RELIABILITY OF A GENERATING SYSTEM CONTAINING PHOTOVOLTAIC POWER GENERATION

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by
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Electrical Engineering Abstract

RELIABILITY OF A GENERATING SYSTEM CONTAINING PHOTOVOLTAIC POWER GENERATION

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M.Sc. Thesis Presented to the College of Graduate Studies

May 1997

ABSTRACT

The construction of large conventional electrical generation stations is becoming more and more controversial, due to environmental impact. The result is that many utility companies would like to turn to alternative energy sources, such as photovoltaics and wind, to meet the increasing power requirements. However, there is a reluctance to consider intermittent sources as generation, rather than negative load, because there have been very few studies indicating the amount of conventional load that can offset. This thesis examines the adequacy of a generating system containing photovoltaic power generation using Monte Carlo simulations. The photovoltaic array simulations utilize weather data from Saskatchewan sites to examine the effect of solar energy in northern utilities. These areas have generally not been considered for grid connected photovoltaic systems due to low levels of solar radiation in the winter months.

The adequacy of photovoltaic generation is assessed through determining its capacity credit and load carrying capability, along with its ability to replace base load generation.

ACKNOWLEDGMENTS

To my husband, Russ: Thank you for your support, encouragement, patience, perseverance and undying love throughout this time. I know it was difficult having the computer as the "other man" in my life, particularly while I was writing. Without you and your love, this thesis would never have been completed.

To my parents, Leo and LaVerne: Thank you for your motivation and encouragement, and for always believing in me. You made me who I am. You are my heroes.

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I would also like to thank Sask Power and the Natural Science and Engineering Research Council of Canada (NSERC) for their financial support through an Industrial Scholarship for the first part of my studies; and thank you to the City of Saskatoon for enabling me to complete this degree while employed there.

> "For who can say, of those who did not see it, how first you bulged that sun into its place, and hammered its brazen face, and shocked it at the heart and set it afire? Who knows the word wherewith you commanded the sun to be? Who knows the beginning of the things which we *can* know? Theory! Theory! We chirp theories like chickadees, because ignorance is a terrifying thing and we need the noise. But when I can with courage know I do not know; when I admit that I stand with my back to a void, that I am indeed blind to the beginning of things, then I am silenced. Then I am chilled by my own triviality - some dust at the edge of a desert. Nevertheless, you kneel down and find me, and tell me that you love me."

Walter Wangerin, Jr. 1984

from **RAGMAN and Other Cries of Faith**
"Meditation on a New Year's Day"

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LIST OF ABBREVIATIONS

ARMA	Autoregressive Moving Average
DSM	Demand Side Management
FOR	Force Outage Rate
GRASS	Generation Reliability Assessment by Sequential Simulation
HLI	Hierarchical Level 1
HLII	Hierarchical Level 2
HLIII	Hierarchical Level 3
hrs	Hours
kW	Kilowatt
kWh	Kilowatt hour
LOLE	Loss of load expectation
LOEE	Loss of energy expectation
MW	Megawatt
MWh	Megawatt hour
PV	Photovoltaic
RBTS	Roy Billinton Test System
SGRASS	Solar Generation Reliability Assessment by Sequential Simulation
yr	Year

1. INTRODUCTION

1.1 Function of Power Systems

Power generation is, in its purest form, a method of ensuring the continuation of modern society. Electricity is the lifeblood of our world, without which, human beings could not survive as we are accustomed, nor could we improve our standard of living. Developing nations view reliable power generation, transmission and distribution as the keys to improving the status of their citizens, and ensuring long term stability, because reliable power supply brings with it improved medical ability, consistent food growing and processing conditions and more functional dwellings. With such an emphasis on electricity, it is no wonder that power systems need to be designed with the lowest likelihood of breaking down. However, it is unreasonable and unrealistic to try designing a system that will be 100% reliable. Thus, the goal of every power system is to be as economical as possible, with an acceptable level of reliability.

Traditionally, utility companies have utilized thermal (coal, oil and gas,) hydro and more recently nuclear power to supply customers with electricity. These sources are able to provide large power outputs with high reliability and a low cost per megawatt. Unfortunately, these conventional energy sources are now known to be heavy polluters of the air, water and land [1]. Thermal plants, which burn non renewable fossil fuels, emit many “greenhouse gasses” (carbon dioxide, carbon monoxide, sulfuric oxides, nitric oxides, particulates etc.) into the atmosphere. Hydro power causes flooding of surrounding lands due to the damming of rivers, in addition to disrupting aquatic life and affecting the spawning patterns of fish. Nuclear power creates radioactive wastes, which currently do not have a safe disposal system. Another problem with conventional energy sources is that the construction of new plants often result in cost overruns due to the length of the construction period [2].

Pollution, combined with the tendency of cost overruns for conventional power plant construction, have caused the North American public to oppose new power plant construction. However, the public still wants to be able to use electricity, and have electricity available precisely when they want to use it. The end result is that more and more utilities are exploring the options of non-conventional energy sources to meet the ever increasing electrical load [3]. The difficulty with most non-conventional energy sources, such as solar, wind and cogeneration is that the sources can not be called upon to supply energy when needed. Thus, their perceived reliability is low, which dissuades utility companies from giving such energy sources a "capacity credit". In other words, if the utility installs 10 MW of solar or wind energy, they will generally not report that their load carrying capacity has increased [3]. This reluctance is compounded by the small amount of research that has been performed on reliability and capacity credit analysis for each type of unconventional energy source. The question of reliability and applying a capacity credit to solar, photovoltaic energy is explored in this thesis.

1.2 Solar Power

1.2.1 Definition

Any power that is created by the sun can be considered to be solar power. This includes photovoltaic energy and active and passive solar heating of water or air. For the purposes of this work, solar energy will be taken to mean photovoltaic (PV) energy, unless otherwise stated in a particular section.

1.2.2 History

The sun was used as an energy source long before written records were kept. Initially the sun was used for heating dwellings and large buildings to ensure comfort during the cooler days. It was later discovered that the sun could also be used as a way of heating water and other liquids, thus keeping buildings warmer at night, because water does not cool off as fast as air. Until 1954, when Chapin and his colleagues developed a practical device to make use of the photovoltaic principles of

Edmond Becquerel, there was no easy way to convert the sun's energy into a high level source of energy such as electricity, rather than a low grade energy source of heat. With Chapin's development of the PV cell, the sun could be used more fully, and his device was used almost immediately after discovery to power a telephone system in Georgia, USA [4]. The photoelectric effect used in modern PV cells involves light hitting a silicon p-n junction (the same type as is used in silicon transistors) causing electrons to move. The electrons flow from one side to the other, creating a current and potential difference. When enough cells are put together, the current and voltage become large enough to power energy consuming devices.

The process of converting light into energy was very initially inefficient and expensive. It wasn't until the 1970's, when the US space program adopted the use of PV for satellites and space crafts, that the technology began to decrease in price and became more widely studied. The focused studies required by the space program resulted in great advancements in the technology through increased efficiencies [5]. By 1990, more than 48 MW of PV were sold annually for calculators, communication systems, buoys and other transportation related systems, along with a small amount for grid connection and stand alone power generation [6]. Each solar installation has a different visual appearance. Diagrams of various installations can be found in many of the references [5, 7 - 9].

1.2.3 Modeling Solar Energy Systems

Solar energy is a very complex energy to model because it is dependent on a large number of factors, ranging from the sensitivity and efficiency of the photovoltaic cell, to the cloud cover, temperature and wind velocity at a given moment. The photovoltaic cell itself responds non-linearly to the sun's radiation. Thus, higher radiation levels do not translate to an equivalent increase in generated energy. This non-linearity is dependent upon the type of solar cell (amorphous or crystalline) the material making up the cell (silicon, germanium or other similar materials) the amount of "holes" infused into the material and the incoming solar radiation [10, 11]. Thus, there is no simple formula to determine the output from a

PV cell. Also, the actual array output is further reduced by losses resulting from resistance in the wiring and the inverter, further contributing to the difficulties in modeling PV.

