A METHODOLOGY FOR EVALUATING PHOTOVOLTAIC-FUEL CELL HYBIRD ENERGY SYSTEMS

by

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(ABSTRACT)

A major issue encountered in the large scale use of Photovoltaic (PV) energy sources for the production of electricity is the variability of the resource itself. Extensive fluctuations of the PV generation may cause dynamic operational problems for an electric utility. In order to remedy this situation it is proposed that fuel cell power plants be operated in parallel with PV arrays. This hybrid operation will help to smooth out the fluctuating PV output. Because of its high ramping capability the fuel cell will be able to absorb such fluctuations.

An overall methodology is presented to evaluate the PV system in a large utility. This methodology has two parts-planning and operation. The aim of the planning study is to determine the capacity credit of a PV system based on the loss of load probability (LOLP). Long term SOLMET data is used to determine the nature of available insolation at a particular site. The expected value of hourly insolation is used in the planning study. The aim of the operation study is to validate the results of planning study in the shorter operational time frame, and determine the fuel cell requirements and associated operating cost savings for each penetration level of PV.

A technique to find the maximum penetration level of PV, without causing any economic penalty, is presented. It is found that the penetration level can be increased upto 15.62% of peak load by adding fuel cells to the system under consideration. The annual peak load for this system is taken as 6400 MW. It must be mentioned here that, similar evaluations for other systems may

yield somewhat different results. This technique is general enough such that it can be used for other intermittent sources of generation as well.

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Table of Contents

List of Illustrations

List of Tables

CHAPTER I

1.0 Introduction

1.1 Purpose

Due to the steep increase in the capital costs of conventional power plants in the last several years, increased interest and incentives have been created for the development of electric supplies utilizing renewable energy sources. Photovoltaic(PV) generation represents one such potential long-range conversion device which is applicable to most geographical regions.

The other factor which increases the interest in PV is the capacity problem. As the demand goes up the utilities look for new capacity. The nuclear and coal capacities come in large sizes and are very expensive. These plants should be built in large sizes to take advantages of the economies of scale, but the large capacity addition does not match the rate of load growth. Smaller capacity additions can match the growing load more evenly. So PV system seems to be a candidate. However, due to high capital cost the PV systems are not yet economically competitive at central station level. Several utilities in this country, Japan and in Europe, however, are building MW size PV plants to explore their acceptability in the generation mix.

Substantial research and development work on PV cells has been done and is continuing in many large and small corporations. Significant cost reductions have been achieved in the last five years but much more needs to be accomplished to make PV cells truly cost effective. Most of the cost reduction efforts have been devoted to crystalline silicon PV cells, primarily through improvements in manufacturing techniques. The thin film designs, however, appear to hold a better long-term potential for providing future cost reduction breakthroughs.

On the other hand, research is going on looking into the integration of PV systems into the utility grid. There are a number of models which are capable of performing various segments of the overall requirements (e.g.,output power, capacity factor, and cost).

In general, these models take a deterministic approach for evaluating the PV performance. In other words, these models use the value for insolation and other weather parameters along with module characteristics to determine output power of PV array under these conditions. They may be called point analysis models. Such models are useful for comparing the performance of different PV cells under a set of given conditions. But there is also a need, may be greater one, to develop models which will be able to predict the performance of PV systems based on long-term climatological data and expected cell performance. This model will be useful for planning purposes and production cost analysis. The deterministic approach which is currently being practiced is not suitable for such applications. A probabilistic approach to performance modeling is necessary to capture the uncertainties in solar radiation and cell performance.

In this study a methodology is presented to predict the performance of photovoltaic PV systems based on long-term climatological data and expected cell performance, A discussion of the methodology is given in chapter III.

A primary application of PV electric generation is expected to be in the electric utility grid. However, any output power variation due to the intermittent nature of the PV can cause undesirable dynamic impacts on the utility system, such as excessive frequency and/or tie-line power flow deviations. As a consequence, spinning reserve, unloadable generation, and load-following requirements and their associated economic penalties tend to increase as PV electric generation is added to the system. However, if fast ramp rate generation units are added to the system, the associated operation and economic penalties can be significantly reduced. In this study fuel cell plants are introduced in conjunction with the PV system. Fuel cells have very high ramping capabilities which can enhance the effectiveness of PV arrays in the utility system. A brief discussion of the operation of fuel cell operation is presented in Chapter II. A discussion of the PV-fuel cell integration technique is provided in Chapter III.

A technique has been developed, and presented in this dissertation, to determine the upper limit of PV penetration into the grid. Because of the integration of fuel cell with the PV system, the upper limit of PV penetration into the grid is expected to be higher than that of PV alone. This technique will be useful for evaluating the potential of PV system to the utilities.

1.2 State of the Art

1.2.1 Photovoltaic system

There are numerous papers/reports that discuss photovoltaic system models for evaluating electricity generation. The value analysis studies that have been completed to date have used hourly average insolation data in a deterministic fashion (that is hourly weather data was simply input directly to a PV performance model). A great majority of authors take this approach for calculating the PV performance. Several such papers/reports are discussed in the following.

Hart [1], Hsiao and Blevins [2] have developed mathematical models for the solar cell I-V characteristics to calculate the array voltage and current at any temperature and insolation level. The hourly insolation data computed using the typical meteorological year (TMY) SOLMET data is used as input to the simulation program. Ku, et al. [3] have presented an algorithm to convert insolation measurements to corresponding insolation intensity on a tilted panel. Then the insolation intensity is converted to electric output using the following efficiency equation:

$$e(T) = e(T_r) - [1 - .0062(T - T_r)] \tag{1}$$

Where,

- T = actual cell temperature
- T_r = cell reference temperature
- e(T) = solar cell efficiency at T
- e(T_r) = solar cell efficiency at T_r

Stranix and Firester [4] use an algorithm to calculate a semi-hourly cumulative energy output from a solar panel. They use the insolation data which describe an average day of each of the four seasons. The calculation is repeated every 30 minutes.

On the other hand, a few other authors have studied the probabilistic nature of variability in insolation levels. Harper and Percival [5], for example, use historical weather data to develop probability information of direct and global insolation for each hour of a typical day of each month. They determine the number of time the reported insolations lie within specified ranges of insolation levels and thus calculate their probability of occurrence. Then the expected insolation at any hour can be calculated by multiplying the insolation by its probability of occurrence and then use it as input to the model. This model is developed from the SOLCELL-II PV system analysis program [6].

B. W. Mcneill and M. A. Mirza [7] introduced a PV cell model which can scale the performance up to account for the series/parallel wiring of the cells in the array. The array model includes a resistance R for the wire from the array to the inverter. An individual cell is modeled using a combination of a single diode and series resistance R_s. The empirical model for the single cell current and voltage are given by :

$$I_c = I_1 - I_0 \exp[(I_c R_s + V_c)q/AKT] - 1 \tag{2}$$

Where I_1 is given by

$$I_1 = I_{sc} \frac{[\exp(V_{oc}q/AKT) - 1]}{[\exp(V_{oc}q/AKT) - \exp(I_{sc}R_s q/AKT)]} \tag{3}$$

If there are N_s cells connected in series and N_p parallel strings in the array then the array current and voltage modeled by the following equation.

$$I_c/N_p = I_1 - I_0 \exp[(I_c/N_p)R_s + (V_c/N_s)q/AKT] - 1 \quad (4)$$

The equivalent circuit they used is shown in figure 1.

P. E. Payne and J. L. Sheehan [8] introduced a hybrid combination of PV system and wind energy conversion systems (WECS) which forms a hybrid alternate energy system. They conclude that this system increases overall energy output and decreases energy storage requirements.

S. Rahman [9] and S. Rahman and K-S. Tam [10] have discussed the hybrid operation of PV and fuel cell power plants that is expected to produce demand sensitive power regardless of the fluctuations introduced by an intermittent PV source.

M. W. Edenbun and et al. [11] presented expression for efficiency that is a linear function of cell temperature and insolation. They used this expression to correlate test data for concentrating PV modules. The expression is used for efficiency is given by the following equation.

$$\eta = a_1 + a_2 (T_r - T) + a_r (1 - S/S_r) \quad (5)$$

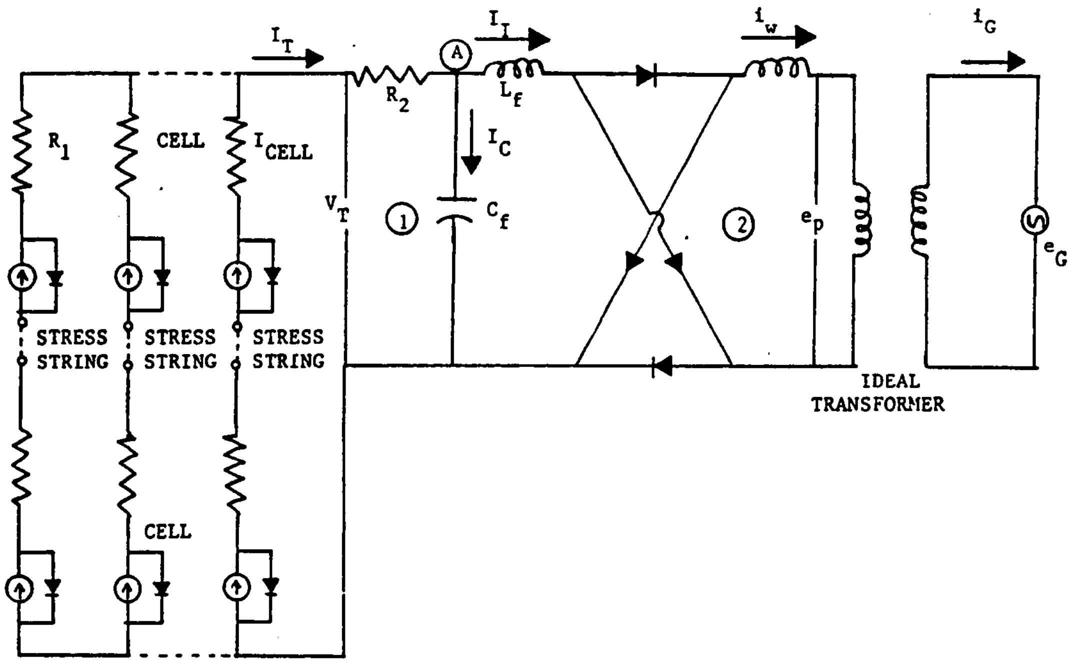
Where,

- η is the module efficiency at cell temperature T and direct insolation S
- a_1 is module efficiency at reference cell temperature T_r and insolation S_r
- a_2 is the temperature coefficient.
- a_3 is the insolation coefficient.

They also included the effect of wind speed and insolation to represent the cell temperature.

An EPRI report [12] published in 1983 calculated the PV power output power as the following.

1. Calculate the PV array efficiency



[Source: Ref. 7]

Figure 1. Equivalent Circuit

$$\eta = \eta_r \,[1 - 0.005(T - T_r)] \tag{6}$$

Where,

- η is the array efficiency.
- η_r is the reference efficiency at reference temperature.
- T_r is the reference temperature.

2. Calculate the total system efficiency

$$\eta_{sys} = \eta \, \eta_{bos} \, \eta_{pcs} \tag{7}$$

Where,

- η_{bos} is the balance of system efficiency,and
- η_{pcs} is the power condition system efficiency.

3. Finally, output power P is calculated by the following equation.

$$P = A.S. \tag{8}$$

Where A is the array area.

The following conclusions emerge from the Photovoltaic system literature review.

1. Most of the methods used for evaluating the performance of PV system are deterministic.

2. Experimental measurements are used to evaluate the performance of PV system by using regression.

3. Cell temperature is modeled by a linear relationship between ambient temperature and insolation level.

4. The solar cell is modeled by a single diode and series resistance.

1.2.2 Operating Problem and Control of PV:

Utility operation consist of two phases-operation planning and operation and the real time operations of the power system. Operations planning is an off-line process which involves the commitment of generation and transmission facilities for use over the next one to three days. Real time operations involve the on-line management and control of generating units and transmission facilities. The overall objective of utility operations is to assure that the power system meets its load. economically and reliably meets Because of the intermittent nature of renewable energy sources and the operating problems associated with it, a lot of operating strategies have been discussed in the literature.

There are many papers and reports that discuss the operating problems caused by increasing the penetration level of renewable sources of energy and suggest various control strategies. A control strategy for an AC/DC/AC interface to smooth or limit wind farm output is developed by A.Shi, J.Thorp and R.Thomas [13]. This strategy is limited to the use of wind generation in order to avoid some operating problems.

T.W.Reddoch, et al. [14] developed strategies for minimizing operational impacts of large wind turbine arrays on automatic generation control system (AGC). These strategies are based on anticipating the array power variations over 10 minutes. AGC will be ready to react before the ramp rate of the wind takes place in the system. These strategies need more control and information processing functions to anticipate the array power variations. Generally, these are very expensive.

Lee and Yamayee [15] concluded that increasing penetration level of wind causes a linear increase in spinning reserve and load following requirements. They found that increased spinning reserve requirements impose the greatest penalty costs for penetration below 5%, but load following requirements impose the greater penalty for penetration over 5%. For any substantial penetration, they find that these two factors eliminate entirely the energy and capacity credits otherwise assignable to wind.

Chan et al [16] concluded that both short and long term changes in wind power generation may alter the cost of system operation, if the penetration is above 10%. At levels of penetrations under 10% of the utility's total capacity, wind output fluctuations are indistinguishable from amount of noise in the generation system, and no additional costs are incurred. Furthermore, the impact of high wind penetrations depends on the generation mix of the system. Systems composed primarily of nuclear and large coal, operating reserve and unloadable generation for wind penetrations exceeding 10% may create additional costs. However, systems which have significant amounts of hydro, gas turbines or oil-fired plants have a high response rate without adding additional generation capacity. The following conclusion emerge for the previous review.

1. The renewable generation (solar, wind, etc.) will be limited unless new strategies to smooth the variations of the load are developed.

2. Most of the strategies which have been attempted in the past have a tendency to decrease the output power of renewable sources in order to smooth out the fluctuations.

1.3 Objective

The present research objective consists of the following tasks:

1. Develop a probabilistic methodology to predict the performance of a PV electric energy system that capture the uncertainties both in solar insolation and solar cell performance (discussion of the methodology is provided in Chapter IV).

2. Add fuel cells to the system to improve its control capability (discussion of the approach is provided in Chapter III).

3. Develop an overall methodology to determine the PV capacity credit and the amount of fuel cell to be added. This is done in two parts-planning and operation. The results of step 1 will be used in planning study. The total net savings will be calculated for each PV penetration level. (discussion of the methodology is provided in Chapter III).

The time span used in this thesis study is six years (from 1985 to 1991). This interval is long enough to reflect the effect of PV generation.

CHAPTER II

2.0 Fuel Cell

2.1 Fuel Cell background

The concept of producing electricity directly by an electro-chemical process in a fuel cell has been known for over a century. It was first demonstrated in England by Sir William Grove in 1839 [17]. However, it remained little more than a laboratory curiosity until the space program. The efficiency and simplicity of the fuel cell led to development of reliable fuel cell electric power system which were used in Apollo space vehicles with the systems' by-product water being consumed by the astronauts.

Many of the fuel cell characteristics such as high efficiency, modular construction and almost no polluting emissions, that made this appealing for space applications, were also attractive to some electric utilities.

In the early 1970's a group of electric utilities initiated a research and development program to determine the potential of fuel cell technology for commercial electric power generation. That program has led to increased developmental efforts and eventually to the installation of the 4.5 MW AC (4.8 MW DC) phosphoric-acid fuel cell demonstrator in New York city on Con Edison's system. Tokoy Electric Power Company (TEPCO) installed another 4.5 MW fuel cell plant which has operated successfully over an extended period of time. The TEPCO demonstrator was operated between 25% and 100% of rated, producing utility-quality power and only minimal emissions [18].

Since then, a lot of papers and reports have been published discussing the fuel cell technology and its future role in electric utility systems.

An EPRI study [19] published in 1976 provided an economic assessment of the use of fuel cells in electric utility systems. In discussing the results of that study, the dollar values shown herein have been extrapolated from those contained in the 1976 study to 1981 costs using an average annual inflation ratio of 8%.

The EPRI study analyzed capacity additions to a reference utility system on a long range optimum generation mix basis. The characteristics of the reference utility system were representative of large utilities in the United States. The analysis suggested that if phosphoric-acid fuel cell were available today with a cost of about $400/kw and a heat rate of 9300 Btu/kwh, they would be attractive for intermediate duty generation. The study indicated that these fuel cell units would capture about 27% of capacity additions competing against nuclear, oil-fired intermediate and combined cycle, and gas turbine units. The fuel cell's competition with gas turbines for peaking duty was not significant. The study also found that the range of fuel cell capacity addition was very sensitive to small changes in the total present worth of capital-related and production costs. For a change of 0.1% in that present worth the fuel cell share of capacity addition varied from 12% to 36% for the reference utility system. Thus one can conclude.

1. Fuel cells have many benefits which can be very useful for electric utilities.

2. Fuel cells are moving from candidate technology status toward commercial service during the next decade.

2.2 Operation and Construction of Fuel Cells

Figure 2 shows how a fuel cell works. The first electric utility fuel cell to be demonstrated used a phosphoric-acid electrolyte. The fuel, a hydrogen-rich gas, is supplied to the anode, where hydrogen is dissociated into hydrogen ions, releasing electron to the anode. The hydrogen ions migrate through the electrolyte to the cathode, where they react with oxygen (from the air) and electron on the cathode surface coming from the anode to form water. The electrons produced on the anode flow through the external electric circuit providing current.

2.3 Fuel Cell Power Station

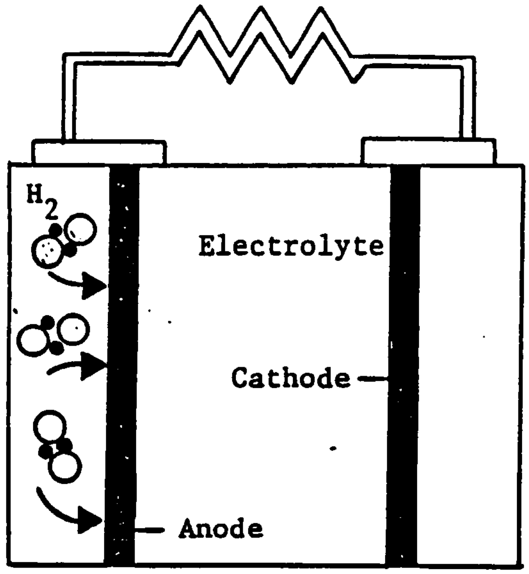
The power station consists of a number of power plants, a station controller and auxiliary subsystems as shown in figure 3. The power plant performs the primary function of generating DC power from fuel and providing DC/AC conversion. Auxiliary subsystems provide fluids and electrical power for effective power plant operation. The power station operator coordinates the operation of the power plant controllers and auxiliary subsystem controllers. The electric fuel cell power plant consists of three major subsystems where operation are shown in figure 3 [20].

i. Fuel processor;

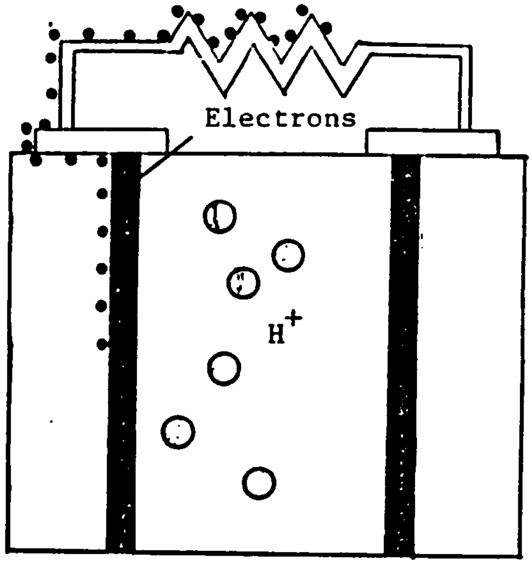
ii. Fuel cell power section; and

iii. DC voltage regulator and inverter.

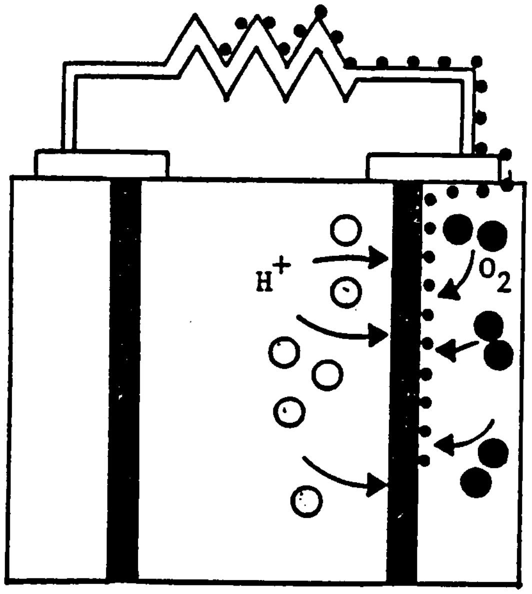
The fuel processor converts a conventional hydrocarbon fuel (e.g., methanol or natural gas) to hydrogen gas that can be used by power section. The power section contains the fuel cells which produce direct current electricity. The water formed by electrochemical reaction can be recycled



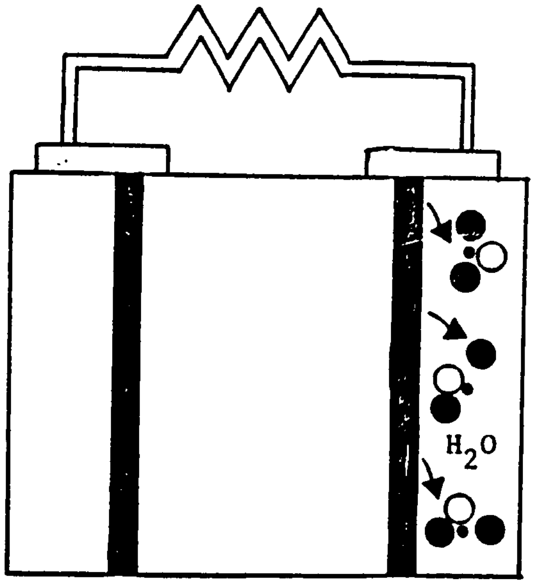
1. Hydrogen gas flows over negative electrode (anode).



2. Electrons split away from hydrogen and flow through anode to external electric load.

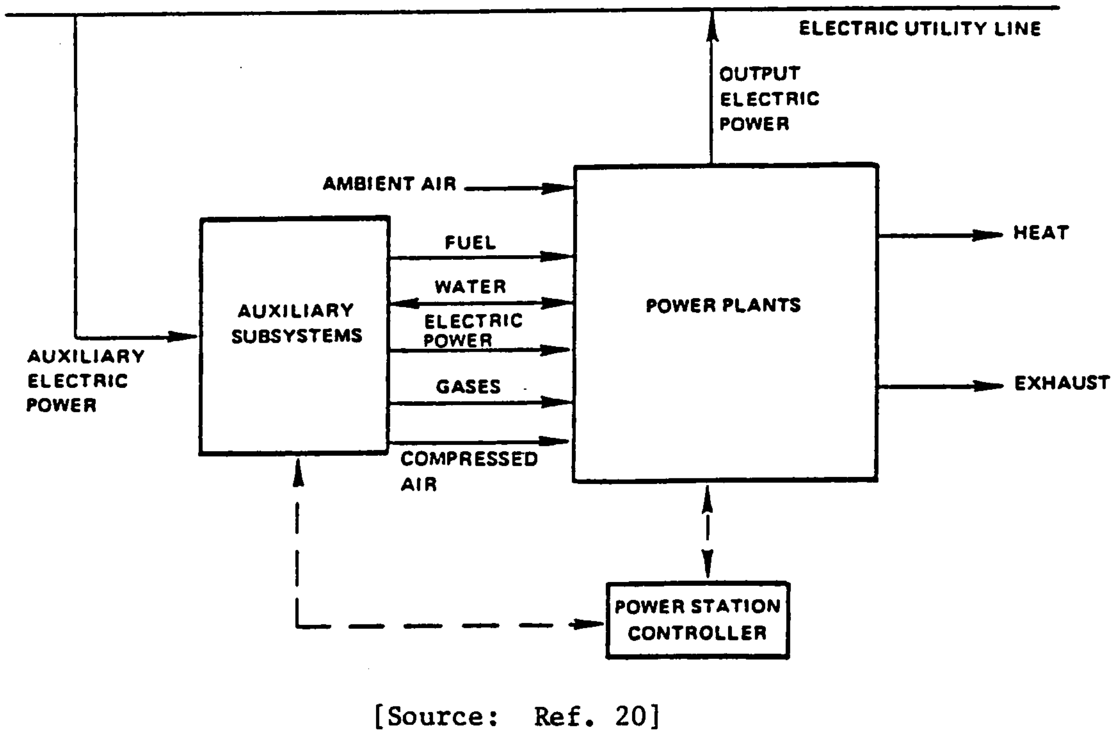


3. Hydrogen ions move through electrolyte to cathode. Electrons stream into cathode from load. Cathode is bathed with oxygen.



4. Hydrogen, electrons, and oxygen combine to form water (steam).

Figure 2. How Fuel Cell Works



[Source: Ref. 20]

Figure 3. Fuel cell power station.

and used for processing the fuel. The voltage regulator maintains constant DC voltage output . The inverter is used to convert the direct current electricity to alternating current.

2.4 Advantages of the Fuel Cell

Some advantages of the fuel cell are highlighted in the following.

1. High efficiency.

Almost all techniques of power generation depend on the conversion of heat to electrical power. Such a process is subject to the well known carnot cycle limitation on efficiency. At present power generation units operate at thermal efficiencies of less than 40%, and it is very difficult to increase the temperature because of a metallurgical problems involved. The fuel cell, however, is not subject to the efficiency restriction of the carnot cycle since a direct conversion of chemical to electrical energy is involved.

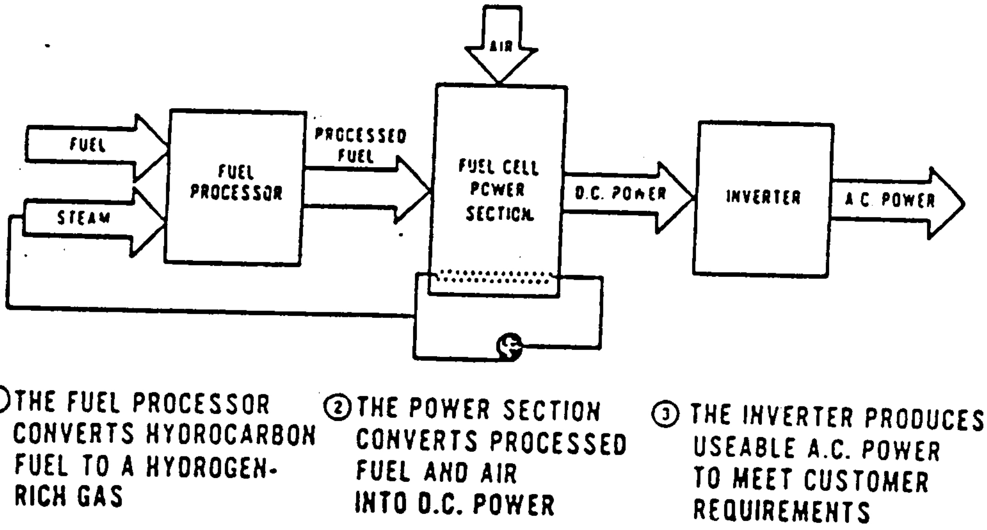
2. Modular design.

Since the efficiency of the fuel cell power plant does not depend on its size, it is possible to construct such power plants in small size modules which can be delivered in less than two years. Moreover, the small size of this plant, compared with the conventional power plant, affords the convenience of siting and incremental capacity addition. This results in a balanced cash flow requirement for responding to load growth.

3. Emission.

Emission levels are less than the level allowed by EPA. It also operates quietly.

4. Reliability .



[Source: Ref. 20]

Figure 4. Fuel cell power plant schematic

Fuel cell power plants have high availability and reliability factor. It is reported in [21] that fuel cell plants have availability factor of 0.88 and reliability factor of 0.92.

5. Dispatch.

The fuel cell responds to the load changes almost instantaneously and maintains its high level of efficiency whether it runs at full power or part power. This is different from conventional units which achieve rated efficiency only when operating at or close to full load. To make this clear let us take this example. At one-quarter load a fuel cell is no less efficient than that at its rated load. At full load a combined cycle fossil-fuel plant achieves a heat rate on the order of 8500 BTU/KWh which is about the same as that of a phosphoric acid fuel cell. At 40% capacity ,however, the heat rate of the combined cycle plant jumps to over 11000 BTU/kwh, while the fuel cell's heat rate remains unchanged. For this reason fuel cells are expected to replace conventional units where they kept running at well below capacity to cope with daily fluctuation in the load. This is especially significant when the PV system is connected to utility grid. It is also possible to use the fuel cell plant in a load-following mode utilizing its high ramp rates.

