A METHODOLOGY FOR ANALYZING ELECTRICAL ENERGY OPTIONS FOR ISOLATED AREAS

BY

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ABSTRACT

There are isolated areas in many countries which cannot be connected by grid systems due to technical or economic reasons. In some of these isolated areas generation and supply of electricity do not exist or even if they exist, the history of load growth of these areas is not properly maintained. It needs to be recognized that the generation plan of an isolated area of the above nature should be different from the conventional planning process. The generation planning process starts with the forecast of load during the planning horizon. In the case of isolated areas the planner must consider the unconventional energy sources, especially the solar and the wind sources and hydro. Previous studies showed that these sources deserve the planner's consideration along with the conventional energy sources. The incorporation of solar and wind sources in the list of competing methods of generation essentially requires the appropriate models of these sources suitable for a planning process. However, it has not been attempted so far to develop a technique of load forecasting suitable for an isolated area without electricity or without the history of load growth. No attempt has been made so far to develop appropriate models of a wind turbine generator,WTG and a photovoltaic generator,PVG.

This research presents a load forecasting technique of an isolated area where the electric power supply as a source of

energy has not been started yet or the history of load development is not available where the supply is in operation already. The technique introduces the concept of deriving the load demand of an isolated area from the forecasted load of another area using a comparative factor. The technique starts with the identification of the variables on which the load growth of an isolated area depend. It also evaluates the contribution of each function towards the load growth.

The research work also develops the probabilistic models of a WTG and a PVG. These models are based on the concept of multistate representation of a generating unit. The basic data used for a WTG is the bivariate function of wind velocity and temperature while that for a PVG is the bivariate function of insolation and temperature. These models are compared with the models developed from the conventional concept of univariate function,that is,in the cases where the output of a WTG is taken as function of wind velocity only and that of a PVG as a function of insolation only.

The proposed load forecasting technique and the models of a WTG and a PVG are applied to find out a most desirable plan of a realistic isolated area. In this planning process the conventional sources are also considered while due attention has been given to the reliability and the presently existing cost structure of the various components.

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CONTENTS

ABBREVIATIONS

AC - Available Capacity.
ACRE - Area Coverage Rural Electrification.
BMD - Bangladesh Meteorological Department.
BPDB - Bangladesh Power Development Board.
CR - Capital Recovery.
C.R.F - Capital Recovery Factor.
DRA - Density Ratio at an Altitude.
DRT - Density Ratio at a Temperature.
EEG - Expected Energy Generation.
EENS - Expected Energy not Served.
ELDC - Equivalent Load Duration Curve.
EQGEN - Equivalent Electrical Power Generation.
EQGEN - Equivalent Capacity Generation.
FAD - Frequency and Duration.
FC - Fuel Cost.
FOR - Forced Outage Rate.
HAWT - Horizontal Axis Wind Turbine.
IC - Installed Capacity.
IEEE - Institution of Electrical and Electronic Engineers.
IFC - Incremental Fuel Cost.
LDC - Load Duration Curve.
LOEP - Loss of Energy Probability.
LOLP - Loss of Load Probability.

MCS - Monte Carlo Simulation.

PBS - Palli Bidhyut Samity (Rural Electric Society).

PDF - Probability Density Function.

PRG - Gross Renewable Production.

PV - Photovoltaic.

PVG - Photovoltaic Generator.

RAPS - Remote Area Power Supply.

REB - Rural Electrification Board.

RTS - Reliability Test System.

RV - Random Variable.

VAWT - Vertical Axis Wind Turbine.

WASP - Wien Automatic System Package.

WECS - Wind Energy Conversion System.

WTG - Wind Turbine Generator.

NOTATIONS

Prob. - Probability

L - System load

L_e - Effective load/equivalent load

Lo_i - Random outage load corresponding to the i-th unit

C - Generating capacity

f_L - PDF of the system load L

f_{Lo} - PDF of outage capacity of generating unit

f_{Le} - PDF of equivalent load L_e

CC_i - Capacity cost of unit i

FCR_i - Fixed charge rate

UC_i - Unit capacity cost

C_i - Capacity of i-th unit

$\tilde{P}_n$ - Zeroeth moment of n-th segment after the convolution

$\hat{P}_n$ - Zeroeth Moment of n-th segment after the shift

P_n - Zeroeth Moment of n-th segment before convolution

q - Forced outage rate of the unit to be convolved

$f_x(x)$ - Probability density function of the random variable x

x - Random variable

m_i - First order moment for i-th segment

P_i - Probability of the random variable x_i

$\tilde{m}_1$ - First order moment of a segment after convolution of a generating unit of FOR = q

m_1 - First moment of the segment prior to convolution

$\hat{m}_1$ - Shifted first moment of the segment

m_o - Zeroeth moment of the segment

m_1^{old} - First moment of a segment prior to shift

m_1^{new} - Shifted first moment

E_n - Expected energy

UE_n^- - Unserved energy before convolving n-th unit

UE_n - Unserved energy after convolving n-th unit

λn - Average incremental cost of the n-th unit

P - First cost of generator/initial capital cost/initial investment

n - Life of study or of generator in years

L - Salvage value at end of n years

i - Interest rate/minimum attractive return

D - Annual depreciation

P(t) - Popultion at time t

LR(t) - Literacy rate at time t

PI(t) - Per capita income at time t

L_D - Domestic load

L_C - Commercial load

L_I - Industrial load

RL(t) - Inland communication length per unit area at time t

$AL(t)$ - Agricultural land in percent of total area at time t

$L(t)$ - Electrical load demand at time t

X - Weighting factors

M - Number of areas considered to generate the distribution of x_i

P_j - Probability that the value of x_i^j will occur

X_i^j - The value of i-th element of vector X corresponding to the j-th area

CF_{ti} - Comparative factor for any interval t_i

$L_{SA}(t_i)$ - Forecasted average load of the selected area for the interval t_i

$L_{IA}(t_i)$ - Forecasted average load of the isolated area for the interval t_i

C_{ew} - Equivalent electrical power from wind

e - Efficiency of the blades (wind turbine)

K - Conversion factor for units (wind turbine)

A - Area swept out by the blades

D - Diameter of the rotor blade

V - Wind velocity

ρ - Density of air

$\rho_{T,A}$ - The density of air at temperature, T and at altitude, A

DRA_A, DRT_T - Density ratio at altitude, A and at temperature, T, respectively

γ - A constant (wind turbine)

V_{Hub}, V_{anem} - Velocity at hub height and at anemometer height respectively

H_{Hub}, H_{anem} - Height of the hub and the anemometer respectively

$\delta(\, . \,)$ - Dirac delta function

$f_{T,V}(t,v)$ - The joint PDF of temperature and wind velocity

$P_{(T,V)i,j}$ - The probability of occurrence of i-th temperature and j-th velocity

$P_{Ce_{w_k}}$ - The probability of occurrence of k-th value of C_{ew}

$f_{Cew}(c_{ew})$ - The PDF of equivalent electrical power

v_c, v_r, v_f - The cut-in, the rated and the furling (cut-out) velocity of wind respectively

$c_{ew_{rf}}$ - The equivalent electrical power corresponding to velocity v_r, or v_f

V_{min} - The minimum wind velocity

$f_{Cw}(c_w)$ - The PDF of wind turbine generator

$f_{Cgw}(c_{gw})$ - The PDF of electrical output from a wind turbine generator

$C_{gw(max)}$ - The maximum value of C_{gw}

C_{gwo} - The capacity output on outage of the multistate wind turbine generator

C_w - Available capacity of a wind turbine generator

I_L - Light generated current

I_c - Cell current

I_o - Diode saturation current

V_c - Cell terminal voltage

R_S - Cell series resistance

R_{SH} - Cell shunt resistance

P_{dc} - The output of a solar cell (a dc power)

q - Charge of an electron

A - Diode quality constant (photovoltaic cell)/Cross- sectional area of a solar cell

K - Boltzmann's constant

T - Temperature

E_g - Energy band gap

J - Current density

G - Generation rate of charge-carriers (electron-hole pairs) due to incident light

λ - Wave length

λ_{av} - Average wave length

N - Number of photon

α - Absorption coefficient

R - Reflection co-efficient

Φ - Intensity of light or solar insolation

ε - Energy of photon

h - Planck's constant

ν - Frequency of wave

c - Speed of propagation

$f_{T,\Phi}(t,\Phi)$ - The PDF of temperature and insolation

$f_{P_{dc}}(p_{dc})$ - The PDF of solar cell output power

C_{es} - Equivalent electrical power from a solar source

η_c - Converter efficiency

$f_{C_{es}}(c_{es})$ - The PDF of equivalent electrical power from a solar source

$f_{C_s}(c_s)$ - The PDF of the output of a solar cell incorporating the randomness of the converter

$f_{C_{gs}}(c_{gs})$ - The PDF of a solar photovoltaic generator

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Electrical energy consumed in a society and its economic developments are correlated. The ultimate goal of the economic development of a society/country is to improve the quality of life. One of the measure of quality of life in a community or a country is the amount of energy it consumes [1]. Because of its sophistication in use, high efficiency and low cost of transmission from one place to another, electrical energy is widely used in modern societies.

In many countries, especially in developing ones, the major portion of the population live in remote and isolated areas. In terms of electrical energy use, isolated areas are those areas which can not be connected with the main electrical grid system due to economic or technical reasons. The economic and technical incapability of connecting isolated areas with the main grid may evolve from the distance between the grid and the isolated area or inconvenient connecting zones.

To meet the demands of electrical energy in such isolated areas where grid interconnection is not possible, there are different sources from which electrical energy may be produced. The major sources of electrical energy are,

i) fossil fuels (coal, oil and gas)

ii) nuclear fuel

iii) hydro power

There are a number of concerns about producing electricity from fossil fuel resources in these isolated areas in the long term. Oil, despite its recent price collapse, is not an attractive option. The recent global reserve to annual consumption ratio or fossil fuels is less than thirty years. Further discoveries may extend the reserve but the regional concentration and the increasing production cost may limit its use [2,3]. Coal is to some extent abundant. The high transportation cost and possibility of major environmental pollution would however, restrict its use in isolated areas. Nuclear fuel is still cheaper than the fossil fuel and the production cost of electricity from nuclear fuel is comparatively less than other fuels. But the installation of a nuclear power plant involve a huge amount of capital and their economic feasibility lies in their sizes. The installation and operation of a nuclear power plant requires specilized and advanced technologies which many countries do not possess. Also, recent disasters involving nuclear power plants made people more aware of their possible hazards. The production cost of hydro electric power is the cheapest. However, the sources of hydro electric power is regional and limited. The capacity cost of a hydro electric power plant is also very high [4].

Taking into consideration of the various pros and cons of aforementioned electrical energy sources, the planners are looking for additional sources of electrical energy through renewable and traditional sources for isolated localities. The major unconventional sources which are being considered for such purpose are,

i) wind
ii) solar (thermal/photovoltaic)
iii) waves
iv) tides
v) biomass
vi) ocean currents
vii) geothermal
viii) mini-hydro

Wave, tidal, and occean currents energy have not yet proved to be matured technology for generation of electricity at a commercial level. Standard models of minihydro and geo-thermal sources are available for probabilistic simulation. Among the above unconventional sources of energy, the remaining three sources, wind, solar and biomass do not have appropriate probabilistic models although the technologies for these sources are matured. However, recent studies [5-10] show that wind and solar sources deserve careful consideration from electrical utilities.

In the above context, two uncoventional sources: wind turbine generator (WTG), photovoltaic generator (PVG) and one conventional source: thermal generator with proven technology and simulations technique are considered in this research as sources of electrical energy.

Since electrical power generation industries are capital intensive, proper planning of electrical energy is essential.

Generation planning begins with estimates of peak demands and associated electrical energy consumption [11]. After identifying the need for generating capacity, the planner develops a number of feasible alternative plans on the following bases:

i) Demand for electricity,
ii) Construction time,
iii) Availability of sites and
iv) Availability of fuel.

Given these alternative options, it is common to subject each option to a detailed reliability analysis to ensure that all options satisfy the desired level of reliability [11]. Options that do not meet the reliability criteria are eliminated or appropriately modified, and options which satisfy the acceptable reliability level are evaluated on the basis of economics. For each potential option, financial and environmental impacts are analyzed. Finally, the alternative options are compared in order to identify the one that impacts on the utility as a whole in the most favourable manner. In figure 1.1 the planning process is depicted in the form of a flow diagram.

Another approach [12], used to some extent in the power industry, is a semiautomated procedure in which capacity requirements are determined over the time horizon using analytical methods. With this information, various expansion plans can be determined by varying the type and the timing of unit additions.

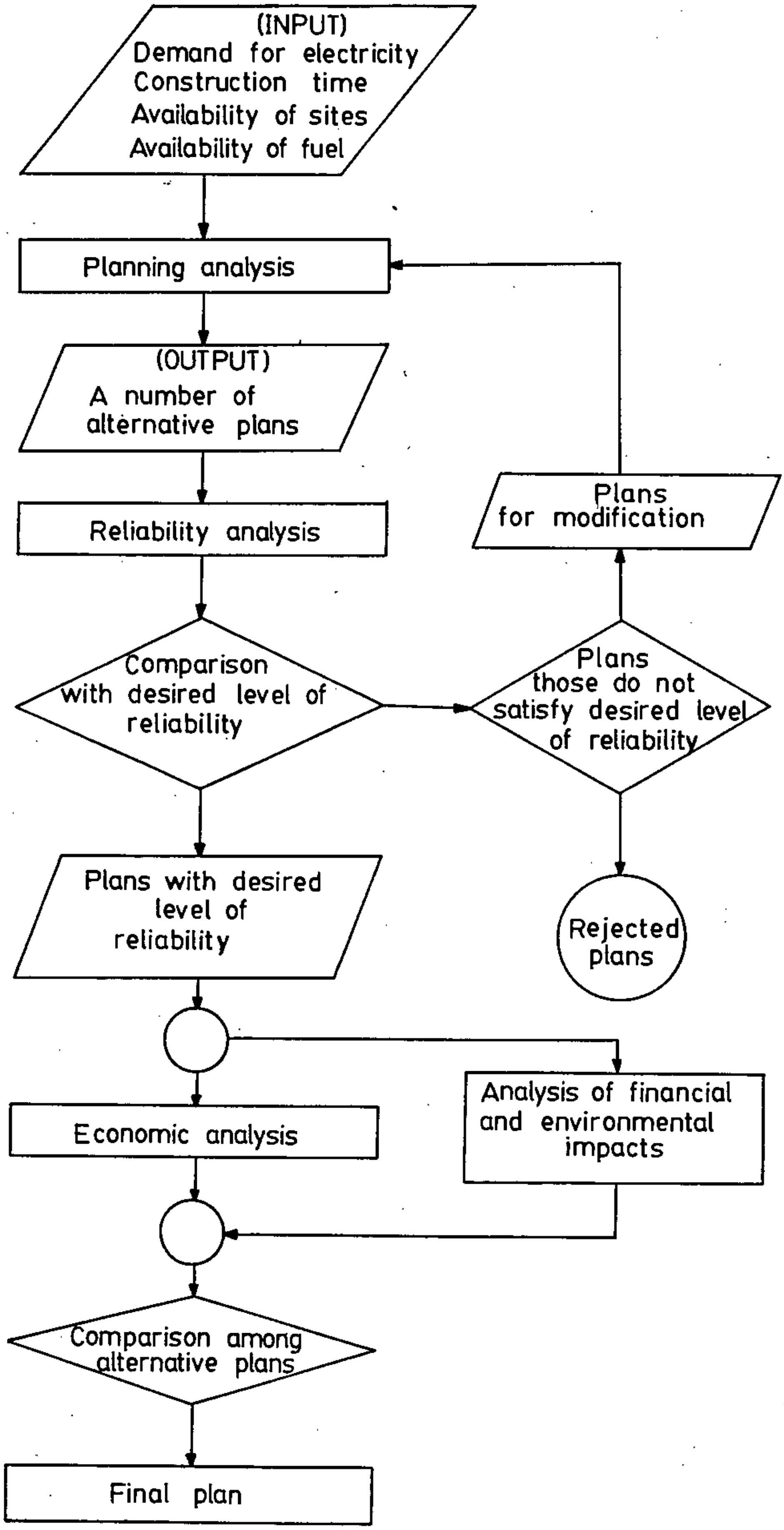


Figure 1.1 : Generation planning process.

Obviously, it is an enormous task to discuss in detail the entire planning process. Therefore, it is chosen to concentrate on the reliability and the economic analysis of generation plan for an isolated area in this research.

1.2 BACKGROUND

There is an increasing interest to develop a generation plan incorporating the renewable/unconventional energy sources.

A number of efforts have been reported which concentrated on developing a suitable long term planning model having the capability to treat efficiently and accurately the introduction of the renewable energy sources to the utility system [13-16]. On the other hand these long term planning models do not utilize short term study to prepare for introducing the renewable energy sources as one of the decision variables.

Some recent studies [17,18] have been addressed to the evaluation of the effect of unconventional sources on economy and reliability of the utility system. However, these studies are mostly focused to short term benefits. The benefits are not enough to decide whether these sources are competitive to the conventional sources or not. Thus, the short term studies can be followed by long term generation expansion and planning studies to decide if any one of the renewable sources or combination of them reduce one or more of the conventional sources.

Bakirtzies et al. [19] presented a method for solving the short term generation scheduling problem in a small autonomous system with both conventional and unconventional energy sources and storage battery. The system generation consists of diesel generators, wind turbine generators and photvoltaic panels. A forecast of the hourly power demand, average wind velocity and average insolation were considered for a scheduling period of the next 24 hours.

Farghal et al.studied [20] the long term competitiveness of introducing the renewable energy sources alongside the conventional generating units in a generation expansion plan by linking between a short term study and a long term planning model. In the short term study, there is a chance to study extensively different combinations of the renewable energy sources which can operate with the conventional generating system with different objectives. These objectives are varied between two general strategies; the fuel saving strategy and the peak shaving strategy. The peak shaving strategy is accomplished by a storage facility to ensure the availability of power in the peak demand periods. In the long term planning, these combinations are considered as decision variables beside the conventional sources. For this purpose, a long term generation expansion planning model is used to decide which strategy can be used and the capacity as well as the time of addition.

The development of a computer model to facilitate the design, sizing and operation of Remote Area Power Supply (RAPS) system was presented by Musgrove [21]. The paper describes the stochastic dynamic programming model, RAPSODY, and gives an example of its use in optimizing the design of a small wind/battery hybrid system including a single auxiliary diesel generator. RAPSODY uses the mathematical technique of dynamic programming to calculate the optimal operating strategy [22] for a RAPS system following some given electrical load profile and subject to a stochastically variable renewable energy input.

Xifan Wang et al.[23] presented a model which concerned the reliability characteristics of a large electric utility having wind turbine generators (WTGs). The effects of various wind turbines/interface system components i.e the forced outage rates (FOR) on the expected annual energy output of the farm were examined. There are also numerous papers/reports that discussed wind turbine generators or photovoltaic generators as stand alone sources or as hybrid systems. Wind / solar electricity generation for stand alone systems with battery and hydrogen storages was presented by Beyer et al. [24]. The model was developed in a deterministic fashion. Beyer et al. [25] also investigated the renewable fraction (F) as function of gross renewable production (PRG), storage capacity battery and wind/solar ratio.

A microcomputer - based analysis of stand - alone photovoltaic energy systems was presented by Rahman and Coulibaly [26]. In the resource assessment part of the package it estimates the hourly insolations for any site under a cloudless sky. So the insolation level determines the upper limit of possible irradiance at the site.

The integrated analysis of new energy sources on the British supply system was presented by Grubb [27]. The developed methods were applied to investigate the optimal thermal plant mix structure as wind and tidal energy use increases.

Optimum load matching in direct-coupled photovoltaic power systems was presented by Khouzam [28]. The load matching factor, the ratio of the load energy to the array maximum energy in a one day period [29-32], is used as a measure for the quality of load matching to the phtovoltaic (PV) array. In order to generalize the results, a per unit system based on the array maximum power point parameter at 100% SUN and 25°C is developed in which clear sky insolation model [29,33-35] is adopted. Simulation of photovoltaic power systems and their performance prediction were presented by Rahman and Chowdhury [36]. In the model development they used the observed global horizontal insolation, wind speed, ambient temperature and modeled direct normal insolation data to estimate the AC power for a 4-kW PV test facility in Raleigh, NC.

Most of the papers discussed so far, use to some extent, the derterministic models of solar and wind turbine generators. However, a probabilistic model of a wind turbine generator or of a photovoltaic generator is more realistic since the input to these generators, wind velocity and temperature, and temperature and insolation respectively are random in nature.

Harper et al. [37] developed a probabilistic model of insolation. The model evaluates the hourly expected insolation used to compute the output of a photovoltaic cell. Khallat and Rahman [38] used a curve fitting technique to generate the probability density function (PDF) of insolation from long term historical observations. This PDF was applied to predict the performance of a photovoltaic cell. Rahman and Chowdhury [39] presented a methodology to evaluate the cluster effects on the power output from a wind farm. They considered the Weibull distribution to develop the PDF of wind.

A method for determining the impact of wind generation on power system reliability was developed by Giorsetto et al. [40]. The method combines the effects of wind turbine forced outage rates (FOR) and varying power output due to wind speed variations only. Loss of power supply probability (LPSP) of stand-alone wind electric conversion systems was presented by Abouzahr et. al [41]. In this paper [41] a closed form solution approach to the evaluation of the LPSP of stand-alone wind-electric conversion systems with energy storage is discussed. This paper assumes; (i) the load is uniformly distributed and (ii) the load and wind speed are statistically independent.

There are several others [42] who have presented probabilistic models of wind and solar energy availabilities in the context of power generation. Schlueter, et al. [43] proposed a modified unit commitment and generation control scheme for utilities with large wind generation penetrations. Chalmers, et al.[44] discussed the effects of photovolataic power generation on electric utility generation control performance. Desrochers, et al. [45] presented a Monte Carlo Simulation method for determining the cost-effectiveness of wind energy considering the random variations in wind speed and the electric load. Sutoh, [46] presented a probabilistic model to evaluate the mean and variance of residential photovoltaic power output based on measured meteorological data. Thomann and Barfield [47] discussed autocorrelation analysis dealing with wind speeds and wind farm outputs to determine the degree of variations in such outputs over time. Bakirtzis, et al. [48] described a probabilistic method of predicting the performance of customer owned grid-connected wind arrays based on the statistical data of customer load and wind velocity. Jaffe [49] proposed that the availability of wind and solar generating units should be treated as the joint availability of the resource and the equipment.

Basically, aforementioned papers consider the output of a WTG as a function of wind velocity only and in case of a PVG its output is considered as a function of insolation only. However, in reality the output of a WTG depends not only on wind velocity but also on temperature. Similarly the output of a PVG depends on temperature and insolation. Moreover, these papers do not present any appropriate model of either a WTG or a PVG similar to the model of a conventional generating unit suitable for generation expansion planning.

Again researchers have developed numerous techniques [50-52] of forecasting loads. All these techniques require the history of load growth over the past. However, in an isolated area the history of load growth may not be available. From available literature it is revealed that no attempt has been made so far to forecast the loads of an isolated area where the history of load growth is not available or the supply of electricity did not start.

1.3 OBJECTIVES OF THE RESEARCH

Review of literature clearly reveals that a technique of load forecasting for an isolated area either without the history of load growth or any electricity has not been attempted [50-52] so far. It also reveals that an appropriate model of a PVG as well as that of a WTG suitable for probabilistic simulation has not been developed so far. Therefore it is decided to carry out a research with the following objectives:

i) To develop a load forecasting technique suitable for an isolated area either without electricity or the history of load growth.

ii) To develop a probabilistic model of a WTG, suitable for application in generation planning process like the model of a conventional unit, considering the output of a WTG as a function of both temperature and wind velocity.

iii) To develop a probabilistic model of a PVG, suitable for application in generation planning process like a conventional unit, considering the output of a PVG as a function of both temperature and insolation.

iv) To apply the proposed technique of load forecasting as well as the models of a WTG and a PVG to the generation planning of a realistic isolated area.

1.4 THESIS ORGANIZATION

Recognizing the work that has already been done in this field, this research attempts to develop appropriate probabilistic models of a WTG as well as that of a PVG for use in generation expansion planning analysis. Unlike many attempts of the past (for example Caramanis et al.[53]) this work does not treat the intermittent sources of generation as negative load. Rather the model of a WTG is developed from the bivariate distribution function of temperature and wind velocity, and that of a PVG from the bivariate distribution function of temperature and insolation.

This research justifies the use of the bivariate function of temperature and wind velocity and that of temperature and insolation as basic data. It utilizes the concept of the multistate representation of a generating unit in developing the models. These models are applied to analyse a generation plan of an isolated area. As forecasted load during the plan period is essentially required for the analysis of a generation plan , this research also develops a technique to forecast the load of an isolated area.

Following is an outline of the research work of different chapters of this thesis.

Chapter 1, presents the background of the research. It also presents the critical review of the work done in the field. The organization as well as the objectives of the thesis are briefly described in the same chapter. This chapter also presents a brief introduction to the generation planning of an isolated area.

In chapter 2, primary stress is given on the concept of reliability and cost analysis of an electrical energy system. This chapter presents the different probabilistic simulation techniques in brief and the segmentation method in detail. General approach of cost analysis is also briefly discussed in this chapter.

A new technique of load forecasting for an isolated area is presented in chapter 3. The developed technique is capable of forecasting the loads of an isolated area where the history of load is not available. It is based on the identification of factors on which electrical load growth depends. The method develops the so called comparative factor using which the hourly load of an isolated area has been derived. The application of the proposed technique to an isolated area of Bangladesh is also presented in this chapter.

Wind as a source of electrical energy is described in chapter-4. This chapter presents the general features of a wind turbine generation (WTG) and its typical characteristics. The basic concept of converting wind energy into electrical energy is also presented in this chapter. Different types of WTGs and their characteristics are also described.

The probabilistic model of a WTG is presented in chapter-5. This chapter presents a methodology to develop a probabilistic model of a WTG based on the concept of the multi-state representation of a generating unit. The probability density function (PDF) of the capacity output from a WTG is derived from the bivariate function of wind velocity and temperature. To justify the development of the proposed capacity generation model of a WTG considering the bivariate function, wind velocity and temperature, a capacity generation model of a WTG is also developed by considering a univariate function, wind velocity, in this chapter. The model development procedure is exemplified through a simple numerical example. In this chapter, the proposed model is applied to evaluate the expected energy generation, the expected energy not served and the loss of load probabilities (LOLPs). The results are compared with those obtained using the model developed from a univariate function. The justification of the multi-state capacity generation model of a WTG by considering the bivariate function of wind velocity and temperature is also discussed in this chapter.

Solar radiation as a source of electrical energy is described in chapter 6. The dependence of the electrical power output of a solar cell is also discussed in this chapter. The characteristics of silicon photovoltaic cells are described in brief in the same chapter.

The probabilistic model of a photovoltaic generator (PVG) is presented in chapter - 7. This chapter presents a methodology to develop a probabilistic simulation model of a PVG based on the concept of the multi-state representation of a generating unit. The probability density function (PDF) of the capacity output from a PVG is derived from the bivariate function of solar radiation (insolation) and temperature. To justify the development of the proposed capacity generation model of a PVG from the bivariate function of insolation and temperature, a capacity generation model of a PVG is also developed by considering the output of a solar cell as a univariate function of insolation only. Both models are applied to evaluate the expected energy generation, the expected energy not served and the LOLPs. The results obtained using these two models are compared and the justification of the proposed model is discussed in this chapter.

The electrical energy system comprising WTG, PVG and thermal generators is presented in chapter-8. The expected energy generation, the expected energy not served and the LOLPs of the system are evaluated considering WTG, PVG and thermal units in the system. For these cases, the costs of the generating system are also evaluated in this chapter. The results are analysed in order to find out the most desirable generation mix for the considered isolated area.

Concluding remarks and the significant contributions of this work is highlighted in the last chapter(9). Also recommendation for further work are presented in this chapter.

CHAPTER 2

RELIABILITY AND COST ANALYSIS

2.1 INTRODUCTION

For a power system planning, it is necessary to select the most reliable and economical generation system for the given requirements. That is, the evaluation of the reliability as well as the cost of alternative plans of generation are the important steps in the process of selecting a plan which suits the system in the most favourable way.

This chapter presents the basic concepts of power system reliability as well as the cost analysis of the system. It also describes the techniques of evaluating the reliability and the cost of an alternative plan.

2.2 BASIC CONCEPT OF RELIABILITY ANALYSIS

Reliability is the probability of a device or system performing its purpose adequately for the period of time intended under the operating conditions encountered [54]. Different approaches are used to evaluate the power system reliability. Some of the commonly used indices are described here.

Loss of Load Probability (LOLP)

The loss of load probability (LOLP) is the probability that the available generating capacity of a system will be insufficient to meet its demand. Thus

$$\text{LOLP} = \text{Prob.}\ [\ AC < L] \qquad (2.1)$$

where ‘AC’ and ‘L’ are the available capacity and system load respectively.

The evaluation of LOLP takes into consideration the forced and scheduled outages of generating units as well as load forecast uncertainty and assistance due to interconnections. The LOLP does not give an indication of the magnitude or duration of generation deficit. This reliability index only provides the probability of occurrence of the loss of load. As LOLP is the simplest and most commonly used reliability index [55,56], it will be used in this research to evaluate the reliability of a power system.

Loss of energy probability (LOEP)

The ratio of the expected amount of energy not supplied during a period to the total energy required during the same period is defined as the loss of energy probability (LOEP). The true loss of energy cannot be accurately computed on the basis of the cumulative load curve. For this reason, this index is rarely used.

Frequency and duration (FAD)[56].

This gives the average number of times and length of time during which available generation is inadequate to the load. This requires consideration of load cycle and data of the frequency and duration of unit outages. One problem with FAD technique is that it requires more detailed data than is usually available. In addition to failure rates of various components, repair times must also be available.

Monte Carlo Simulation (MCS)[56]

Monte Carlo simulation (MCS) methods are more popular in Europe than in Canada or the USA. In MCS, the actual realization of the life process of a component or a system is simulated on the computer and after having observed the simulated process for some time, estiamtes are made of the desired reliability indices. The MCS is the best suited to problems in which reliability is significantly affected by system operating policies. The method is computationally expensive. However, it may produce a solution in cases where more traditional analytical techniques fail.

Among the above reliability indices the LOLP is the most popular index to evaluate the reliability of a electrical system. This thesis considers it (LOLP) as the measuring index of reliability.

2.3 LOSS OF LOAD PROBABILITY (LOLP)

In section 2.2, the LOLP is expressed in terms of available capacity (AC) and system load (L) as

$$\text{LOLP} = \text{Prob. } [AC < L] \qquad \ldots(2.1)$$

However, this definition does not take into account the random outage of generating units.

A fictitious load, L_e, is usually defined to take the random outages of the unit in evaluating LOLP. In what follows the concept of the effective load is presented.

2.3.1 Effective Load

The randomness in the availability of generating capacity is taken into account by defining a fictitious load, known as 'effective load' (L_e) [57]. Figure 2.1 depicts the relationship between the system load and generating units, where the actual units have been replaced by fictitious perfectly reliable units and fictitious random loads, whose probability density functions (PDFs) are the outage capacity density functions of the units.

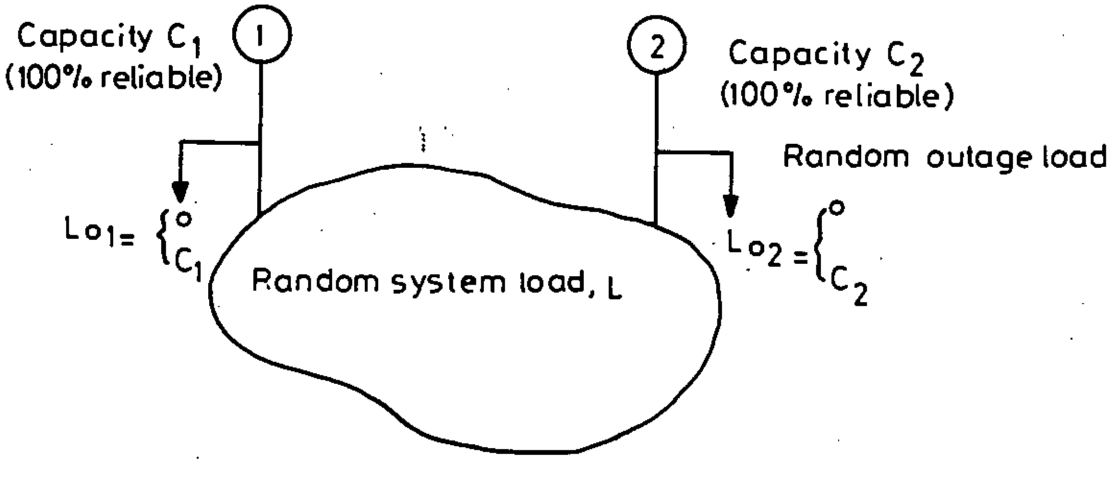


Figure-2.1 Fictitious generating units and system load.

If Lo_i represents the random outage load corresponding to the i-th unit, the equivalent load (L_e) may be expressed as

$$L_e = L + \sum_{i=1}^{n} Lo_i \qquad \ldots(2.2)$$

where n is the total number of generating units. When $Lo_i = C_i$, the net demand injected into the system for the i-th unit is zero, just as if the actual unit of capacity C_i were forced off-line.

The PDF of outage capacity of generating units may be taken as independent of system load. Then the distribution of effective load will be the convolution of two distributions: f_L and f_{Lo} representing the PDFs of the system load and outage capacity of generating units respectively. For the discrete case the PDFs, f_L and f_{Lo} respectively, can be written as

$$f_L(l) = \sum_i P_{Li} \; \delta(l-l_i) \qquad \ldots(2.3)$$

$$f_{Lo}(l_o) = \sum_j P_{Loj} \; \delta(l_o - lo_j) \qquad \ldots(2.4)$$

Therefore, the PDF of equivalent load f_{Le} is

$$f_{le}(l_e) = f_l(l) * f_{Lo}(l_o)$$

$$= \sum_{i,j} P_{Li} \; P_{Loj} \; \delta(l_e - (l_i + l_{oj})) \qquad \ldots(2.5)$$

where * indicates the convolution and P_L and P_{Lo} are the probabilities of load and outages of generating unit respectively. The small letters within bracket of equation (2.5) are the values of corresponding random variables (RVs).

2.3.2 The LOLP in Terms of the Equivalent Load:

The LOLP of a system may be defined in terms of the equivalent load as is the probability that the equivalent load will be greater than the installed capacity of the system and it is expressed as,

$$\text{LOLP} = \text{Prob.}[L_e > \text{IC}] \qquad \ldots(2.6)$$

where IC is the installed capacity. Installed capacity IC, may be expressed as

$$\text{IC} = \sum_i C_i \qquad \ldots(2.7)$$

2.4 BASIC CONCEPTS OF COST ANALYSIS

The main components which enter into the determination of revenue requirements for a given alternative plan are:

i) Capacity cost;

ii) Production cost;

iii) Operating and maintenance cost.

Besides these three major factors, timing of unit additions is also important in cost analysis.

2.4.1 Capacity Cost

Utilities require a very high investment in plant and equipment in comparison to annual revenues and annual operating cost. The relative high plant investment is the most distinguishing feature of an electric utility. Factors which affect capacity costs include type of generating unit, unit size, depreciation, taxes, labour costs, environmental requirements, capital and financing costs.

The capacity cost of unit i, denoted by CC_i , is usually defined as follows [82]

$$CC_i = FCR_i \; UC_i \; C_i \qquad (\$) \qquad \ldots(2.8)$$

where

FCR_i = fixed charge rate,

UC_i = unit capacity cost ($/kW),

C_i = capacity of i-th unit (kW).

The fixed charge rate reflects the annual amount of revenue requirement to pay for the facility over its lifetime, and is designed to meet the annual costs associated with capital investment. In general, the FCR consists of depreciation, income taxes, and annual return (interest on debt, dividents on preferred stock and earnings on common equity).

Unit capacity cost is self-explanatory; however, it is important to be aware of the relative capacity cost for various types of units. The capital cost of PVG units varies considerably depending upon such variables as panel size, site and others. Their capital cost, however, tends to be higher than that of corresponding WTGs or thermal units.

2.4.2 Production Cost

The estimation of the energy production cost of an electric utility is by far the most complex part of cost analysis associated with a particular expansion plan. It depends on the loading order procedure, availability of units, and the demand for electric energy in the day to day operation of the system, which are highly variable and unpredictable, especially when the calculation extends far into the future.

The production cost associated with a given generation plan includes both fuel cost (FC), which reflects the cost of fuel, and start-up and shut-down costs. Start-up and shut-down costs are fixed operating costs and can be estimated quite accurately from past data and they are added to the system fuel cost at the end. In what follows the expected fuel cost is referred to as the production cost.

2.4.3 Operating and Maintenance Cost

The operating and maintenance costs include all fixed non-production costs such as labour, supplies and materials required to maintain and operate a plant. These costs also include all variable costs associated with preparing the unit for daily operation. Essentially these costs do not depend on the amount of energy produced. Data regarding operating and maintenance cost are estimated on an annual basis in order to be integrated into the economic analysis.

2.5 TECHNIQUES OF PROBABILISTIC SIMULATION

Various methods have been developed for predicting future production costs as well as the system reliability among which probabilistic load duration method by far is the most popular method. The method represents the actual operation of the system more accurately than other methods. It considers the forced outage rates (FOR) and maintenance scheduling of the generating units as well as the merit order loading.

In the probabilistic method, it is recognized that the energy generated by a particular unit is represented by the area it occupies beneath the load duration curve. The position of the unit depends, however, on the availability of the more efficient units which take priority in loading. If a large base load unit is unavailable, a less efficient unit is likely to generate more than otherwise.

The objective of the probabilistic method is to determine the expected amount of energy generated by each unit, and to evaluate the system reliability.

Two following exact techniques for probabilistic simulation have so far been developed:

(i) 'Baleriaux-Booth' [58,59] technique more commonly known as the 'recursive' method and

(ii) 'segmentation method' [60].

An approximate technique is also used in the power industries. This approximate technique based on the concept of Gram-Charlier series expansion. The method is popularly known as cumulant method [61,62]. But the accuracy of this technique is system dependent i.e. depends on the number of units, unit size, FOR, load shape etc. Studies [63,64,65] show that the segmentation method is the most desirable one regarding computational time and computer memory requirement.

In what follows the segmentation method is described in brief.

2.6 SEGMENTATION METHOD

The method uses the probability density function (PDF)of demand by sampling the chronological load curve every hour or any other suitable interval. The segmentation method is based on segmenting the demand or load axis into equal capacity segments. Each segment size is equal to the largest common factor of the capacities of all units. These segments are filled with the zeroeth and first order moments obtained from the distribution of load. The total number of segments is decided through the knowledge of the installed capacity of the system as well as the segment size and one segment beyond the installed capacity is considered. The method uses hourly loads and the frequency distribution of demand thus obviating the use of LDC. In addition the numerical errors in calculating the area under the LDC are also avoided.

2.6.1 Evaluation of LOLP

In order to account for the random outages of units it is necessary in the segmentation method to get a new distribution of each segment incorporating the outages of all units. Prior to finding this new distribution, each segment is assigned with a probability value which is equal to the sum of the probabilities i.e. zeroeth moments of the impulses of PDF of load lying in the range of that segment. Now the zeroeth moment of all the segments are recalculated as generating units are convolved. When a unit is convolved,the new value of zeroeth moment of n-th segment is found from the relation

$$\widetilde{P}_n = P_n(1-q) + \widehat{P}_n q \qquad \ldots(2.9)$$

where

$\widetilde{P}_n$ = zeroeth moment of n-th segment after the convolution

$\widehat{P}_n$ = zeroeth moment of n-th segment after the shift

P_n = zeroeth moment of n-th segment before convolution

q = forced outage rate of the unit to be convolved.

Following steps are used to convolve a generating unit:

a) The original moment of segments are multiplied by the availability of the unit.

b) The original segments are then shifted by the capacity of the unit to be convolved and are multiplied by the FOR of the unit

c) The values obtained in (a) and (b) of corresponding segments are added to obtain the final disribution.

Note that the probability value of the last segment is the sum of the probabilities of all the segments exceeding the installed capacity. After all the generating units are convolved, the zeroeth moment of the last segment is the LOLP of the system.

2.6.2 Evaluation of Expected Energy Generation

The expected energy generated by a particular generating unit is obtained from the difference of unserved energies before and after the convolution of that unit. In the segmentation method the evaluation of expected energy generation also starts with the formation of segments. A probability value is assigned to each segment from the knowledge of load impulses lying within the segment size. Each segment is also assigned with another value which is the first order moment of the load impulses lying in the range of corresponding segment. The first order moment is given by

$$m_1 = \int_{-\infty}^{\infty} X f_X(x)\,dx \qquad \ldots(2.10)$$

where, x is the random variable and $f_X(x)$ is the probability density function. For discrete case the first order moment for a particular segment is

$$m_i = \sum_i x_i\, p_i \qquad \ldots(2.11)$$

where

x_i = value of the random variable

p_i = probability of the random variable x_i

Initially, the expected energy not served (unserve energy) is the summation of the first moment of all the segments. The generating units are then convolved according to the merit order of loading. The concept of merit order load is described in section 2.6.3. As the generators are convolved, the first moment is recalculated for each segment. In this case, unlike the shifted zeroeth order moments the shifted first order moments are changed [84]. The first moment of any shifted segment is calculated by using the following relation

$$m_1^{new} = m_1^{old} + shift * m_o \qquad ...(2.12)$$

where, m_o is the zeroeth moment of the segment. m_1^{old} is the first moment of a segment prior to shift and m_1^{new} is the shifted first moment. The first moment of a segment after convolution is found by

$$\widetilde{m_1} = m_1 (1-q) + \widehat{m}_1 q \qquad ...(2.13)$$

where

$\widetilde{m_1}$ = first order moment of a segment after convolution of a generating unit of FOR = q

$\widehat{m_1}$ = shifted first moment of that segment

m_1 = first moment of the segment prior to convolution

Unserved demands are calculated before and after the convoluation of each unit. The unserved demands multiplied by the period of study is the expected energy not served. For n-th unit, expected energy generation is found from the relation

$$E_n = UE_n^- - UE_n \qquad ...(2.14)$$

where

E_n = expected energy generated by n-th unit,

UE_n^- = unserved energy before convolving n-th unit,

UE_n = unserved energy after convolving n-th unit,

It should be noted that the first moment of last segment is the sum of the moments of all segments exceeding the installed capacity. When all the generating units are convolved the first moment of the last segment is the expected energy not served.

2.6.3 Merit Order Loading

The basic tenet in the loading order procedure is that the generating units are loaded in the order of their average incremental costs. The most efficient generating unit is the one with the lowest incremental cost; this generating unit is loaded first. Next in line are generating units with higher average incremental costs.

The merit order loading procedure to be followed in the case of different sizes of conventional (thermal) units to select the generating unit, from among the set of generating units, with the lowest average incremental cost, to be loaded first. This is followed by the next most efficient unit among the remaining sets and so on. That is, if s generators from a total of n generators are already committed, then the average incremental cost of the most efficient unit, λi, in the set of the units which are to be committed, is expressed as

$$\lambda_i = \text{Min} \left\{ \lambda_k,\ k=1,2,\ldots\ (n-s) \right\} \qquad \ldots(2.15)$$

where

$$i = (s + 1) \qquad \ldots(2.16)$$

2.6.4 Evaluation of Production Cost

As the expected energy generated by a unit is known, the production cost associated with the unit is found by multiplying the expected energy generation (En) with the average incremental cost of the unit.

$$EC_n = \lambda_n E_n \qquad \ldots(2.17)$$

where

EC_n = production cost of n-th unit

λ_n = average incremental cost of the n-th unit.

2.7 THE GLOBAL COST ANALYSIS

The final cost analysis must also consider,

i) service life of a generating unit.

ii) interest rate,

iii) depreciation and

iv) the salvage value of the generating unit.

Several economic methods are available to determine the global cost.. Two of them are common;

i) the annual cost method,

ii) the present worth method.

In what follows, the annual cost method, used in the research, is described.

In essence, this method compares the annual costs (capital recovery plus operating costs) of obtaining a service from two or more generators. The annual capital recovery (CR) cost may be calculated by the following formula (for equal annual costs)[66,67]

$$CR = (P - L) \left[\frac{i(1 + i)^n}{(1 + i)^n - 1} \right] + Li \qquad \ldots(2.18)$$

or $CR = (P - L)$ (Capital Recovery Factor) $+ Li$

or $CR = (P - L)\,(C.R.F.) + Li$

where

P = first cost of generator or initial investment (initial capital cost)

n = life of study or generator in years

L = salvage value at end of n years

C.R.F = Capital Recovery Factor

i = interest rate or minimum attractive return

The following example illustrates the use of the annual cost method to compare two alternative plans. Note that in this case it is considered that each alternative comprises of only one generating unit.

	Generator A	Generator B
Initial cost :	$10,000	$15,000
Annual operating costs:	2,000	1,500
Expected years of life:	10	10
Salvage value:	1,000	2,000

Interest rate = 6 percent

For Generator A:

CR at 6% = ($10,000 - $1,000)(0.13587)+($1000)(.06)

= $1222.83 + $60.00 = $1282.83

Total annual costs = CR + Operating costs

= $1282.83 + $2000 = $3282.83

For Generator B:

CR at 6% = ($15,000 - $2,000)(0.13587) + ($2000)(.06)

= $1766.31 +$120 = $1886.31

Total annual costs = $1886.31 + $1500 = $3386.31

On the basis of this analysis, Generator A would be favoured.

The concepts of depreciation is the spreading of the cost of a long-term asset over the life, or expected years of usage of the asset. It is an arbitrary figure used to "write off" the financial investment in such assests in terms of yearly operating expense. Factors that enter into the calculation of depreciation are the initial cost of the item, its anticipated life, and its estimated salvage value at the end of the depreciation period.

Any reasonable method that is consistently applied may be used in computing depreciation [68]. The three methods most generally used are the

i) straight line method,

ii) the declining balance method, and

iii) the sum of the years-digits method. In what follows the straight line method is described.

The straight line method is the simplest method for computing depreciation. Under this method, the cost of the equipment less its salvage value is generally deducted in equal annual amounts over its period of estimated useful life. The method of calculating this amount may be illustrated by the following example: For an engine lathe that cost \$6000, is estimated to have a service life of 8 years, and a salvage value after 8 years is \$1200, the annual depreciation (D) would be:

$$D = \frac{\$6000 - \$1200}{8} = \$600 \text{ per year}$$

2.8 SELECTION OF AN ALTERNATIVE PLAN

When the reliability and the capacity, production and operating and maintanance costs of the alternative plans are known then the problem to an utility is to decide which plan it should adopt. Many factors may influence the final decision, such as: service policy, delivery dates, and reputation of the manufacturer. Assuming that everything else is equal, the problem tends to become essentially one of economic selection. That is, the problem is to pick up a plan that minimizes the cost.

CHAPTER 3

A LOAD FORECASTING TECHNIQUE FOR AN ISOLATED AREA

3.1 INTRODUCTION

In the future planning of any power sector, generation, transmission or distribution, the forecasted load during the planning period is the core information. A plan would be effective if the forecasted load becomes closer to the realistic value. Researchers have developed numerous techniques [50-52,69] of forecasting loads. All these techniques require the history of load growth over the past. However, in an isolated area the history of load growth may not be available. Recall that an isolated area is a place where the electrical consumers can not be interconnected with the main grid system either because of technical reasons or of economic reasons.

Some isolated areas may be industrially (commercially) important and they might have developed their own electric power system. However, it may not be the case for every isolated area. There may exist some isolated areas where electric power might not have even developed and the question of history of electrical load growth does not arise. This chapter presents a methodology to forecast the loads of an isolated area where the history of load is not available, if it does, the information does not represent the realistic demand of electricity.

The proposed methodology is based on the identification of the factors on which electrical load growth depends. Area/Areas with the known load deciding variables similar to those of the isolated area are selected to evaluate the contribution of load deciding variables. A suitable area in which the load deciding variable are similar to those of the typical isolated area and whose hourly load data are known is selected. The average loads of the selected area and the typical isolated area are estimated to calculate a comparative factor. Utilizing the comparative factor the load of the typical isolated area is derived from the load of the selected area. The proposed methodology is applied by using the data available for some selected Rural Electric Societies(PBSs) of Bangladesh.

3.2 PROPOSED METHODOLOGY

The method starts with the identification of factors on which load growth depends. These factors may be different for different types of loads. Usually electric loads are domestic, commercial and industrial.

The domestic load may be a function of population and standard of living of people. The variation of standard of living is caused by per capita income and literacy rate. All these factors are time varying quantities. The domestic load L_D may then be expressed as

$$L_D(t) = f_1\ (P(t),\ LR(t),\ PI(t)) \qquad ...(3.1)$$

where

$P(t)$ = population at time t,

$LR(t)$ = literacy rate at time t,

$PI(t)$ = per capita income at time t .

However, the industrial load may depend on the per capita income, inland communication per unit area, literacy rate and agricultural land per unit area. This industrial load L_I may then be expressed as

$$L_I(t) = f_2(PI(t), RL(t), LR(t), AL(t)) \qquad ...(3.2)$$

where

$RL(t)$ = inland communication (Road) length per unit area at time t

$AL(t)$ = agricultual land in percent of total area at time t

In some isolated areas instead of inland communication, communication across the sea may be the major type of communication. In that case the communication must include the sea route length also.

The commercial load L_C mainly depends on the per capita income and inland communication. This type of load may be expressed as

$$L_C(t) = f_3 (PI(t), RL(t)) \qquad ...(3.3)$$

The total electrical load demand $L(t)$ in an isolated area is the sum of the above three types of loads. That is,

$$L(t) = L_D(t) + L_I(t) + L_C(t) \qquad ...(3.4)$$

Therefore, the load of an isolated area may be expressed as

$$L(t) = f(P(t),LR(t),PI(t),RL(t),AL(t)) \qquad ...(3.5)$$

Although equation (3.5) expresses that the load is a function of five time dependent variables, however, all variables will not contribute equally to the generation of load. Let $x_1,...,x_5$ represent the weighting factors by which each time varying factor P(t), LR(t), PI(t),RL(t), AL(t),respectively, contributes towards the load growth. The weighting factors X are also random in nature. They may vary with different areas. Now the load can be expressed as

$$[\, L\,(t)\,] = [\, X\,] \begin{bmatrix} P(t) \\ LR(t) \\ - \\ AL(t) \end{bmatrix} \qquad ...\ (3.6)$$

Solving equation (3.6) the weighting factors X can be determined as

$$[\, X\,] = \begin{bmatrix} P\ (t) \\ LR(t) \\ - \\ AL\ (t) \end{bmatrix}^{-1} [\, L(t)\,] \qquad ...(3.7)$$

Now each element of the row vector [X], x_i may be obtained from the relation

$$x_i = \sum_{j=1}^{M} x^j{}_i .\ P_j \qquad ...(3.8)$$

where, M is the number of areas considered to generate the distribution of x_i and P_j is the probability that the value of x^j_i will occur. In equation (3.8), the superscript refers to the area, i.e. x^j_i is the value of i-th element of vector X corresponding to the j-th area. Since, the contributions of different areas in the evaluation of the load of an isolated area may be different in reality, therefore, the values of P_j's may be different.

3.3 COMPARATIVE FACTOR

In many cases, especially in generation expansion planning, the hourly load during the plan period is required instead of monthly or annual average demand. However, in equation (3.6) the load deciding factors do not vary hourly. The variation of these factors become only salient, if these are recorded annually or half yearly. Even consecutive monthly data may not show the difference prominently. Therefore, the equation may provide only the half yearly or yearly average load. However, the hourly variation is the required infromation. The above problem may be solved by introducing a comparative factor. In doing so, the first step is to select an area in which the load deciding factors are similar to those of an isolated area and whose load variation with time is known.

Now represent the planning horizon by the time interval $[t_o,T]$ with both t_o and T assumed finite. Partition the time interval $[t_o, T]$ into M subintervals given by

$$t_o \leqslant t_1 \leqslant t_2 \ldots\ldots \leqslant t_n \leqslant t_m = T$$

so that

$$\bigcup_{k=1}^{M} (t_{k-1}, t_k] = (t_o, T] \qquad \ldots(3.9)$$

Note that the time interval size should be such that the variations in the values of the factors are identifiable.

The next step is to forecast the load growth deciding factors for each interval of the planning period for both the selected area and the isolated area. Using the forecasted values of load growth deciding factors of each area estimate the load for both the areas using equation (3.6)

The next step in this process is to determine the comparative factor for any interval t_i as

$$CF_{ti} = \frac{l_{IA}(t_i)}{l_{SA}(t_i)} \qquad \ldots(3.10)$$

where, $l_{SA}(t_i)$ and $l_{IA}(t_i)$ are the forecasted average load of the selected area and the considered isolated area respectively for the interval t_i.