Once the array itself has been modeled, the amount of solar radiation hitting the array needs to be determined. Solar radiation hitting a horizontal surface on earth is dependent upon a number of different variables, including latitude, temperature, cloud cover, humidity and wind speed. Many models have been developed to model the expected solar energy [12 - 18], and have taken years of modification to obtain something that gives adequate results. The models chosen for these simulations, WATGEN and WATSUN-PV, were developed at the University of Waterloo in Waterloo, Ontario, Canada. WATGEN utilizes a transformation of the autoregressive moving average (ARMA) of cloud cover, while factoring in average temperature, humidity, wind speed and sunlight intensity to determine the expected available solar energy on an hourly basis [19]. The simulation used to determine the expected solar energy is pseudo-random in nature, and has been shown to give reasonable results for Canadian locations [20]. WATSUN-PV utilizes the available solar energy obtained in the WATGEN simulation, or from other sources, and calculates the expected solar output from a collection of commercially available photovoltaic panels and inverters [21]. The PV panel and inverter used in this thesis were chosen from the available collection and are not changed as their characteristics are not at issue in this study.

1.2.4 Benefits of Solar Energy

Despite the difficulties in modeling, solar energy can provide enormous benefits to a utility. The obvious benefit is that new capacity can be added without adding to the utility's overall pollution production. This is particularly valuable as the Environmental Protection Agency continues to raise the penalties for pollution [7]. In addition, the greatest energy use tends to occur on days when the sun is brightest, which enables PV energy to provide "peak shaving" for the utilities [5, 22]. This occurs due to increased air conditioner loads in the summer, and increased lighting and heating loads in the winter. Southern, summer peaking utilities can benefit greatly from PV installations due to the load following characteristics, and have been the leaders in solar testing and implementation [8]. Figure 1.1 shows the load following characteristics of PV energy in Phoenix, Arizona, as modeled by WATSUN and WATGEN-PV.

A further benefit of solar energy is dependent upon how PV arrays are installed in the grid. If the arrays are located in one central location, in the manner of California wind farms, there may be less losses within the transmission system because the energy can be produced closer to the end user, resulting in the energy having to travel less distance. If, however, the PV arrays are installed in various locations throughout the power grid, the benefit of reduced losses within the transmission system can be seen, along with reduced strain on the distribution system [2]. For the Sacramento Municipal Utility District, this has meant that they were able to avoid upgrading the distribution lines to handle the addition of a new subdivision, making the incremental cost of installing PV far lower than normal [23].

1.3 Reliability

1.3.1 Types of Reliability Analysis

One of the problems that utility companies have with non-conventional energy is that they are unable to determine how it will affect the reliability of their system, and they are thus unable to assign such power types a capacity credit. Consequently, power system reliability analysis needs to be conducted on a system that contains varying amounts of solar energy. Power system reliability evaluation provides a quantitative assessment of the ability of the system to supply electricity to its customers. The two branches of power system reliability are adequacy and security, as seen in Figure 1.2. System security is related to the ability of the system to respond to disturbances occurring in the system. It is involved with analyzing dynamic changes within the system, and determining whether the system will be able to meet the load demand under the given disturbances. On the other hand, system adequacy assesses the ability of the system to meet the load under more stable and

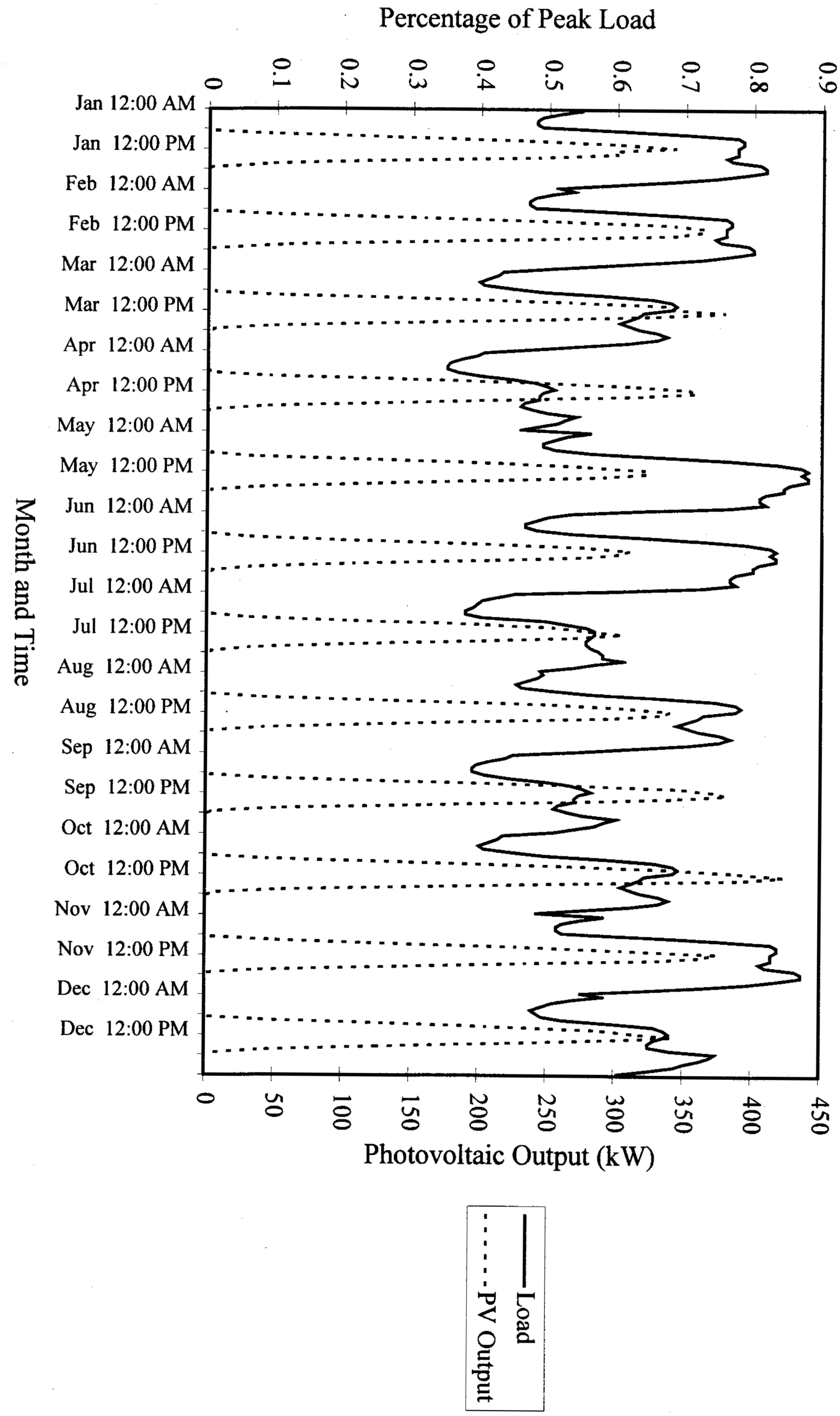

Figure 1.1 - Photovoltaic Ouput Load Following Characteristics for Phoenix, Arizona

static disturbances, including but not limited to the planned and unplanned shut down of generating stations.

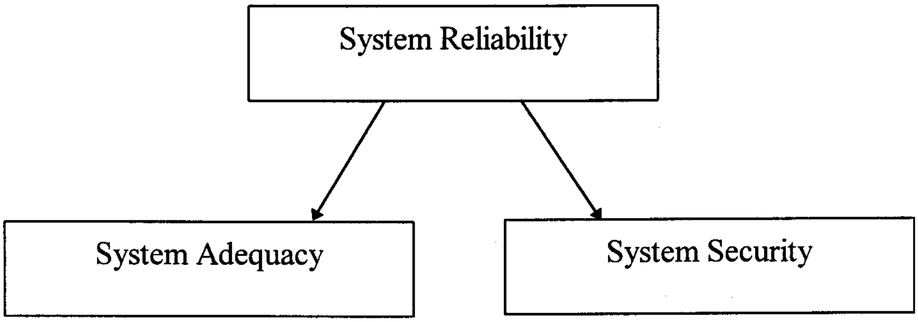

Figure 1.2 - System Reliability

1.3.2 Adequacy Assessment

System adequacy can be categorized by three levels, which correspond to the applications involved in a complete power system. Figure 1.3 shows the three levels, known as the functional zones of generation, transmission and distribution. The hierarchical levels are defined by combining the functional zones.