2.5 Operating Modes

Operation of the fuel cell power plant can be defined in terms of four operation modes. These modes, programmed as operating states in the plant controller, are:- ON, OFF, STANDBY, and HOLD. The operating mode can be selected by the operator through the power plant control console. In the ON mode, all power plant systems are operating. The power plant is on load between 30% and 100% real power. In this state the power plant is capable of supplying both real and reactive power. The rated power can be achieved within 10 seconds. In the OFF state, the power plant is essentially at ambient temperature and pressure. Rated power is achievable within

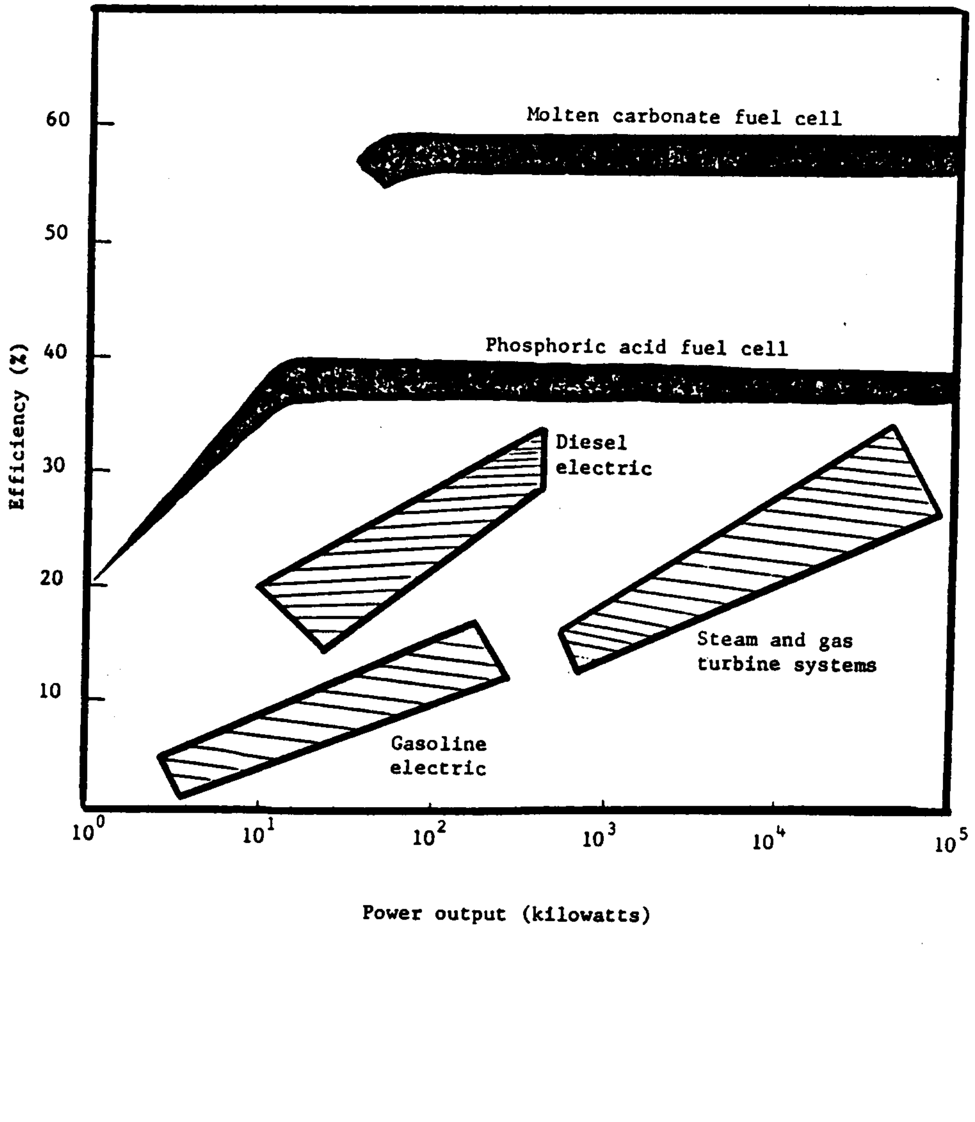


Figure 5. Fuel cell characteristic

four hours from this condition. STANDBY is a non-power-production mode. All system are in the ON state but no dispatchable power is being produced. Full power is available within 15 seconds. HOLD is an energy efficient non-power-producing mode designed to maintain the power plant in the state of readiness. The rated power can be achieved within an hour.

CHAPTER III

3.0 Problem Statement and Formulation of the Overall Methodology

3.1 Problem Statement

Integration of PV generation into the utility can cause undesirable dynamic impacts, especially at a large penetration level. These problems emanate from the operating characteristics of the PV power system. PV generation is affected by weather conditions (e.g., clouds, insolation level, temperature, wind speed and wind direction). When a large cloud, moving at constant speed, covers the entire solar array, the PV generation changes in a ramp fashion. In response to the change, the conventional generation is directed by the control center to change its output to correct the load generation imbalance. This correction, however, is limited to only those units that are on regulation or on automatic control and those regulated generators are capable of a limited response rate, usually in the range of 2-3%/min of their maximum generation. This means that the control error will not be corrected rapidly and there is a possibility that the standard reliability criteria will be exceeded. The exact amount of control response depends on the size of the PV generator and whether this generation increases or decreases. When the PV generation decreases (the array covered by cloud) the system control sees this change as sudden increase in load, and the regulated generation may reach its upper limit before attaining a balanced load-generation condition. The regulated units are not able to follow the load because their ramp rate is less than the ramp rate of PV generation. This happens because the PV generation is uncontrolled and appears to the system as a part of the load (negative load concept).

There are a lot of corrective measures and suggestions that may be employed by the utility in order to improve the system performance and thereby permit the increase of PV penetration levels. Some of these measures are:

1. Scheduling of more units to regulation duty (i.e., to shift from efficient but responding to less efficient but fast responding regulation units).

2. Use of more combustion turbines or combined cycle generating units. These units have high response gas or oil firing systems that make the generators highly maneuverable.

3. Spread the PV system to different locations.

The first two approaches can handle the problem when the penetration level of PV generation is relatively low. However, with increasing penetration levels, regulated units (combustion turbines and combined cycle units) cannot follow the load because their combined rate cannot keep up with the fluctuations of the PV system output. This problem can of course be dealt with by large numbers of regulated units.

The last approach addresses the point of distributed versus centralized systems. the main advantage of distributed systems is that the PV output fluctuations will not be substantial. This is because variation in outputs of different PV systems may cancel each other and as a result the aggregate output may not change rapidly. It is more likely that the distributed systems will be built in small PV stations (commercial and residential). However, there are three concerns which may strongly influence the rate of introduction of PV systems in various applications. These concerns are:

1. The product marketing and distribution is relatively expensive. In order to deploy energy-significant numbers of small systems, it is very unlikely that the costs of the wholesale/retail chain can be avoided. Figure 6 shows typical costs for product marketing and distribution of construction materials and appliances for the residential and commercial sectors. The ranges shown in the figure reflect the wide variations of margins received over a variety of products, but generally reflect the cost of doing business.

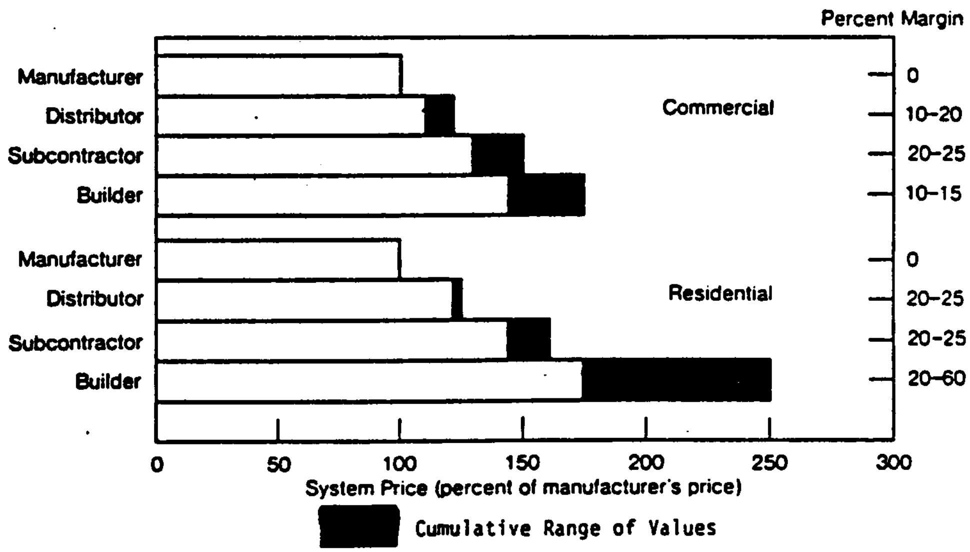
2. A number of distributed systems interconnect issues remain unresolved which may become particularly important at moderate and high penetration of PV. These include: requirements for dc isolation; the quality of relays required to protect the system; the need for, and location of power factor correction capacitors, metering and load reporting requirements, and allowable levels of harmonic distortion. Personnel and equipment safety is a primary concern at all penetration levels.

3. As more and more dispersed generation devices (PV, wind, battery storage,...etc) are integrated in the utility distribution system, additional capabilities are needed for the management, co-ordination and operation of the dispersed facilities. This will require expansion of the existing supervisory control system and will introduce further complexity into the design and operation of utility systems.

3.2 New Approach for the Array Ramp Rate

A simple strategy of operating an electric utility with a large PV array is to treat the PV power output as a negative load on the system load curve. This strategy has the following advantages:

1. PV energy produced by array is maximized since the power system absorbs PV generation whenever it is available.



[Source: EPRI REPORT]

Figure 6. Product Marketing and Distribution Costing.

2. No modification of the utility's control system is necessary.

Since, in this strategy, the array output variation is uncontrolled, the maximum increase or decrease in PV generation over a certain time will be large. Thus, a major effect of PV array operated as negative load will be to increase load following requirements.

The fuel cell offers an attractive power generation option for electric utilities. Ramp rate characteristics of the fuel cell power plant can handle the array ramp rate. It can work as a load-following unit so that by adding fuel cell plants to the grid, the penetration level of PV can be increased. The advantages of this step to the power systems are the following:

1. Since the concept of negative load is used, the array output may be maximized without any modification of the utility's control system.

2. The load-following requirement will be met more efficiently.

3. It will be possible to have large levels of PV penetration.

The fuel cell and PV plant are connected to the DC side of the inverter as shown in figure 7. This arrangement allows the inverter to operate at near rated capacity. As the fuel cell power plant responds to changing PV output to match the load demand, the net DC output "seen" by the inverter does not change intermittently. By this connection there will be no dispatch problem of reactive power because the inverter will receive a constant power regardless of the PV-output.

3.3 Formulation of the Overall Methodology

The overall methodology for the assessment of PV power in a sample utility is developed. This methodology is applicable to both planning and operation. The methodology is employed in two

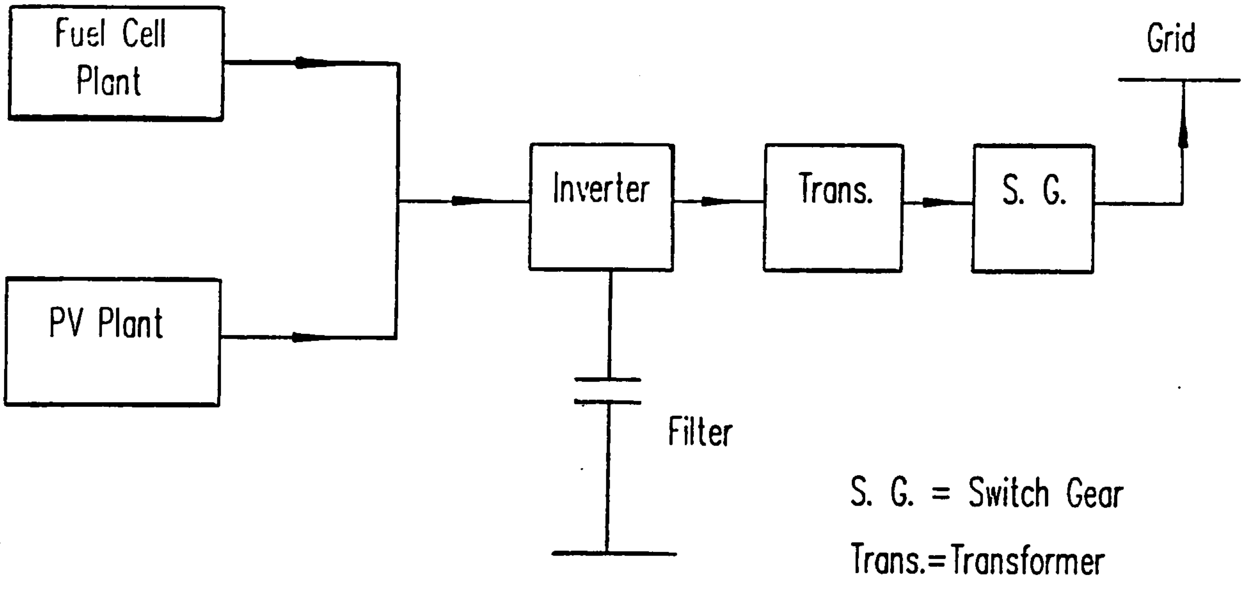


Figure 7. PV-Fuel Cell Connection.

stages. In the planning stage an outer limit on the PV penetration level was determined using the negative load concept and equivalent LOLP. In the second stage the operational considerations are examined. There, the level of fuel cell power plant support needed to maintain system integrity in the light of fluctuating PV output is determined. Then an iterative technique is utilized to fine tune the PV penetration and necessary fuel cell support for an economic generation expansion scenario. Figure 8 shows the flowchart of overall methodology.

3.4 Planning Study

The following steps describe the methodology and procedures to be used:

1. Formulate a statistical process to convert insolation data to hourly electric energy production patterns for average days of each season. The PV performance model, presented in section 3.6 is utilized in order to generate the energy production patterns. Various scenarios are considered here.

2. Using the sample utility system as a basis, develop a long-range generation expansion reference scenario.

   The intermittent and diurnal nature of power output from various nonconventional sources needs to be carefully reflected in any production costing model. The traditional means of meeting the load demand with conventional generation is to obtain a load duration curve (LDC) for the utility systems and assign generation to meet the LDC. The LDC is constructed from a chronological load curve. The load duration curve can be constructed for a day, week, month, season, or even a year. Therefore the generation assigned to a particular plant by the way of using the load duration curve will only indicate the number of hours during a given period a set of generators will operate. This is obviously insufficient for PV penerators whose outputs are intermittent in nature.

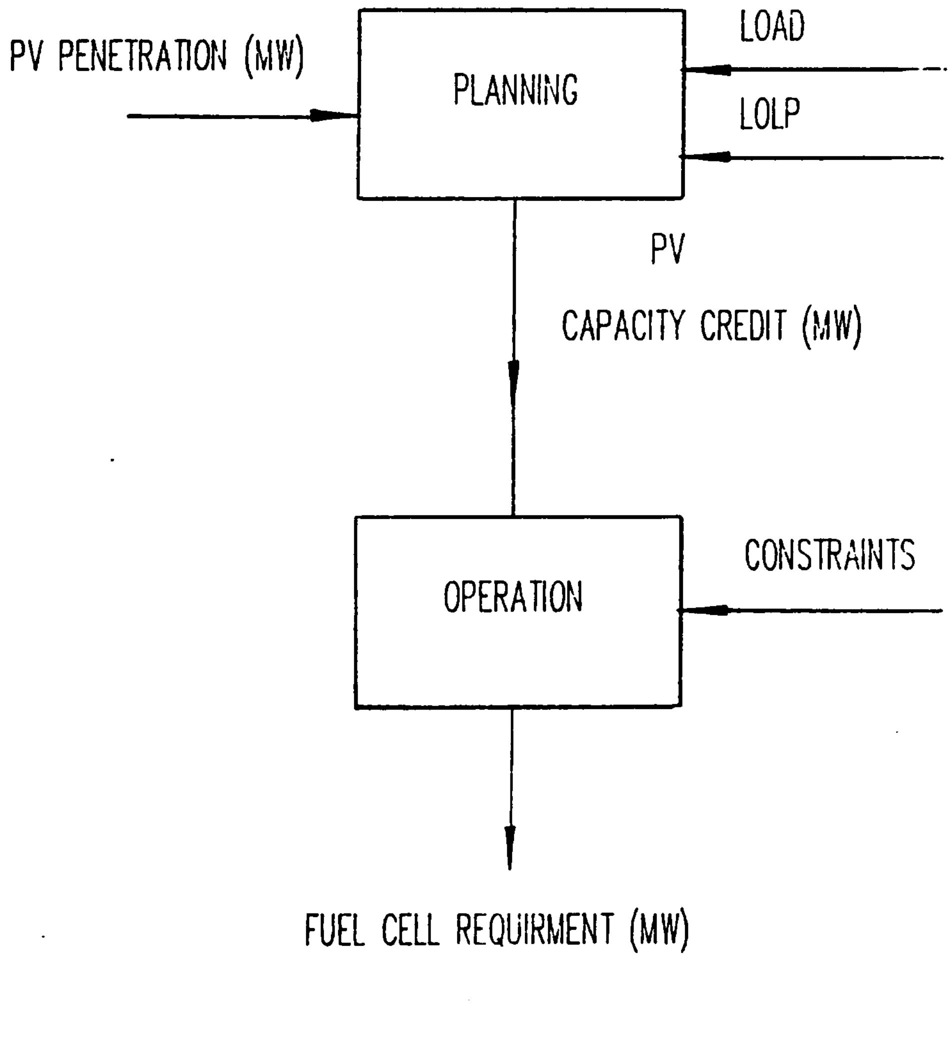


Figure 8. Flowchart of Overall Methodology.

In order to reflect the intermittent nature of PV generators, the concept of negative load will be used in the production costing model. A modified load duration curve can be obtained using the information on load demand and hourly outputs from the PV generator.

The information about the original and the modified load duration curves are used in a generation simulation model in order to determine the loss of load probability (LOLP), expected energy unserved and the production cost. WASP (Wien Automatic System Planning Package) is utilized for this purpose. For the purpose of this study we consider the use of advanced design combustion turbine units.

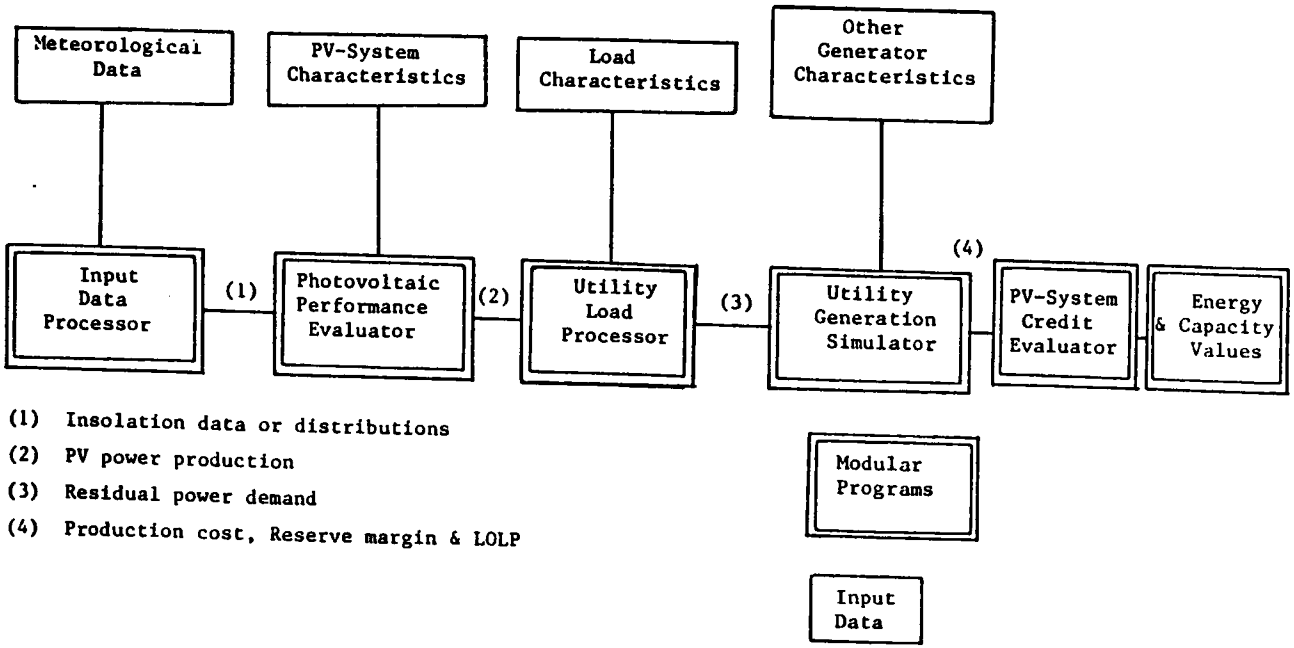
3. Substitute various amounts of advanced combustion turbine capacity additions with appropriate equivalent amounts of PV generating capacity which correspond to different levels of PV penetration expressed as percent of annual system peak load.

4. For each level of PV penetration, determine the capacity value of PV generation. In other words determine the amount of PV capacity in order to provide the same level of system reliability. Develop a method for this reliability evaluation. Figure 9 shows flow chart of planning study.

3.5 Operation Study

The following steps describe the methodology and production to be in the operation study:

1. Run the economic dispatch (ED) program with PV capacity generation that was obtained from the planning study. Use the concept of negative load to absorb the PV output into the grid.



[Source: Ref. 31]

Figure 9. Flowchart of the Planning Study

The task of economic dispatch is to determine the output of each committed unit to satisfy the system load in the most economical manner. It is performed at a regular, fixed interval which may range from 1-10 minutes in length. The most economical outputs have to be determined within the following constraints:

a. Power balance equation (the total generation should equal the load plus losses);

b. The minimum and maximum limits on each generator's output have to be observed; and

c. The fixed rate at which the output of a generator can be increased or decreased (ramp rate) has to be observed.

2. Check the ED output if the generation can meet the load variation.

3. If not, add fuel cell plant start with a small capacity and run ED. From the ED output find out how much fuel cell capacity should be added to meet the variation.

4. After several iterations, a PV-fuel cell hybrid will be identified. Figure 10 shows flowchart of operation study.

After these two stages are done, the net savings will be determined for each PV penetration level. The net savings are determined as follows:

1. Find the operating cost of the reference system. This can be calculated by running ED without PV and fuel cell.

2. Repeat step number 2 with the modified system (with PV and fuel cell).

3. Find the fuel saving by subtracting the operating cost of the modified system from the operating cost of the reference system.

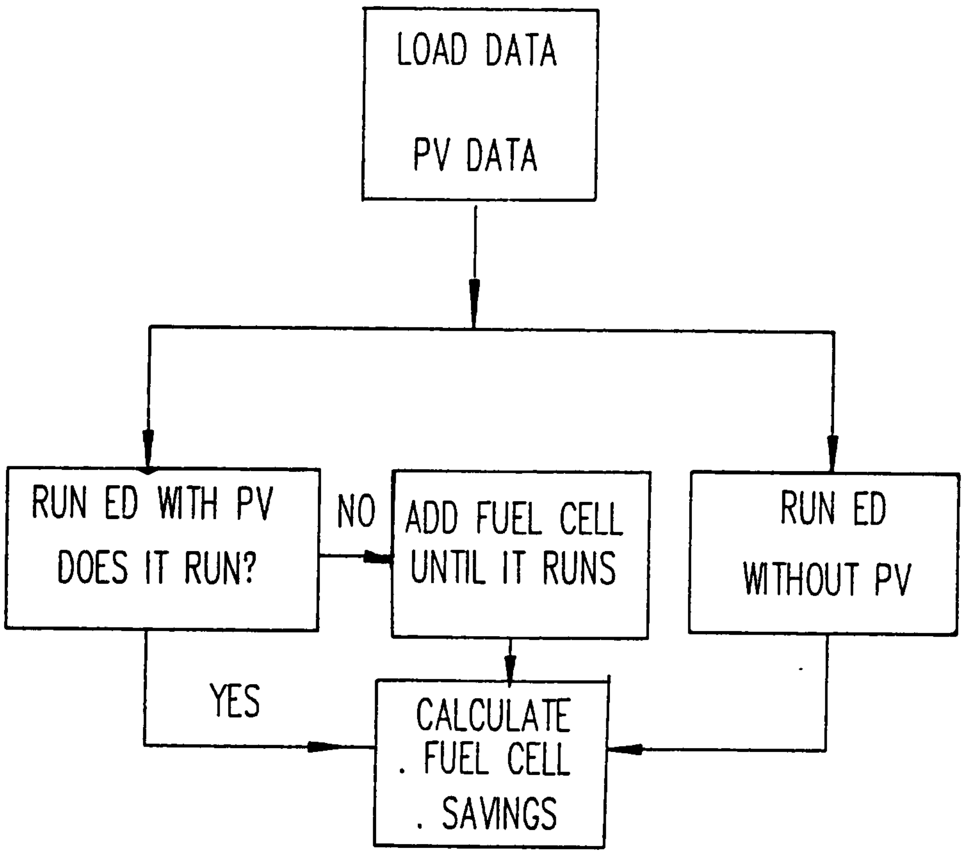


Figure 10. Simplified Operation Study_Flowchart

4. Draw a relation between net savings and PV penetration level.

5. Draw a relation between fuel cell added, capacity credit and PV.

3.6 PV Cell Model Formulation

In order to integrate the performance of the photovoltaic arrays into the overall system planning and operation study, it was necessary to use a simple but reasonably accurate PV cell model which was developed at the Jet Propulsion Laboratory (JPL) [22]. The model is used to determine the module and array output for the sample PV systems used in this study. Details about this model are presented in the following.

3.6.1 Variables

- α- Current change temperature coefficient at reference insolation ($A/^{\circ}C$)
- β - Voltage change temperature coefficient ($V/^{\circ}C$)
- I_0- Diode saturation current (A)
- I_L- Light generated current (A)
- I_c- Cell current (A)
- I- Array current (A)
- V_c- Cell terminal voltage (V)

- q- Charge on electron (coul.)
- V- Array terminal voltage (V)
- R_s- Cell series resistance (Ω)
- T- Cell temperature (K)
- T_A- Ambient temperature (K)
- T_r- Cell reference temp. (K)
- S- Insolation (W/m^2)
- S_r- Reference insolation (W/m^2)
- R_{sh}- Cell shunt resistance (Ω)
- V_r- Cell voltage at reference condition (V)
- I_r- Cell current at reference condition (A)
- N_p- Number of parallel strings in PV system
- N_s- Number of cells connected in series in each string in PV system
- K- Boltzmann's constant
- $f(s)$- Probability density function
- A- Diode quality constant (between 1 and 5)

3.6.2 Formulation of PV cell

Generally the solar cell is modeled by the equivalent circuit shown in figure 11.

The cell current is given by [2].

$$I_c = I_l - I_0 \{ \exp[q(V_c + I_c R_s)/AKT] - 1\} - V_{sh}/R_{sh} \tag{9}$$

However, in a well designed cell the value of shunt resistance R_{sh} is quite large. So, for simplicity we will neglect last term and equation (9) becomes

$$I_c = I_l - I_o \{ \exp[q (V_c + I_c R_s) AKT] - 1\} \tag{10}$$

Equation (10) is only applicable at one particular insolation level and all temperatures. In this study JPL model [19] will be used for obtaining expressions under non-reference insolation and temperature conditions. This model shifts any (V,I) reference point of the reference I-V curve to a new point (V_c, I_c). The transformation is performed according to the following equations:

- Change in temperature (from T_r to T)

$$\Delta T = T - T_r \tag{11}$$

- Change in current from T_r and S_r to T and S

$$\Delta I = \alpha [S/S_r] \Delta T + [S/S_r - 1] I_{sc} \tag{12}$$

- Change in voltage from T_r and S_r to T and S

$$\Delta V = -\beta \Delta T - R_s \Delta I \tag{13}$$

Then, cell voltage at (S,T)

$$V_c = V_r + \Delta V \tag{14}$$

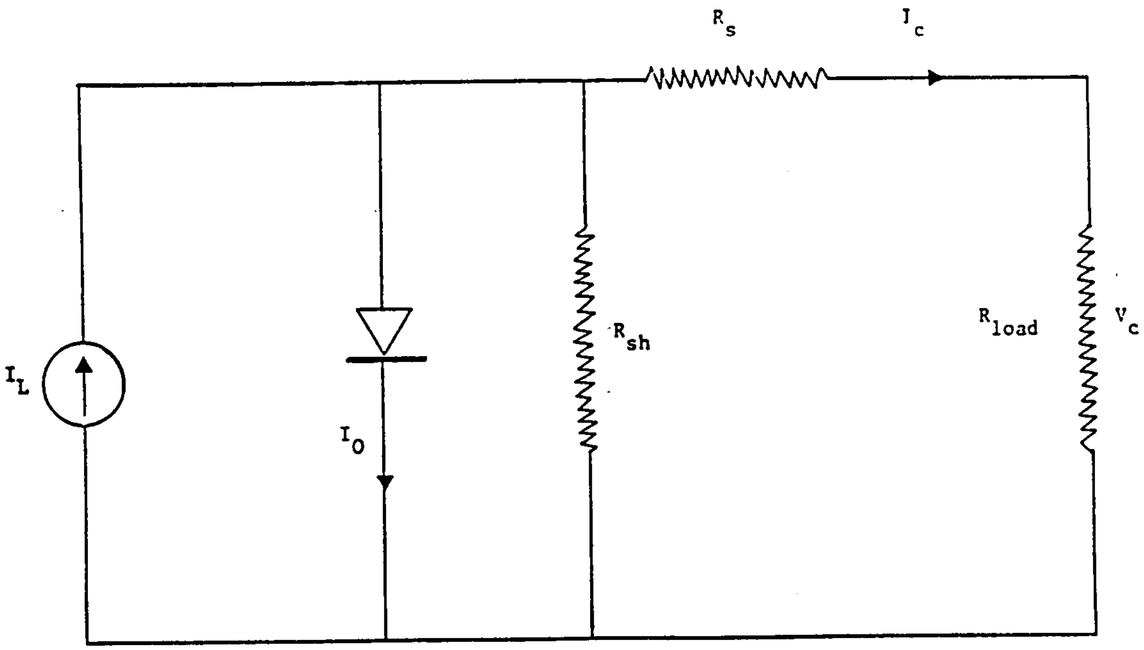


Figure 11. Equivalent Circuit

Cell current at (S,T)

$$I_c = I_r + \Delta I \tag{15}$$

where, the cell temperature is modeled by a linear relationship between ambient temperature, insolation and rate of change in cell temperature with respect to insolation. Then,

$$T = T_A + MS \tag{16}$$

The value of M should be calculated by a linear regeneration of the actual cell temperature, ambient temperature and insolation. But because of lack of actual cell temperature data the value of M has been chosen 0.02.

It is assumed that the short circuit current and open circuit voltage are constant at any insolation level and temperature.