Then forecast the hourly load of the selected area using its historical load in any standard technique [69]. The hourly load of the isolated area for the interval t_i may be obtained using the following relation,

$$L_{IAti}(t) = CF_{ti}\ L_{SAti}(t) \qquad \ldots(3.11)$$

Note that t must lie within the time interval t_i.

3.4 APPLICATION OF THE PROPOSED TECHNIQUE

The proposed methodology is applied to a typical island. It is located in the southern end of Bangladesh and it is an island of the Bay of Bengal. The distance of the typical island from main land is 2 kilometer. The total population and area are respectively 72000 and 70 km^2. Because of its distance inside the sea, economically it is not possible to interconnect this area with the main grid system of Bangladesh Power Development Board (BPDB). Basically, the source of earnings of peoples of this island are agriculture products and fishing. There is no industry in this island.

3.4.1 BASIC DATA TO DEVELOP COMPARATIVE FACTOR

In Bangladesh, Rural Electrification Programme is implemented under the Area Coverage Rural Electrification (ACRE) system. Each of the electrified area is managed by an independent co-operative society known as Palli Bidhyut Samity (Rural Electric Society), PBS. Starting from 1981, 30 PBSs have been electrified upto 1987. Peak demand of electricity for all the energized PBSs for 1987 and their respective load deciding variables are shown in table 3.1.

Table 3.1 : Basic data of demand deciding factors

Sl. No. PBS Name	Area (km^2	(P) Population (1000)	(LR) Literacy rate (%)	(PI) Per cap. income (TK)	Total area (acres)	(AL) Agriculture land	(RL) Comunication (km/km^2)	(PK) Max. demand (MW) 1987
1.Dhaka-1	953	570	37.8	4492	237440	73.57	0.106	16.80
2.Tangail-1	1526	1032	25.3	4114	315233	84.43	0.088	9.76
3.Comilla-1	1492	1285	29.1	3865	389380	78.16	0.088	7.40
4.Chandpur-1	1704	1643	29.1	3865	419437	77.80	0.042	5.10
5.Habigonj	1254	584	23.6	4171	309120	59.03	0.171	5.20
6.Moulovibazar	1228	470	23.6	4171	304640	54.02	0.1156	7.20
7.Pabna-1	769	366	24.3	3553	190720	81.70	0.052	2.80
8.Pabna-2	945	463	24.3	3553	234240	68.10	0.115	3.90
9.Serajgonj	1005	682	24.3	3553	248960	85.67	0.173	6.10
10.Jessore-1	1191	680	29.5	3874	334720	75.97	0.219	5.75
11.Jessore-2	948	532	29.5	3874	234880	77.68	0.159	6.50
12.Natore-1	1269	564	26.0	3711	312160	73.78	0.139	5.50
13.Natore-2	1202	602	26.0	3711	348060	65.21	0.201	6.30
14.Rangpur-1	1310	637	22.7	3930	333819	72.51	0.077	3.00
15.Satkhira	1299	573	38.3	5322	343466	67.93	0.283	1.70
16.Feni	1175	1016	32.5	3583	279146	66.53	0.187	3.20
17.Mymensingh-1	1943	804	21.5	3800	437080	73.18	0.203	2.30
18.Dinajpur	1063	449	27.4	3962	350080	79.17	0.215	3.00
19.Kushtia-1	1171	507	22.3	3763	312960	69.71	0.416	2.10
20.Joypurhat	909	422	28.3	4195	240150	80.26	0.230	0.70
21.Pirojpur	865	465	40.9	3605	286160	70.88	0.216	0.40
22.Rangpur-2	1106	827	22.7	3930	236461	71.06	0.241	1.00
23.Jamalpur-1	1106	1366	18.1	3690	273280	80.85	0.064	0.40

Table 3.1 : Basic data of demand deciding factors (Continued)

Sl. No.	PBS Name	Area (km^2	(P) Population (1000)	(LR) Literacy rate (%)	(PI) Per cap. income (TK)	Total area (acres)	(AL) Agriculture land	(RL) Comunication (km/km^2)	(PK) Max. demand (MW) 1987
24.	Bogra	1080	642	28.3	4195	311370	81.62	0.332	0.40
25.	Thakurgaon	1060	404	27.4	3962	215040	54.69	0.149	0.50
26.	Madaripur	805	575	26.2	3739	199040	78.57	0.273	1.30
27.	Barisal	917	688	40.9	3605	277760	71.27	0.465	1.30
28.	Chittagong-2	1347	714	33.8	6504	406622	41.29	0.234	0.40
29.	Meherpur	1347	493	22.3	3763	262400	71.93	0.245	0.30
30.	Noakhali	951	981	32.5	3583	251110	69.87	0.136	0.30
**	A typical island	70	72	35.0	6504	17280	61.92	0.60	-

Sources :a) Rural Electrification Programme, Bangladesh, 1986-87,REB,1987.
b) A brief on Bangladesh Rural Electrification Programme, REB, 3rd ed. July, 1988.
c) Statistical Yearbooks of Bangladesh,1981-89,Bangladesh Bureau of Statistics (BBS).
d) District Statistics, 1983 and 1987,BBS.

A close observation of the data of table 3.1 shows that there are closeness among the factors of some areas. However, the peak demand varies widely. Similarly, the peak demands of some areas have closeness, however, other different factors of these areas vary widely.

For the purpose of present analysis a group of 5 PBS having similar loads have been selected for estimating the contribution of load deciding variables and the relevant data are shown in table 3.2. Note that, all the PBS grouped in table 3.2 are among the latest energized PBSs and are in operation from the same year (1986-87).

Table 3.2 : DATA OF PBSs OF ALMOST SIMILAR DEMAND

	Load deciding variables					Loads		
NAME OF PBS	P	LR	PI	AL	RL	Peak Load (MW)	Average Load (MW)	Load Ratio K
Meherpur	493	22.3	3763	71.93	0.24	0.30	0.015	20.00
Noakhali	981	32.5	3283	69.87	0.14	0.30	0.028	10.71
Bogra	642	28.3	4195	81.62	0.33	0.40	0.130	3.08
Pirojpur	465	40.9	3605	70.88	0.22	0.40	0.063	6.35
Chittagong-2	714	33.8	6504	41.29	0.23	0.40	0.078	5.13

3.4.2 SIMULATION RESULTS

The data of table 3.2 are used to evaluate [X]. The evaluated values of weighting factors are given in table 3.3.

Table 3.3: Weighting factors of load growth deciding variables:

COMPUTED VALUE OF UNKNOWN VARIABLES				
X1 (P)	X2 (LR)	X3 (PI)	X4 (AL)	X5 (RL)
0.000015	0.00507	0.000006	0.000001	0.70

Of the 30 PBS actual hourly load data of Jamalpur PBS was available for the reference year. Because of this reason Jamalpur PBS is selected to evaluate the hourly load of the typical island.The contribution of load deciding variables for Jamalpur PBS and the typical island are evaluated and the simulation results with percentage of the total forecasted demand and the evaluated forecasted average load and the comparative factor are given in table 3.4.

Table 3.4 Contribution of load deciding variables for Jampalpur PBS and a typical island.

Name of area	P MW (% of total)	LR MW (% of total)	PI MW (% of total)	AL MW (% of total)	RL MW (% of total)	Forecasted Average load(MW)	Comparative factor
Jamalpur PBS	0.0205 (10.76)	0.092 (48.30)	0.02214 (12.63)	0.000081 (0.0004)	0.0558 (29.30)	0.1905	3.36
The typical island	0.00108 (0.02)	0.1775 (27.73)	0.04 (6.30)	0.000062 (0.001)	0.42 (65.7)	0.64	

Using this comparative factor the hourly load of the typical island is derived applying equation (3.11). The hourly load of Jamalpur and its corresponding load of the typical island of 192 hours are depicted in figure 3.1.

Previous presentation indicate that the methodology developed by the present study is suitable to estimate the hourly load variation of a typical island on the basis of known data of load and load deciding factors of some selected areas for a particular year.

The following presentation is made to forecast the average/peak load data of the typical island for future date.

The load demand of different PBSs that are energized during the first phase of REB programme are considered and shown in table 3.5. Among these 13 PBSs only the load demand of Dhaka PBS is

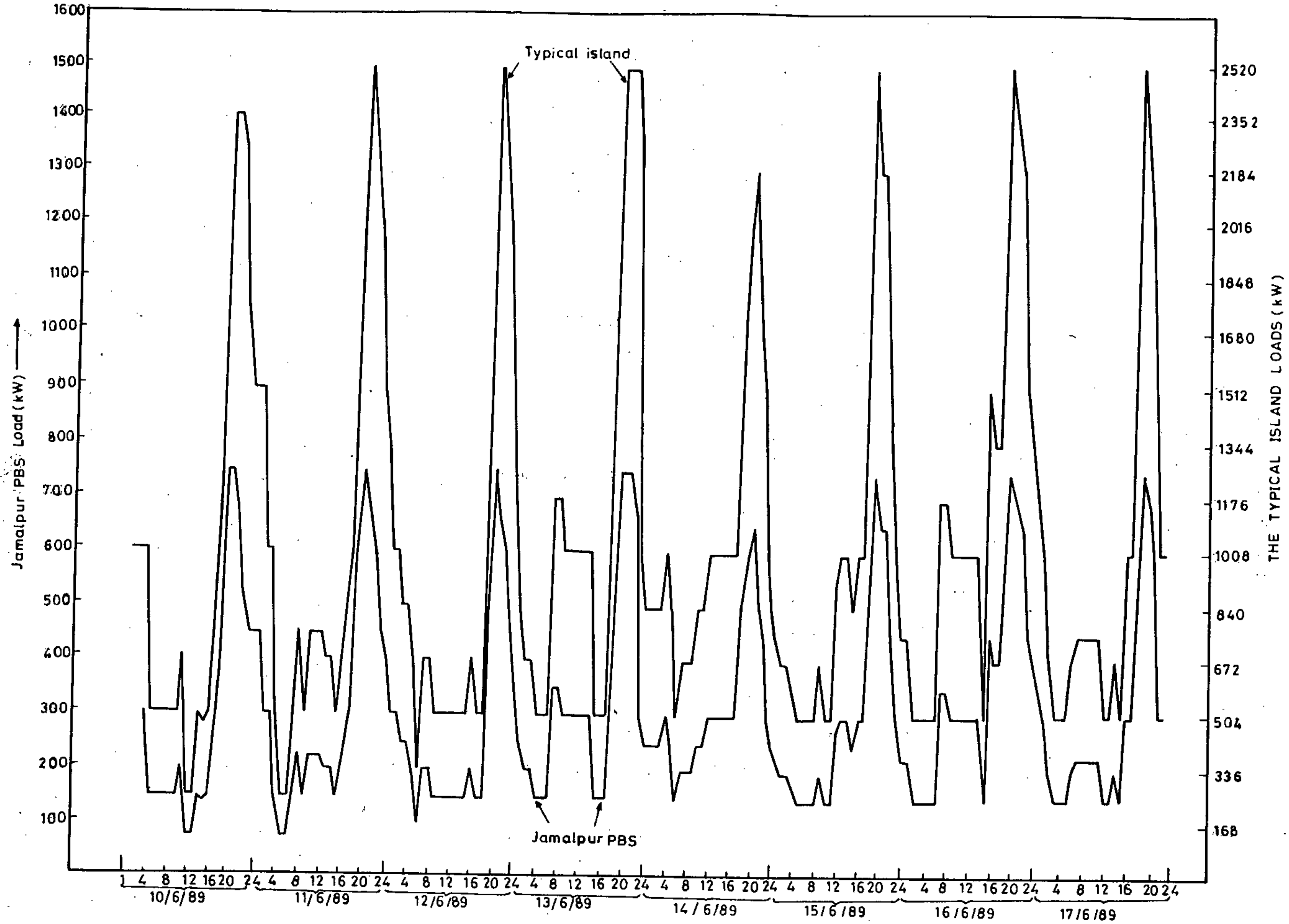


Figure 3.11 Hourly loads of Jamalpur PBS and a typical island

Table 3.5 : Load demand of different PBSs.

	Average Load demands in MW									Peak Load (MW) 1987
Name of PBS	1981	1982	1983	1984	1985	1986	1987	1988	1989	
1.Dhaka	1.03	1.83	2.87	3.54	4.62	5.42	5.94	7.39	8.15	16.80
2.Tangail-1	0.14	1.09	1.77	2.28	2.92	3.30	3.68	4.46	3.77	9.76
3.Comilla-1	0.26	0.63	1.29	1.98	2.31	2.76	3.39	4.05	4.07	7.40
4.Chandpur	0.02	0.17	0.61	0.94	0.98	1.12	1.27	1.56	1.38	5.10
5.Habigonj	0.001	0.04	0.39	1.22	1.47	1.68	1.88	2.16	2.21	5.20
6.Moulabibazar	0.07	0.25	0.59	1.52	1.84	1.96	2.22	2.42	2.74	7.20
7.Pabna-1	0.0	0.15	0.45	0.68	0.81	0.95	1.03	1.36	1.02	2.80
8.Pabna-2	0.00	0.08	0.31	0.64	0.73	1.15	1.52	1.66	1.69	3.90
9.Serajgonj	0.25	0.78	1.36	1.93	1.85	2.11	2.34	2.68	2.32	6.10
10.Jessore-1	0.07	0.41	0.98	1.36	1.44	1.56	1.92	2.29	2.12	5.75
11.Jessore-2	0.14	0.35	0.64	1.15	1.88	2.23	2.46	2.69	2.79	6.50
12.Natore-1	0.13	0.47	0.84	1.14	1.34	1.54	1.83	2.35	2.89	5.50
13.Natore-2	0.02	0.35	0.64	1.36	1.77	1.86	1.96	2.31	2.54	6.30

influenced by the Dhaka city and its surrounding environment of growing different industries and other commerical institutions. Therefore, the load demand of Dhaka PBS is different from the load demands of other PBSs. To develop the empirical equations to forecast the average/peak load, the average load demands of two PBSs, Tangail and Serajgonj are considered and these are depicted in figure 3.2

By considering the average demands of Tangail and Serajgonj PBSs,the following two empirical equations are developed,

$$L_T = 5.313 - 14.488x + 14.729x^2 - 6.94x^3 + 1.743x^4 - 0.231x^5 + 0.013x^6 \quad ...(3.12)$$

$$L_S = - 15.984 + 39.346x - 36.294x^2 + 16.885x^3 - 4.232x^4 + 0.561x^5 - 0.033x^6 \quad ...(3.13)$$

where

L_T = Load demand of Tangail PBS.

L_S = Load demand of Serajgonj PBS.

x = number of energized year of the PBS.

The above two equations satisfy the load demands of these areas for 1981 to 1989. One may use these two equations to have an idea about the possible range of variation of loads with time. Note that, the above equations are developed by considering the available average load demand of Tangail and Serajgonj PBSs. One may use the load ratio factor, K (Peak load/Average load) shown in table 3.2, and the above two empirical equations to evaluate the peak demands.

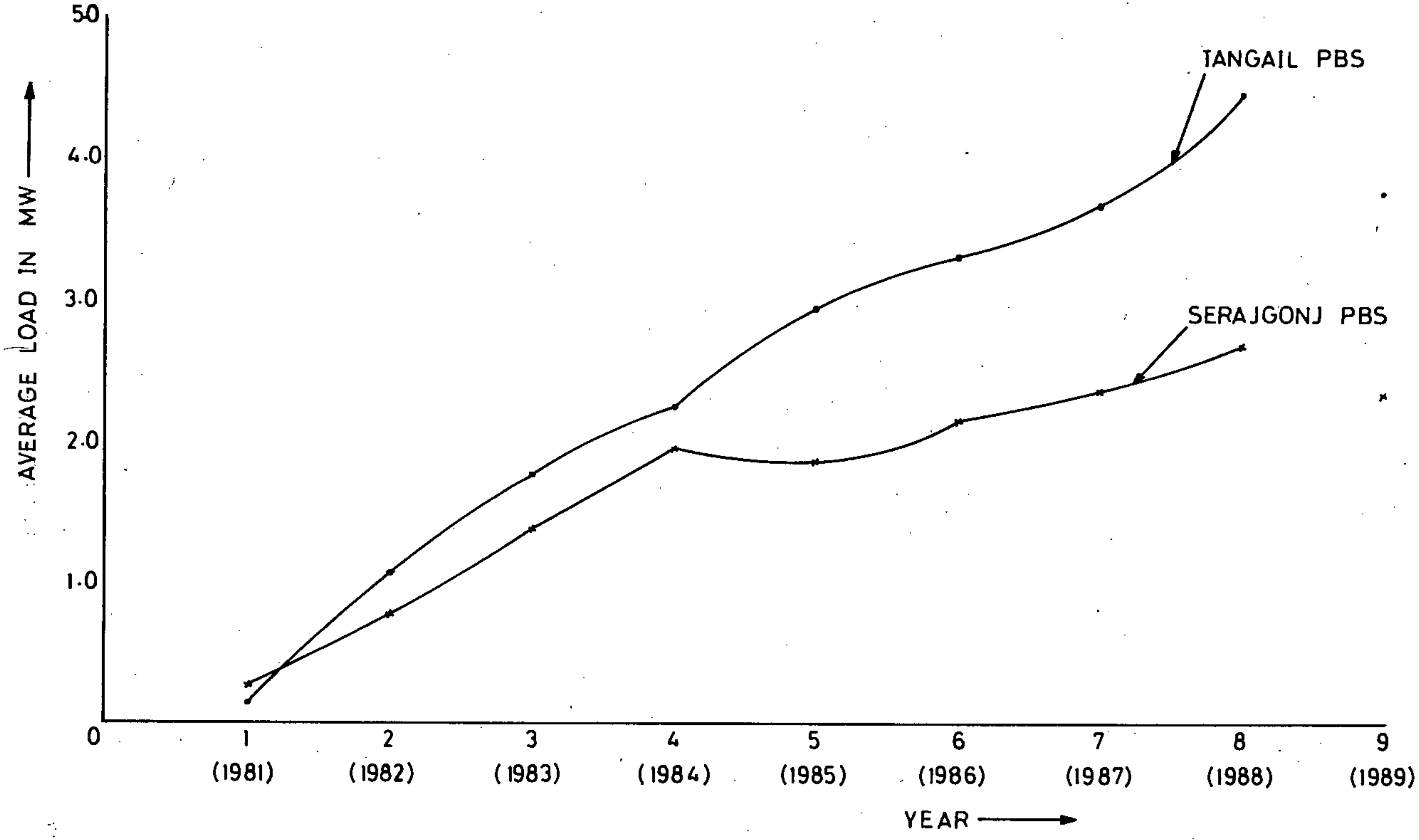


Figure 3.2 Average load demands of Tangail and Serajgonj PBSs for different years.

3.5 OBSERVATION AND DISCUSSION

Table 3.3 shows that the weighting factors evaluated for different load deciding variables are not same. This clearly indicates that the load growths do not depend equally on all factors. This is because some factors are very sensitive to the development of peak/average load while the others are not.

It is observed from table 3.4 that the value of the weighting factor relating to communication is the highest while that relating to agricultural land is the lowest. However, the variable 'literacy rate' has the highest contribution towards the load growth of Jamalpur PBS. The reason is that although the value of the weighting factor relating to literacy rate is lower, however, the numerical value of literacy rate is much higher than the other variables. Therefore, the product of literacy rate and its weighting factor becomes higher (48.30% of the total load demand). The load demand pattern of a typical island is quite different than that of the load of Jamalpur PBS, because the weighting factor as well as the road communication is much better in a typical island. Therefore, the product of road length and its weighting factor becomes higher(65.7% of the total load demand).

Comparative factor of table 3.4 and the figure 3.1 shows that the load of the considered typical island is 3.36 times of Jamalpur PBS. The justification for the higher value corresponding to this typical island can be easily made from the data of table 3.1. For example, the road communication of a typical island is 7.5 times better than that of Jamalpur PBS. Note that this variable contributes maximum to the load growth.

CHAPTER 4

WIND AS A SOURCE OF ENERGY

4.1 INTRODUCTION

The wind power has been harnessed by man for many centuries. Windmills which were used to grind wheat are still in use in many countries and similar devices were also common in America where they were used to pump water from deep wells. Of course, the crowning glory of wind technology was clipper ship, used to speed tea and other goods from India to Britain [70]. In recent years, after the oil crisis of 1973-74, there has been renewed interest in the application of wind power to electricity generation. This stimulated world-wide interest in alternative sources of energy, with the U.S.A, Sweden, Denmark, Canada and the Netherland being particularly active in funding wind energy research including the construction of prototype wind turbines. This activity led to progressive advances in understanding and technology, together with increasingly encouraging assessments of generation costs. The construction of around 12,000 wind turbines(1500 MW) during the past several years has firmly established wind energy as a potential source of electricity [71]. The California Energy Commission has set a goal for providing 10% of the state's electricity from wind energy by the year 2000 [39,72,73]. The international activity on wind energy has recognized wind power as one of the most promising non-hydro renewable electricity sources.

This chapter presents the general features of a wind turbine generator (WTG) and its typical characteristics. The basic concept of converting wind energy into electrical energy is also presented in this chapter.

4.2 ENERGY FROM THE WIND

The kinetic energy in the wind (energy contained in the speeding air) is proportional to the square of its velocity (just as for a falling weight). Kinetic energy in the wind is partially transformed to pressure against an object when that object is approached and air slows down. This pressure, added up over the entire object, is the total force on that object.

Power is force times velocity. This also applies to wind power. Since wind forces are proportional to the square of velocity, wind power is proportional to wind speed cubed.

The power that wind turbine blades can extract from the wind is given by the following expression [74]:

$$\text{Power} = 1/2 \; e \; k \; A \rho \; V^3 \qquad \ldots(4.1)$$

where

e = efficiency of the blades

k = conversion factor for units (e.g. if units on the right side are ft, lb and seconds, and results are desired in kW)

A = area swept out by the blades (depends on solidity of rotors, the relationship is given in section 4.3.1)

V = wind velocity, far enough upstream so as not to be affected by the wind turbine.

ρ = the density of air.

Using the laws of physics, it has been shown that the maximum efficiency of conventional wind system cannot exceed 59.3% [74]. Well designed blades operating at ideal conditions can extract most, but not all of the 59.3% maximum power available. About 70% of this 59.3% is typical. Thus, a wind turbine rotor might have a maximum efficiency of 0.7 x 0.593 = 41.5%.

Also, gearbox, chain drive or pully losses, plus generator or pump losses, could decrease overall wind turbine efficiency to about 30%. This is about the maximum efficiency possible from a conventional, well designed wind turbine, operating at its best condition.

In equation 4.1 the symbol k is simply a number, depending on the units used for density, velocity and area. The equation may be written in simplified form incorporating the available relevent data of air density [74]:

$$\text{Power} = K \times e \times DRA \times DRT \times A \times V^3 \qquad \ldots(4.2)$$

Where DRA is the density ratio at an altitude and it is defined as the ratio between the densities of air at an altitude to that at the sea level. The DRAs at various altitudes are given in table 4.1.

Table 4.1: DRA at various altitude [74,75]

Altitude, (m)	0	762	1524	2286
DRA (at 15.56^{o}C)	1	0.912	0.832	0.756

In equation (4.2), DRT is the density ratio at a temperature and it is defined as the ratio between the densities of air at a temperature to that at a standard temperature. The standard temperature considered to be 15.56° [74]. The DRT at different temperatures are given in table 4.2 [73].

Table 4.2 : DRT at various temperature [74,75]

Temperature (°C)	-17.78	-6.6	4.45	15.56	26.67	37.78	48.89
DRT	1.13	1.08	1.04	1.00	0.96	0.93	0.89

4.3.BASIC ELEMENTS OF WIND ENERGY CONVERSION SYSTEMS

Historically, the wind machines have gone through many changes and improvements. Basically, there are two types of wind machines, Vertical Axis Wind Turbine (VAWT) and Horizontal Axis Wind Turbine(HAWT).

The VAWTs have rotors which run about a vertical axis and which respond equally to all wind directions.The Savonius rotor is an example of such a wind machine. The HAWTs are one or multi-bladed machines having horizontal shafts. They have the advantages of better yaw control, higher power coefficients and thus better efficiency. The Darrieus rotor is an example of this type of wind machine.

To evaluate any wind turbine for its power and energy yields, it is important to consider the rated wind velocity of the machine at which rated power is achieved. Also, it is necessary to know the cut-in velocity, which is the wind velocity at which the generator begins to produce power. Figure 4.1, illustrates the cut-in and cut-out velocities and power curve of a hypothetical wind turbine generator (WTG). Note that the cut-out velocity related to a WTG in that wind speed beyond which the output power of the WTG is zero [74,76]

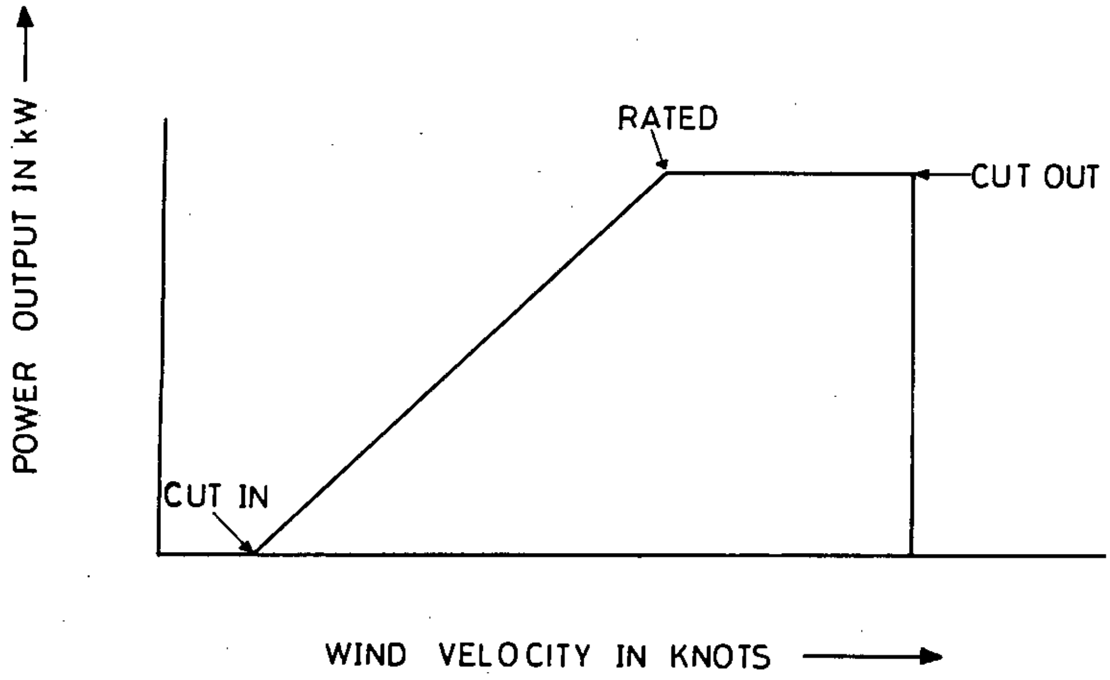


Figure - 4.1 Power curve of a sample wind turbine generator.

4.3.1 Performance of Wind Machines:

The relative efficiencies of different types of wind energy conversion system (WECS)are illustrated in figure 4.2. The maximum amount of power a simple rotor (without a shroud or tip vanes) can extract from the wind is 59.3% of the wind power that would pass through that windwheel. From figure 4.2, it is also seen that no windwheel actually extracts 59.3%. Figure 4.3 shows the variations in the power coefficient (C_p) with different blade angles, and with tip speed ratio. It is seen that a fixed blade setting of 5^o is the most favourable, for the design and wind regime considered , for all tip-speed ratios.

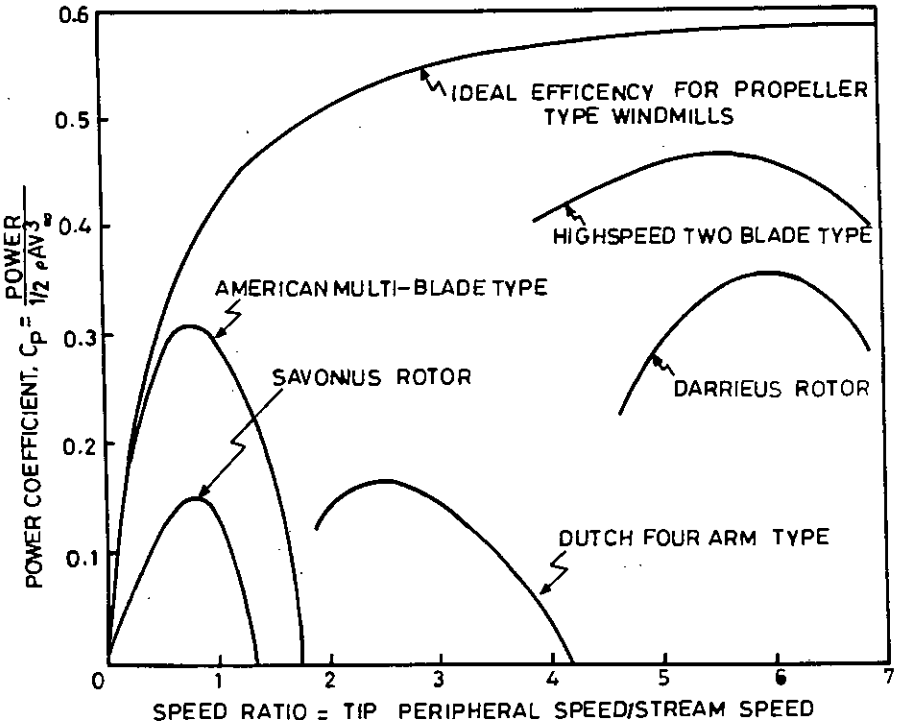


Figure - 4.2 Typical performance of wind power machines.

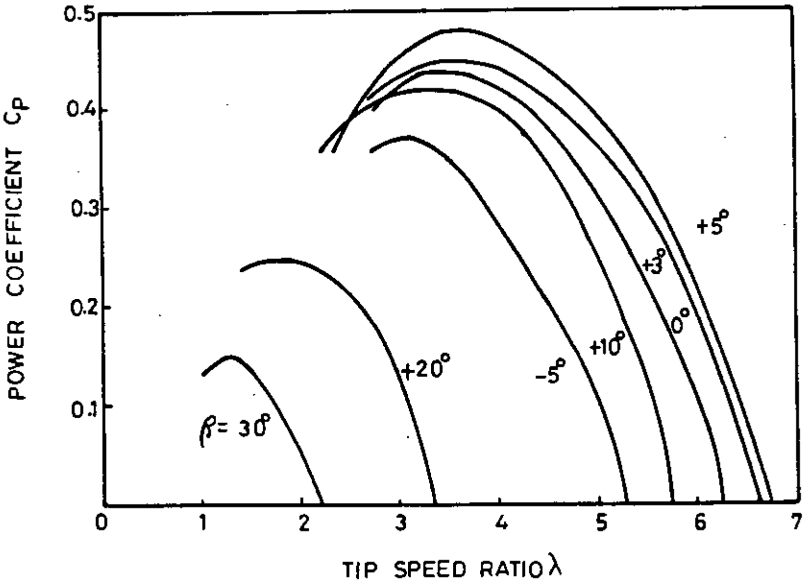


Figure - 4.3 Power co-efficient Vs. tip speed ratio for different blade angles.

4.3.2 Overspeed Control

It is important to understand the various methods of rotor speed control. Blades are designed to withstand a certain centrifugal force and a certain wind load. The centrifugal force tends to exert a pull on the blades, whereas wind loads tend to bend the blades . A control is needed to prevent over stressing the WECS in high winds. Obviously, one could design a wind turbine strong enough to withstand the highest possible wind, but this would be an expensive installation compared to a more fragile unit having a good control system.

Two primary methods exist for controlling a wind turbine: i) tilting the out of excessive winds, and ii) changing the blades (pitch) angles (feathering) to lower their loads.

4.3.3 Hub Height Correction

The wind speed increases with height. Therefore, if the anemometer (to measure the wind speed) height is different from that of the wind turbine generator's blades (hub) height, then a simple wind speed correction is necessary according to so-called 1/7 power law [77] as,

$$V_{hub} = V_{anem} \left[\frac{H_{hub}}{H_{anem}} \right]^{1/7} \qquad \ldots(4.3)$$

Where

V_{hub} = wind velocity at hub height,

V_{anem} = measured wind velocity at anemometer height,

H_{anem} = anemometer height,

H_{hub} = height of the hub.

For example, if a wind velocity of 10 knots as recoreded at an anemometer height of 10 meters from ground, then the corrected wind velocity at a hub height of 60 meters will be,

$$V_{60} = 10 \left[60/10 \right]^{1/7} = 12.9 \text{ knots} \qquad \ldots(4.4)$$

CHAPTER 5

MODEL OF A WIND TURBINE GENERATOR (WTG)

5.1 INTRODUCTION

There is an increasing interest to extract electrical power through a wind turbine generator (WTG) due to its almost nonexisting operating cost, nonpolluting environmental impacts and availability as most favourable ways of converting natural resources to electrical power in isolated areas.

This chapter presents a methodology to develop a probabilistic model of a WTG, applicable like a conventional generating unit in the probabilistic simulation. The model is based on the concept of the multi-state representation of a generating unit. The probability density function (PDF) of the capacity output from a WTG is derived from bivariate function of wind velocity and temperature. To justify the development of the proposed capacity generation model of a WTG considering the bivariate function, wind velocity and temperature, a capacity generation model of a WTG is also developed by considering a univariate function, wind velocity, in this chapter. The model development procedure is exemplified through a simple numerical example. In this chapter, the proposed model is applied to evaluate the expected energy generation, the expected energy not served and the LOLPs. The results are compared with those obtained using the model developed from a univariate function. The justification of the multi-state capacity generation model of a WTG by considering the bivariate function of wind velocity and temperature is also discussed in this chapter.

5.2 METHODOLOGY FOR DEVELOPING A WTG MODEL

As discussed in chapter 4,the kinetic energy available in the wind can be converted into electrical energy through wind turbines. The equivalent electric power extracted from wind can be expressed in terms of the parameters of a wind turbine as [74] presented in equation (4.1). The equation (4.1) can be written as

$$C_{ew} = 1/2\ eKA\rho V^3 \qquad \ldots(5.1)$$

where

C_{ew} = Equivalent electrical power from wind

Recall that, if the wind velocity is recorded at a height different from the height of a wind turbine, in that case the appropriate modification of the values of V is required. The modification may be obtained using the empirical relation of section 4.3.5. The relation is again presented below [77]:

$$V_{Hub} = V_{anem}\ [H_{Hub}/H_{anem}]^{1/7} \qquad \ldots(4.3)$$

In equation (5.1), the density of air , ρ , depends on the temperature and altitude. The density of air at temperature,T, and at altitude,A, may be expressed as

$$\rho_{T,A} = \rho_s\ DRA_A\ \ DRT_T \qquad \ldots(5.2)$$

Where, ρ_s is the standard density of air, defined as the density of air at sea level and at temperature 288.15°K. This is considered as 1.225 kg/m^3 [75]. The DRA_A and DRT_T, respectively, are density ratios at altitude A, and at temperature T. Recall that DRA_A and DRT_T are defined in section 4.2 as

$$DRA_A = \frac{\text{Density at altitude A}}{\text{Density at sea level}} \qquad \ldots(5.3)$$

$$DRT_T = \frac{\text{Density at temperature T}}{\text{Density at temperature } 288.15^{o}K} \qquad \ldots(5.4)$$

Now, using DRA_A and DRT_T equation (5.1) may be rewritten as

$$C_{ew} = \gamma \, DRT_T V^3 \qquad \ldots(5.5)$$

$$\text{where, } \gamma = 1/2 \; e \; KA \, \rho_s \, DRA_A. \qquad \ldots(5.6)$$

Equations (5.5) and (5.6) clearly reveal that for a given type of wind turbine located at a particular place the equivalent electrical power converted from wind depends on the temperature and wind velocity of that place. That is,

$$C_{ew} = f_{(T,V)} \qquad \ldots(5.7)$$

The temperature and wind velocity at any place vary randomly in the temperature and velocity domains and these random variables are correlated. The ranges of these domains depend on the time and geographical locations. Assuming only discrete values of these two random variables for computational clarity, the PDF of temperature and wind velocity may be expressed as

$$f_{T,V}(t,v) = \sum_{i,j}\sum P_{(T,V)i,j} \; \delta(T-t_i) \; \delta(V-v_j) \qquad \ldots(5.8)$$

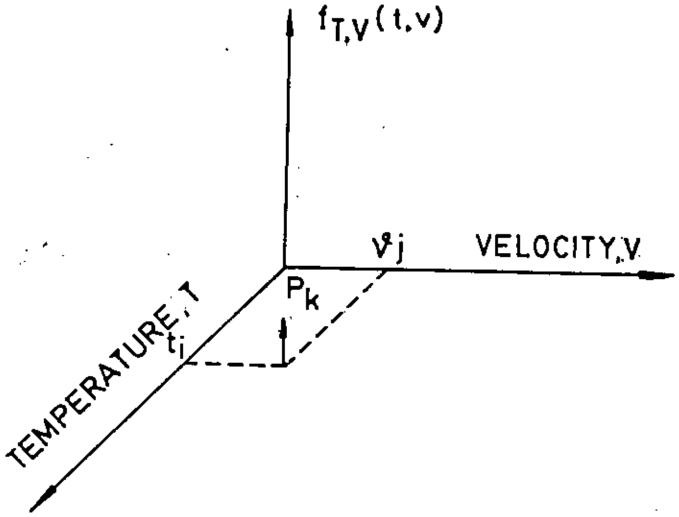


Figure - 5.1 Joint PDF of temperature and wind velocity

The delta function in equation (5.8), implies here that the function $f_{T,V}(t,v)$ have values only for some values of T and V. The graphical representation of $f_{T,V}(t,v)$ is shown in figure 5.1. The impulse with probability, P_k, represents the probability of occurrence of temperature, t_i, and its corresponding velocity, v_j.

The PDF of equivalent electrical power, $f_{Cew}(c_{ew})$ may be derived from the PDF of $f_{T,V}(t,v)$, since γ maps T and V onto C_{ew} as in equation (5.5). That is, for every value of C_{ew} in the C_{ew} domain there exists at least one pair of t and v in the (T,V) domain. If a value of C_{ew} is generated from only one pair of (t,v), then the probability of occurrence of that value of C_{ew} is equal to the probability of occurrence of the corresponding pair of (t.v). That is,

$$P_{Cewk} = P_{(t,v)i,j} \qquad \ldots(5.9)$$

However, a particular value of C_{ew} may be generated from a number of (t,v) pairs. In that case,

$$P_{Cewk} = \sum_{i=1}^{m} \sum_{j=1}^{n} P_{(T,V)i,j} \; \delta(T-t_i) \; \delta(V-v_j) \qquad \ldots(5.10)$$

where, (m,n) is the number of impulses which correspond to the generation of the k-th value of C_{ew}.

Now, the general form of the PDF of equivalent electrical power may be written as

$$f_{Cew}(c_{ew}) = \sum_{i} P_{Cewi} \; \delta(C_{ew} - c_{ewi}) \qquad \ldots(5.11)$$

So far, it has been considered that the wind velocity of any magnitude is convertible to electrical power. However, the reality differs. A realistic wind turbine fails to produce electrical power if the wind velocity goes below certain lower limit, v_c, or exceeds certain upper limit, v_f, and it produces the same output for any wind velocity greater than or equal to the rated velocity, v_r, upto the velocity, v_f [74,76]. The velocity limits and the corresponding equivalent electrical power output are depicted in figure 5.2. In relation with a wind turbine the lower and the upper limits of wind velocities are called 'cut-in' and 'cut-out' velocity, respectively.

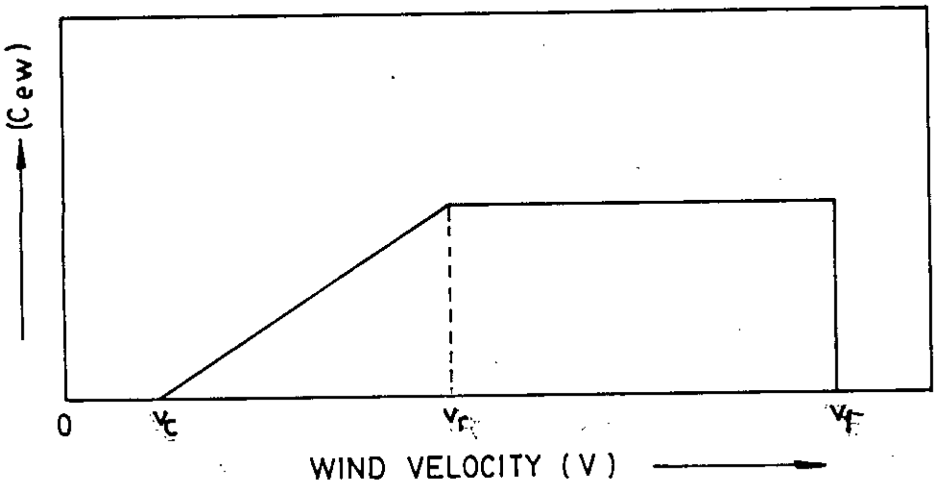


Figure - 5.2 Electrical power output vs wind velocity

The equivalent electrical power, C_{ew}, corresponding to v_c, v_r and v_f velocities may be expressed as,

$$C_{ew} = \begin{cases} 0 & \text{for } V<v_c \text{ and } V>v_f \\ C_{ew} & \text{for } v_c \leqslant V \leqslant v_r \\ C_{ew_{rf}} & \text{for } v_r \leqslant V \leqslant v_f \end{cases} \qquad \ldots(5.12)$$

Note that since C_{ew} is a function of temperature and velocity, the wind velocity, v_r or v_f may not produce the maximum equivalent electrical power.

The value of the function, $f_{Cew}(c_{ew})$, at $C_{ew_{rf}}$,that is, the probability that C_{ew} will be equal to C_{ew}, any value of temperature is obtained by summing the marginal probabilities of the joint PDF, $f_{T,V}(t,v)$, starting from a point corresponding to the wind velocity, v_r, upto the point corresponding to the wind velocity, v_f. That is,

$$P(C_{ew} = C_{ew_{rf}}) = \sum_{j=K_r}^{K_f} P(T,V)_{i,j}\ \delta(T-t_i)\ \delta(V-v_j) \qquad \ldots(5.13)$$

In equation (5.13), K_r and K_f correspond to the wind velocities v_r and v_f respectively. Similarly the value of the function $f_{C_{ew}}(c_{ew})$ at zero equivalent capacity is obtained by summing the marginal probabilities starting from a point corresponding to the minimum wind velocity upto the point corresponding to the wind velocity v_c and those starting from a point corresponding to the wind velocity v_f upto the point corresponding to the maximum velocity. That is,

$$P\{C_{ew} = 0\} = \sum_{j=K_{min}}^{K_c} \sum_i P_{(T,V)(i,j)} \, \delta(T-t_i) \, \delta(V-v_j)$$

$$+ \sum_{j=K_f}^{K_{max}} \sum_i P_{(T,V)i,j} \, \delta(T-t_i) \, \delta(V-v_j). \quad \ldots(5.14)$$

That is,

$$P\{C_{ew} = 0\} = \sum_{j=K_{min},K_f}^{K_c,K_{max}} \sum_i P_{(T,V)i,j} \, \delta(T-t_i) \, \delta(V-v_j) \quad \ldots(5.15)$$

In equation (5.15) K_{min}, K_c, K_f and K_{max} correspond to minimum, cut-in, cut-out and maximum velocities respectively.

So far, it has been assumed that the wind turbine generator is 100% reliable . However, it is not in reality. Assuming the PDF of wind turbine generator as

$$f_{C_w}(c_w) = \sum_i P_{Cwi} \, \delta(C_w - c_{wi}) \quad \ldots(5.16)$$

the PDF of electrical output ,$f_{C_{gw}}(c_{gw})$, from a wind turbine generator may be obtained by multiplying $f_{C_{ew}}(c_{ew})$ by $f_{C_w}(c_w)$

$$f_{C_{gw}}(c_{gw}) = \sum_{i} \sum_{j} P_{C_{ewi}} \ \delta(C_{ew} - c_{ewi}) \ P_{C_{wj}} \ \delta(C_w - c_{wj}) \qquad \ldots(5.17)$$

Note that $f_{C_{gw}}(c_{gw})$, is equivalent to the PDF of the available capacities of a multistate generating unit.

The maximum value of C_{gw} is the minimum of the two random variables C_{ew} and C_w, since the values of C_{gw} can not exceed the values of any one of these two. That is,

$$C_{gw} = \mathrm{Min}(\, C_{ew},\, C_w) \qquad \ldots(5.18)$$

The capacity output on outage of the multistate wind turbine generator, C_{gwo}, may be obtained by subtracting the value of capacity output from $C_{gw(max)}$. That is,

$$C_{gwo} = C_{gw(max)} - C_{gw(rated)} \qquad \ldots(5.19)$$

The probability of occurrence of C_{gwo} is the probability of its corresponding value of C_{gw} and C_{gwo} lying between 0 and C_{gw}

That is,

$$0 \leqslant C_{gwo} \leqslant C_{gw(max)} \qquad \ldots(5.20)$$

5.3 NUMERICAL EXAMPLE TO CLARIFY THE METHODOLOGY

In order to clarify the proposed methodology to develop a model,a simple but revealing example will be considered in what follows.

Consider the chronological variation of temperature and wind velocity as shown in figure 5.3. The dotted curves show the chronological variation and firm curves show two hourly average variation.

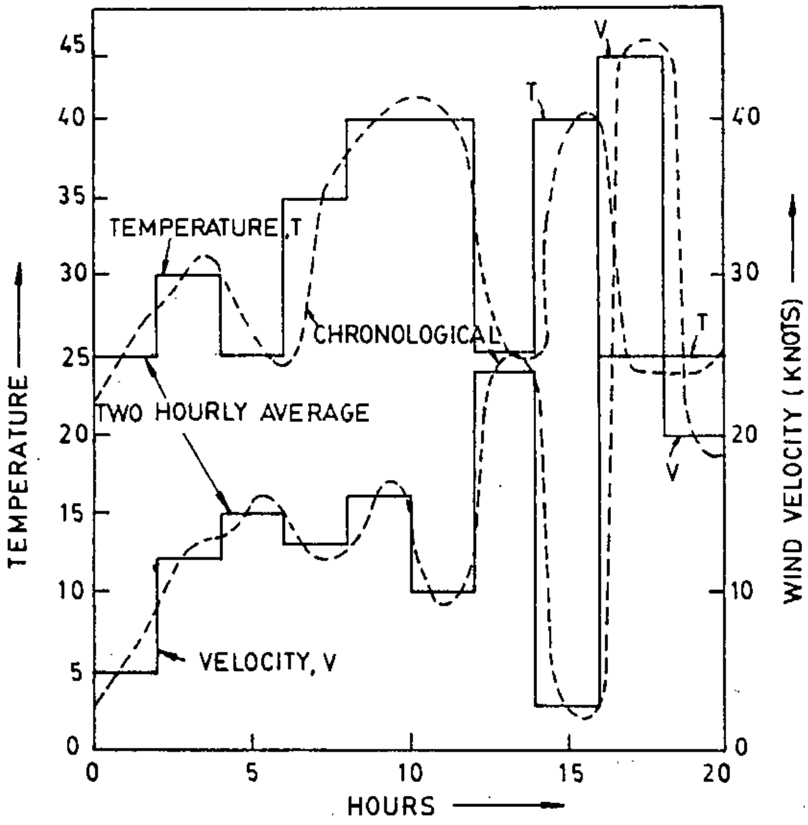


Figure - 5.3 Chronological variation of temperature and wind velocity and their two hourly average

Note that the average is taken only for computational clarity. Now, sample the termperature and wind velocity. The sampling interval may be one hour or any appropriate interval. In this case, the interval size is two hours. Assigning equal probability of occurrence to each sample, the joint PDF of temperature and wind velocity as shown in figure 5.4 is obtained.

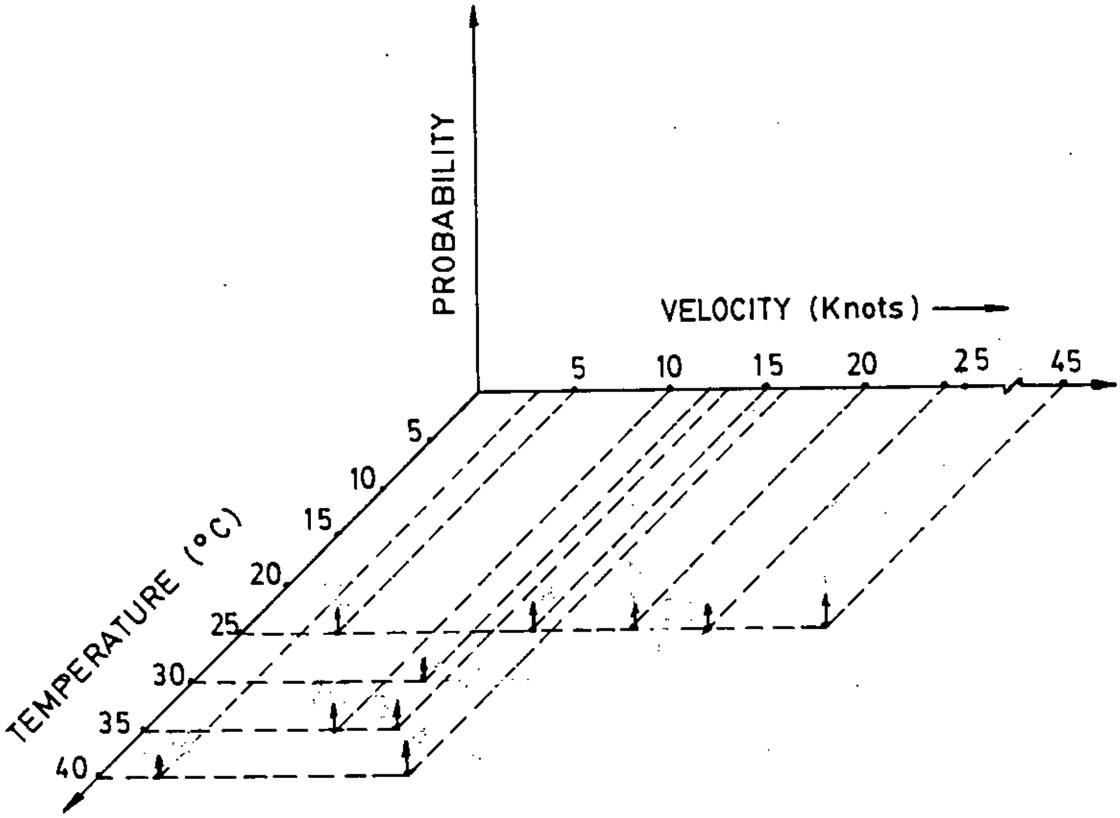


Figure - 5.4 Joint PDF of temperature and wind velocity

Note that there are ten samples and as each sample is considered to be equally probable, the probability of occurrence of a sample will be 1/10.

Using equations (5.1) through (5.6), for every value of temperature and its corresponding value/values of wind velocity of figure 5.4 the value/values of equivalent eletrical power can be calculated. The distribution of equivalent electrical power may be obtained from the distribution of figure 5.4 and it is depicted in figure 5.5.

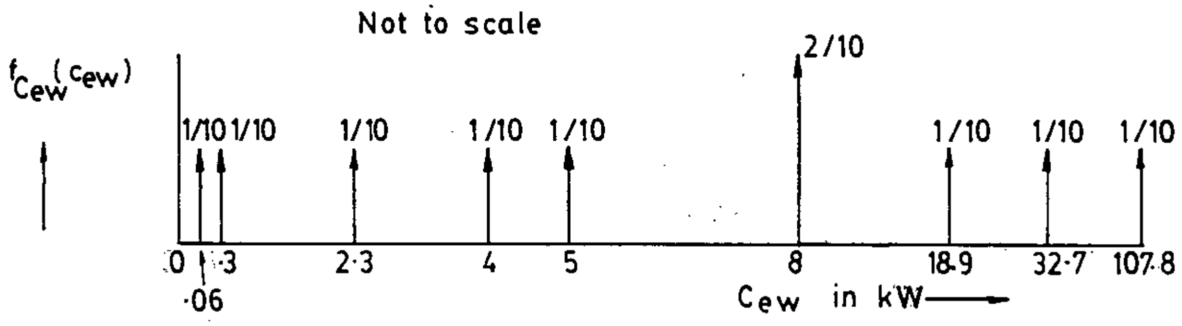


Figure - 5.5 PDF of equivalent electrical power

Note that each impulse of figure 5.5, corresponds to a single pair of temperature and velocity of figure 5.4, except the impulse at 8 kW. The impulse at 8 kW is generated from two pairs of temperature and velocity, 25°C and 15 knots, and 40°C and 15.27 knots respectively.