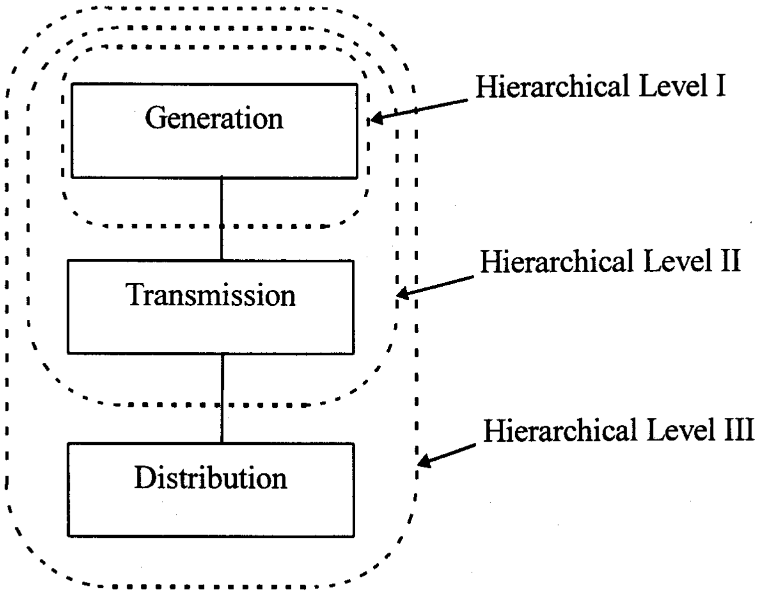

Figure 1.3 - Hierarchical Level Structure

Hierarchical level I (HLI) is solely concerned with generation. At this level, reliability evaluation examines the adequacy of the generation system to meet the expected load. Effects or problems associated with the transmission and distribution system are not included. HLI analysis is concerned with ensuring that there is enough generating capacity available to satisfy the load, taking into account the effects of random failures resulting in emergency shutdown and repair, and planned outages due to preventive maintenance. Reliability evaluation at the next level, known as hierarchical level II (HLII) goes beyond initial generation analysis, and includes the transmission system. At this level, some of the larger power consumers are involved, because their processes are fed directly from the transmission system. The inclusion of the transmission network normally increases the complexity of the analysis. Hierarchical level III (HLIII) evaluation is the most complex type of analysis in a power system because it includes the effects of all three functional zones. It is not normally conducted on practical, or large systems due to the computational effort involved. Reliability analysis at this level often utilizes set inputs from the transmission system which take into account the reliability of the transmission and generation systems.

This work examines the adequacy of a generation system which includes solar energy and therefore the work involves only hierarchical level I. This analysis is usually known as "generating capacity adequacy evaluation."

1.3.3 Generating Capacity Adequacy Evaluation

Large amounts of research have been conducted in the area of generating capacity adequacy assessment [24 - 29]. The listed references, are a small sample of the work in this area. The most widely used reliability evaluation indices are the loss of load expectation (LOLE), and the loss of energy expectation (LOEE) [30]. Both of these utilize the mathematical probability of how much power or energy will not be supplied, due to power failures caused through generation deficiencies. Due to advances in computer power and capabilities, complex systems can be evaluated using Monte Carlo Simulation [28]. This approach is non analytical in nature, and utilizes a set of simulations that represent possible scenarios.

1.4 Scope of This Thesis

This thesis presents the results and analysis of research into the development of a simulation technique for the determination of solar energy reliability. Simulations have been performed using solar data from five Saskatchewan cities. These data were used in conjunction with the Roy Billinton Test System (RBTS) to determine the best Saskatchewan location for a solar energy trial, and determine the solar energy capacity credit. Chapter 2 provides some of the basic theory required to understand the analysis, including basic reliability, Monte Carlo, and solar theory. Chapter 3 presents the datum for this analysis by examining the analytical and simulated results of a conventional generating system represented by the RBTS, and determines the parameters to be used in the solar evaluation. Chapter 4 looks at the load following characteristics of Saskatchewan systems, together with a comparison of the effect of PV installations in various parts of the province. Chapter 5 examines photovoltaic energy in detail, by comparing it closely with conventional energy through sensitivity analysis, and presents a formula which can be used on the RBTS for making preliminary evaluations on the effects of grid connected solar energy. Chapter 6 presents the conclusions of this thesis, and some suggestions for future work that should be done in this area.

2. GENERATING SYSTEM ADEQUACY EVALUATION AND SOLAR THEORY

2.1 Adequacy Assessment

2.1.1 Introduction

Generating system adequacy evaluation involves the convolution of the two basic models of load and generation to obtain the overall risk model. The load model consists of an estimation of the load at each hour based on historical data. The generation model involves accounting for all generating units using their forced outage rates, or mean time to failure and mean time to repair information. The convolution of the two models is shown graphically in Figure 2.1.

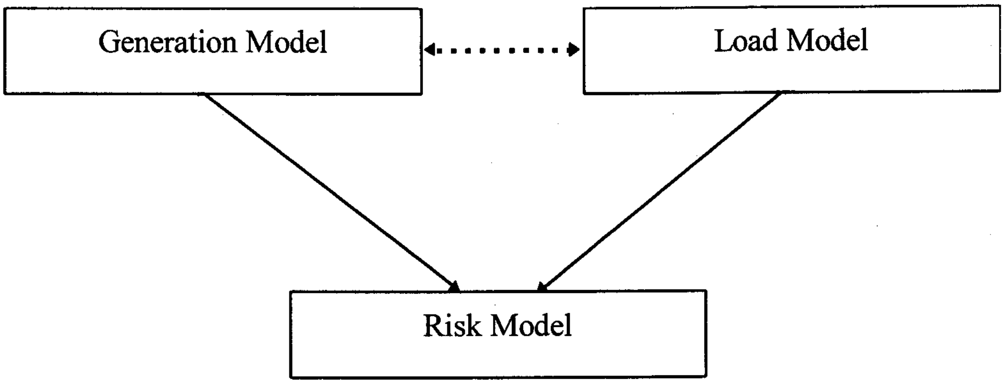

Figure 2.1 - Risk Model Development

Failures which occur within the transmission and distribution systems are not considered in conventional generation adequacy evaluation. The evaluation considers the ability of the generating system to meet the load demands, as shown in Figure 2.2. The evaluation of the system's ability to meet the load requirements can be evaluated analytically or by simulation. Each method of evaluation is briefly presented in this chapter, together with its advantages and disadvantages. Irrespective of the evaluation method chosen, most adequacy assessments focus on two indices which can be used to compare different systems. These indices are the Loss of Load Expectation (LOLE), and the Loss of Energy Expectation (LOEE). The LOLE provides the estimated number of hours or days that the load will not be supplied in a year, while the LOEE estimates the amount of energy, in megawatt hours, that will not be served.

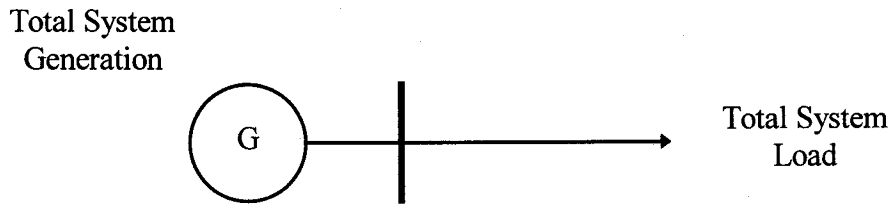

Figure 2.2 - Generation Adequacy Evaluation

2.1.2 Analytical Evaluation

Analytical evaluation of the generating system provides a utility with information on the likelihood that the generating capacity will be unable to serve the load. The results obtained through this type of evaluation are the expected values of the various adequacy indices. Analytical techniques are relatively simple to apply and are easily reproduced. However, because they are unable to provide density functions, they may give a false sense of security due to their perceived exactness.

2.1.2.1 Capacity Outage Probability Table

The first step in analyzing a system analytically is to develop its capacity outage probability table. This table lists the probabilities of experiencing varying levels of generating capacity outages. A recursive technique in which generating units are added sequentially to the table, is often used to develop capacity outage probability tables in order to simplify the computational effort required for large systems.

. If none of the generating units have derated states, the following recursive equation can be used to develop the table [30]:

$$P(X) = (1-U)P'(X) + (U)P'(X-C) \tag{2.1}$$

where:

X = number of megawatts of generating capacity in the particular outage state

P(X) = Cumulative probability of the capacity outage of X MW before the unit is added

P'(X) = Cumulative probability of the capacity outage of X MW after the unit is added

U = Forced outage rate of the added unit

C = Capacity of the added unit.

Equation 2.1 is initialized by setting, P'(X) = 1.0 for $X \leq 0$, and P'(X) = 0 otherwise.

