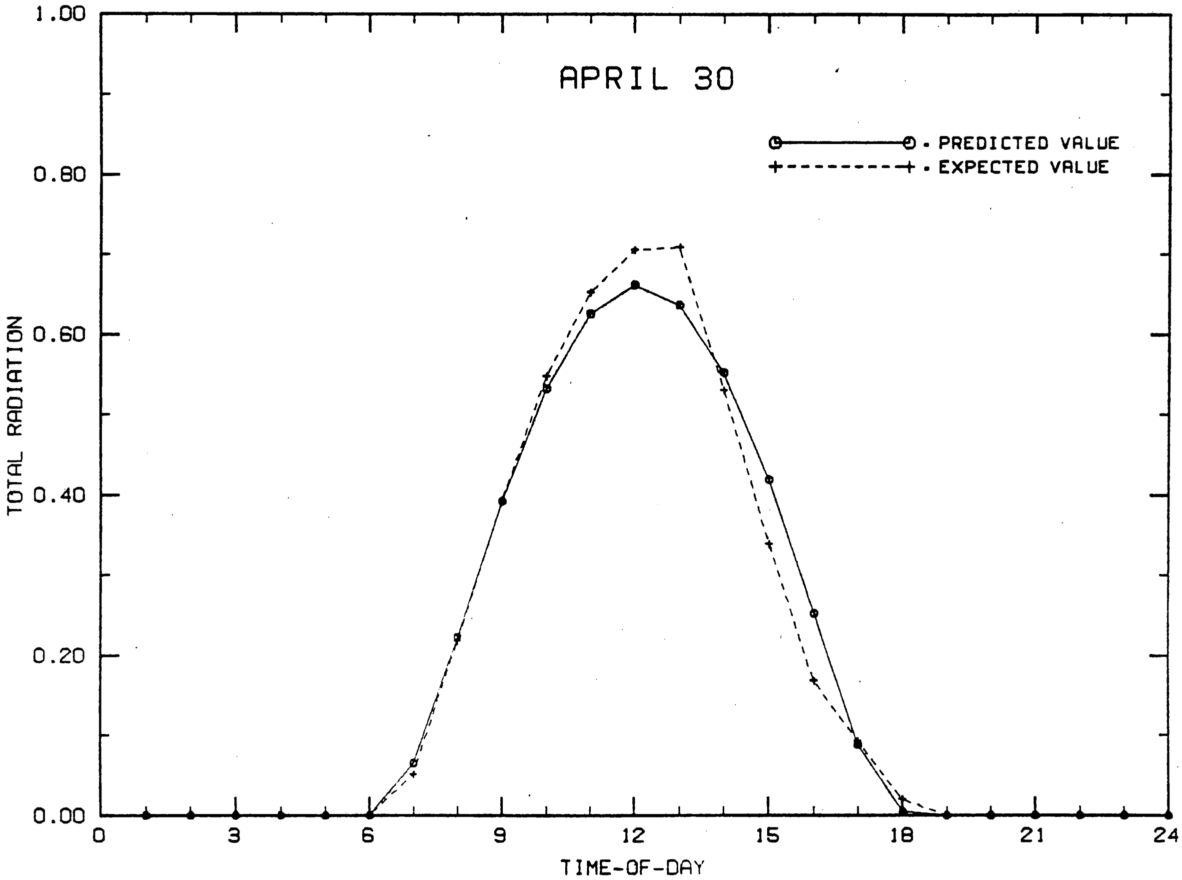
```
 W

Do you want to Maximize output (Y/N)?

 N

Type the month in which you want to calculate  energy

 3

Type the day on which you want to calculate  energy

22

   DAY 22    MONTH 3

 TIME 1 TOTALR .0000
 TIME 2 TOTALR .0000
 TIME 3 TOTALR .0000
 TIME 4 TOTALR .0000
 TIME 5 TOTALR .0000
 TIME 6 TOTALR .0000
 TIME 7 TOTALR .0336
 TIME 8 TOTALR .1694
```