Now, consider the velocity constraints v_c, v_r and v_f as 5, 20 and 40 knots respectively and modify the PDF of equivalent electrical power of figure 5.5 using equation (5.12). The modified distribution is depicted in figure 5.6.

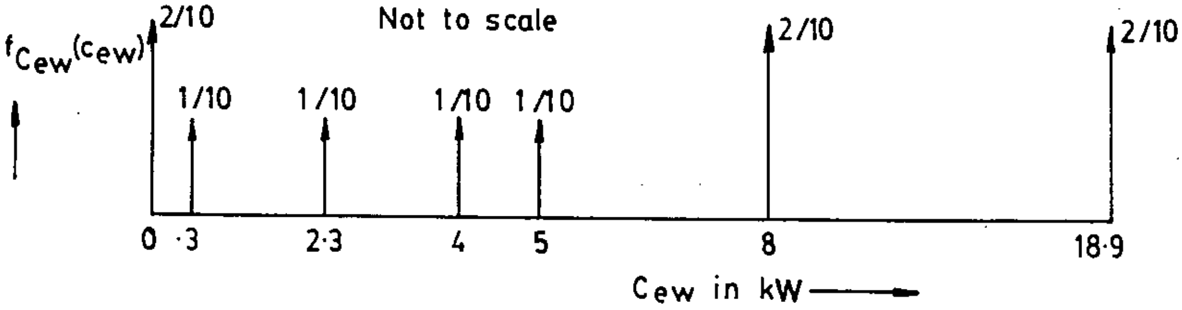


Figure - 5.6 PDF of equivalent electrical power incorporating the velocity constraints.

Note that in figure 5.5 the impulse at 0.06 kW corresponds to a velocity, 3 knots, less than v_c and that at 107.8kW corresponds to a velocity, 45 knots, greater than v_f as seen from figure 5.4. Therefore, the equivalent electrical power must be zero corresponding to these velocities and the impulse at 0 kW power of figure 5.6 represents this result. Also note that the two impulses at 18.9 and 32.7 kW of figure 5.5 correspond to the velocities 20 and 24 knots of figure 5.4 which lie within v_r and v_f. Therefore, both the velocities 20 and 24 knots must produce the same output as these two impulses also correspond to the same temperature, 25°C. The impulse at 18.9 kW of figure 5.6 confirms this.

Consider the PDF of a wind turbine generator of 20 kW capacity as shown in figure 5.7. Note that the available capacity of a wind turbine generator does not depend on the velocity of wind or temperature.

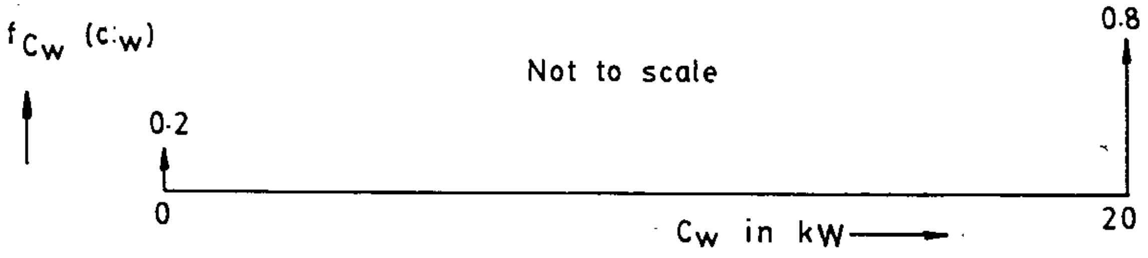


Figure - 5.7 PDF of available capacity of a wind turbine generator

From the PDFs of figures 5.6 and 5.7 the PDF of electrical output may be obtained using equation (5.17) and it is shown in figure 5.8.

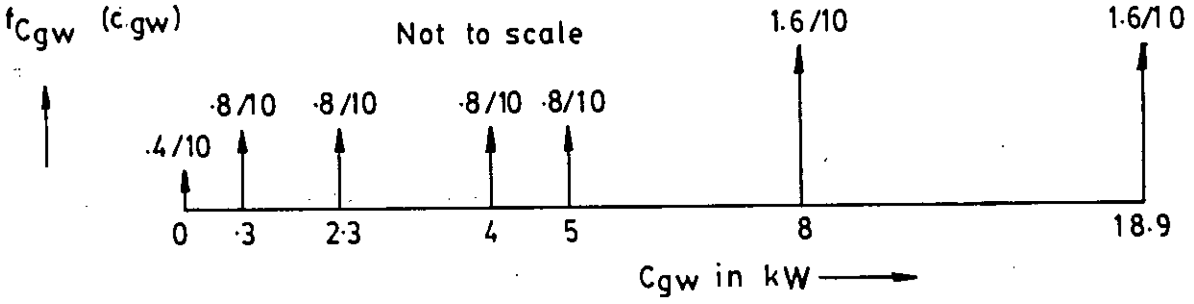


Figure 5.8 PDF of electrical output from a wind turbine generator

This figure shows that although the rated capacity of the wind turbine generator is 20 kW the maximum electrical power output is limited to only 18.9 kW because of the equivalent electrical power generation constraint.

Considering the PDF of electrical power output shown in figure 5.8, equivalent to a multistate probabilistic model of a wind turbine generator, the PDF of capacity output on outage may be developed as in figure 5.9. Now the probabilistic model of figure 5.9 may be used like the conventional generating unit in any standard method [55,60,61] for probabilistic simulation .

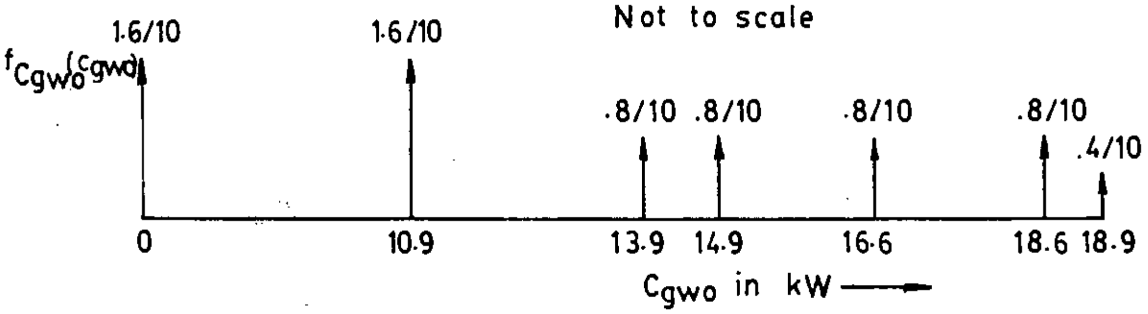


Figure - 5.9 PDF of capacity output on outage

5.4 NUMERICAL EVALUATION

For a reliable hybrid electrical energy system from intermittent sources namely wind turbine, a model has been developed in section 5.2. The developed model is applied to realistic systems. In the numerical evaluation the segmentation method is applied to determine the reliability of the systems. The reliability and the segmentation method are described in details in chapter 2. The model of a wind turbine generator (WTG) is developed from the bivariate function of wind velocity and temperature. The methodology justifies the use of bivariate function of wind velocity and temperature for a WTG model.

This section presents a brief description of the systems. The simulation results are also presented in this section. The result of each model includes the multistate representation of the individual generating unit. This section also presents the description of the data used for the probabilistic simulation of a WTG. It also presents the simulation results of WTGs.

5.4.1 Basic Data

Wind Velocities and Temperatures

As discussed in section 5.2 the output of a WTG is a function of wind velocity and temperature. From the Bangladesh Meteorological Department (BMD), the wind velocities as well as the corresponding temperatures of 1987 to 1989 were collected.

The BMD records wind velocities and temperatures at every three hour. Analyzing the data of wind velocities for the above three years it is observed that the higher profile of wind velocities are recorded during the months of June to August.

The three hourly wind velocities and the corresponding temperatures from June to August of 1989 are shown in tables AW1 and AW2 respectively in Appendix-A. The wind velocities and the corresponding temperatures are given in nautical mile per hour (knots) and in degree celsius (°C) respectively. Recall that, in computing the equivalent capacity generation using equation (5.1) the wind velocities should be appropriately modified through equation (5.2) to take into consideration the difference between the heights of an anemometer and the hub of a WTG.

Note that the highest wind velocity during this period is 24 knots and the minimum velocity is zero knots. Most of the time the wind flows at a speed less than 10 knots. The maximum and the minimum temperatures during this period, June to August, are 33.5°C and 24.2°C respectively.

Parameters of a WTG

For this research a WTG of Energy Development Co., USA is considered. The parameters of this WTG supplied by the manufacturer are given in table 5.1 [74]. The cut-out and cut-in velocities of this WTG are 34.7 and 4.3 knots respectively. That is, for any wind velocity less than 4.3 knots or greater than

34.7 knots the output will be zero kW. The rated output of this WTG is 45 kW and it harnesses a constant output power for any wind velocity that lies between 23.4 to 34.7 knots. This is shown in figure 5.10. Note that with the variation of temperature, the rated output will also vary. In this WTG,the overspeed control is accomplished through a system of mechanical brake.

Load data

The load data used for the simulation of a WTG is the load of a typical island. As presented in chapter 3, the load of the typical island is obtained by evaluating first the so called comparative factor. Then the load for the plan period is derived from the load of that period of the area corresponding to which the comparative factor is evaluated. Recall that in determining the loads of the typical island, Jamalpur Palli Bidhyut Samity (PBS) is considered as the model area. The peak and base loads during the plan period are 2520 and 252 kW respectively.

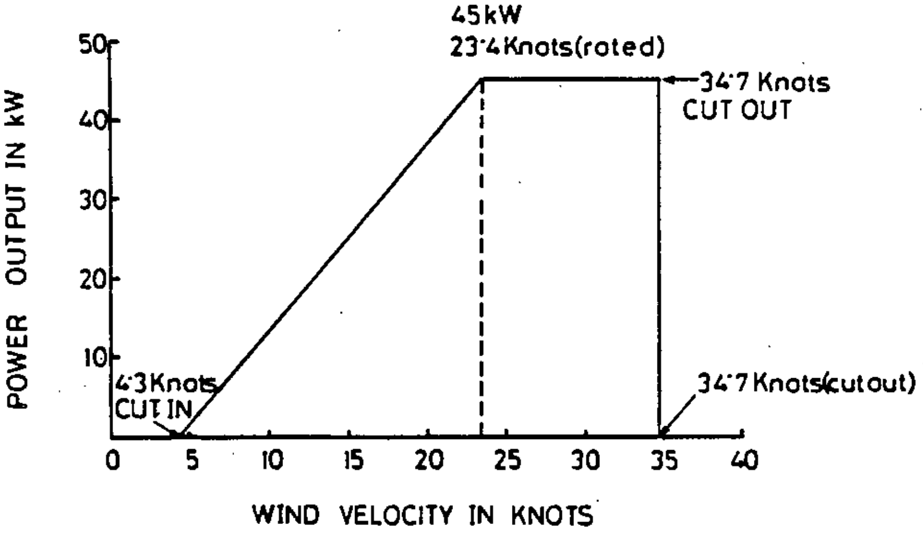


Figure-5.10 Power output curve(Energy Development Co.model 4-45)

Table 5.1: Parameters of a WTG a Energy Development Co[74].

Model Number :	4-45
Rated power (kW):	45.0 @ 23.4 knots (shown in Figure 5.10)
Power output at 10.4 knots :	16 kW
Power output at 12.2 knots:	20 kW
Rotor blade diameter :	12.2 meters
Number of blades :	4
Machine type:	Downwind horizontal-axis
Operating speed :	
Rated speed (knots):	23.4
Cut-in speed (knots):	4.3
Cut-out speed (knots):	34.7
RPM at rated output :	60
Blade materials :	Aluminium T-6
Rotor weight :	567 Kg.
System weight on tower :	4309 Kg.
Overspeed control :	Mechanical brake

* 1 knot = 1.15 mph or 1.85 kmph.

5.4.2 The PDF of Equivalent Capacity Generation from the Wind

In what follows, the probability density function (PDF) of equivalent capacity generation from wind is developed. In this development process, wind velocities and temperatures are sampled at every three hours. Each sample is considered to be equally probable. That is, the probability of occurrence of a sample of 0.0 knots wind velocity and 27.5°C temerature is same as the probability of occurence of a sample of 4 knots wind velocity and 31.5 °C temperature. It is also considered that wind velocities and temperatures are completely correlated for a particular time. By complete correlation, it is meant that for a particular wind velocity there exists only one particular temperature for that particular time in the bivariate (wind and temperature) domain. On the other hand, if wind velocities and temperatures are independent for a particular time, in that case, for a particular wind velocity any value of the temperature in the temperature domain may occur.

In what follows,the PDF of equivalent capacity generation is developed assuming this as a function of a wind velocity and a temperature (bivariate function). The PDF is also developed assuming that the equivalent capacity generation is a function of wind veloctiy only (univariate function).

5.4.3 Multi-State Model of a WTG Developed from Bivariate Function

In this case, the equivalent capacity generation from wind is assumed to be a function of wind velocities and temperatures.

Wind velocities and temperatures are sampled at an equal interval of time. The interval considered here is three hours. To reduce the computational involvement, data of eight days from June 10 to 17 are considered. Using equations (5.1) through (5.5) the value of equivalent capacity generation for each sample is computed. In this computation, the velocity constraints of a WTG is implemented through equation (5.12). The values of equivalent capacity generation along with the corresponding wind velocities and temperatures are presented in table 5.2. Since the occurrence of each sample is considered to be equally probable, the probability of each sample would be 1/(total number of samples), that is, 1/64.

Table 5.2 : Equivalent capacity generation considering bivariate function

WIND VELOCITY (Knots)	TEMPERATURE (°C)	EQUIVALENT CAPACITY GENERATION (kW)
02	27.8	0.0000
02	31.6	0.0000
03	31.5	0.0000
04	31.8	0.3258
04	29.5	0.3287
02	29.0	0.0000
02	28.6	0.0000
01	28.2	0.0000
02	27.8	0.0000
02	32.3	0.0000
04	33.5	0.3236
03	33.2	0.0000
06	30.2	1.1062
05	29.4	0.6421
09	28.6	3.7565
10	27.8	5.1687
10	27.2	5.1806
12	30.8	8.8294
10	31.8	5.0899
13	29.8	11.2691
13	28.0	11.3471
10	27.2	5.1806
08	26.6	2.6585

Table 5.2 : Equivalent capacity generation considering bivariate function (Continued)

WIND VELOCITY (Knots)	TEMPERATURE (^oC)	EQUIVALENT CAPACITY GENERATION (kW)
09	26.2	3.7910
07	25.8	1.7864
06	25.2	1.1275
03	27.0	0.0000
14	28.0	14.1722
16	27.7	21.1793
11	27.6	6.8848
12	27.4	8.9452
12	27.4	8.9452
13	27.3	11.3774
11	27.1	6.8980
12	28.5	8.9077
12	28.6	8.9043
13	28.3	11.3341
14	28.2	14.1614
10	28.0	5.1648
24	27.7	45.0030
11	27.4	6.8901
12	27.3	8.9486
14	25.3	14.3183
00	25.4	0.0000
08	26.7	2.6575
08	25.8	2.6666
04	25.6	0.3336
04	26.0	0.3331
05	25.8	0.6510
05	25.8	0.6510
04	27.2	0.3316
06	28.2	1.1147
05	28.4	0.6446
03	27.0	0.0000
04	26.6	0.3323
04	26.0	0.3331
04	25.5	0.3337
04	25.2	0.3341
03	26.0	0.0000
05	29.0	0.6431
03	29.2	0.0000
03	28.0	0.0000
03	27.4	0.0000
03	27.0	0.0000
03	26.6	0.0000

The fractional values of equivalent capacity generations in table 5.2 are rounded off and the probabilities of the equal capacities are added. The probability density function (PDF) of equivalent electrical power generation computed in the above fashion from a WTG, is depicted in figure 5.11

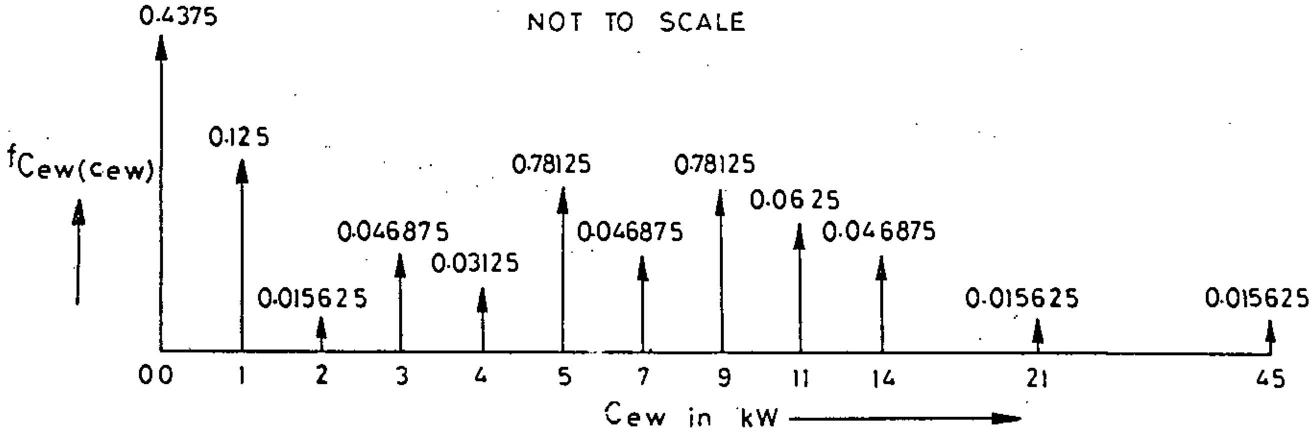


Figure - 5.11 PDF of equivalent electrical generation considering bivariate function.

To incorporate the random outages of a WTG the binary model of the generator, shown in figure 5.12, is considered. Note that this model is independent of wind velocities and temperatures. That is, the model assumes that the WTG is always capable of producing the rated power output. The impulse at 0 kW is due to the mechanical failure of the WTG. The PDF of figure 5.12 is convolved with the PDF of figure 5.11

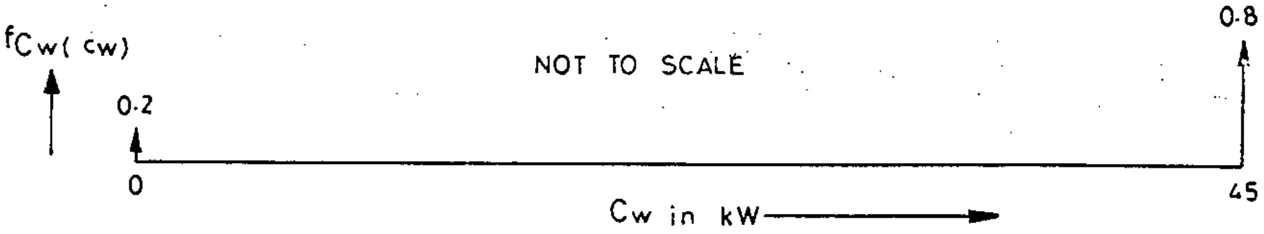


Figure - 5.12 PDF of available capacity of a WTG.

The outcome of this convolution results in the multistate model of a WTG. The values of different states of the multistate WTG in terms of the innage and outage capacities and their corresponding probabities are given in table 5.3.

Table 5.3: Capacity states of a WTG and the corresponding state probabilities (for bivariate function)

CAPACITIES (kW)		PROBABILITY(P_i)
INNAGE(C_i)	OUTAGE(Co_i)	
0.0	45	0.5500
01	44	0.1000
02	43	0.0125
03	42	0.0375
04	41	0.0250
05	40	0.0625
07	38	0.0375
09	36	0.0625
11	34	0.0500
14	31	0.0375
21	24	0.0125
45	0.0	0.0125

The PDF of this multistate WTG is also depicted in figure 5.13. The state values in this figure are given in terms of capacity on outages.

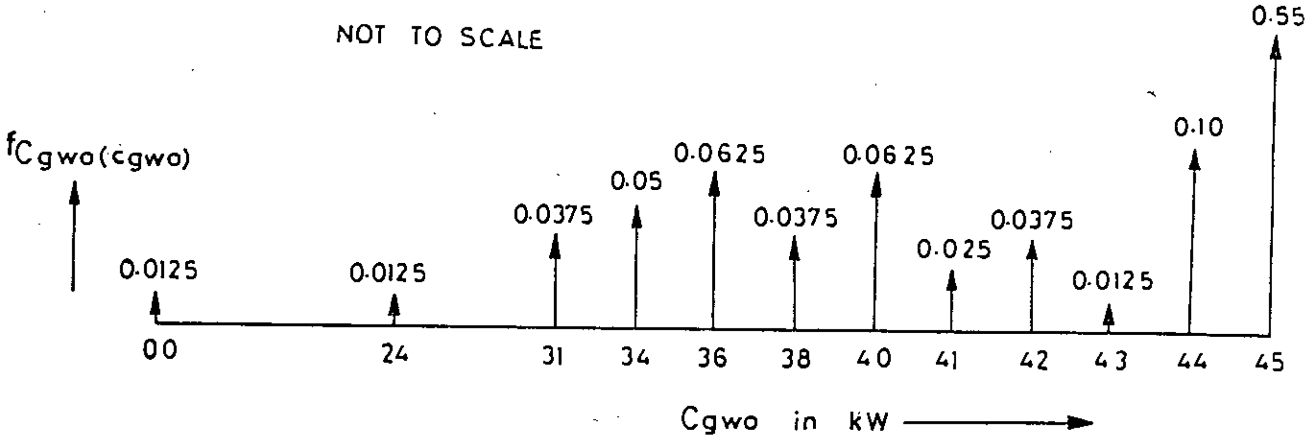


Figure - 5.13 PDF of capacity output on outage considering bivariate function.

5.4.4. Multistate Model of a WTG Developed from a Univariate Function

In order to justify that the equivalent capacity generation from a WTG is a function of both wind velocities and temperatures, the multistate model of a WTG is also developed from a univariate function. In this case, only the profile of wind velocities is sampled at every three hour interval and a temperature of constant value, 15.15^{o}C, is considered. Note that in this case also, the occurrence of each sample is assumed to be equally probable. Therefore, the probability of each sample would be 1/64. The capacity constraint of the WTG is not considered.

The equivalent capacity generation for each sample is computed using equation (5.1) through (5.5). The velocity constraints are implemented by utilizing equation (5.12). The values of equivalent capacity generations along with the wind velocities are presented in table 5.4.

Table 5.4: EQUIVALENT CAPACITY GENERATION CONSIDERING UNIVARIATE FUNCTION.

WIND VELOCITY (knots)	EQUIVALENT CAPACITY GENERATION (kW)
02	0.0000
02	0.0000
03	0.0000
04	0.3423
04	0.3423
02	0.0000
02	0.0000
01	0.0000
02	0.0000
02	0.0000
04	0.3423
03	0.0000
06	1.1552
05	0.6685

Table 5.4: EQUIVALENT CAPACITY GENERATION CONSIDERING UNIVARIATE FUNCTION (Continued)

WIND VELOCITY (knots)	EQUIVALENT CAPACITY GENERATION (kW)
09	3.8987
10	5.3480
10	5.3480
12	9.2414
10	5.3480
13	11.7496
13	11.7496
10	5.3480
08	2.7382
09	3.8987
07	1.8344
06	1.1552
03	0.0000
14	14.6750
16	21.9055
11	7.1182
12	9.2414
13	11.7496
11	7.1182
12	9.2414
12	9.2414
13	11.7496
14	14.6750
10	5.3480
24	46.5462
11	7.1182
12	9.2414
14	14.6750
00	0.0000
08	2.7382
08	2.7382
04	0.3423
04	0.3423
05	0.6685
05	0.6685
04	0.3423
06	1.1552
03	0.0000
04	0.3423
04	0.3423
04	0.3423
04	0.3423
03	0.0000
05	0.6685
03	0.0000
03	0.0000
03	0.0000
03	0.0000
03	0.0000

After rounding off the fractional values of equivalent capacity generation in table 5.4, the PDF of equivalent capacity generation for a univariate function is depicted in figure 5.14. The PDF of figure 5.14 is then convolved with the binary model of a WTG. The final distribution is depicted in figure 5.15 which is a probabilistic model of a WTG considering the output of a WTG as independent of temperature. The different

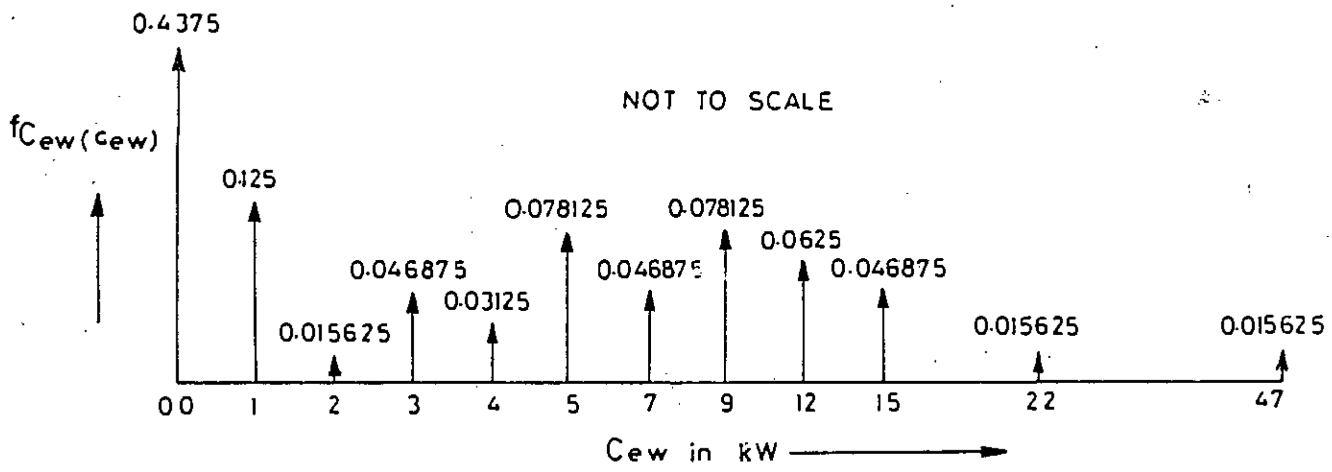


Figure - 5.14 PDF of equivalent electrical generation considering univariate function

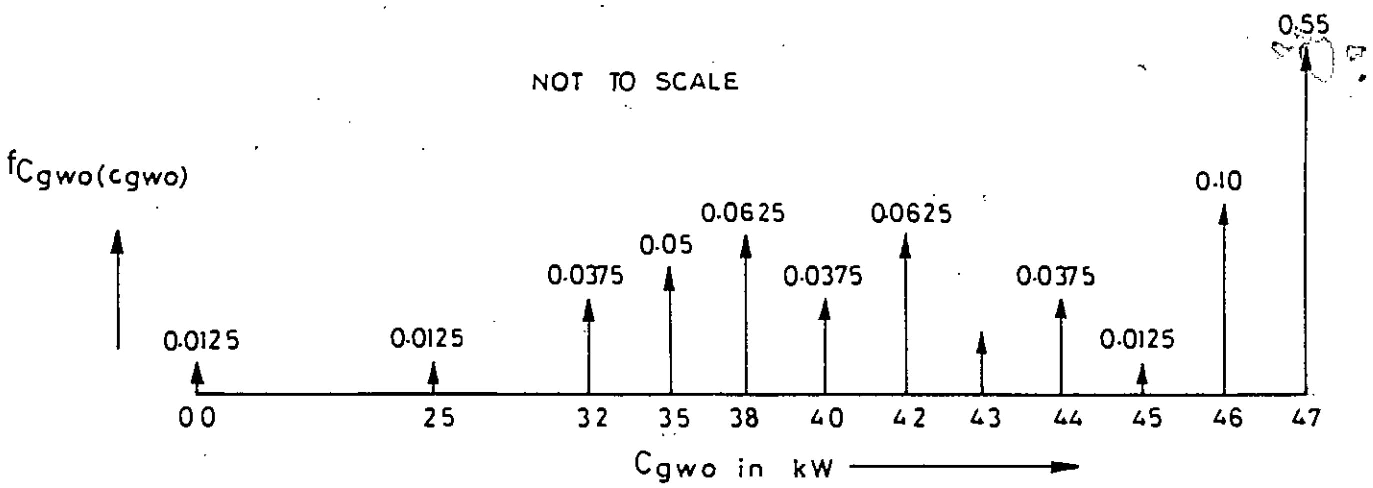


Figure - 5.15 PDF of capacity output on outage considering univariate function states of the multistate model of the WTG for a univariate function ; in terms of outage and innage capacities, along with the corresponding probabilities are presented in table 5.5.

Table 5.5 : Capacity states of a WTG and the corresponding state probabilities (for univariate function)

CAPACITY(kW) INNAGE (C_i)	OUTAGE (C_{oi})	PROBABILITY (P_i)
0.0	47	0.5500
01	46	0.1000
02	45	0.0125
03	44	0.0375
04	43	0.0250
05	42	0.0625
07	40	0.0375
09	38	0.0625
12	35	0.0500
15	32	0.0375
22	25	0.0125
47	0.0	0.0125

5.4.5 Simulation Results

The two multistate models of a WTG developed in section 5.2 are applied separately to evaluate the expected energy generation, expected energy not served and LOLP of the system. The segmentation method [60] is used for the numerical evaluation and the segment size considered for the segmentation method is 1 kW. The load data used in this evaluation is described in chapter 3. Note that in the simulation, the WTG is considered as the only source of energy supply to meet the system demand.

The expected energy generation, expected energy not served and LOLP evaluated corresponding to different number of WTGs from

15 to 160 are presented in tables 5.6 and 5.7. The results of table 5.6 corresponds to the model of a WTG developed from a bivariate function and those of table 5.7 corresponds to the model of a WTG developed from a univariate function. The second column of these two tables presents the maximum possible available capacities from the corresponding number of WTGs. The expected energy generated by each individual unit of a generating system comprising of 112 WTGs is also presented in table 5.8. The results of second column of this table are obtained by applying the model developed from a bivariate function and those of last column obtained applying the model developed from a univariate function.

Table 5.6 : Simulation results for the bivariate model

NO.OF UNITS	INSTALLED CAPACITY (kW)	E ENERGY GENERATION (MWh)	E(ENS) (MWh)	LOLP (%)
15	675.00	9.720	184.780	99.999
20	900.00	12.960	186.540	99.999
25	1125.00	16.200	183.300	99.999
30	1350.00	19.440	180.060	99.998
35	1575.00	22.680	176.820	99.994
40	1800.00	25.919	173.581	99.982
45	2025.00	29.158	170.342	99.953
50	2250.00	32.395	167.105	99.897
56	2520.00	36.275	163.224	99.776
60	2700.00	38.859	160.641	99.655
65	2925.00	42.082	157.418	99.459
70	3150.00	45.298	154.202	99.218
75	3375.00	45.506	150.994	98.950
80	3600.00	51.704	147.796	98.670
85	3825.00	54.893	144.607	98.395
90	4050.00	58.074	141.426	98.127
95	4275.00	61.246	138.254	97.860
100	4500.00	64.409	135.091	97.569
112	5040.00	71.948	127.552	96.527
125	5625.00	79.966	119.534	94.191
160	7200.00	99.757	99.743	80.505

Table 5.7 : Simulation results for the univariate model

NO.OF UNITS	INSTALLED CAPACITY (KW)	E ENERGY GENERATION (MWh)	E (ENS) (MWh)	LOLP (%)
15	705	10.080	189.420	99.999
20	900	13.440	186.060	99.999
25	1175	16.800	182.700	99.999
30	1410	20.160	179.340	99.997
35	1645	23.520	175.980	99.990
40	1880	26.880	172.621	99.972
45	2115	30.240	169.263	99.931
50	2350	33.592	165.910	99.856
56	2632	37.614	161.886	99.704
60	2820	40.290	159.210	99.560
65	3055	43.630	155.870	99.337
70	3290	46.960	152.540	99.076
75	3525	50.280	149.220	98.794
80	3760	53.591	145.910	98.508
85	3995	56.894	142.606	98.226
90	4230	60.190	139.313	97.942
95	4465	63.470	136.031	97.635
100	4700	66.740	132.761	97.268
112	5264	74.514	124.986	95.836
160	7520	102.724	96.776	78.083

Table 5.8 : Expected energy generation of individual generators for bivariate and univariate function.

UNIT SL.NO.	EXPECTED ENERGY GENERATION (MWh)	
	CONSIDERING VARIABLE TEMPERATURE (BIVARIATE FUNCTION)	CONSIDERING CONSTANT TEMPERATURE (UNIVARIATE FUNCTION)
1	648.000	672.000
2	648.000	672.000
3	648.000	672.000
4	648.000	672.000
5	648.000	672.000
6	648.000	672.000
7	647.999	671.999
8	647.999	671.999
9	647.999	671.999
10	647.999	671.999
11	647.999	671.999
12	647.999	671.999
13	647.999	671.999
14	647.999	671.999
15	647.999	671.999
16	647.999	671.999
17	647.999	671.999

Table 5.8 : Expected energy generation of individual generators for bivariate and univariate function.(Continued)

UNIT SL.NO.	EXPECTED ENERGY GENERATION (MWh)	
	CONSIDERING VARIABLE TEMPERATURE (BIVARIATE FUNCTION)	CONSIDERING CONSTANT TEMPERATURE (UNIVARIATE FUNCTION)
18	647.999	671.999
19	647.999	671.999
20	647.999	671.999
21	647.999	671.999
22	647.999	671.998
23	647.998	671.997
24	647.998	671.996
25	647.997	671.995
26	647.996	671.993
27	647.995	671.990
28	647.993	671.987
29	647.991	671.982
30	647.987	671.977
31	647.983	671.969
32	647.978	671.960
33	647.971	671.949
34	647.963	671.935
35	647.952	671.918
36	647.940	671.897
37	647.924	671.872
38	647.905	671.842
39	647.883	671.807
40	647.856	671.766
41	647.824	671.719
42	647.787	671.663
43	647.744	671.600
44	647.694	671.528
45	647.637	671.446
46	647.572	671.354
47	647.498	671.251
48	647.415	671.136
49	647.321	671.009
50	647.218	670.869
51	647.102	670.716
52	646.975	670.550
53	646.836	670.369
54	646.684	670.174
55	646.519	669.964
56	646.341	669.741
57	646.149	669.502
58	645.944	669.250
59	645.725	668.984
60	645.493	668.705
61	645.247	668.412
62	644.989	668.108
63	644.718	667.792

Table 5.8 : Expected energy generation of individual generators for bivariate and univariate function.(Continued)

UNIT SL.NO.	EXPECTED ENERGY GENERATION (MWh)	
	CONSIDERING VARIABLE TEMPERATURE (BIVARIATE FUNCTION)	CONSIDERING CONSTANT TEMPERATURE (UNIVARIATE FUNCTION)
64	644.436	667.465
65	644.142	667.128
66	643.837	666.782
67	643.523	666.428
68	643.199	666.066
69	642.868	665.699
70	642.529	665.326
71	642.184	664.950
72	641.833	664.570
73	641.478	664.187
74	641.120	663.803
75	640.760	663.418
76	640.397	663.034
77	640.034	662.649
78	639.671	662.266
79	639.309	661.883
80	638.948	661.502
81	638.589	661.122
82	638.232	660.744
83	637.877	660.366
84	637.525	659.989
85	637.176	659.611
86	636.828	659.233
87	636.483	658.852
88	636.140	658.468
89	635.797	658.080
90	635.454	657.685
91	635.111	657.282
92	634.766	656.870
93	634.417	656.445
94	634.064	656.007
95	633.705	655.553
96	633.338	655.079
97	632.962	654.584
98	632.574	654.065
99	632.172	653.519
100	631.754	652.943
101	631.317	652.335
102	630.860	651.690
103	630.379	651.007
104	629.872	650.281
105	629.336	649.511
106	628.769	648.692
107	628.167	647.822
108	627.528	646.898
109	626.849	645.917

Table 5.8 : Expected energy generation of individual generators for bivariate and univariate function.(Continued)

UNIT SL.NO.	EXPECTED ENERGY GENERATION (MWh)	
	CONSIDERING VARIABLE TEMPERATURE (BIVARIATE FUNCTION)	CONSIDERING CONSTANT TEMPERATURE (UNIVARIATE FUNCTION)
110	626.126	644.877
111	625.358	643.774
112	624.541	642.606
TOTAL NO. OF UNITS=112	TOTAL EEG=71.949 MWh E(ENS)=127.552 MWh and LOLP =96.53%	TOTAL EEG=74.514 MWh E(ENS)=124.986 MWh,and LOLP =95.84%

This table also presents the total expected energy generation (EEG), total expected energy not served E(ENS) and LOLP corresponding to 112 WTGs at the bottom of the table.

To justify the consideration of the output of a WTG as a function of wind velocity and temperature (bivariate function), the simulation results obtained using both the models (bivariate and univariate) are also compared graphically. Figures 5.16, 5.17 and 5.18 respectively, depict the LOLP, expected energy generation and expected energy not served for different number of WTGs obtained using both the models.

Note that the total system energy demand for the plan period considered is 199.50 MWh.

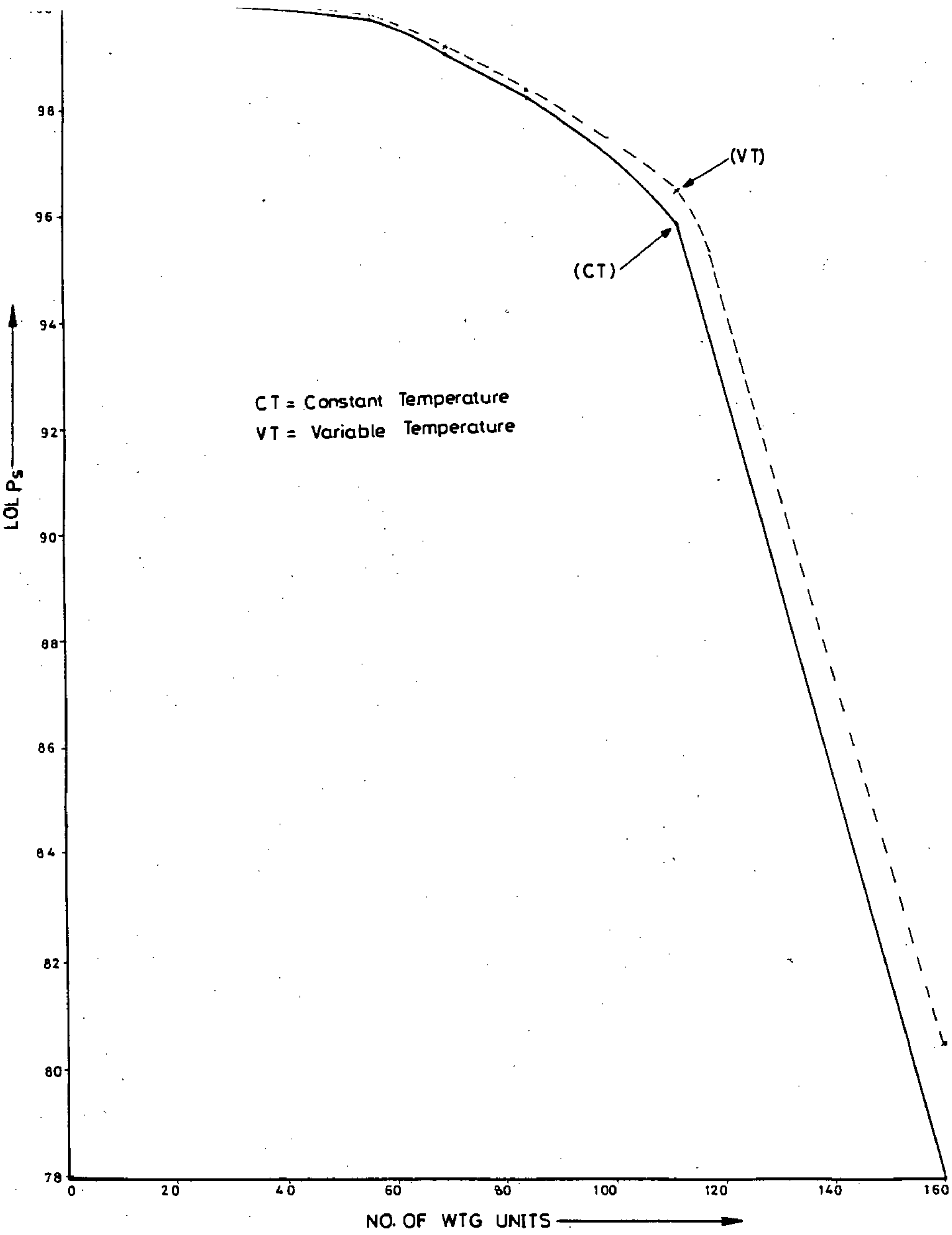


Figure - 5.16 LOLPs for different number of WTGs

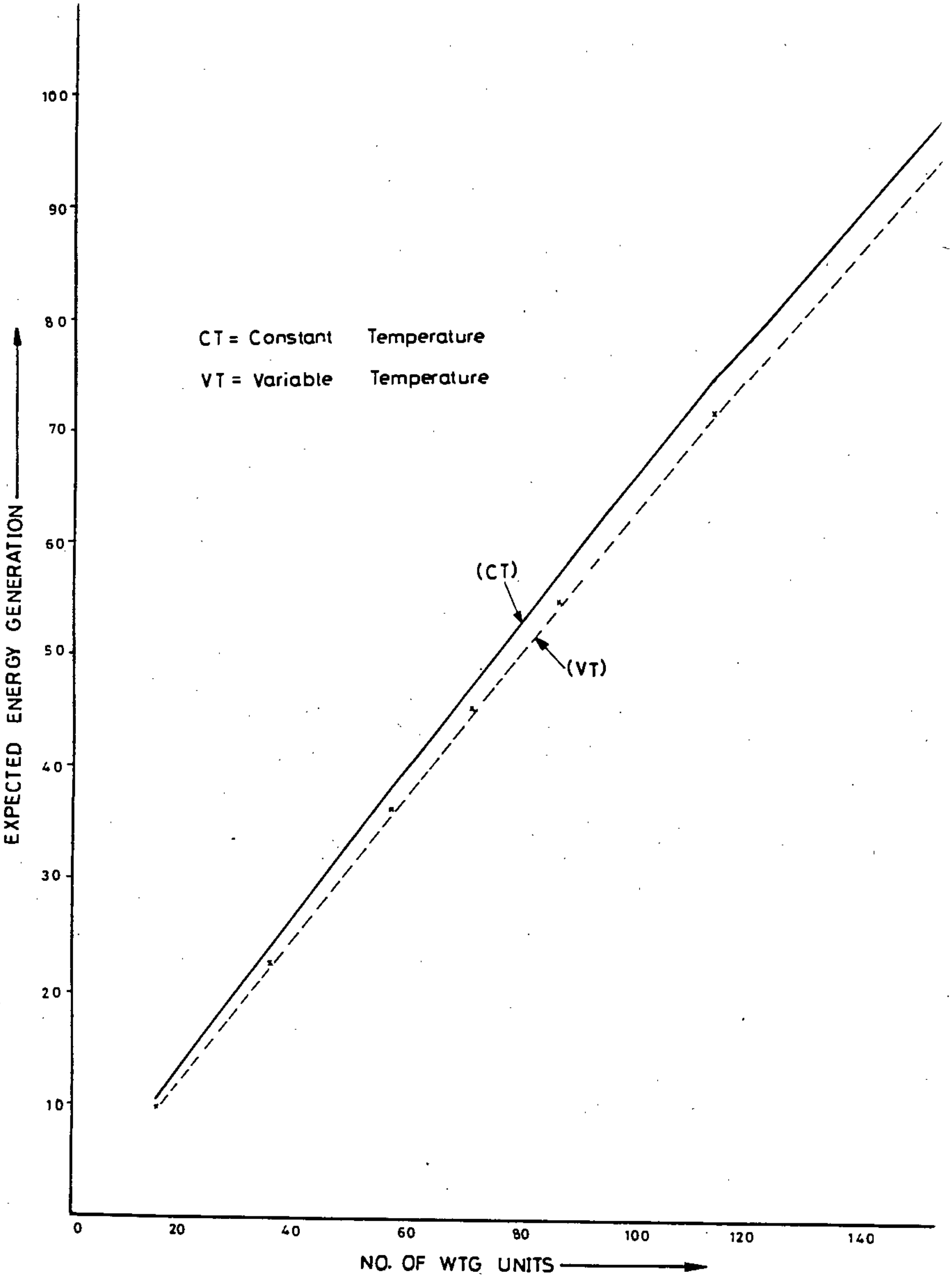


Figure - 5.17 Expected energy generation for different number of WTGs

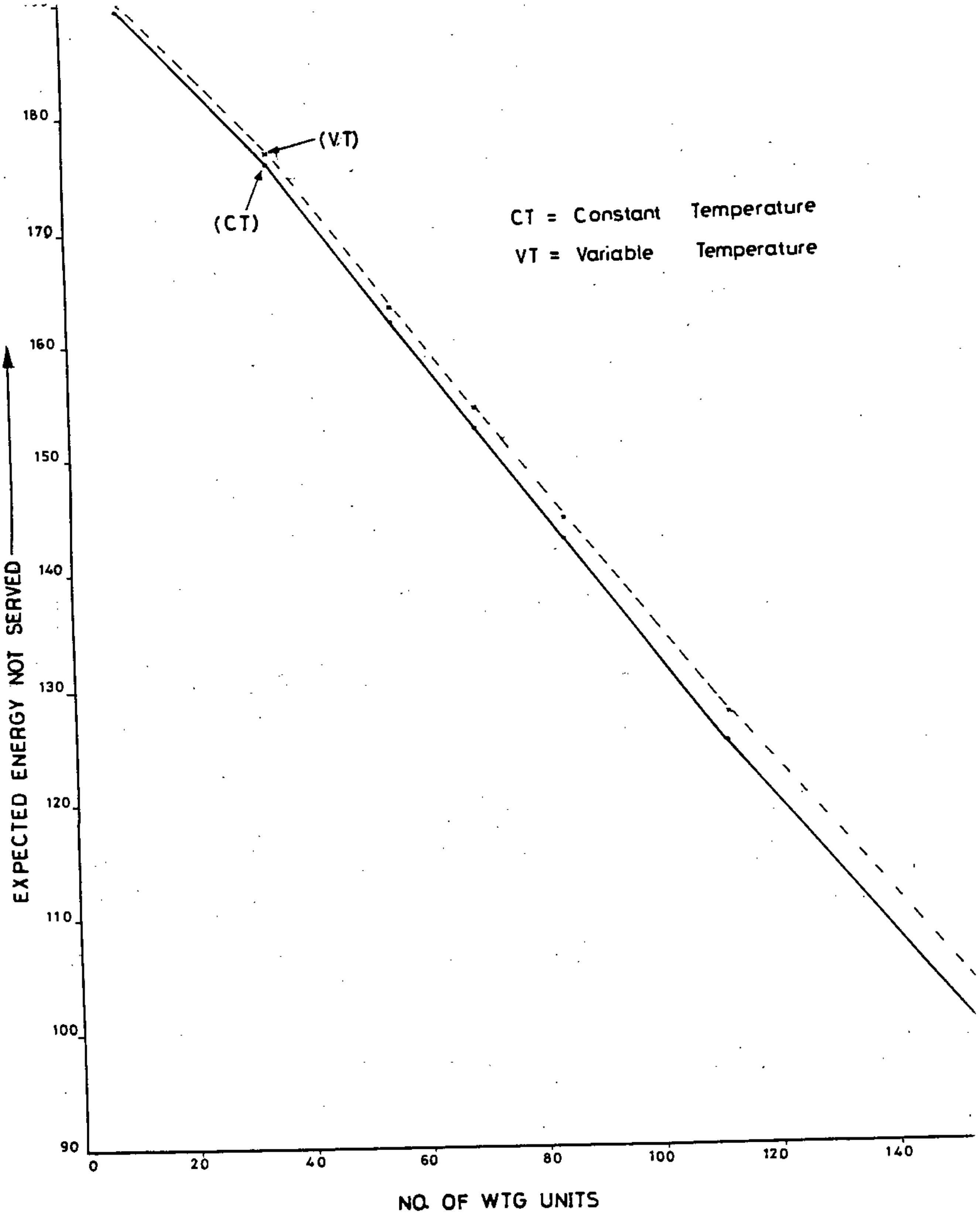


Figure - 5.18 Expected energy not served for different number of WTGs.

5.5 DISCUSSION

In what follows, the salient points observed from the numerical evaluation of the proposed WTG model are briefly discussed.

It is observed from table 5.2 that for many samples the equivalent capacity generations are zero. These zero capacity generations are because of the wind velocities corresponding to their samples are less than the cut-in velocity of the considered WTG. Note that the cut-in velocity of the WTG is 5 knots which corresponds to 4.39 knots before hub height correction. The table 5.2 also shows that the equivalent capacity generations vary with the variation of temperatures. For example, the two samples with 13 knots wind velocity and 29.8 ^{o}C temperature and 13 knots wind velocity and 28.0 ^{o}C temperature produce two different magnitude of equivalent capacity generations of 11.2691 and 11.3471 kW respectively.

Now, the comparision of the equivalent capacity generation of tables 5.2 and 5.4 reveals that the values are different for each set of temperature and wind velocity. Recall that table 5.2 presents the equivalent capacity generation from a WTG considering temperature as a variable quantity, while table 5.4 presents the equivalent capacity generation considering temperature as a constant quantity .Similar observations are also made regarding the capacity states of tables 5.3 and 5.5. That is, the innage or outage capacities of a WTG obtained applying the model corresponding to the bivariate function, wind velocity and variable temperatures, and those obtained applying the model corresponding to the univariable function, wind velocity and a constant temperature of 15.15°C, are different. For the considered data the maximum generation capacity for the model corresponding to bivariate function is 45 kW while for the model corresponding to univariate function, it is 47 kW. The comparison between figure 5.11 and figure 5.14 also clearly reveals the above difference. Although the values of the random variables, outage capacities, given in tables 5.3 and 5.5 are different in two cases, however, the probability values for the impulses become same in the process of rounding off.

It is expected that with the increase of number of WTGs /the installed capacities in the system, the total expected energy generation should increase and the expected energy not served and the LOLP should decrease. Table 5.6 as well as table 5.7 confirms this. However, it is observed from table 5.6 that the expected energy generated by WTGs is very low and the LOLP is very high. For example, the installed capacity of 285.71% of peak load (corresponding to 160 WTGs), that is, for 185.71% reserve capacity, the total expected energy generation is only 50.004% of total energy demand and the LOLP of the system reaches to only 80.506%.

The poor performance of the WTG would be clear from the capacity states of table 5.3 or from the distribution of the WTG of figure 5.11. This table or the figure shows that although the maximum possible available capacity is 45 kW, however, the expected capacity of the WTG is only 3.375 kW. That is, the probability values of capacity states of higher innage capacity are smaller compared to those of the capacity states of lower innage capacity. Similar observation can also be easily made from table 5.5 or from figure 5.14 in case of univariate function.

The comparison of tables 5.6 and 5.7 show that the expected energy generations, the expected energy not served and the LOLPs are different for the same number of WTGs, if the model of a WTG applied for the evaluation is different. The expected energy generation is higher and the expected energy not served and the LOLP are lower when the model of a WTG developed from a univariate function is applied for the evaluation.

The higher expected capacity generation is also observed from table 5.8 even for each individual unit. For example, in table 5.8, the unit at 10th loading order position is expected to generate 647.999 MWh if the model of a WTG developed from a bivariate function is applied, while it is expected to generate by the same unit an energy of 671.999 MWh if the model developed from a univariate function is applied.

Note that the maximum possible capacity as well as the expected energy generation of the model developed from a univariate function are higher than those of the model developed from a bivariate function.

From figure 5.16 it is observed that for the smaller number of WTGs, the LOLPs obtained applying both the models are very close. However, the difference in LOLPs increases with the increase of higher number of WTGs and it is quite high, 2.43 % (80.51% for the model of bivariate function and 78.08% for the model of univariate function) in case of 160 WTGs in the system.

The comparison among the expected energy generations as well as the expected energy not served obtained applying two different models in figure 5.17 and in figure 5.18 respectively, show the increased saliency in difference between the results with the increase of number of WTGs in the system. For example, for 25 WTGs in the system, the difference in case of expected energy not served is 0.6 MWh and in case of LOLP, the difference is 0.0002%; while for 160 WTGs in the system, the difference in case of expected energy generation is 2.967 MWh and in case of LOLP the difference is 2.43%.