A more general recursive model, used for systems where one or more generating units have at least one derated state, is given by [30]:

$$P(X) = \sum_{i=1}^{n} p_i P'(X - C_i) \tag{2.2}$$

where:

n = number of unit outage states

X = number of megawatts of generating capacity in the particular outage state

P(X) = Cumulative probability of the capacity outage of X MW before the unit is added

P'(X) = Cumulative probability of the capacity outage of X MW after the unit is added

p_i = probability that the added unit will exist in state i

C_i = capacity outage of state i for the added unit.

When the number of generating states is 2 (i.e., operational and failed), Equation 2.2 reduces to Equation 2.1.

For large systems, the capacity outage probability table can become quite large and cumbersome. However, if the cumulative probability of any given state is less than 10^{-8}, its effect on the overall system is small enough to be neglected, and thus, most tables are truncated at the point where the cumulative probability drops below 10^{-8} [30]. The resulting error from this truncation is usually minimal.

2.1.2.2 Basic Indices

The probability and capacity values displayed in the capacity outage probability table are used in the calculation of the basic reliability indices of loss of load expectation and loss of energy expectation. The loss of load expectation is used to determine how many hours or days per year a system will be unable to supply all of the load. The problem with this index is that it does not provide any indication as to the amount of energy that will be unsupplied. In other words, a total blackout and a failure that affects a single customer are considered to be equal. From a utility perspective, however, LOLE gives an indication of the ability of the system to meet the total system load. Loss of energy expectation provides an estimate of the amount of energy that will not be supplied in a given year. The two indices taken together provide a good basis for measuring the ability of the system to perform its expected function.

The LOLE and LOEE are calculated utilizing actual or forecasted load curves. The LOLE is calculated using either a load duration curve, or a daily peak load variation curve, while the LOEE utilizes the load duration curve. Both curves look similar in form, however, the area under the load duration curve gives the total energy used in a given time period, while the daily peak load variation curve indicates the maximum daily demand [30].

In Figure 2.3, O_k is the magnitude of the k^{th} outage in the system capacity outage probability table, while t_k is the time that the magnitude O_k would result in the inability to supply the load. The system loss of load expectation is then given by Equation 2.3:

$$LOLE = \sum_{k=1}^{n} p_n t_k \quad \text{(hrs/yr)} \tag{2.3}$$

where p_n is the individual probability from the capacity outage probability table for the O_k capacity outage state.

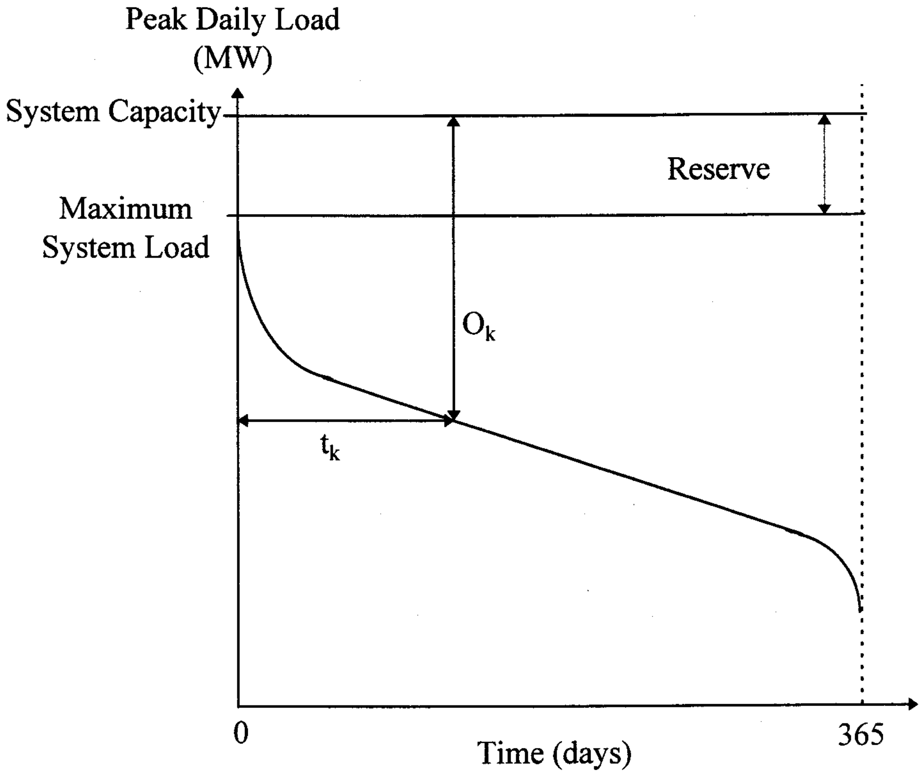

Figure 2.3 - Daily Peak Load Variation Curve

The LOEE calculation can be illustrated using Figure 2.4. In this figure, the total unserved energy, E_k, due to the k^{th} outage is the area under the load duration curve above the available capacity. The LOEE is then determined by:

$$LOEE = \sum_{k=1}^{n} E_k p_k \quad \text{(MWh/yr)} \tag{2.4}$$

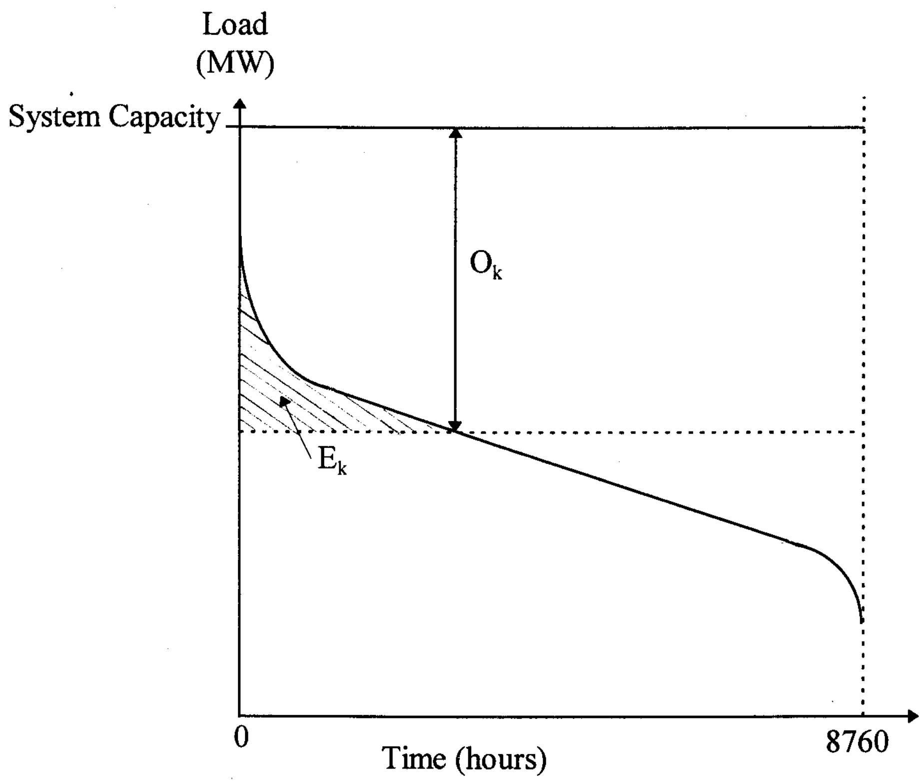

Figure 2.4 - Annual Load Duration Curve

2.1.3 Monte Carlo Simulation

The analytical techniques described above work well for conventional generating systems and have been used by many utilities throughout the world. Such techniques are, however, unable to provide density functions, or indicate the uncertainty or standard deviation of the results. For example, although the analytical calculation indicates that a tossed coin will show a head 50% of the time, the reality is that 5 tails may be flipped before any heads are, or vice versa. The sequence of events is not recognized in the analytical approach, but can be approximated through stochastic simulation of the system. The simulation approach is generally known as Monte Carlo Simulation, named after the famous casino in Monaco [31].

Stochastic simulations require a large amount of computational effort when used to simulate the actual operation of a system under a large variety of circumstances. Fortunately, with the powerful computers now available, this is much less of an issue than it was as little as five to ten years ago. Density functions and standard deviations of the basic indices can be obtained in a very straight forward manner by simulating various possible scenarios through many simulation years.