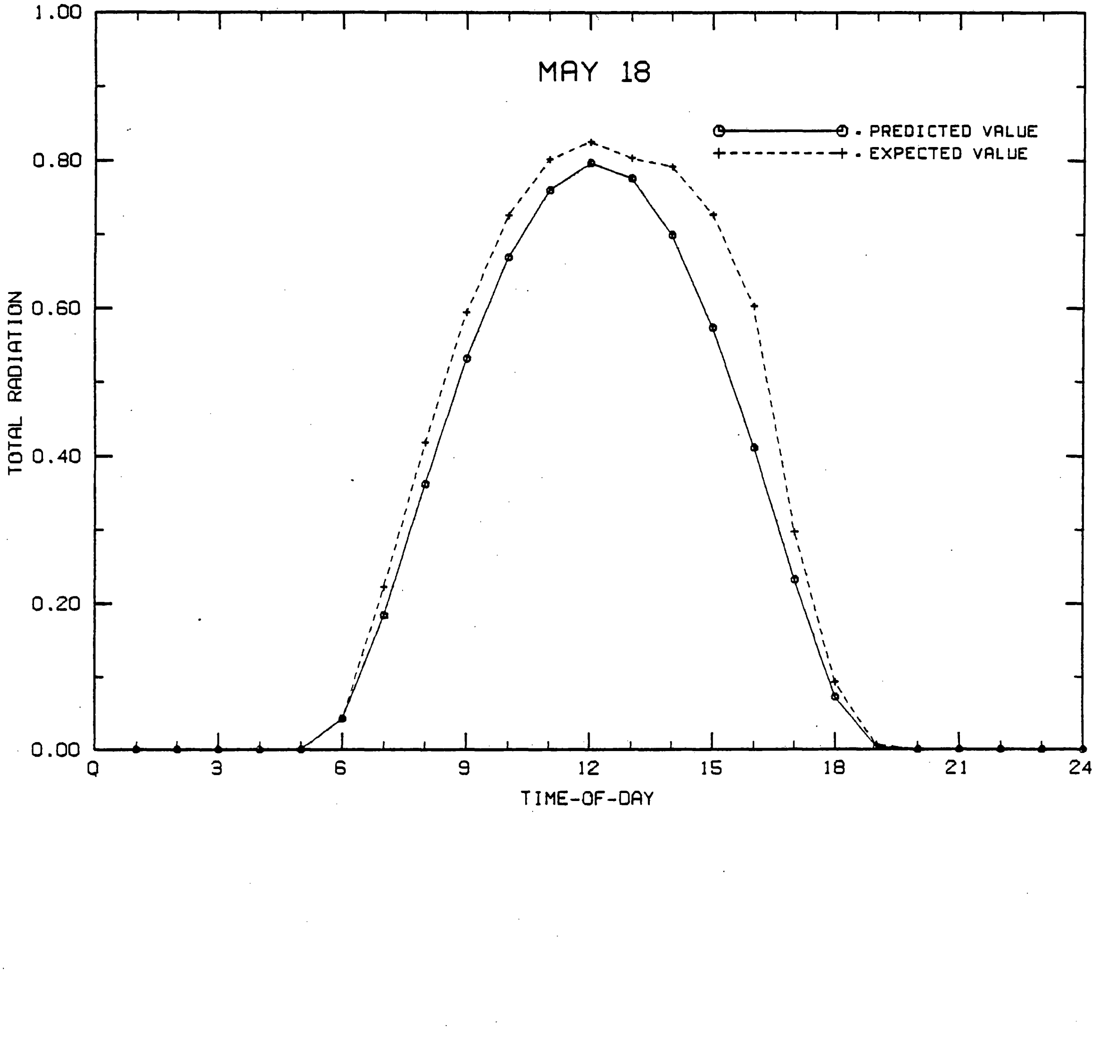
```
TIME 9 TOTALR .3376
TIME10 TOTALR .4855
TIME11 TOTALR .5903
TIME12 TOTALR .6398
TIME13 TOTALR .6292
TIME14 TOTALR .5595
TIME15 TOTALR .4379
TIME16 TOTALR .2795
TIME17 TOTALR .1139
TIME18 TOTALR .0123
TIME19 TOTALR .0000
TIME20 TOTALR .0000
TIME21 TOTALR .0000
TIME22 TOTALR .0000
TIME23 TOTALR .0000
TIME24 TOTALR .0000

Do you want to continue the analysis?

N
```