The R_s solar cell resistance is calculated using the method of Wolf and Rauschenbach [23]. It is approximated by:

$$R_S = \frac{(V_2 - V_1)}{(I_1 - I_2)} \tag{17}$$

where the values of V_1 , V_2, I_1, and I_2 are shown in figure 12.
The resultant voltage and current of the array are calculated as follows:

$$V = N_p V_c \tag{18}$$

$$I = N_p I_c \tag{19}$$

Array output power at (S,T) can thus be readily calculated

$$P(S) = P(S,I) = VI \tag{20}$$

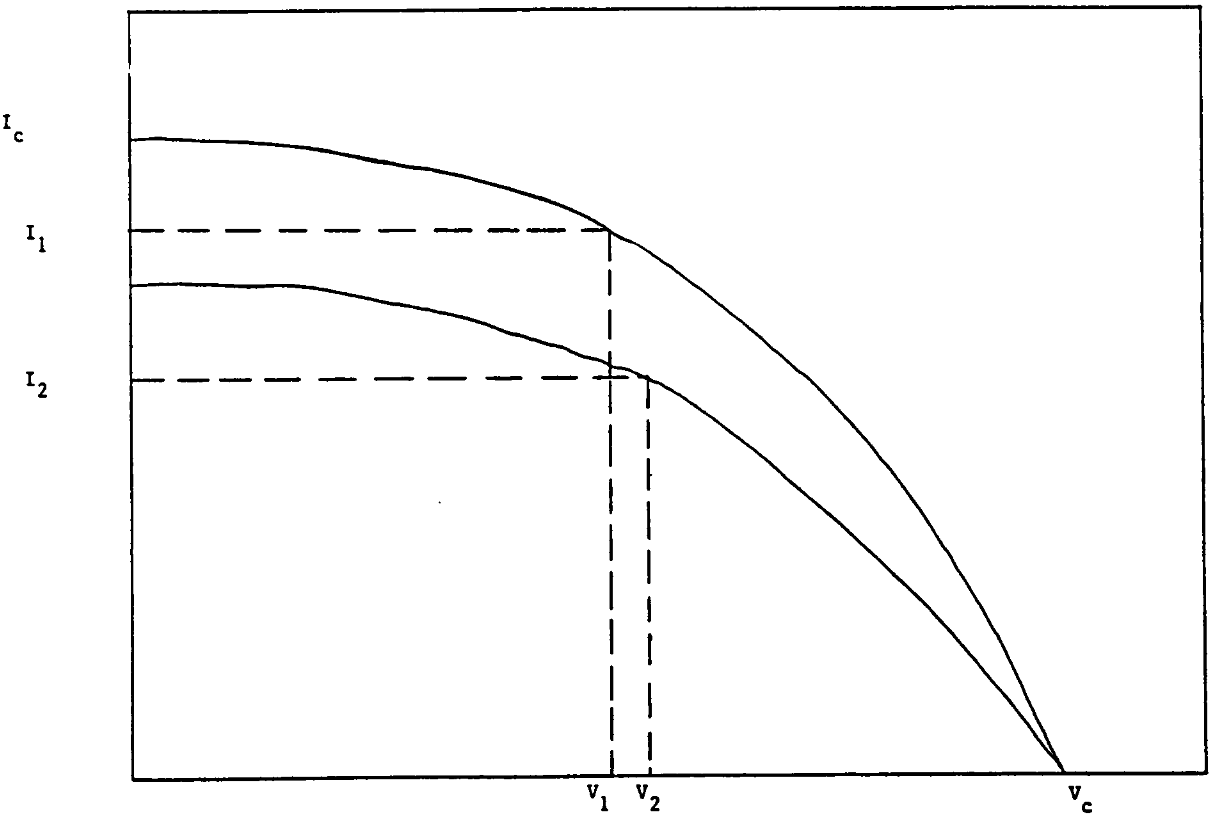


Figure 12. Calculation of Series Resistance.

Where V and I are functions of insolation and temperature.

Once the basic equations for the cell model are formulated, we can use them in the PV performance model which are to be discussed in chapter IV.

CHAPTER IV

4.0 Planning Study Analysis

The purpose of this study as mentioned in previous chapters, is to determine the amount of PV MW capacity required to replace each MW of combustion turbines in order to provide the same level of system reliability.

Mathematical models, computer algorithms and the associated FORTRAN and SAS programs have been developed for this purpose. The basic activities involved are the following:

1. Processing of meteorological data;

2. Calculation of photovoltaic array outputs;

3. Processing of utility load data;

4. Electric utility generation simulation; and

5. Capacity credit evaluation.

The algorithm and models are designed to be used in such a way that results in an open loop process. See the flow chart in figure 9. This arrangement fits well with the objective of the study.

The open-loop and modular nature of the overall algorithm provides a fast-running screening tool. Various scenarios can easily be analyzed using various combinations of these modular programs.

4.1 Processing of Meteorological Data

As seen from the flowchart in figure 13, the PV value determination process begins with the processing of the long term meteorological data in order to produce the typical hourly insolation data or insolation data distributions. The function of this module is to convert the multi-year SOLMET meteorological data into a format acceptable to the next module. Following steps describe the procedure used in this module which is summarized in figure 13.

1. Plot the histograms for hourly insolation data for a typical day in each month. The histograms shown in figure 14 and 15 suggest that insolation data, for the same hour over a number of days, would have two distinct segments. First segment does not have a uniform shape and cannot be fitted by using any of the known distributions. The second segment, however, has a uniform shape and can fit a known distribution.

   The "mode" technique has been suggested for the first segment and distribution fitting technique for the second segment. Steps 2 and 3 describe these two techniques, respectively.

2. Find the "mode" for the data in the first segment. The definition and description of this technique are given in the following.

   The "mode" is defined as the value that occurs most frequently in a sample [24]. If data is grouped into class intervals, it is difficult to locate the mode exactly. Under such circumstances the best approach is to approximate the mode. This is accomplished by first choosing the modal class and then picking out the class interval that shows the highest frequency. The sample modal is then approximated by:

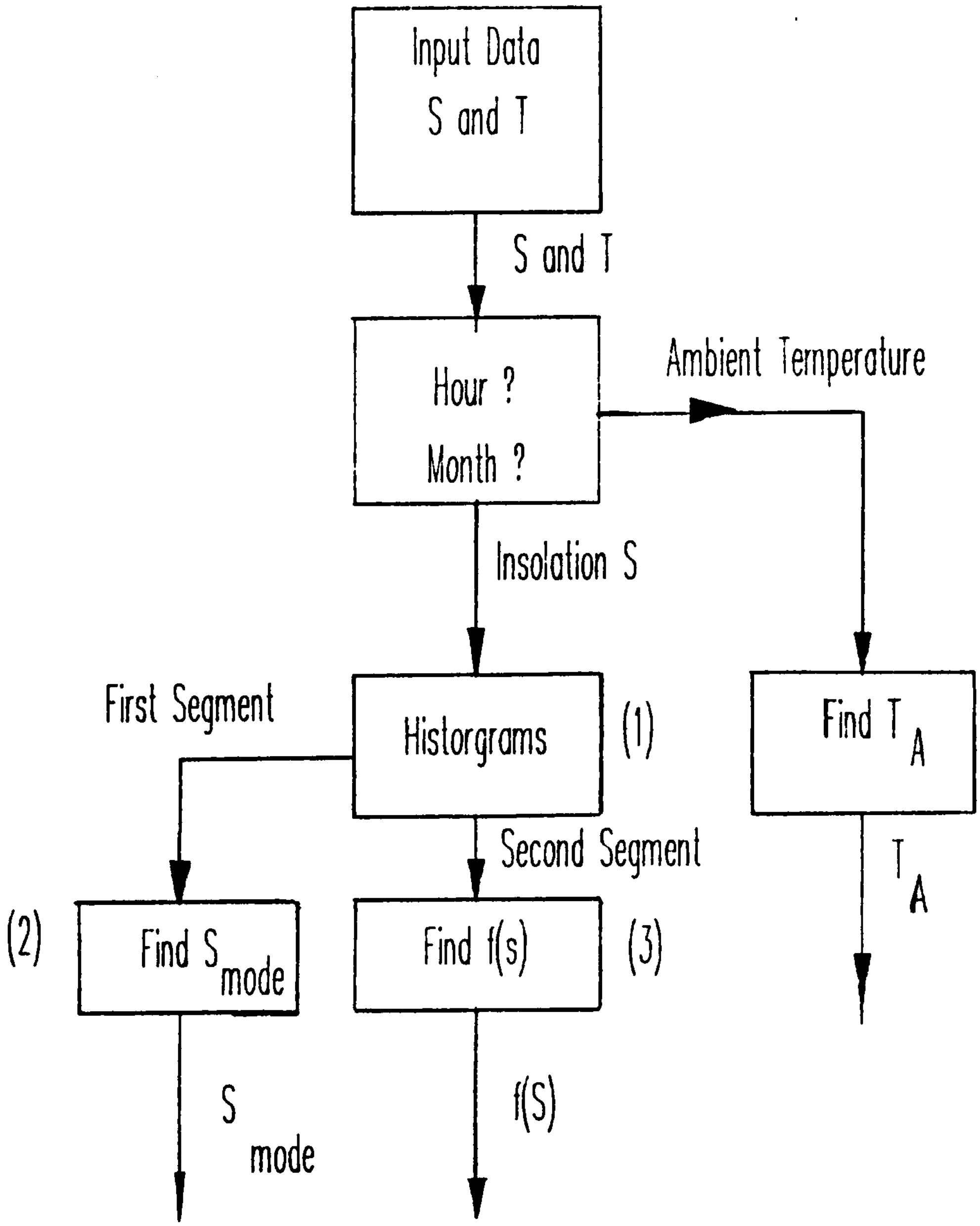
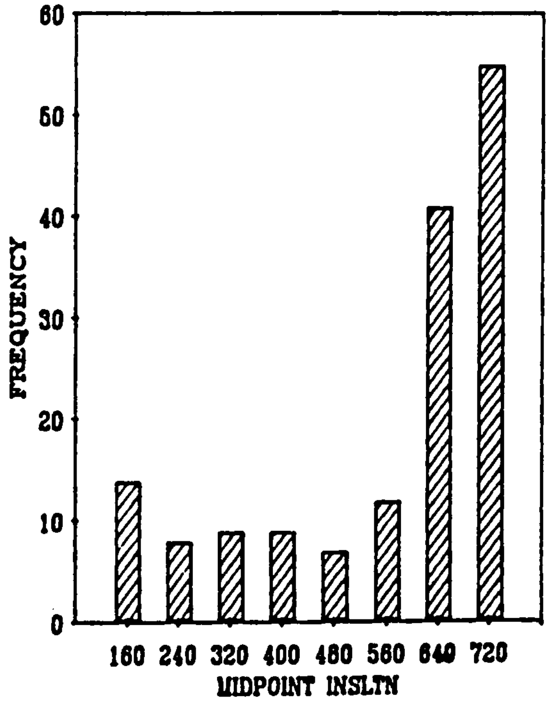
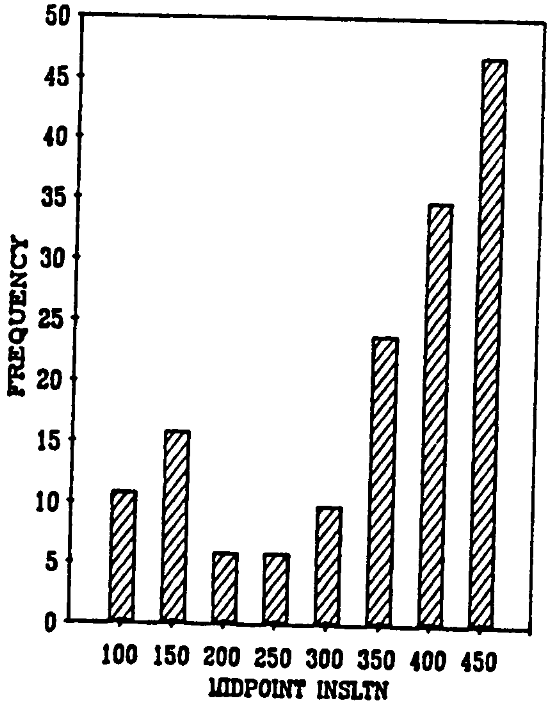


Figure 13. Flowchart of Meteorological Data.



(2 p.m.)



(4 p.m.)

Figure 14. Histograms (Whole Period)

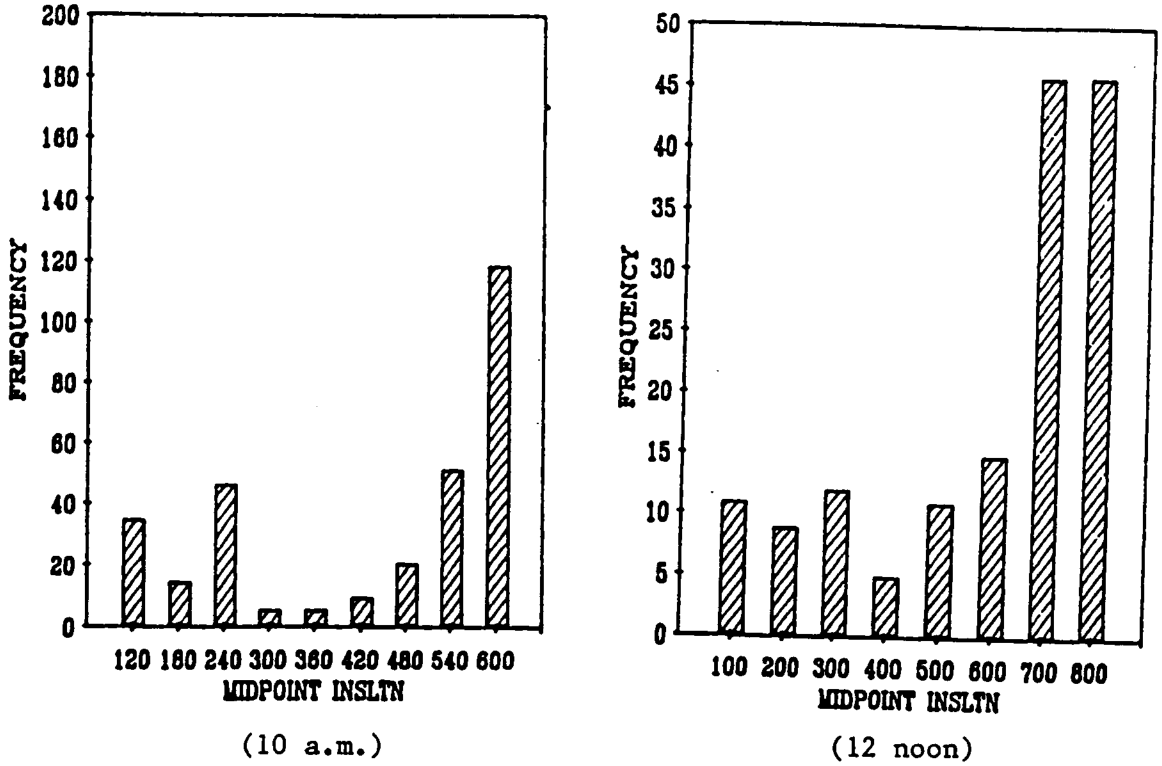


Figure 15. Histograms (Whole Period)

$$MO = L_{mo} + [\frac{d_1}{(d_1 + d_2)}](w) \tag{21}$$

where,

L_{mo} = lower limit of modal class.

d_1 = the difference (sign neglected) between the frequency of the modal class and the frequency of the proceeding class

d_2 = the difference (sign neglected) between the the frequency of the modal class and the the frequency of the following class.

w = width of the modal class.

3. Select the best distribution among different distributions of insolation data of the second segment of the long-term data. This has been done by a technique called "distribution fitting technique". Further discussion on fitting distribution is provided in the following sections:

4.1.1 Insolation Histograms

In order to characterize the insolation data for various times during the day, long term observations of insolation levels for the same hour of the day (for a large number of days) are examined. Histograms are plotted to check the type of variations encountered in the global horizontal insolation data for the same hour on different days.

4.1.2 Fitting distributions

The appropriate probability distribution model needed to describe a random phenomenon, like the insolation level, is difficult to discern. There are, however, occasions when the required distribution is determined empirically. Alternatively an assumed distribution is accepted or rejected on the basis of observed data. Histograms, which have been discussed in step 1 (in section 4.1), often provide the clue for initially selecting such distributions. This approach has been taken for fitting a distribution to observed insolation data.

Once it is determined that a known distribution would fit the observed data, several distributions are tested for the best fit. The three most likely probability distributions are tested for the best fit are Normal, Weibull and Beta. The predicted and observed class frequencies are then compared by using four measures of fit. These are Cramer-Von Misses-Smirov, Chi-Square, Kolmogorov-Smirnov and log likelihood.

Distributions chosen to fit the insolation are discussed in the following:

- *Lognormal distribution* - Its probability density function is given by:

$$f(x) = [\frac{1}{(cx\sqrt{2\pi})}]\exp[-1/2(\frac{lnx - k}{c})^2] \quad x \geq o \tag{22}$$

where,

$$mean(\mu) = \exp[k + 1/2c^2]$$

$$variance = \mu^2[\exp(c^2) - 1]$$

This distribution has two parameters k and c.

- *Weibull distribution* - Its probability density function is given by:

$$f(x) = [(k/c)(x/c)^{(k-1)}]\exp[-(x/c)^k] \quad 0 < x < \infty \tag{23}$$

where,

c = scale factor,

k = shape factor

This is also a two-parameter distribution and is used to characterize wind speed data as well. A sample Weibull distribution is shown in figure 16.

- *Beta distribution* - A probability distribution appropriate for a random variable where values are bounded, between finite limits a and b, is the Beta distribution. Its density function is given by:

$$f(x) = [1/B(k,c)]\frac{[(x-a)^{(k-1)}(b-x)^{(c-1)}]}{[(b-a)^{(k+c-1)}]} \quad a \le x \le b \tag{24}$$

where,

k and c are the parameters of the distribution. Also

$$B(k,c) = \int_0^1 x^{(k-1)}(1-x)^{(c-1)}dx \tag{25}$$

$$B(k,c) = [\Gamma(k)\Gamma(c)/\Gamma(k+c)] \tag{26}$$

The mean and variance of the beta distribution, equation (24), are

$$\mu X = a + \frac{K}{K+c}(b-a)$$

$$\sigma X^2 = \frac{Kc}{(k+c)^2(K+c+1)}(b-a)^2$$

When the values of the variance are limited between 0 and 1.0 (i.e., a=0.0, b=1.0) then equation 24 can be called the standard Beta distribution. Figure 17 shows the Beta density

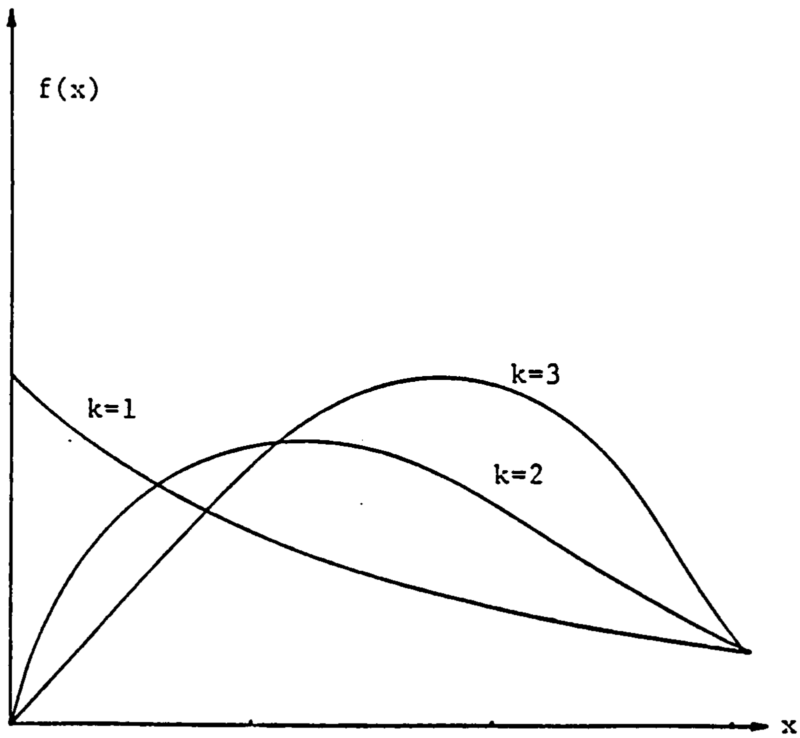


Figure 16. Weibull Distribution (c = 1)

function with different values of k and c. Since this distribution is bounded between two finite limits, it is expected to be able to replicate the random nature of the insolation levels for any given hour over a number of days.

The four goodness-of-fit criteria that have been utilized to determine the best fit for the distribution of insolation data are briefly discussed in Appendix A.

Mode, probability density function and average ambient temperature will be utilized in the Photovoltaic performance evaluator. Appendix B shows plots of the average temperature for some sample days of the year.

4.2 Photovoltaic Performance Evaluator Module

The objective of this module is to calculate the electric output, of the PV array under investigation, using the probabilistic and deterministic simulation models. The flowchart of the model is shown in figure 18. The density function f(s), mode, insolation and average ambient temperature are fed into the module. The PV cell model formulation to be used in the module has been described in chapter III. The physical parameters combined with cell characteristics determine the overall performance of the PV energy system. A computational procedure to use the simulation model is given in the next section.

4.2.1 Computational Procedure to Calculate PV Energy Output:

1. Compute the cell temperature,

$$T = T_A + .02S \tag{27}$$

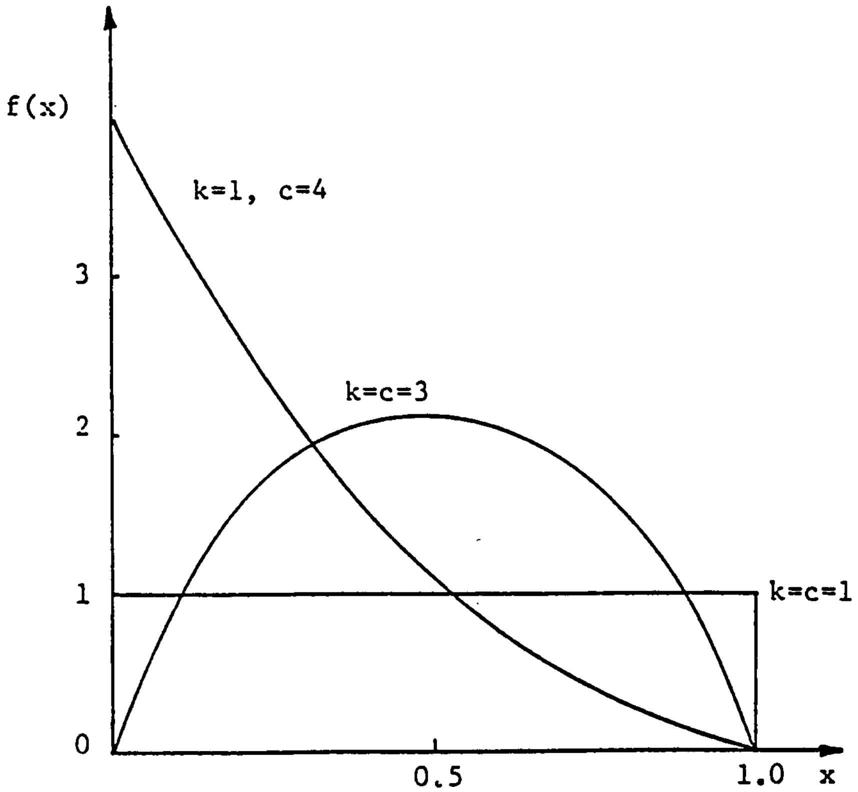


Figure 17. Beta Distribution

2. Generate equations for cell voltage, V(s) and array cell current, I(s).

3. Obtain equations for array voltages, V(s) and array current, I(s).

4. Formulate the array output power, P(s) as a function of insolation.

5. Calculate the expected value of output power. This has been done in three steps:

   a. Calculate the output power (OP1) of the first segment substituting S by S_{mode} in P(s) equation.

   b. Calculate the output power (OP2) of the second segment using the equation

$$OP2 = \int_{s_{min}}^{s_{max}} f(s)p(s)d(s) \tag{28}$$

   c. Weighted average of the output power from both segments is the expected power output of the array.

6. Calculate the capacity factor (C.F.) using the following formula.

$$C.F. = \frac{Expected\ \ PV\ \ Output}{Rated\ \ \ PV\ \ Output} \tag{29}$$

The hourly capacity factor value, along with the rating of PV array under consideration, are used to develop daily PV output profiles.

Appendix B shows some plots of PV output of a typical days of the year.

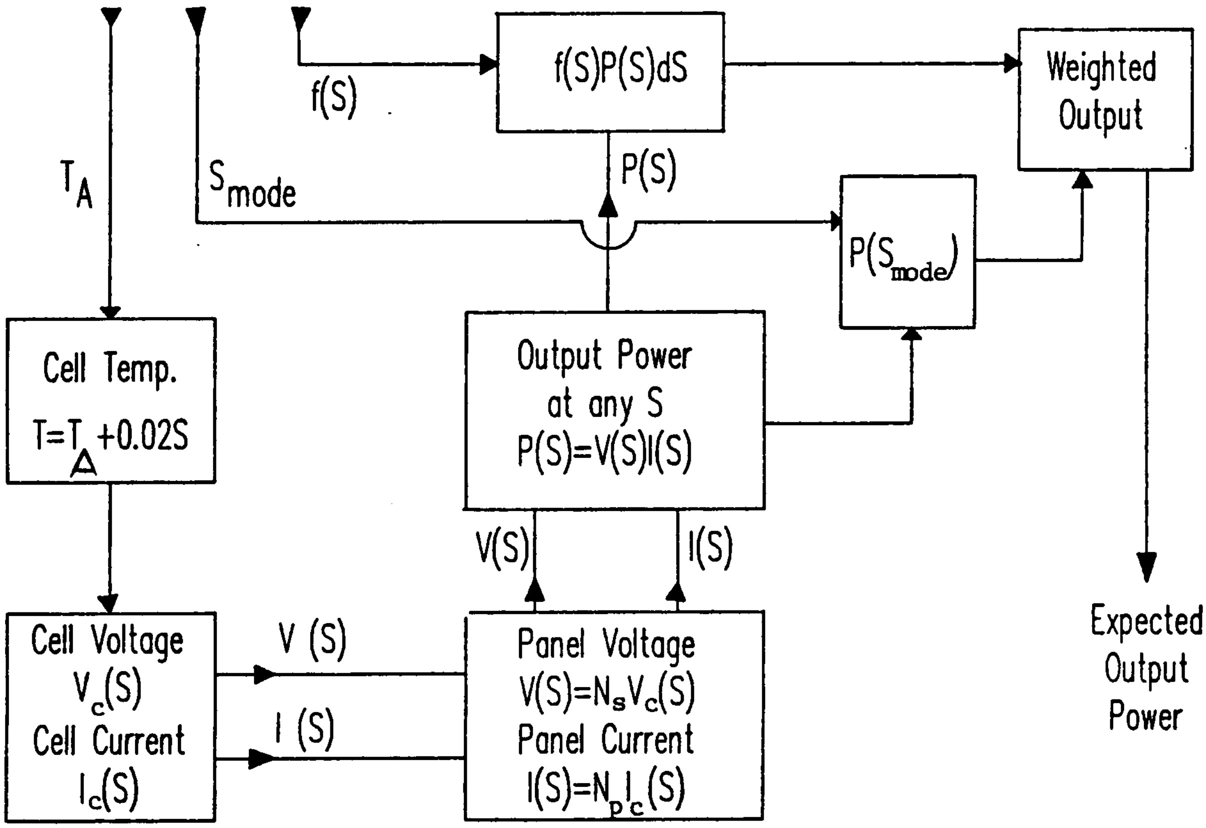


Figure 18. Flowchart of Photovoltaic Performance Evaluator

4.3 Utility Load Processor

The utility load module is designed to process the PV system output and the utility system load data in order to determine the equivalent load. The module consists of SAS and FORTRAN programs that are used to perform the following functions:

1. Subtract the PV derived power output from the hourly demand in order to obtain the modified chronological load data.

2. Sort these chronological data in order to generate the load duration curve.

3. Do a curve fitting to obtain a 5th order polynomial representation for the load duration curve.

4. Prepare a tabular representation of the load duration data.

The modified chronological load data are stored in descending order for obtaining the load duration curve for each season. A curve fitting is performed on these data points for getting a fifth order polynomial of the following form.

$$y = 1.0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + a_5 x^5 \qquad (30)$$

where,

y = load

x = fraction of time (duration) for which the load is at or above the corresponding y value.

$a_1 ...... a_5$ = the polynomial coefficients generated for curve fitting.

It should be pointed out here that, the intercept for the curve-fit is to be 1. In other words, the demand data for each season has to be normalized by the peak load in that season. Four such polynomials are used in the utility generation simulator in order to get reliability information for the year being studied.

Another way to pass the load demand data to the utility generation simulator module is to use the tabular representation of the load duration data. In that, the load demand is represented by using its percent duration. A series of percent durations are provided for which the load is at or above the corresponding value.

Feed the output data of this module to the utility generation simulator module which is discussed in the following section. Appendix C shows reference and residual load curves of some days of the year.

4.4 Utility Generation Simulator

The Booth-Baleriaux probabilistic simulation method of estimating the expected operating cost has been utilized in this study. In general, the unavailability data for the generators in the system are used to probabilistically simulate their outages. These outage data are convolved with the inverted load duration curve in order to come up with the so-called equivalent load duration curve.

The following information is needed for the utility generation simulator module.

1. System load duration curve;

2. Loading order of units;

3. Generating unit characteristics;

4. Maintenance schedule;

5. Fuel costs;

6. Operation & Maintenance costs; and

7. Energy supplied by energy limited units.

The output of this module includes:

1. Production expense;

2. Unserved energy cost;

3. Available capacity;

4. Total reserve;

5. Loss-of-load probability;

6. Unserved energy; and

7. System capacity factor.

An equivalent load duration curve can be generated to include forced outages of any number of units by the recursive application of the following equation:

$$EL_n(x) = P_n EL_{(n-1)}(x) + Q_n EL_{(n-1)}(x - MW_n) \quad (31)$$

The expected generation of each unit is:

$$E_n = P_n T \int_{a_n}^{b_n} EL_{(n-1)}(x)dx \quad (32)$$

Also, the equivalent load is defined by:

$$EL_n = L + 0_n \tag{33}$$

where,

- $EL_{(n-1)}(x)$ = expected value of load considering the outages of units before unit n in the loading order.
- P_n = probability that unit n is available.
- q_n = probability that unit n is unavailable
- EL_n = expected value of energy to be generated by unit n.
- a_n = Cumulative capacity of units 1, 2,...,n-1
- b_n = Cumulative capacity of units 1, 2,...,n
- T = time period represented by the load duration curve
- MW_n = capacity of unit n
- L = system load duration curve
- O_n = additional operation required of unit n due to the outages of units prior to unit n in the loading order.

A recursive procedure is followed in applying equation (31) so that ultimately all generating units are considered and the resulting equivalent load duration curve includes the forced outage effects of all units.

Additional information about the system can be obtained from the final equivalent load duration curve. Figure 19 shows this curve when the outages of all generating units have been convolved with the inverted load duration curve. The system capacity (SC) for all N units is also shown. The shaded area represents the expected energy demand U that the generating system will be unable to serve.