CHAPTER 6

SOLAR RADIATION AS A SOURCE OF ENERGY

6.1 INTRODUCTION

Solar radiation energy is as an important renewable energy resource which will be increasingly used in the future to meet the world's growing energy requirements. Photovoltaic devices, which convert light directly into electricity, provide a particularly attractive and promising method of solar radiation energy utilization.

Such photovoltaic devices had long been used in light exposure meters, but it was not until the 1950's that higher performance devices became available that could be used for powering small specialised equipment in remote areas. The technology was greatly advanced in the 1960's when photovoltaic generators first came into regular use for space satellites. Costs were initially very high, but over the last 15 years improvements in manufacturing techniques and increased volume of production have enabled photovoltaic cell costs to be greatly reduced [78].

This chapter presents the basic concepts of the conversion from solar radiation into electrical energy. It describes the operating principle and characteristics of a solar cell. This chapter also presents the description and operation of an instrument which measures solar radiation.

6.2 BASIC CONCEPTS OF PHTOVOLTAIC SYSTEM

A photovoltaic generator consists of photovoltaic cells mounted in modules which form part of an array. The cells are electrically connected and the modules are in turn interconnected by wires to take the electricity to some form of control and power conditioning system. In the simplest systems,all that is required is a switch to isolate the array from the electrical load. The term 'photovoltaic system' is applied to the set of components needed to convert solar energy into electrical energy. The power produced by any photovoltaic device is direct current (dc), and conversion to alternating current (ac) at standard voltage and frequency is often required.

6.3 THE PHTOVOLTAIC PROCESS

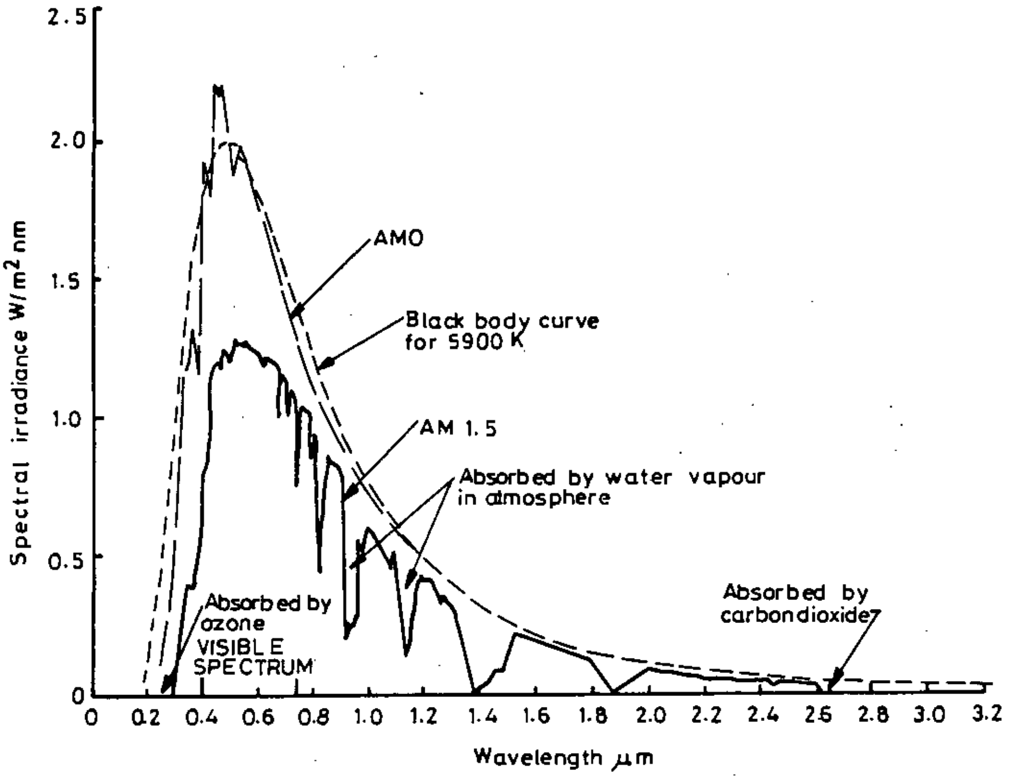
The interaction between photons and electrons is the basic principle underlying all photovoltaic devices. The energy generated continously by the sun is radiated as a stream of photons of various energy levels leaving the surface of the sun in all directions.The total radiant power from the sun received by a surface of unit area is known as the 'irradiance'. Outside the earth's atmosphere, the irradiance on a plane normal to the solar beam amounts to about 1367 W/m^2 [78,79].

As the radiation passes through the earth's atmosphere, a considerable amount is lost by scattering and absorption, some wavelengths being affected more than others. The amount of energy lost depends on the path length through the atmosphere and the amount of dust and water vapour at the time. The term 'air mass' is commonly used to denote the length of path traversed through the atmosphere the direct solar beam, expressed as a multiple of the path traversed to a point at sea level with the sun overhead. Air Mass 1 (AM 1) is the path length to sea level with the sun directly overhead, but Air Mass 1.5(AM 1.5) is generally more appropriate for latitudes between 30° and 60° [78,79]. Figure 6.1 shows the spectral energy distribution of direct sunlight at sea level on a clear day for AM 1.5. The spectral energy distribution outside the atmosphere (AM 0) is also shown for comparison. This bears a marked similarity with the curve for a black-body radiator at 5900° K, the temperature of the surface of the sun [78,79].

The irradiance at ground level is made up of two components: direct and diffuse. The sum of these two components is termed the 'global irradiance'. The diffuse component can vary from about 20% of the global on clear day to 100% in heavily overcast conditions. On a clear day in the topics, with the sun high overhead,the global irradiance can be as high as $1000 W/m^2$ [78,79].

The conversion (or cell) efficiency is defined as the ratio of the maximum power output to the product of area and irradiance expressed as a percentage:-

$$\text{efficiency} = \frac{\text{maximum power}}{\text{irradiance} \times \text{gross cell area}} \times 100\% \qquad \ldots(6.1)$$



Figure–6.1 Spectral energy distribution

NOTE : The total irradiance under the AM1.5 curve amounts to 834.6 W/m²

Figure 6.1 Spectral energy distribution.

6.4 OPERATING PRINCIPLE OF SOLAR CELLS

The material most commonly used at present to make photovoltaic cells is mono-crystalline silicon. The essential features of this type of cell are shown in figure 6.2. It is made from a thin wafer of high purity silicon crystal, doped with a minute quantity of boron. Phosphorous is diffused into the active surface of the slice at high temperature. The front electrical contact is made by a metallic grid and the back contact usually covers the whole surface. The front surface has an anti-reflective coating.

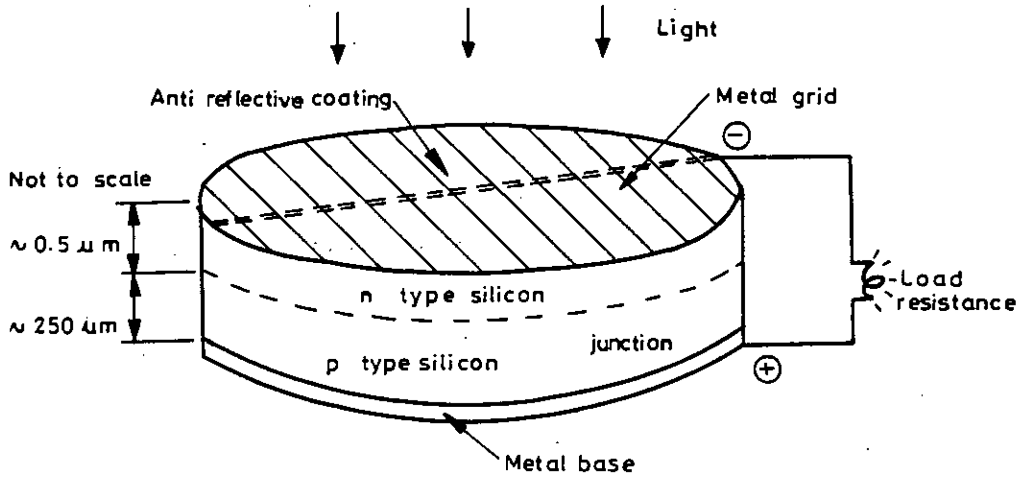


Figure - 6.2 Silicon solar cell.

The phosphorous introduced into the silicon gives rise to an excess of what is known as conduction-band electrons and the boron and excess of holes, which act like positive charges. At the junction, conduction electrons from the n (negative) region diffuse into the p (positive) region and combine with holes, thus cancelling their charges. The opposite action also occurs, with holes from the p region crossing into the n region and combining with electrons. The area around the junction is thus 'depleted' by the disappearance of electrons and holes. Layers of charged impurity atoms, positive in the n region and negative in the p region, are formed on either side of the junction, thereby setting up a 'reverse' electric field.

When light falls on the active surface, photons with energy exceeding a certain critical level known as the bandgap or energy gap (1.1 electron volts in the case of silicon) [78-81] interact with the valence electrons and elevate them to the conduction band. This activity leaves 'holes', so the photons are said to generate 'electron-hole pairs'. These electron-hole pairs are generated throughout the thickness of the silicon in concentrations depending on the intensity and spectral distribution of the light. The electrons move throughout the crystal and the less-mobile holes also move by valence-electron substitution from atom to atom. Some recombine, neutralising their charges and the energy is converted to heat.Others reach the junction and are separated by the reverse field, the electrons being accelerated to the negative contact and the holes towards the positive. A potential difference is established across the cell which is capable of driving a current through an external load.

The generated current is built up from increments produced by photons of different energy levels (wavelengths). The high energy (short wavelength) photons are absorbed near the surface while the longer wavelength photons penetrate deeper, most being absorbed within 100 μm. By plotting the incremental current generated by unit irradiance against wavelength, the 'absolute spectral response' is obtained, as shown in figure 6.3

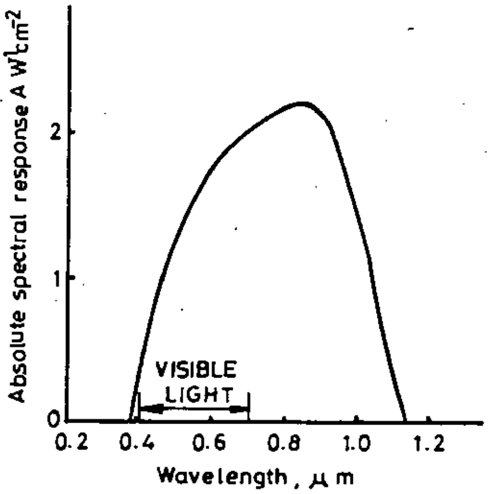


Figure - 6.3 Spectral response of silicon cell.

6.5 CHARACTERISTICS OF SOLAR CELLS

The commonly used equivalent circuit of a solar cell is depicted in figure 6.4. By multiplying the ordinates of the absolute spectral response of figure 6.3 by the ordinates of the spectral energy distribution of figure 6.1 of the incident radiation and integrating, the total generated current I_L is obtained . The load current I_C is the difference between the generated current I_L and the junction current I_J. In the short-circuit condition (V_C=0), I_J is very small. As the cell series resistance R_S is also very small for most types of solar cell, the short-circuit current provides a useful measure of the generated current. The open-circuit voltage is about 0.6V at 25° C for crystalline silicon cells [78].

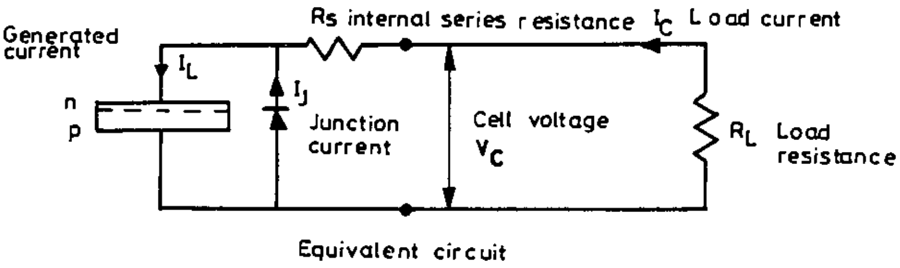


Figure - 6.4 Equivalent circuit a silicon cell

The current/voltage (I-V) characteristic for a typical silicon cell is dependent on irradiance and temperature, as illustrated in figures 6.5(a) and (b). The fill factor is the ratio of the maximum power to the product of short-circuit current and open-circuit voltage. In general, the higher the fill factor, the better the cell as a practical photovoltaic device. Maximum power is represented by the area of the largest rectangle that can be fitted under the curve. The output current is practically constant for all voltages up to a voltage close to that for peak power, and is proportional to cell area. Figure 6.5(b) shows that as temperature increases the current increases slightly and the voltage decreases; in cosequence the maximum power obtainable decreases. It is therefore desirable to operate the cells at as low a temperature as possible.

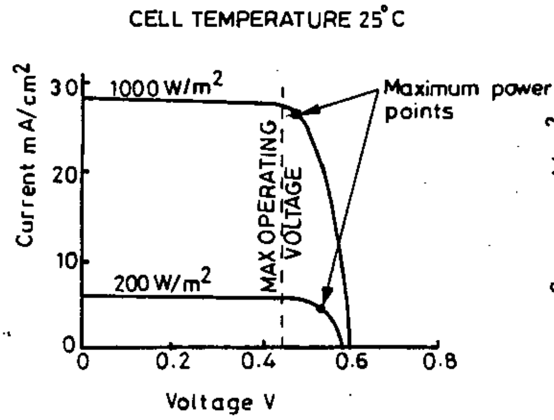


Figure 6.5(a) I-V characteristics for different irradiances

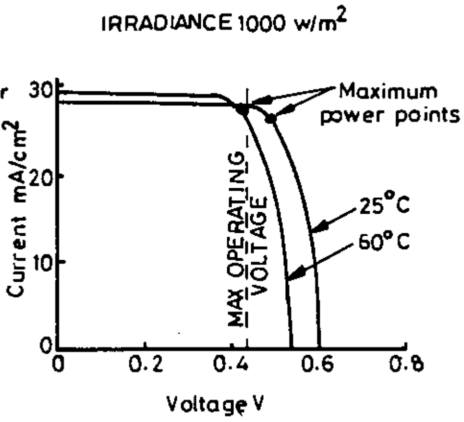


Figure 6.5(b) I-V characteristics for different temperatures

CHAPTER 7

MODEL OF A PHOTOVOLTAIC GENERATOR (PVG)

7.1 INTRODUCTION

Due to the recent tumultuous events in the power industries, utilities are putting their renewed emphasis on unconventional sources. The photovoltaic generator (PVG) attracts the power system planners to consider it as a source to meet the electrical demand, because of its nonpolluting environmental impacts, nonhazardious operation and almost nonexisting operating cost [37,38]. However, an appropriate model of a PVG, suitable for probabilistic simulation, is essentially required to consider it as an alternative source of electricity.

A probabilistic model of a PVG , applicable like a conventional multistate generator in the probabilistic simulation,is presented in this chapter. The model is based on the concept of the multi-state representation of a generating unit. The probability density function (PDF) of the capacity output from a PVG is derived from the bivariate function of solar radiation (insolation) and temperature. To justify the proposed model of a PVG function of insolation and temperature, a model of a PVG is also developed by considering the output of a solar cell as a function of insolation only. Both the models are applied to evaluate the expected energy generation, the expected energy not served and the LOLPs. The results obtained using these two models are compared and the justification of the proposed model is discussed in this chapter.

7.2 METHODOLOGY FOR DEVELOPING A PVG MODEL

The behaviour of a photovoltaic generator may be closely represented by a current source in parallel with a p-n junction diode. The commonly used equivalent circuit of a photovoltaic cell is shown in figure 7.1

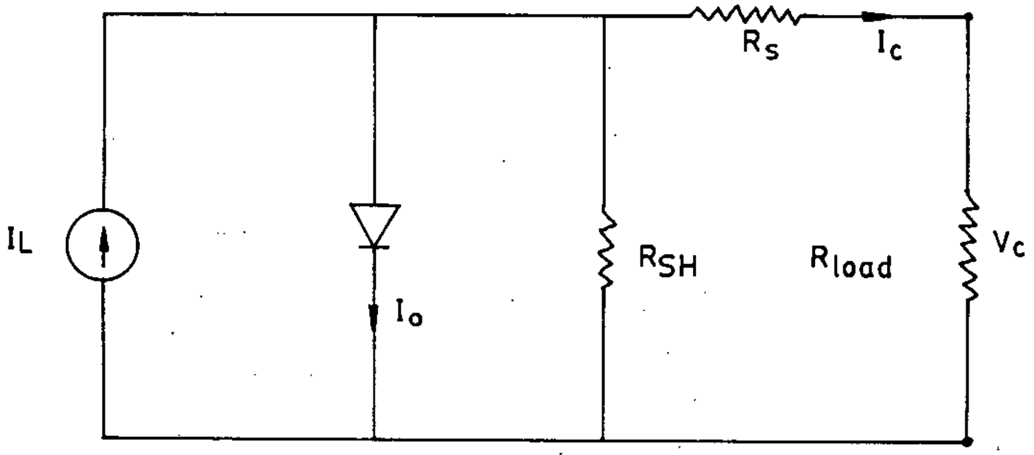


Figure - 7.1 Equivalent circuit of a photovoltaic Cell

The shunt resistance, R_{SH}, is introduced in the equivalent circuit to incorporate the leakage around the edge of the cell, while , R_S, takes care of the contact resistance between the metallic contacts and the semiconductor as well as the resistance of the semiconductor material of the solar cell.

The output of a solar cell, a dc power source, may be expressed in terms of the cell current, I_C, and the cell terminal voltage, V_C, as

$$P_{dc} = V_C I_C \qquad ...(7.1)$$

The cell current may be expressed in terms of cell parameters as [38,79,80,81-84]

$$I_c = I_L - I_o \{ \exp[q(V_c + I_c R_S)/AKT] - 1 \} - V_c/R_{SH} \qquad \ldots(7.2)$$

Where, I_L and I_o is light generated and diode saturation current respectively and q is the charge of an electron. In equation (7.2), A,K,T represent diode quality constant, Boltzmann's constant and temperature respectively. The last term of equation (7.2), V_c/R_{SH}, is much less compared to first two terms of the right hand side. Thus neglecting the effect of R_{SH}, the equation (7.2) can be rewritten as,

$$I_c = I_L - I_o \{ \exp[q(V_c + I_c R_S)/AKT] - 1 \} \qquad \ldots(7.3)$$

The terminal voltage, V_c, of a cell may be derived from equation (7.3) as

$$V_c = \frac{AKT}{q} \ln \left[\frac{I_L - I_c}{I_o} + 1\right] - I_c R_s \qquad \ldots(7.4)$$

The diode saturation current, I_o, of equation (7.3) or of equation (7.4)(the minimum value) is given approximately as [81]

$$I_o = 1.5 \times 10^5 \exp(-E_g/KT) \qquad \ldots(7.5)$$

Where, E_g is the energy band gap. The E_g for a semiconductor is almost constant. Therefore, I_o is the function of temperature only. That is

$$I_o = f_1(T) \qquad \ldots(7.6)$$

The light generated current, I_L, may be expressed as

$$I_L = A\ J \qquad \ldots(7.7)$$

The current density J of equation (7.7) is given as [85]

$$J = q \int_{0}^{L} G(x)\, dx \qquad \ldots(7.8)$$

Where, L is the thickness of the cell, and G(x) is the generation rate of charge-carriers at a point x.

Now, the generation term is given at a point, x, as a function of wavelength as [85]

$$G(\lambda) = [1-R(\lambda)]\alpha(\lambda)N(\lambda)\exp[-\alpha(\lambda)\, x] \qquad \ldots(7.9)$$

where

$N(\lambda)$ = number of incident photons with energies greater than the band gap (no./cm^2s)

$\alpha(\lambda)$ = absorption coefficient (cm^{-1})

$R(\lambda)$ = reflection coefficeint

Now the intensity of light, sometime termed as insolation corresponding to a solar cell, Φ is expressed in terms of number of photon, N, and its energy, ε, as [80]

$$\Phi = N\varepsilon \qquad \ldots(7.10)$$

where

$$\varepsilon = h\nu \qquad \ldots(7.11)$$

and

$$\nu = \frac{c}{\lambda} \qquad \ldots(7.12)$$

That is,

$$\Phi = N h \frac{c}{\lambda} \qquad \ldots(7.13)$$

where, h is the Planck's constant and c is the speed of propagation.

If one sees the energy spectrum of the sun as shown in figure 6.1 in chapter 6, he will observe that the wave length, λ, varies in the neighbourhood of 0.3 to 2.3 microns and the maximum energy contribution comes from a small range of λ. Moreover, a solar cell of a particular semiconductor material does not operate all through the range of λ. Therefore, reasonably one can assume some average value of λ, λ_{av}, for a particular cell. In that case, for a given insolation the number of photons N can be computed using equation (7.13) as

$$N = \frac{\Phi}{K} \qquad \ldots(7.14)$$

where

$$K = h \frac{c}{\lambda_{av}} \qquad \ldots(7.15)$$

Again for a given λ_{av} and for a particular cell J and I_L in-turn become

$$J = f_2\ (\Phi) \qquad \ldots(7.16)$$

$$I_L = f_3\ (\Phi) \qquad \ldots(7.17)$$

In this condition, from equation (7.3), (7.4) and (7.1) one can write

$$I_c = f_4(T,\ \Phi) \qquad \ldots(7.18)$$

$$V_c = f_5(T,\ \Phi) \qquad \ldots(7.19)$$

$$P_{dc} = f_6(T,\ \Phi) \qquad \ldots(7.20)$$

Like the temperature and the wind velocity, the temperature and the insolation are random in nature, they vary with time and locations. The density function of these two random variables, temperature and insolation, may be expressed like $f_{T,V}(t,v)$ of equation (5.8) as of chapter 5

$$f_{T,\Phi}(t,\phi) = \sum_i \sum_j P_{(T,V)i,j}\,\delta(T-t_i)\,\delta(\Phi-\phi_j) \qquad \ldots(7.21)$$

Equation (7.20) shows that the output power of a solar cell is a function of temperature and insolation only. However, as the temperature and insolation are two correlated random variables, therefore, the output power P_{dc} will also be a random variable. The univariate distribution of P_{dc}, $f_{Pdc}(p_{dc})$, may be obtained from the bivariate distribution, $f_{T,\Phi}(t,\phi)$. The $f_{Pdc}(p_{dc})$ may be expressed as

$$f_{Pdc}(p_{dc}) = \sum_i P_{Pdci}\,\delta(P_{dc} - p_{dci}) \qquad \ldots(7.22)$$

The dc power output may be converted to alternating power using a converter. Thus,

$$C_{es} = \eta_c P_{dc} \qquad \ldots(7.23)$$

where, C_{es} is the equivalent electrical power generated from a solar source and η_c is the converter efficiency. The PDF of C_{es}, $f_{Ces}(c_{es})$, is similar to $f_{Pdc}(p_{dc})$. That is, η_c maps $f_{Pdc}(p_{dc})$ onto $f_{Ces}(c_{es})$ and for every value of P_{dc} in the dc power output domain there exists a value of C_{es} in C_{es} domain.

The probability of C_{es} is same as the probability of P_{dc} and the value C_{es} may be obtained from equation (7.23). Now, $f_{C_{es}}(c_{es})$ may be written as

$$f_{C_{es}}(c_{es}) = \sum_{i} P_{C_{esi}} \delta(C_{es} - c_{esi}) \qquad \ldots(7.24)$$

The availability of the output of a solar cell, C_{gs}, depends on the availability of a solar cell and a converter. If the PDF of a solar cell incorporating the random outages of a converter, $f_{C_s}(c_s)$ is

$$f_{C_s}(c_s) = \sum_{i} P_{C_{si}} \delta(C_s - c_{si}) \qquad \ldots(7.25)$$

then the PDF of C_{gs}, $f_{C_{gs}}(c_{gs})$, can be expressed as

$$f_{C_{gs}}(c_{gs}) = \sum_{i} \sum_{j} P_{C_{si}} P_{C_{sj}} \delta(C_{es} - c_{esi}) \delta(C_s - c_{sj}) \qquad \ldots(7.26)$$

Note that this time also the PDF, $f_{C_{gs}}(c_{gs})$ is equivalent to a multistate representation of a generating unit.

7.3 NUMERICAL VERIFICATION OF THE PROPOSED (PVG) MODEL

The proposed model of a photovoltaic cell of section 7.2 is justified by developing two different multistate models of a photovoltaic generator (PVG) using realistic data in this section. The first one is developed by considering the electrical power output from a PVG as a function of both solar radiation and temperature (bivariate function) and the second one is developed by considering the elctrical power output from a PVG as a function of solar radiation (univariate function) only. Both these models are applied, in this section, to evaluate the reliability indices and expected energy generation. This section also describes the basic data used for the probabilistic simulation of a PVG. In this study, a solar panel consisting of 1 million solar cells is considered.

7.3.1 Basic Data

Solar Radiation and Temperature

The amount of irradiance available at any location on earth at any given time depends on various factors [26]. The most important ones are:

i) the earth-sun distance,

ii) the declination angle of the earth's axis with respect to the sun,

iii) the atmospheric conditions,

iv) the location (i.e. the latitude),

v) the time of day, and

vi) solar clock time relationships

Using the data of the above factors the maximum radiations,diffused and direct, for a particular day of a month under clear sky condition may be calculated. With the calculated values of diffused and direct radiations and the daily average sunshine hours, the average daily or monthly solar insolation at noon time may be calculated as [26].

$$\text{Insolation} = \frac{(\text{Diffused radiation} + \text{Direct radiation})}{(\text{Maximum} + \text{Minimum sunshine hours})/2} \quad \ldots(7.27)$$

However, now a days, the instruments are available to measure the solar radiation directly.

Bangladesh Meteorological Department (BMD) [86,87] has installed Solar Radiation Recorders,R 401- Mechanical Pyranograph [87], to record daily solar radiation at different places in the country. However, it has no arrangement to record solar radiation at the typical island. Therefore, the solar radiations of Barisal nearest to the typical island are considered for this research .

The pyranograph makes continuous record on a graph paper. From such a graph one can easily calculate the hourly solar radiation. Note that the ordinate of the graph gives the solar radiation in cal/cm^2/min. To convert this value into watt/m^2 a conversion factor is used. In what follows, the conversion procedure is described.

$$\text{Solar insolation, } \Phi = K \times [\text{chart (graph) reading}] \quad \ldots (7.28)$$

where , K = instrument constant. The value of K for this instrument is 0.398. For example, consider that the if the chart reading is 2.75, then the solar radiation Φ may be calculated as,

$$\Phi = 0.398 \times 2.75 \text{ cal/cm}^2\text{/min}$$

$$\Phi = 0.398 \times 2.75 \times 697.8 \text{ w/m}^2$$

$$\Phi = 763.74 \text{ w/m}^2 \text{ or } 0.076342 \text{ w/cm}^2 \quad \ldots(7.29)$$

In equations (7.29), 697.8 is the conversion factor [86,88] to convert (cal/cm^2/min) into (w/m^2). Pertinent information and one sample graph (figure BP-1) collected from BMD are given in Appendix-B. The hourly solar radiation in cal/cm^2/min (chart value) and the corresponding hourly temperature in ^{o}C for the same period from June to August are given in table BP-1 in Apppendix-B . Note that this table presents the solar radiation from 6 A.M. upto 7 P.M. Moreover, in some hours between 6 A.M and 7 P.M. the solar radiation and its corresponding temperature are not shown. During these hours the solar radiation are zero (nil). That is, during the hours in which the data value of solar radiations are not shown in the table indicate the zero value of solar radiation. During this period the temperature varies from 23.0 to 34.5 ^{o}C while the insolation varies from 0.0 to 2.75 cal/cm^2/min.

Solar Cell Characteristics

Solar cells made of different semiconducing materials have differrent characteristics. The electrical power output from solar cells of different materials will be different even for the same insolation. In this research, silicon solar cell is considered.

The energy band gap for the silicon cell is considered to be 1.1 eV [79-81]. A solar cell with a geometry of 2 cm x 1 cm area, 0.05 cm thickness, shown in figure 7.2, is considered [84].

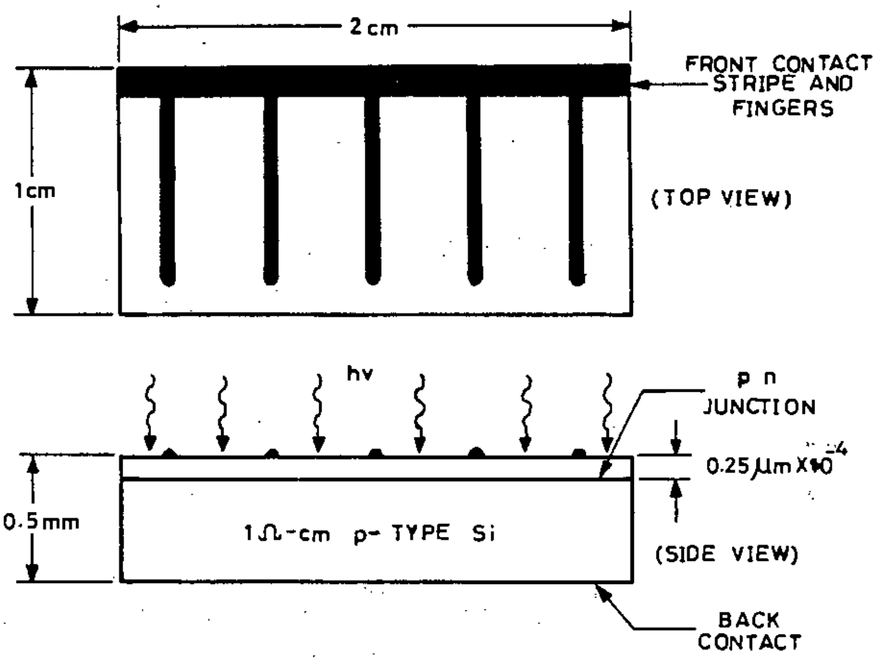


Figure - 7.2 Typical schematic representation of a solar cell

The series resistance of a silicon cell assumed to be 0.7 ohm [84]. The spectral distribution of sunlight presented in figure 6.2 [79-81,89] in section 6.3 shows that the solar energy per unit area is a contribution of photons of different wavelengths. The bandwidth of this wavelength is usually from 0.3 to 2.3 μm. However, the major contributors towards the energy lie within a small range of wave lengths.

Moreover, the equations (7.7) through (7.9) express that the light generated current, I_L varies with the variation of wavelength. Thus to calculate I_L for a measured value of insolation, the energy density function for this insolation is to be evaluated by comparing with the standard one (as in figure - 6.2). Using this density function I_L is to be calculated for each values of wavelength. To avoid this complicated computational procedure and as the photons within a smaller range of wavelength contribute maximum to the total insolation, an average value of wavelength for this research is assumed. The average value is of wavelength 6000 A [80]. The absorption coefficient α for a silicon solar cell for the assumed value of λ(wave length) is obtained from figure 7.3 [84,89]. Note that this figure presents the variation of α at 300°K. For simplicity it is assumed that α is independent of temperature.

Now, the reflection coefficient (R) can be calculated by using the following relation [79,80],

$$R = (n-1)^2/(n+1)^2 \qquad \ldots(7.30)$$

where, n is the index of refraction.

An empirical relation due to Moss [90] is used to estimate the index of refraction [79,80],

$$E_g n^4 = 173 \qquad \ldots(7.31)$$

Thus, for E_g =1.1 ev, n=3.54 the reflection coefficient would be 0.313.

The properties of silicon solar cell and other physical constants considered for this research are summarized in tables 7.1 and 7.2.

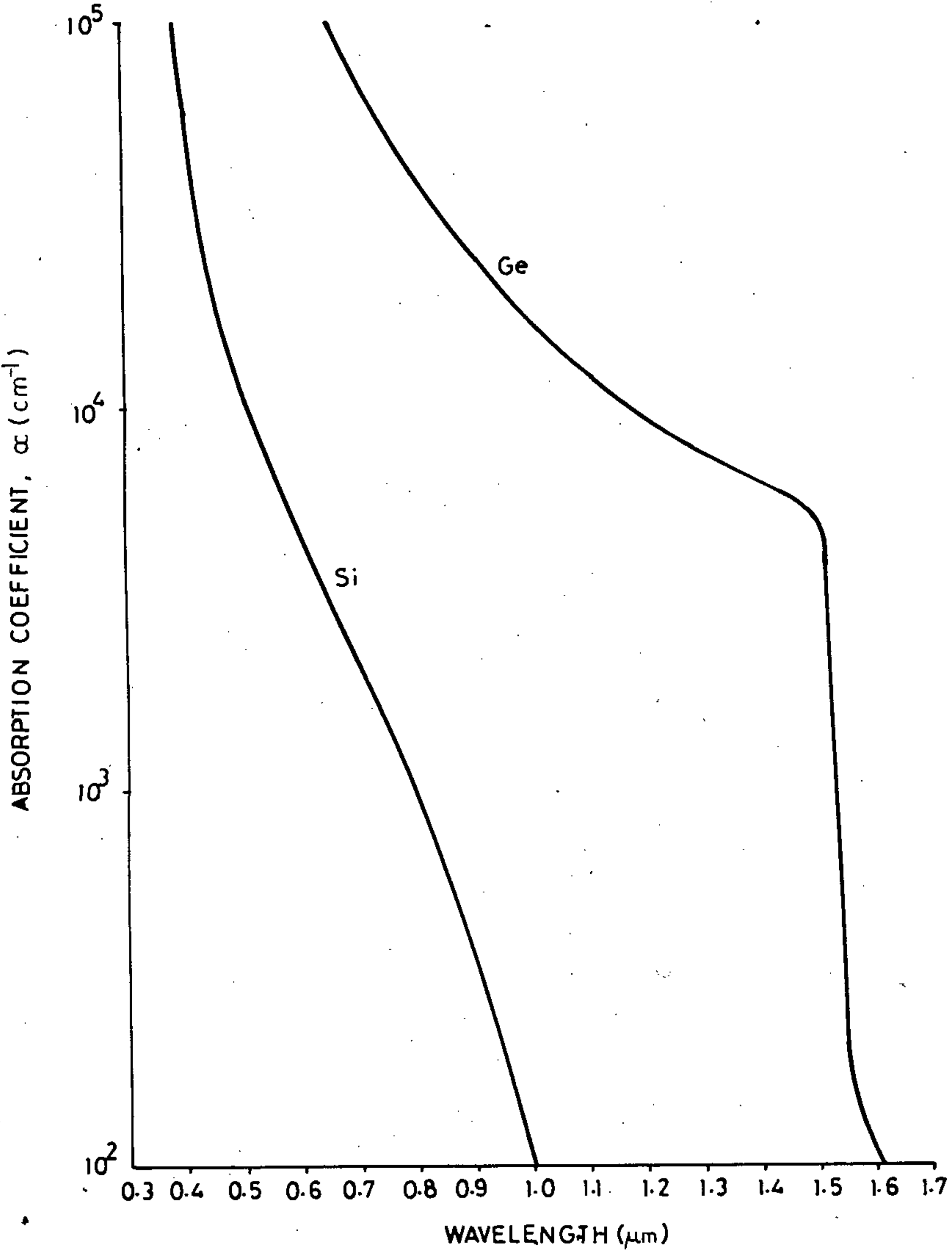


Figure - 7.3 Absorption coefficient Vs. wavelength for Ge and Si at 300°K

Table 7.1 : Physical constants [38,79,81]

Symbol	Short Description	Value
g	electric charge	1.602×10^{-19} coulomb
c	velocity of light in vacuum	2.998×10^{10} cm/s
h	Planck's constant	6.625×10^{-34} Joule-s
k	Boltzman's constant	1.380×10^{-23} Joule/k
A	diode quality constant (a dimensionless constant)	3

Table 7.2: Selected properties of silicon (at 300°K) [38,79-81,84,89,90]

Symbol	Short description	Value
E_g	Energy gap	1.1 eV or $1.1 \times 1.602 \times 10^{-19}$ Joule
λav	average wave between .3 to 2.3 microns	6000 A 6000×10^{-8} cm
R(λav)	reflection coefficent or monochromatic reflectively at wave length av	0.313
α (λav)	absorption coefficient	4.5×10^{-3} cm^{-1}
L	thickness of the cell	500 μm = 0.05 cm
R_s	series resistance	0.7 ohm
A	Area of solar cell	(2 cm x 1 cm) = 2 cm^2

7.3.2 Equivalent Capacity Generation Considering it as a Bivariate Function

The values of solar insolations (obtained from the charts) and the corresponding temperatures, table BP-1, in appendix - B, are utilized in model equations (7.3) through (7.15) to compute the values of cell current, I_C, cell voltage, V_C. The corresponding equivalent electrical power generation (EQGEN) is also computed using equation (7.1). For each set of insolation and temperature the values of I_C and V_C are computed through trial and error approach. In this approach, the value of ξ (error function or criteria of convergence) is considered to be 5×10^{-5}. The radiation (cal/cm^2/min), temperature (^{o}C) and computed values of cell voltage (volts), cell current (amps), and EQGEN (watts) are given in table BP-2 in appendix-B. Note that the maximum power output from a solar cell is 0.0198 watt.

The distribution of EQGENs is obtained by assuming that each sample of insolation and corresponding temperature is equally probable. The equal value impulses are added and also the values of impulses are rounded off. The distribution of EQGENs is depicted in figure 7.4.

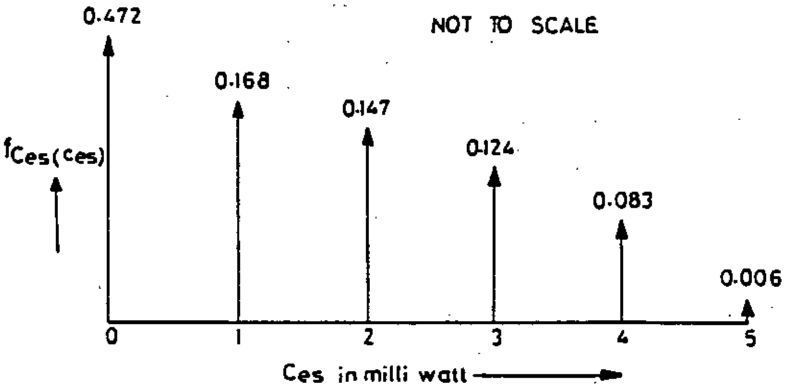


Figure - 7.4 PDF of equivalent electrical generation of a silicon solar cell considering bivariate function.

7.3.3 Equivalent Capacity Generation Considering it as a Univariate Function

To justify the consideration of the output of a solar cell as a function of temperature and insolation, the equivalent capacity generation is also computed assuming the output as independent of temperature.

A constant temperature of 34.5^{0}C is considered. All other pertinent data are taken from tables 7.1 and 7.2 solar radiation data from table BP.1 in Appendix-B is considered. The computed cell current, I_C, cell voltage, V_C, and the EQGEN are given in table BP.3 in appendix. B.

Proceeding in the similar vein of section 7.3.1 the PDF of equivalent capacity generation is developed from table BP.3 in appendix - B and this is depicted in figure 7.5.

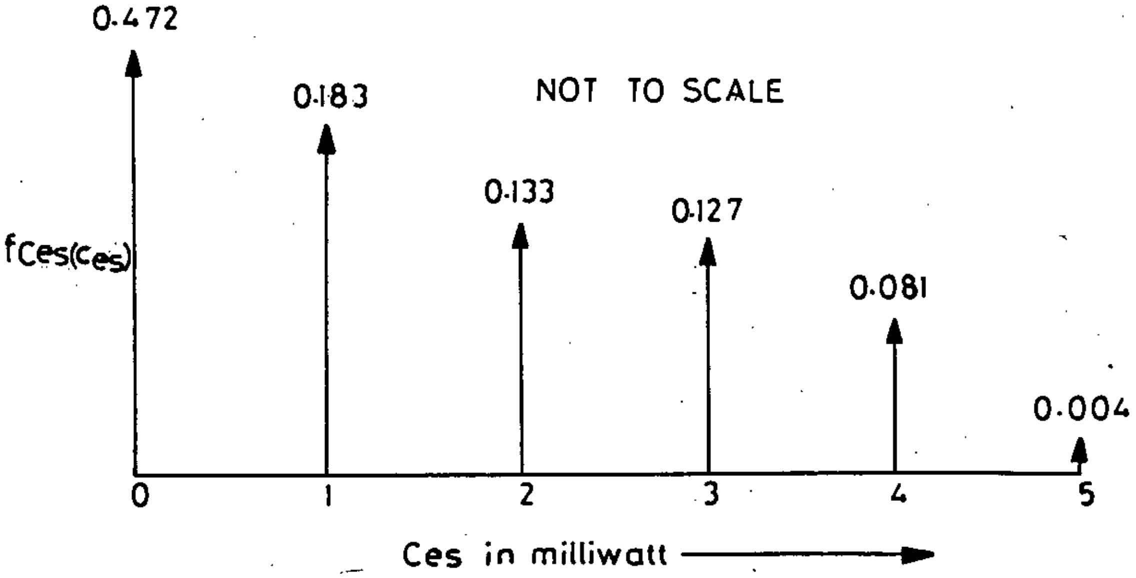


Figure - 7.5 PDF of equivalent electrical generation of a silicon solar cell considering univariate function

7.3.4 Multistate model of a PVG

Photovoltaic solar cells are very reliable. However, in reality, there is no device which is 100% reliable. Therefore, consider the FOR of a solar cell as 0.001. The realistic data may be lower than this assumed value.

To take the FOR of a solar cell into consideration the binary distribution of a solar cell, shown in figure 7.6 is convolved with the distribution of EQGEN of figure 7.4. The resultant distribution of the solar cell is depicted in figure 7.7.

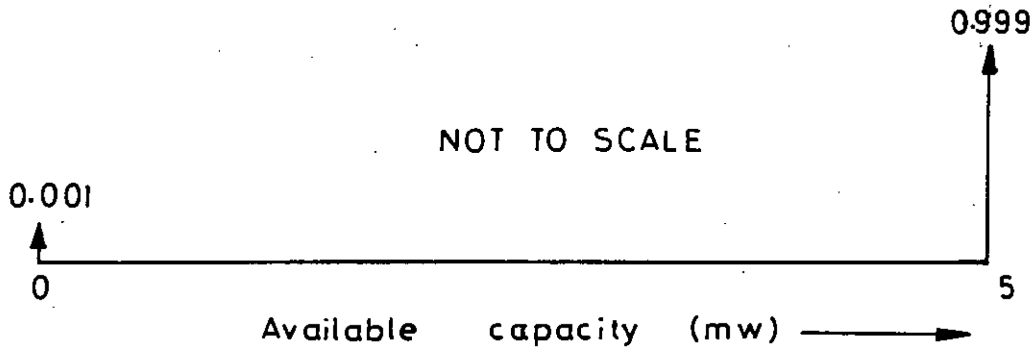


Figure - 7.6 The binary model of a solar cell.

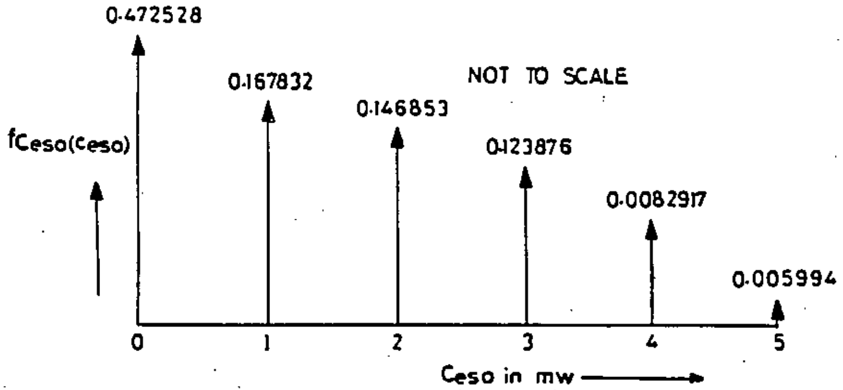


Figure - 7.7 Available solar cell output

Now, if one compares the distributions of EQGEN in figure 7.7 with the distribution of a solar cell in figure 7.4 it would be clear that the probabilities values are almost same. Moreover, to find the distribution of a panel of a unit which consists of 1 million solar cells, 1 million times convolution would be required. This definitely involves a huge computational requirements. Therefore, a solar cell with zero FOR is considered in this study.

Now, the distribution of a panel of 1 million solar cells is obtained by appropriately modifying the values of the random variables (EQGEN) of figure 7.4. That is, the values of the random variables are multiplied by 1 million. The resulting distribution is depicted in figure 7.8. Note that the maximum avaiable capacity from the solar panel is 5 kW. The PDF of the corresponding capacity on outage is depicted in figure 7.9. Figures 7.10 and 7.11 depict the PDFs of equivalent capacity

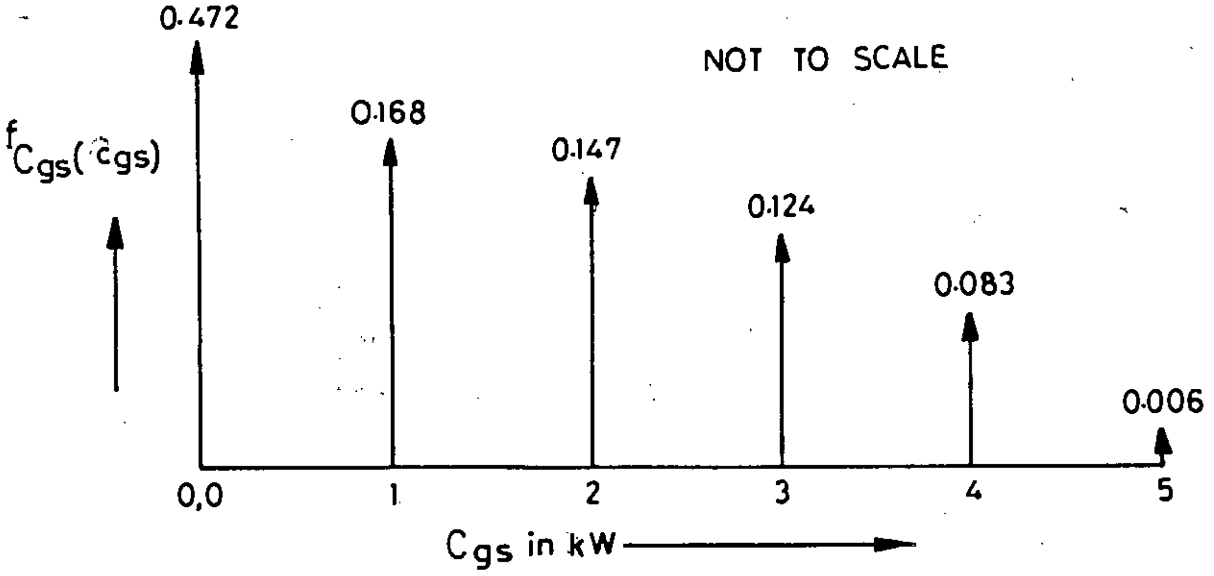


Figure - 7.8 PDF of equivalent generation (of 1 million solar cells) considering bivariate function.

generation and the capacity of a solar panel on outage respectively considering the output of a cell as a function of univariate function.

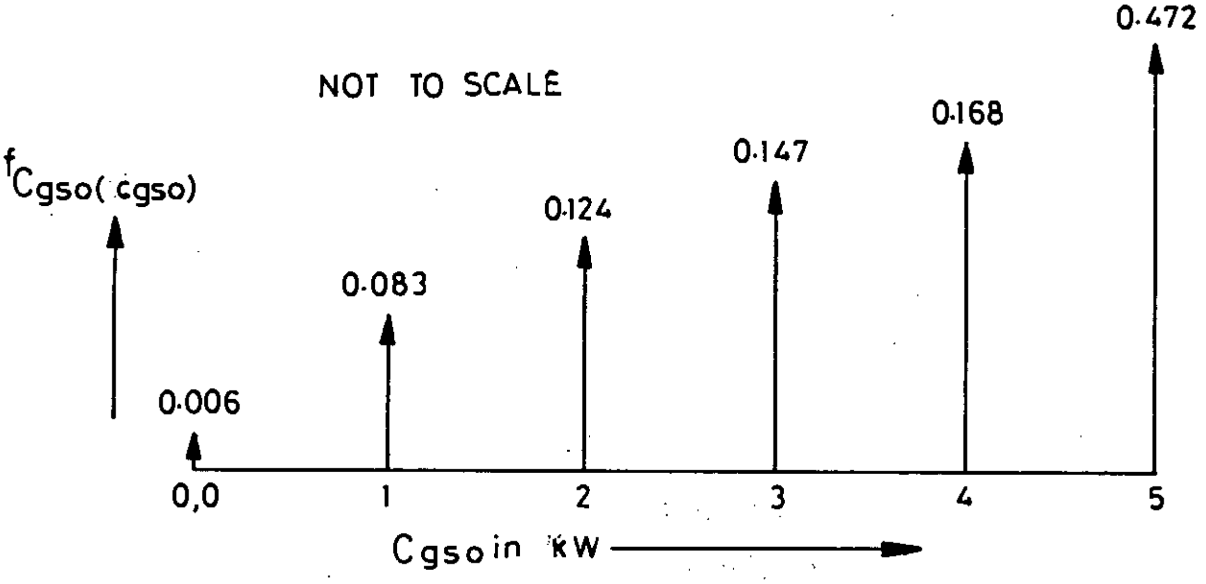


Figure - 7.9 PDF of capacity output on outage (of 1 million solar cells) considering bivariate function.

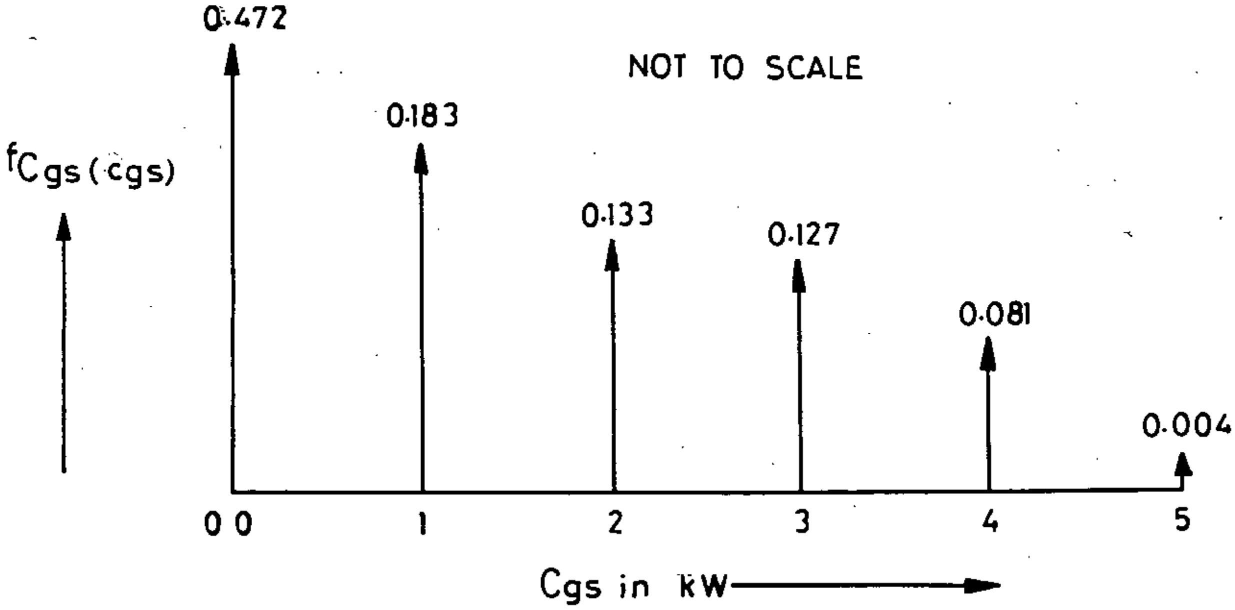


Figure - 7.10 PDF of equivalent electrical generation of (1 million solar cells) considering univariate function.