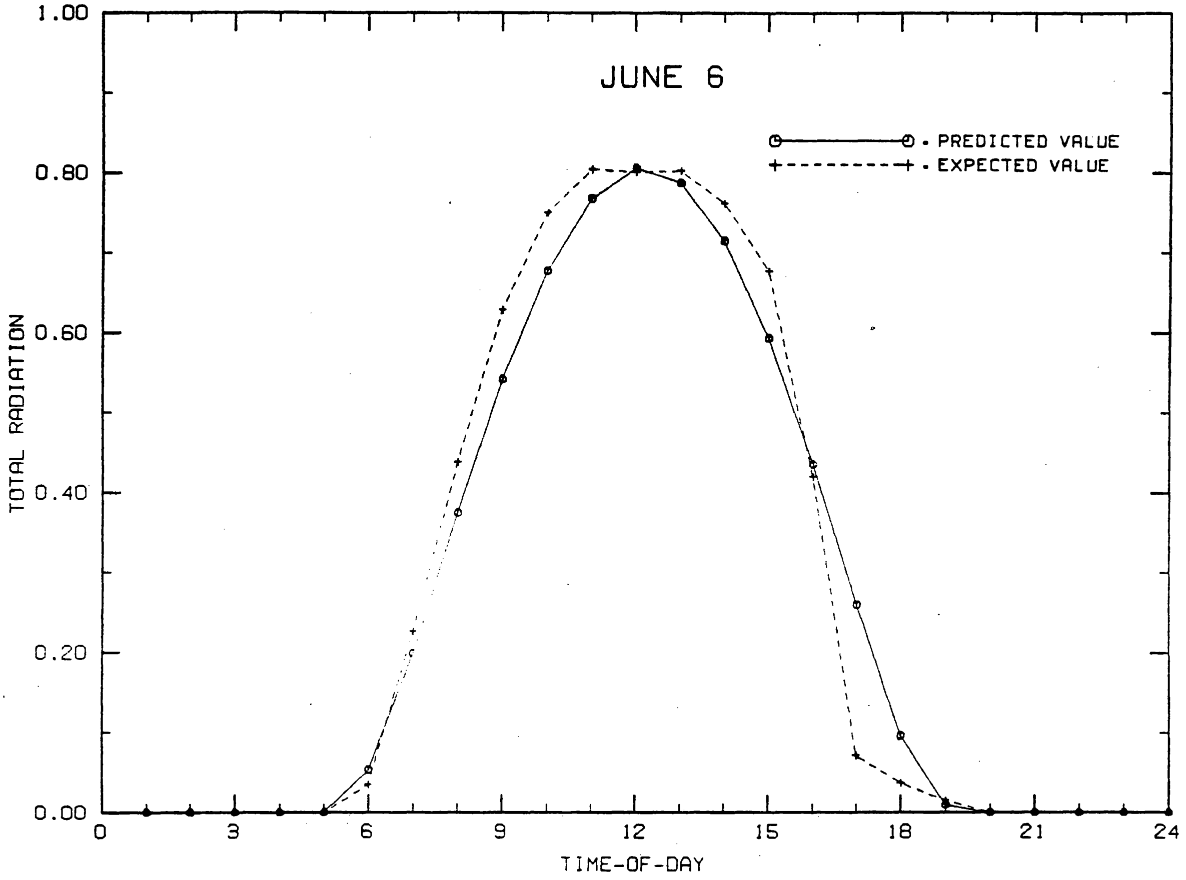
APPENDIX B.