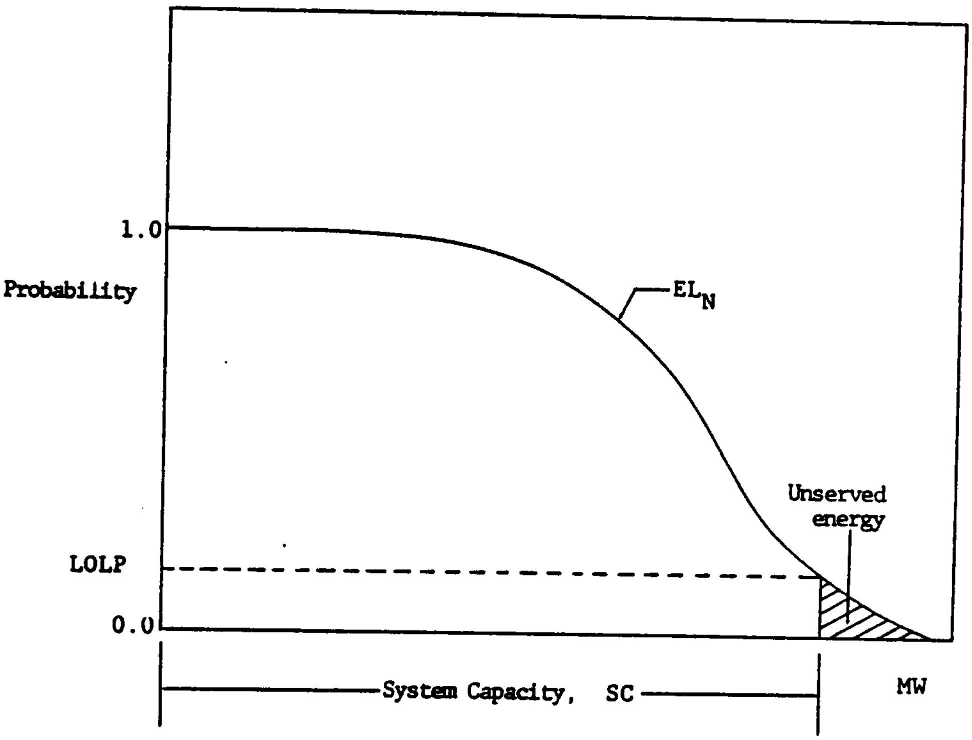
$$U = T\int_{sc} EL_n(x)dx \tag{34}$$

The generation expansion program package, called WASP, has been used in this study. Brief discussion about it is given in the following section.

4.4.1 The Wien Automatic System Planning Package (WASP)

The WASP package is designed to find optimal generation expansion policy for an electric utility system. A dynamic programming algorithm is used in the optimization. A probabilistic simulation mode is used to evaluate the operating cost.

The WASP package evolved from the Tennessee Valley Authority's System Analysis Generation Expansion (SAGE) program and was specifically designed in its present form for the International Atomic Energy Agency's Market Survey for Nuclear Power in developing countries. The package consists of six computer programs which can be run either independently or in series. Figure 20 shows a simplified WASP flow chart illustrating the flow of information from various WASP modules and associated data files. The first three modules can be executed independently of each other in any order. For convenience, however, these three modules have been given number 1, 2 and 3 as shown in the flow chart. Modules 4, 5 and 6, however, must be executed in order, after execution of Modules 1, 2 and 3. There is also a seventh moduel, REPROBAT, which produces a summary report on the first six modules. The following paragraphs describe each of these modules.



[Source: Ref. 31]

Figure 19. Equivalent Load Duration Curve.

Module 1, LOADSY (load system description), describes present and forecasted system load characteristics on which the capacity expansion and power generation requirements are based. This module is assisted by a curve-fit routine to calculate up to 5th order polynomial fit for the periodical load duration curves.

Module 2, FIXSYS (fixed system description), processes information describing the existing generation system and any pre-determined additions or retirements.

Module 3, VARSYS (variable system description), processes information describing the various generating plants which are to be considered as candidates for expanding the generation system.

Module 4, CONGEN (configuration generator), calculates all possible combinations of expansion candidate additions which satisfy certain input constraints and which in combination with the fixed system can satisfy the loads. It provides all possible generation expansion for each year of the study period.

Module 5, MERSIM (merge and simulate), considers all configurations put forward by CONGEN and use probabilistic simulation to calculate the associated operating costs and system reliability for each configuration. The module also calculates plant loading orders if desired and keeps track of all previously simulated configurations.

Module 6, DYNPRO (dynamic programming optimization), determines the optimum expansion programme based on previously derived operating costs along with input information on capital cost, economic parameters and reliability criteria.

Module 7, REPROBAT (report writer code), writes a report summarizing the total or partial results for the optimum or near optimum power system expansion programme and for fixed expansion schedule.

The three first modules create data files which are used in the three remaining ones. Additional files are created by the fourth and fifth modules and used in the sixth. Each module produces a separate printed summary. A more detailed description of each module and their data requirements is given in [25].

WASP computer code is used only as a generation simulation code for the screening tool presented here. The information on system demand can be provided to WASP in one of the following ways.

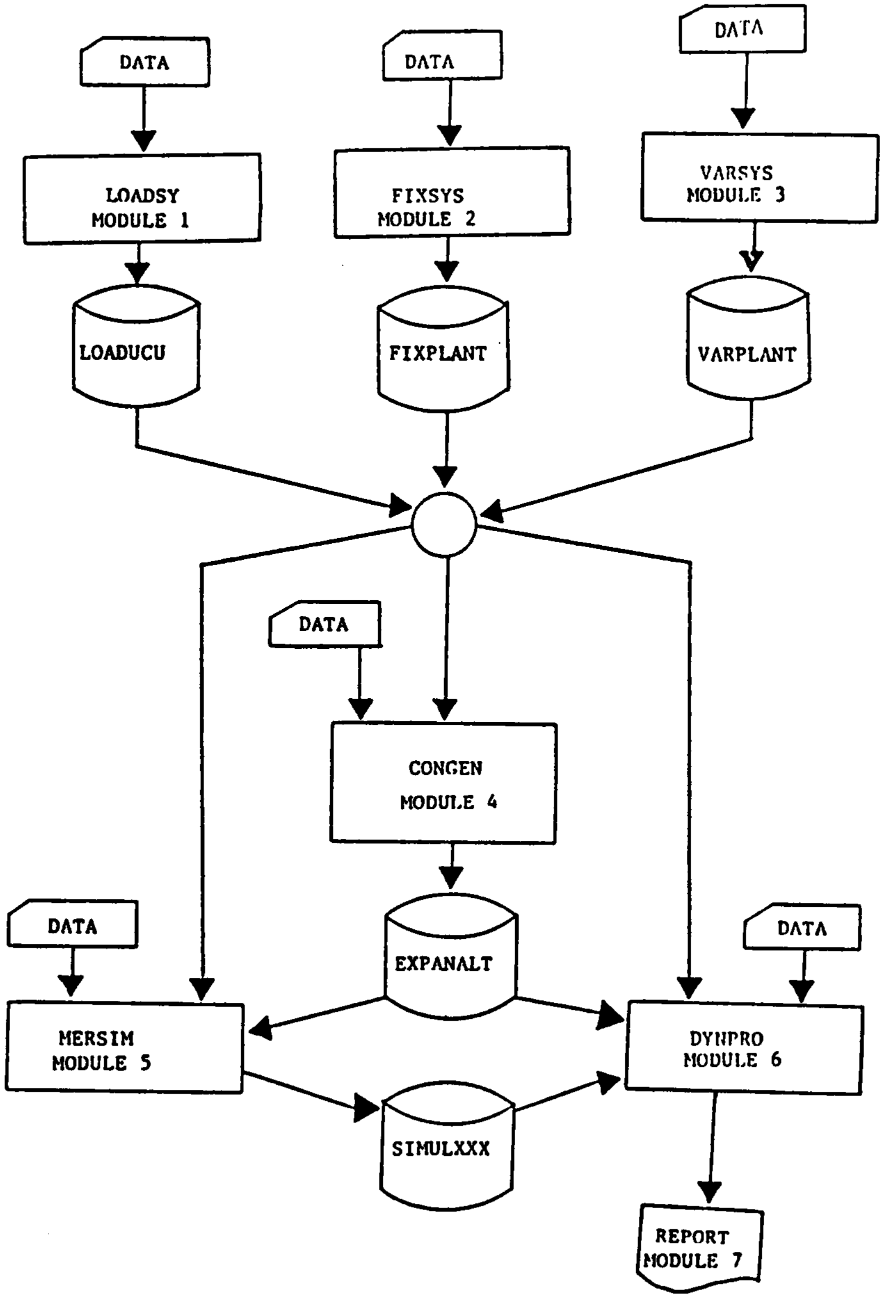
1. 5th order polynomial obtained by curve fittings of the utility load data.

2. Tabular representation of the load duration data. In that, the load demand is represented by using its percent duration. This representation provides faster processing time with more accurate results than the polynomial representation.

The use of this generation simulation code provides reserve margin, maintenance outage and reliability information for different load and generator availability scenarios. These are used to evaluate the Photovoltaic generators using the PV system credit evaluator module as discussed in the next section.

4.5 Evaluation of Capacity Credit

Capacity credit for an alternate energy source gives the amount of conventional generation the alternate energy source would replace, without any appreciable change in system performance. The performance index used in the loss of load probability LOLP of the system. The permitted LOLP for a power system is usually very small, of the order of 1 day in 10 years. The intermittent nature of alternate energy sources, and the small value of LOLP required for a power system



[Source: Ref. 25]

Figure 20. WASP Flowchart

combine to make the capacity credit of an alternate energy source considerably less than its rated output. it also makes it an important index in deciding the viability of the source.

4.5.1 Method of Evaluation

Results from the first four modules are serially processed and consolidated in the PV system credit evaluator module. This module, unlike the previous ones, is not based on a set of computer codes. Rather, this is a set of instructions to be followed in order to determine the PV system credit. A sample instruction set is given in the following:

1. Run the utility generation simulator using the system projected load demand and information on all generators.

2. Run WASP to determine the optimal generation expansion over a specified period, and maintaining system reliability at a specified acceptable level. This is reference case (without PV).

3. Run the utility generation simulator using the modified load demand (obtained by subtracting the PV output). Repeat step number 2 and the determine the optimal generation expansion using the modified load demand.

4. In the reference case, appropriate capacity additions are provided to maintain the same system reliability level.

5. Capacity value is then calculated as the difference of the alternative generation capacity between the reference and modified cases.

The modules which are needed in this dissertation have been discussed in this chapter. They have to be run in sequence. PV system can be easily incorporated in these modules. Once the data of the case study is ready, the capacity credit can be evaluated following the above steps. The following chapter presents the results of planning study.

CHAPTER V

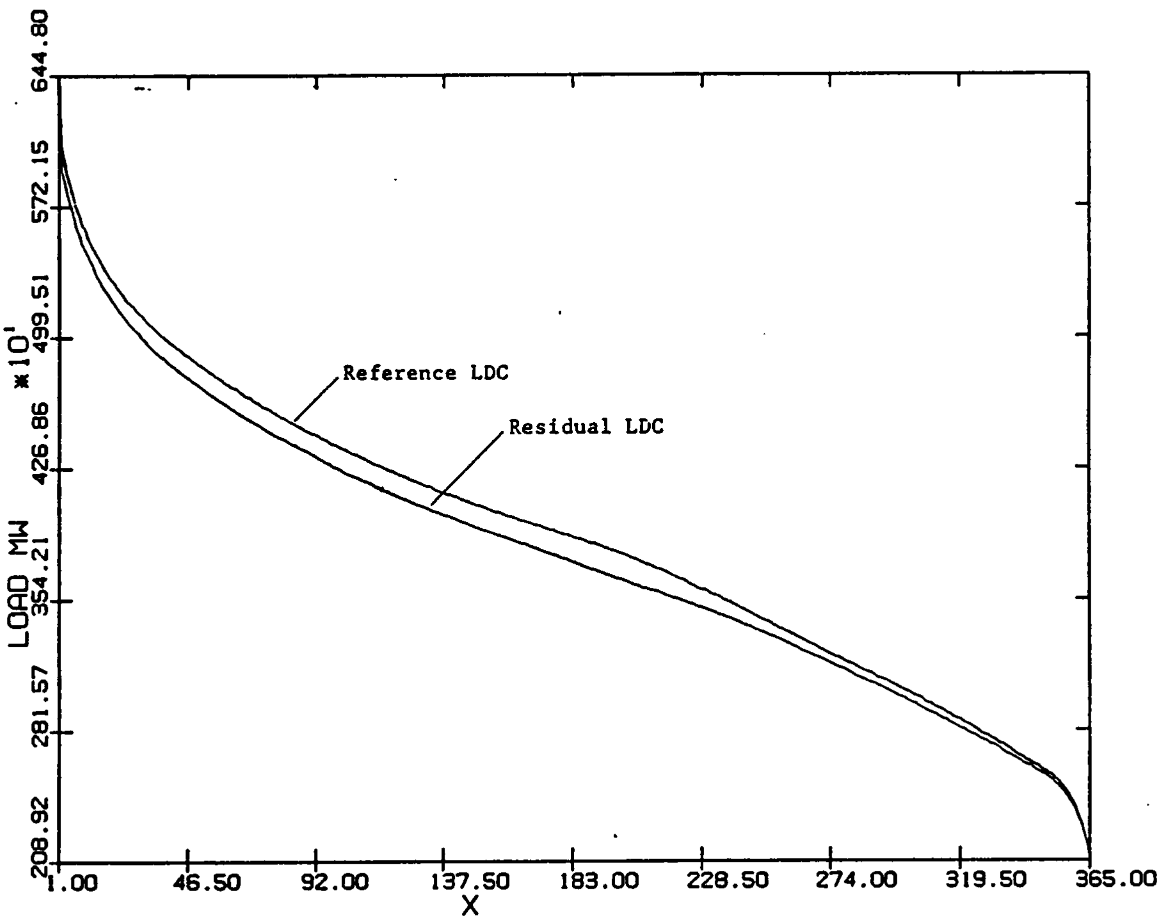
5.0 Planning Study Results

Evaluation models, described in the previous chapter, have been run for the Raleigh-Durham meteorological data, and load and generation data for a typical southeastern utility. This chapter discusses the results obtained from this exercise.

5.1 Input Data Set

An annual, hourly chronological load curve has been used that is representative of the load shape of a southeastern utility. Figure 21 shows load duration curves with and without incorporating the PV output into the system load. Shapes of these load curves suggest that they can be well approximated by a 5th order polynomial (see polynomial equation # 30). The polynomial coefficients of the reference load without PV are listed in Table 1. The polynomial coefficients of the modified load with 500 MW PV are listed in Table 2. These coefficients are used in LOADSYS data (from WASP program). The system peak is taken to be 6400 MW and assumed to occur in August 1985. The load growth is assumed to be 3% per year.

Operating data for a set of generators has been synthesized that is representative of the generating units of the southeastern utility. This set includes 3 nuclear, 15 coal, 4 oil fired, 1 hydro and 29 combustion turbines with total capacity of (7105 MW). The generation data is provided in



[Source: Ref. 31]

Figure 21. Reference and Residual Load Duration Curves

TABLE 1. Polynomial Coefficients of Reference Load

Coef.	Winter	Spring	Summer	Fall
a_0	1.000	1.000	1.000	1.000
a_1	-2.651	-3.503	-2.086	-3.513
a_2	11.567	16.958	8.276	16.565
a_3	-25.679	-38.208	-18.491	-36.764
a_4	26.053	37.914	18.613	36.408
a_5	-9.894	-13.769	-6.926	-13.318

TABLE 2. Polynomial Coefficients of Modified Load

Coef.	Winter	Spring	Summer	Fall
a_0	1.000	1.000	1.000	1.000
a_1	-2.903	-3.744	-2.381	-3.533
a_2	12.842	17.548	9.534	16.096
a_3	-28.484	-38.697	-21.096	-35.049
a_4	28.904	38.124	21.332	34.415
a_5	-10.972	-13.839	-8.014	-12.549

Table 3. This data was presented in the WASP format (FIXSYS file). No attempt has been made to integrate the PV system into the currently operational set of generators in the sample utility system. Such an attempt will not be realistic because of the existing uncertainties in the cost and performance of the PV system of such high capacity. The fuel cost data presented in Table 3 was based on the 1985 dollar value.

A discussion of results of the meteorological data processor module is presented in the following.

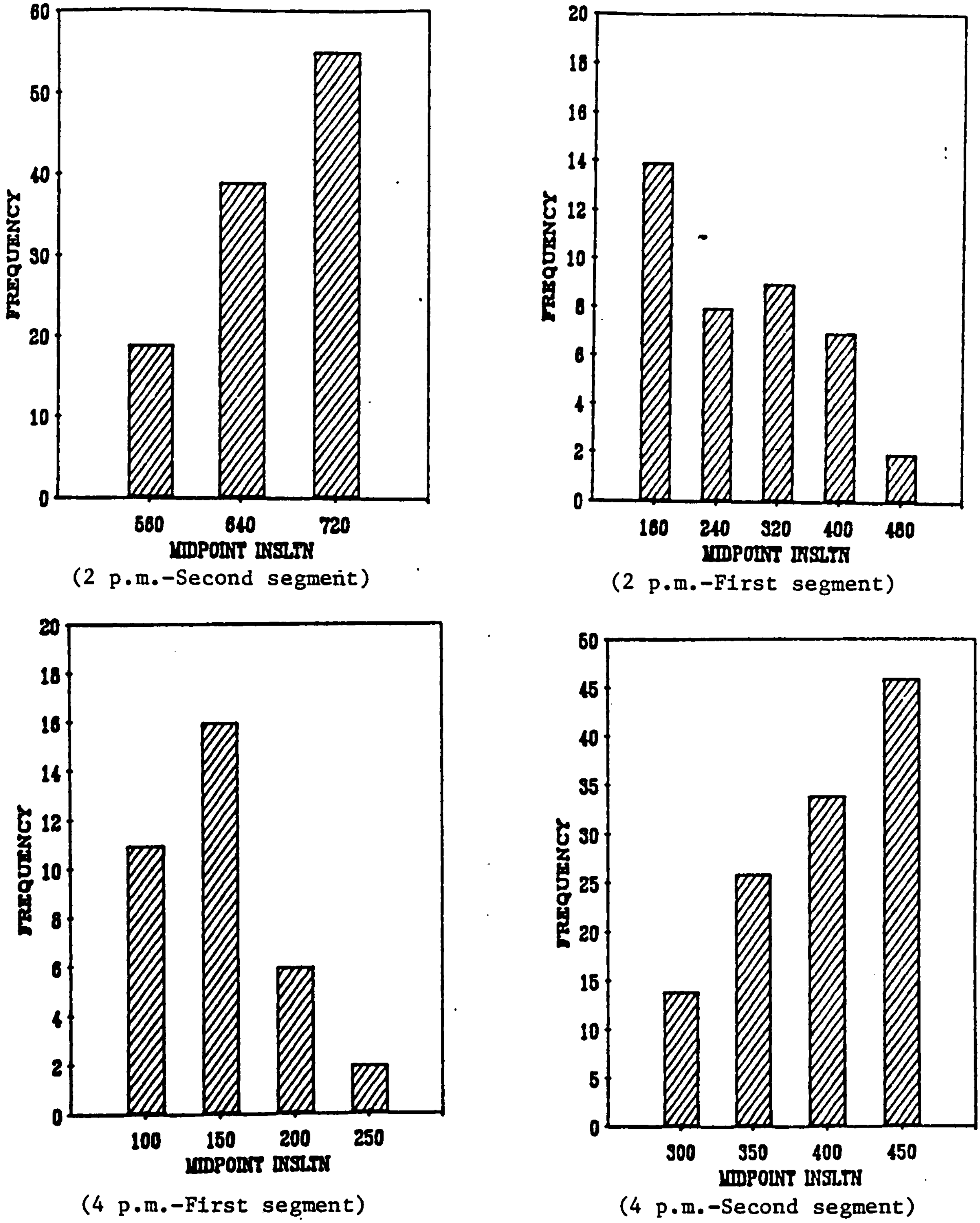
Data processing has been performed in two steps, mode calculation and distribution fitting. The mode, as it has been discussed earlier, is determined for the first segment of the insolation after identifying the break point for each hour. The break points are determined by inspection. The transition points in histograms are called break points (see figure 14 and 15). Results of the distribution fit are discussed in the following.

Results obtained by applying four goodness-of-fit criteria to determine the best distribution fit (out of three examined) for the second segment data are presented and discussed. As a sample, the distribution fit for the months of March and January data is presented. The data was obtained from the Raleigh-Durham, NC SOLMET tape. Figure 22 and 23 show histograms of the second segment of sample insolation data four hours in March. These histograms were derived from the original histograms shown in figure 14 and 15. In Table 4 the D-statistics are presented for Kolmogrov-Smirnov (K-S) test for the three distributions tested for the second segment of the sample insolation data. These D-statistics are compared against the critical value of D for 5% significance level (05) for the sample sizes as shown. It is seen that for all hours the D-statistics for the Beta distribution are below critical values. It , therefore, passes the K-S tests at this significance level.

It is clear, then, that Beta distribution provides the best fit in comparison with Weibull or Lognormal distributions.

TABLE 3. Generation Data

1985		4												
ASH	2	70	196	10633.	8943.		211.0	350	4.52	29	170		.73	.16
CF34	2	12	32	14400.	10912.		211.0	370	3.10	24	25		.54	.19
CF5	1	45	143	10684.	9194.		211.0	350	3.10	29	170		.54	.19
CF6	1	50	173	13645.	9376.		211.0	350	1.40	29	170		.54	.19
LC12	2	38	78	11560.	10678.		211.0	370	3.10	24	70		.71	.21
LCE3	1	70	252	11228.	8337.		211.0	350	4.00	35	300		.71	.21
ROB1	1	50	174	11321.	9069.		211.0	350	7.80	29	170		.67	.18
ROX1	1	125	385	10276.	9186.		211.0	350	6.80	35	300		.38	.69
ROX2	1	250	670	10076.	8750.		211.0	350	10.80	47	700		.38	.69
RX3	1	250	720	10440.	8825.		211.0	350	14.40	47	700		.96	1.74
SUT1	1	35	97	11557.	10029.		211.0	370	4.20	32	100		.63	.22
SUT2	1	35	106	10681.	8909.		211.0	350	2.30	32	100		.63	.22
SUT3	1	125	415	10852.	9151.		211.0	350	16.30	35	300		.63	.22
WP12	2	20	49	12132.	10765.		211.0	370	3.10	24	70		.78	.29
WP3	1	33	78	10659.	9447.		211.0	350	3.10	24	70		.78	.29
NROB	1	228	665	11080.	9969.		30.0	010	7.80	52	700		.67	.18
NBRU	2	173	790	13580.	9270.		36.0	010	17.8	52	700		.93	.39
IC29	9	15	29	13920.	13920.		553.	275	7.80	17	25		.15	.57
IC14	9	7	14	14800.	14800.		553.	275	7.80	17	25		.14	.78
IC52	11	26	52	12442.	12442.		553.	275	7.80	17	70		.64	3.95
IC84	1	32	84	11446.	10289.		553.	275	7.80	17	70		.13	.57
NHYD	1	25	220	0.	0.	0.		5 0	0.0	0	0	719.	.0	1.30
MYR4	0	250	720	10440.	8825.		211.0	350	14.4	54	700		.96	1.74
NHAR	0	179	900	15353.	9237.		41.4	010	17.80	62	900		.29	.87
	.96		1.0	.98	.96									
	1.0		1.0	1.0	1.0									
	.332		.282	.170	.216									



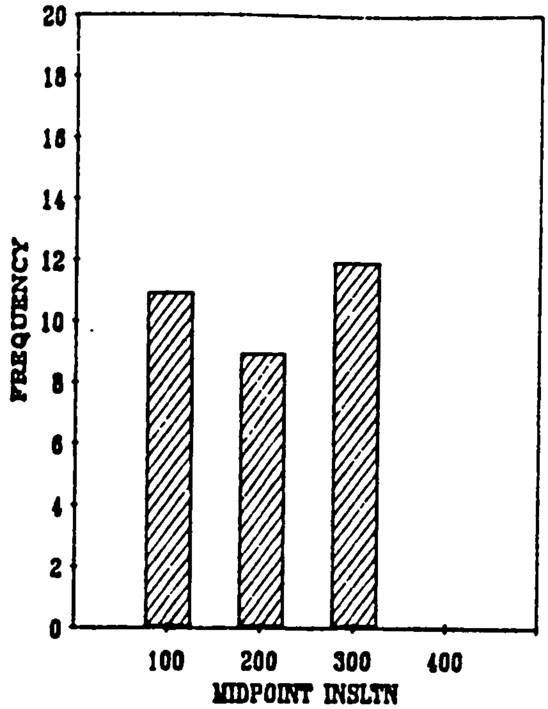
(2 p.m.-Second segment)

(2 p.m.-First segment)

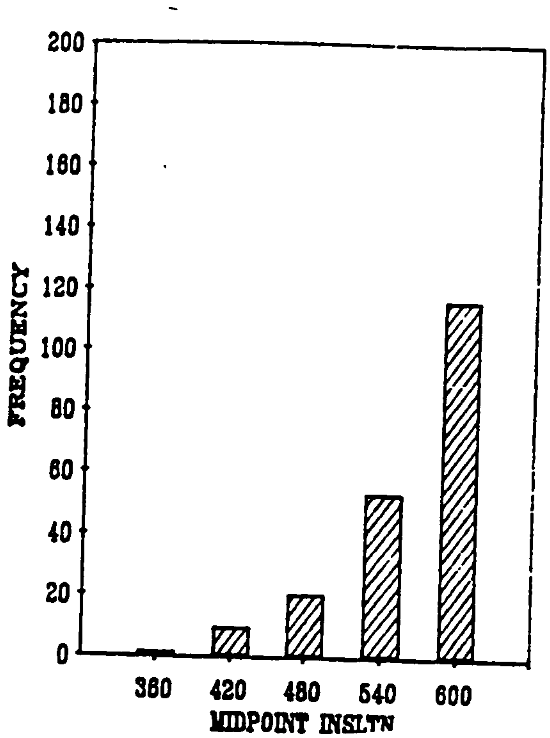
(4 p.m.-First segment)

(4 p.m.-Second segment)

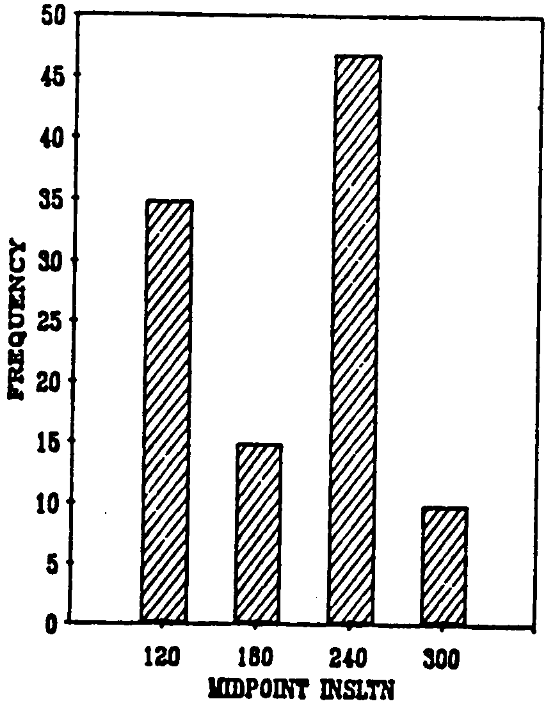
Figure 22. Histograms



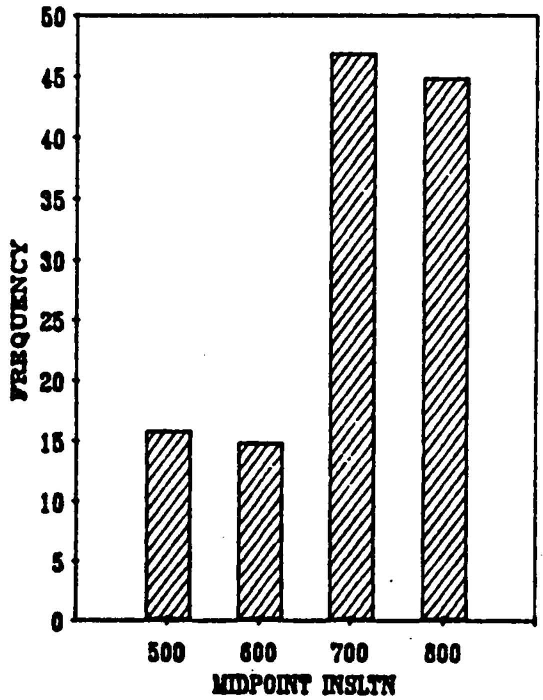
(10 a.m.-First segment)



(10 a.m.-Second segment)



(12 noon-First segment)



(12 noon-Second segment)

Figure 23. Histograms

TABLE 4. K-S test for March insolation data

Time (hour)	No of observations	D α (critical)	Lognormal	Weibull	Beta
1000	204	0.0952	0.2005	0.0816	0.0700
1200	204	0.0952	0.1913	0.0850	0.0675
1400	221	0.0915	0.2280	0.1101	0.0847
1600	223	0.0911	0.1617	0.0471	0.0498

The information presented in Table 5 is similar to that in Table 1, except that January data has been used. It is observed that Beta distribution satisfies th K-S tests for January insolation data as well.

In Table 6 the k and c parameters for Beta distribution for March data has been presented. The number of observations and the maximum values of insolations at those hours are also listed. In Table 7 the k and c parameters for Beta distribution for January data are presented. The number of observations and the maximum values of insolations are also shown.

Once the Beta distribution fit is validated using Kolmogrov-Smirnov test we would like to see how do the Lognormal and Weibull distributions compare when several other goodness-of-fit tests are applied. In Table 8 the results of the distribution fit have been summarized for March data. These tests are ranked in order, with 1 being the best. The goodness-of-fit tests applied were: -(i)Chi-Square (C-S), (ii) Kolmogrov-Smirnov (K-S), (iii) Cramer-Von Mises-Smirnov (C-V-S) and (iv) Loglikelihood (L-L).

It is observed that the Beta distribution represents the Raleigh-Durham data better than the other two distributions. There is one exception, however. For 1600 hour the the K-S test indicates that the Weibull distribution has a better D-statistic than the Beta distribution. If one looks at Table 4 it will be found that D-statistics for Weibull and Beta distributions at this hour are very close and they are well below the critical D-statistic shown for that hour. Thus Beta distribution fits the observed insolation data equally well.

The information presented in Table 9 is similar to that of Table 8, except that January data has been used.