The biggest challenge with simulation techniques is often found in the selection of stopping criteria which must be selected on the basis of obtaining the best results within a reasonable length of time. Often, the stopping criteria utilizes both a maximum number of simulation years and a desired accuracy in one of the basic indices. This procedure ensures that if the simulation does not converge, there is a stopping point to avoid infinite loops.

The reliability of the generating system is estimated by mimicking the actual operation of the system. The simulation utilizes time as a sequential process, and models each generating unit separately. The total generation at any given time is compared to the load during that hour. If the load is not met, the amount of energy unsupplied is increased appropriately and a counter indicating the total number of failures is incremented. In total, six different generating events are recognized and accounted for: a change in load; a change in reserve requirements; the failure of a generating unit; the completion of a unit repair; the derating of a generating unit; and the completion of repair to the derated unit [32]. The possible generating unit states are shown in Figure 2.5.

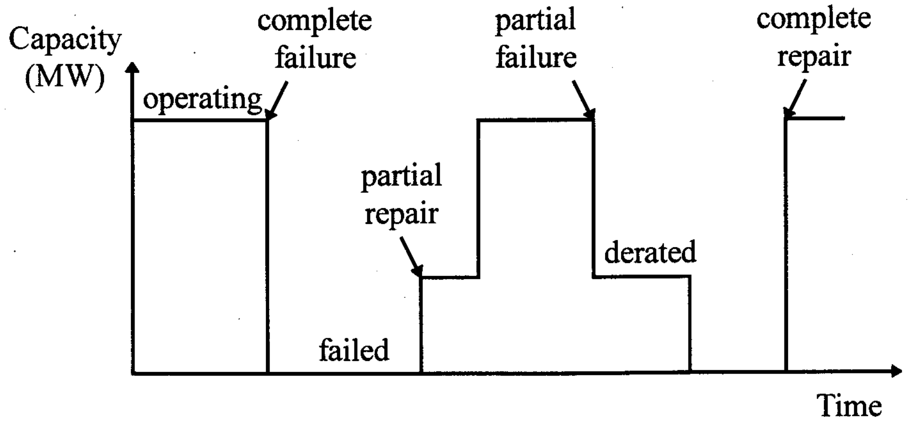

Figure 2.5 - Outage History of a Single Generating Unit

Sequential simulation involves the generation of a random or pseudo-random number between 0 and 1 for each unit, which is used in conjunction with an exponential function to determine the state residence time. The exponential function utilizes the mean time to failure, if the unit is in an operating state, and the mean time to repair if the unit is in a derated or failed state. All units are assumed to be fully operational at the beginning of the simulation period. After every unit is simulated for a full year, the total generating capacity at each hour is compared to the load during that hour. Figure 2.6 gives a visual description of the generating unit operating and repair times, which can be determined sequentially, and the overall system states. The basic adequacy indices can be determined through assessing the total number of times where the load is not supplied, n, the number of simulation years, N, the total failure time, $\sum_{i=1}^{n} t_i$, and the total unsupplied energy, $\sum_{i=1}^{n} x_i$. The LOLE and LOEE can be calculated from these basic parameters, as shown in Equations 2.5 and 2.6.

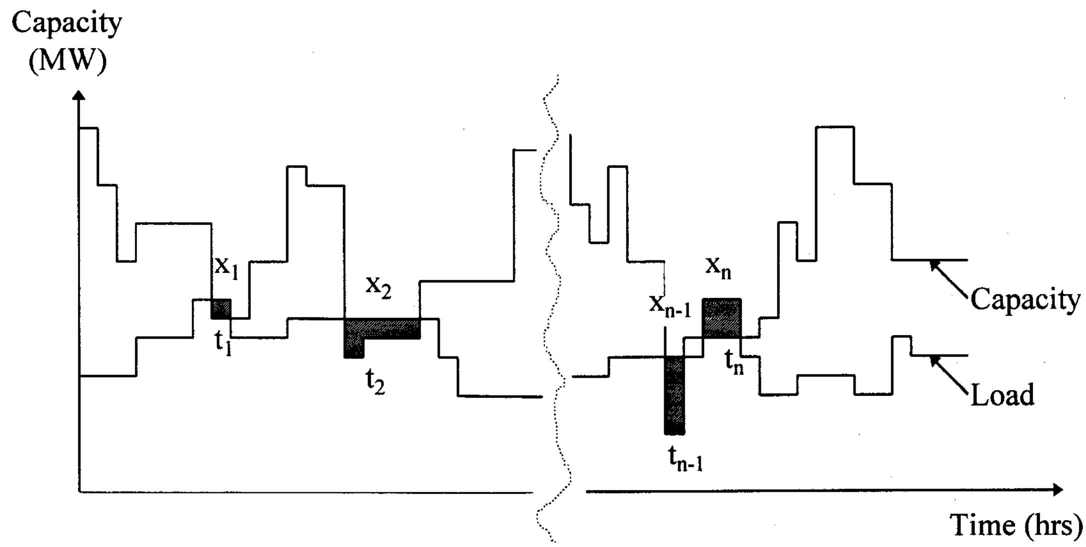

Figure 2.6 - Superposition of Generation Capacity States and Load Profile

Loss of Load Expectation (LOLE):

$$LOLE=\frac{\sum_{i=1}^{n} t_i}{N} \qquad \text{(hrs/yr)} \tag{2.5}$$

Loss of Energy Expectation (LOEE):

$$LOEE=\frac{\sum_{i=1}^{n} x_i}{N} \qquad \text{(MWh/yr)} \tag{2.6}$$

The above indices are cumulative, in that they represent all prior years up to the final year of simulation. Each of these indices has a standard deviation associated with it, which can be found using Equation 2.7:

$$\sigma(y)=\left[\frac{\sum_{i=1}^{K} y_i^2}{K-1}-\frac{K}{K-1}\overline{Y}^2\right]^{1/2} \tag{2.7}$$

where:

y = index of LOLE, LOEE or another reliability index

σ(y) = standard deviation of the index

y_i = ith observation of an index

$\overline{Y}$ = estimated average of the index

K = total number of observations.

The LOLE and LOEE indices provide an overall indication of the adequacy of the generating system to meet the total system demand. The distribution of these indices and variability expressed by the standard deviation of the index provide useful additional information which can only be obtained through Monte Carlo simulation.

2.1.4 Roy Billinton Test System

The Roy Billinton Test System (RBTS,) shown in Figure 2.7, was developed at the University of Saskatchewan as a research and teaching tool. It represents a small power system which is simple enough to learn on, yet complex enough to represent a practical power system. It consists of 11 hydro and thermal generating units ranging from 5 to 40 MW in size, for a total installed capacity of 240 MW. Nine lines connect the generating stations to six buses. The peak load of the system is 185 MW, with a load duration curve equivalent to that used for the IEEE Reliability Test System. The RBTS was used at HLI for all the studies reported in this thesis.

2.2 Solar Theory

2.2.1 Global Radiation

Solar energy begins with the sun, which emits radiation towards the earth, providing light and warmth. Due to the atmosphere, most of the radiation arriving at the Earth's surface is in the range of 0.3 - 3 μm, which consists of the visible spectrum, and part of the infra red and ultra violet ranges. The amount of radiation reaching the area just outside of the Earth's atmosphere is known as the solar constant and is equal to 1353 W/m^2 [9]. This radiation is then reduced by the atmosphere. The actual amount of terrestrial radiation hitting a particular location on earth depends upon the latitude, time of year and weather variables such as cloud cover, humidity, temperature and wind.