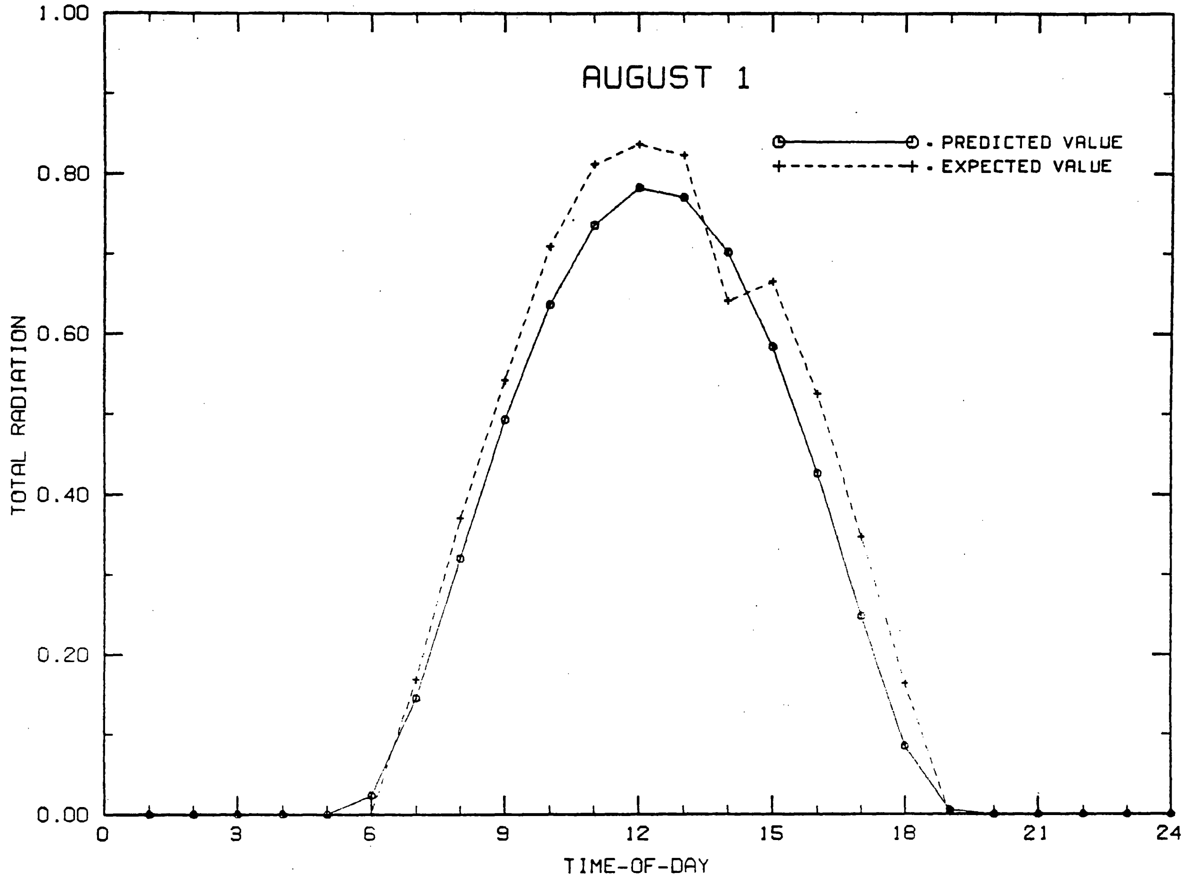
The graph comparing the radiation estimated by SOLAR model and the one given by typical meteriological data is shown in Figure 5 on page 20. As already mentioned earlier the model was analysed extensively and was found adequate for the purpose. Some more graphs showing the comparison between the estimated and the actual value are attached on the following pages.

The graphs help us to validate the model for clear sky radiation. For a more involved study a better model using the effect of cloud cover can be used.