It is observed that the Beta distribution represents the Raleigh-Durham data for January as well. There are two exceptions. For 1500 and 1600 hour the K-S test indicates that the Weibull distribution has a better D-statistic than the Beta distribution. If one looks at Table 4 it will be found that the D-statistics for Weibull and Beta distributions at these two hours are close and they

TABLE 5. K-S test for January insolation data

Time (hour)	No of observations	D α (critical)	Lognormal	Weibull	Beta
1200	195	0.0974	0.2143	0.1345	0.1000
1400	200	0.0962	0.2043	0.1093	0.0842
1500	187	0.0994	0.1569	0.7756	0.0849
1600	172	0.1037	0.0717	0.0315	0.0502

TABLE 6. K and C parameters for March data

Time (hour)	No of observations	Max Value (w/m^2)	K	C
1000	204	671	2.3445	1.223
1200	204	847	1.9820	1.1130
1400	221	793	1.6880	0.9131
1600	223	505	1.7675	1.2526

TABLE 7. K and C parameters for January data

Time (hour)	No of observations	Max Value (w/m^2)	K	C
1200	195	514	2.0782	1.1956
1400	200	516	2.0774	1.2498
1500	187	401	1.9953	1.2498
1600	172	247	1.4110	1.4497

TABLE 8. Summary of tests on 3 distributions for March data

Distribut.	Time	C-S	K-S	C-V-S	L-L
Lognormal	1000	3	3	3	3
	1200	3	3	3	3
	1400	3	3	3	3
	1600	3	3	3	3
Weibull	1000	2	2	2	2
	1200	2	2	2	2
	1400	2	2	2	2
	1600	2	1	2	2
Beta	1000	1	1	1	1
	1200	1	1	1	1
	1400	1	1	1	1
	1600	1	2	1	1

TABLE 9. **Summary of tests on 3 distributions for January data**

Distribu.	Time	C-S	K-S	C-V-S	L-L
Lognormal	1200	3	3	3	3
	1400	3	3	3	3
	1500	3	3	3	3
	1600	3	3	3	3
Weibull	1200	2	2	2	2
	1400	2	2	2	2
	1500	2	1	2	2
	1600	2	1	2	2
Beta	1200	1	1	1	1
	1400	1	1	1	1
	1500	1	2	1	1
	1600	1	2	1	1

are both below critical D-statistic. Thus the Beta distribution fits the insolation data for January equally well.

Results presented here are based on March and January data for 10 years. Similar results have been seen for other months as well. Thus it can be concluded that Beta distribution represents the long term hourly insloation data (second segment). As seen in equation 24, Beta is a two-parameter distribution. The k and c parameters can easily be determined using statistical packages. The mode for the first segment and the distribution for the second segment are then used in the photovoltaic performance analysis model to evaluate the PV electrical output to be used for the other models. PV electrical output for first and second segments for April and October are listed in Table 10 and 11 respectively.

5.2 PV Capacity Credit Results.

The capacity credit of PV generation is obtained by applying the capacity credit evaluation methodology discussed earlier in chapter IV. Figure 24 shows the resulting capacity credit of PV generation in terms of each MW of PV capacity installed. Table 12 shows the resulting capacity of PV generation and its size with respect to the system load. All values are shown with respect to different levels of PV capacity penetration expressed in percent of annual system peak load (system peak = 6400 MW). For study purposes it is more convenient to define the percent penetration in terms of peak load instead of system installed capacity. This is because the amount of required installed capacity in each year is determined by the need to maintain certain a predetermined reliability index.

It can be concluded from these results that:

TABLE 10. PV Output for April (500 MW)

Time (hour)	PV output from first segment	PV output from second segment	Total PV output (MW)
700	0.000	234.830	234.830
800	95.430	1119.523	1214.953
900	239.750	1830.367	2070.117
1000	333.330	2476.119	2814.500
1100	673.826	2796.029	3473.825
1200	600.559	2488.251	3088.702
1300	608.542	2366.185	2974.726
1400	306.563	2454.884	2761.448
1500	313.446	2480.375	2840.375
1600	210.313	1893.695	2314.322
1700	140.837	1102.721	1243.557
1800	0.000	234.679	234.679

TABLE 11. PV Output for October (500 MW)

Time (hour)	PV output from first segment	PV output from second segment	Total PV output (MW)
800	0.000	226.0357	218.744
900	117.869	1193.736	1311.606
1000	374.773	1885.911	2260.685
1100	170.275	2372.639	2542.992
1200	254.785	2597.702	2852.487
1300	226.678	2610.396	2837.747
1400	188.644	2287.991	2476.634
1500	125.679	1903.970	2029.649
1600	36.816	1191.495	1228.314
1700	0.000	467.4173	467.4173

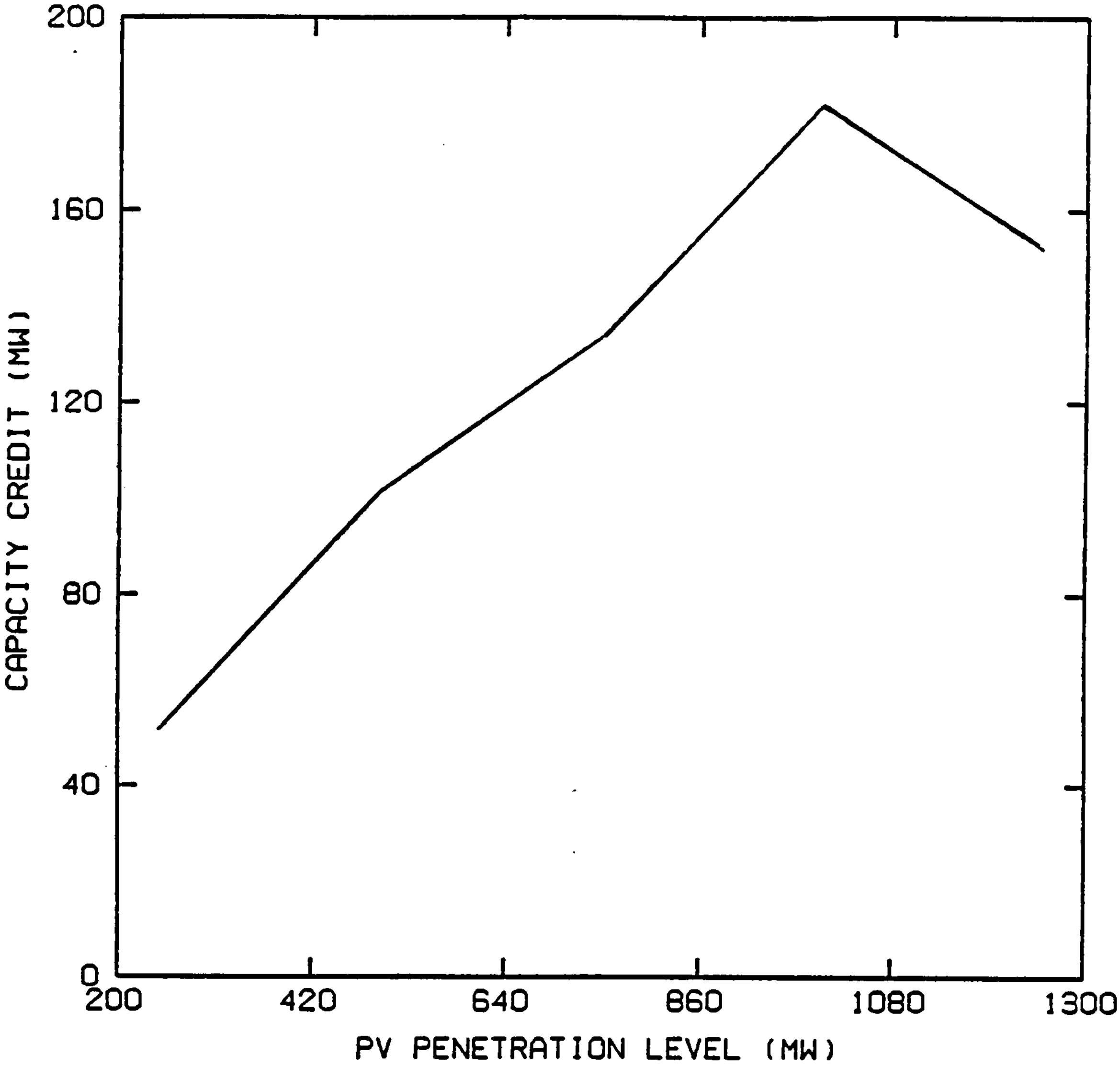


Figure 24. Capacity Credit Via Penetration Level.

TABLE 12. Capacity Credit of PV

PV Pen. %	PV Added, MW	Cap. Credit
3.9	250	52
7.8	500	102
11.72	750	134
15.62	1000	182
19.53	1250	152

1. As the penetration level of PV increases the capacity credit increases upto 15.62% PV penetration level (see figure 24). For higher penetration of PV into the system under study the capacity credit starts to decrease.

2. There are two reasons for relatively low capacity credit.

   a. The PV peak does not match with the system peak load.

   b. Only fixed flat plate arrays are considered for the PV installation.

3. Presence of the PV system can result in peak shifting. On August 8, the hour of the system peak was shifted from 5:00 PM to 6:00 PM (see figure 25). The peak was also reduced.

These results are obtained on the basis of LOLP comparison. The load variations and ramp rate of generating units (short-term study) have not been considered. In order to include these factors to validate the capacity credit results, an operation study utilizing short term analysis has to be done. Next chapter is the operation study analysis where these factors be considered and discussed in details.

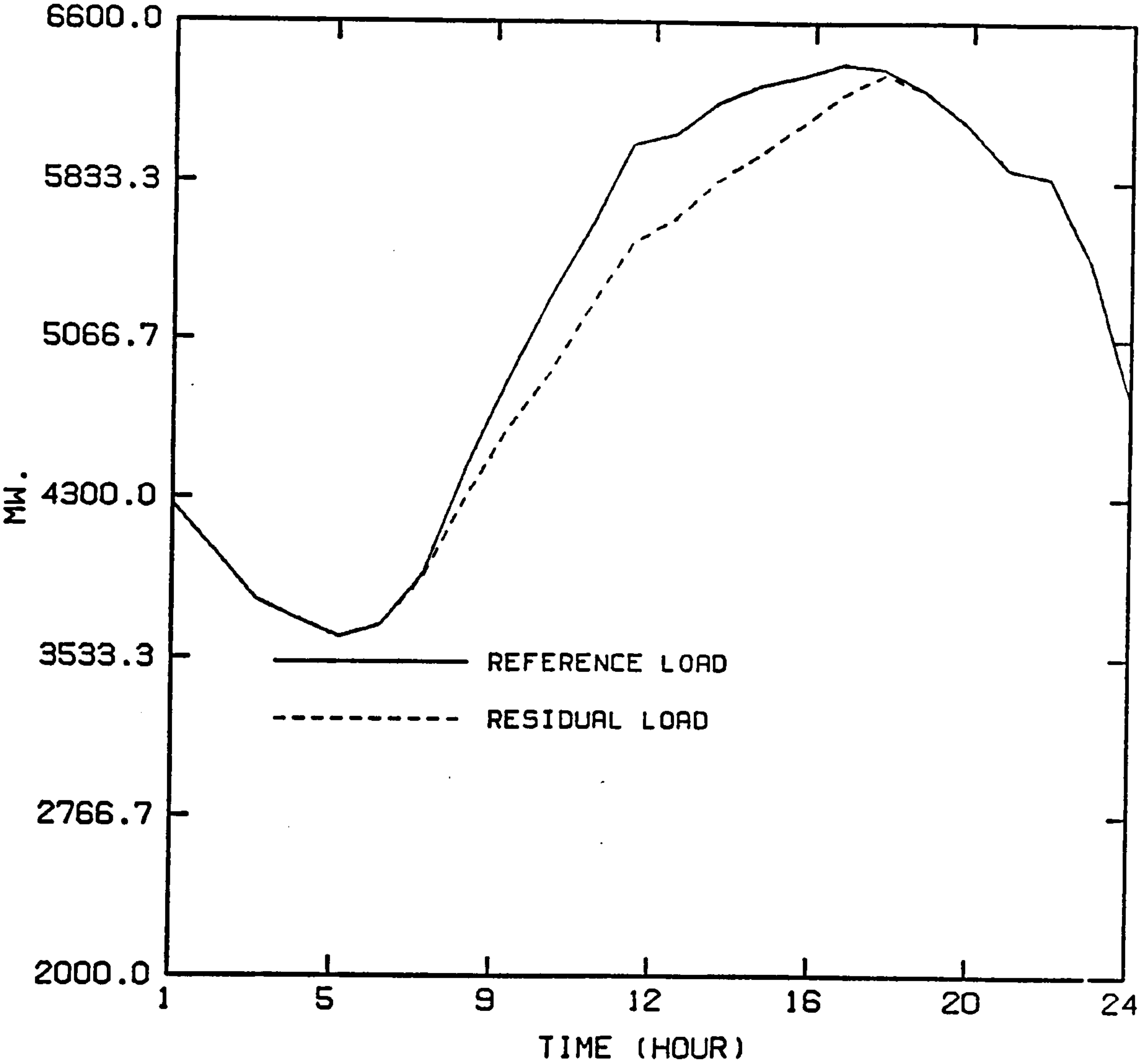


Figure 25. August 8 Reference and Residual Load

CHAPTER VI

6.0 Operation Study

The purpose of this study is to determine a short-term value of grid-connected PV system. The value is estimated through a short range utility operation approach which models the capacity and operating changes that would be associated with the introduction of PV system. A case study approach is used to find the value of PV under utility specific conditions of generating equipment, capacity options, fuel costs, and load patterns. By analyzing the complex interactions of PV market penetration and the utility operation responses over a time horizon, long enough for a significant number of PV systems to be installed, realistic estimates of the value of PV are obtained.

The capacity credit of PV system has been calculated in previous study (PLANNING STUDY) which was based on planning point of view. In this study, the validation of the capacity credit under short term operating conditions is the main purpose.

6.1 Utility Operation

The utility operations referred to here are the ones that are performed on a daily basis. The time frame has to be restricted to 24 hours because of the variation of the insolation and demand. The sequence of operations in this frame time can be summarized as follows.

1. At the start of the daily operations cycle, the unit commitment is decided for ensuing 24 hours. Some utilities may use a 48-hour unit commitment, but no loss of generality occurs if a 24-hour unit commitment is decided on the basis of forecasted hourly load, system reserve, hydro availability and system security constraints. The objective is to meet all the above requirements at a minimum cost.

2. During the 24 hour time frame for which the unit commitment was drawn up, more accurate load forecasts are made at periodic intervals.

3. At fixed intervals of length of 2.0 to 10.0 minutes the available committed generation units are dispatched to meet the system load at the minimum cost. The economic dispatch provides the desired loading levels of the committed units for the suggested interval.

4. At intermediate intervals of the order of few seconds the automatic generation control (AGC) system adjusts the generation to match the load, till the next economic dispatch computation is performed. Further, intermediate control is required by AGC during the economic dispatch interval because the load does vary on an instantaneous basis during the interval and the equality of system generation and load has to be maintained for secure system operation and frequency maintenance.

The above four steps form a cycle .

In the context of the above description of on-line system operations, it is necessary that any methodology for the dispatch of PV generation has to take into consideration the following factors:

1. The integration of PV output into the unit commitment,

2. Interface PV dispatch with the economic dispatch of system generation resources.

3. Take into consideration any operational restrictions introduced by PV power.

Satisfaction of the requirement will allow PV to be integrated into the process of utilizing resources for optimum operation of the power system. The following section discusses the model development.

6.2 UNIT COMMITMENT

The function of unit commitment is to provide an hourly schedule of available on-line units for a 24-48 hour period. Unit commitment is a required function because:

1. All displaceable and most peaking units have start-up times which determine how long it takes the unit before it can be expected to be on-line and ready to serve the load; and

2. All units have maximum up-time and minimum down-time constraints which have to be observed and considered.

Thus, the constraints on the units have to be maintained which ensure that at any hour of the day there is sufficient on-line capacity to:

1. Meet the expected load plus losses;

2. Satisfy the system reserve requirements; and

3. Provide a sufficient regulating margin.

When all the above requirement are placed within the unit constraints, it is evident that a scheduling function is required which will coordinate unit startups and shutdowns in a manner which meets all the requirements and satisfies all the constraints in the most economic manner. This is the function of unit commitment.

The basic single area unit commitment problem requires that

$$P_{\max} \geq L + X + S_r$$

$$P_{\min} \leq L + X$$

Where,

- P_{max} = sum of maximum generation capacity.
- P_{min} = sum of minimum generation capacity.
- L = real system load plus losses.
- X = net area power interchange.
- S_r = spinning reserve requirement.

Most of the unit commitment programs utilize dynamic programming algorithm to select the least cost generator combination which will meet the above constraints. The specific program used in this study, is the "Unit Commitment and Production Costing Program (GPUC)" developed by Boeing Computer services for the the Electric Power Research Institute (EPRI) [26]. A brief discussion of the program is given in the following section.

6.2.1 EPRI'S UNIT COMMITMENT PROGRAM

The program is designed to analyze the operation of generation and transmission systems consisting primarily of thermal dispatchable generating units with possible additional capacity in the form of non-dispatchable combustion turbine, pumped storage hydro, and hydro units. Its main function is to schedule generation and interchange on an hourly basis for periods ranging to one week. The schedule is generated such that the expected system load is met at a suitably low cost without violating any of the numerous operating constraints on the generation and transmission system. Once a schedule has been determined, the total production costs of that schedule are computed. The program also monitors fuel consumption by generating unit, fuel type, station and fuel type and compares this usage with any fuel usage constraints. The following subsections describe briefly the scheduling process used by the program.

6.2.1.1 Input Data:

The input data required by GPUC consists of:

1. Processing options such as spinning reserve requirements, priority list generation options, load specification option, etc.

2. Unit identification, cost and performance data such as heat rate curve, startup time, minimum downtime, maximum up time, boiler cool down time, etc.

3. Load models for a week. The load for each 24 hour period is assumed to start at 8:00 a.m. and the loads specified have to be hourly integrated loads.

4. Manual scheduling data for hydro, pumped hydro and thermal units, and interchange.

5. Transmission loss data appropriate to the option exercised. There are three options for this purpose:

    a. Ignore transmission losses,

    b. Compute transmission losses using B-constants, or

    c. Use a quadratic function of the load for computing losses.

6.2.1.2 Priority Generation List:

Commitment of dispatchable units proceeds on the basis of a single priority list may be provided by the user or generated by GPUC. The priority list generation is based on the operating cost of a unit at a user specified fraction of the generator set capacity.

6.2.1.3 Hourly Generation Maximum Capacity:

This quantity is central to the scheduling of non dispatchable capacity. It is determined as the summation of:

1. The maximum capacities of all on-line dispatchable units.

2. The maximum capacities of any combustion turbines which are user scheduled to be on-line, and

3. Any used scheduled interchange and hydro capacity.

6.2.1.4 Reserve Capacity from Non-dispatchable Sources:

All non-dispatchable sources contribute to two types of reserves (ten minute and spinning reserve) as a function of the unit type status during the hour. The reserve capacity from non-dispatchable sources is required in order to compute the ten minute and spinning reserves, and to estimate the additional reserve capacity, if needed, from the dispatchable sources.

6.2.1.5 Precommitment of Peaking Units:

The function of this process is to schedule combustion turbines and interchange on an hourly basis such that, for each hour there is sufficient on-line generating capacity and interchange to meet the expected load plus losses.

6.2.1.6 Hourly Regulation Requirement:

Generation units ramp rates are not required by GPUC. However, it attempts to provide sufficient regulating margin during periods of load pickup. The policy followed in the program is, that "in an average system, bringing additional capacity on-line at a given hour, equal to the load pickup the next hour, should ensure a system response rate sufficient to meet the increased demand".

6.2.1.7 Dispatchable Unit Commitment Schedule:

The dispatchable unit commitment schedule is basically arrived at by considering a shutdown decision for each unit on an hour-by-hour basis. The default status of dispatchable units is the economic run status, therefore, the decision which is being considered is that of shutting down units for a period of time. The approach used allows the decision to shut down units to be made hour by-hour. Estimate of the cost of starting up a unit being considered for shutdown will be made taking into consideration the period of time that the unit may be expected to be shut down before the generation requirements or schedules will dictate the the unit be restarted. The total startup cost is then prorated over the shutdown period. Comparison of an hour's fuel costs plus the hour's prorated value of the startup costs will allow the determination of the set of on-line generators, which will result in minimum fuel cost plus prorated stratup costs, and hence the near minimum production cost over the commitment period.

6.2.1.8 Interfacing PV System to The Unit Commitment:

The approach which has been adopted in this dissertation is to treat the PV output as negative load and use it to modify the load shape accordingly. From the point of view of interfacing PV system to the unit commitment process, an off-line estimation of the impact of the PV system dispatch can be used to input a modified load profile to the program. This should be able to provide a unit commitment schedule which reflects the load shape impacts of PV system

6.3 The Economic Dispatch

The economic dispatch is the calculation of generator outputs from on-line units to satisfy the system load plus losses at the minimum cost. If the fuel cost of each generator is generalized as $F_i(P_i)$, P_i being the power output of the generator, then the economic dispatch problem can be stated as following:

$$\textit{Minimize cost } C = \sum_{i=1}^{i=N} F_i(P_i) \tag{35}$$

$$\textit{such that } \sum_{i=1}^{i=N} P_i - P_r - P_l = 0 \tag{36}$$

Where,

1. P_r = system load.

2. P_l = losses.

3. N = number of on-line generators.

Knowing the cost characteristic of the generating units, the above can be solved as an unconstrained minimization problem using the Lagrang multiplier method. This leads to the well known $\lambda - \textit{dispatch}$. λ is the system incremental cost or the cost of generating one additional MW. The $\lambda - \textit{dispatch}$ leads to the necessary condition for the existence of a minimum cost operating condition for the thermal power system which stated as "The incremental cost rates of all the units be equal". The algorithm for $\lambda - \textit{dispatch}$ is usually an iterative one. The derivation of the closed form solution is presented below:

Given quadratic cost curve of the form:

$$F_i(P_i) = \alpha_i + \beta_i P_i + \gamma_i P_i^2 \tag{37}$$

Equation can be converted to unconstrained minimization problem using a Lagrange multiplier.

$$Minimize \;\; C = \sum_{i=1}^{i=N} F_i(P_i) - \lambda \left[\sum_{i=1}^{i=N} P_i - P_r - P_l \right] \tag{38}$$

By applying the Kuhn-Tucker theorem yields to the following conditions:

$$\frac{\partial c}{\partial P_i} = \beta_i + 2\gamma_i P_i = \lambda \left(1 - \frac{\partial P_l}{\partial P_i}\right) \tag{39}$$

The,

$$P_i = \lambda \frac{\left(1 - \frac{\partial P_l}{\partial P_i}\right)}{2\gamma_i} - \frac{\beta_i}{2\gamma_i} \tag{40}$$

Substituting into the power balance equation

$$\lambda \sum_{i=1}^{i=N} \left(1 - \frac{\partial P_l}{\partial P_i}\right) / 2\gamma_i - \sum_{i=i}^{i=N} \beta_i / 2\gamma_i + P_r - P_l = 0 \tag{41}$$

Equation can be solved for λ, the equal incremental cost at which all generators should operate.

The above formulation and solution account only for the power balance equation. There are four classic constraints imposed on the economic dispatch. Thus, the complete set of constraints on economic dispatch consists of.

1. The power balance;

2. Generator power limit;

3. Generator ramping limits in the raise and lower directions;

4. System spinning reserve requirements; and

5. Ten minute reserve requirements

The economic dispatch program which has been used in this dissertation was developed by Bhatnagar [27]. In the following subsections a discussion of the program.

6.3.1 Economic Dispatch Program

This program has included the ramp rates of the generator units into consideration in addition to the classical constraints. The close form solution has been derived under the following assumptions:

1. Generator costs are characterized by quadratic polynomials which are function of generation output; and

2. The reserve and regulating margin constraints are excluded on the basis that they are accounted for in the unit commitment program.

The economic dispatch is performed based on a forecast of load ΔT minutes in the future. The closed form solution was derived resulting in the following equation:

$$\bar{\lambda} \sum_{i=1}^{i=N} \Delta M W_i^2 / 2\bar{\gamma}_i - \{ \sum_{i=1}^{i=N} \Delta M W_i \bar{\beta}_i / 2\bar{\gamma}_i + P_d - \sum_{i=1}^{i=N} \bar{P}_{min,i} \} = 0 \qquad (42)$$

Where,

1. $\Delta MW_i = \bar{P}_{max,i} - \bar{P}_{min,i}$

2. $\bar{P}_{max,i}$ = modified maximum limits

3. $\bar{P}_{min,i}$ = modified minimum limits

4. $\tilde{\lambda}$ = modified lambda

Once $\tilde{\lambda}$ is known, the x_i can be calculated by substituting in the following equation:

$$x_i = \bar{\lambda}_i \frac{\Delta MW_i}{2\bar{\gamma}_i} - \frac{\bar{\beta}_i}{2\bar{\gamma}_i} \tag{43}$$

$\bar{\beta}_i, \bar{\gamma}_i$ are modified cost equation coefficients. Finally, the new generator output can be calculated on the following manner:

$$P_{op,i} = (1 - x_i)\bar{P}_{min,i} + x_i\bar{P}_{max,i} \tag{44}$$

Substituting the above expression into the quadratic expression for the generator cost to find the operating cost. The following section describes the overall operation of the program.

6.3.1.1 Input Data:

The economic dispatch requires the following data:

1. System generation;

   -Unit identification

   -Unit type

   -Fuel type

   -Quadratic heat rate type

-Per unit fuel cost ($/MBTU-HR)

-Unit minimum and maximum capacities, and

-Unit ramp rates

2. Expected load curve for 24 hour period;

3. Economic dispatch interval;

4. The unit commitment for dispatchable units; and

5. Transmission losses (has been included in the program as a percentage of the load)

The program has the ability to enter the data either as input file or interactively from the keyboard. Processing required to run the program consists of:

1. Initial values of load and PV output;

2. Interpolation and storage of the load at economic dispatch intervals; and

3. Rearranging and storing the unit commitment schedule, the output of GPUC , in the form that can be used by the economic dispatch program.

The program consists of many output files. However, the outputs which are required in this dissertation are listed as following:

1. Time;

2. Total dispatchable and non-dispatcable generators;

3. System incremental cost (λ); and

4. Total generation costs.

6.4 Method of Analysis

The method of analysis presented in this study involves calculation of operating cost savings and fuel requirements. A utility operation model is used to compute the changes in the utility's generation system and operating cost when the load is modified by the use of PV system. The analysis process is completed in three steps. First is the process of modifying the load to incorporate the PV system, this follows a utility operation analysis to determine the amount of fuel cell requirements, finally, calculation of operating cost savings for each penetration level of PV. Figure 26 shows the flow chart of operation study. In the following subsections the discussion of these three steps according to the this flow chart.

6.4.1 System Load Process

This process involves the following:

- Choose hourly load data for one day which has a relatively high peak and the PV output in the same day has a very high fluctuations.
- Perform a linear interpolation to generate intermediate data for dynamic study.
- Make the PV hourly data available (the same data which has been used in the planning study).
- Make 3-minute PV data available.
- Modify the hourly load data to be used by unit commitment program.

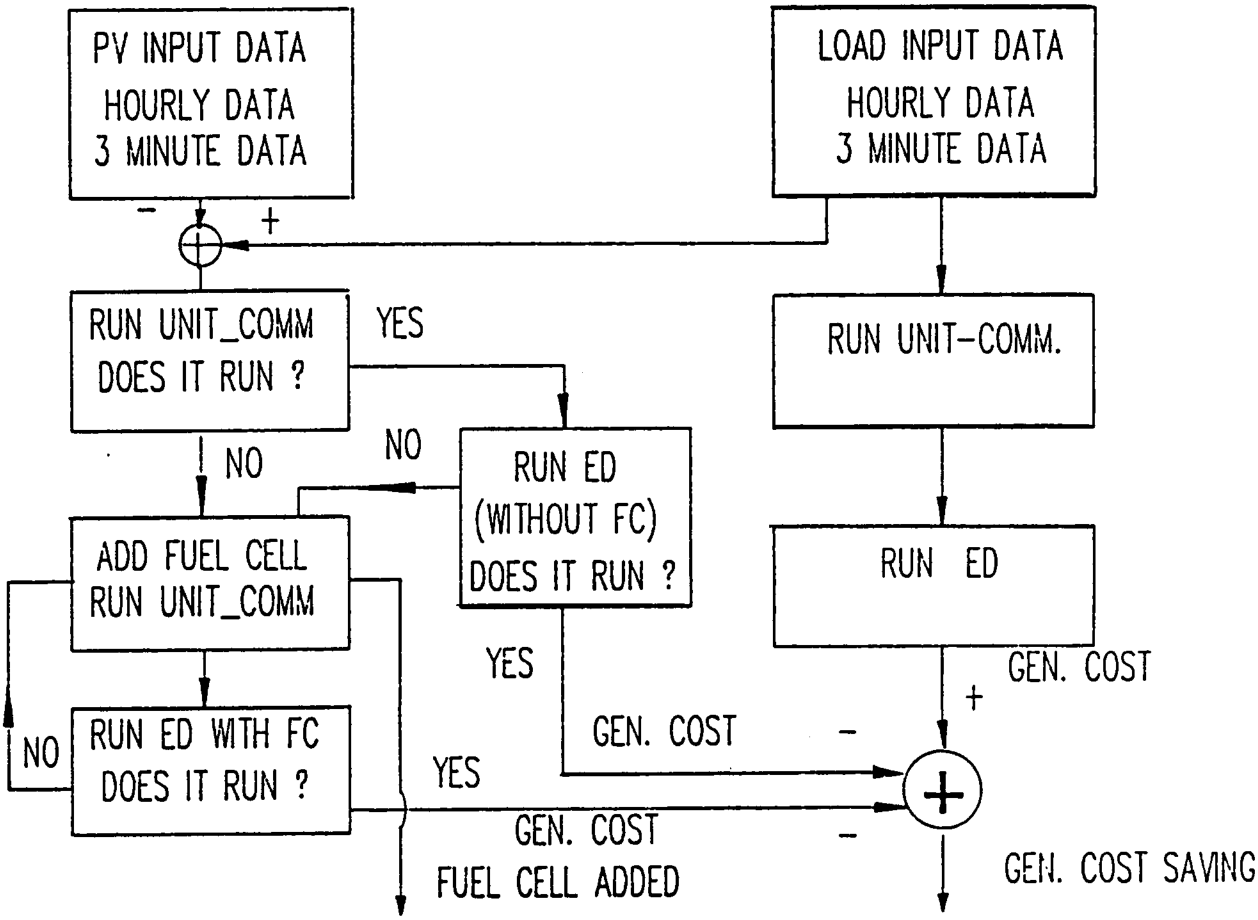


Figure 26. Operation Study Flowchart

- Modify the 3 minute load data to be used by economic dispatch program.