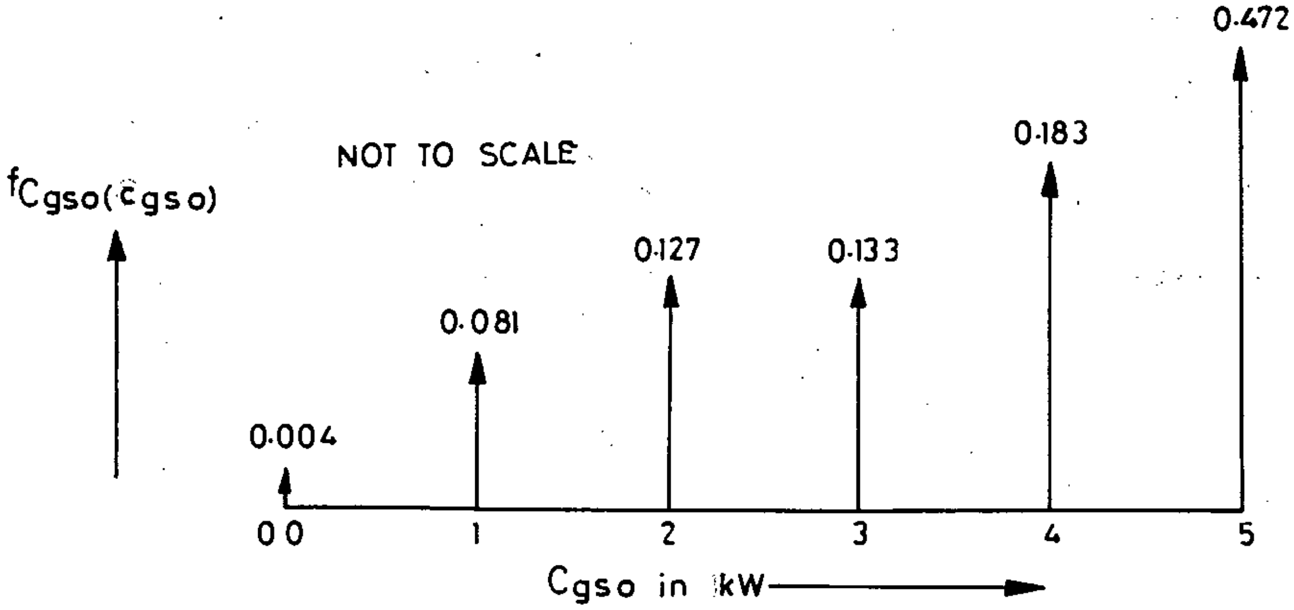


Figure - 7.11 PDF of capacity output on outage (of 1 million solar cells) considering univariate function.

7.3.5 Numerical Results

The two generation models developed in sections 7.3.1-3 are applied separately to evaluate expected energy generation, expected energy not served and LOLP considering different number of solar panels from 50 upto 1550 as the only source of energy to the system. The results obtained, using the model of a PVG developed from a bivariate function, are given in table 7.3 and table 7.4 presents the results obtained using the model of a PVG developed from an univariate function. Note that in this case also the load data used are those evaluated in chapter 3.

The first column of table 7.3 as well as of table 7.4 represents the total generating capacities of the system. The corresponding number of solar panels are shown in the second column of both these tables.

Table 7.3: Numerical results corresponding to the model developed from bivariate function

INSTALLED CAPACITY (kW)	NO.OF SOLAR PANELS	E ENERGY GENERATION (MWh)	E(ENS) (MWh)	LOLP (%)
250	50	11.457	188.043	100.000
500	100	22.830	176.670	99.512
750	150	33.628	165.872	96.868
1000	200	43.108	159.392	92.287
1250	250	51.546	147.954	90.274
1500	300	58.083	141.417	82.598
1750	350	63.941	135.559	78.132
2000	400	68.839	130.661	76.414
2250	450	73.255	126.245	74.781
2500	500	77.428	122.072	74.612
2750	550	80.439	119.061	66.407
3000	600	83.099	116.401	65.053
3250	650	85.526	113.974	64.623
3500	700	87.670	111.830	62.266
3700	750	89.627	109.873	61.944
4000	800	91.280	108.220	59.958
4250	850	92.794	106.706	57.639
4500	900	93.985	105.515	57.562
4750	950	95.158	104.342	57.387
5000	1000	96.323	103.177	57.387
5250	1050	97.132	102.368	53.423
5500	1100	97.860	101.640	53.040
5750	1150	98.513	100.987	52.810
6000	1200	99.093	100.407	52.043
7750	1550	101.787	97.713	50.225

Table 7.4: Numerical results corresponding to the model developed from an univariate function

INSTALLED CAPACITY (kW)	NO.OF SOLAR PANELS	E ENERGY GENERATION (MWh)	E (ENS) (MWh)	LOLP (%)
250	50	11.271	188.229	100.000
500	100	22.460	177.040	99.514
750	150	33.103	166.397	96.989
1000	200	42.443	157.057	92.385
1250	250	50.756	148.744	90.391
1500	300	57.235	142.265	83.057
1750	350	63.046	136.454	78.680
2000	400	67.914	131.586	77.051
2250	450	72.324	127.176	75.527
2500	500	76.505	122.995	75.377
2750	550	79.548	119.951	67.123
3000	600	82.245	117.255	65.806
3250	650	84.717	114.783	65.384

Table 7.4: Numerical results corresponding to the model developed from an univariate function (Continued)

INSTALLED CAPACITY (kW)	NO.OF SOLAR PANELS	E ENERGY GENERATION (MWh)	E (ENS) (MWh)	LOLP (%)
3500	700	86.901	112.599	62.901
3750	750	88.893	110.607	62.572
4000	800	90.580	108.920	60.547
4250	850	92.127	107.372	58.166
4500	900	93.350	106.150	58.097
4750	950	94.554	104.946	57.906
5000	1000	95.750	103.750	57.906
5250	1050	96.571	102.929	53.679
5500	1100	97.310	102.190	53.334
5750	1150	97.981	101.519	53.127
6000	1200	98.582	100.918	52.322
7750	1550	101.481	98.019	50.488

The LOLPs obtained for different number of solar panels using the PVG model developed from bivariate function and those obtained using the PVG model developed from the univariate function are depicted in figure 7.12 for comparison. The expected energy generation and expected energy not served obtained for different number of solar panels applying the above two different models are also compared in figures 7.13 and 7.14 respectively.

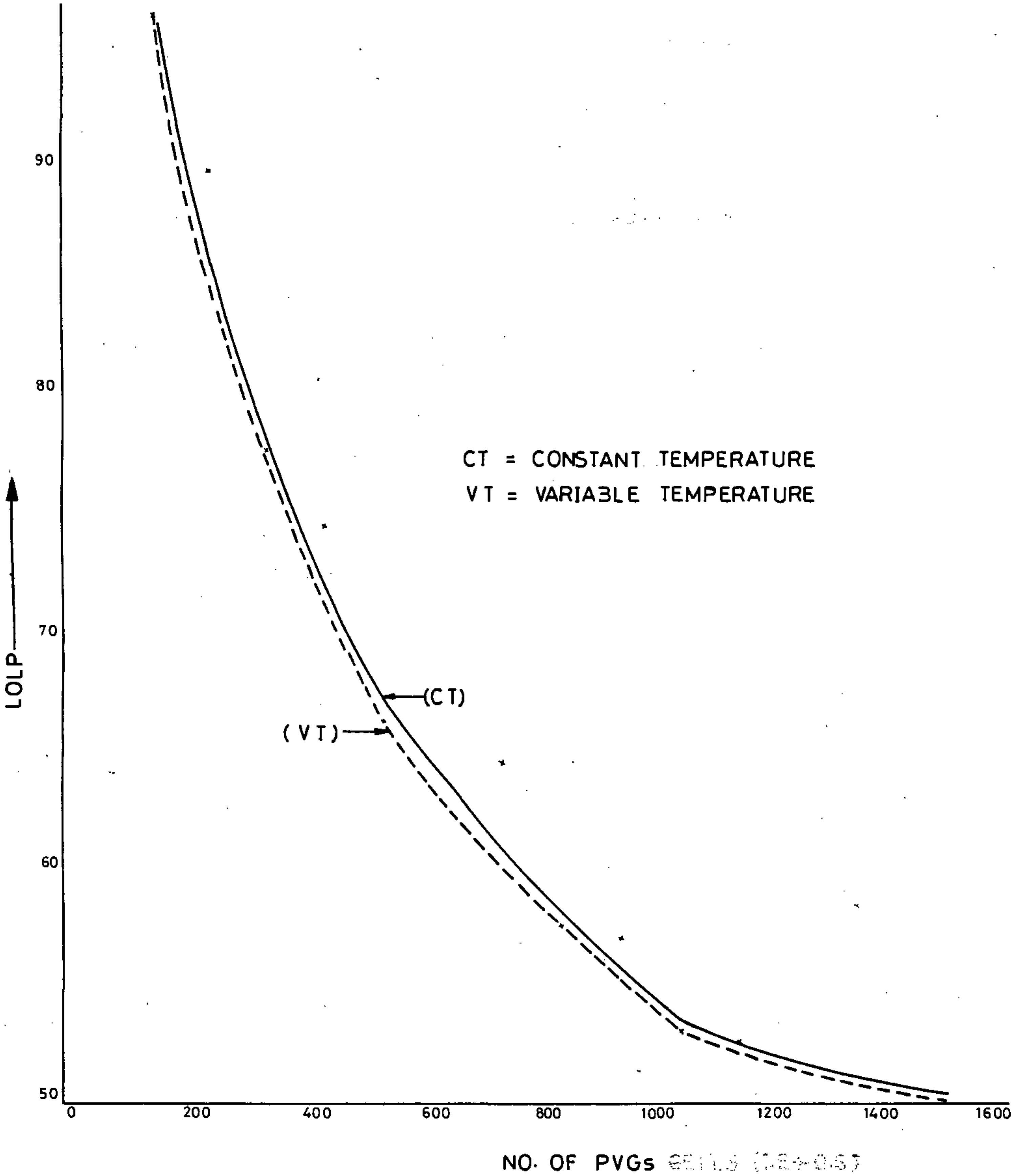


Figure - 7.12 LOLPs for different no. of PVGs.

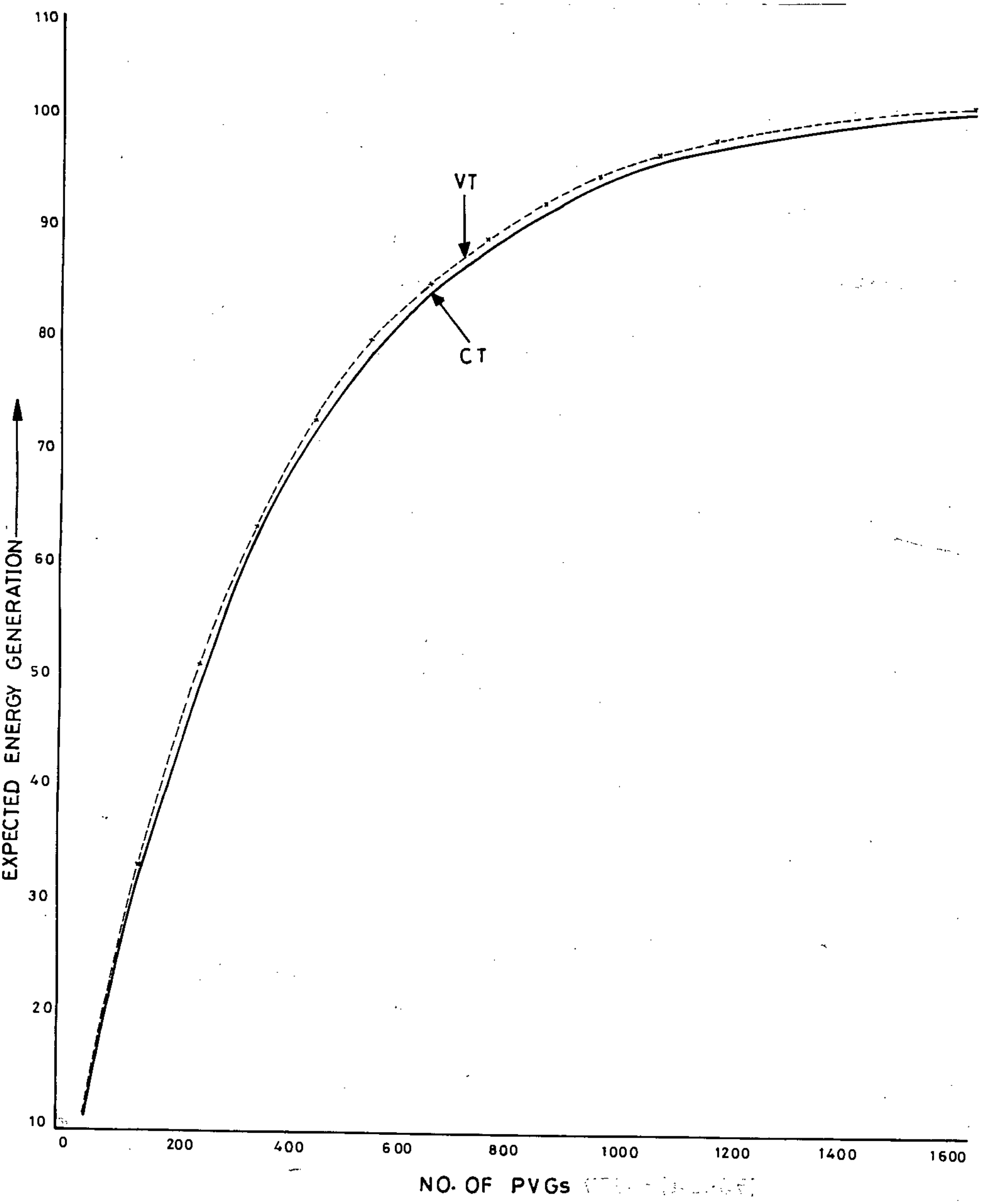


Figure - 7.13 Expected energy generation for different PVGs

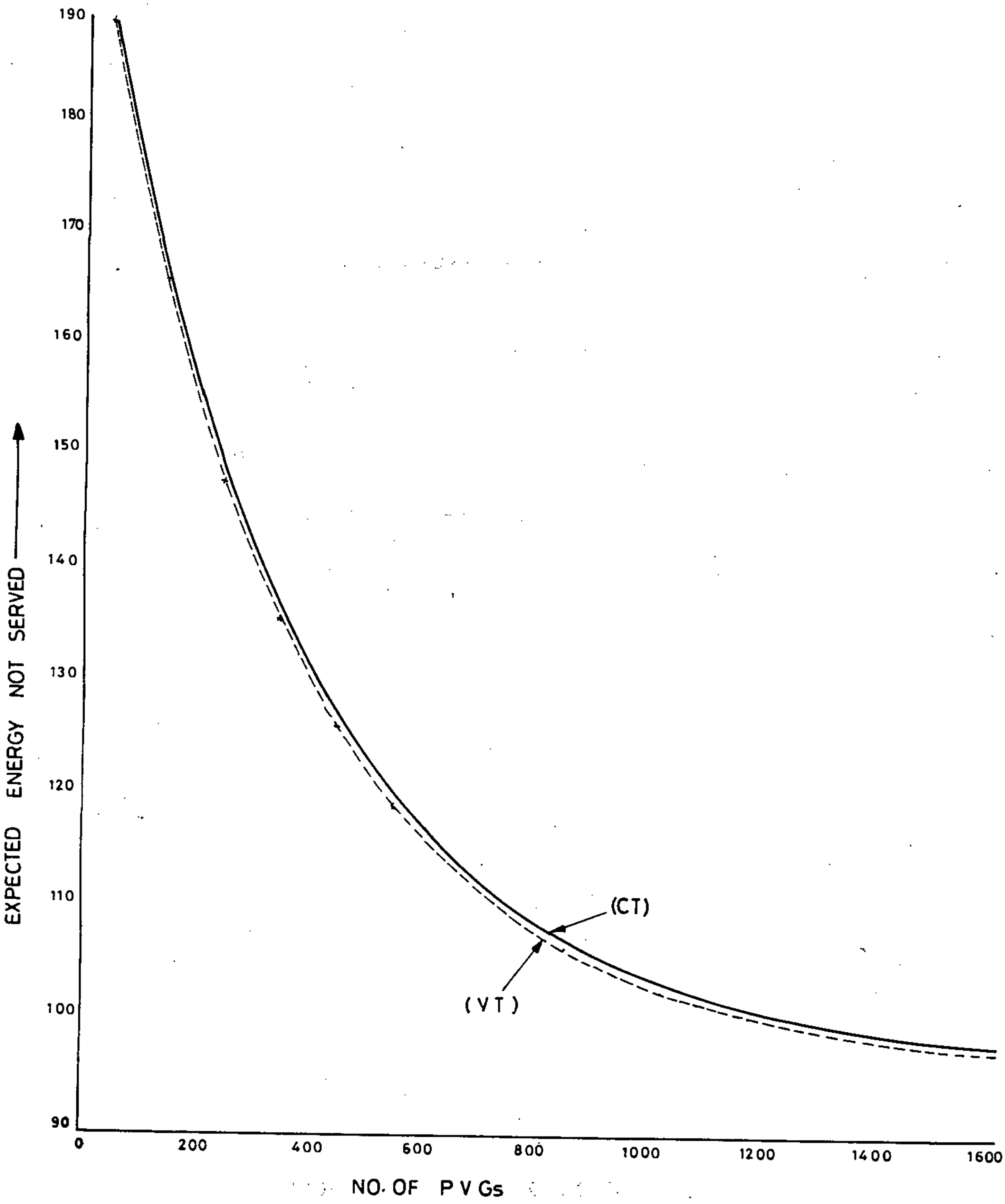


Figure-7.14 Expected energy not served for different PVGs

7.4 DISCUSSION

In what follows, the salient points observed from the numerical evaluation of the proposed PVG model are briefly described below.

The comparison between tables DP-2 and DP-3 shows that the value of equivalent electrical power generation (EQGEN) for each sample of insolation and its corresponding temperature is different. Recall that the EQGEN in table DP-2 is computed considering EQGEN as a function of insolation and temperature while the EQGEN of table DP-3 is computed considering EQGEN as independent of temperature.

Comparing the figures 7.4 and 7.5 it is observed that though the equivalent capacity generation are same, however, the probability values show significant variations. The similarity between the values of EQGENs of figures 7.4 and 7.5 occur only due to the rounding off digits. It is also observed from figures 7.8 and 7.10 or from figures 7.9 and 7.11 that the PDFs of available equivalent capacities or capacities on outage of a solar panel developed considering the output of a solar cell as a function of both temperature and insolation are significantly different from the PDFs of those developed considering the output of a solar cell as a function of insolation only.

It is clearly observed from tables 7.3 and 7.4 as well as from the figures 7.12 to 7.14 that the expected energy generation of the system increases while the LOLPs as well as the expected energy not served decrease with the increase of number of solar panels in the system. The results are expected.

In table 7.3, it is observed that the LOLPs corresponding to 950 and 1000 solar panels are same which is 57.387%. However, the expected energy genration, expected energy not served are different. Similarly, it is also observed in table 7.4 that the LOLPs corresponding to 950 panels is same as the LOLP corresponding to 1000 panels. The difference, for these two solar panels, in expected energy generation and expected energy not served is also observed in table 7.4. The reason of this similarity in LOLPs is that there is no load impluse within the range of 4750 and 5000 kW as observed from the load model of chapter 3 . However, as the installed capacity increases from 4750 kW to 5000 kW the expected energy generation increases and the expected energy not served decreases.

Tables 7.3 and 7.4 as well as the figures 7.12 to 7.14 clearly show that the results obtained using two different model of a solar cell are distinctly different.

It is observed in figure 7.12 that although the difference between the LOLPs obtained considering the output of a solar cell as a bivariate function and those obtained considering the output as a univariate function is less for lesser number of PVG panels however, this difference increases with the increase of the number of solar panels.

Similarly it is also observed from figures 7.13 and 7.14 that the difference between the results obtained using the two different PVG models increases with the increase of number of solar panels.

CHAPTER 8

THE EVALUATION OF RELIABILITY AND COSTS OF AN ISOLATED AREA WITH DIFFERENT SOURCES

8.1 INTRODUCTION

Uninterrupted supply of electricity is very much important for a modern society. To secure continuous supply of elctrical power, different areas are supplied from a grid. The interconnection even among the utilities is a common practice - now a days. However, there are many isolated areas that cannot be connected with the main electrical grid because of geographical or meteorological or economic reasons.

For an isolated area, the potential sources of energy may be:

Conventional:

i) thermal

ii) nuclear, and

iii) hydro

Unconventional:

i) wind

ii) solar photovoltaic

iii) wave, and

iv) tidal

However, wave and tidal energy have not yet proved to be matured technology. Therefore, for the target isolated area a generation mix of WTGs, PVGs and thermal (diesel) generators are considered. For obvious reasons, hydro units and nuclear units are not considered as possible source of electrical energy for the target isolated area.

This chapter presents a comprehensive comparison among the different sources of electrical energy to meet the demand of the target isolated area in terms of reliability and cost. It also presents a brief description of the data required for this study.

8.2 CASE STUDY

The proposed models of a WTG and a PVG as well as the load forecasting technique are applied to analyze the generation plan of a typical isolated area. It is located in the southern end of Bangladesh and it is an island of the Bay of Bengal. The distance of this island from the main land is more than 2 km. Because of its distance inside the sea, economically it is not possible to interconnect this island with main grid system of Bangladesh Power Development Board(BPDB). The necessary geographical data of this island are presented in chapter 3. The load data considered for the analysis of the generation plan are those obtained for this island in chapter 3. Note that the base and peak demands of this area are 252 and 2520 kW.

8.2.1 Generation System

Three different types of generating sources are considered to meet the demand of the typical island. Among these three types, two are unconventional, WTG and PVG and one is conventional, thermal (diesel) unit.

Wind turbine generator (WTG)

The model of a WTG used to evaluate the reliability and cost of the potential power system of the typical island is developed in chapter 5. The developed multistate model shown in figure 5.13 is redrawn below in figure 8.1.

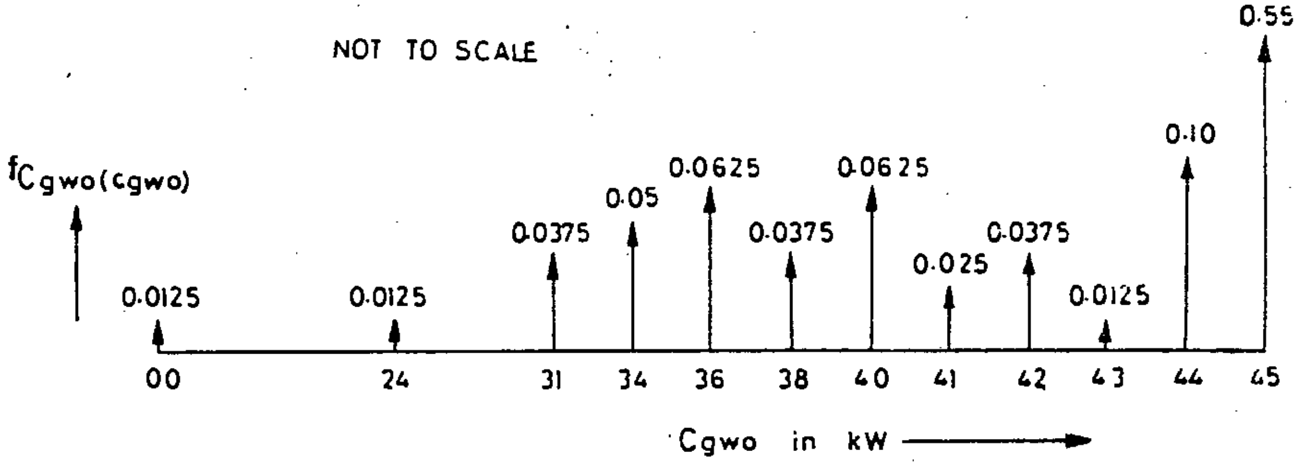


Figure - 8.1 Multistate model of a WTG

Note that the maximum possible output of this WTG is 45 kW. The WTG similar to that in chapter 5 is considered in this chapter. The general parameters of this WTG is given in table 5.1 of chapter 5. The additional features of this WTG required for the cost analysis is given in table CC-1 in appendix C. Also note that the actual cost data of all items are not available. For the purpose of sample cost analysis, data available from published literatures [19,26,74,92] and local source [93] are utilized. The annual operation and maintenance cost of a WTG is of fixed type.

Photovoltaic generator (PVG)

Like a WTG the multistate model of a PVG developed in chapter 7 is considered in this chapter. The PDF of a PVG panel of figure 7.9 is depicted in figure 8.2 again.

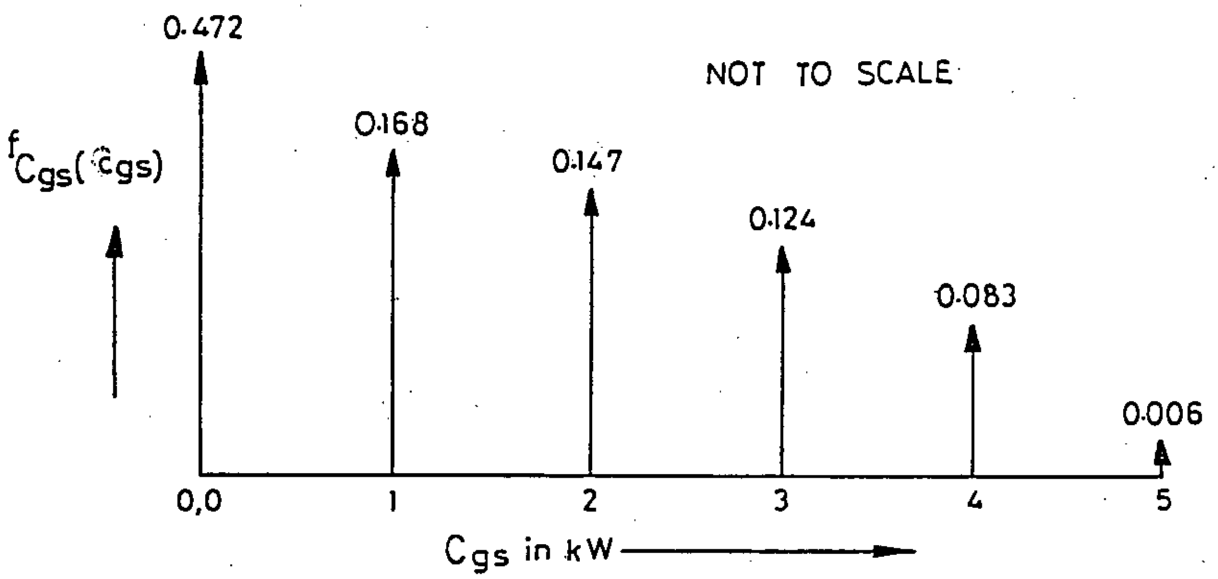


Figure - 8.2 The PDF of a PVG panel

Recall that the maximum possible output from a solar panel of 1 million solar cells is 5 kW. The parameters of a solar cell is given in tables 7.1 and 7.2 of chapter 7. The additional data required for the cost analysis is presented in table-CC.1 in appendix C. Like that of a WTG, the operation and maintenance cost of a PVG does not depend on the variation of its output power. The maintenance cost of a PVG is higher than that of a WTG because of its delicate technology. The study also assumes that the solar cell is 100% reliable. Recall that this assumption is only to reduce the computational requirements. It is considered for this research that the average life of a WTG as well as that of a PVG is 10 years.

Thermal

Thermal (diesel) generating units of two different capacities are considered in order to find out a most desirable generation mix. Some relevant data of these two thermal generators are given in table 8.1.

Table 8.1 : Basic data relating to the considered thermal units [19,23,38]

Types of fuel	Capacity (kW)	FOR
Oil	100	0.04
Oil	200	0.10

The data related to cost analysis are given in table CC-1 in appendix - C. Note that the operation and maintenance costs of these two thermal units depend on the amount of energy produced and the major portion of the cost is the fuel cost. The fixed portion of this cost which arise due to wages of employees etc. is much lower compared to fuel cost.

The data of the two thermal units are obtained from the local market [93]

8.3 NUMERICAL EVALUATION

The power system of a typical island is evaluated considering each of the above three different types of units separately. That is, the system is evaluated assuming that the power system of the typical island comprises only one type of source to meet the demand. Moreover, for each type of sources different number of units are considered.

In case of a WTG, the expected energy generation, expected energy not served and LOLPs are evaluated for WTG units ranging in number from 15 upto 160,each of capacity 45 kW . That is, the system is evaluated quite a number of times varying the installed capacities of the typical island from 675 to 7200 kW. The results are tabulated in table 5.6. Similarly, the power system of the typical island is also evaluated considering PVGs as the only sources of energy to meet the demand. In this case, the installed capacities of the system are varied from 250 to 7750 kW.The results are presented in table 7.3.

Finally thermal generating units are considered as the only source of energy to meet the demand of the system. The system is evaluated assuming that the thermal units of two different capacities, 100 kW and 200 kW, with different numbers comprise the generating system. The results are presented in table 8.2. The first column of this table presents the number of units and the corresponding capacity and the second column presents the total installed capacity of the system. Table 8.2 also presents the total annual cost in the last column. The sixth column of this table presents the expected fuel cost which varies with the expected energy generation. Recall that the annual recovery cost may be computed using the formula presented in chapter 2. The formula is rewritten below.

$$CR = (P-L)\ [\{i\ (1+i)^n\}/\{(1+i)^n-1\}] + Li \qquad ...(2.19)$$

$$\text{or} \quad CR = (P-L)\ (\text{Capital Recovery factor}) + Li$$

$$\text{or} \quad CR = (P-L)\ (CRF) + Li$$

Table 8.2 : Simulation results when thermal(diesel) generators of 100 and 200 kW capacities are considered.

NO.OF UNITS AND CORRESPONDING CAPACITIES(kW)	INSTALLED CAPACITY (kW)	E ENERGY GENERATION (MWh)	E(ENS) (MWh)	LOLP (%)	ANNUAL FUEL + O & M COST ($)	TOTAL ANNUAL COST(M$)
2x100 1x200	400	70.867	128.633	97.69600	4669.54	0.017
3x100 1x200	500	88.852	110.648	97.47424	5851.10	0.022
2x100 2x200	600	101.186	98.314	78.76743	6673.68	0.024
3x100 2x200	700	115.051	84.449	70.15680	7582.81	0.029
4x100 2x200	800	126.864	72.636	61.08727	8356.48	0.034
5x100 2x200	900	137.357	62.143	53.78981	9042.88	0.038
6x100 2x200	1000	146.930	52.570	50.73341	9669.86	0.043
5x100 3x200	1100	152.732	46.768	37.13704	10059.13	0.044
6x100 3x200	1200	158.961	40.539	31.87383	10465.14	0.049
5x100 4x200	1300	163.306	36.194	27.65216	10758.06	0.500
6X100 4X200	1400	168.056	31.444	24.58955	11066.29	0.056
5X100 5x200	1500	171.807	27.693	23.55242	11319.99	0.056
6x100 5x200	1600	175.706	23.794	20.57811	11571.96	0.060
7x100 5x200	1700	179.314	20.186	18.15459	11805.22	0.064
8x100 5x200	1800	182.428	17.072	16.23323	12006.45	0.068

Table 8.2:Simulation results when thermal(diesel)generators of 100 and 200 kW capacities are considered(Continued)

NO.OF UNITS AND CORRESPONDING CAPACITIES(kW)	INSTALLED CAPACITY (kW)	E ENERGY GENERATION (MWh)	E(ENS) (MWh)	LOLP (%)	ANNUAL FUEL + O & M COST ($)	TOTAL ANNUAL COST(M$)
7x100 6x200	1900	184.934	14.564	15.10859	12176.80	0.069
8x100 6x200	2000	187.639	11.861	14.32001	12350.92	0.073
7x100 7x200	2100	189.730	9.770	12.84244	12493.70	0.074
10x100 6x200	2200	192.295	7.205	11.19279	12650.93	0.081
9x100 7x200	2300	193.910	5.590	9.61605	12761.35	0.082
10x100 7x200	2400	195.567	3.933	8.06166	12867.23	0.086
9x100 8x200	2500	196.756	2.744	7.11746	12949.52	0.092
10x100 8x200	2600	197.774	1.726	4.76237	13013.12	0.092
11x100 8x200	2700	198.522	0.978	3.67782	13059.86	0.096
12x100 8x200	2800	198.969	0.531	2.02782	13087.28	0.099
11x100 9x200	2900	199.187	0.313	1.46478	13103.83	0.100

Thermal units of only 100 kW capacity type is also considered as stand-alone source. For this type of unit this system is again evaluated varying the installed capacities of the system from 400 upto 1600 kW. The results are presented in table 8.3.

The cost of the generating system is also evaluated for WTGs as well as PVGs as stand alone source.The calculation procedure of the total annual costs for WTG, PVG and thermal generators are shown in appendix - C. Note that, in the total annual cost calculation, the depreciation is not considered. The fuel costs for WTGs and PVGs are considered to be zero in the cost analysis.

The simulation results of the total annual costs corresponding to WTGs & PVGs are presented in tables 8.4 and 8.5 respectively.

The results obtained considering three different types of generating units as stand-alone sources are compared in the figures from 8.3 to 8.7 . Figure 8.3 presents the expected energy generation for different installed capacities of the system. The variation of reliability indices; expected energy not served and LOLP with the installed capacities are compared in figures 8.4 and 8.5 respectively.

Table 8.3 : Simulation results when thermal(diesel) generators of only 100 kW capacity are considered

NO.OF UNITS	INSTALLED CAPACITY (kW)	E ENERGY GENERATION (MWh)	E(ENS) (MWh)	LOLP (%)	ANNUAL FUEL+ O & M COST($)	ANNUAL RECOVARY COST(M$)
4	400	73.144	126.356	97.49325	4805.54	0.020
5	500	91.103	108.397	97.40477	5985.49	0.025
6	600	105.515	93.985	77.82757	6932.32	0.030
7	700	118.610	80.890	65.69419	7792.69	0.035
8	800	130.107	69.393	58.44581	8548.04	0.040
10	1000	149.435	50.065	49.22414	9817.86	0.049
11	1100	156.076	43.424	35.27374	10254.22	0.053
12	1200	161.427	38.073	27.07471	10605.73	0.057
13	1300	166.118	33.382	24.58226	10913.92	0.062
14	1400	170.466	29.034	22.88177	11199.61	0.066
15	1500	174.604	24.896	22.13667	11471.50	0.070
16	1600	178.296	21.204	19.75877	11714.03	0.074

Table 8.4: Total annual cost of WTGs

INSTALLED CAPACITY(kW)	NO.OF WTGs.	TOTAL ANNUAL COST(M$)
675	15	0.083
900	20	0.111
1125	25	0.138
1350	30	0.166
1575	35	0.194
1800	40	0.221
2025	45	0.249
2250	50	0.277
2520	56	0.310
2700	60	0.332
2925	65	0.360
3150	70	0.387
3375	75	0.415
3600	80	0.443
3825	85	0.470
4050	90	0.498
4275	95	0.526
4500	100	0.533
5040	112	0.620
5625	125	0.692
7200	160	0.886

Table 8.5: Total annual cost for PVGs

INSTALLED CAPACITY (kW)	NO.OF SOLAR PANELS	TOTAL ANNUAL COST(M$)
250	50	0.311
500	100	0.622
750	150	0.933
1000	200	1.243
1250	250	1.554
1500	300	1.865
1750	350	2.176
2000	400	2.487
2250	450	2.798
2500	500	3.109
2750	550	3.419
3000	600	3.730
3250	650	4.041
3500	700	4.352
3750	750	4.663
4000	800	4.974
4250	850	5.285
4500	900	5.595
4750	950	5.906
5000	1000	6.217

Table 8.5: Total annual cost for PVGs (Continued)

INSTALLED CAPACITY (kW)	NO.OF SOLAR PANELS	TOTAL ANNUAL COST(M$)
5250	1050	6.528
5500	1100	6.839
5750	1150	7.150
6000	1200	7.461
7750	1550	9.637

Figure 8.6 depicts the comparison of the total cost for the above three types of units. This figure also depicts the variation of costs with the variation of installed capacities. Figure 8.6(A) also depicts the comparison of costs for the three types of units. However, in this case a different set of data is considered: the capacity costs given in table CC-1 in appendix-C for wind and solar are decreased by 50% and those of thermal units are increased by 100%. The fuel and O & M cost of wind and solar are considered to be same while those for thermal units are increased by 300%. For all three types of units the interest rate is increased from 12% to 16%.

In order to make the decision of the inclusion of the generating units in the mix, the performance comparison among the three differrent types of units is depicted in figure 8.7. This figure shows the requirement of the total cost to achieve different levels of reliability for different types of units.

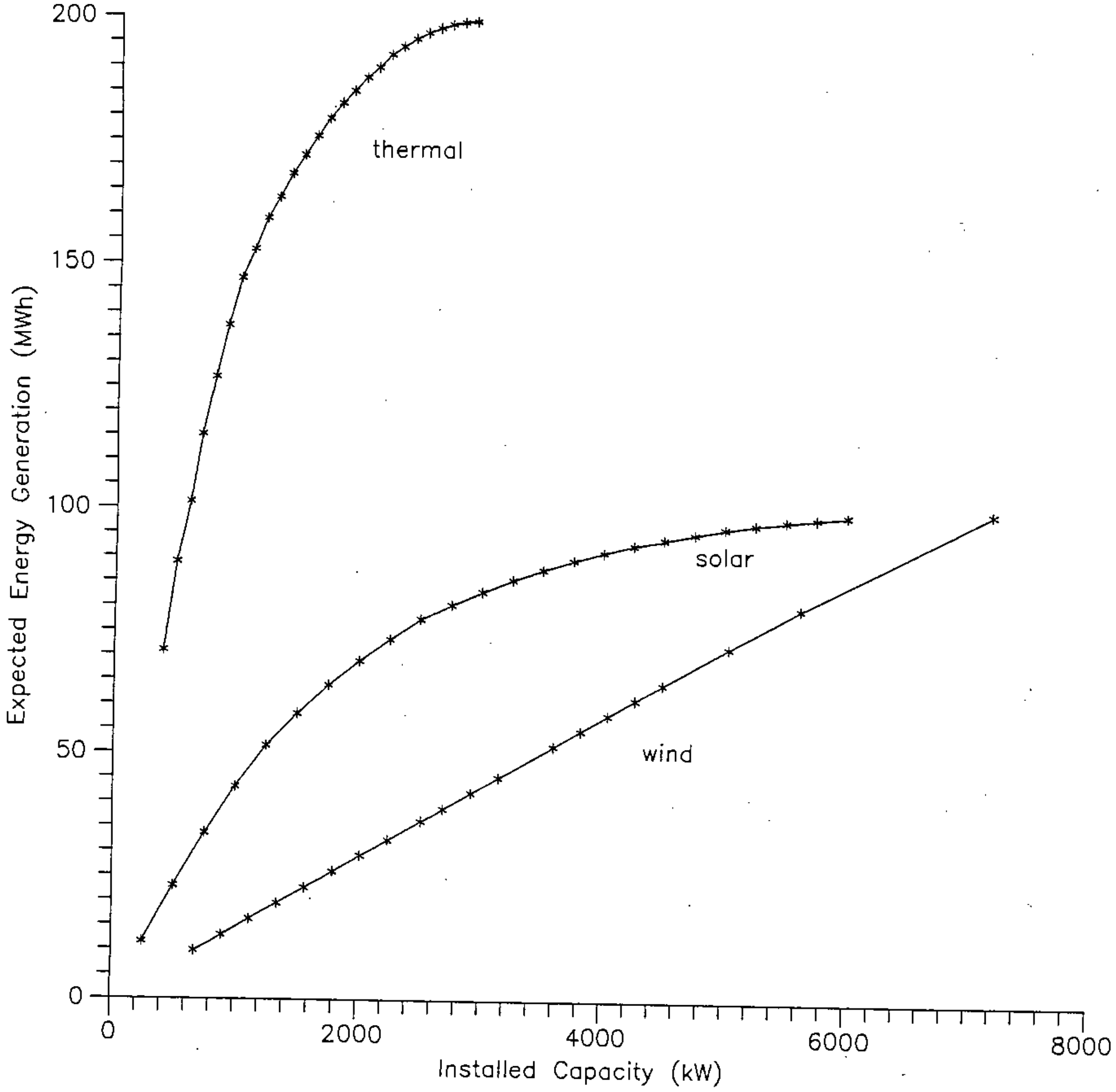


Figure - 8.3 Expected energy generation Vs. installed capacity

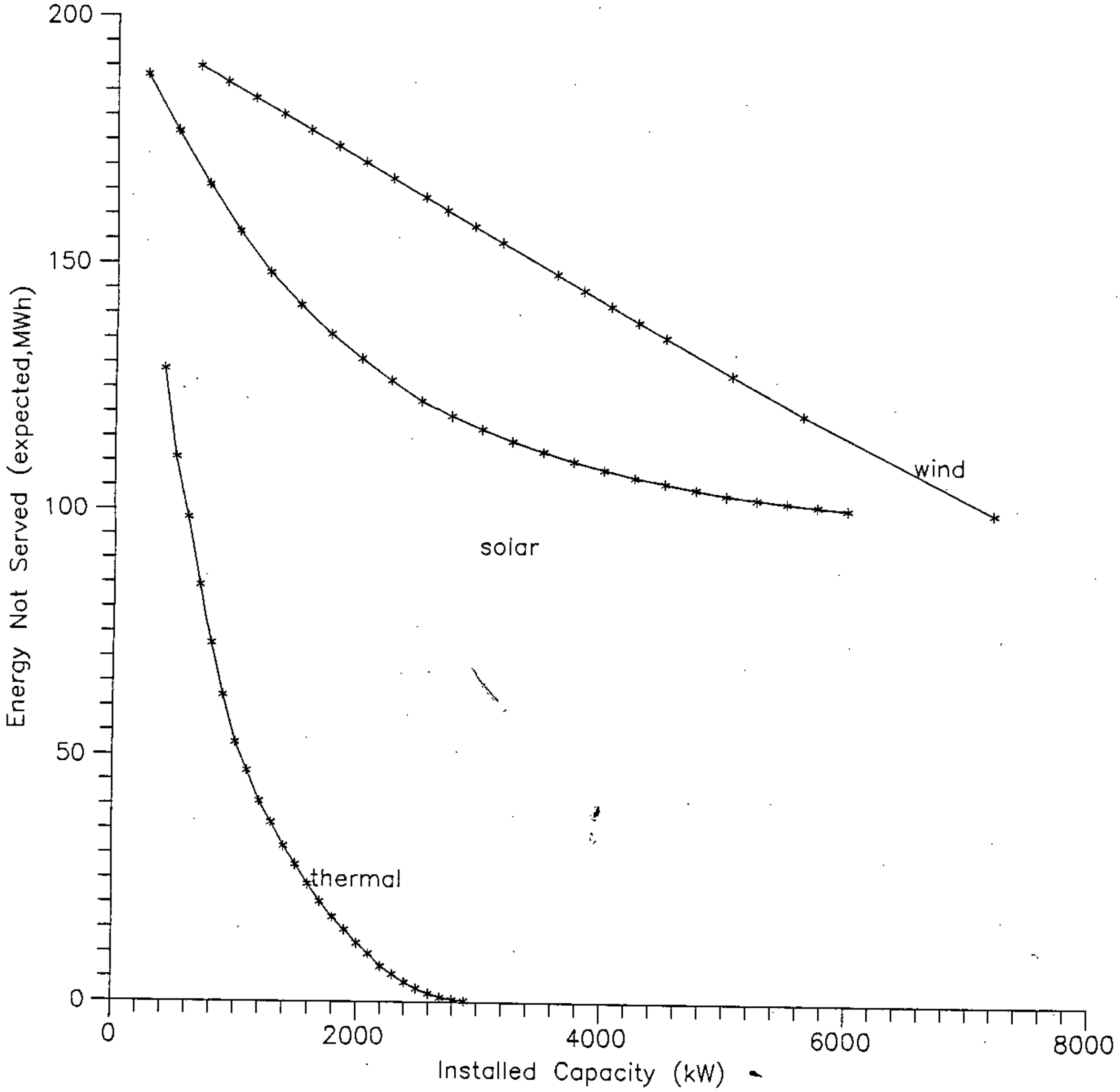


Figure - 8.4 Expected energy not served Vs. installed capacity

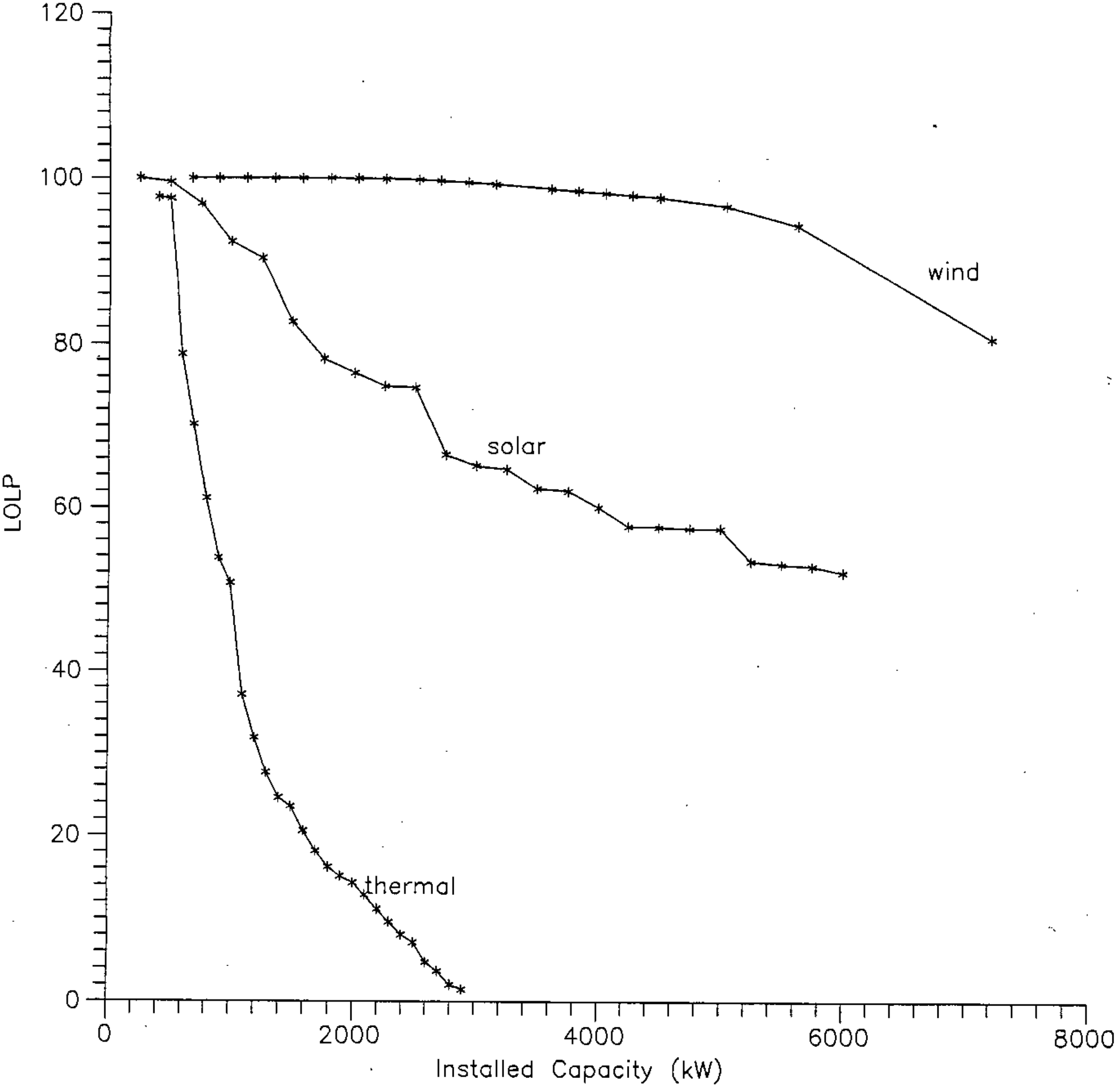


Figure - 8.5 LOLP Vs. installed capacity

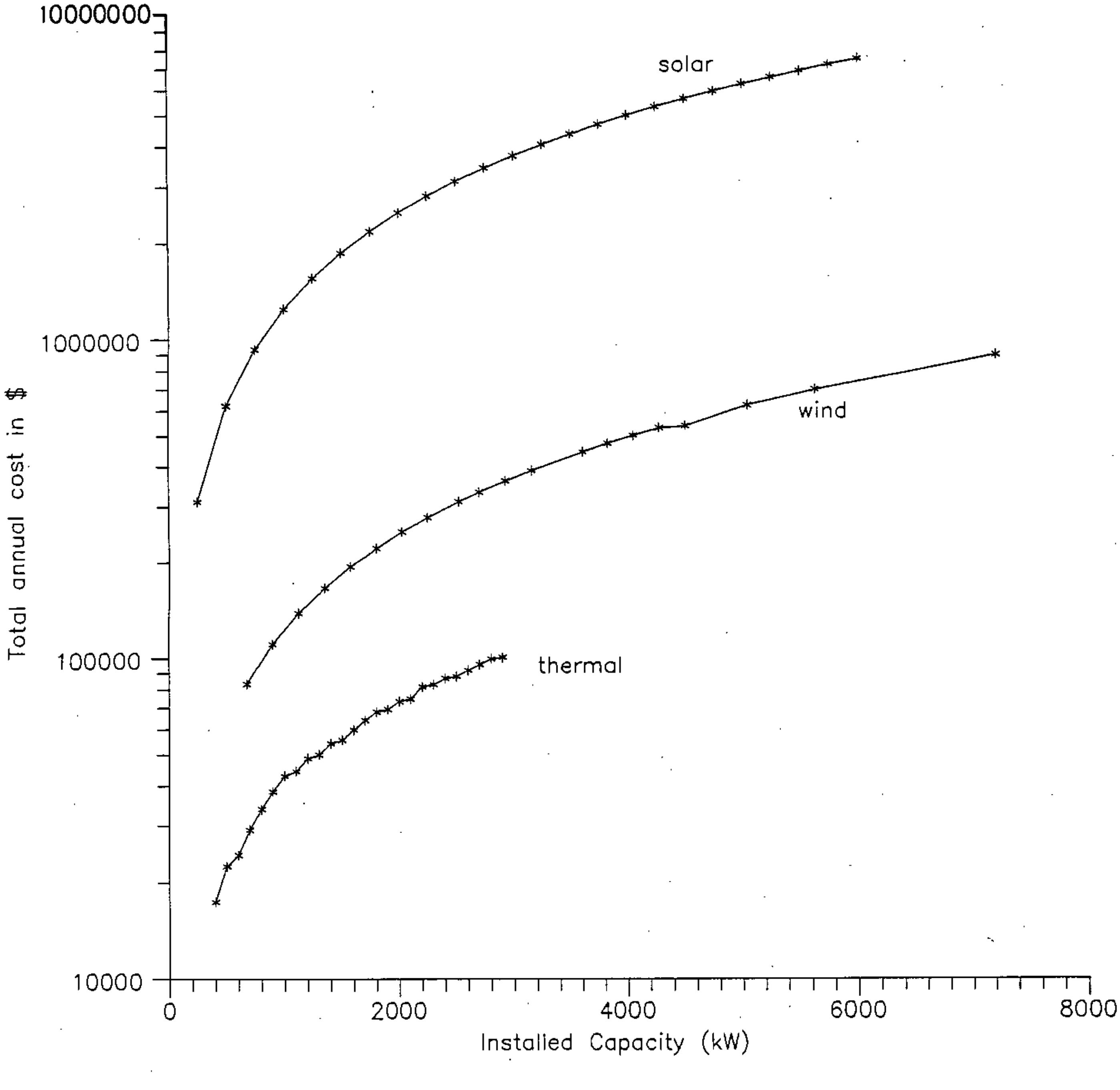


Figure - 8.6 Total annual cost Vs. installed capacity

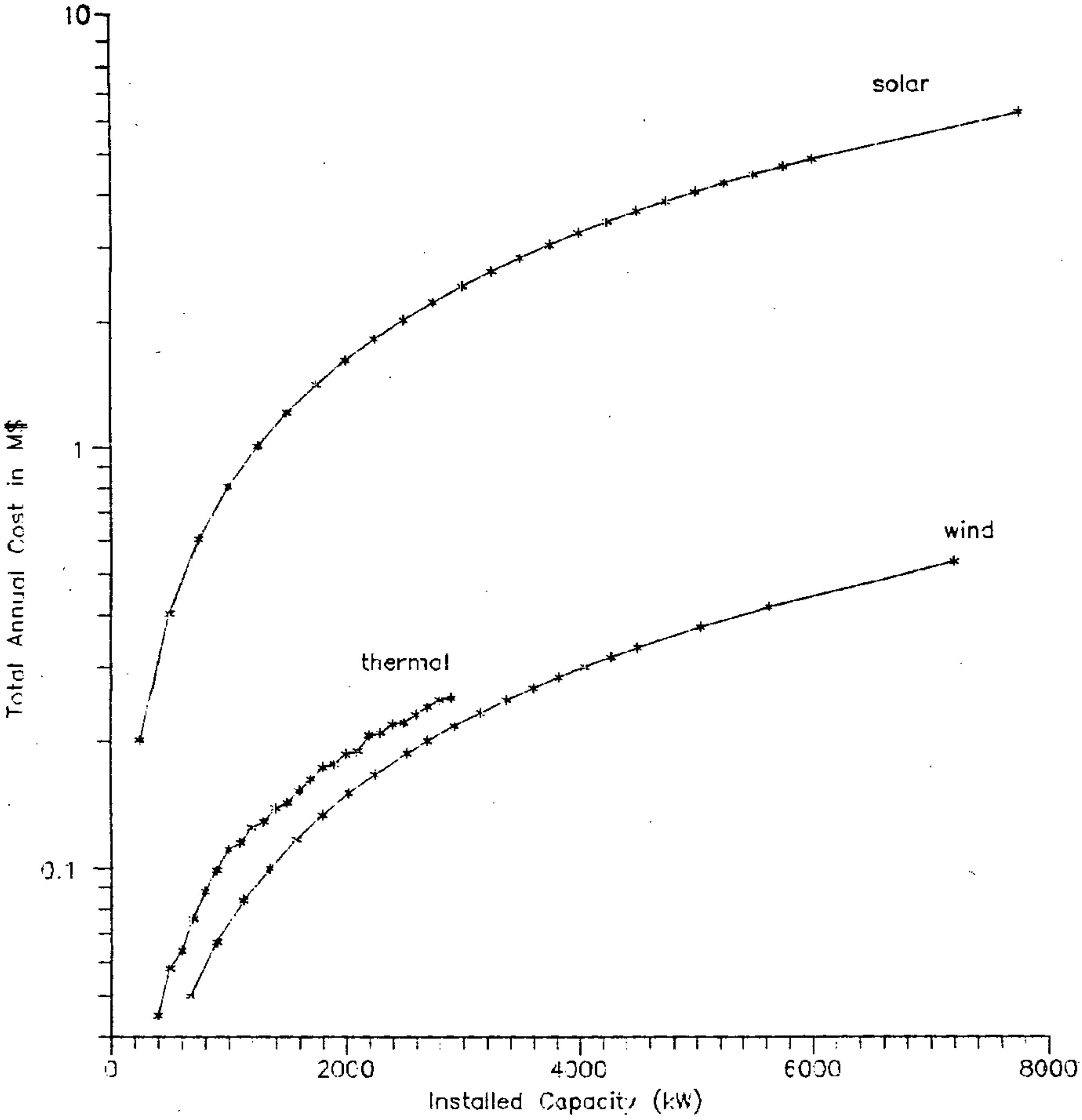
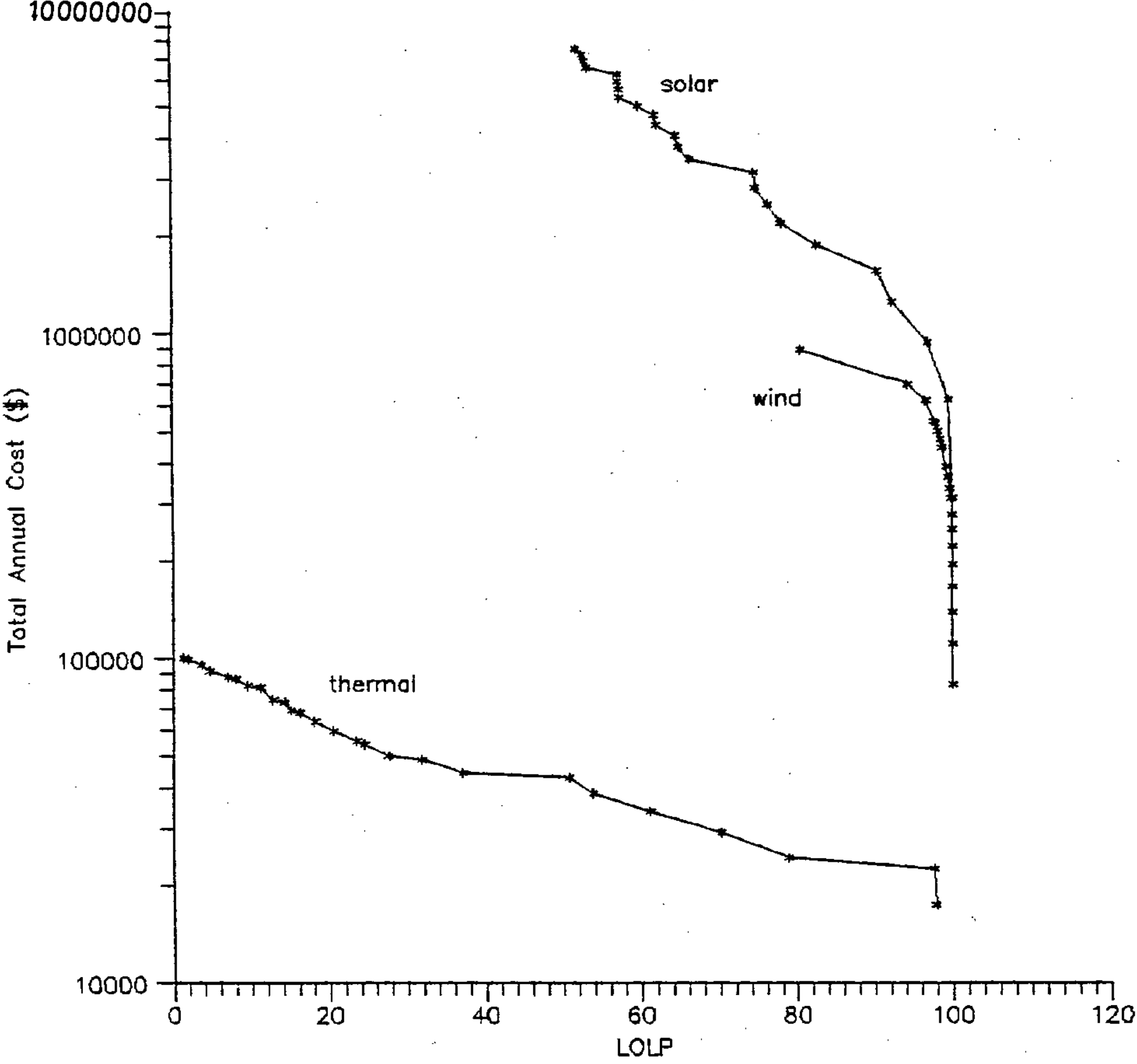


Figure- 8.6A :Total annual cost Vs. Installed Capacity



Figure— 8.7 : Total annual cost Vs. LOLP (%)

8.4 DISCUSSION

In what follows, the salient points observed from the computer simulation of different types of units are discussed.