APRIL 30
PREDICTED VALUE
EXPECTED VALUE
TOTAL RADIATION
1.00
0.80
0.60
0.40
0.20
0.00
0
3
6
9
12
15
18
21
24
TIME-OF-DAY


MAY 18
PREDICTED VALUE
EXPECTED VALUE
TOTAL RADIATION
TIME-OF-DAY
1.00
0.80
0.60
0.40
0.20
0.00
0
3
6
9
12
15
18
21
24

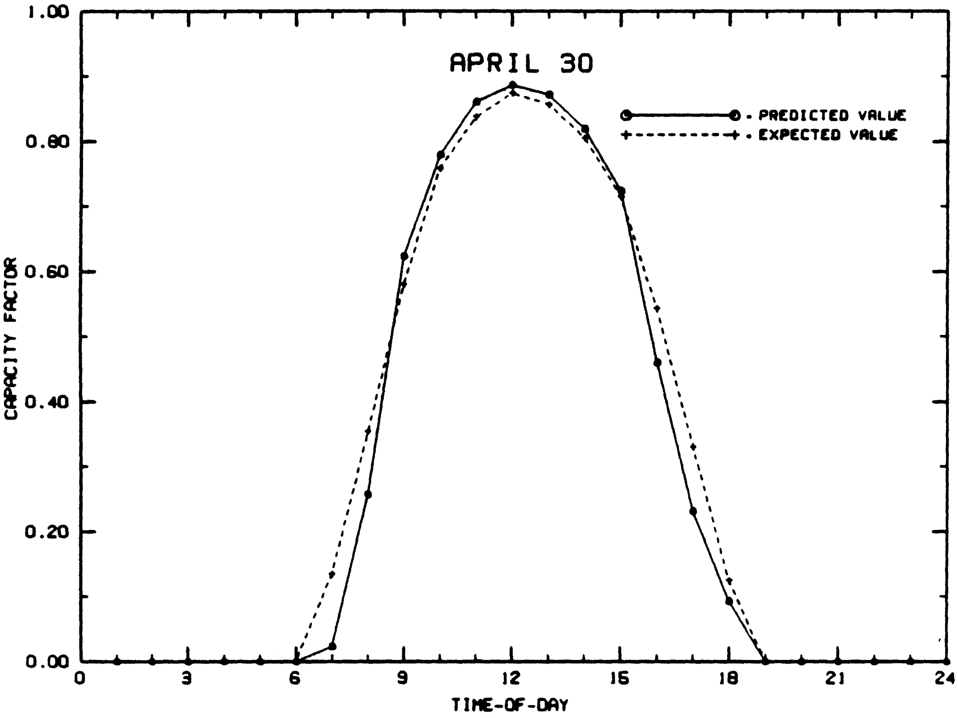

JUNE 6
PREDICTED VALUE