6.4.2 Calculation of Operating Cost and Fuel Cell Requirements

The operation model has to be run off-line in order to calculate the operating cost of fuel cell requirements. Once fuel cell requirements are calculated, the system generation can be modified and the operation model can run in an on-line mode. The flow chart of operating study leads to two scenarios, with and without PV. The reference scenario starts by feeding the hourly load data to GPUC and 3 minute data to ED program. From this scenario the reference operating cost (ROC) can be calculated. In PV scenario, the GPUC and ED have to feed them with the modified load data (hourly and 3 minute). Because of the high fluctuations of PV output (especially at high penetration level) the PV scenario has to run in the following fashion:

1. Modify the system generation to include the capacity credit of PV system (by subtracting the capacity credit (MW) from system generation).

2. Run GPUC with the following inputs:

   a. Modify load data (hourly data)

   b. Modify system generation.

3. Run ED program with the following inputs:

   a. Modify load data (3-minute data).

   b. Unit commitment scheduling for the same day.

It is important to check whether the operation model runs or not. If it does not run fuel cell has to be added to the system generation of GPUC until it runs. There is a possibility that ED will not run. In this case the fuel cell has to be added to the generation capacity list of GPUC until it modifies the unit commitment schedule which can run ED. The output of this scenario can be summarized in the following:

1. *Operating cost (OC).* The difference between ROC and OC represents the operating cost saving.

$$If \quad ROC - OC = 0 \quad Same\ credit$$

$$If \quad ROC - OC < 0 \quad penalty$$

$$If \quad ROC - OC > 0 \quad More\ credit.$$

2. The amount of fuel cell which has been added finally will be the required fuel cell (MW) (FCR).

$$If \quad CC - FCR = 0 \quad Same\ credit$$

$$If \quad CC - FCR < 0 \quad Penalty$$

$$If \quad CC - FCR > 0 \quad Credit$$

Where CC is the capacity credit which has been evaluated in the planning study.

In next chapter, a case study showing the use of the operation model and some results are presented.

CHAPTER VII

7.0 Results and Discussion

There are three types of results in this dissertation, they can be listed as following:

- Planning study results which have been discussed in details in chapter IV.
- Operating study results which have been calculated by running the operation model discussed in chapter VI.
- Overall results which are a combination of two results (operating and planning).

The operation and overall results are the subject of this chapter.

The operation model was used to study a number of simulated scenarios in order to investigate the effect of various PV system in utility's operation system. In order to investigate PV system effect alone and to filter out extraneous effects, it was necessary to synthesize a test system for use in the simulations. A set of generators have been synthesized that represent a southeastern utility generating units. The generating unit data is the same as that used in planning study.

7.1 Test System

The major requirement in synthesizing the test system was that it reflected, as closely as possible, a real utility system. Since all the data required was not available from a single source, it was necessary to draw on several data sources to synthesize a test system which would meet the realistic criterion. The following data is provided for each system:

1. Number and capacities of all units,
2. Heat rate curves,
3. Unit availabilities,
4. Fuel cost, and
5. Generation unit loading order.

The heat rate of fuel cell was drawn from EPRI report [28]. The following is the data for 26 MW fuel cell:

$$Size \ = 26MW$$

$$Heat\ rate\ at\ 25\ \ percent\ \ of\ the\ load = 8900\ \ Btu/KWh.$$

$$Heat\ rate\ at\ 50\ \ percent\ \ of\ the\ load = 8900\ \ Btu/KWh.$$

$$Heat\ rate\ at\ 80\ \ percent\ \ of\ the\ load = 9000\ \ Btu/KWh.$$

$$Heat\ rate\ at\ 100\ percent\ \ of\ the\ load = 9000\ \ Btu/KWh.$$

It can be noted that the heat rates at part and full load are almost the same. The heat rates of the other sizes can be scaled according to their capacities.

7.2 Load Data

Simulation for studying the effect of PV system in utility's operation system was carried out on 24 hour load data. Load data for July 4th and July 12th were investigated. The criterions to choose these days are listed as following:

- The load data for July 12th has a relatively high peak and PV fluctuations are very high.

- The load data for July 4th has a relatively low peak and PV output fluctuations are small.

The load shapes of these two days are shown in figure 27. As can be seen from the figure, the load peak of July 12th is high and has a well defined system peak for 24 hours and a higher average load. July 4th load shape, on the other hand, has lower peak and a flatter profile. Figure 28 represents 3-minute PV data for July 12th. It has very high fluctuations and high PV output. However, figure 29 represents the data for July 4th. It has low output. Although it has fluctuations, these fluctuations dose not have major effects on the operation system because it has low output. It is clear that July 12th PV data will have major effects on the operation system of the utility. The PV data was based on 4 Kw rating. In order to use this data for other penetration levels, the data was converted to capacity factor.

The linear interpolation was done to hourly load data to get 3-minute data. Figure 30 shows 3 minute load data for July 12th. The load data without PV has no high fluctuations which might cause problem to the operation system of the utility. However, the modified load has a lot of fluctuations (see figure 31).

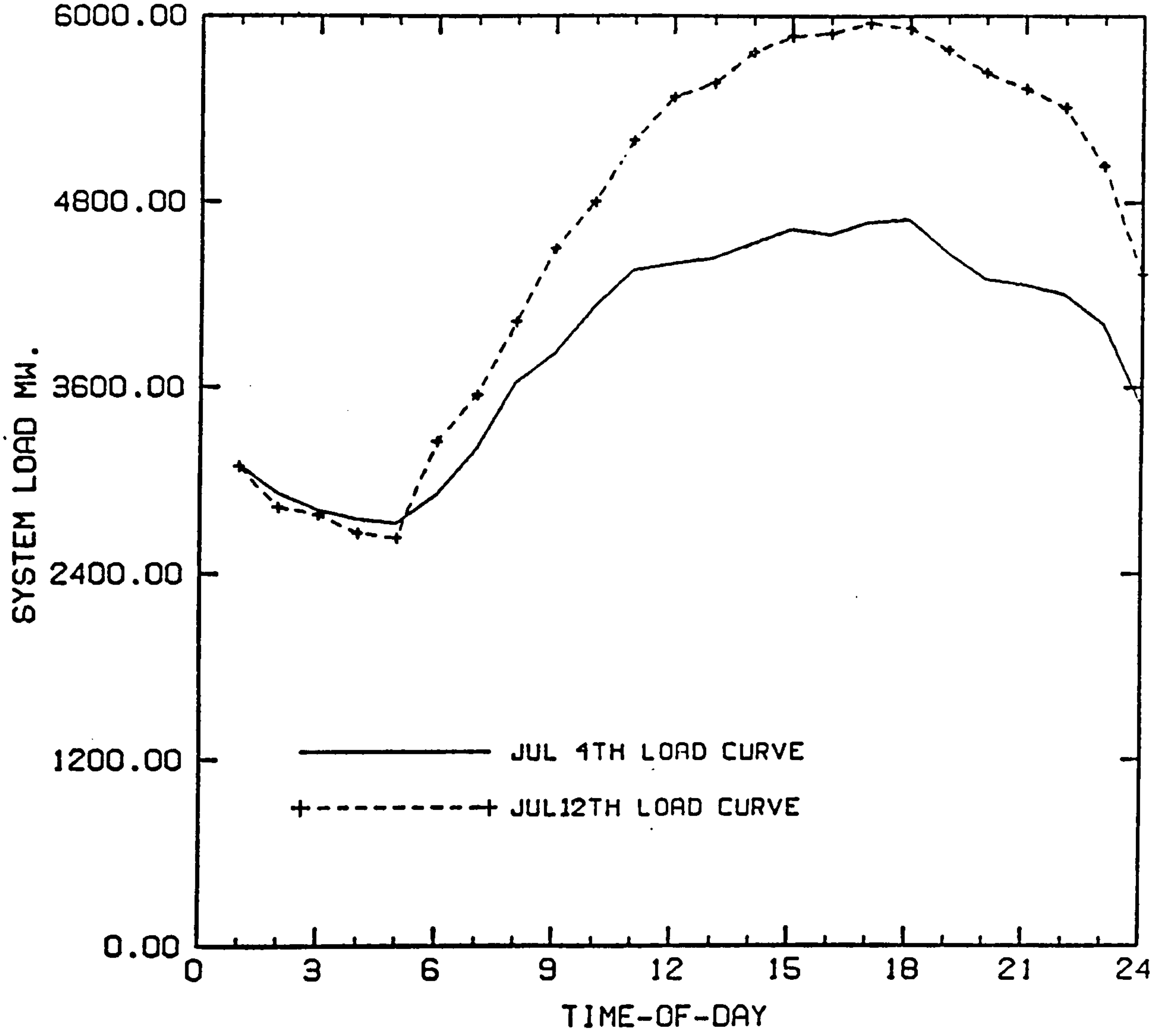


Figure 27. Load Data for July 4th & 12th

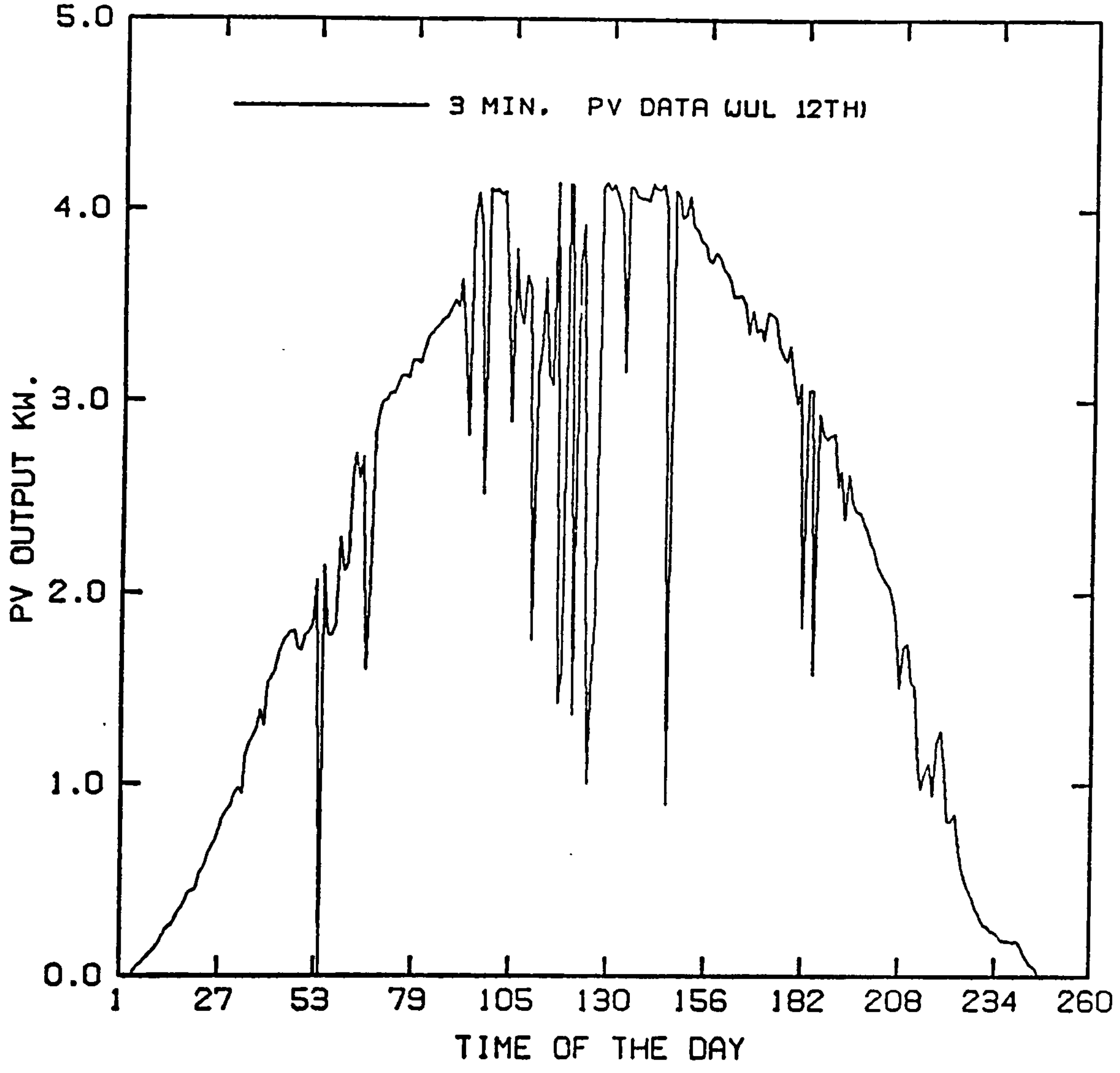


Figure 28. PV Data for July 12th

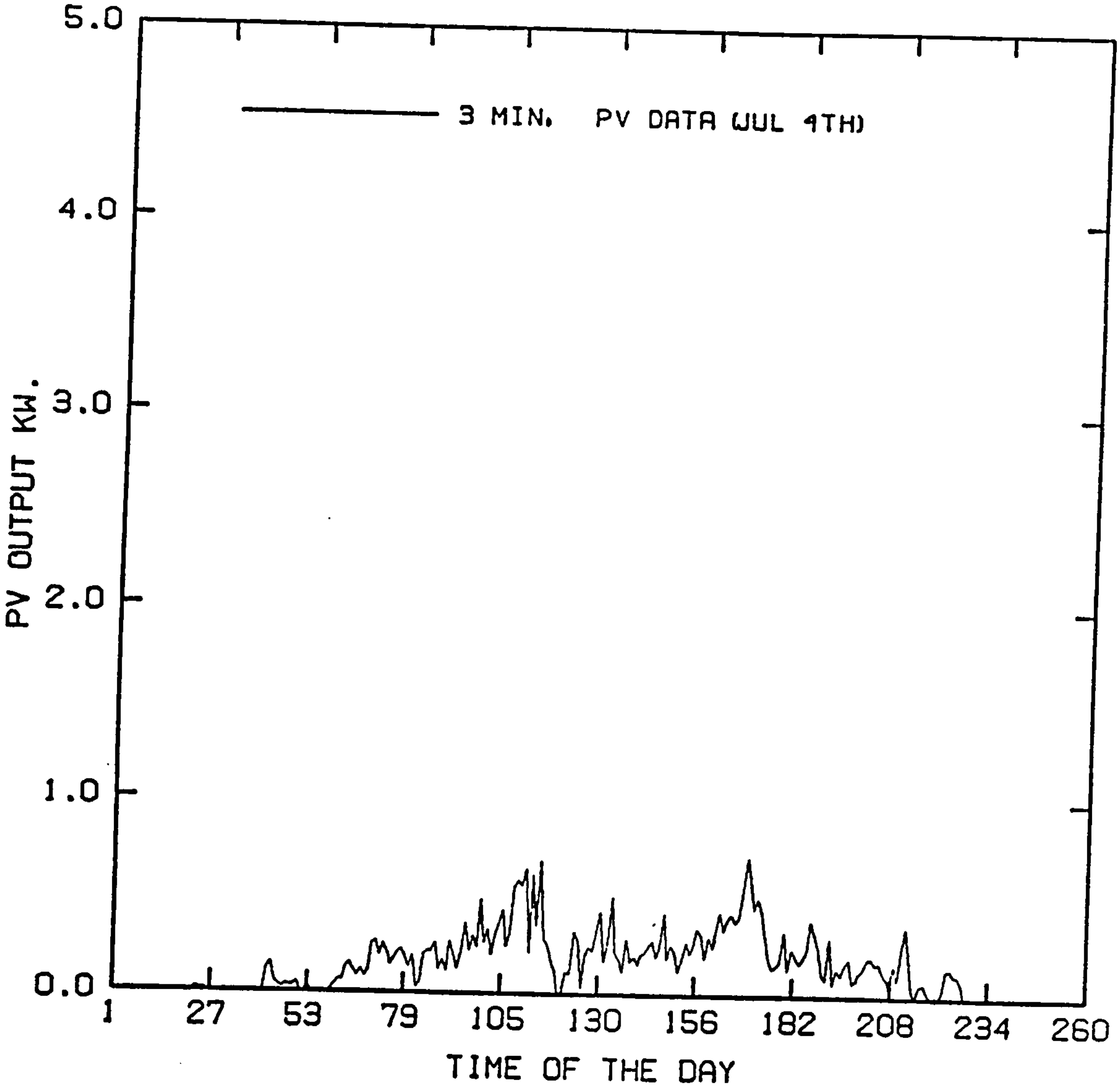


Figure 29. PV DATA FOR JULY 4th

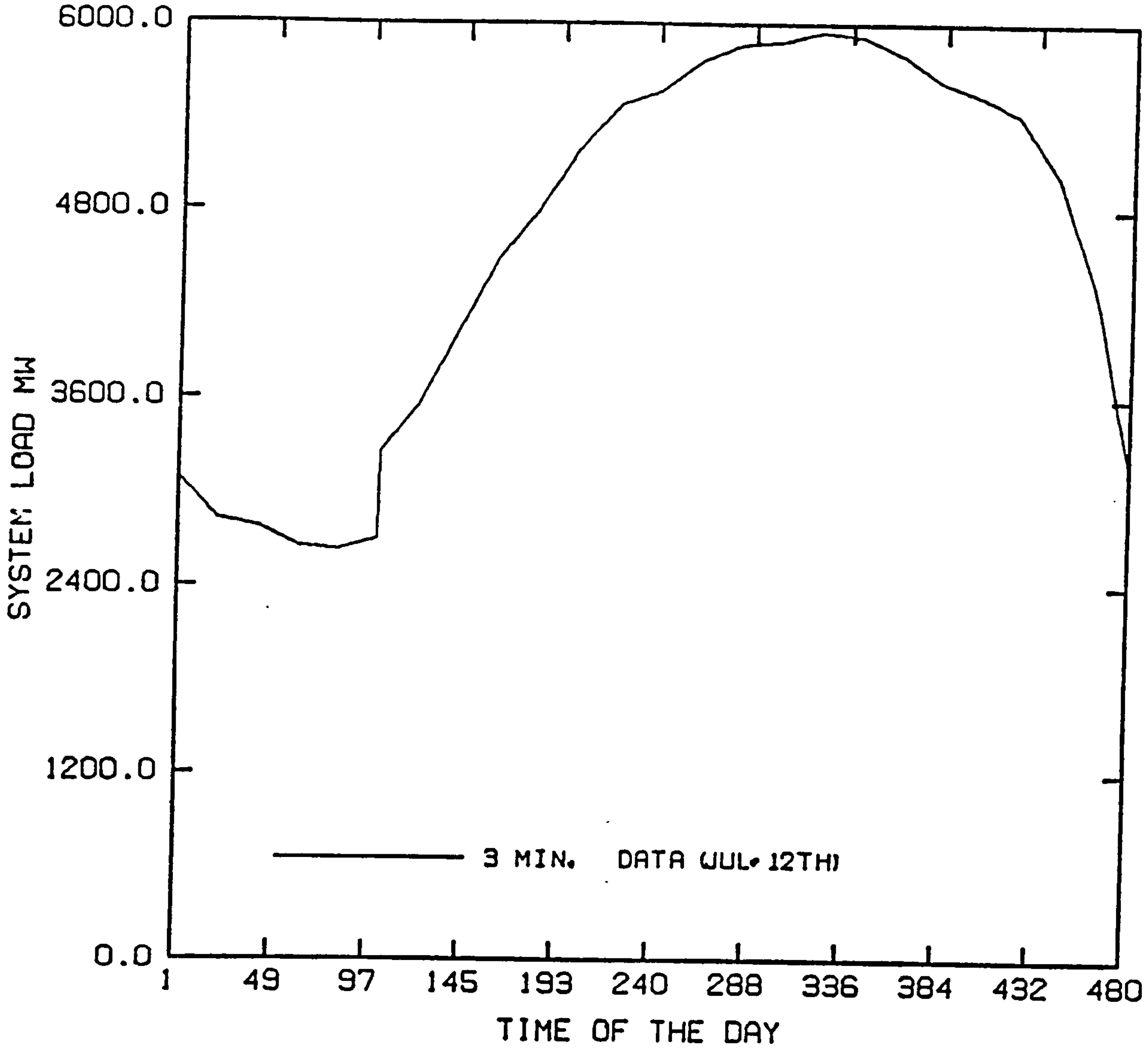


Figure 30. 3 Minute Load Data

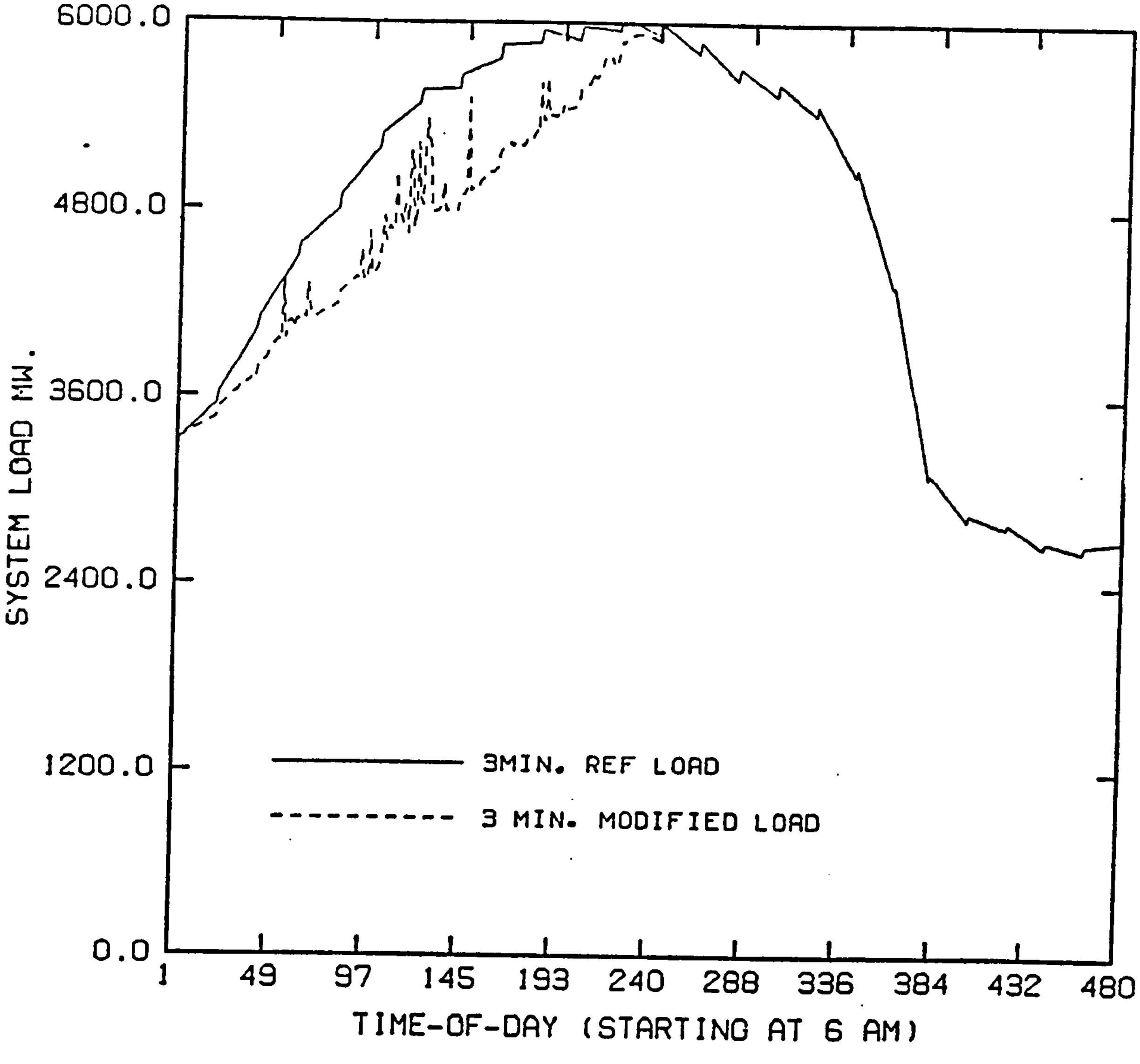


Figure 31. 3 Minute Data (Modified load)

7.3 Operation Results

With a series of simulation studies, the amount of fuel cell requirements and operation saving were evaluated at various PV penetrations. Two cases are presented here. In the first case, PV and load data of July 4th were studied. The generation cost, operating cost savings and fuel cell requirements are listed in Table 10. These values are compared with the reference case data which are given as following:

$$Peak\ Load \quad = \quad 4685\ MW$$

$$Generation\ cost \quad = \quad 1146291.000\$$$

Since the PV has low output and it has small fluctuations which can be handled by conventional units, the fuel cell requirements were zero in all cases. The reason for this results is that the system generation has enough combustion turbines which have the capability to handle the ramp rate of the modified load. It can be observed from Table 10 that there are operating cost savings due to the interconnection of PV system to the grid (without adding fuel cell).

In the second case, July 12th load and PV data were used to investigate the effect of PV on the system operation of utility. Table 10 summarizes the generating cost, cost saving and amount of fuel cell requirements (MW) as a function of PV penetration level (MW). These results were compared with the reference case. The peak load and generating cost of the reference were given as following:

$$Peak\ load = 5952.0\ MW$$

$$Generation\ cost = 1541447.00\$$$

TABLE 13. July 4th Case Study

PV	Operating Cost $	Saving $	Fuel Cell (MW)
250	1106964.00	39327.00	0.0
500	1069769.00	76522.00	0.0
750	1070066.00	76225.00	0.0
1000	1079567.0	78724.00	0.0
1250	1080000.0	66291.00	0.0

TABLE 14. July 12th Case Study

PV	Operating Cost $	Saving $	Fuel Cell (MW)
250	1479819.00	61628.00	38.0
500	1425864.00	115583.00	72.0
750	1382382.00	159065.00	48.0
1000	1343588.0	197859.00	88.0
1250	1360479.0	180968.00	188.0

Since the July 12th data has high variations which could not be handled by conventional units, fuel cell requirements were necessary as it was expected. It can be observed from figure 32 that the relationship between PV penetration level and fuel cell requirements does not have a general trend. However, in the higher penetration level, the fuel cell increases linearly with PV penetration level. The operating cost savings in other hand, has a general trend with PV. It increases linearly as PV penetration increases upto 1000 MW PV. For a higher penetration the operating cost savings starts to decrease. This indicates that PV fuel cell hybrid system is not economical beyond 1000 MW PV for a system with 6400 MW peak and the load shape expected for southeastern utility.

Since the system load and PV (for July 12th) were considered to be the worst case which can face the utility's operation system, these results will be considered to be the most pessimistic that may be encountered by the utility in the entire year.

7.4 Overall Results

Up to now, two types of results have been evaluated, planning and operation results. These results have been evaluated independently. In order to get the real evaluation, the two results have to be merged and studied carefully. The combined results include:

1. Capacity credit results which were evaluated from planning study,

2. Fuel cell requirements which were evaluated from operating study,

3. Operating cost savings which were evaluated from operating study.

The merged results are summarized in Table 12. Figure 33 shows the capacity credit, fuel cell requirements and operating cost savings plot as a function of penetration level. This plot is very

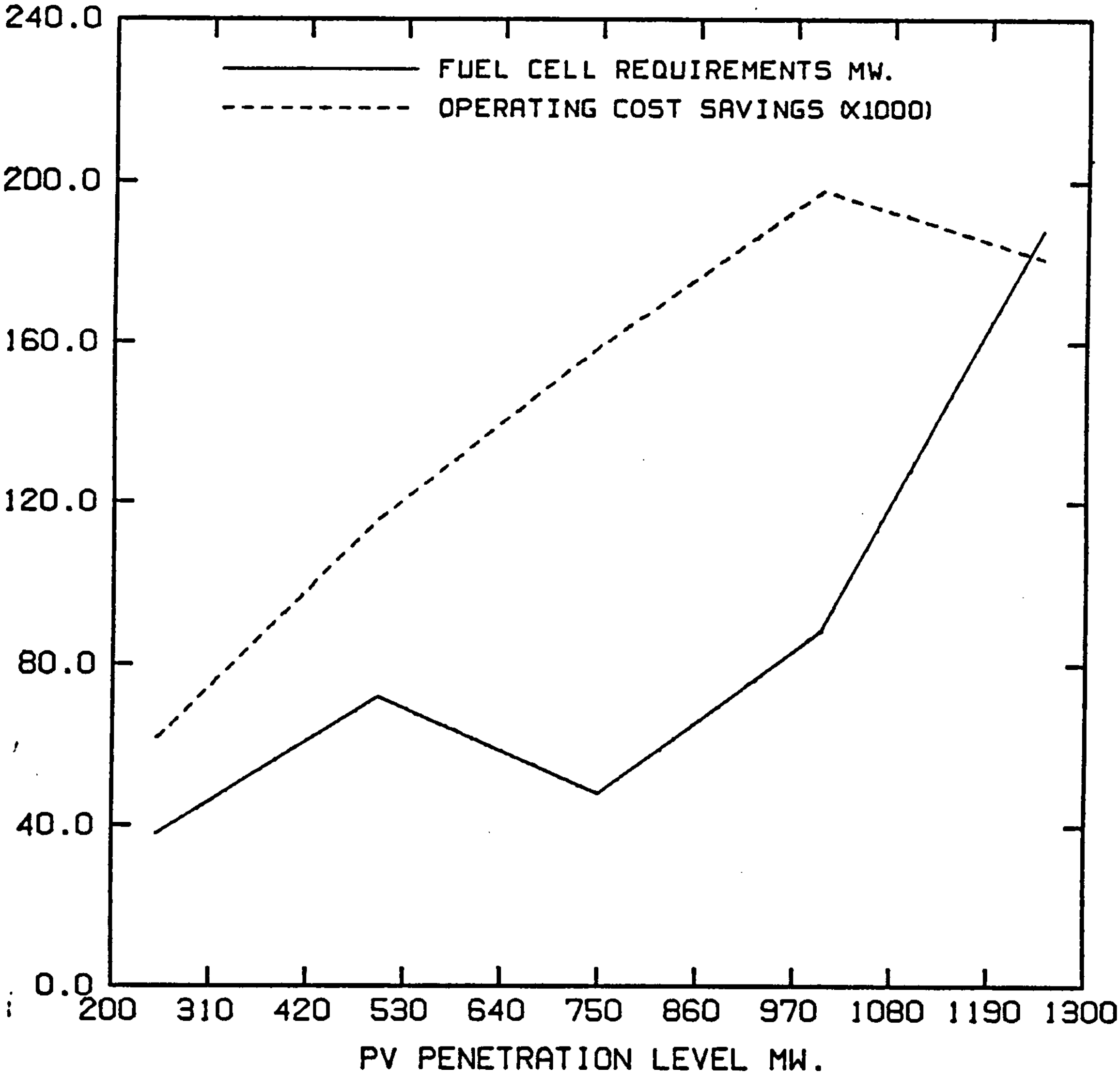


Figure 32. Fuel Cell & Operating Cost Savings Via PV.