Figure 8.5 clearly shows that the rate of improvement of the reliability of the system is very slow in case of WTGs, as stand-alone source, however, the rate is very fast in case of thermal units. In case of PVGs, the rate of reliability improvement lies between that for WTGs and the rate for thermal units. It is observed from tables 5.6, 7.3 and 8.2 that even with a reserve of 185.71%,the LOLP of the system falls to 80.50% if WTGs are installed as the source of electrical supply. However, the LOLP falls to 19.759% for 100 kW type unit (table 8.3) and to 23.794% for 100 and 200 kW types together (table 8.2) with an installed capacity of 1600 kW, equivalent to -36.50% reserve,if thermal units are the source of power supply. If an installed capacity of 1600 kW comprises of PVGs, the reliability is again very low; the LOLP is about 80% and in case of WTGs, the LOLP is about 99.99% in case of PVGs. The reason behind the poor performance of WTGs or PVGs in improving the system reliability is the low probability values of output capacities . Although the rated capacity of a WTG is 45 kW , however, the expected capacity output of a WTG is only 3.375 kW and the expected capacity of a solar panel is 1.196 kW while the rated capacity of a solar pannel is 5 kW. Note that, the output from a PVG is available during the day time only while its output is zero during the night time. Also note that, the output of a WTG is zero if the wind velocity is less than cut-in velocity or greater than cut-out velocity.

From figure 8.4, it is observed that the performances of different types of units are similar to the performances of those observed in figure 8.5. That is, the expected energies not served are very high when WTGs or PVGs are considered as the sources of power supply, while the expected energy not served of the system becomes very low when thermal units are considered as the sources of power supply. For example, at 2500 kW installed capacity the expected energies not served are 1.375%, 81.7% and 61.64% of the total energy demand for thermal units, WTG and PVG units respectively.

From figure 8.3, it is clearly observed that the expected energies generated by the different types of units are different for a given installed capacity. The thermal units generate maximum while the WTGs generate minimum energy.

The thermal units are quite superior to WTG or to PVG regarding the cost also. This is clearly observed from figures 8.6 and 8.7. For example, for an installed capacity of 2000 kW the thermal units require only 0.073 (M$) to meet the total annual cost while WTG and PVGs require about 0.24 (M$) and 2.487 (M$) respectively. However, figure 8.6(A) shows that the superiority of the thermal unit among the considered three types of units does not hold if the capacity cost as well as the cost of fuel and O & M cost of thermal units increase with the gradual exhaustion of fuel and those of WTG and PVG decrease with the more familiarization of the technology.

The differences in cost for different types are very much distinct from figure 8.7. The total annual cost increases very rapidly for slight improvement of the reliability of the system when WTG, or PVGs are considered. The curve related to thermal units lies with the abscissa for the variation of LOLP from 97.696% to 0.313%.

The comparison of different types of unit clearly reveals that the addition of thermal units at any level of installed capacity provides better improvement of the system reliability as well as involves lower additional cost compared to the addition of either WTGs or PVGs. For example, at an installed capacity of 1500 kW comprising of thermal units the system LOLP and the total annual cost are 23.552% and 0.056 M$ respectively. Now an addition of 500 kW thermal units increases the annual cost by 30.36% and decreases the LOLP by 39.19%. However,if 500 kW of WTG are added the annual cost increases by about 98.21% (with respect to thermal unit cost) and the LOLP decreases only by 0.04% and the addition of 500 kW of PVGs the total annual cost increases by about 1111% (with respect to thermal unit cost) and the LOLP decreases only by 6.184%. Therefore, the thermal units installation in the system to meet the demand is the most desirable solution for the considered isolated area from the cost as well as reliability point of view.

CHAPTER 9

CONCLUSION AND RECOMMENDATION

9.1 CONCLUSION

Electrical energy and the economic development of a society are interlinked and the quality of life achieved in a community or country can be assessed from the amount of energy it consumes.

In a modern society, uninterrupted electric power supply is desirable. To ensure the uninterrupted power supply, usually the electric networks are interconnected to form a grid. However, there are areas, which may not be incorporated within a grid due to technical or economic reasons. This makes the generation plan of an isolated area different from that of an area which is a part of a grid and in a generation plan, the appropriate models of load and generating sources are the basic requirements.

Therefore, the objectives of this research have been to develop:

i) a load forecasting technique appropriate for an isolated area,

ii) an appropriate probabilistic model of a WTG considering the output of the WTG as a function of both temperature and wind velocity,

iii) a suitable probabilistic model of a PVG considering the output of the PVG as a function of both temperature and insolation, and

iv) to apply the developed load forecasting technique and the models of a WTG and a PVG to a typical isolated area.

The first objective of this research has been achieved by presenting a load forecasting technique of an isolated area where either the electric power supply as a source of energy has not started yet or the history of load development is not available . The technique is based on the concept of the development of a comparative factor and consists of the following steps: a) identification of the load dependent variables; b) evaluation of the weighting factor for each load deciding variable from the data of different known electrified areas; c) selection of a suitable area in which the load deciding variables are similar to those of the typical isolated area and whose hourly load data are known ; d) evaluation of the average loads of the selected area and the typical isolated area to estimate the comparative factor. Utilizing this comparative factor the load of the typical isolated area is derived from the load of the selected area.

The second and third objectives of this research have been achieved by developing models of a WTG as well as that of a PVG. The basic input to the model of a WTG is the bivariate distribution of wind velocity and temperature and the input to the model of a PVG is the bivariate distribution of solar insolation and temperature. The models are based on the concept of multistate representation of a generating unit.

The fourth objective of the research has been achieved by applying the load forecasting technique and the models of a WTG and a PVG to a typical isolated area.

In the cost analysis , two sets of data are utilized; one set is based on published literatures and local data and the other one represents a hypothetical situation . The studies show that the results are sensitive to case studies.

9.2 RECOMMENDATION FOR FURTHER RESEARCH

The sensitivity study of the proposed load forecasting technique may be performed by incorporating additional prospective load growth depended variables.

The accuracy of the proposed load forecasting technique may be compared with the conventional one.

Only one type of WTGs and PVGs are considered here, different WTGs and PVGs of different make may be considered to verify the applicability of the proposed models.

A study may be conducted to find out the break even point in which WTGs and PVGs are comparable, in terms of reliability and cost, with the conventional generating units.

A study may be carried out to evaluate the optimal generation mix of an isolated area by considering all possible sources of energy.

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APPENDIX - A

REPRESENTIVE WIND VELOCITY AND TEMPERATURE DATA

TABLE-AW.1 : THREE HOURLY WIND VELOCITY(IN KNOTS)

DATE TIME	00UTC	03UTC	06UTC	09UTC	12UTC	15UTC	18UTC	21UTC
JUNE 1	00	00	00	00	04	06	06	08
JUNE 2	00	00	04	04	04	04	04	03
JUNE 3	02	00	07	08	03	03	04	04
JUNE 4	05	06	05	06	05	04	06	06
JUNE 5	04	06	06	04	04	06	03	03
JUNE 6	04	06	08	06	06	03	03	02
JUNE 7	00	04	03	04	04	00	00	00
JUNE 8	00	00	03	02	02	02	02	02
JUNE 9	02	00	03	02	02	03	03	03
JUNE 10	02	02	03	04	04	02	02	01
JUNE 11	02	02	04	03	06	05	09	10
JUNE 12	10	12	10	13	13	10	08	09
JUNE 13	07	06	03	14	16	11	19	13
JUNE 14	11	12	12	13	14	10	24	11
JUNE 15	12	14	00	08	08	04	04	05
JUNE 16	05	04	06	05	03	04	04	04
JUNE 17	04	03	05	03	03	03	03	03
JUNE 18	03	02	04	03	04	03	04	06
JUNE 19	08	10	08	09	14	13	14	14
JUNE 20	12	14	08	12	11	08	08	09
JUNE 21	09	08	08	08	05	05	04	03
JUNE 22	03	04	03	06	03	03	03	03
JUNE 23	03	04	04	04	03	04	03	03
JUNE 24	04	04	04	04	04	03	03	03
JUNE 25	03	03	03	04	04	04	03	03
JUNE 26	03	03	02	05	05	06	05	05
JUNE 27	05	04	05	08	08	07	05	06
JUNE 28	06	05	07	08	03	06	06	06
JUNE 29	04	07	03	03	03	03	03	03
JUNE 30	07	06	07	10	04	03	03	03
JULY 1	03	05	07	10	09	04	04	04
JULY 2	04	05	06	04	02	05	06	05
JULY 3	04	05	07	04	03	04	04	04
JULY 4	03	03	03	02	02	03	03	03
JULY 5	03	03	05	06	02	03	03	03
JULY 6	03	03	03	02	02	02	02	02
JULY 7	02	02	02	02	02	02	02	02
JULY 8	03	03	03	02	02	02	02	02
JULY 9	00	04	03	06	04	05	05	03
JULY 10	04	02	03	03	05	04	04	04
JULY 11	04	04	06	05	03	04	03	03
JULY 12	03	03	02	03	02	02	03	03
JULY 13	04	04	05	06	07	07	06	06
JULY 14	07	02	04	05	03	00	00	00

TABLE-AW.1 : THREE HOURLY WIND VELOCITY(IN KNOTS)(Continued)

DATE TIME	00UTC	03UTC	06UTC	09UTC	12UTC	15UTC	18UTC	21UTC
JULY 15	00	02	02	04	00	00	06	06
JULY 16	02	06	04	06	04	04	04	04
JULY 17	04	04	04	06	02	06	06	04
JULY 18	04	06	02	02	04	04	06	06
JULY 19	00	04	02	02	00	02	04	04
JULY 20	02	03	06	04	04	06	04	04
JULY 21	00	03	02	02	06	04	12	15
JULY 22	06	06	08	12	10	06	16	14
JULY 23	10	08	08	07	12	08	08	08
JULY 24	09	09	05	08	03	05	03	04
JULY 25	00	06	04	05	05	06	05	06
JULY 26	08	08	05	10	04	05	06	05
JULY 27	04	04	13	12	15	14	13	11
JULY 28	14	14	08	18	21	14	12	12
JULY 29	13	14	12	12	04	06	06	06
JULY 30	10	08	08	02	02	02	02	02
JULY 31	02	03	06	02	02	03	03	03
AUG. 1	07	06	07	12	06	04	03	02
AUG. 2	02	02	04	02	08	10	10	12
AUG. 3	08	12	08	08	06	08	10	10
AUG. 4	06	06	06	12	10	08	08	08
AUG. 5	04	06	06	08	08	08	10	10
AUG. 6	06	06	04	06	06	06	08	06
AUG. 7	03	06	04	08	06	04	10	10
AUG. 8	07	06	08	15	12	08	08	08
AUG. 9	06	03	03	04	04	04	10	06
AUG.10	00	04	05	04	05	04	05	04
AUG.11	03	07	13	13	13	12	10	11
AUG.12	13	11	11	16	09	06	05	04
AUG.13	05	05	07	07	05	07	07	07
AUG.14	05	07	05	09	05	07	07	03
AUG.15	04	05	02	03	04	03	04	03
AUG.16	03	05	05	05	03	04	03	03
AUG.17	05	06	05	05	08	05	03	03
AUG.18	03	04	04	05	05	03	03	03
AUG.19	03	02	02	02	03	02	02	02
AUG.20	03	03	02	02	02	02	02	02
AUG.21	02	03	03	02	02	02	02	02
AUG.22	02	02	02	03	03	03	00	00
AUG.23	00	06	06	06	08	12	10	08
AUG.24	03	06	06	10	10	08	06	10
AUG.25	03	03	06	06	06	04	06	06
AUG.26	03	04	04	06	06	06	06	04
AUG.27	00	04	06	06	04	04	04	08
AUG.28	04	04	04	04	04	06	06	04
AUG.29	04	03	03	03	03	03	02	03
AUG.30	02	07	08	11	14	12	12	11
AUG.31	06	06	05	08	10	06	04	03

TABLE - AW.2 : THREE HOURLY DRY-BULB TEMPERATURE (IN DEGREE CELSIUS)

DATE	00UTC	03UTC	06UTC	09UTC	12UTC	15UTC	18UTC	21UTC
JUNE 1	27.5	31.0	32.7	33.2	31.5	30.5	29.4	28.2
JUNE 2	27.6	31.0	32.0	31.5	30.5	30.0	28.8	28.2
JUNE 3	27.5	27.5	31.0	31.5	29.8	29.0	28.5	28.0
JUNE 4	26.4	30.0	31.8	31.5	28.8	28.2	28.0	27.8
JUNE 5	27.5	27.8	28.5	29.8	29.5	29.0	28.0	27.2
JUNE 6	26.8	30.0	31.5	31.0	30.0	28.8	27.8	26.2
JUNE 7	27.0	31.0	31.5	31.7	30.5	29.0	28.0	27.0
JUNE 8	27.5	30.4	31.5	32.1	30.2	29.0	28.4	27.8
JUNE 9	27.2	32.6	32.3	33.2	31.6	30.8	30.0	28.6
JUNE 10	27.8	31.6	31.5	31.8	29.5	29.0	28.6	28.2
JUNE 11	27.8	32.3	33.5	33.2	30.2	29.4	28.6	27.8
JUNE 12	27.2	30.8	31.8	29.8	28.0	27.2	26.6	26.2
JUNE 13	25.8	25.2	27.0	28.0	27.7	27.6	27.4	27.3
JUNE 14	27.1	28.5	28.6	28.3	28.2	28.0	27.7	27.4
JUNE 15	27.3	25.3	25.4	26.7	25.8	25.6	26.0	25.8
JUNE 16	25.8	27.2	28.2	28.4	27.0	26.6	26.0	25.5
JUNE 17	25.2	26.0	29.0	29.2	28.0	27.4	29.0	26.6
JUNE 18	26.0	27.8	29.0	29.0	28.5	28.0	27.4	26.2
JUNE 19	25.8	27.8	26.0	27.5	27.1	26.2	25.6	25.0
JUNE 20	24.7	26.7	26.4	27.2	27.6	27.0	26.4	25.8
JUNE 21	25.4	25.5	24.4	25.6	26.0	25.6	25.4	25.0
JUNE 22	24.8	28.5	30.5	29.7	29.0	28.0	27.2	26.6
JUNE 23	26.0	29.3	30.0	29.6	28.5	28.0	26.8	25.4
JUNE 24	25.8	28.3	29.5	29.5	28.0	27.2	28.0	25.6
JUNE 25	25.2	27.8	29.2	30.0	28.0	27.2	27.0	26.8
JUNE 26	26.6	29.0	30.0	30.4	28.7	28.0	27.4	27.0
JUNE 27	26.7	29.0	30.5	31.0	29.2	28.6	28.0	27.4
JUNE 28	27.0	29.0	29.3	30.5	28.5	28.0	27.5	26.0
JUNE 29	25.5	28.3	27.5	25.8	27.4	27.0	26.4	26.0
JUNE 30	25.6	28.0	29.4	30.6	26.2	26.2	26.0	25.8
JULY 1	25.8	27.3	29.5	27.6	28.4	27.8	27.0	26.4
JULY 2	25.5	26.5	25.5	27.0	27.1	26.6	26.2	25.8
JULY 3	25.6	27.8	27.8	27.4	26.6	26.4	26.2	25.8
JULY 4	25.5	26.7	26.0	26.8	26.3	26.0	26.4	26.2
JULY 5	26.0	28.0	29.8	30.4	28.7	28.0	27.2	26.7
JULY 6	26.0	27.7	28.8	27.0	26.6	26.0	25.6	25.4
JULY 7	25.0	25.4	26.8	25.2	25.7	25.6	25.4	25.2
JULY 8	25.0	27.4	28.2	27.5	27.7	25.5	26.0	25.5
JULY 9	26.0	29.0	30.6	31.2	29.0	28.0	27.5	27.0
JULY 10	27.1	28.5	30.0	30.4	29.0	28.2	27.3	27.0
JULY 11	26.8	29.5	31.0	31.5	30.0	28.2	27.4	26.6
JULY 12	26.0	27.6	25.6	27.4	27.0	26.6	26.3	26.0
JULY 13	25.8	27.0	30.5	30.0	28.0	26.4	25.8	25.2
JULY 14	24.8	26.7	30.0	30.3	19.0	28.0	27.2	26.8
JULY 15	26.8	28.5	31.5	31.7	30.7	29.8	29.0	28.0
JULY 16	27.5	29.6	31.5	32.2	30.0	29.5	29.0	28.5
JULY 17	27.0	29.0	31.5	32.5	29.2	29.0	28.5	28.0
JULY 18	27.4	27.7	29.7	28.4	27.0	26.8	26.5	25.7
JULY 19	25.0	27.7	30.5	30.7	30.4	29.0	28.1	27.8
JULY 20	27.0	30.2	30.7	30.2	29.4	29.0	28.1	27.0

TABLE - AW.2 : THREE HOURLY DRY-BULB TEMPERATURE (IN DEGREE CELSIUS)(Continued)

DATE	00UTC	03UTC	06UTC	09UTC	12UTC	15UTC	18UTC	21UTC
JULY 21	26.6	30.8	32.0	32.5	29.7	29.2	28.5	28.0
JULY 22	27.0	29.2	31.8	30.8	29.2	29.0	28.4	27.0
JULY 23	26.0	29.0	31.4	31.3	29.0	26.4	26.0	25.8
JULY 24	25.7	28.6	30.5	30.0	28.6	28.0	27.0	26.3
JULY 25	25.7	28.5	30.0	30.0	29.0	27.6	27.0	26.5
JULY 26	26.0	28.4	29.7	29.4	27.7	27.2	26.8	26.3
JULY 27	26.0	27.0	29.5	28.0	27.7	27.4	27.1	26.7
JULY 28	26.7	27.0	26.7	27.0	25.0	26.2	27.2	27.0
JULY 29	27.0	26.7	27.0	27.2	26.2	26.5	26.8	26.7
JULY 30	26.6	27.5	28.0	28.6	25,5	27.0	26.6	26.3
JULY 31	26.0	28.0	26.8	29.0	26.8	26.0	25.2	24.6
AUG. 1	24.2	24.8	27.0	26.2	26.0	25.8	25.6	25.5
AUG. 2	25.4	26.4	27.8	26.2	26.4	25.7	25.4	25.2
AUG. 3	25.0	26.0	27.5	29.0	27.5	27.0	26.5	26.0
AUG. 4	25.5	28.2	30.4	30.8	28.5	28.0	27.0	26.5
AUG. 5	26.2	28.8	30.0	29.5	28.0	27.0	26.8	26.5
AUG. 6	25.7	27.4	30.5	30.8	27.4	27.0	26.0	25.0
AUG. 7	24.8	27.8	30.5	30.5	28.7	28.0	27.1	26.0
AUG. 8	25.5	27.6	29.0	28.2	27.3	27.0	26.8	26.5
AUG. 9	26.2	26.2	29.6	30.2	29.0	28.0	27.4	26.2
AUG. 10	25.8	29.0	30.5	30.7	28.6	26.5	26.0	25.8
AUG. 11	25.8	27.2	30.2	29.3	29.0	27.0	26.8	26.0
AUG. 12	26.6	27.5	29.2	29.5	28.2	27.0	26.5	26.0
AUG. 13	25.7	29.0	30.4	31.0	29.0	28.8	28.5	28.0
AUG. 14	26.4	29.0	31.7	29.5	28.5	28.0	27.8	26.5
AUG. 15	25.2	25.7	26.5	28.5	27.8	26.5	26.0	25.8
AUG. 16	26.0	27.5	29.8	30.0	28.0	27.0	26.6	26.0
AUG. 17	25.6	28.7	29.8	27.8	28.5	28.0	27.4	26.2
AUG. 18	25.8	29.3	31.2	30.6	28.7	28.0	27.2	26.6
AUG. 19	25.8	27.0	27.8	27.6	27.4	27.0	26.6	26.2
AUG. 20	25.8	28.0	30.0	30.5	28.8	28.0	27.4	27.0
AUG. 21	26.5	28.0	29.7	28.2	27.8	27.2	26.9	26.2
AUG. 22	25.8	29.0	31.2	30.3	28.0	27.5	27.3	26.5
AUG. 23	26.1	29.0	31.0	30.0	28.5	27.5	27.2	26.8
AUG. 24	26.2	27.5	28.5	30.8	28.6	28.0	27.4	26.5
AUG. 25	26.0	28.8	31.0	31.7	29.0	28.5	28.0	27.4
AUG. 26	26.8	29.8	31.8	31.0	30.3	29.0	28.5	27.5
AUG. 27	26.5	27.8	29.0	31.5	28.5	28.0	27.5	27.0
AUG. 28	26.2	29.5	30.6	31.8	30.6	29,8	28,0	27,2
AUG. 29	26.5	29.4	30.9	31.4	29.6	28.4	27.8	27.2
AUG. 30	26.5	29.2	30.7	31.2	28.0	27.0	26.2	25.6
AUG. 31	25.4	26.5	27.8	28.8	27.8	27.0	26.6	26.0

APPENDIX - B

SOLAR RADIATION AND TEMPERATURE DATA AND SIMULATION RESULTS OF A SOLAR CELL

TABLE BP-1 : HOURLY SOLAR RADIATION* AND TEMPERATURE

RADIATIONS(R)* IN Cal/cm^2/min, TEMPERATURE (T) IN °K & TIME IN HOUR (HR)

HR	6	7	8	9	10	11	12	13	14	15	16	17	18	19
R	0.050	0.250	0.700	1.250	1.650	1.920	2.100	2.150	2.100	1.700	1.200	0.850	0.400	0.050
T	25.0	25.0	25.0	23.0	23.0	23.0	31.6	31.6	31.6	31.8	31.8	31.8	31.4	31.4
R	0.100	0.550	1.350	1.750	2.050	2.150	2.170	1.650	1.050	1.070	1.070	0.900	0.800	0.600
T	27.0	27.0	27.0	30.4	30.4	30.4	32.8	32.8	32.8	34.0	34.0	34.0	32.5	32.5
R	0.030	0.120	0.400	0.900	1.570	2.000	1.900	1.670	1.400	1.150	0.900	0.100		
T	25.4	26.4	26.4	29.6	29.6	29.6	32.0	32.0	32.0	33.6	33.6	33.6		
R	0.050	0.250	0.700	1.250	1.620	1.820	1.900	1.850	1.720	1.570	1.300	0.750	0.300	0.800
T	27.6	27.6	27.6	31.2	31.2	31.2	30.0	30.0	30.0	31.0	31.0	31.0	32.0	32.0
R	0.050	0.200	0.450	0.800	1.250	1.800	2.100	2.050	1.900	1.650	0.950	0.300	0.100	
T	27.0	27.0	27.0	31.0	31.0	31.0	33.6	33.6	33.6	34.5	34.5	34.5	33.0	
R	0.150	0.550	0.110	1.470	1.600	1.570	1.150	0.600	0.350	0.250	0.120	0.030		
T	29.6	29.6	29.6	32.0	32.0	32.0	33.8	33.8	33.8	28.6	28.6	28.6		
R	0.030	0.080	0.250	0.450	1.300	2.100	2.000	1.550	0.900	0.450	0.200			
T	28.4	28.4	28.4	24.4	24.4	24.4	24.8	24.8	24.8	29.0	29.0			
R	0.100	0.300	0.500	0.750	1.050	1.350	1.600	1.700	1.700	1.600	1.400	1.100	0.700	0.350
T	26.6	26.6	26.6	29.6	29.6	29.6	30.4	30.4	30.4	30.0	30.0	30.0	29.4	29.4
R	0.050	0.150	0.300	0.450	0.600	0.750	0.920	1.050	0.900	0.650	0.450	0.350	0.220	0.070
T	26.0	26.0	26.0	25.8	25.8	25.8	28.6	28.6	28.6	28.0	28.0	28.0	28.0	28.0
R	0.150	0.550	1.100	1.420	1.320	0.900	0.500	0.350	0.220	0.070				
T	26.6	26.6	26.6	28.2	28.2	28.2	29.4	29.4	29.4	27.4				
R	0.100	0.300	0.450	0.500	0.450	0.350	0.300	0.250	0.100					
T	27.6	27.6	27.6	25.0	25.0	25.0	27.0	27.0	27.0					
R	0.050	0.100	0.250	0.350	0.520	0.770	1.050	2.300	2.350	2.200	1.900	0.520	0.220	0.050
T	27.0	27.0	27.0	29.0	29.0	29.0	30.0	30.0	30.0	29.0	29.0	29.0	29.0	29.0
R	0.030	0.100	0.220	0.370	0.670	1.250	1.750	1.970	2.050	2.000	1.750	1.300	0.750	0.350
T	27.0	27.0	27.0	30.3	30.3	30.3	31.8	31.8	31.8	32.5	32.5	32.5	30.5	30.5
R	0.120	0.470	0.970	1.300	1.550	1.650	1.700	1.670	1.550	1.200	0.700	0.250	0.050	
T	27.4	27.4	27.4	30.6	30.6	30.6	31.6	31.6	31.6	32.5	32.5	32.5	31.0	
R	0.075	0.225	0.350	0.550	0.800	0.950	0.950	0.800	0.575	0.350	0.125			
T	25.6	25.6	25.6	25.0	25.0	25.0	26.0	26.0	26.0	28.6	28.6			
R	0.025	0.100	0.200	0.250	0.425	0.575	0.725	0.900	0.975	0.925	0.700	0.400	0.200	0.050
T	27.0	27.0	27.0	28.8	28.8	28.8	27.0	27.0	27.0	28.6	28.6	28.6	28.6	28.6
R		0.050	0.250	0.850	1.700	2.150	2.150	1.950	1.650	1.200	0.650	0.250		
T		27.0	27.0	30.0	30.0	30.0	30.2	30.2	30.2	31.4	31.4	31.4		
R		0.050	0.150	0.300	0.420	0.480	0.470	0.470	0.450	0.425	0.375	0.300	0.200	0.075

TABLE BP-1 : HOURLY SOLAR RADIATION* AND TEMPERATURE (Continued)

RADIATIONS(R)* IN Cal/cm^2/min, TEMPERATURE (T) IN ^{o}K & TIME IN HOUR (HR)

HR	6	7	8	9	10	11	12	13	14	15	16	17	18	19
T	27.4	27.4	29.4	29.4	29.4	32.0	32.0	32.0	32.0	32.0	32.0	30.0	30.0	
R	0.100	0.375	0.750	1.100	1.500	1.750	1.550	1.000	0.550	0.300	0.150	0.050		
T	27.0	27.0	27.0	29.4	29.4	29.4	31.0	31.0	31.0	30.6	30.6	30.6		
R	0.100	0.300	0.650	0.850	1.250	1.750	2.250	2.225	2.075	1.650	1.250	0.900	0.600	0.350
T	26.8	26.8	26.8	29.0	29.0	29.0	30.2	30.2	30.2	32.0	32.0	32.0	30.0	30.0
R	0.125	0.525	1.000	1.350	1.575	1.650	1.600	1.575	1.350	1.100	0.815	0.400	0.100	
T	27.2	27.2	27.2	29.0	29.0	29.0	30.0	30.0	30.0	32.0	32.0	32.0	31.0	
R	0.050	0.200	0.400	0.655	0.975	1.250	1.550	1.850	2.250	2.750	2.175	1.900	1.450	0.950
T	28.0	28.0	28.0	30.0	30.0	30.0	32.0	32.0	32.0	33.0	33.0	33.0	32.4	32.4
R	0.200	0.650	1.050	1.450	1.675	1.790	1.800	1.725	1.475	1.200	0.700	0.375	0.125	0.013
T	27.4	27.4	27.4	29.6	29.6	29.6	31.0	31.0	31.0	30.5	30.5	30.5	29.4	29.4
R	0.125	0.400	0.675	0.950	1.200	1.375	1.475	1.375	1.150	0.850	0.600	0.350	0.100	
T	27.8	27.8	27.8	29.6	29.6	29.6	29.0	29.0	29.0	27.6	27.6	27.6	28.8	
R	0.050	0.250	0.450	0.625	0.850	1.150	1.400	1.475	1.275	0.900	0.600	0.345	0.100	
T	27.8	27.8	27.8	28.0	28.0	28.0	29.0	29.0	29.0	30.2	30.2	30.2	29.4	
R	0.050	0.175	0.400	0.700	1.150	1.550	1.750	1.700	1.475	1.200	0.900	0.675	0.350	0.100
T	27.9	27.9	27.9	28.3	28.3	28.3	31.0	31.0	31.0	31.6	31.6	31.6	30.0	30.0
R	0.300	0.850	1.350	1.800	2.100	2.200	2.150	1.950	1.650	1.300	0.800	0.300	0.050	
T	27.8	27.8	27.8	31.0	31.0	31.0	31.5	31.5	31.5	32.0	32.0	32.0	30.4	
R	0.050	0.200	0.400	0.555	0.775	1.250	1.550	1.250	1.000	0.715	0.500	0.325	0.250	0.050
T	27.4	27.4	27.4	29.0	29.0	29.0	30.0	30.0	30.0	29.5	29.5	29.5	28.0	28.0
R	0.050	0.200	0.400	0.650	0.950	1.200	1.350	1.375	1.275	1.100	0.750	0.450	0.250	
T	26.0	26.0	26.0	27.4	27.4	27.4	30.0	30.0	30.0	30.0	30.0	30.0	29.0	
R	0.150	0.500	0.800	1.000	1.100	1.150	1.175	1.075	1.025	0.925	0.725	0.500	0.300	0.100
T	26.4	26.4	26.4	29.4	29.4	29.4	30.0	30.0	30.0	28.0	28.0	28.0	28.4	28.4
R	0.050	0.300	0.650	1.000	1.400	1.700	1.850	1.825	1.625	1.350	1.000	0.650	0.400	0.200
T	27.4	27.4	27.4	29.4	29.4	29.4	31.2	31.2	31.2	31.0	31.0	31.0	30.0	30.0
R	0.100	0.350	0.800	1.550	1.700	2.000	2.100	2.000	1.750	1.400	0.950	0.450	0.100	
T	27.6	27.6	27.6	29.4	29.4	29.4	28.0	28.0	28.0	31.0	31.0	31.0	30.0	
R	0.125	0.375	0.650	0.950	1.250	1.500	1.750	1.700	1.800	1.600	1.250	0.800	0.450	0.200
T	27.8	27.8	27.8	28.8	28.8	28.8	29.0	29.0	29.0	30.0	30.0	30.0	29.4	29.4
R	0.050	0.225	0.475	0.800	1.150	1.500	1.825	2.000	1.975	1.875	1.600	1.200	0.700	0.300
T	27.8	27.8	27.8	30.0	30.0	30.0	31.0	31.0	31.0	31.6	31.6	31.6	31.0	31.0
R	0.050	0.200	0.400	0.750	1.550	2.100	2.000	1.700	1.300	0.950	0.650	0.300	0.050	
T	27.6	27.6	27.6	28.0	28.0	28.0	29.6	29.6	29.6	29.0	29.0	29.0	29.5	
R	0.045	0.175	0.350	0.500	0.700	0.925	1.225	1.600	1.800	1.650	1.250	0.650	0.275	
T	27.2	27.2	27.2	28.6	28.6	28.6	27.0	27.0	27.0	30.0	30.0	30.0	28.0	
R	0.050	0.150	0.400	1.300	2.050	2.050	1.800	1.350	0.950	0.650	0.300	0.050		
T	26.0	26.0	26.0	27.6	27.6	27.6	31.0	31.0	31.0	31.0	31.0	31.0		

TABLE BP-1 : HOURLY SOLAR RADIATION* AND TEMPERATURE (Continued)

RADIATIONS(R)* IN Cal/cm^2/min, TEMPERATURE (T) IN ^{o}K & TIME IN HOUR (HR)

HR	6	7	8	9	10	11	12	13	14	15	16	17	18	19
R	0.050	0.200	0.425	0.675	0.900	1.300	1.900	2.100	1.775	1.425	1.200	0.950	0.650	0.250
T	27.0	27.0	27.0	29.8	29.8	29.8	30.0	30.0	30.0	30.2	30.2	30.2	30.0	30.0
R	0.100	0.450	1.200	1.650	1.550	1.375	1.125	0.825	0.525	0.250	0.050			
T	26.5	26.5	26.5	26.8	26.8	26.8	30.0	30.0	30.0	29.6	29.6			
R	0.750	0.250	0.400	0.525	0.600	0.650	0.625	0.550	0.450	0.250	0.050			
T	26.6	26.6	26.8	26.8	26.8	27.8	27.8	27.8	27.0	27.0	27.0			
R	0.050	0.200	0.450	0.800	1.350	1.700	1.100	0.300	0.050					
T	26.8	26.8	26.8	28.4	28.4	28.4	30.6	30.6	30.6					
R	0.050	0.200	0.550	0.925	1.215	1.350	1.225	1.000	0.750	0.400	0.100			
T	26.2	26.2	26.2	26.8	26.8	26.8	29.2	29.2	29.2	29.4	29.4			
R	0.050	0.150	0.350	0.650	1.400	1.950	1.500	0.925	0.650	0.400	0.150			
T	26.8	26.8	26.8	28.4	28.4	28.4	29.8	29.8	29.8	28.2	28.2			
R	0.025	0.075	0.175	0.475	1.100	1.450	1.250	1.000	0.800	0.600	0.400	0.150		
T	26.0	26.0	26.0	27.4	27.4	27.4	29.0	29.0	29.0	31.0	31.0	31.0		
R		0.150	0.500	0.800	1.000	1.200	1.400	1.550	1.550	1.400	1.150	0.800	0.450	0.150
T		27.4	27.4	29.4	29.4	29.4	31.0	31.0	31.0	32.0	32.0	32.0	30.2	30.2
R		0.150	1.550	1.050	1.450	1.700	1.800	1.750	1.600	1.250	0.750	0.350	0.100	
T		27.0	27.0	29.8	29.8	29.8	28.0	28.0	28.0	30.4	30.4	30.4	28.8	
R		0.100	0.450	0.950	1.400	1.800	2.000	1.950	1.800	1.550	1.150	0.700	0.250	0.050
T		26.4	26.4	29.6	29.6	29.6	30.0	30.0	30.0	30.2	30.2	30.2	29.6	29.6
R		0.125	0.400	0.725	1.050	1.450	1.800	1.800	1.600	1.350	1.000	0.600	0.250	
T		27.0	27.0	29.6	29.6	29.6	28.4	28.4	28.4	31.6	31.6	31.6	28.6	
R		0.100	0.350	0.750	1.200	1.450	1.525	1.450	1.200	0.900	0.700	0.500	0.250	0.050
T		27.4	27.4	27.4	27.4	27.4	27.4	27.0	27.0	27.0	26.8	26.8	26.8	27.8
R	0.100	0.350	0.600	0.800	1.050	1.300	1.400	1.350	1.200	0.800	0.400	0.150		
T	26.4	26.4	26.4	28.6	28.6	28.6	30.0	30.0	30.0	30.6	30.6	30.6		
R	0.200	0.650	1.150	1.550	1.715	1.700	1.500	1.150	0.900	0.700	0.450	0.150		
T	27.0	27.0	27.0	29.6	29.6	29.6	31.6	31.6	31.6	30.2	30.2	30.2		
R		0.100	0.350	0.650	0.875	1.075	1.275	1.350	1.350	1.150	0.850	0.550	0.250	
T		27.0	27.0	29.0	29.0	29.0	30.2	30.2	30.2	30.5	30.5	30.5	29.2	
R	0.150	0.450	0.700	0.925	1.225	1.550	1.750	1.650	1.100	0.750	0.600	0.250	0.050	
T	27.0	27.0	27.0	29.0	29.0	29.0	31.0	31.0	31.0	31.6	31.6	31.6	30.0	
R	0.100	0.400	0.850	1.300	1.650	1.900	2.025	2.025	1.850	1.150	0.500	0.200		
T	27.6	27.6	30.2	30.2	30.2	31.4	31.4	31.4	30.6	30.6	30.6	29.0		
R	0.050	0.200	0.450	0.800	1.150	1.325	1.325	1.250	1.000	0.650	0.400	0.200	0.050	
T	28.2	28.2	28.2	29.6	29.6	29.6	30.0	30.0	30.0	29.6	29.6	29.6	28.4	
R		0.050	0.300	0.700	1.025	1.200	1.250	1.225	1.100	0.800	0.550	0.300	0.150	
T		27.0	27.0	30.2	30.2	30.2	26.0	26.0	26.0	27.4	27.4	27.4	28.6	

* (reading)x (instrument constant,k=.398)=insolation in Cal/cm^2/min

TABLE BP-2: SIMULATION RESULTS OF A SOLAR CELL CONSIDERING BIVARIATE MODEL

Radiation* cal/cm^2/min	Temp. (^{o}K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.50000E-01	.29815E+03	.50445E+00	.53701E-02	.27090E-02
.25000E+00	.29815E+03	.54394E+00	.74553E-02	.40552E-02
.70000E+00	.29815E+03	.56926E+00	.12147E-01	.69147E-02
.12500E+01	.29615E+03	.58671E+00	.17881E-01	.10491E-01
.16500E+01	.29615E+03	.59352E+00	.22051E-01	.13088E-01
.19200E+01	.29615E+03	.59723E+00	.24866E-01	.14851E-01
.21000E+01	.30475E+03	.58617E+00	.26743E-01	.15676E-01
.21500E+01	.30475E+03	.58676E+00	.27264E-01	.15997E-01
.21000E+01	.30475E+03	.58617E+00	.26743E-01	.15676E-01
.17000E+01	.30495E+03	.58054E+00	.22572E-01	.13104E-01
.12000E+01	.30495E+03	.57177E+00	.17360E-01	.99257E-02
.85000E+00	.30495E+03	.56310E+00	.13711E-01	.77204E-02
.40000E+00	.30455E+03	.54482E+00	.90191E-02	.49138E-02
.50000E-01	.30455E+03	.49278E+00	.53701E-02	.26463E-02
.10000E+00	.30015E+03	.51789E+00	.58914E-02	.30511E-02
.55000E+00	.30015E+03	.56004E+00	.10583E-01	.59268E-02
.13500E+01	.30015E+03	.58229E+00	.18923E-01	.11019E-01
.17500E+01	.30355E+03	.58344E+00	.23094E-01	.13474E-01
.20500E+01	.30355E+03	.58741E+00	.26221E-01	.15403E-01
.21500E+01	.30355E+03	.58861E+00	.27264E-01	.16048E-01
.21700E+01	.30595E+03	.58515E+00	.27472E-01	.16076E-01
.16500E+01	.30595E+03	.57823E+00	.22051E-01	.12751E-01
.10500E+01	.30595E+03	.56682E+00	.15796E-01	.89534E-02
.10700E+01	.30715E+03	.56540E+00	.16004E-01	.90487E-02
.10700E+01	.30715E+03	.56540E+00	.16004E-01	.90487E-02
.90000E+00	.30715E+03	.56101E+00	.14232E-01	.79843E-02
.80000E+00	.30565E+03	.56045E+00	.13189E-01	.73919E-02
.60000E+00	.30565E+03	.55320E+00	.11104E-01	.61428E-02
.30000E-01	.29855E+03	.49119E+00	.51616E-02	.25354E-02
.12000E+00	.29955E+03	.52345E+00	.60999E-02	.31930E-02
.40000E+00	.29955E+03	.55316E+00	.90191E-02	.49890E-02
.90000E+00	.30275E+03	.56806E+00	.14232E-01	.80846E-02
.15700E+01	.30275E+03	.58197E+00	.21217E-01	.12348E-01
.20000E+01	.30275E+03	.58803E+00	.25700E-01	.15112E-01
.19000E+01	.30515E+03	.58303E+00	.24657E-01	.14376E-01
.16700E+01	.30515E+03	.57978E+00	.22260E-01	.12906E-01
.14000E+01	.30515E+03	.57534E+00	.19445E-01	.11187E-01
.11500E+01	.30675E+03	.56785E+00	.16838E-01	.95617E-02
.90000E+00	.30675E+03	.56165E+00	.14232E-01	.79934E-02
.10000E+00	.30675E+03	.50621E+00	.58914E-02	.29823E-02
.50000E-01	.30075E+03	.49970E+00	.53701E-02	.26835E-02
.25000E+00	.30075E+03	.53951E+00	.74553E-02	.40222E-02
.70000E+00	.30075E+03	.56504E+00	.12147E-01	.68633E-02
.12500E+01	.30435E+03	.57375E+00	.17881E-01	.10259E-01
.16200E+01	.30435E+03	.58026E+00	.21738E-01	.12614E-01
.18200E+01	.30435E+03	.58319E+00	.23823E-01	.13894E-01
.19000E+01	.30315E+03	.58613E+00	.24657E-01	.14452E-01
.18500E+01	.30315E+03	.58546E+00	.24136E-01	.14131E-01

TABLE BP-2: SIMULATION RESULTS OF A SOLAR CELL CONSIDERING BIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (^{o}K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.17200E+01	.30315E+03	.58363E+00	.22781E-01	.13296E-01
.15700E+01	.30415E+03	.57979E+00	.21217E-01	.12301E-01
.13000E+01	.30415E+03	.57505E+00	.18402E-01	.10582E-01
.75000E+00	.30415E+03	.56125E+00	.12668E-01	.71099E-02
.30000E+00	.30515E+03	.53660E+00	.79765E-02	.42802E-02
.80000E+00	.30515E+03	.56125E+00	.13189E-01	.74025E-02
.50000E-01	.30015E+03	.50080E+00	.53701E-02	.26893E-02
.20000E+00	.30015E+03	.53501E+00	.69340E-02	.37098E-02
.45000E+00	.30015E+03	.55507E+00	.95404E-02	.52956E-02
.80000E+00	.30415E+03	.56286E+00	.13189E-01	.74238E-02
.12500E+01	.30415E+03	.57406E+00	.17881E-01	.10265E-01
.18000E+01	.30415E+03	.58322E+00	.23615E-01	.13773E-01
.21000E+01	.30675E+03	.58310E+00	.26743E-01	.15593E-01
.20500E+01	.30675E+03	.58249E+00	.26221E-01	.15274E-01
.19000E+01	.30675E+03	.58056E+00	.24657E-01	.14315E-01
.16500E+01	.30765E+03	.57559E+00	.22051E-01	.12692E-01
.95000E+00	.30765E+03	.56159E+00	.14753E-01	.82851E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.10000E+00	.30615E+03	.50727E+00	.58914E-02	.29885E-02
.15000E+00	.30275E+03	.52338E+00	.64127E-02	.33563E-02
.55000E+00	.30275E+03	.55577E+00	.10583E-01	.58816E-02
.11000E+00	.30275E+03	.51566E+00	.59957E-02	.30917E-02
.14700E+01	.30515E+03	.57657E+00	.20174E-01	.11632E-01
.16000E+01	.30515E+03	.57870E+00	.21530E-01	.12459E-01
.15700E+01	.30515E+03	.57823E+00	.21217E-01	.12268E-01
.11500E+01	.30695E+03	.56754E+00	.16838E-01	.95563E-02
.60000E+00	.30695E+03	.55108E+00	.11104E-01	.61193E-02
.35000E+00	.30695E+03	.53746E+00	.84978E-02	.45672E-02
.25000E+00	.30175E+03	.53780E+00	.74553E-02	.40095E-02
.12000E+00	.30175E+03	.51958E+00	.60999E-02	.31694E-02
.30000E-01	.30175E+03	.48523E+00	.51616E-02	.25046E-02
.30000E-01	.30155E+03	.48561E+00	.51616E-02	.25065E-02
.80000E-01	.30155E+03	.50988E+00	.56829E-02	.28976E-02
.25000E+00	.30155E+03	.53814E+00	.74553E-02	.40120E-02
.45000E+00	.29755E+03	.55939E+00	.95404E-02	.53368E-02
.13000E+01	.29755E+03	.58546E+00	.18402E-01	.10774E-01
.21000E+01	.29755E+03	.59726E+00	.26743E-01	.15972E-01
.20000E+01	.29795E+03	.59544E+00	.25700E-01	.15303E-01
.15500E+01	.29795E+03	.58916E+00	.21008E-01	.12377E-01
.90000E+00	.29795E+03	.57577E+00	.14232E-01	.81943E-02
.45000E+00	.30215E+03	.55175E+00	.95404E-02	.52639E-02
.20000E+00	.30215E+03	.53157E+00	.69340E-02	.36859E-02
.10000E+00	.29975E+03	.51860E+00	.58914E-02	.30553E-02
.30000E+00	.29975E+03	.54571E+00	.79765E-02	.43529E-02
.50000E+00	.29975E+03	.55834E+00	.10062E-01	.56178E-02
.75000E+00	.30275E+03	.56351E+00	.12668E-01	.71386E-02
.10500E+01	.30275E+03	.57192E+00	.15796E-01	.90338E-02
.13500E+01	.30275E+03	.57820E+00	.18923E-01	.10941E-01

TABLE BP-2: SIMULATION RESULTS OF A SOLAR CELL CONSIDERING BIVARIATE MODEL(Continued)