EXPECTED VALUE
TOTAL RADIATION
1.00
0.80
0.60
0.40
0.20
0.00
0
3
6
9
12
15
18
21
24
TIME-OF-DAY

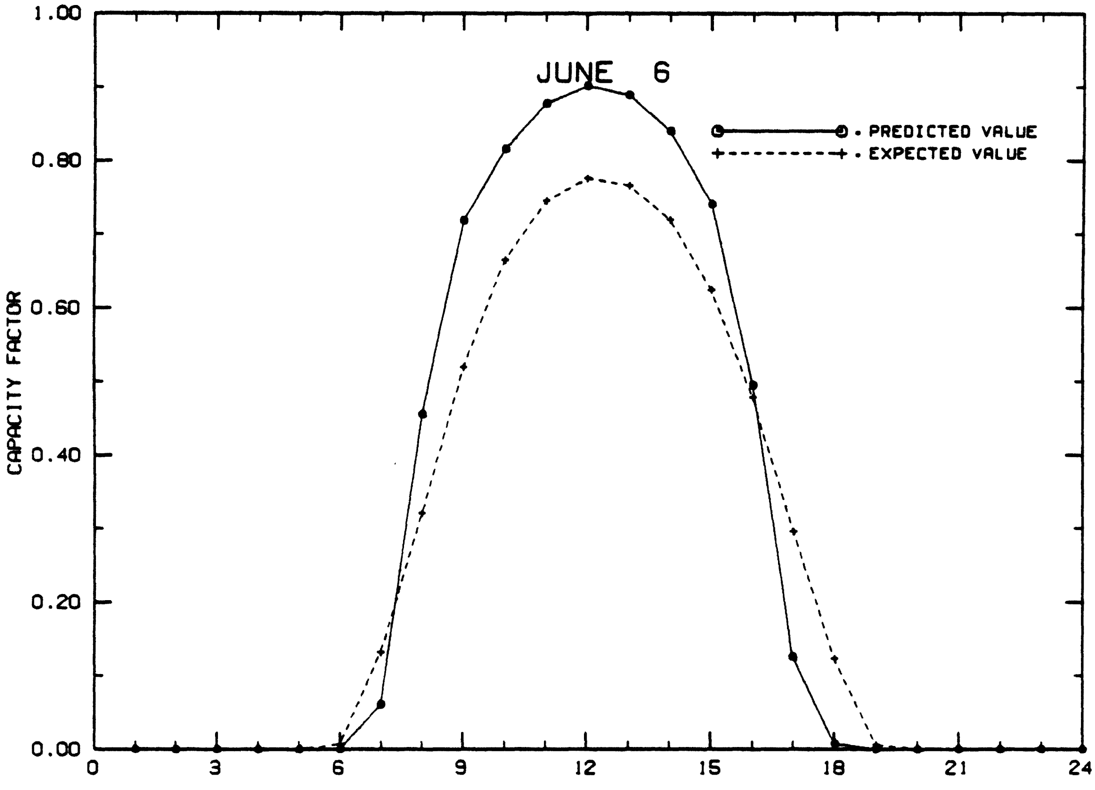

AUGUST 1
PREDICTED VALUE
EXPECTED VALUE
TOTAL RADIATION
1.00
0.80
0.60
0.40
0.20
0.00
TIME-OF-DAY
0
3
6
9
12
15
18
21
24

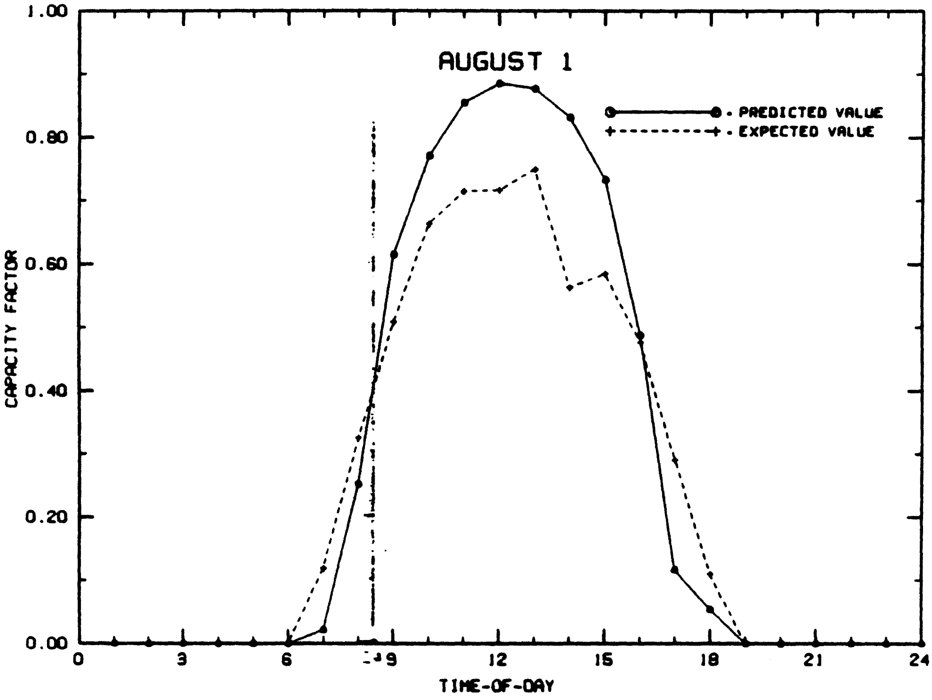
APPENDIX C.