TABLE 15. July 12th Case Study

PV	Capacity Credit	Saving $	Fuel Cell (MW)
250	52.00	61628.00	38.0
500	102.00	115583.00	72.0
750	134.00	159065.00	48.0
1000	182.0	197859.00	88.0
1250	152.0	180968.00	188.0

important since it compares all results beside the operating cost savings. The following points can be observed from this plot:

1. After 1000 MW penetration level of PV (15.62%) the capacity credit starts to decrease. It means that PV will replace less amount of conventional units and this will discredit the PV system.

2. After 1000 MW PV the operating cost savings start to decrease. It means that the more PV system penetration level the more operating cost. This might cause a penalty which cancel the capacity credit of PV system.

3. After 1000 MW PV system fuel cell requirements keep increasing. This is logical because increasing PV penetration levels lead to more modified load fluctuations to more fuel cell to overcome theses fluctuations.

From the above observations it can be concluded that the maximum penetration level of PV system can be upto 1000 MW (15.62%) for the system considered. This was accomplished by using fuel cell interconnected with PV system.

It has to be noticed here that the fuel cell benefits were not included in this study. It is quite conceivable that if these benefits ($/MW) were included the maximum penetration level and operating cost savings can be increased. These benefits can be listed as following:

1. Air-emission offset,

2. Load following,

3. Spinning reserve,

4. VAR control,

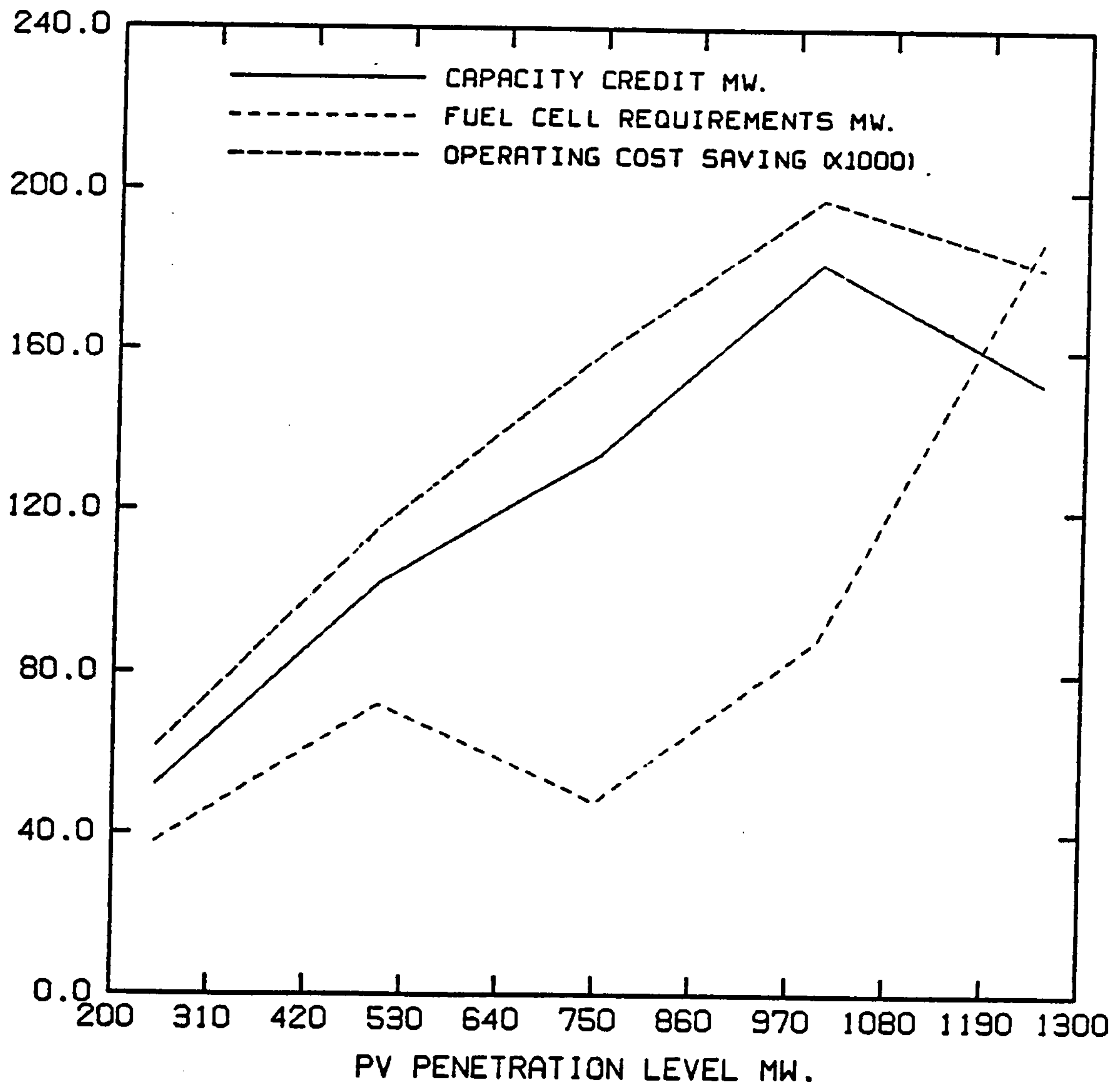


Figure 33. Plot of Overall Results

5. Deferred T&D capacity,

6. Reduce T&D losses,

7. Cogeneration potential,

These benefits were estimated for thirty-seven utilities [28], they found that they ranged from $ 54/KW to $ 610/KW and averaged $ 155/ KW. The capital cost of PV and fuel cell has not been included here, assuming that they will be competitive with the conventional units in the future.

7.5 Summary and Conclusions

The aim of the study was to develop an overall methodology which can be used to analyze the impact of PV on a utility system. The methodology consists of two parts-, planning and operation. In the planning the following methodologies have been developed:

1. A probabilistic methodology to predict the performance of PV system that capture the uncertainties in the solar data.

2. A probabilistic methodology to calculate the capacity credit using generation expansion over a six year period.

In the operation study, the following methodology was developed:

1. A method to determine the amount of fuel cell requirements.

2. A method to calculate the operating cost savings due to the use of PV-fuel cell hybrid system.

Overall conclusion of this study can be listed as following:

1. The penetration level of PV system can be increased upto 15.62%. This was achieved by adding fuel cell power plant to the grid.

2. Presence of the PV system can replace some combustion turbine units over a six year period. This was evaluated by the planning study and validated by the operating study.

3. Presence of the PV system cause the peak load to shift and reduce its value.

4. Operating cost savings are possible by adding PV alone or PV and fuel cell.

5. The study results are derived from applying this technique to a particular utility system. Similar evaluations for other system may yield somewhat different results.

6. The methodology presented in this study can be used for any renewable energy source.

7.6 Recommendations for Further Research

The methodology developed in this dissertation is a part of an emerging philosophy of PV utilization. As with any new methodologies, those presented hare, require considerable development, testing, and refining. Efforts have been made to develop models of power systems planning and operation incorporating the PV-fuel cell hybrid system to the grid. The PV fuel cell hybrid system need to be explored further. Some issues which needs to be researched further or considered are:

- Include the effect of wind speed and ambient temperature in the probabilistic model. It should be noted here that the effect of wind speed was neglected and average value of temperature was used to represent the effect of ambient temperature. Aprobabilistic approach (similar to the one used for insolation data) can be applied to wind speed and temperature variables. These two factors can be included in the following equation:

$$Expected\ output\ power = \int\int\int F(s)\ F(T)\ F(W)\ P(s,T,W)\ ds\, dT\, dW$$

Where,

F(s) = distribution function of the insloation data which is known in this study as Beta distribution.

F(T) = distribution function of the temperature data. It can be investigated using the same technique used in this study for insolation data.

F(W) = distribution function of wind speed data. It has been modeled as Weibull distribution by Justus [26].

P(S,T,W) = power equation of solar array. This integral can be solved by convolution.

- Further research in the PV model formulation to include all factors (e.g.,cloud cover, availability of the insolation,...etc) which effect the solar cell performance.

- Economic cost study of PV-fuel cell hybrid system which includes fuel cell benefits.

- Study the short variations (e.g few seconds) of solar generated electricity to determine the fuel cell power capacity and response needed to match the load for stand-alone applications.

- Develop an statistical algorithm to predict the insolation data in short term (e.g minutes) period.

- Testing and evaluation of PV-fuel cell hybrid electrical energy systems are needed to demonstrate the operation of the hybrid system.

- For a large scale PV penetration studies, the impact on existing and/or planned transmission and distribution facilities should be examined.

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Appendix A. Goodness of fit Statistics

Four goodness of fit statistics are checked for each distribution in order to chose the parameters for the probability density function that best fits the available isolation data. The statistics are given in the following [30]:

Chi-square:

$$X^2 = \sum_{i=1}^{K} (nP_{oi} - nP_{ci})^2 / nP_{ci}$$

Where,

- n = sample size
- *P_{oi} = Observed probability for class i*
- *P_{ci} = Computer probability for class i*

- K = *Number of classes the data is grouped into*
- $K = n$ *when the data is ungrouped*
- $P_{oi} = 1/n$ *for all i*

Kolmogorov_Smirnov:

$$d = \max_i | S_{oi} - F_{ci} |$$

Where,

- S_{oi} = observed cumulative probability in class i
- F_{ci} = computed cumulative probability in class i

Cramer-von Mises-Smirnov:

$$W^2 = \sum_{i=1}^{K} (S_{oi} - F_{ci})^2 nP_{ci}$$

Log Likelihood:

The Log-Likelihood test takes different forms for different forms for different distributions as shown in the following:

Normal Distribution:

$$\ln L = -\frac{n}{2}(1 + ln2bi + \ln \sigma^2)$$

Where,

- σ = standard deviation

Weibull Distribution:

$$lnL = -n[1 - (K-1)\mu + (K-1)\ln C - \ln(\frac{K}{C})]$$

Where,

- μ = mean
- K, C are defined in equation (23).

Beta Distribution:

$$\ln L = -n \ln \frac{\Gamma(K+C)}{\Gamma(K)\Gamma(C)} - n(K+C-1)\ln(b-a) + n(k-1)\sum_{i=1}^{K} P_{oi}\ln(x_{i-a}) +$$

$$n(C-1)\sum_{i=1}^{K} P_{oi}\ln(b-x_i)$$

These parameters have already been defined in equation (24).

Appendix B. PV output and Average Temperature Plots

Plots of PV output based on 500 MW and average temperature for some typical days of the year are shown in following pages.

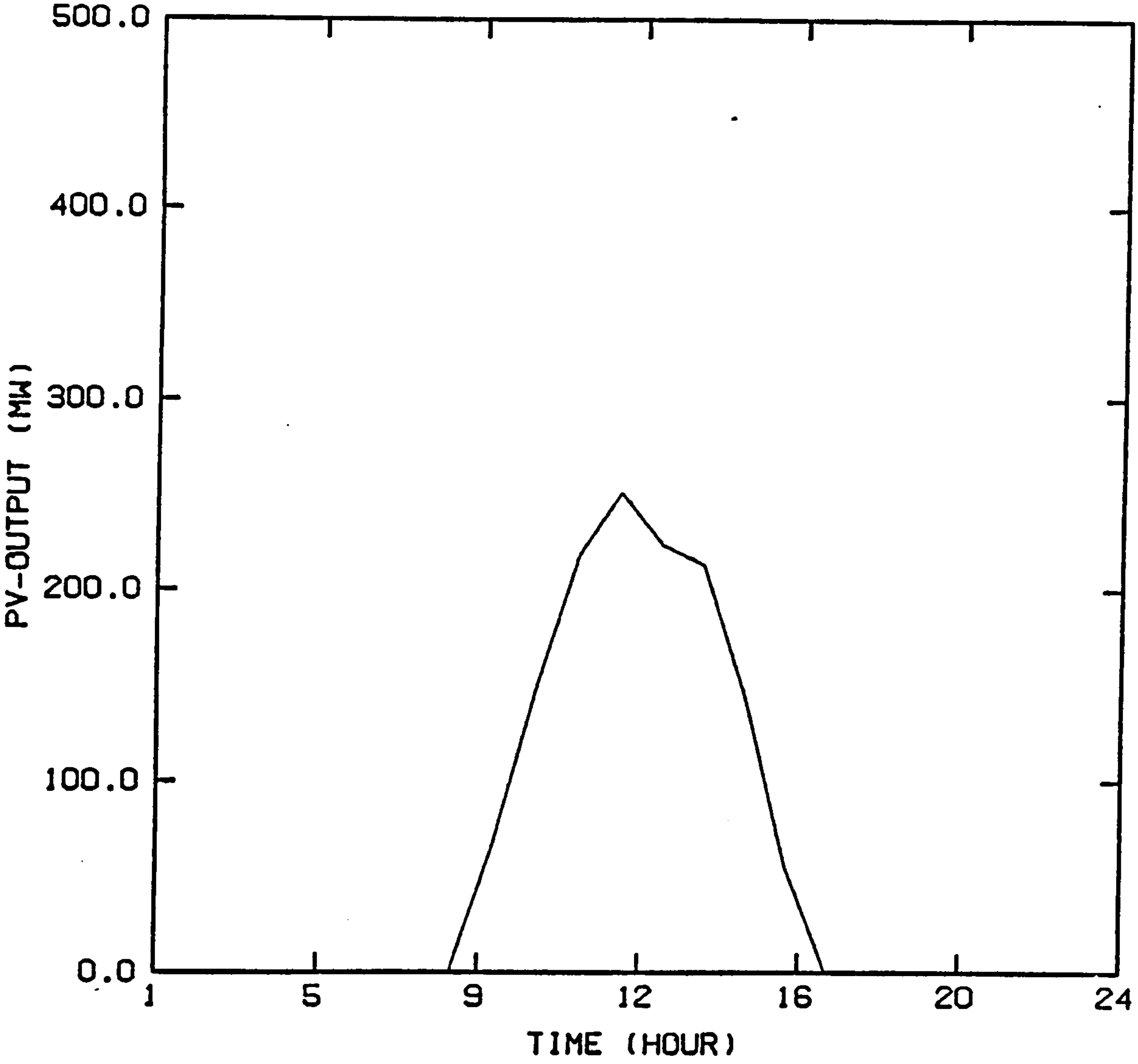

Figure 34. PV Output Data for Jan.

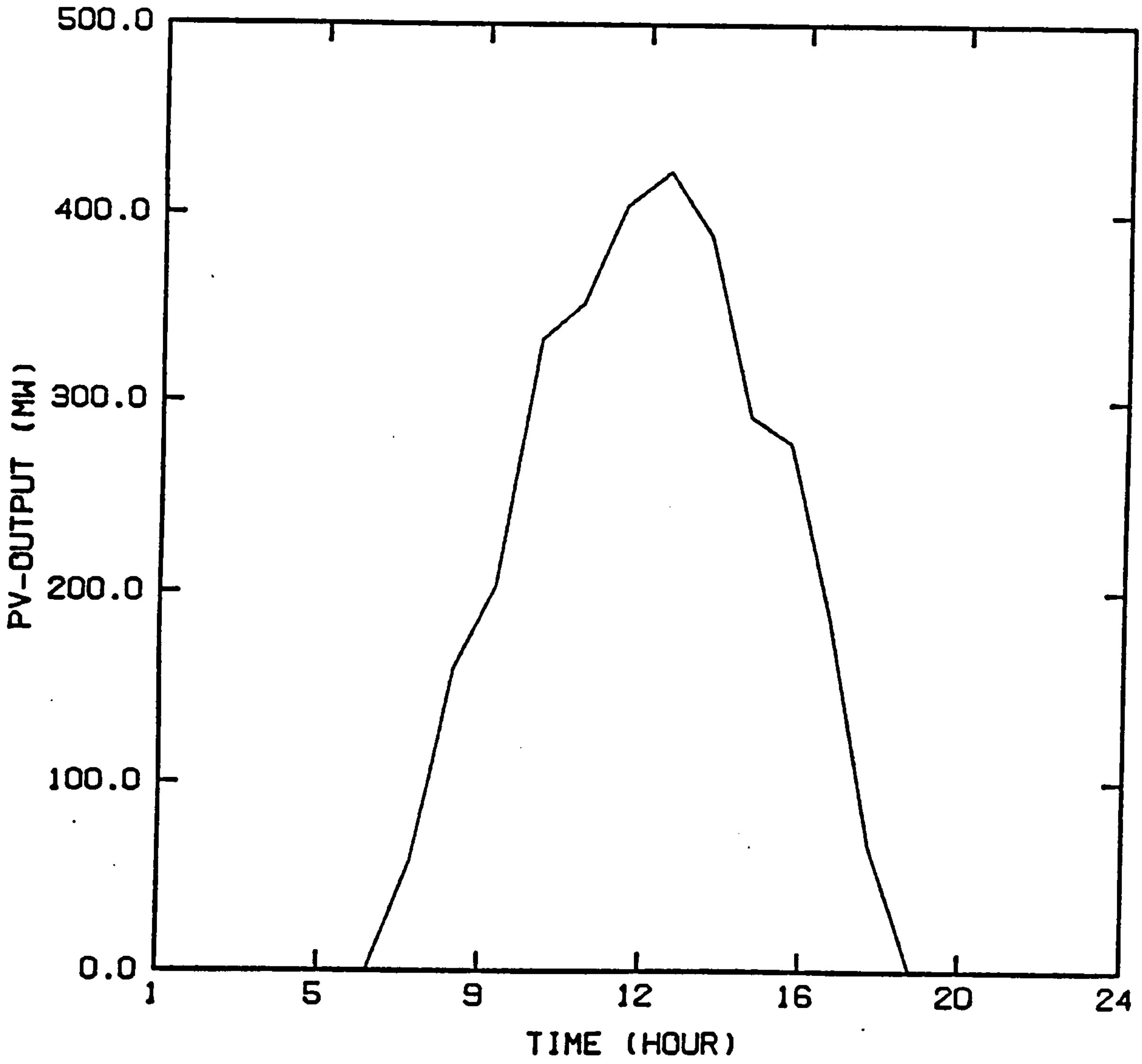

Figure 35. PV Output Data for Apr.

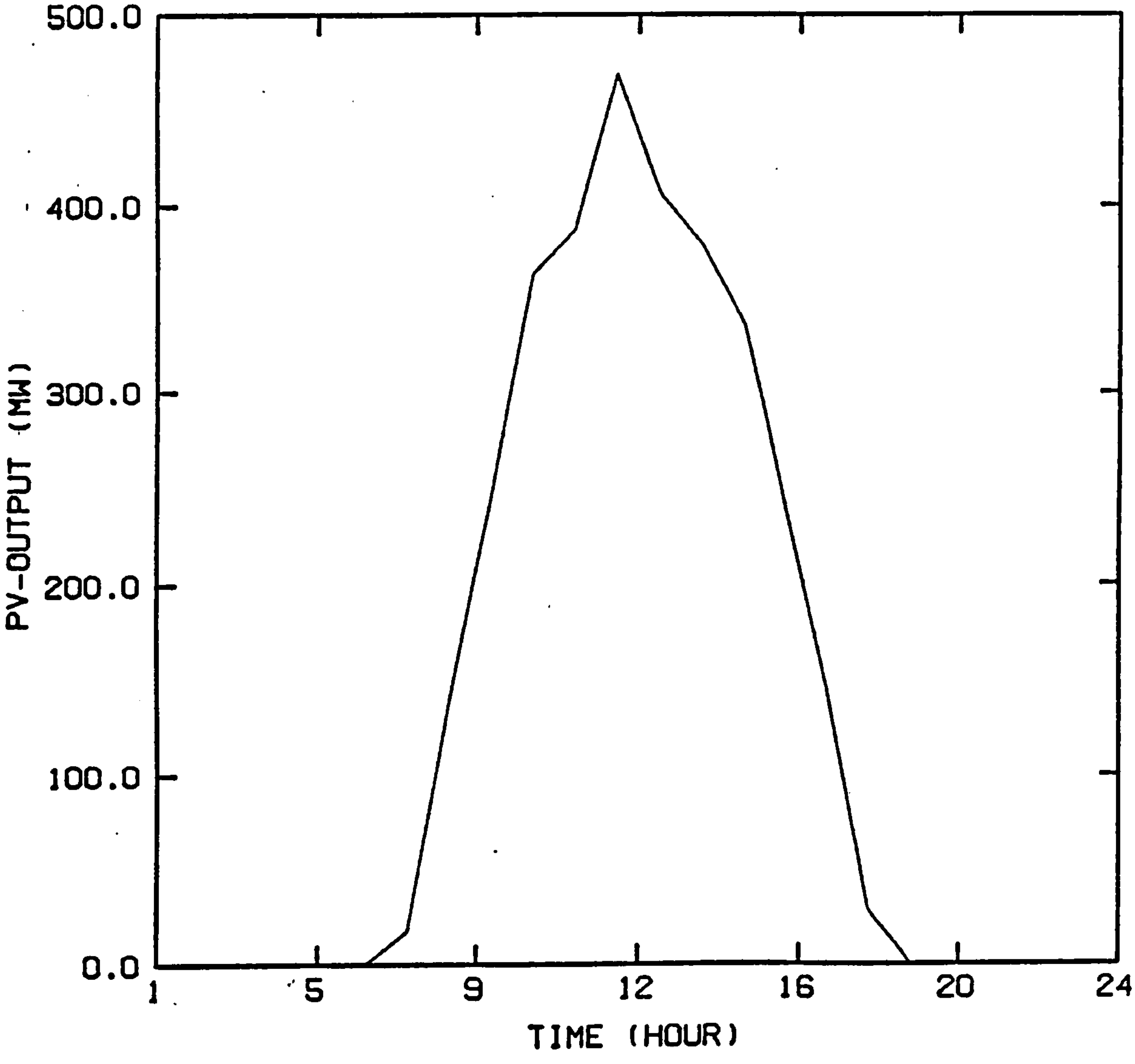

Figure 36. PV Output Data for Aug.

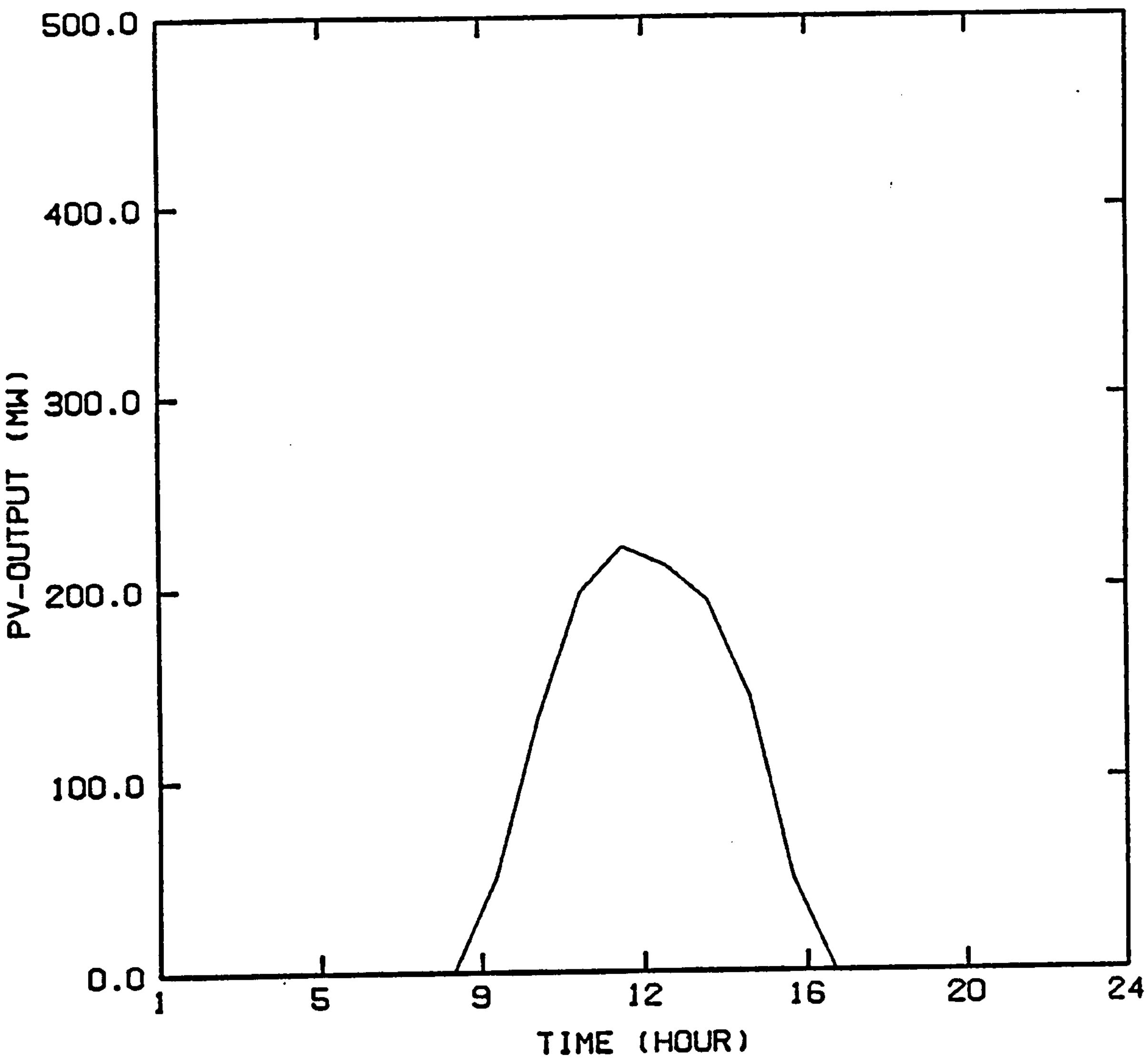

Figure 37. PV Output Data for Dec.

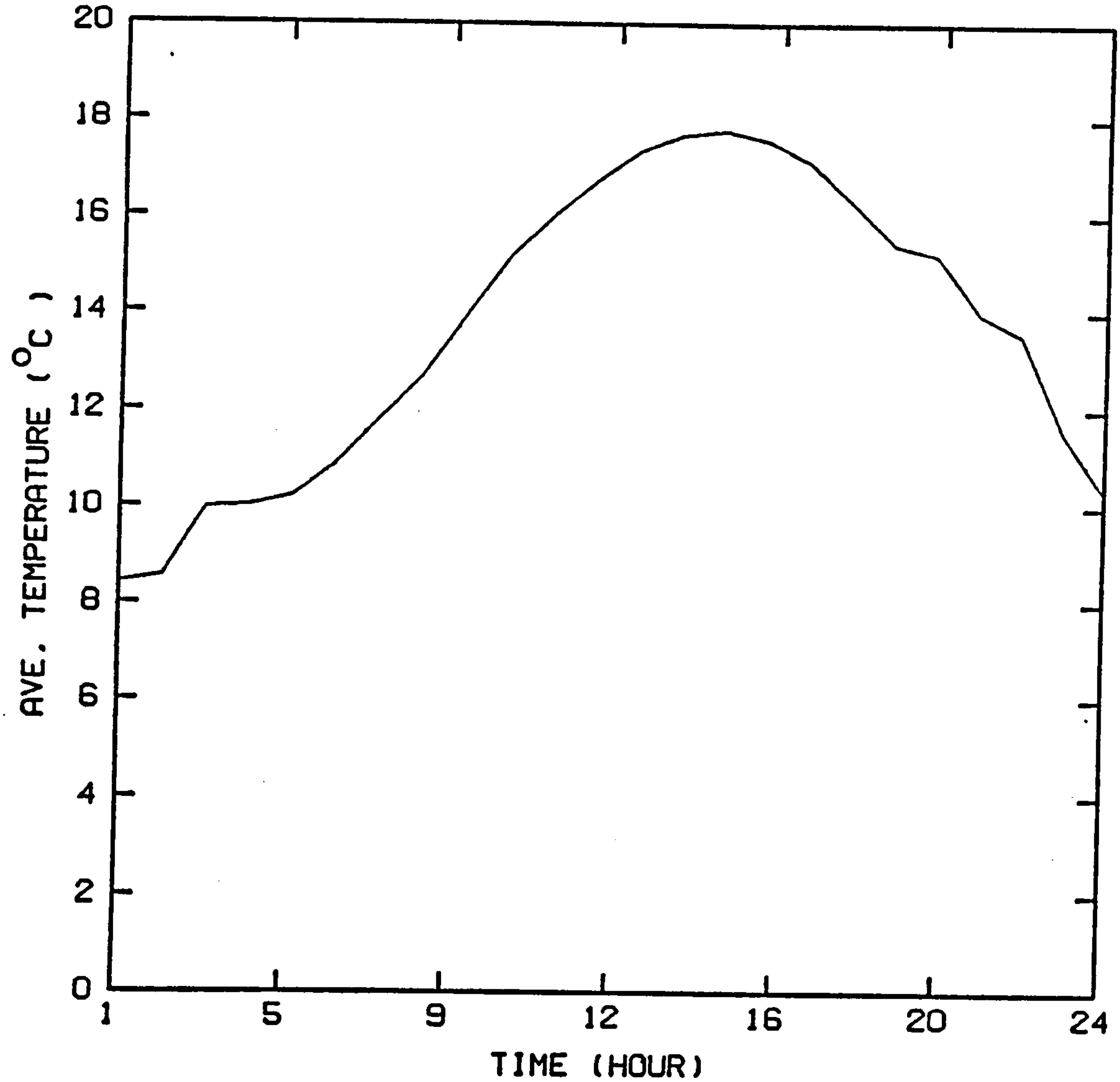

Figure 38. Ave. Temp. for Apr.