Radiation* $cal/cm^2/min$	Temp. (°K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.16000E+01	.30355E+03	.58120E+00	.21530E-01	.12513E-01
.17000E+01	.30355E+03	.58272E+00	.22572E-01	.13153E-01
.17000E+01	.30355E+03	.58272E+00	.22572E-01	.13153E-01
.16000E+01	.30315E+03	.58182E+00	.21530E-01	.12526E-01
.14000E+01	.30315E+03	.57848E+00	.19445E-01	.11248E-01
.11000E+01	.30315E+03	.57244E+00	.16317E-01	.93405E-02
.70000E+00	.30255E+03	.56211E+00	.12147E-01	.68278E-02
.35000E+00	.30255E+03	.54482E+00	.84978E-02	.46298E-02
.50000E-01	.29915E+03	.50262E+00	.53701E-02	.26991E-02
.15000E+00	.29915E+03	.52965E+00	.64127E-02	.33965E-02
.30000E+00	.29915E+03	.54673E+00	.79765E-02	.43610E-02
.45000E+00	.29895E+03	.55706E+00	.95404E-02	.53146E-02
.60000E+00	.29895E+03	.56416E+00	.11104E-01	.62645E-02
.75000E+00	.29895E+03	.56967E+00	.12668E-01	.72165E-02
.92000E+00	.30175E+03	.57022E+00	.14440E-01	.82341E-02
.10500E+01	.30175E+03	.57351E+00	.15796E-01	.90590E-02
.90000E+00	.30175E+03	.56967E+00	.14232E-01	.81075E-02
.65000E+00	.30115E+03	.56254E+00	.11625E-01	.65398E-02
.45000E+00	.30115E+03	.55341E+00	.95404E-02	.52797E-02
.35000E+00	.30115E+03	.54717E+00	.84978E-02	.46498E-02
.22000E+00	.30115E+03	.53565E+00	.71425E-02	.38259E-02
.70000E-01	.30115E+03	.50729E+00	.55787E-02	.28300E-02
.15000E+00	.29975E+03	.52860E+00	.64127E-02	.33898E-02
.55000E+00	.29975E+03	.56070E+00	.10583E-01	.59338E-02
.11000E+01	.29975E+03	.57785E+00	.16317E-01	.94287E-02
.14200E+01	.30135E+03	.58166E+00	.19653E-01	.11431E-01
.13200E+01	.30135E+03	.57984E+00	.18611E-01	.10791E-01
.90000E+00	.30135E+03	.57031E+00	.14232E-01	.81166E-02
.50000E+00	.30255E+03	.55372E+00	.10062E-01	.55713E-02
.35000E+00	.30255E+03	.54482E+00	.84978E-02	.46298E-02
.22000E+00	.30255E+03	.53326E+00	.71425E-02	.38088E-02
.70000E-01	.30055E+03	.50837E+00	.55787E-02	.28360E-02
.10000E+00	.30075E+03	.51683E+00	.58914E-02	.30448E-02
.30000E+00	.30075E+03	.54402E+00	.79765E-02	.43394E-02
.45000E+00	.30075E+03	.55407E+00	.95404E-02	.52861E-02
.50000E+00	.29815E+03	.56098E+00	.10062E-01	.56444E-02
.45000E+00	.29815E+03	.55839E+00	.95404E-02	.53272E-02
.35000E+00	.29815E+03	.55221E+00	.84978E-02	.46926E-02
.30000E+00	.30015E+03	.54504E+00	.79765E-02	.43475E-02
.25000E+00	.30015E+03	.54053E+00	.74553E-02	.40298E-02
.10000E+00	.30015E+03	.51789E+00	.58914E-02	.30511E-02
.50000E-01	.30015E+03	.50080E+00	.53701E-02	.26893E-02
.10000E+00	.30015E+03	.51789E+00	.58914E-02	.30511E-02
.25000E+00	.30015E+03	.54053E+00	.74553E-02	.40298E-02
.35000E+00	.30215E+03	.54550E+00	.84978E-02	.46355E-02
.52000E+00	.30215E+03	.55535E+00	.10270E-01	.57036E-02
.77000E+00	.30215E+03	.56514E+00	.12877E-01	.72770E-02
.10500E+01	.30315E+03	.57128E+00	.15796E-01	.90238E-02

TABLE BP-2: SIMULATION RESULTS OF A SOLAR CELL CONSIDERING BIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (^oK)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.23000E+01	.30315E+03	.59091E+00	.28828E-01	.17035E-01
.23500E+01	.30315E+03	.59145E+00	.29349E-01	.17358E-01
.22000E+01	.30215E+03	.59133E+00	.27785E-01	.16430E-01
.19000E+01	.30215E+03	.58767E+00	.24657E-01	.14490E-01
.52000E+00	.30215E+03	.55535E+00	.10270E-01	.57036E-02
.22000E+00	.30215E+03	.53394E+00	.71425E-02	.38137E-02
.50000E-01	.30215E+03	.49715E+00	.53701E-02	.26698E-02
.30000E-01	.30015E+03	.48821E+00	.51616E-02	.25200E-02
.10000E+00	.30015E+03	.51789E+00	.58914E-02	.30511E-02
.22000E+00	.30015E+03	.53737E+00	.71425E-02	.38381E-02
.37000E+00	.30345E+03	.54471E+00	.87063E-02	.47424E-02
.67000E+00	.30345E+03	.55956E+00	.11834E-01	.66218E-02
.12500E+01	.30345E+03	.57517E+00	.17881E-01	.10284E-01
.17500E+01	.30495E+03	.58127E+00	.23094E-01	.13424E-01
.19700E+01	.30495E+03	.58425E+00	.25387E-01	.14833E-01
.20500E+01	.30495E+03	.58526E+00	.26221E-01	.15346E-01
.20000E+01	.30565E+03	.58356E+00	.25700E-01	.14997E-01
.17500E+01	.30565E+03	.58019E+00	.23094E-01	.13399E-01
.13000E+01	.30565E+03	.57269E+00	.18402E-01	.10539E-01
.75000E+00	.30365E+03	.56205E+00	.12668E-01	.71201E-02
.35000E+00	.30365E+03	.54298E+00	.84978E-02	.46142E-02
.12000E+00	.30055E+03	.52169E+00	.60999E-02	.31823E-02
.47000E+00	.30055E+03	.55548E+00	.97489E-02	.54153E-02
.97000E+00	.30055E+03	.57345E+00	.14962E-01	.85798E-02
.13000E+01	.30375E+03	.57568E+00	.18402E-01	.10594E-01
.15500E+01	.30375E+03	.58009E+00	.21008E-01	.12187E-01
.16500E+01	.30375E+03	.58166E+00	.22051E-01	.12826E-01
.17000E+01	.30475E+03	.58085E+00	.22572E-01	.13111E-01
.16700E+01	.30475E+03	.58040E+00	.22260E-01	.12920E-01
.15500E+01	.30475E+03	.57853E+00	.21008E-01	.12154E-01
.12000E+01	.30565E+03	.57067E+00	.17360E-01	.99065E-02
.70000E+00	.30565E+03	.55708E+00	.12147E-01	.67667E-02
.25000E+00	.30565E+03	.53117E+00	.74553E-02	.39600E-02
.50000E-01	.30415E+03	.49350E+00	.53701E-02	.26502E-02
.75000E-01	.29875E+03	.51331E+00	.56308E-02	.28903E-02
.22500E+00	.29875E+03	.54032E+00	.71946E-02	.38874E-02
.35000E+00	.29875E+03	.55120E+00	.84978E-02	.46840E-02
.55000E+00	.29815E+03	.56333E+00	.10583E-01	.59617E-02
.80000E+00	.29815E+03	.57255E+00	.13189E-01	.75516E-02
.95000E+00	.29815E+03	.57678E+00	.14753E-01	.85094E-02
.95000E+00	.29915E+03	.57518E+00	.14753E-01	.84857E-02
.80000E+00	.29915E+03	.57094E+00	.13189E-01	.75302E-02
.57500E+00	.29915E+03	.56278E+00	.10844E-01	.61025E-02
.35000E+00	.30175E+03	.54617E+00	.84978E-02	.46412E-02
.12500E+00	.30175E+03	.52059E+00	.61521E-02	.32027E-02
.25000E-01	.30015E+03	.48373E+00	.51095E-02	.24716E-02
.10000E+00	.30015E+03	.51789E+00	.58914E-02	.30511E-02
.20000E+00	.30015E+03	.53501E+00	.69340E-02	.37098E-02

TABLE BP-2: SIMULATION RESULTS OF A SOLAR CELL CONSIDERING BIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (°K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.25000E+00	.30195E+03	.53746E+00	.74553E-02	.40069E-02
.42500E+00	.30195E+03	.55066E+00	.92797E-02	.51100E-02
.57500E+00	.30195E+03	.55819E+00	.10844E-01	.60527E-02
.72500E+00	.30015E+03	.56688E+00	.12407E-01	.70335E-02
.90000E+00	.30015E+03	.57224E+00	.14232E-01	.81440E-02
.97500E+00	.30015E+03	.57422E+00	.15014E-01	.86212E-02
.92500E+00	.30175E+03	.57035E+00	.14492E-01	.82658E-02
.70000E+00	.30175E+03	.56341E+00	.12147E-01	.68436E-02
.40000E+00	.30175E+03	.54949E+00	.90191E-02	.49559E-02
.20000E+00	.30175E+03	.53226E+00	.69340E-02	.36907E-02
.50000E-01	.30175E+03	.49788E+00	.53701E-02	.26737E-02
.50000E-01	.30015E+03	.50080E+00	.53701E-02	.26893E-02
.25000E+00	.30015E+03	.54053E+00	.74553E-02	.40298E-02
.85000E+00	.30315E+03	.56599E+00	.13711E-01	.77601E-02
.17000E+01	.30315E+03	.58334E+00	.22572E-01	.13167E-01
.21500E+01	.30315E+03	.58922E+00	.27264E-01	.16064E-01
.21500E+01	.30335E+03	.58891E+00	.27264E-01	.16056E-01
.19500E+01	.30335E+03	.58647E+00	.25179E-01	.14766E-01
.16500E+01	.30335E+03	.58228E+00	.22051E-01	.12840E-01
.12000E+01	.30455E+03	.57241E+00	.17360E-01	.99367E-02
.65000E+00	.30455E+03	.55701E+00	.11625E-01	.64755E-02
.25000E+00	.30455E+03	.53304E+00	.74553E-02	.39739E-02
.50000E-01	.30055E+03	.50007E+00	.53701E-02	.26854E-02
.15000E+00	.30055E+03	.52721E+00	.64127E-02	.33808E-02
.30000E+00	.30255E+03	.54098E+00	.79765E-02	.43152E-02
.42000E+00	.30255E+03	.54937E+00	.92276E-02	.50694E-02
.48000E+00	.30255E+03	.55270E+00	.98531E-02	.54458E-02
.47000E+00	.30515E+03	.54788E+00	.97489E-02	.53412E-02
.47000E+00	.30515E+03	.54788E+00	.97489E-02	.53412E-02
.45000E+00	.30515E+03	.54678E+00	.95404E-02	.52165E-02
.42500E+00	.30515E+03	.54535E+00	.92797E-02	.50607E-02
.37500E+00	.30515E+03	.54220E+00	.87584E-02	.47489E-02
.30000E+00	.30515E+03	.53660E+00	.79765E-02	.42802E-02
.20000E+00	.30315E+03	.52985E+00	.69340E-02	.36740E-02
.75000E-01	.30315E+03	.50541E+00	.56308E-02	.28459E-02
.10000E+00	.30015E+03	.51789E+00	.58914E-02	.30511E-02
.37500E+00	.30015E+03	.55056E+00	.87584E-02	.48220E-02
.75000E+00	.30015E+03	.56772E+00	.12668E-01	.71919E-02
.11000E+01	.30255E+03	.57340E+00	.16317E-01	.93561E-02
.15000E+01	.30255E+03	.58115E+00	.20487E-01	.11906E-01
.17500E+01	.30255E+03	.58500E+00	.23094E-01	.13510E-01
.15500E+01	.30415E+03	.57947E+00	.21008E-01	.12174E-01
.10000E+01	.30415E+03	.56846E+00	.15274E-01	.86829E-02
.55000E+00	.30415E+03	.55347E+00	.10583E-01	.58573E-02
.30000E+00	.30375E+03	.53896E+00	.79765E-02	.42990E-02
.15000E+00	.30375E+03	.52164E+00	.64127E-02	.33451E-02
.50000E-01	.30375E+03	.49423E+00	.53701E-02	.26541E-02
.10000E+00	.29995E+03	.51825E+00	.58914E-02	.30532E-02

TABLE BP-2: SIMULATION RESULTS OF A SOLAR CELL
CONSIDERING BIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (°K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.30000E+00	.29995E+03	.54537E+00	.79765E-02	.43502E-02
.65000E+00	.29995E+03	.56450E+00	.11625E-01	.65626E-02
.85000E+00	.30215E+03	.56760E+00	.13711E-01	.77822E-02
.12500E+01	.30215E+03	.57722E+00	.17881E-01	.10321E-01
.17500E+01	.30215E+03	.58562E+00	.23094E-01	.13524E-01
.22500E+01	.30335E+03	.59005E+00	.28306E-01	.16702E-01
.22250E+01	.30335E+03	.58977E+00	.28046E-01	.16541E-01
.20750E+01	.30335E+03	.58802E+00	.26482E-01	.15572E-01
.16500E+01	.30515E+03	.57948E+00	.22051E-01	.12778E-01
.12500E+01	.30515E+03	.57249E+00	.17881E-01	.10237E-01
.90000E+00	.30515E+03	.56422E+00	.14232E-01	.80299E-02
.60000E+00	.30315E+03	.55728E+00	.11104E-01	.61882E-02
.35000E+00	.30315E+03	.54382E+00	.84978E-02	.46213E-02
.12500E+00	.30035E+03	.52305E+00	.61521E-02	.32178E-02
.52500E+00	.30035E+03	.55856E+00	.10322E-01	.57656E-02
.10000E+01	.30035E+03	.57453E+00	.15274E-01	.87756E-02
.13500E+01	.30215E+03	.57914E+00	.18923E-01	.10959E-01
.15750E+01	.30215E+03	.58299E+00	.21269E-01	.12400E-01
.16500E+01	.30215E+03	.58415E+00	.22051E-01	.12881E-01
.16000E+01	.30315E+03	.58182E+00	.21530E-01	.12526E-01
.15750E+01	.30315E+03	.58143E+00	.21269E-01	.12366E-01
.13500E+01	.30315E+03	.57757E+00	.18923E-01	.10930E-01
.11000E+01	.30515E+03	.56927E+00	.16317E-01	.92887E-02
.81500E+00	.30515E+03	.56172E+00	.13346E-01	.74965E-02
.40000E+00	.30515E+03	.54382E+00	.90191E-02	.49048E-02
.10000E+00	.30415E+03	.51081E+00	.58914E-02	.30094E-02
.50000E-01	.30115E+03	.49897E+00	.53701E-02	.26795E-02
.20000E+00	.30115E+03	.53329E+00	.69340E-02	.36978E-02
.40000E+00	.30115E+03	.55049E+00	.90191E-02	.49649E-02
.65500E+00	.30315E+03	.55948E+00	.11678E-01	.65333E-02
.97500E+00	.30315E+03	.56943E+00	.15014E-01	.85492E-02
.12500E+01	.30315E+03	.57564E+00	.17881E-01	.10293E-01
.15500E+01	.30515E+03	.57790E+00	.21008E-01	.12141E-01
.18500E+01	.30515E+03	.58236E+00	.24136E-01	.14056E-01
.22500E+01	.30515E+03	.58730E+00	.28306E-01	.16624E-01
.27500E+01	.30615E+03	.59084E+00	.33519E-01	.19804E-01
.21750E+01	.30615E+03	.58491E+00	.27524E-01	.16099E-01
.19000E+01	.30615E+03	.58149E+00	.24657E-01	.14338E-01
.14500E+01	.30555E+03	.57560E+00	.19966E-01	.11492E-01
.95000E+00	.30555E+03	.56494E+00	.14753E-01	.83346E-02
.20000E+00	.30055E+03	.53432E+00	.69340E-02	.37050E-02
.65000E+00	.30055E+03	.56352E+00	.11625E-01	.65512E-02
.10500E+01	.30055E+03	.57542E+00	.15796E-01	.90892E-02
.14500E+01	.30275E+03	.57998E+00	.19966E-01	.11580E-01
.16750E+01	.30275E+03	.58359E+00	.22312E-01	.13021E-01
.17900E+01	.30275E+03	.58525E+00	.23511E-01	.13760E-01
.18000E+01	.30415E+03	.58322E+00	.23615E-01	.13773E-01
.17250E+01	.30415E+03	.58215E+00	.22833E-01	.13292E-01

TABLE BP-2: SIMULATION RESULTS OF A SOLAR CELL CONSIDERING BIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (°K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.14750E+01	.30415E+03	.57822E+00	.20227E-01	.11695E-01
.12000E+01	.30365E+03	.57383E+00	.17360E-01	.99614E-02
.70000E+00	.30365E+03	.56033E+00	.12147E-01	.68061E-02
.37500E+00	.30365E+03	.54471E+00	.87584E-02	.47708E-02
.12500E+00	.30255E+03	.51919E+00	.61521E-02	.31941E-02
.13000E-01	.30255E+03	.46303E+00	.49844E-02	.23079E-02
.12500E+00	.30095E+03	.52200E+00	.61521E-02	.32113E-02
.40000E+00	.30095E+03	.55082E+00	.90191E-02	.49679E-02
.67500E+00	.30095E+03	.56381E+00	.11886E-01	.67015E-02
.95000E+00	.30275E+03	.56942E+00	.14753E-01	.84007E-02
.12000E+01	.30275E+03	.57525E+00	.17360E-01	.99861E-02
.13750E+01	.30275E+03	.57866E+00	.19184E-01	.11101E-01
.14750E+01	.30215E+03	.58135E+00	.20227E-01	.11759E-01
.13750E+01	.30215E+03	.57960E+00	.19184E-01	.11119E-01
.11500E+01	.30215E+03	.57514E+00	.16838E-01	.96844E-02
.85000E+00	.30075E+03	.56986E+00	.13711E-01	.78131E-02
.60000E+00	.30075E+03	.56121E+00	.11104E-01	.62318E-02
.35000E+00	.30075E+03	.54784E+00	.84978E-02	.46555E-02
.10000E+00	.30195E+03	.51470E+00	.58914E-02	.30323E-02
.50000E-01	.30095E+03	.49934E+00	.53701E-02	.26815E-02
.25000E+00	.30095E+03	.53916E+00	.74553E-02	.40196E-02
.45000E+00	.30095E+03	.55374E+00	.95404E-02	.52829E-02
.62500E+00	.30115E+03	.56157E+00	.11365E-01	.63822E-02
.85000E+00	.30115E+03	.56921E+00	.13711E-01	.78042E-02
.11500E+01	.30115E+03	.57673E+00	.16838E-01	.97111E-02
.14000E+01	.30215E+03	.58005E+00	.19445E-01	.11279E-01
.14750E+01	.30215E+03	.58135E+00	.20227E-01	.11759E-01
.12750E+01	.30215E+03	.57772E+00	.18141E-01	.10481E-01
.90000E+00	.30335E+03	.56710E+00	.14232E-01	.80709E-02
.60000E+00	.30335E+03	.55696E+00	.11104E-01	.61846E-02
.34500E+00	.30335E+03	.54312E+00	.84457E-02	.45871E-02
.10000E+00	.30255E+03	.51364E+00	.58914E-02	.30261E-02
.50000E-01	.30105E+03	.49915E+00	.53701E-02	.26805E-02
.17500E+00	.30105E+03	.53015E+00	.66733E-02	.35379E-02
.40000E+00	.30105E+03	.55065E+00	.90191E-02	.49664E-02
.70000E+00	.30145E+03	.56390E+00	.12147E-01	.68495E-02
.11500E+01	.30145E+03	.57625E+00	.16838E-01	.97031E-02
.15500E+01	.30145E+03	.58368E+00	.21008E-01	.12262E-01
.17500E+01	.30415E+03	.58251E+00	.23094E-01	.13452E-01
.17000E+01	.30415E+03	.58179E+00	.22572E-01	.13132E-01
.14750E+01	.30415E+03	.57822E+00	.20227E-01	.11695E-01
.12000E+01	.30475E+03	.57209E+00	.17360E-01	.99312E-02
.90000E+00	.30475E+03	.56486E+00	.14232E-01	.80390E-02
.67500E+00	.30475E+03	.55763E+00	.11886E-01	.66280E-02
.35000E+00	.30315E+03	.54382E+00	.84978E-02	.46213E-02
.10000E+00	.30315E+03	.51258E+00	.58914E-02	.30198E-02
.30000E+00	.30095E+03	.54368E+00	.79765E-02	.43367E-02
.85000E+00	.30095E+03	.56953E+00	.13711E-01	.78086E-02

TABLE BP-2: SIMULATION RESULTS OF A SOLAR CELL CONSIDERING BIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (^{o}K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.13500E+01	.30095E+03	.58103E+00	.18923E-01	.10995E-01
.18000E+01	.30415E+03	.58322E+00	.23615E-01	.13773E-01
.21000E+01	.30415E+03	.58709E+00	.26743E-01	.15700E-01
.22000E+01	.30415E+03	.58826E+00	.27785E-01	.16345E-01
.21500E+01	.30465E+03	.58692E+00	.27264E-01	.16002E-01
.19500E+01	.30465E+03	.58446E+00	.25179E-01	.14716E-01
.16500E+01	.30465E+03	.58026E+00	.22051E-01	.12795E-01
.13000E+01	.30515E+03	.57347E+00	.18402E-01	.10553E-01
.80000E+00	.30515E+03	.56125E+00	.13189E-01	.74025E-02
.30000E+00	.30515E+03	.53660E+00	.79765E-02	.42802E-02
.50000E-01	.30355E+03	.49460E+00	.53701E-02	.26561E-02
.50000E-01	.30055E+03	.50007E+00	.53701E-02	.26854E-02
.20000E+00	.30055E+03	.53432E+00	.69340E-02	.37050E-02
.40000E+00	.30055E+03	.55149E+00	.90191E-02	.49739E-02
.55500E+00	.30215E+03	.55698E+00	.10635E-01	.59235E-02
.77500E+00	.30215E+03	.56530E+00	.12929E-01	.73086E-02
.12500E+01	.30215E+03	.57722E+00	.17881E-01	.10321E-01
.15500E+01	.30315E+03	.58103E+00	.21008E-01	.12206E-01
.12500E+01	.30315E+03	.57564E+00	.17881E-01	.10293E-01
.10000E+01	.30315E+03	.57006E+00	.15274E-01	.87073E-02
.71500E+00	.30265E+03	.56248E+00	.12303E-01	.69203E-02
.50000E+00	.30265E+03	.55355E+00	.10062E-01	.55696E-02
.32500E+00	.30265E+03	.54281E+00	.82372E-02	.44712E-02
.25000E+00	.30115E+03	.53882E+00	.74553E-02	.40171E-02
.50000E-01	.30115E+03	.49897E+00	.53701E-02	.26795E-02
.50000E-01	.29915E+03	.50262E+00	.53701E-02	.26991E-02
.20000E+00	.29915E+03	.53673E+00	.69340E-02	.37217E-02
.40000E+00	.29915E+03	.55382E+00	.90191E-02	.49950E-02
.65000E+00	.30055E+03	.56352E+00	.11625E-01	.65512E-02
.95000E+00	.30055E+03	.57294E+00	.14753E-01	.84526E-02
.12000E+01	.30055E+03	.57874E+00	.17360E-01	.10047E-01
.13500E+01	.30315E+03	.57757E+00	.18923E-01	.10930E-01
.13750E+01	.30315E+03	.57803E+00	.19184E-01	.11089E-01
.12750E+01	.30315E+03	.57614E+00	.18141E-01	.10452E-01
.11000E+01	.30315E+03	.57244E+00	.16317E-01	.93405E-02
.75000E+00	.30315E+03	.56286E+00	.12668E-01	.71304E-02
.45000E+00	.30315E+03	.55010E+00	.95404E-02	.52481E-02
.25000E+00	.30215E+03	.53712E+00	.74553E-02	.40044E-02
.15000E+00	.29955E+03	.52895E+00	.64127E-02	.33920E-02
.50000E+00	.29955E+03	.55867E+00	.10062E-01	.56211E-02
.80000E+00	.29955E+03	.57029E+00	.13189E-01	.75217E-02
.10000E+01	.30255E+03	.57102E+00	.15274E-01	.87219E-02
.11000E+01	.30255E+03	.57340E+00	.16317E-01	.93561E-02
.11500E+01	.30255E+03	.57451E+00	.16838E-01	.96737E-02
.11750E+01	.30315E+03	.57409E+00	.17099E-01	.98164E-02
.10750E+01	.30315E+03	.57187E+00	.16056E-01	.91821E-02
.10250E+01	.30315E+03	.57068E+00	.15535E-01	.88655E-02
.92500E+00	.30115E+03	.57131E+00	.14492E-01	.82798E-02

TABLE BP-2: SIMULATION RESULTS OF A SOLAR CELL CONSIDERING BIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (°K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.72500E+00	.30115E+03	.56526E+00	.12407E-01	.70134E-02
.50000E+00	.30115E+03	.55603E+00	.10062E-01	.55945E-02
.30000E+00	.30155E+03	.54267E+00	.79765E-02	.43286E-02
.10000E+00	.30155E+03	.51541E+00	.58914E-02	.30365E-02
.50000E-01	.30055E+03	.50007E+00	.53701E-02	.26854E-02
.30000E+00	.30055E+03	.54436E+00	.79765E-02	.43421E-02
.65000E+00	.30055E+03	.56352E+00	.11625E-01	.65512E-02
.10000E+01	.30255E+03	.57102E+00	.15274E-01	.87219E-02
.14000E+01	.30255E+03	.57942E+00	.19445E-01	.11267E-01
.17000E+01	.30255E+03	.58427E+00	.22572E-01	.13188E-01
.18500E+01	.30435E+03	.58360E+00	.24136E-01	.14086E-01
.18250E+01	.30435E+03	.58326E+00	.23875E-01	.13926E-01
.16250E+01	.30435E+03	.58034E+00	.21790E-01	.12646E-01
.13500E+01	.30415E+03	.57600E+00	.18923E-01	.10900E-01
.10000E+01	.30415E+03	.56846E+00	.15274E-01	.86829E-02
.65000E+00	.30415E+03	.55766E+00	.11625E-01	.64830E-02
.40000E+00	.30315E+03	.54715E+00	.90191E-02	.49348E-02
.20000E+00	.30315E+03	.52985E+00	.69340E-02	.36740E-02
.10000E+00	.30075E+03	.51683E+00	.58914E-02	.30448E-02
.35000E+00	.30075E+03	.54784E+00	.84978E-02	.46555E-02
.80000E+00	.30075E+03	.56835E+00	.13189E-01	.74961E-02
.15500E+01	.30255E+03	.58196E+00	.21008E-01	.12226E-01
.17000E+01	.30255E+03	.58427E+00	.22572E-01	.13188E-01
.20000E+01	.30255E+03	.58834E+00	.25700E-01	.15120E-01
.21000E+01	.30115E+03	.59171E+00	.26743E-01	.15824E-01
.20000E+01	.30115E+03	.59050E+00	.25700E-01	.15176E-01
.17500E+01	.30115E+03	.58717E+00	.23094E-01	.13560E-01
.14000E+01	.30415E+03	.57691E+00	.19445E-01	.11218E-01
.95000E+00	.30415E+03	.56718E+00	.14753E-01	.83676E-02
.45000E+00	.30415E+03	.54844E+00	.95404E-02	.52323E-02
.10000E+00	.30315E+03	.51258E+00	.58914E-02	.30198E-02
.12500E+00	.30095E+03	.52200E+00	.61521E-02	.32113E-02
.37500E+00	.30095E+03	.54922E+00	.87584E-02	.48103E-02
.65000E+00	.30095E+03	.56287E+00	.11625E-01	.65436E-02
.95000E+00	.30195E+03	.57070E+00	.14753E-01	.84196E-02
.12500E+01	.30195E+03	.57754E+00	.17881E-01	.10327E-01
.15000E+01	.30195E+03	.58208E+00	.20487E-01	.11925E-01
.17500E+01	.30215E+03	.58562E+00	.23094E-01	.13524E-01
.17000E+01	.30215E+03	.58490E+00	.22572E-01	.13202E-01
.18000E+01	.30215E+03	.58632E+00	.23615E-01	.13846E-01
.16000E+01	.30315E+03	.58182E+00	.21530E-01	.12526E-01
.12500E+01	.30315E+03	.57564E+00	.17881E-01	.10293E-01
.80000E+00	.30315E+03	.56448E+00	.13189E-01	.74451E-02
.45000E+00	.30255E+03	.55109E+00	.95404E-02	.52576E-02
.20000E+00	.30255E+03	.53088E+00	.69340E-02	.36811E-02
.50000E-01	.30095E+03	.49934E+00	.53701E-02	.26815E-02
.22500E+00	.30095E+03	.53655E+00	.71946E-02	.38603E-02
.47500E+00	.30095E+03	.55508E+00	.98010E-02	.54404E-02

TABLE BP-2: SIMULATION RESULTS OF A SOLAR CELL CONSIDERING BIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (°K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.80000E+00	.30315E+03	.56448E+00	.13189E-01	.74451E-02
.11500E+01	.30315E+03	.57356E+00	.16838E-01	.96577E-02
.15000E+01	.30315E+03	.58021E+00	.20487E-01	.11887E-01
.18250E+01	.30415E+03	.58357E+00	.23875E-01	.13933E-01
.20000E+01	.30415E+03	.58587E+00	.25700E-01	.15057E-01
.19750E+01	.30415E+03	.58555E+00	.25439E-01	.14896E-01
.18750E+01	.30475E+03	.58332E+00	.24397E-01	.14231E-01
.16000E+01	.30475E+03	.57933E+00	.21530E-01	.12473E-01
.12000E+01	.30475E+03	.57209E+00	.17360E-01	.99312E-02
.70000E+00	.30415E+03	.55952E+00	.12147E-01	.67963E-02
.30000E+00	.30415E+03	.53828E+00	.79765E-02	.42936E-02
.50000E-01	.30075E+03	.49970E+00	.53701E-02	.26835E-02
.20000E+00	.30075E+03	.53398E+00	.69340E-02	.37026E-02
.40000E+00	.30075E+03	.55115E+00	.90191E-02	.49709E-02
.75000E+00	.30115E+03	.56610E+00	.12668E-01	.71714E-02
.15500E+01	.30115E+03	.58415E+00	.21008E-01	.12272E-01
.21000E+01	.30115E+03	.59171E+00	.26743E-01	.15824E-01
.20000E+01	.30275E+03	.58803E+00	.25700E-01	.15112E-01
.17000E+01	.30275E+03	.58396E+00	.22572E-01	.13181E-01
.13000E+01	.30275E+03	.57725E+00	.18402E-01	.10623E-01
.95000E+00	.30215E+03	.57038E+00	.14753E-01	.84148E-02
.65000E+00	.30215E+03	.56091E+00	.11625E-01	.65209E-02
.30000E+00	.30215E+03	.54166E+00	.79765E-02	.43206E-02
.50000E-01	.30265E+03	.49624E+00	.53701E-02	.26649E-02
.45000E-01	.30035E+03	.49783E+00	.53180E-02	.26475E-02
.17500E+00	.30035E+03	.53137E+00	.66733E-02	.35460E-02
.35000E+00	.30035E+03	.54851E+00	.84978E-02	.46612E-02
.50000E+00	.30175E+03	.55504E+00	.10062E-01	.55846E-02
.70000E+00	.30175E+03	.56341E+00	.12147E-01	.68436E-02
.92500E+00	.30175E+03	.57035E+00	.14492E-01	.82658E-02
.12250E+01	.30015E+03	.57988E+00	.17620E-01	.10218E-01
.16000E+01	.30015E+03	.58651E+00	.21530E-01	.12627E-01
.18000E+01	.30015E+03	.58943E+00	.23615E-01	.13919E-01
.16500E+01	.30315E+03	.58259E+00	.22051E-01	.12847E-01
.12500E+01	.30315E+03	.57564E+00	.17881E-01	.10293E-01
.65000E+00	.30315E+03	.55929E+00	.11625E-01	.65020E-02
.27500E+00	.30115E+03	.54119E+00	.77159E-02	.41758E-02
.50000E-01	.29915E+03	.50262E+00	.53701E-02	.26991E-02
.15000E+00	.29915E+03	.52965E+00	.64127E-02	.33965E-02
.40000E+00	.29915E+03	.55382E+00	.90191E-02	.49950E-02
.13000E+01	.30075E+03	.58041E+00	.18402E-01	.10681E-01
.20500E+01	.30075E+03	.59173E+00	.26221E-01	.15516E-01
.20500E+01	.30075E+03	.59173E+00	.26221E-01	.15516E-01
.18000E+01	.30415E+03	.58322E+00	.23615E-01	.13773E-01
.13500E+01	.30415E+03	.57600E+00	.18923E-01	.10900E-01
.95000E+00	.30415E+03	.56718E+00	.14753E-01	.83676E-02
.65000E+00	.30415E+03	.55766E+00	.11625E-01	.64830E-02
.30000E+00	.30415E+03	.53828E+00	.79765E-02	.42936E-02

TABLE BP-2: SIMULATION RESULTS OF A SOLAR CELL CONSIDERING BIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (^oK)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.50000E-01	.30415E+03	.49350E+00	.53701E-02	.26502E-02
.50000E-01	.30015E+03	.50080E+00	.53701E-02	.26893E-02
.20000E+00	.30015E+03	.53501E+00	.69340E-02	.37098E-02
.42500E+00	.30015E+03	.55366E+00	.92797E-02	.51378E-02
.67500E+00	.30295E+03	.56055E+00	.11886E-01	.66628E-02
.90000E+00	.30295E+03	.56774E+00	.14232E-01	.80800E-02
.13000E+01	.30295E+03	.57694E+00	.18402E-01	.10617E-01
.19000E+01	.30315E+03	.58613E+00	.24657E-01	.14452E-01
.21000E+01	.30315E+03	.58863E+00	.26743E-01	.15742E-01
.17750E+01	.30315E+03	.58442E+00	.23354E-01	.13649E-01
.14250E+01	.30335E+03	.57861E+00	.19705E-01	.11402E-01
.12000E+01	.30335E+03	.57430E+00	.17360E-01	.99696E-02
.95000E+00	.30335E+03	.56846E+00	.14753E-01	.83865E-02
.65000E+00	.30315E+03	.55929E+00	.11625E-01	.65020E-02
.25000E+00	.30315E+03	.53542E+00	.74553E-02	.39917E-02
.10000E+00	.29965E+03	.51878E+00	.58914E-02	.30563E-02
.45000E+00	.29965E+03	.55590E+00	.95404E-02	.53035E-02
.12000E+01	.29965E+03	.58016E+00	.17360E-01	.10071E-01
.16500E+01	.29995E+03	.58758E+00	.22051E-01	.12957E-01
.15500E+01	.29995E+03	.58603E+00	.21008E-01	.12312E-01
.13750E+01	.29995E+03	.58306E+00	.19184E-01	.11185E-01
.11250E+01	.30315E+03	.57301E+00	.16578E-01	.94991E-02
.82500E+00	.30315E+03	.56525E+00	.13450E-01	.76025E-02
.52500E+00	.30315E+03	.55395E+00	.10322E-01	.57180E-02
.25000E+00	.30275E+03	.53610E+00	.74553E-02	.39968E-02
.50000E-01	.30275E+03	.49605E+00	.53701E-02	.26639E-02
.75000E+00	.29975E+03	.56837E+00	.12668E-01	.72001E-02
.25000E+00	.29975E+03	.54121E+00	.74553E-02	.40349E-02
.40000E+00	.29995E+03	.55249E+00	.90191E-02	.49829E-02
.52500E+00	.29995E+03	.55922E+00	.10322E-01	.57724E-02
.60000E+00	.29995E+03	.56252E+00	.11104E-01	.62463E-02
.65000E+00	.30095E+03	.56287E+00	.11625E-01	.65436E-02
.62500E+00	.30095E+03	.56190E+00	.11365E-01	.63859E-02
.55000E+00	.30095E+03	.55872E+00	.10583E-01	.59129E-02
.45000E+00	.30015E+03	.55507E+00	.95404E-02	.52956E-02
.25000E+00	.30015E+03	.54053E+00	.74553E-02	.40298E-02
.50000E-01	.30015E+03	.50080E+00	.53701E-02	.26893E-02
.50000E-01	.29995E+03	.50116E+00	.53701E-02	.26913E-02
.20000E+00	.29995E+03	.53536E+00	.69340E-02	.37121E-02
.45000E+00	.29995E+03	.55540E+00	.95404E-02	.52987E-02
.80000E+00	.30155E+03	.56706E+00	.13189E-01	.74791E-02
.13500E+01	.30155E+03	.58009E+00	.18923E-01	.10977E-01
.17000E+01	.30155E+03	.58583E+00	.22572E-01	.13224E-01
.11000E+01	.30375E+03	.57149E+00	.16317E-01	.93250E-02
.30000E+00	.30375E+03	.53896E+00	.79765E-02	.42990E-02
.50000E-01	.30375E+03	.49423E+00	.53701E-02	.26541E-02
.50000E-01	.29935E+03	.50226E+00	.53701E-02	.26972E-02
.20000E+00	.29935E+03	.53639E+00	.69340E-02	.37193E-02

TABLE BP-2: SIMULATION RESULTS OF A SOLAR CELL CONSIDERING BIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (^{o}K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.55000E+00	.29935E+03	.56135E+00	.10583E-01	.59408E-02
.92500E+00	.29995E+03	.57324E+00	.14492E-01	.83077E-02
.12150E+01	.29995E+03	.58000E+00	.17516E-01	.10159E-01
.13500E+01	.29995E+03	.58261E+00	.18923E-01	.11025E-01
.12250E+01	.30235E+03	.57640E+00	.17620E-01	.10156E-01
.10000E+01	.30235E+03	.57134E+00	.15274E-01	.87268E-02
.75000E+00	.30235E+03	.56416E+00	.12668E-01	.71468E-02
.40000E+00	.30255E+03	.54815E+00	.90191E-02	.49438E-02
.10000E+00	.30255E+03	.51364E+00	.58914E-02	.30261E-02
.50000E-01	.29995E+03	.50116E+00	.53701E-02	.26913E-02
.15000E+00	.29995E+03	.52825E+00	.64127E-02	.33875E-02
.35000E+00	.29995E+03	.54919E+00	.84978E-02	.46669E-02
.65000E+00	.30155E+03	.56189E+00	.11625E-01	.65323E-02
.14000E+01	.30155E+03	.58099E+00	.19445E-01	.11297E-01
.19500E+01	.30155E+03	.58925E+00	.25179E-01	.14837E-01
.15000E+01	.30295E+03	.58052E+00	.20487E-01	.11893E-01
.92500E+00	.30295E+03	.56843E+00	.14492E-01	.82380E-02
.65000E+00	.30295E+03	.55961E+00	.11625E-01	.65057E-02
.40000E+00	.30135E+03	.55015E+00	.90191E-02	.49619E-02
.15000E+00	.30135E+03	.52581E+00	.64127E-02	.33719E-02
.25000E-01	.29915E+03	.48560E+00	.51095E-02	.24812E-02
.75000E-01	.29915E+03	.51259E+00	.56308E-02	.28863E-02
.17500E+00	.29915E+03	.53344E+00	.66733E-02	.35598E-02
.47500E+00	.30055E+03	.55575E+00	.98010E-02	.54469E-02
.11000E+01	.30055E+03	.57658E+00	.16317E-01	.94080E-02
.14500E+01	.30055E+03	.58344E+00	.19966E-01	.11649E-01
.12500E+01	.30215E+03	.57722E+00	.17881E-01	.10321E-01
.10000E+01	.30215E+03	.57165E+00	.15274E-01	.87317E-02
.80000E+00	.30215E+03	.56609E+00	.13189E-01	.74663E-02
.60000E+00	.30415E+03	.55565E+00	.11104E-01	.61700E-02
.40000E+00	.30415E+03	.54549E+00	.90191E-02	.49198E-02
.15000E+00	.30415E+03	.52094E+00	.64127E-02	.33406E-02
.15000E+00	.30055E+03	.52721E+00	.64127E-02	.33808E-02
.50000E+00	.30055E+03	.55702E+00	.10062E-01	.56045E-02
.80000E+00	.30255E+03	.56545E+00	.13189E-01	.74578E-02
.10000E+01	.30255E+03	.57102E+00	.15274E-01	.87219E-02
.12000E+01	.30255E+03	.57557E+00	.17360E-01	.99916E-02
.14000E+01	.30415E+03	.57691E+00	.19445E-01	.11218E-01
.15500E+01	.30415E+03	.57947E+00	.21008E-01	.12174E-01
.15500E+01	.30415E+03	.57947E+00	.21008E-01	.12174E-01
.14000E+01	.30515E+03	.57534E+00	.19445E-01	.11187E-01
.11500E+01	.30515E+03	.57039E+00	.16838E-01	.96043E-02
.80000E+00	.30515E+03	.56125E+00	.13189E-01	.74025E-02
.45000E+00	.30335E+03	.54976E+00	.95404E-02	.52450E-02
.15000E+00	.30335E+03	.52233E+00	.64127E-02	.33496E-02
.15000E+00	.30015E+03	.52790E+00	.64127E-02	.33853E-02
.15500E+01	.30015E+03	.58572E+00	.21008E-01	.12305E-01
.10500E+01	.30295E+03	.57160E+00	.15796E-01	.90288E-02

TABLE BP-2: SIMULATION RESULTS OF A SOLAR CELL CONSIDERING BIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (°K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.14500E+01	.30295E+03	.57967E+00	.19966E-01	.11574E-01
.17000E+01	.30295E+03	.58365E+00	.22572E-01	.13174E-01
.18000E+01	.30115E+03	.58787E+00	.23615E-01	.13883E-01
.17500E+01	.30115E+03	.58717E+00	.23094E-01	.13560E-01
.16000E+01	.30115E+03	.58494E+00	.21530E-01	.12594E-01
.12500E+01	.30355E+03	.57501E+00	.17881E-01	.10282E-01
.75000E+00	.30355E+03	.56222E+00	.12668E-01	.71222E-02
.35000E+00	.30355E+03	.54315E+00	.84978E-02	.46156E-02
.10000E+00	.30195E+03	.51470E+00	.58914E-02	.30323E-02
.10000E+00	.29955E+03	.51896E+00	.58914E-02	.30574E-02
.45000E+00	.29955E+03	.55607E+00	.95404E-02	.53051E-02
.95000E+00	.30275E+03	.56942E+00	.14753E-01	.84007E-02
.14000E+01	.30275E+03	.57911E+00	.19445E-01	.11261E-01
.18000E+01	.30275E+03	.58539E+00	.23615E-01	.13824E-01
.20000E+01	.30315E+03	.58741E+00	.25700E-01	.15096E-01
.19500E+01	.30315E+03	.58678E+00	.25179E-01	.14774E-01
.18000E+01	.30315E+03	.58477E+00	.23615E-01	.13809E-01
.15500E+01	.30335E+03	.58071E+00	.21008E-01	.12200E-01
.11500E+01	.30335E+03	.57324E+00	.16838E-01	.96523E-02
.70000E+00	.30335E+03	.56081E+00	.12147E-01	.68121E-02
.25000E+00	.30275E+03	.53610E+00	.74553E-02	.39968E-02
.50000E-01	.30275E+03	.49605E+00	.53701E-02	.26639E-02
.12500E+00	.30015E+03	.52340E+00	.61521E-02	.32200E-02
.40000E+00	.30015E+03	.55215E+00	.90191E-02	.49799E-02
.72500E+00	.30275E+03	.56266E+00	.12407E-01	.69812E-02
.10500E+01	.30275E+03	.57192E+00	.15796E-01	.90338E-02
.14500E+01	.30275E+03	.57998E+00	.19966E-01	.11580E-01
.18000E+01	.30155E+03	.58725E+00	.23615E-01	.13868E-01
.18000E+01	.30155E+03	.58725E+00	.23615E-01	.13868E-01
.16000E+01	.30155E+03	.58432E+00	.21530E-01	.12580E-01
.13500E+01	.30475E+03	.57505E+00	.18923E-01	.10882E-01
.10000E+01	.30475E+03	.56751E+00	.15274E-01	.86683E-02
.60000E+00	.30475E+03	.55467E+00	.11104E-01	.61592E-02
.25000E+00	.30175E+03	.53780E+00	.74553E-02	.40095E-02
.10000E+00	.30055E+03	.51718E+00	.58914E-02	.30469E-02
.35000E+00	.30055E+03	.54818E+00	.84978E-02	.46583E-02
.75000E+00	.30055E+03	.56707E+00	.12668E-01	.71837E-02
.12000E+01	.30055E+03	.57874E+00	.17360E-01	.10047E-01
.14500E+01	.30055E+03	.58344E+00	.19966E-01	.11649E-01
.15250E+01	.30055E+03	.58469E+00	.20748E-01	.12131E-01
.14500E+01	.30015E+03	.58406E+00	.19966E-01	.11661E-01
.12000E+01	.30015E+03	.57937E+00	.17360E-01	.10058E-01
.90000E+00	.30015E+03	.57224E+00	.14232E-01	.81440E-02
.70000E+00	.29995E+03	.56634E+00	.12147E-01	.68791E-02
.50000E+00	.29995E+03	.55801E+00	.10062E-01	.56145E-02
.25000E+00	.29995E+03	.54087E+00	.74553E-02	.40323E-02
.50000E-01	.30095E+03	.49934E+00	.53701E-02	.26815E-02
.10000E+00	.29955E+03	.51896E+00	.58914E-02	.30574E-02

TABLE BP-2: SIMULATION RESULTS OF A SOLAR CELL CONSIDERING BIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (°K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.35000E+00	.29955E+03	.54986E+00	.84978E-02	.46726E-02
.60000E+00	.29955E+03	.56318E+00	.11104E-01	.62536E-02
.80000E+00	.30175E+03	.56674E+00	.13189E-01	.74749E-02
.10500E+01	.30175E+03	.57351E+00	.15796E-01	.90590E-02
.13000E+01	.30175E+03	.57883E+00	.18402E-01	.10652E-01
.14000E+01	.30315E+03	.57848E+00	.19445E-01	.11248E-01
.13500E+01	.30315E+03	.57757E+00	.18923E-01	.10930E-01
.12000E+01	.30315E+03	.57462E+00	.17360E-01	.99751E-02
.80000E+00	.30375E+03	.56351E+00	.13189E-01	.74323E-02
.40000E+00	.30375E+03	.54615E+00	.90191E-02	.49258E-02
.15000E+00	.30375E+03	.52164E+00	.64127E-02	.33451E-02
.20000E+00	.30015E+03	.53501E+00	.69340E-02	.37098E-02
.65000E+00	.30015E+03	.56418E+00	.11625E-01	.65588E-02
.11500E+01	.30015E+03	.57831E+00	.16838E-01	.97378E-02
.15500E+01	.30275E+03	.58165E+00	.21008E-01	.12220E-01
.17150E+01	.30275E+03	.58418E+00	.22729E-01	.13278E-01
.17000E+01	.30275E+03	.58396E+00	.22572E-01	.13181E-01
.15000E+01	.30475E+03	.57770E+00	.20487E-01	.11836E-01
.11500E+01	.30475E+03	.57102E+00	.16838E-01	.96150E-02
.90000E+00	.30475E+03	.56486E+00	.14232E-01	.80390E-02
.70000E+00	.30335E+03	.56081E+00	.12147E-01	.68121E-02
.45000E+00	.30335E+03	.54976E+00	.95404E-02	.52450E-02
.15000E+00	.30335E+03	.52233E+00	.64127E-02	.33496E-02
.10000E+00	.30015E+03	.51789E+00	.58914E-02	.30511E-02
.35000E+00	.30015E+03	.54885E+00	.84978E-02	.46640E-02
.65000E+00	.30215E+03	.56091E+00	.11625E-01	.65209E-02
.87500E+00	.30215E+03	.56832E+00	.13971E-01	.79402E-02
.10750E+01	.30215E+03	.57346E+00	.16056E-01	.92076E-02
.12750E+01	.30335E+03	.57582E+00	.18141E-01	.10446E-01
.13500E+01	.30335E+03	.57725E+00	.18923E-01	.10924E-01
.13500E+01	.30335E+03	.57725E+00	.18923E-01	.10924E-01
.11500E+01	.30365E+03	.57276E+00	.16838E-01	.96443E-02
.85000E+00	.30365E+03	.56519E+00	.13711E-01	.77491E-02
.55000E+00	.30365E+03	.55429E+00	.10583E-01	.58660E-02
.25000E+00	.30235E+03	.53678E+00	.74553E-02	.40018E-02
.15000E+00	.30015E+03	.52790E+00	.64127E-02	.33853E-02
.45000E+00	.30015E+03	.55507E+00	.95404E-02	.52956E-02
.70000E+00	.30015E+03	.56601E+00	.12147E-01	.68752E-02
.92500E+00	.30215E+03	.56971E+00	.14492E-01	.82565E-02
.12250E+01	.30215E+03	.57672E+00	.17620E-01	.10162E-01
.15500E+01	.30215E+03	.58259E+00	.21008E-01	.12239E-01
.17500E+01	.30415E+03	.58251E+00	.23094E-01	.13452E-01
.16500E+01	.30415E+03	.58104E+00	.22051E-01	.12812E-01
.11000E+01	.30415E+03	.57086E+00	.16317E-01	.93146E-02
.75000E+00	.30475E+03	.56028E+00	.12668E-01	.70976E-02
.60000E+00	.30475E+03	.55467E+00	.11104E-01	.61592E-02
.25000E+00	.30475E+03	.53270E+00	.74553E-02	.39714E-02
.50000E-01	.30315E+03	.49533E+00	.53701E-02	.26600E-02

TABLE BP-2: SIMULATION RESULTS OF A SOLAR CELL CONSIDERING BIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (^{o}K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.10000E+00	.30075E+03	.51683E+00	.58914E-02	.30448E-02
.40000E+00	.30075E+03	.55115E+00	.90191E-02	.49709E-02
.85000E+00	.30335E+03	.56567E+00	.13711E-01	.77557E-02
.13000E+01	.30335E+03	.57631E+00	.18402E-01	.10605E-01
.16500E+01	.30335E+03	.58228E+00	.22051E-01	.12840E-01
.19000E+01	.30455E+03	.58396E+00	.24657E-01	.14399E-01
.20250E+01	.30455E+03	.58556E+00	.25961E-01	.15202E-01
.20250E+01	.30455E+03	.58556E+00	.25961E-01	.15202E-01
.18500E+01	.30375E+03	.58453E+00	.24136E-01	.14108E-01
.11500E+01	.30375E+03	.57260E+00	.16838E-01	.96417E-02
.50000E+00	.30375E+03	.55174E+00	.10062E-01	.55514E-02
.20000E+00	.30215E+03	.53157E+00	.69340E-02	.36859E-02
.50000E-01	.30135E+03	.49861E+00	.53701E-02	.26776E-02
.20000E+00	.30135E+03	.53295E+00	.69340E-02	.36954E-02
.45000E+00	.30135E+03	.55308E+00	.95404E-02	.52766E-02
.80000E+00	.30275E+03	.56512E+00	.13189E-01	.74536E-02
.11500E+01	.30275E+03	.57419E+00	.16838E-01	.96683E-02
.13250E+01	.30275E+03	.57773E+00	.18663E-01	.10782E-01
.13250E+01	.30315E+03	.57710E+00	.18663E-01	.10770E-01
.12500E+01	.30315E+03	.57564E+00	.17881E-01	.10293E-01
.10000E+01	.30315E+03	.57006E+00	.15274E-01	.87073E-02
.65000E+00	.30275E+03	.55994E+00	.11625E-01	.65095E-02
.40000E+00	.30275E+03	.54782E+00	.90191E-02	.49408E-02
.20000E+00	.30275E+03	.53054E+00	.69340E-02	.36788E-02
.50000E-01	.30155E+03	.49824E+00	.53701E-02	.26756E-02
.50000E-01	.30015E+03	.50080E+00	.53701E-02	.26893E-02
.30000E+00	.30015E+03	.54504E+00	.79765E-02	.43475E-02
.70000E+00	.30335E+03	.56081E+00	.12147E-01	.68121E-02
.10250E+01	.30335E+03	.57036E+00	.15535E-01	.88605E-02
.12000E+01	.30335E+03	.57430E+00	.17360E-01	.99696E-02
.12500E+01	.29915E+03	.58196E+00	.17881E-01	.10406E-01
.12250E+01	.29915E+03	.58146E+00	.17620E-01	.10246E-01
.11000E+01	.29915E+03	.57880E+00	.16317E-01	.94443E-02
.80000E+00	.30055E+03	.56867E+00	.13189E-01	.75004E-02
.55000E+00	.30055E+03	.55938E+00	.10583E-01	.59199E-02
.30000E+00	.30055E+03	.54436E+00	.79765E-02	.43421E-02
.15000E+00	.30175E+03	.52512E+00	.64127E-02	.33674E-02

*(reading) x (instrument constant, k=.398)=insolation in cal/cm^2/min.