The solar radiation constant is attenuated due to the molecules in the atmosphere along very select radiation bandwidths. First, practically all radiation below 0.3 microns is absorbed by atmospheric ozone, along with a small band near 0.6 microns. Water vapor absorbs almost all radiation along 1, 1.4 and 1.8 microns. Then, above 2.3 microns, water and carbon dioxide absorb most of the radiation. The pattern of radiation entering the earth's atmosphere can be seen in Figure 2.8 [9], for

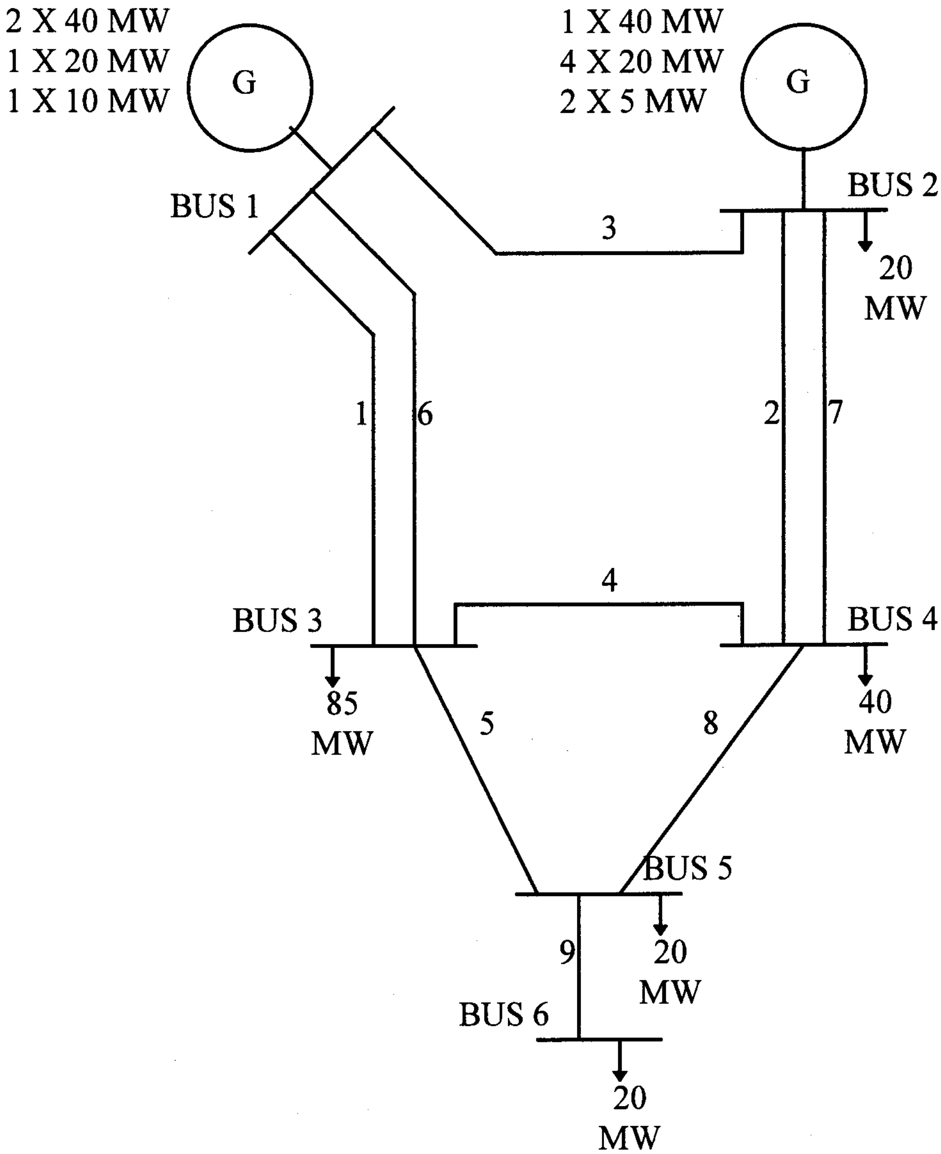

Figure 2.7 - Single Line Diagram of the RBTS

an air mass of 1. (An air mass of 0 indicates extraterrestrial radiation.) It should be noted from the graph that the solar radiation is most intense in and immediately around the visible spectrum.

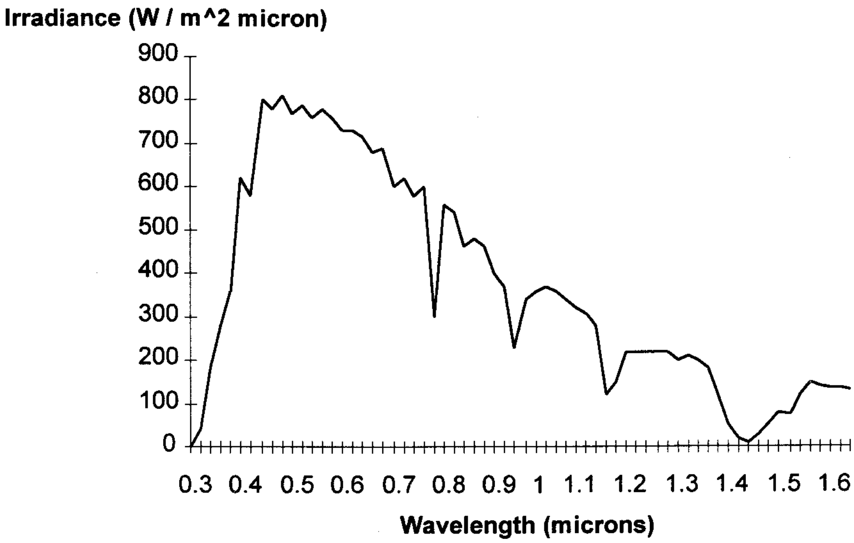

Figure 2.8 - Terrestrial Radiation for an Air Mass of 1.0

2.2.2 Photovoltaics

Photovoltaics are the basis for producing solar energy directly from the sun. The photovoltaic effect has been recognized in the scientific world since 1839 when Edwin Becquerel discovered that when light hits certain substances, a measurable current is produced [4]. Since that time, the process to most easily achieve this effect has been studied and improved to the point where it is relatively simple to obtain energy from the sun.

Light itself exists in waves of photons (small packets of energy) [33]. These photons can free an electron from material, giving it energy to move through the material. The minimum energy required to move the electrons is called the material's "band gap" energy. PV cells, used in creating solar panels, are designed so that the freed electrons move primarily in one direction, creating a measurable and usable current.

Photovoltaic cells operate in a manner similar to that of a silicon transistor or diode. The current moves in a single direction by joining two materials into a junction known as a p-n junction. The "p-type" material has very few electrons, but has a lot of "holes" which are indicated in Figure 2.9 as positive signs. These holes allow the free electrons (indicated as negative signs in Figure 2.9) which exist in the "n-type" material to move freely over the junction. The voltage across the junction increases until the number of holes driven from the n-type to the p-type equals the number of holes flowing from p to n. If there is no wire connected to the junction, the movement eventually reaches an equilibrium where the currents I_V and I_D are equal to each other, eliminating the voltage drop.

A well designed photovoltaic cell will enable a large fraction of the holes created in the n-type material, and a large number of the free electrons created in the p-type material to reach the junction point [5]. These electrons and holes are forced across the junction due to the potential difference across it, creating an increase in the current, I_V. Because the concentration of holes in the p-type material will remain relatively constant, the current, I_D, will be essentially unchanged by the movement. Thus, the voltage across the junction is able to remain, creating a current that continues through low resistance wires, as shown in Figure 2.9.

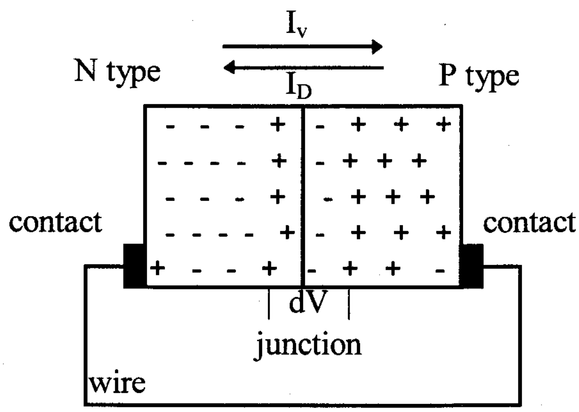

Figure 2.9 - Short Circuited Photovoltaic Cell

By attaching several of the photovoltaic cells together into an array, a usable voltage and current can be generated. This array arrangement is known as a solar panel or solar module. Due to variations in voltage drops across each cell, the actual voltage and current output from the panel will be lower than if the cells were exactly identical. The voltage and current lost through inexact matches of PV cells is one of the losses within the system. Other losses occur due to the efficiency of the cells in converting solar radiation into usable energy, along with resistance losses in the wiring. In total, the best commercial solar panels convert between 10% and 15% of the available radiation into usable energy, while efficiencies of up to 25% have been achieved in laboratories [5]. In addition, the conversion process is non-linear and dependent upon the type of material making up the individual cells. Thus, doubling the amount of solar radiation hitting a given solar panel will not necessarily double the panel's output.

2.2.3 Modeling Solar Energy

Modeling available solar energy for use in supplying power to a utility company is a two step process. The first step involves determining the amount of radiation that arrives on the earth at the location of the photovoltaic panel. The second step is the model of the panel itself, taking into account its efficiencies, losses and physical orientation. Each step requires a model that deals with a large number of variables, and the results of the first model are used as inputs into the second model.