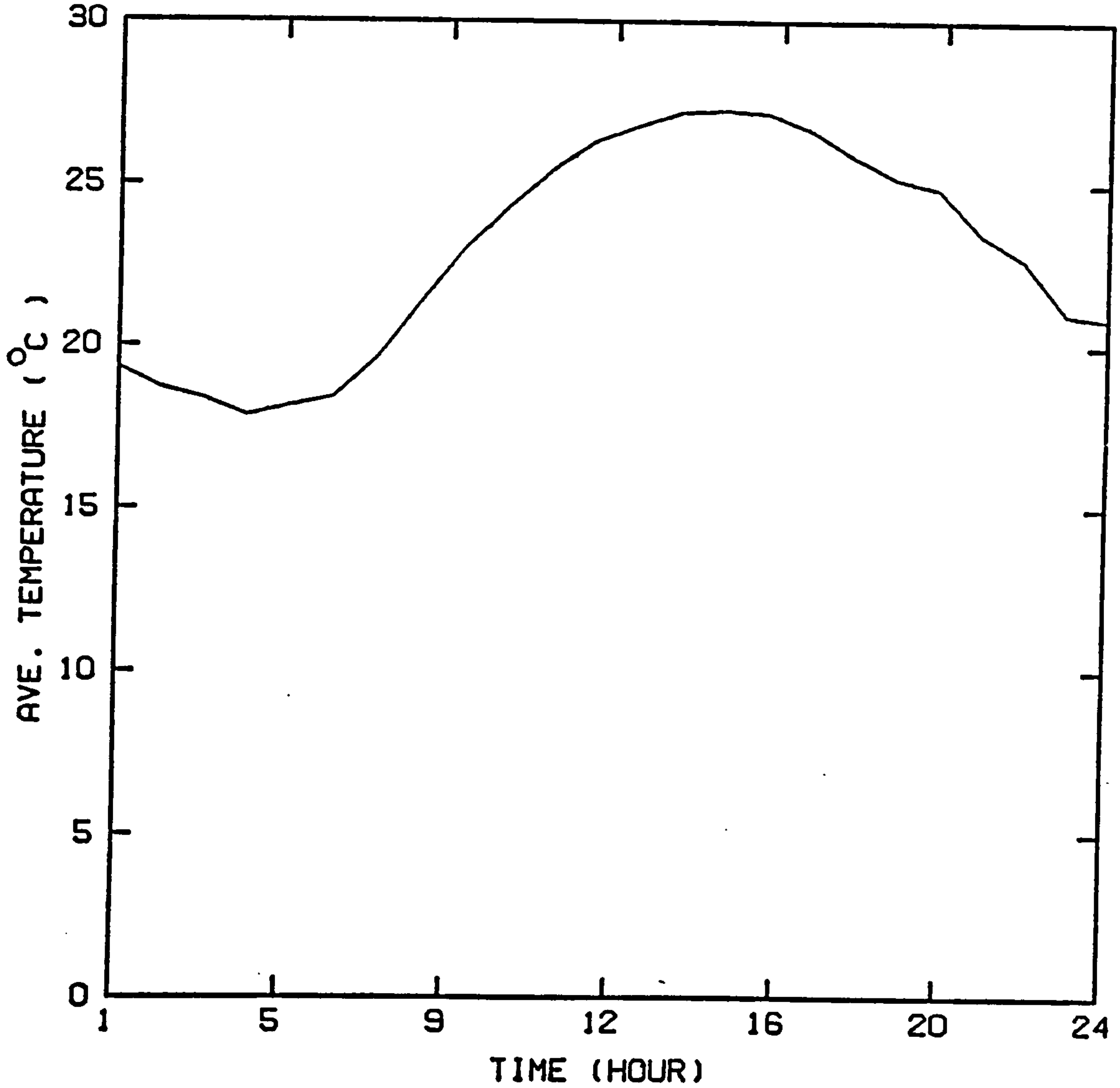

Figure 39. Ave. Temp. for Jun.

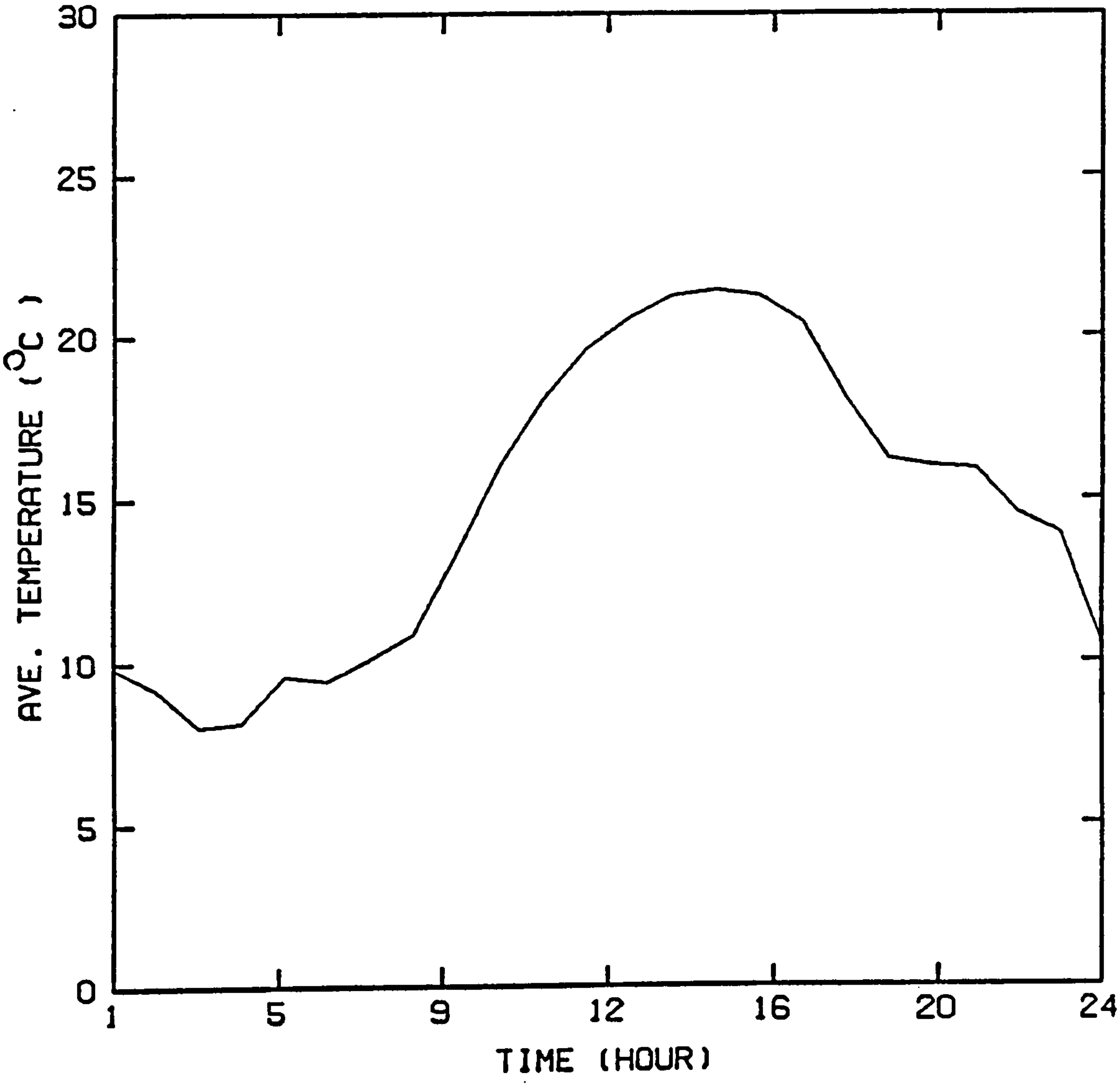

Figure 40. Ave. Temp. for Oct.

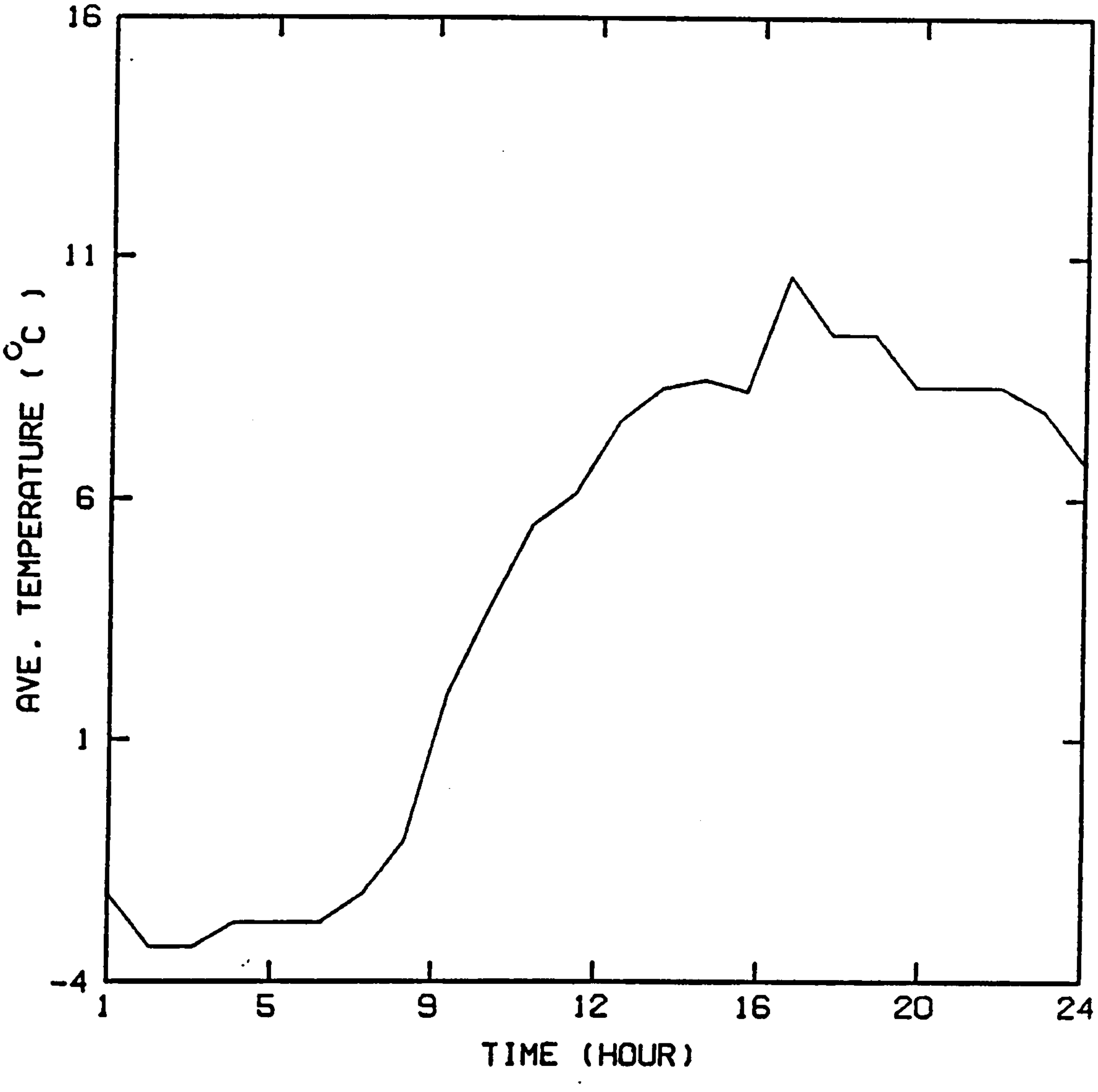

Figure 41. Ave. Temp. for Dec.

Appendix C. Load Data Plots

Plots of the reference and residual load are shown in the following pages.

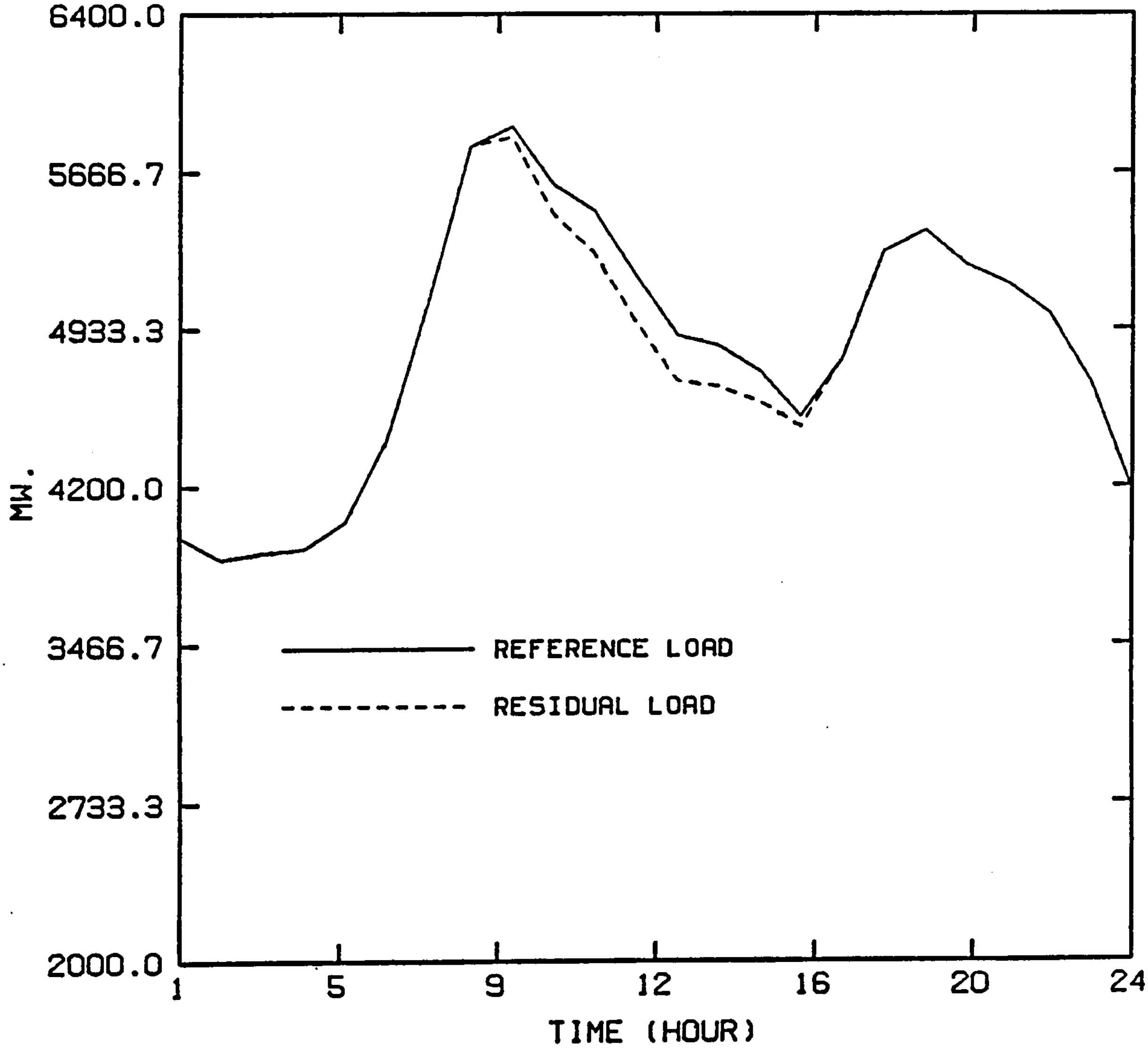

Figure 42. Refe. & Res. Load Data for Jan.

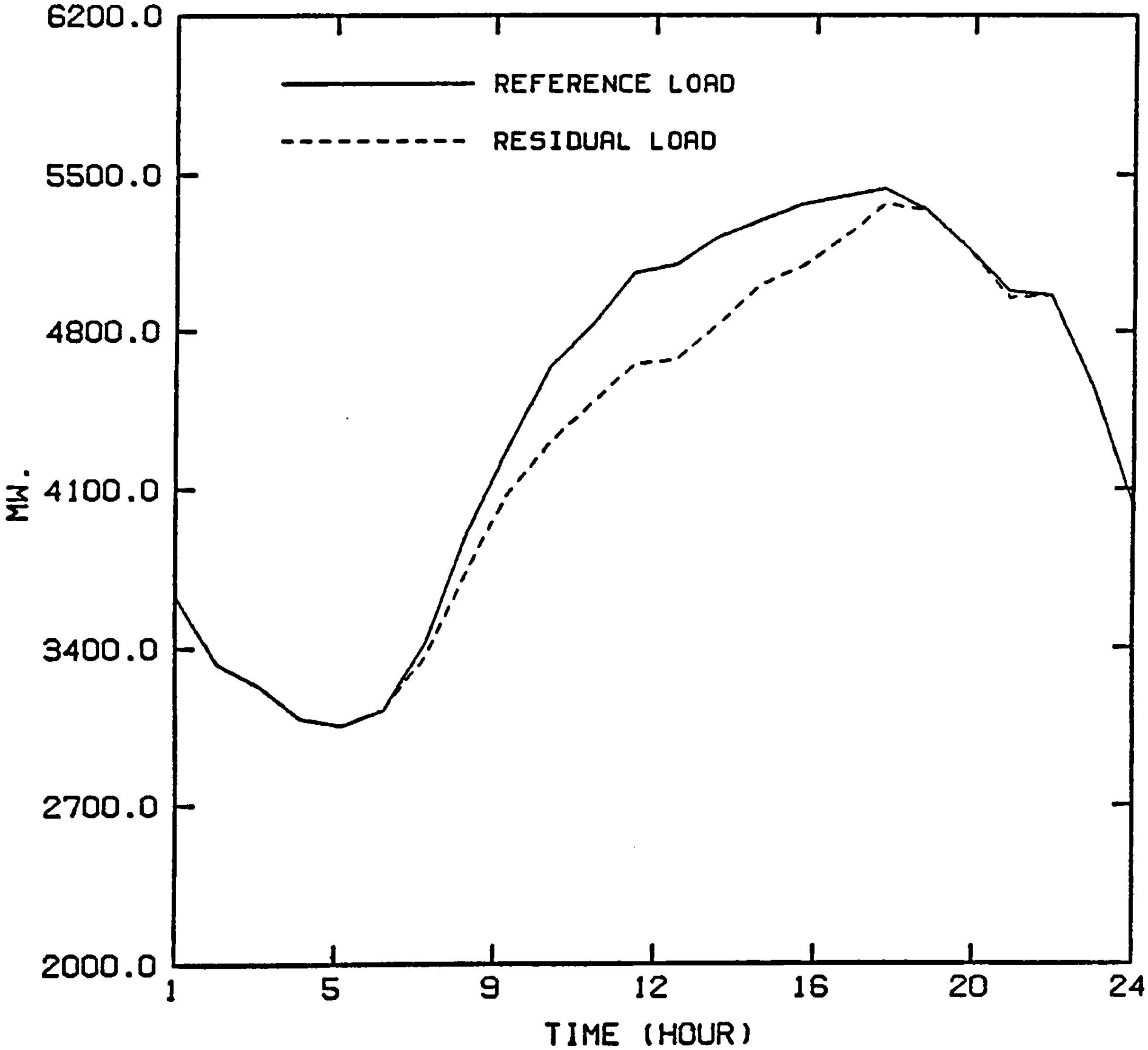

Figure 43. Refe. & Res. Load Data for Jun.

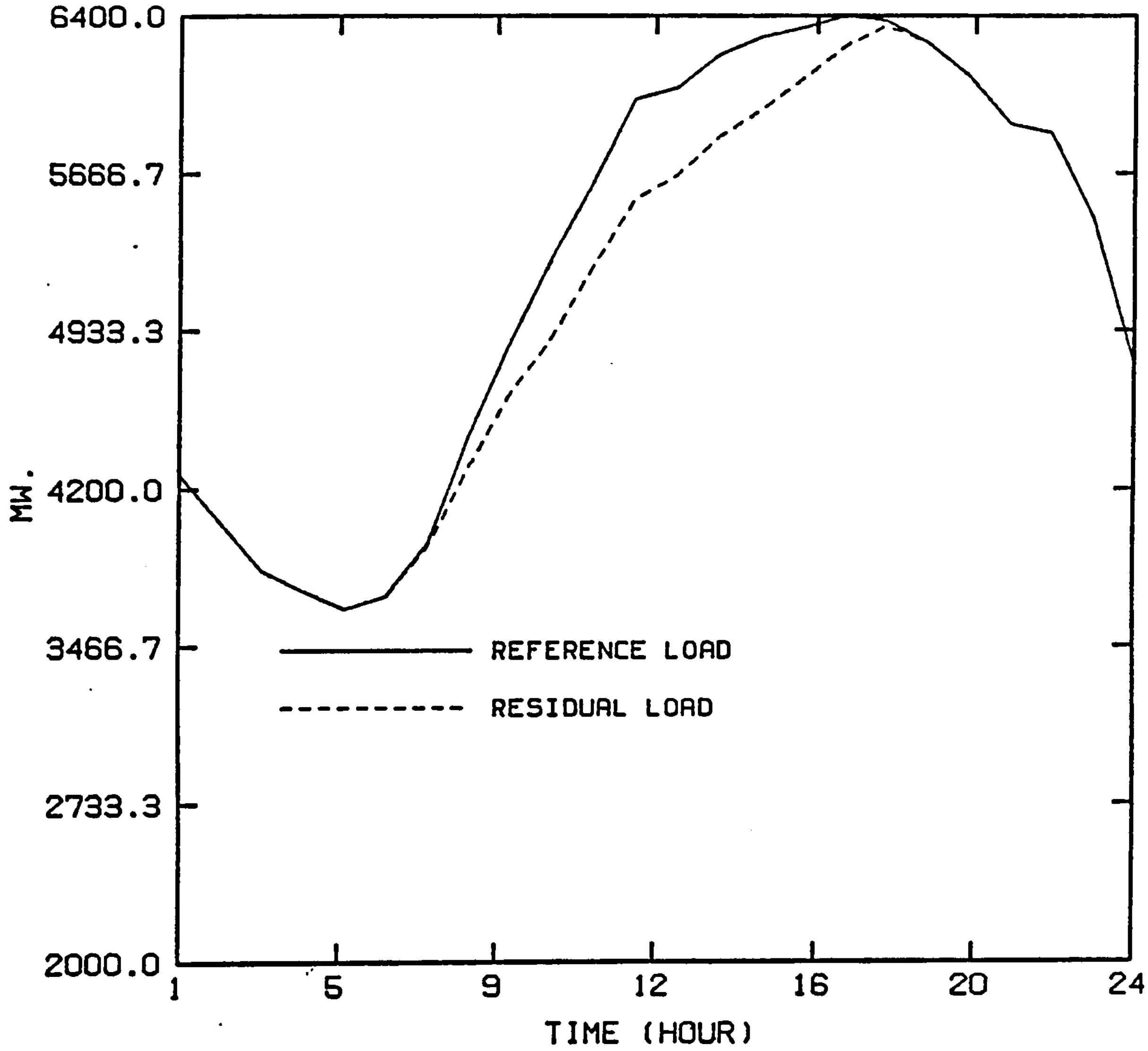

Figure 44. Refc. & Res. Load Data for Aug.

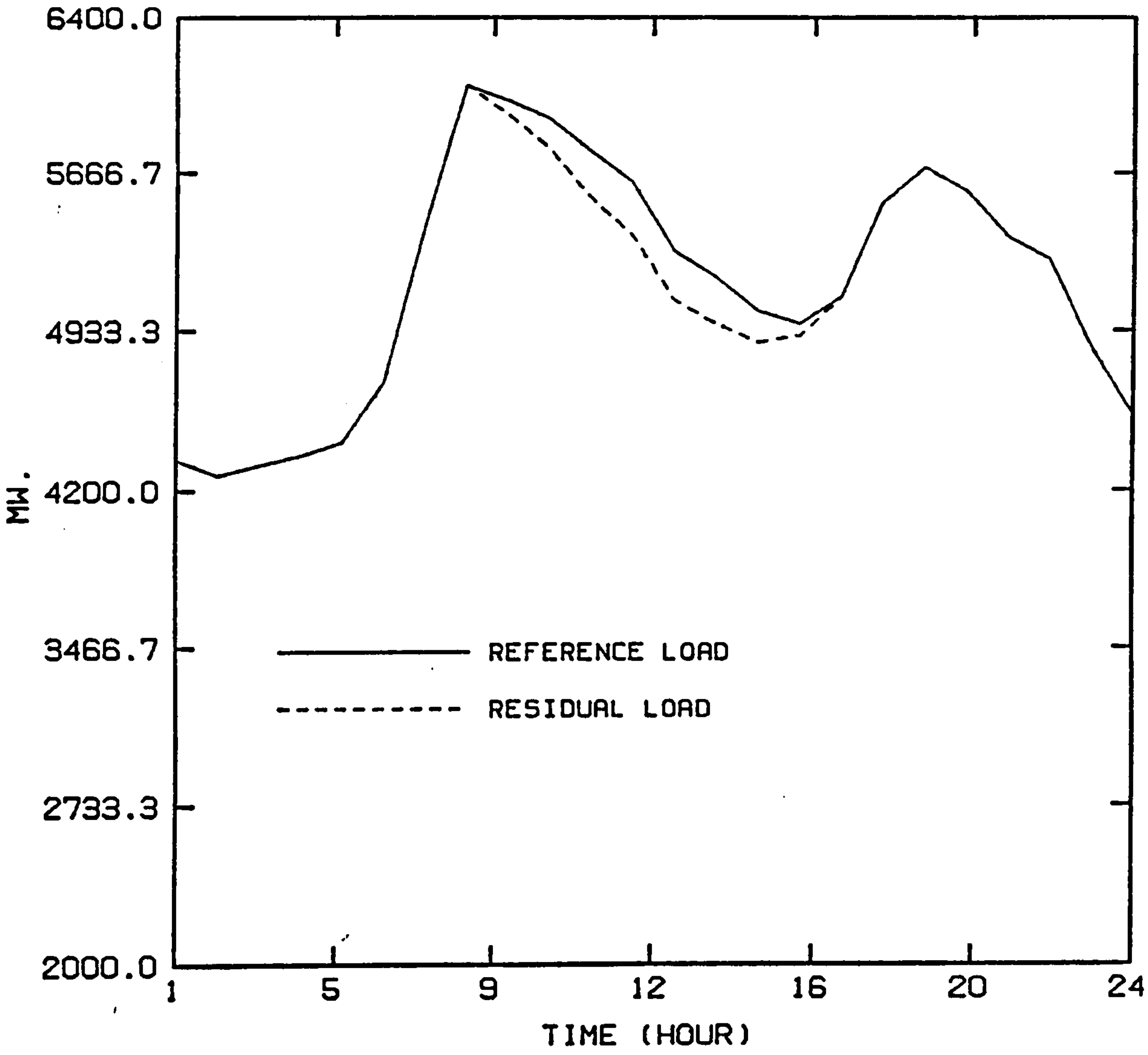

Figure 45. Refe. & Res. Load Data for Dec.

Appendix D. 3 MINUTE PV DATA

The following is the 3-minute PV data of JULY 12th based on 3 KW rating.

- - -*********************************

6	48	0.344
6	51	0.382
6	54	0.423
6	57	0.442
7	0	0.451
7	3	0.534
7	6	0.562
7	9	0.623
7	12	0.664
7	15	0.711
7	18	0.756
7	21	0.819
7	24	0.855
7	27	0.884
7	30	0.948
7	33	0.982
7	36	0.951
7	39	1.139
7	42	1.211
7	45	1.241
7	48	1.282
7	51	1.380
7	54	1.305
7	57	1.531
8	0	1.545
8	3	1.585
8	6	1.681
8	9	1.741

8	12	1.772
8	15	1.793
8	18	1.806
8	21	1.712
8	24	1.702
8	27	1.779
8	30	1.795
8	33	1.833
8	36	2.058
8	39	0.000
8	42	2.142
8	45	1.780
8	48	1.782
8	51	1.836
8	54	2.286
8	57	2.113
9	0	2.150
9	3	2.600
9	6	2.726
9	9	2.597
9	12	2.710
9	15	1.595
9	18	2.039
9	21	2.829
9	24	2.946
9	27	2.996
9	30	3.006
9	33	3.040

9	36	3.041
9	39	3.089
9	42	3.128
9	45	3.128
9	48	3.119
9	51	3.208
9	54	3.208
9	57	3.197
10	0	3.271
10	3	3.335
10	6	3.353
10	9	3.375
10	12	3.397
10	15	3.427
10	18	3.433
10	21	3.473
10	24	3.518
10	27	3.485
10	30	3.632
10	33	3.307
10	36	2.820
10	39	3.934
10	42	4.083
10	45	3.904
10	48	2.514
10	51	4.110
10	54	4.093
10	57	4.105

11	0	4.081
11	3	4.097
11	6	3.577
11	9	2.889
11	12	3.793
11	15	3.475
11	18	3.402
11	21	3.648
11	24	3.579
11	27	1.757
11	30	3.138
11	33	3.296
11	36	3.642
11	39	3.135
11	42	3.078
11	45	4.139
11	48	1.420
11	51	1.584
11	54	4.130
11	57	4.127
12	0	1.358
12	3	3.708
12	6	3.918
12	9	2.354
12	12	0.998
12	15	1.599
12	18	1.858
12	21	4.113

12	24	4.138
12	27	4.098
12	30	4.131
12	33	4.058
12	36	3.973
12	39	3.151
12	42	4.118
12	45	4.115
12	48	4.064
12	51	4.060
12	54	4.058
12	57	4.046
13	0	4.137
13	3	4.110
13	6	4.105
13	9	4.129
13	12	4.006
13	15	0.892
13	18	4.102
13	21	4.070
13	24	3.955
13	27	3.975
13	30	4.068
13	33	3.914
13	36	3.896
13	39	3.834
13	42	3.821
13	45	3.741

13	48	3.724
13	51	3.777
13	54	3.752
13	57	3.686
14	0	3.667
14	3	3.609
14	6	3.539
14	9	3.544
14	12	3.552
14	15	3.501
14	18	3.350
14	21	3.468
14	24	3.360
14	27	3.382
14	30	3.320
14	33	3.460
14	36	3.449
14	39	3.432
14	42	3.285
14	45	3.236
14	48	3.204
14	51	3.285
14	54	3.113
14	57	2.983
15	0	3.097
15	3	1.822
15	6	3.060
15	9	3.061

15	12	1.571
15	15	2.934
15	18	2.837
15	21	2.806
15	24	2.825
15	27	2.834
15	30	2.557
15	33	2.642
15	36	2.387
15	39	2.622
15	42	2.473
15	45	2.425
15	48	2.424
15	51	2.371
15	54	2.335
15	57	2.271
16	0	2.224
16	3	2.139
16	6	2.106
16	9	2.066
16	12	2.036
16	15	1.961
16	18	1.850
16	21	1.502
16	24	1.717
16	27	1.739
16	30	1.532
16	33	1.510

16	36	1.085
16	39	0.976
16	42	1.054
16	45	1.112
16	48	0.944
16	51	1.213
16	54	1.275
16	57	1.060
17	0	0.806
17	3	0.802
17	6	0.840
17	9	0.660
17	12	0.538
17	15	0.474
17	18	0.432
17	21	0.393
17	24	0.341
17	27	0.304
17	30	0.260
17	33	0.253
17	36	0.229
17	39	0.226
17	42	0.209
17	45	0.185
17	48	0.182
17	51	0.179
17	54	0.173
17	57	0.182

18	0	0.153
18	3	0.107
18	6	0.085
18	9	0.054
18	12	0.046
18	15	0.009
18	18	0.000
18	21	0.000
18	24	0.000
18	27	0.000
18	30	0.000
18	33	0.000
18	36	0.000
18	39	0.000
18	42	0.000
18	45	0.000
18	48	0.000
18	51	0.000
18	54	0.000
18	57	0.000

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