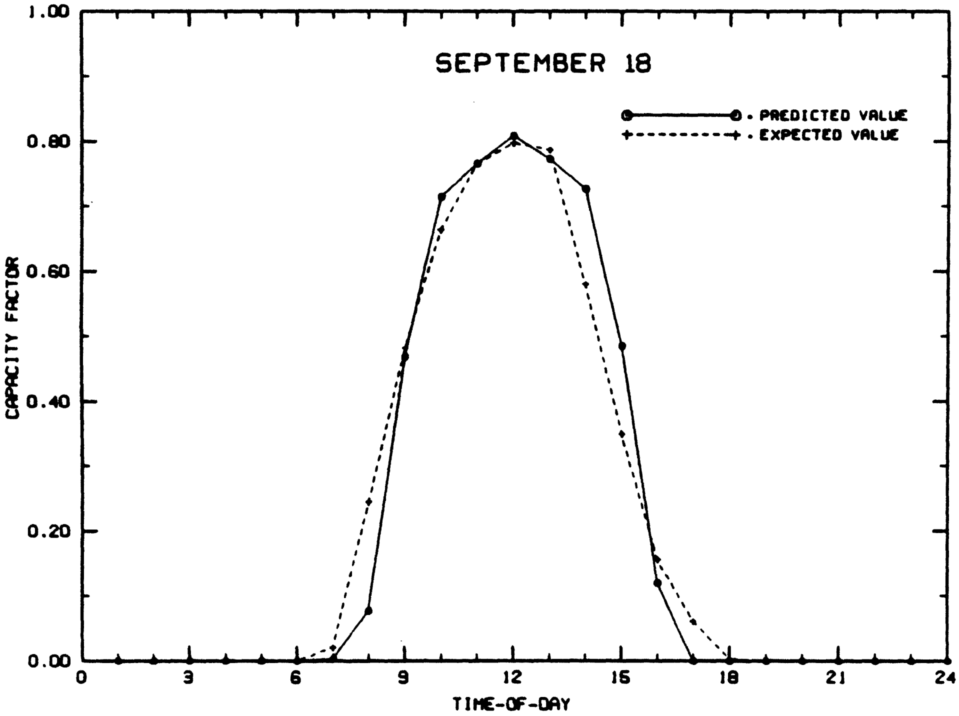
To validate the PVPM model capacity factor was used as an index of comparison. The values of capacity factors obtained for a typical day are shown in Figure 11 on page 35. Some more graphs showing the caparison for different days are attached herewith.

As mentioned earlier their is a discrepancy in the values especially at low values due to the poor effficeincy of inverter at low d.c. input values. Thus the results will be closer for a tilted collector. With availability of more data about the inverter efficiency the model can be upgraded further.


APRIL 30
PREDICTED VALUE
EXPECTED VALUE
CAPACITY FACTOR
1.00
0.80
0.60
0.40
0.20
0.00
0
3
6
9
12
15
18
21
24
TIME-OF-DAY


JUNE 6
PREDICTED VALUE
EXPECTED VALUE
CAPACITY FACTOR
1.00
0.80
0.60
0.40
0.20
0.00
0
3
6
9
12
15
18
21
24
TIME-OF-DAY


AUGUST 1
PREDICTED VALUE
EXPECTED VALUE
CAPACITY FACTOR
TIME-OF-DAY
1.00
0.80
0.60
0.40
0.20
0.00
0
3
6
9
12
15
18
21
24


SEPTEMBER 18
PREDICTED VALUE
EXPECTED VALUE
CAPACITY FACTOR
1.00
0.80
0.60
0.40
0.20
0.00
0
3
6
9
12
15
18
21
24
TIME-OF-DAY