2.2.3.1 Solar Radiation Modeling

Solar radiation on the Earth's surface is complicated to model due to the number of associated variables that affect radiation inside the Earth's atmosphere. The solar constant of 1353 W/m^2 outside the atmosphere is attenuated by factors such as latitude, time of day, season and weather variables. In addition, there are two components of radiation which make up the global radiation which creates energy in a solar panel, direct and diffuse. Direct radiation is not reflected or disbursed by cloud cover, buildings or vegetation, but comes "straight" from the sun, while diffuse radiation is scattered by clouds, water vapour and anything else in the area. Diffuse radiation can make up more than 50% of global radiation and is more difficult to model due to the number of variables that affect it [9].

The first important model of solar radiation was developed in 1960 by Liu and Jordan [12]. Their approach was probabilistic in nature, utilizing statistical averages for cloud cover, along with variations in atmospheric water vapour, dust and ozone contents to determine the direct and diffuse components of solar radiation which arrives on a horizontal surface for various locations within North America. This model has become the standard against which the modern radiation models are compared. The Liu and Jordan model has been modified and adjusted by many different researchers [13 - 18]. These newer models take into account discontinuities in cloud cover and enable radiation to be estimated even if some of the historical data is missing. In addition, the newer models are working to increase the accuracy of the simulated radiation, particularly for latitudes that are not covered in the original model.

For Canadian latitudes, the modifications made at the University of Waterloo in Waterloo, Canada have proven to be fairly accurate when compared with actual radiation measurements. The overall model utilizes a stochastic probability transformation of the clearness index in order to obtain a Gaussian random variable which has the same mean and variance for each month. This new variable is then used in an ARMA (1,0) model to compute the hourly radiation on a horizontal surface [13, 14]. The model takes into account effects such as average monthly temperature, wind speed and humidity to provide further refinement and was developed into a commercially available solar radiation modeling program known as WATGEN, which is used by research councils, utility companies and universities across Canada. Version 1.0 of WATGEN was used in the simulations contained in this work.

2.2.3.2 Photovoltaic Modeling

Solar radiation provides the basis for the input into a photovoltaic panel. Modeling of the panels is also a complex process due to the number of variables within the cells, differing construction methods, and differing radiation collection methods. Within the literature, there are many different models available to model PV arrays [10, 11, 21]. All the models take into account the current-voltage curve provided by panel manufacturers, along with the tracking ability of the hardware. The accuracy of the models is based on how well they relate to actual field and laboratory tests. The greatest difficulty in utilizing any of the models is to obtain all of the information required for the inputs. In this work, a modeling program, known as WATSUN-PV, is used. The program provides a catalogue of input data for a larger number of solar panels and inverters, from which the user can select appropriate units.

The simulation process within WATSUN-PV requires input information on the angle of the PV array, its tracking ability (if any), and specific characteristics of the array and inverter. From hourly radiation data, the simulation calculates an expected array output for each hour of the year, along with wiring losses and inverter losses. WATSUN-PV has been shown [20, 34] to provide acceptable estimations of array output.

2.3 Solar Generation Adequacy Assessment

Adequacy assessment of a generating system containing solar photovoltaic energy involves incorporating solar panels into the Monte Carlo simulation of a system. Analytical techniques, though tried by several researchers [35, 36] do not provide satisfactory results because of the random nature of cloud cover, which affects solar array output. In this work, the output from WATSUN-PV was utilized as an input to a Monte Carlo reliability assessment program known as GRASS (Generation Reliability Assessment by Sequential Simulation). The resulting program, called SGRASS (Solar GRASS), can accommodate both types of solar energy, photovoltaic and wind, although only photovoltaic energy is evaluated here.

The process of incorporating solar energy into a Monte Carlo simulation program requires developing a reliability model for the solar energy, recognizing that each panel will have separate failure characteristics, but those located in the same vicinity will have similar output features. Solar array failure rates were superimposed on the input from WATSUN-PV to provide the overall reliability of a generation system containing solar energy. Figure 2.10 shows how the conventional and solar energies relate to each other.

The solar generation was used in the reliability assessment of the entire system through a process known as load reduction. In a Monte Carlo simulation process, decreasing the load by X MW, or increasing the generation by X MW results in identical indices being calculated. Fewer steps were required within the SGRASS program to reduce the load rather than increase the generation. The load reduction technique was therefore used for computational efficiency.

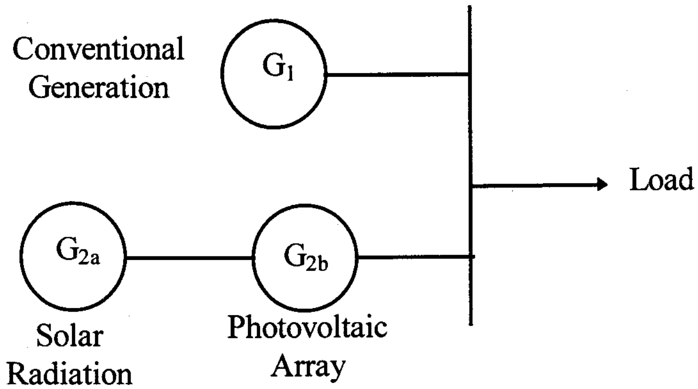

Figure 2.10 - Adequacy Assesment With Solar Energy

The process used to incorporate the output from WATSUN-PV into SGRASS required the simulation of 100 years of hourly photovoltaic output from a 1 kW array. This data was then read into SGRASS where the forced outage rate of the panels were used to determine whether each array was operational or had failed. Initially, a batch file was developed so that each simulation year would have new simulated data from WATSUN-PV. However, this process resulted in computation time of over five minutes per simulation year, which is unreasonable for completing sensitivity analysis on the solar resource. The end result of utilizing a finite number of years of hourly solar array output gave a reduction in the random characteristics of the solar energy, however the error is small because the hourly load profile used in the RBTS remains constant each simulation year. It is shown in Chapter 3 that only 1 year of hourly solar array output is needed to provide acceptable values.

The overall simulation process used to perform generation adequacy assessment on a utility grid containing solar photovoltaic energy is:

1) Simulate the expected radiation and resulting hourly PV array output for a particular location.
2) Simulate the hourly operation of the conventional generating units.
3) Superimpose reliability characteristics upon the PV array output.
4) Reduce the hourly load by the available PV power.
5) Determine whether the reduced load is able to be satisfied by the conventional generating units.
6) Calculate the reliability indices and determine whether the stopping criteria are met.

The above method is used in SGRASS. The effect of incorporating PV into the RBTS was determined using solar data for locations within Saskatchewan. These results are shown in the subsequent chapters.

3 BASIC PARAMETERS AND DATUM

3.1 Generating System Without Photovoltaics

3.1.1 Introduction

When examining the effect of non-conventional power generation in an otherwise conventional generating system, it is necessary to fully explore the characteristics of the basic system. Standard generation systems are usually made up of thermal (fossil fuel and nuclear) or hydro generators, which are generally large in size to incorporate the economies in scale, contributing to lower energy costs for the consumer. The construction of base load generating stations, in particular, incorporate the philosophy of "bigger is better," as larger stations generally have a lower cost per megawatt of production capacity [2].

Peak load generating stations are generally not as large as base load stations because they are used irregularly and must be able to follow the load. The load following requirement is most easily met by a large number of smaller units which can be brought on line whenever the system load increases beyond what the base load units can handle. Power is usually produced using natural gas or oil, and is often able to supply a variable amount of generation [2]. The units are scheduled to meet the anticipated load, and can also be brought on line quickly if the load exceeds anticipated levels in a particular hour.

In addition to the scheduling of peak load generating stations to ensure that the system load is satisfied, utility companies ensure planning incorporates sufficient generation reserve within their systems to meet future load requirements. The amount of reserve that is considered sufficient varies from utility to utility, and often depends on the method of reserve evaluation. The reserve itself is the difference between the peak load and the maximum generating capacity. In the past, utilities set their reserve at least equal to the largest generating unit. In this way, if the largest unit fails while the load is at its peak, the system will still be able to meet the demand. Some utilities continue to use this method today, however more companies are utilizing reliability indices such as the LOLE and LOEE to determine whether their system is adequate. The utility chooses a criterion value for each index, such as a LOLE ≤1.0 hour per year, which is considered to provide acceptable reliability. The reserve magnitude is then set based on this index.