TABLE BP-3 : SIMULATION RESULTS OF A SOLAR CELL CONSIDERING UNIVARIATE MODEL

Radiation* cal/cm^2/min	Temp. (^{o}K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.70000E+00	.30765E+03	.55384E+00	.12147E-01	.67274E-02
.12500E+01	.30765E+03	.56855E+00	.17881E-01	.10166E-01
.16500E+01	.30765E+03	.57559E+00	.22051E-01	.12692E-01
.19200E+01	.30765E+03	.57944E+00	.24866E-01	.14408E-01
.21000E+01	.30765E+03	.58172E+00	.26743E-01	.15557E-01
.21500E+01	.30765E+03	.58231E+00	.27264E-01	.15876E-01
.21000E+01	.30765E+03	.58172E+00	.26743E-01	.15557E-01
.17000E+01	.30765E+03	.57635E+00	.22572E-01	.13010E-01
.12000E+01	.30765E+03	.56751E+00	.17360E-01	.98517E-02
.85000E+00	.30765E+03	.55876E+00	.13711E-01	.76610E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.55000E+00	.30765E+03	.54773E+00	.10583E-01	.57966E-02
.13500E+01	.30765E+03	.57050E+00	.18923E-01	.10796E-01
.17500E+01	.30765E+03	.57709E+00	.23094E-01	.13327E-01
.20500E+01	.30765E+03	.58110E+00	.26221E-01	.15237E-01
.21500E+01	.30765E+03	.58231E+00	.27264E-01	.15876E-01
.21700E+01	.30765E+03	.58255E+00	.27472E-01	.16004E-01
.16500E+01	.30765E+03	.57559E+00	.22051E-01	.12692E-01
.10500E+01	.30765E+03	.56412E+00	.15796E-01	.89107E-02
.10700E+01	.30765E+03	.56460E+00	.16004E-01	.90360E-02
.10700E+01	.30765E+03	.56460E+00	.16004E-01	.90360E-02
.90000E+00	.30765E+03	.56021E+00	.14232E-01	.79729E-02
.80000E+00	.30765E+03	.55723E+00	.13189E-01	.73494E-02
.60000E+00	.30765E+03	.54994E+00	.11104E-01	.61066E-02
.30000E-01	.30765E+03	.47427E+00	.51616E-02	.24480E-02
.12000E+00	.30765E+03	.50923E+00	.60999E-02	.31063E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.90000E+00	.30765E+03	.56021E+00	.14232E-01	.79729E-02
.15700E+01	.30765E+03	.57433E+00	.21217E-01	.12186E-01
.20000E+01	.30765E+03	.58048E+00	.25700E-01	.14918E-01
.19000E+01	.30765E+03	.57917E+00	.24657E-01	.14281E-01
.16700E+01	.30765E+03	.57590E+00	.22260E-01	.12819E-01
.14000E+01	.30765E+03	.57142E+00	.19445E-01	.11111E-01
.11500E+01	.30765E+03	.56643E+00	.16838E-01	.95377E-02
.90000E+00	.30765E+03	.56021E+00	.14232E-01	.79729E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.70000E+00	.30765E+03	.55384E+00	.12147E-01	.67274E-02
.12500E+01	.30765E+03	.56855E+00	.17881E-01	.10166E-01
.16200E+01	.30765E+03	.57513E+00	.21738E-01	.12502E-01
.18200E+01	.30765E+03	.57808E+00	.23823E-01	.13772E-01
.19000E+01	.30765E+03	.57917E+00	.24657E-01	.14281E-01
.18500E+01	.30765E+03	.57850E+00	.24136E-01	.13963E-01

TABLE BP-3 : SIMULATION RESULTS OF A SOLAR CELL CONSIDERING UNIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (^{o}K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.17200E+01	.30765E+03	.57665E+00	.22781E-01	.13136E-01
.15700E+01	.30765E+03	.57433E+00	.21217E-01	.12186E-01
.13000E+01	.30765E+03	.56954E+00	.18402E-01	.10481E-01
.75000E+00	.30765E+03	.55559E+00	.12668E-01	.70383E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.80000E+00	.30765E+03	.55723E+00	.13189E-01	.73494E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.80000E+00	.30765E+03	.55723E+00	.13189E-01	.73494E-02
.12500E+01	.30765E+03	.56855E+00	.17881E-01	.10166E-01
.18000E+01	.30765E+03	.57780E+00	.23615E-01	.13645E-01
.21000E+01	.30765E+03	.58172E+00	.26743E-01	.15557E-01
.20500E+01	.30765E+03	.58110E+00	.26221E-01	.15237E-01
.19000E+01	.30765E+03	.57917E+00	.24657E-01	.14281E-01
.16500E+01	.30765E+03	.57559E+00	.22051E-01	.12692E-01
.95000E+00	.30765E+03	.56159E+00	.14753E-01	.82851E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.15000E+00	.30765E+03	.51486E+00	.64127E-02	.33017E-02
.55000E+00	.30765E+03	.54773E+00	.10583E-01	.57966E-02
.11000E+00	.30765E+03	.50704E+00	.59957E-02	.30401E-02
.14700E+01	.30765E+03	.57266E+00	.20174E-01	.11553E-01
.16000E+01	.30765E+03	.57481E+00	.21530E-01	.12376E-01
.15700E+01	.30765E+03	.57433E+00	.21217E-01	.12186E-01
.11500E+01	.30765E+03	.56643E+00	.16838E-01	.95377E-02
.60000E+00	.30765E+03	.54994E+00	.11104E-01	.61066E-02
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.12000E+00	.30765E+03	.50923E+00	.60999E-02	.31063E-02
.30000E-01	.30765E+03	.47427E+00	.51616E-02	.24480E-02
.30000E-01	.30765E+03	.47427E+00	.51616E-02	.24480E-02
.80000E-01	.30765E+03	.49899E+00	.56829E-02	.28357E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.13000E+01	.30765E+03	.56954E+00	.18402E-01	.10481E-01
.21000E+01	.30765E+03	.58172E+00	.26743E-01	.15557E-01
.20000E+01	.30765E+03	.58048E+00	.25700E-01	.14918E-01
.15500E+01	.30765E+03	.57401E+00	.21008E-01	.12059E-01
.90000E+00	.30765E+03	.56021E+00	.14232E-01	.79729E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.50000E+00	.30765E+03	.54532E+00	.10062E-01	.54868E-02
.75000E+00	.30765E+03	.55559E+00	.12668E-01	.70383E-02
.10500E+01	.30765E+03	.56412E+00	.15796E-01	.89107E-02
.13500E+01	.30765E+03	.57050E+00	.18923E-01	.10796E-01

TABLE BP-3 : SIMULATION RESULTS OF A SOLAR CELL CONSIDERING UNIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (^{o}K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.16000E+01	.30765E+03	.57481E+00	.21530E-01	.12376E-01
.17000E+01	.30765E+03	.57635E+00	.22572E-01	.13010E-01
.17000E+01	.30765E+03	.57635E+00	.22572E-01	.13010E-01
.16000E+01	.30765E+03	.57481E+00	.21530E-01	.12376E-01
.14000E+01	.30765E+03	.57142E+00	.19445E-01	.11111E-01
.11000E+01	.30765E+03	.56530E+00	.16317E-01	.92240E-02
.70000E+00	.30765E+03	.55384E+00	.12147E-01	.67274E-02
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.15000E+00	.30765E+03	.51486E+00	.64127E-02	.33017E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.60000E+00	.30765E+03	.54994E+00	.11104E-01	.61066E-02
.75000E+00	.30765E+03	.55559E+00	.12668E-01	.70383E-02
.92000E+00	.30765E+03	.56077E+00	.14440E-01	.80977E-02
.10500E+01	.30765E+03	.56412E+00	.15796E-01	.89107E-02
.90000E+00	.30765E+03	.56021E+00	.14232E-01	.79729E-02
.65000E+00	.30765E+03	.55197E+00	.11625E-01	.64169E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.22000E+00	.30765E+03	.52454E+00	.71425E-02	.37465E-02
.70000E-01	.30765E+03	.49562E+00	.55787E-02	.27649E-02
.15000E+00	.30765E+03	.51486E+00	.64127E-02	.33017E-02
.55000E+00	.30765E+03	.54773E+00	.10583E-01	.57966E-02
.11000E+01	.30765E+03	.56530E+00	.16317E-01	.92240E-02
.14200E+01	.30765E+03	.57178E+00	.19653E-01	.11237E-01
.13200E+01	.30765E+03	.56993E+00	.18611E-01	.10607E-01
.90000E+00	.30765E+03	.56021E+00	.14232E-01	.79729E-02
.50000E+00	.30765E+03	.54532E+00	.10062E-01	.54868E-02
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.22000E+00	.30765E+03	.52454E+00	.71425E-02	.37465E-02
.70000E-01	.30765E+03	.49562E+00	.55787E-02	.27649E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.50000E+00	.30765E+03	.54532E+00	.10062E-01	.54868E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.52000E+00	.30765E+03	.54631E+00	.10270E-01	.56107E-02
.77000E+00	.30765E+03	.55626E+00	.12877E-01	.71627E-02
.10500E+01	.30765E+03	.56412E+00	.15796E-01	.89107E-02

TABLE BP-3 : SIMULATION RESULTS OF A SOLAR CELL CONSIDERING UNIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (^{o}K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.23000E+01	.30765E+03	.58403E+00	.28828E-01	.16836E-01
.23500E+01	.30765E+03	.58457E+00	.29349E-01	.17157E-01
.22000E+01	.30765E+03	.58290E+00	.27785E-01	.16196E-01
.19000E+01	.30765E+03	.57917E+00	.24657E-01	.14281E-01
.52000E+00	.30765E+03	.54631E+00	.10270E-01	.56107E-02
.22000E+00	.30765E+03	.52454E+00	.71425E-02	.37465E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.30000E-01	.30765E+03	.47427E+00	.51616E-02	.24480E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.22000E+00	.30765E+03	.52454E+00	.71425E-02	.37465E-02
.37000E+00	.30765E+03	.53769E+00	.87063E-02	.46813E-02
.67000E+00	.30765E+03	.55273E+00	.11834E-01	.65410E-02
.12500E+01	.30765E+03	.56855E+00	.17881E-01	.10166E-01
.17500E+01	.30765E+03	.57709E+00	.23094E-01	.13327E-01
.19700E+01	.30765E+03	.58009E+00	.25387E-01	.14727E-01
.20500E+01	.30765E+03	.58110E+00	.26221E-01	.15237E-01
.20000E+01	.30765E+03	.58048E+00	.25700E-01	.14918E-01
.17500E+01	.30765E+03	.57709E+00	.23094E-01	.13327E-01
.13000E+01	.30765E+03	.56954E+00	.18402E-01	.10481E-01
.75000E+00	.30765E+03	.55559E+00	.12668E-01	.70383E-02
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.12000E+00	.30765E+03	.50923E+00	.60999E-02	.31063E-02
.47000E+00	.30765E+03	.54375E+00	.97489E-02	.53010E-02
.97000E+00	.30765E+03	.56211E+00	.14962E-01	.84101E-02
.13000E+01	.30765E+03	.56954E+00	.18402E-01	.10481E-01
.15500E+01	.30765E+03	.57401E+00	.21008E-01	.12059E-01
.16500E+01	.30765E+03	.57559E+00	.22051E-01	.12692E-01
.17000E+01	.30765E+03	.57635E+00	.22572E-01	.13010E-01
.16700E+01	.30765E+03	.57590E+00	.22260E-01	.12819E-01
.15500E+01	.30765E+03	.57401E+00	.21008E-01	.12059E-01
.12000E+01	.30765E+03	.56751E+00	.17360E-01	.98517E-02
.70000E+00	.30765E+03	.55384E+00	.12147E-01	.67274E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.75000E-01	.30765E+03	.49736E+00	.56308E-02	.28005E-02
.22500E+00	.30765E+03	.52511E+00	.71946E-02	.37780E-02
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.55000E+00	.30765E+03	.54773E+00	.10583E-01	.57966E-02
.80000E+00	.30765E+03	.55723E+00	.13189E-01	.73494E-02
.95000E+00	.30765E+03	.56159E+00	.14753E-01	.82851E-02
.95000E+00	.30765E+03	.56159E+00	.14753E-01	.82851E-02
.80000E+00	.30765E+03	.55723E+00	.13189E-01	.73494E-02
.57500E+00	.30765E+03	.54886E+00	.10844E-01	.59516E-02
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.12500E+00	.30765E+03	.51026E+00	.61521E-02	.31392E-02
.25000E-01	.30765E+03	.46969E+00	.51095E-02	.23999E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02

TABLE BP-3 : SIMULATION RESULTS OF A SOLAR CELL CONSIDERING UNIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (^{o}K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.42500E+00	.30765E+03	.54120E+00	.92797E-02	.50222E-02
.57500E+00	.30765E+03	.54886E+00	.10844E-01	.59516E-02
.72500E+00	.30765E+03	.55473E+00	.12407E-01	.68828E-02
.90000E+00	.30765E+03	.56021E+00	.14232E-01	.79729E-02
.97500E+00	.30765E+03	.56224E+00	.15014E-01	.84414E-02
.92500E+00	.30765E+03	.56091E+00	.14492E-01	.81290E-02
.70000E+00	.30765E+03	.55384E+00	.12147E-01	.67274E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.85000E+00	.30765E+03	.55876E+00	.13711E-01	.76610E-02
.17000E+01	.30765E+03	.57635E+00	.22572E-01	.13010E-01
.21500E+01	.30765E+03	.58231E+00	.27264E-01	.15876E-01
.21500E+01	.30765E+03	.58231E+00	.27264E-01	.15876E-01
.19500E+01	.30765E+03	.57983E+00	.25179E-01	.14599E-01
.16500E+01	.30765E+03	.57559E+00	.22051E-01	.12692E-01
.12000E+01	.30765E+03	.56751E+00	.17360E-01	.98517E-02
.65000E+00	.30765E+03	.55197E+00	.11625E-01	.64169E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.15000E+00	.30765E+03	.51486E+00	.64127E-02	.33017E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.42000E+00	.30765E+03	.54090E+00	.92276E-02	.49912E-02
.48000E+00	.30765E+03	.54428E+00	.98531E-02	.53629E-02
.47000E+00	.30765E+03	.54375E+00	.97489E-02	.53010E-02
.47000E+00	.30765E+03	.54375E+00	.97489E-02	.53010E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.42500E+00	.30765E+03	.54120E+00	.92797E-02	.50222E-02
.37500E+00	.30765E+03	.53803E+00	.87584E-02	.47123E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02
.75000E-01	.30765E+03	.49736E+00	.56308E-02	.28005E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.37500E+00	.30765E+03	.53803E+00	.87584E-02	.47123E-02
.75000E+00	.30765E+03	.55559E+00	.12668E-01	.70383E-02
.11000E+01	.30765E+03	.56530E+00	.16317E-01	.92240E-02
.15000E+01	.30765E+03	.57317E+00	.20487E-01	.11743E-01
.17500E+01	.30765E+03	.57709E+00	.23094E-01	.13327E-01
.15500E+01	.30765E+03	.57401E+00	.21008E-01	.12059E-01
.10000E+01	.30765E+03	.56289E+00	.15274E-01	.85978E-02
.55000E+00	.30765E+03	.54773E+00	.10583E-01	.57966E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.15000E+00	.30765E+03	.51486E+00	.64127E-02	.33017E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02

TABLE BP-3 : SIMULATION RESULTS OF A SOLAR CELL CONSIDERING UNIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (°K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.65000E+00	.30765E+03	.55197E+00	.11625E-01	.64169E-02
.85000E+00	.30765E+03	.55876E+00	.13711E-01	.76610E-02
.12500E+01	.30765E+03	.56855E+00	.17881E-01	.10166E-01
.17500E+01	.30765E+03	.57709E+00	.23094E-01	.13327E-01
.22500E+01	.30765E+03	.58347E+00	.28306E-01	.16516E-01
.22250E+01	.30765E+03	.58318E+00	.28046E-01	.16356E-01
.20750E+01	.30765E+03	.58141E+00	.26482E-01	.15397E-01
.16500E+01	.30765E+03	.57559E+00	.22051E-01	.12692E-01
.12500E+01	.30765E+03	.56855E+00	.17881E-01	.10166E-01
.90000E+00	.30765E+03	.56021E+00	.14232E-01	.79729E-02
.60000E+00	.30765E+03	.54994E+00	.11104E-01	.61066E-02
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.12500E+00	.30765E+03	.51026E+00	.61521E-02	.31392E-02
.52500E+00	.30765E+03	.54655E+00	.10322E-01	.56417E-02
.10000E+01	.30765E+03	.56289E+00	.15274E-01	.85978E-02
.13500E+01	.30765E+03	.57050E+00	.18923E-01	.10796E-01
.15750E+01	.30765E+03	.57441E+00	.21269E-01	.12217E-01
.16500E+01	.30765E+03	.57559E+00	.22051E-01	.12692E-01
.16000E+01	.30765E+03	.57481E+00	.21530E-01	.12376E-01
.15750E+01	.30765E+03	.57441E+00	.21269E-01	.12217E-01
.13500E+01	.30765E+03	.57050E+00	.18923E-01	.10796E-01
.11000E+01	.30765E+03	.56530E+00	.16317E-01	.92240E-02
.81500E+00	.30765E+03	.55770E+00	.13346E-01	.74429E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.65500E+00	.30765E+03	.55216E+00	.11678E-01	.64479E-02
.97500E+00	.30765E+03	.56224E+00	.15014E-01	.84414E-02
.12500E+01	.30765E+03	.56855E+00	.17881E-01	.10166E-01
.15500E+01	.30765E+03	.57401E+00	.21008E-01	.12059E-01
.18500E+01	.30765E+03	.57850E+00	.24136E-01	.13963E-01
.22500E+01	.30765E+03	.58347E+00	.28306E-01	.16516E-01
.27500E+01	.30765E+03	.58856E+00	.33519E-01	.19728E-01
.21750E+01	.30765E+03	.58261E+00	.27524E-01	.16036E-01
.19000E+01	.30765E+03	.57917E+00	.24657E-01	.14281E-01
.14500E+01	.30765E+03	.57231E+00	.19966E-01	.11427E-01
.95000E+00	.30765E+03	.56159E+00	.14753E-01	.82851E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02
.65000E+00	.30765E+03	.55197E+00	.11625E-01	.64169E-02
.10500E+01	.30765E+03	.56412E+00	.15796E-01	.89107E-02
.14500E+01	.30765E+03	.57231E+00	.19966E-01	.11427E-01
.16750E+01	.30765E+03	.57597E+00	.22312E-01	.12851E-01
.17900E+01	.30765E+03	.57766E+00	.23511E-01	.13581E-01
.18000E+01	.30765E+03	.57780E+00	.23615E-01	.13645E-01
.17250E+01	.30765E+03	.57672E+00	.22833E-01	.13168E-01

TABLE BP-3 : SIMULATION RESULTS OF A SOLAR CELL CONSIDERING UNIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (^{o}K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.14750E+01	.30765E+03	.57275E+00	.20227E-01	.11585E-01
.12000E+01	.30765E+03	.56751E+00	.17360E-01	.98517E-02
.70000E+00	.30765E+03	.55384E+00	.12147E-01	.67274E-02
.37500E+00	.30765E+03	.53803E+00	.87584E-02	.47123E-02
.12500E+00	.30765E+03	.51026E+00	.61521E-02	.31392E-02
.13000E-01	.30765E+03	.45325E+00	.49844E-02	.22592E-02
.12500E+00	.30765E+03	.51026E+00	.61521E-02	.31392E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.67500E+00	.30765E+03	.55292E+00	.11886E-01	.65721E-02
.95000E+00	.30765E+03	.56159E+00	.14753E-01	.82851E-02
.12000E+01	.30765E+03	.56751E+00	.17360E-01	.98517E-02
.13750E+01	.30765E+03	.57096E+00	.19184E-01	.10953E-01
.14750E+01	.30765E+03	.57275E+00	.20227E-01	.11585E-01
.13750E+01	.30765E+03	.57096E+00	.19184E-01	.10953E-01
.11500E+01	.30765E+03	.56643E+00	.16838E-01	.95377E-02
.85000E+00	.30765E+03	.55876E+00	.13711E-01	.76610E-02
.60000E+00	.30765E+03	.54994E+00	.11104E-01	.61066E-02
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.62500E+00	.30765E+03	.55097E+00	.11365E-01	.62617E-02
.85000E+00	.30765E+03	.55876E+00	.13711E-01	.76610E-02
.11500E+01	.30765E+03	.56643E+00	.16838E-01	.95377E-02
.14000E+01	.30765E+03	.57142E+00	.19445E-01	.11111E-01
.14750E+01	.30765E+03	.57275E+00	.20227E-01	.11585E-01
.12750E+01	.30765E+03	.56905E+00	.18141E-01	.10323E-01
.90000E+00	.30765E+03	.56021E+00	.14232E-01	.79729E-02
.60000E+00	.30765E+03	.54994E+00	.11104E-01	.61066E-02
.34500E+00	.30765E+03	.53592E+00	.84457E-02	.45262E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.17500E+00	.30765E+03	.51876E+00	.66733E-02	.34618E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.70000E+00	.30765E+03	.55384E+00	.12147E-01	.67274E-02
.11500E+01	.30765E+03	.56643E+00	.16838E-01	.95377E-02
.15500E+01	.30765E+03	.57401E+00	.21008E-01	.12059E-01
.17500E+01	.30765E+03	.57709E+00	.23094E-01	.13327E-01
.17000E+01	.30765E+03	.57635E+00	.22572E-01	.13010E-01
.14750E+01	.30765E+03	.57275E+00	.20227E-01	.11585E-01
.12000E+01	.30765E+03	.56751E+00	.17360E-01	.98517E-02
.90000E+00	.30765E+03	.56021E+00	.14232E-01	.79729E-02
.67500E+00	.30765E+03	.55292E+00	.11886E-01	.65721E-02
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.85000E+00	.30765E+03	.55876E+00	.13711E-01	.76610E-02

TABLE BP-3 : SIMULATION RESULTS OF A SOLAR CELL CONSIDERING UNIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (^{o}K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.13500E+01	.30765E+03	.57050E+00	.18923E-01	.10796E-01
.18000E+01	.30765E+03	.57780E+00	.23615E-01	.13645E-01
.21000E+01	.30765E+03	.58172E+00	.26743E-01	.15557E-01
.22000E+01	.30765E+03	.58290E+00	.27785E-01	.16196E-01
.21500E+01	.30765E+03	.58231E+00	.27264E-01	.15876E-01
.19500E+01	.30765E+03	.57983E+00	.25179E-01	.14599E-01
.16500E+01	.30765E+03	.57559E+00	.22051E-01	.12692E-01
.13000E+01	.30765E+03	.56954E+00	.18402E-01	.10481E-01
.80000E+00	.30765E+03	.55723E+00	.13189E-01	.73494E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.55500E+00	.30765E+03	.54796E+00	.10635E-01	.58276E-02
.77500E+00	.30765E+03	.55642E+00	.12929E-01	.71938E-02
.12500E+01	.30765E+03	.56855E+00	.17881E-01	.10166E-01
.15500E+01	.30765E+03	.57401E+00	.21008E-01	.12059E-01
.12500E+01	.30765E+03	.56855E+00	.17881E-01	.10166E-01
.10000E+01	.30765E+03	.56289E+00	.15274E-01	.85978E-02
.71500E+00	.30765E+03	.55438E+00	.12303E-01	.68206E-02
.50000E+00	.30765E+03	.54532E+00	.10062E-01	.54868E-02
.32500E+00	.30765E+03	.53441E+00	.82372E-02	.44020E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.65000E+00	.30765E+03	.55197E+00	.11625E-01	.64169E-02
.95000E+00	.30765E+03	.56159E+00	.14753E-01	.82851E-02
.12000E+01	.30765E+03	.56751E+00	.17360E-01	.98517E-02
.13500E+01	.30765E+03	.57050E+00	.18923E-01	.10796E-01
.13750E+01	.30765E+03	.57096E+00	.19184E-01	.10953E-01
.12750E+01	.30765E+03	.56905E+00	.18141E-01	.10323E-01
.11000E+01	.30765E+03	.56530E+00	.16317E-01	.92240E-02
.75000E+00	.30765E+03	.55559E+00	.12668E-01	.70383E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.15000E+00	.30765E+03	.51486E+00	.64127E-02	.33017E-02
.50000E+00	.30765E+03	.54532E+00	.10062E-01	.54868E-02
.80000E+00	.30765E+03	.55723E+00	.13189E-01	.73494E-02
.10000E+01	.30765E+03	.56289E+00	.15274E-01	.85978E-02
.11000E+01	.30765E+03	.56530E+00	.16317E-01	.92240E-02
.11500E+01	.30765E+03	.56643E+00	.16838E-01	.95377E-02
.11750E+01	.30765E+03	.56698E+00	.17099E-01	.96947E-02
.10750E+01	.30765E+03	.56472E+00	.16056E-01	.90673E-02
.10250E+01	.30765E+03	.56351E+00	.15535E-01	.87542E-02
.92500E+00	.30765E+03	.56091E+00	.14492E-01	.81290E-02

TABLE BP-3 : SIMULATION RESULTS OF A SOLAR CELL CONSIDERING UNIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (°K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.72500E+00	.30765E+03	.55473E+00	.12407E-01	.68828E-02
.50000E+00	.30765E+03	.54532E+00	.10062E-01	.54868E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.65000E+00	.30765E+03	.55197E+00	.11625E-01	.64169E-02
.10000E+01	.30765E+03	.56289E+00	.15274E-01	.85978E-02
.14000E+01	.30765E+03	.57142E+00	.19445E-01	.11111E-01
.17000E+01	.30765E+03	.57635E+00	.22572E-01	.13010E-01
.18500E+01	.30765E+03	.57850E+00	.24136E-01	.13963E-01
.18250E+01	.30765E+03	.57815E+00	.23875E-01	.13804E-01
.16250E+01	.30765E+03	.57520E+00	.21790E-01	.12534E-01
.13500E+01	.30765E+03	.57050E+00	.18923E-01	.10796E-01
.10000E+01	.30765E+03	.56289E+00	.15274E-01	.85978E-02
.65000E+00	.30765E+03	.55197E+00	.11625E-01	.64169E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.80000E+00	.30765E+03	.55723E+00	.13189E-01	.73494E-02
.15500E+01	.30765E+03	.57401E+00	.21008E-01	.12059E-01
.17000E+01	.30765E+03	.57635E+00	.22572E-01	.13010E-01
.20000E+01	.30765E+03	.58048E+00	.25700E-01	.14918E-01
.21000E+01	.30765E+03	.58172E+00	.26743E-01	.15557E-01
.20000E+01	.30765E+03	.58048E+00	.25700E-01	.14918E-01
.17500E+01	.30765E+03	.57709E+00	.23094E-01	.13327E-01
.14000E+01	.30765E+03	.57142E+00	.19445E-01	.11111E-01
.95000E+00	.30765E+03	.56159E+00	.14753E-01	.82851E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.12500E+00	.30765E+03	.51026E+00	.61521E-02	.31392E-02
.37500E+00	.30765E+03	.53803E+00	.87584E-02	.47123E-02
.65000E+00	.30765E+03	.55197E+00	.11625E-01	.64169E-02
.95000E+00	.30765E+03	.56159E+00	.14753E-01	.82851E-02
.12500E+01	.30765E+03	.56855E+00	.17881E-01	.10166E-01
.15000E+01	.30765E+03	.57317E+00	.20487E-01	.11743E-01
.17500E+01	.30765E+03	.57709E+00	.23094E-01	.13327E-01
.17000E+01	.30765E+03	.57635E+00	.22572E-01	.13010E-01
.18000E+01	.30765E+03	.57780E+00	.23615E-01	.13645E-01
.16000E+01	.30765E+03	.57481E+00	.21530E-01	.12376E-01
.12500E+01	.30765E+03	.56855E+00	.17881E-01	.10166E-01
.80000E+00	.30765E+03	.55723E+00	.13189E-01	.73494E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.22500E+00	.30765E+03	.52511E+00	.71946E-02	.37780E-02
.47500E+00	.30765E+03	.54402E+00	.98010E-02	.53319E-02

TABLE BP-3 : SIMULATION RESULTS OF A SOLAR CELL CONSIDERING UNIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (^{o}K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.80000E+00	.30765E+03	.55723E+00	.13189E-01	.73494E-02
.11500E+01	.30765E+03	.56643E+00	.16838E-01	.95377E-02
.15000E+01	.30765E+03	.57317E+00	.20487E-01	.11743E-01
.18250E+01	.30765E+03	.57815E+00	.23875E-01	.13804E-01
.20000E+01	.30765E+03	.58048E+00	.25700E-01	.14918E-01
.19750E+01	.30765E+03	.58016E+00	.25439E-01	.14759E-01
.18750E+01	.30765E+03	.57884E+00	.24397E-01	.14122E-01
.16000E+01	.30765E+03	.57481E+00	.21530E-01	.12376E-01
.12000E+01	.30765E+03	.56751E+00	.17360E-01	.98517E-02
.70000E+00	.30765E+03	.55384E+00	.12147E-01	.67274E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.75000E+00	.30765E+03	.55559E+00	.12668E-01	.70383E-02
.15500E+01	.30765E+03	.57401E+00	.21008E-01	.12059E-01
.21000E+01	.30765E+03	.58172E+00	.26743E-01	.15557E-01
.20000E+01	.30765E+03	.58048E+00	.25700E-01	.14918E-01
.17000E+01	.30765E+03	.57635E+00	.22572E-01	.13010E-01
.13000E+01	.30765E+03	.56954E+00	.18402E-01	.10481E-01
.95000E+00	.30765E+03	.56159E+00	.14753E-01	.82851E-02
.65000E+00	.30765E+03	.55197E+00	.11625E-01	.64169E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.45000E-01	.30765E+03	.48448E+00	.53180E-02	.25765E-02
.17500E+00	.30765E+03	.51876E+00	.66733E-02	.34618E-02
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.50000E+00	.30765E+03	.54532E+00	.10062E-01	.54868E-02
.70000E+00	.30765E+03	.55384E+00	.12147E-01	.67274E-02
.92500E+00	.30765E+03	.56091E+00	.14492E-01	.81290E-02
.12250E+01	.30765E+03	.56803E+00	.17620E-01	.10009E-01
.16000E+01	.30765E+03	.57481E+00	.21530E-01	.12376E-01
.18000E+01	.30765E+03	.57780E+00	.23615E-01	.13645E-01
.16500E+01	.30765E+03	.57559E+00	.22051E-01	.12692E-01
.12500E+01	.30765E+03	.56855E+00	.17881E-01	.10166E-01
.65000E+00	.30765E+03	.55197E+00	.11625E-01	.64169E-02
.27500E+00	.30765E+03	.53019E+00	.77159E-02	.40909E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.15000E+00	.30765E+03	.51486E+00	.64127E-02	.33017E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.13000E+01	.30765E+03	.56954E+00	.18402E-01	.10481E-01
.20500E+01	.30765E+03	.58110E+00	.26221E-01	.15237E-01
.20500E+01	.30765E+03	.58110E+00	.26221E-01	.15237E-01
.18000E+01	.30765E+03	.57780E+00	.23615E-01	.13645E-01
.13500E+01	.30765E+03	.57050E+00	.18923E-01	.10796E-01
.95000E+00	.30765E+03	.56159E+00	.14753E-01	.82851E-02
.65000E+00	.30765E+03	.55197E+00	.11625E-01	.64169E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02

TABLE BP-3 : SIMULATION RESULTS OF A SOLAR CELL CONSIDERING UNIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (^{o}K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02
.42500E+00	.30765E+03	.54120E+00	.92797E-02	.50222E-02
.67500E+00	.30765E+03	.55292E+00	.11886E-01	.65721E-02
.90000E+00	.30765E+03	.56021E+00	.14232E-01	.79729E-02
.13000E+01	.30765E+03	.56954E+00	.18402E-01	.10481E-01
.19000E+01	.30765E+03	.57917E+00	.24657E-01	.14281E-01
.21000E+01	.30765E+03	.58172E+00	.26743E-01	.15557E-01
.17750E+01	.30765E+03	.57745E+00	.23354E-01	.13486E-01
.14250E+01	.30765E+03	.57187E+00	.19705E-01	.11269E-01
.12000E+01	.30765E+03	.56751E+00	.17360E-01	.98517E-02
.95000E+00	.30765E+03	.56159E+00	.14753E-01	.82851E-02
.65000E+00	.30765E+03	.55197E+00	.11625E-01	.64169E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.12000E+01	.30765E+03	.56751E+00	.17360E-01	.98517E-02
.16500E+01	.30765E+03	.57559E+00	.22051E-01	.12692E-01
.15500E+01	.30765E+03	.57401E+00	.21008E-01	.12059E-01
.13750E+01	.30765E+03	.57096E+00	.19184E-01	.10953E-01
.11250E+01	.30765E+03	.56587E+00	.16578E-01	.93808E-02
.82500E+00	.30765E+03	.55801E+00	.13450E-01	.75052E-02
.52500E+00	.30765E+03	.54655E+00	.10322E-01	.56417E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.75000E+00	.30765E+03	.55559E+00	.12668E-01	.70383E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.52500E+00	.30765E+03	.54655E+00	.10322E-01	.56417E-02
.60000E+00	.30765E+03	.54994E+00	.11104E-01	.61066E-02
.65000E+00	.30765E+03	.55197E+00	.11625E-01	.64169E-02
.62500E+00	.30765E+03	.55097E+00	.11365E-01	.62617E-02
.55000E+00	.30765E+03	.54773E+00	.10583E-01	.57966E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.80000E+00	.30765E+03	.55723E+00	.13189E-01	.73494E-02
.13500E+01	.30765E+03	.57050E+00	.18923E-01	.10796E-01
.17000E+01	.30765E+03	.57635E+00	.22572E-01	.13010E-01
.11000E+01	.30765E+03	.56530E+00	.16317E-01	.92240E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02

TABLE BP-3 : SIMULATION RESULTS OF A SOLAR CELL CONSIDERING UNIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (°K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.55000E+00	.30765E+03	.54773E+00	.10583E-01	.57966E-02
.92500E+00	.30765E+03	.56091E+00	.14492E-01	.81290E-02
.12150E+01	.30765E+03	.56783E+00	.17516E-01	.99460E-02
.13500E+01	.30765E+03	.57050E+00	.18923E-01	.10796E-01
.12250E+01	.30765E+03	.56803E+00	.17620E-01	.10009E-01
.10000E+01	.30765E+03	.56289E+00	.15274E-01	.85978E-02
.75000E+00	.30765E+03	.55559E+00	.12668E-01	.70383E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.15000E+00	.30765E+03	.51486E+00	.64127E-02	.33017E-02
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.65000E+00	.30765E+03	.55197E+00	.11625E-01	.64169E-02
.14000E+01	.30765E+03	.57142E+00	.19445E-01	.11111E-01
.19500E+01	.30765E+03	.57983E+00	.25179E-01	.14599E-01
.15000E+01	.30765E+03	.57317E+00	.20487E-01	.11743E-01
.92500E+00	.30765E+03	.56091E+00	.14492E-01	.81290E-02
.65000E+00	.30765E+03	.55197E+00	.11625E-01	.64169E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.15000E+00	.30765E+03	.51486E+00	.64127E-02	.33017E-02
.25000E-01	.30765E+03	.46969E+00	.51095E-02	.23999E-02
.75000E-01	.30765E+03	.49736E+00	.56308E-02	.28005E-02
.17500E+00	.30765E+03	.51876E+00	.66733E-02	.34618E-02
.47500E+00	.30765E+03	.54402E+00	.98010E-02	.53319E-02
.11000E+01	.30765E+03	.56530E+00	.16317E-01	.92240E-02
.14500E+01	.30765E+03	.57231E+00	.19966E-01	.11427E-01
.12500E+01	.30765E+03	.56855E+00	.17881E-01	.10166E-01
.10000E+01	.30765E+03	.56289E+00	.15274E-01	.85978E-02
.80000E+00	.30765E+03	.55723E+00	.13189E-01	.73494E-02
.60000E+00	.30765E+03	.54994E+00	.11104E-01	.61066E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.15000E+00	.30765E+03	.51486E+00	.64127E-02	.33017E-02
.15000E+00	.30765E+03	.51486E+00	.64127E-02	.33017E-02
.50000E+00	.30765E+03	.54532E+00	.10062E-01	.54868E-02
.80000E+00	.30765E+03	.55723E+00	.13189E-01	.73494E-02
.10000E+01	.30765E+03	.56289E+00	.15274E-01	.85978E-02
.12000E+01	.30765E+03	.56751E+00	.17360E-01	.98517E-02
.14000E+01	.30765E+03	.57142E+00	.19445E-01	.11111E-01
.15500E+01	.30765E+03	.57401E+00	.21008E-01	.12059E-01
.15500E+01	.30765E+03	.57401E+00	.21008E-01	.12059E-01
.14000E+01	.30765E+03	.57142E+00	.19445E-01	.11111E-01
.11500E+01	.30765E+03	.56643E+00	.16838E-01	.95377E-02
.80000E+00	.30765E+03	.55723E+00	.13189E-01	.73494E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.15000E+00	.30765E+03	.51486E+00	.64127E-02	.33017E-02
.15000E+00	.30765E+03	.51486E+00	.64127E-02	.33017E-02
.15500E+01	.30765E+03	.57401E+00	.21008E-01	.12059E-01
.10500E+01	.30765E+03	.56412E+00	.15796E-01	.89107E-02

TABLE BP-3 : SIMULATION RESULTS OF A SOLAR CELL CONSIDERING UNIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (^{o}K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.14500E+01	.30765E+03	.57231E+00	.19966E-01	.11427E-01
.17000E+01	.30765E+03	.57635E+00	.22572E-01	.13010E-01
.18000E+01	.30765E+03	.57780E+00	.23615E-01	.13645E-01
.17500E+01	.30765E+03	.57709E+00	.23094E-01	.13327E-01
.16000E+01	.30765E+03	.57481E+00	.21530E-01	.12376E-01
.12500E+01	.30765E+03	.56855E+00	.17881E-01	.10166E-01
.75000E+00	.30765E+03	.55559E+00	.12668E-01	.70383E-02
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.95000E+00	.30765E+03	.56159E+00	.14753E-01	.82851E-02
.14000E+01	.30765E+03	.57142E+00	.19445E-01	.11111E-01
.18000E+01	.30765E+03	.57780E+00	.23615E-01	.13645E-01
.20000E+01	.30765E+03	.58048E+00	.25700E-01	.14918E-01
.19500E+01	.30765E+03	.57983E+00	.25179E-01	.14599E-01
.18000E+01	.30765E+03	.57780E+00	.23615E-01	.13645E-01
.15500E+01	.30765E+03	.57401E+00	.21008E-01	.12059E-01
.11500E+01	.30765E+03	.56643E+00	.16838E-01	.95377E-02
.70000E+00	.30765E+03	.55384E+00	.12147E-01	.67274E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.12500E+00	.30765E+03	.51026E+00	.61521E-02	.31392E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.72500E+00	.30765E+03	.55473E+00	.12407E-01	.68828E-02
.10500E+01	.30765E+03	.56412E+00	.15796E-01	.89107E-02
.14500E+01	.30765E+03	.57231E+00	.19966E-01	.11427E-01
.18000E+01	.30765E+03	.57780E+00	.23615E-01	.13645E-01
.18000E+01	.30765E+03	.57780E+00	.23615E-01	.13645E-01
.16000E+01	.30765E+03	.57481E+00	.21530E-01	.12376E-01
.13500E+01	.30765E+03	.57050E+00	.18923E-01	.10796E-01
.10000E+01	.30765E+03	.56289E+00	.15274E-01	.85978E-02
.60000E+00	.30765E+03	.54994E+00	.11104E-01	.61066E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.75000E+00	.30765E+03	.55559E+00	.12668E-01	.70383E-02
.12000E+01	.30765E+03	.56751E+00	.17360E-01	.98517E-02
.14500E+01	.30765E+03	.57231E+00	.19966E-01	.11427E-01
.15250E+01	.30765E+03	.57359E+00	.20748E-01	.11901E-01
.14500E+01	.30765E+03	.57231E+00	.19966E-01	.11427E-01
.12000E+01	.30765E+03	.56751E+00	.17360E-01	.98517E-02
.90000E+00	.30765E+03	.56021E+00	.14232E-01	.79729E-02
.70000E+00	.30765E+03	.55384E+00	.12147E-01	.67274E-02
.50000E+00	.30765E+03	.54532E+00	.10062E-01	.54868E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02

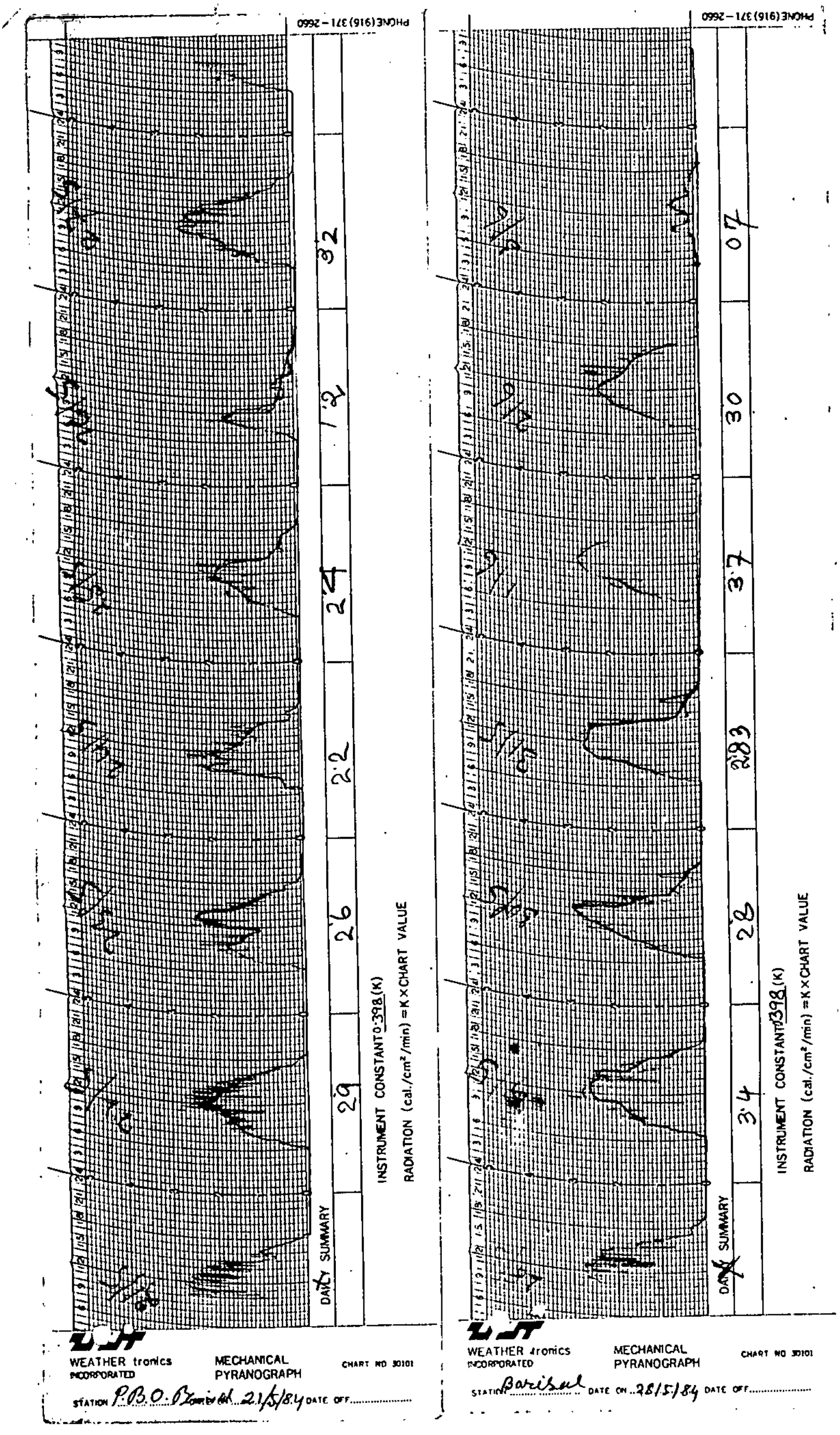
TABLE BP-3 : SIMULATION RESULTS OF A SOLAR CELL CONSIDERING UNIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (^{o}K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.60000E+00	.30765E+03	.54994E+00	.11104E-01	.61066E-02
.80000E+00	.30765E+03	.55723E+00	.13189E-01	.73494E-02
.10500E+01	.30765E+03	.56412E+00	.15796E-01	.89107E-02
.13000E+01	.30765E+03	.56954E+00	.18402E-01	.10481E-01
.14000E+01	.30765E+03	.57142E+00	.19445E-01	.11111E-01
.13500E+01	.30765E+03	.57050E+00	.18923E-01	.10796E-01
.12000E+01	.30765E+03	.56751E+00	.17360E-01	.98517E-02
.80000E+00	.30765E+03	.55723E+00	.13189E-01	.73494E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.15000E+00	.30765E+03	.51486E+00	.64127E-02	.33017E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02
.65000E+00	.30765E+03	.55197E+00	.11625E-01	.64169E-02
.11500E+01	.30765E+03	.56643E+00	.16838E-01	.95377E-02
.15500E+01	.30765E+03	.57401E+00	.21008E-01	.12059E-01
.17150E+01	.30765E+03	.57657E+00	.22729E-01	.13105E-01
.17000E+01	.30765E+03	.57635E+00	.22572E-01	.13010E-01
.15000E+01	.30765E+03	.57317E+00	.20487E-01	.11743E-01
.11500E+01	.30765E+03	.56643E+00	.16838E-01	.95377E-02
.90000E+00	.30765E+03	.56021E+00	.14232E-01	.79729E-02
.70000E+00	.30765E+03	.55384E+00	.12147E-01	.67274E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.15000E+00	.30765E+03	.51486E+00	.64127E-02	.33017E-02
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.35000E+00	.30765E+03	.53629E+00	.84978E-02	.45573E-02
.65000E+00	.30765E+03	.55197E+00	.11625E-01	.64169E-02
.87500E+00	.30765E+03	.55950E+00	.13971E-01	.78169E-02
.10750E+01	.30765E+03	.56472E+00	.16056E-01	.90673E-02
.12750E+01	.30765E+03	.56905E+00	.18141E-01	.10323E-01
.13500E+01	.30765E+03	.57050E+00	.18923E-01	.10796E-01
.13500E+01	.30765E+03	.57050E+00	.18923E-01	.10796E-01
.11500E+01	.30765E+03	.56643E+00	.16838E-01	.95377E-02
.85000E+00	.30765E+03	.55876E+00	.13711E-01	.76610E-02
.55000E+00	.30765E+03	.54773E+00	.10583E-01	.57966E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.15000E+00	.30765E+03	.51486E+00	.64127E-02	.33017E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.70000E+00	.30765E+03	.55384E+00	.12147E-01	.67274E-02
.92500E+00	.30765E+03	.56091E+00	.14492E-01	.81290E-02
.12250E+01	.30765E+03	.56803E+00	.17620E-01	.10009E-01
.15500E+01	.30765E+03	.57401E+00	.21008E-01	.12059E-01
.17500E+01	.30765E+03	.57709E+00	.23094E-01	.13327E-01
.16500E+01	.30765E+03	.57559E+00	.22051E-01	.12692E-01
.11000E+01	.30765E+03	.56530E+00	.16317E-01	.92240E-02
.75000E+00	.30765E+03	.55559E+00	.12668E-01	.70383E-02
.60000E+00	.30765E+03	.54994E+00	.11104E-01	.61066E-02
.25000E+00	.30765E+03	.52777E+00	.74553E-02	.39347E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02

TABLE BP-3 : SIMULATION RESULTS OF A SOLAR CELL CONSIDERING UNIVARIATE MODEL(Continued)

Radiation* cal/cm^2/min	Temp. (°K)	Cell Voltage (volts)	Cell Current (amp)	EQGEN (watt)
.10000E+00	.30765E+03	.50462E+00	.58914E-02	.29729E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.85000E+00	.30765E+03	.55876E+00	.13711E-01	.76610E-02
.13000E+01	.30765E+03	.56954E+00	.18402E-01	.10481E-01
.16500E+01	.30765E+03	.57559E+00	.22051E-01	.12692E-01
.19000E+01	.30765E+03	.57917E+00	.24657E-01	.14281E-01
.20250E+01	.30765E+03	.58079E+00	.25961E-01	.15078E-01
.20250E+01	.30765E+03	.58079E+00	.25961E-01	.15078E-01
.18500E+01	.30765E+03	.57850E+00	.24136E-01	.13963E-01
.11500E+01	.30765E+03	.56643E+00	.16838E-01	.95377E-02
.50000E+00	.30765E+03	.54532E+00	.10062E-01	.54868E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02
.45000E+00	.30765E+03	.54265E+00	.95404E-02	.51771E-02
.80000E+00	.30765E+03	.55723E+00	.13189E-01	.73494E-02
.11500E+01	.30765E+03	.56643E+00	.16838E-01	.95377E-02
.13250E+01	.30765E+03	.57002E+00	.18663E-01	.10638E-01
.13250E+01	.30765E+03	.57002E+00	.18663E-01	.10638E-01
.12500E+01	.30765E+03	.56855E+00	.17881E-01	.10166E-01
.10000E+01	.30765E+03	.56289E+00	.15274E-01	.85978E-02
.65000E+00	.30765E+03	.55197E+00	.11625E-01	.64169E-02
.40000E+00	.30765E+03	.53967E+00	.90191E-02	.48673E-02
.20000E+00	.30765E+03	.52213E+00	.69340E-02	.36205E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.50000E-01	.30765E+03	.48714E+00	.53701E-02	.26160E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.70000E+00	.30765E+03	.55384E+00	.12147E-01	.67274E-02
.10250E+01	.30765E+03	.56351E+00	.15535E-01	.87542E-02
.12000E+01	.30765E+03	.56751E+00	.17360E-01	.98517E-02
.12500E+01	.30765E+03	.56855E+00	.17881E-01	.10166E-01
.12250E+01	.30765E+03	.56803E+00	.17620E-01	.10009E-01
.11000E+01	.30765E+03	.56530E+00	.16317E-01	.92240E-02
.80000E+00	.30765E+03	.55723E+00	.13189E-01	.73494E-02
.55000E+00	.30765E+03	.54773E+00	.10583E-01	.57966E-02
.30000E+00	.30765E+03	.53239E+00	.79765E-02	.42466E-02
.15000E+00	.30765E+03	.51486E+00	.64127E-02	.33017E-02

* Chart reading X (instrument constant,K=0.398)=Insolation in Cal/cm^2/min.



Figure–BP.1 Solar radiation graphs.

APPENDIX - C

Table CC-1 : Data used for cost analysis [19,26,74,92,93]

ITEM/TYPES OF UNIT	WIND	SOLAR	THERMAL	
RATED CAPACITY (KW)	45	5 (1 M Solar Cells)	100	200
CAPACITY	$29,900[c]	$29800[e] (@ $ 5.961/Wpeak)	$26800[e]	$34000[e]
EXPECTED LIFE(YRS)	10[d]	10[d]	15[d]	15[d]
FUEL COST O & M COST ($)	$300/year [d]	$ 1000/year [b]	$0.0657/kwh [a]	$0.0661/kwh [a]
SALVAGE VALUE($)	$1000[d]	$1000[d]	$1500[d]	$1500[d]
INTEREST RATE(%)	12[d]	12[d]	12[d]	12[d]

[a] Reference 19
[b] Reference 26
[c] Reference 74
[d] Reference 92
[e] Reference 93

ANNUAL CAPITAL (RECOVERY) COST

ANNUAL CAPITAL RECOVERY COST

P = Initial Investment (Initial Capital Cost)

L = Salvage value at the end of n years

n = Life of the machine

i = Interest rate

Cost Analysis

(a) WIND TURBINE GENERATOR

P = Capacity Cost = 29,900 \$ for 45 KW, WTG

L = \$ 1000

i = 12%

n = 10 years

Annual Capital Recovery Cost (excluding O & M Cost)

$$= (29,900-1000) \quad \frac{.12(1 + .12)^{10}}{(1 + .12)^{10} - 1} + 0.12 \times 1000$$

$$= 28900 \quad \frac{.12\ (3.105848208)}{3,105848208 - 1} + 120$$

$$= 28900\ (.176984164) + 120$$

$$= 5234.842345$$

TOTAL ANNUAL COST (INCLUDING O & M COST/YEAR)

$$= 5234.842345 + 300$$

$$= \$\ 5534.842345$$

(b) SOLAR

SOLAR PHOTOVOLTAIC GENERATOR

P = \$ 29800 for 1M Solar Cells generating 5 KW capacity

L = \$ 1000

i = 12%

n = 10 years

Annual Capital Recovery Cost (Excluding O & M Cost)

$$=(29,800 - 1000)\ \frac{0.12(1 + 0.12)^{10}}{(1 + 0.12)^{10} - 1} + 0.12 \times 1000$$

= 288800 0.37270178/2.105848208 + 0.12 x 1000

= 28,800 [0.176984164) + 120

= 5217.143923

TOTAL ANNUAL COST (INCLUDING O & M COST)

= 5217.143923 + 1000

= \$ 6217.143923

(c) THERMAL GENERATOR

(I) 100 KW GENERATOR UNIT

P = \$ 26800

L = \$ 1500

i = 12%

n = 15 years

TOTAL CAPITAL RECOVERY COST (EXCLUDING FUEL +(O & M)COST)

$= 26800 - 1500\ [\ 0.12(1 + 0.12)^{15}/((1 + 0.12)^{15} - 1)] + 0.12 \text{ X } 1500$

$= 25300\ [0.146824239\ ] + 180$

$= \$\ 3894.653263$

ANNUAL EXPECTED FUEL AND O & M COST

= [Expected Fuel Cost/NH] x 8760

(ii) <u>200 KW GENERATOR UNIT</u>

$P = \$\ 34000$

$L = \$\ 1500$

$i = 12\%$

$n = 15$ years

ANNUAL CAPITAL RECOVERY COST (EXCLUDING O & M COST)

$= 34000 - 1500\ [\ 0.12(1 + 0.12)^{15}/((1 + 0.12)^{15} - 1)] + 0.12 \times 1500$

$= 32500\ [\ 0.146824239] + 180$

$= 4771.787768 + 180$

$= \$\ 4951.787768$