3.1.2 The Roy Billinton Test System

As noted in Chapter 2, the Roy Billinton Test System is made up of 11 generating units, ranging in size from 5 to 40 MW, with forced outage rates from 1% to 3%. The system has a generating capacity of 240 MW, with a peak load of 185 W, providing a reserve margin greater that the largest generating station. Utilizing SGRASS, with 0 MW of photovoltaic generation, the LOLE and LOEE are comparable to that obtained analytically in Table 3.1. The simulated indices were determined utilizing a stopping criterion where the difference between subsequent simulation years of LOLE is less than 0.05 hours/year. The desired accuracy was obtained after 5440 simulation years. After the simulation period, the difference between the analytical and simulated values in the LOLE is less than 1.9%, while the difference in the LOEE is less than 1.2%.

Table 3.1: LOLE and LOEE for the RBTS

Method	LOLE (hrs/yr)	LOEE (MWh/yr)
Analytical	1.084	9.731
Simulated	1.105 $\sigma = 4.08$	9.623 $\sigma = 50.63$

3.1.3 Adding Conventional Units to the RBTS

Most utilities today are faced with constantly increasing loads caused by increasing population levels, higher plug loads, and more industries and businesses being established. Plug load increases are interesting, as many utility companies have created demand side management (DSM) programs to assist consumers to reduce their energy use. However, as consumers reduce their lighting and heating loads, they are also adding computers, laser printers, larger stereo systems, and the like. Over the past few years, the increase in these plug loads has been leveling off, due in large part, to programs such as Power Smart in Canada, and Green Lights and Energy Star in the United States. Although power loads are increasing, the speed of increase has been slowed down by the DSM programs.

A 1 MW conventional generating unit with varying forced outage rates was added to the RBTS. The first simulation was completed with a perfect generating unit, i.e. one that cannot fail. The unit mean times to failure were then set to 4380, 2190 and 1460 hours, with mean times to repair of 45 hours (FOR = 1%, 2% and 3% respectively.) The results are shown in Table 3.2.

Table 3.2: Reliability Parameters for the Addition of a 1 MW Conventional Generating Unit to the RBTS

FOR	LOLE (hrs/yr)	LOEE (MWh/yr)
0%	0.870 $\sigma = 3.63$	7.414 $\sigma = 47.59$
1%	0.928 $\sigma = 3.78$	8.611 $\sigma = 50.09$
2%	0.932 $\sigma = 3.79$	8.633 $\sigma = 50.21$
3%	0.932 $\sigma = 3.79$	8.642 $\sigma = 50.25$

As shown in Table 3.2, the reliability decreases with increasing forced outage rate. The difference between successive LOLE and LOEE, however, is reduced as the FOR increases. The reduced differences in reliability indices is due, in part, to the small amount of added generation (less than 0.5%).

3.2 Photovoltaic Generation

3.2.1 Introduction

Although adding conventional generation to meet increasing base loads and demands is an option, utilities generally prefer to install large conventional generating stations. If the load is not growing rapidly enough to install large plants, the utility must then make the choice between having too much generation available or making due with a lower reserve (hence, reliability) than desired. The alternative is to look at non-conventional generating sources. These generally consist of smaller installations that can be located in areas where the load is highest, allowing the load and reliability parameters to be met without the compromises posed by conventional generation. Figure 3.1 diagrams the initial system, with only conventional generation. As load levels increase, the system could begin to look like Figure 3.2, if the utility chooses to utilize non-conventional generation. As indicated by Figure 3.2, the non-conventional generation would require the transmission of electricity in both directions along the transmission line so that any excess energy generated could be put into the power grid.

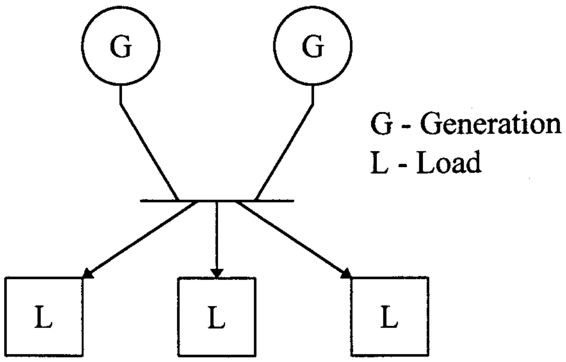

Figure 3.1 - Representation of Conventional Generating System and Loads

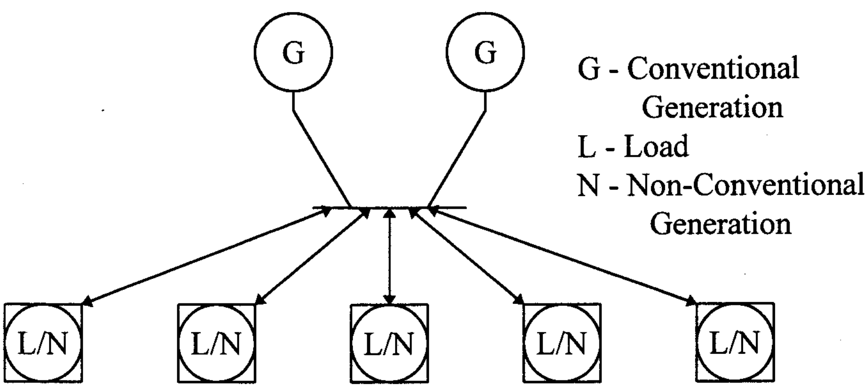

Figure 3.2 - Possible Future Distributed Generation System and Loads

From an environmental perspective, non-conventional sources usually have less impact than conventional generation. Conventional systems have several pollution problems associated with them. First, their construction often damages the environment, particularly with hydro power which requires the damming of rivers to create a reservoir. With thermal systems, the mining of fuel can create havoc with the land surrounding the mine site, although this is less of an issue now that there are stronger regulations regarding coal and uranium mining and oil and natural gas drilling [7]. From the electricity production standpoint, hydro systems have few emissions, but thermal systems usually emit a large number of pollutants, including acid rain agents such as sulfuric oxides and nitric oxides, along with ozone harming molecules such as carbon dioxide [2]. Non-conventional sources, when properly produced, have very few emissions. Photovoltaic panels are produced utilizing toxic chemicals, however the process has evolved to the point where the chemicals can be reused and recycled. This allows for careful production processes which ensure that the chemicals are not disposed of improperly, and that only a small amount of pollution is created. The panels themselves can be located on existing buildings, or situated in a location which does not decrease the amount of arable land, reducing concerns that food production would be compromised by widespread use of PV [37]. The pollution created by wind power is in similar amounts to solar power, however there is the added concern of increased bird kill from the blades. The pollution from other non-conventional sources is also generally due to the production of the equipment itself, with very little created during energy production.

The largest problem, from the utility perspective, with non-conventional generation is that such sources can not be relied upon to meet load demand. Without storage, the energy must be used when generated, or lost. However, if the generated power is used near the load location, with any surplus supplied to the grid, some of this concern can be alleviated because the non-conventional generation appears to the large base load generating units as reduced load levels [22]. Since load levels can fluctuate more rapidly than wind speed or incoming solar radiation, the method of load prediction for system generation scheduling should not change.

3.2.2 Characteristics of Photovoltaic Panels and Inverters

In order to assess the reliability of incorporating photovoltaics into a generating system, the characteristics of the PV arrays must be determined. For simulations and in practice, the PV array and inverter must be chosen to provide a reasonable power output, given the available radiation and total area the array is able to take up. For reliability analysis, the mean time to failure and mean time to repair must be determined on the basis of experimental estimations or real world analysis.

Utilizing the components available in data files provided with WATSUN-PV, various PV panel and inverter combinations were simulated for a 1 kW array. The combination that was able to provide the greatest amount energy to the grid was chosen as the basis for the reliability simulations. The basic characteristics of the PV panel were high efficiency in conversion of solar radiation into electricity, low internal resistance, good current and voltage matching of the cells within the panel, and a small panel size so that the 1 kW array can fit into a fairly small area. The specifics of the array utilized in the simulations can be found in Appendix A. The inverter must be well matched with the panel, and allow a large range of voltage and current inputs, so that the overall array can be effective over the greatest range of incoming radiation. The characteristics of the selected inverter are found in Appendix B.

3.2.3 Photovoltaic Array Failure Characteristics

The reliability of the PV array was determined based on field tests done by utilities and researchers throughout North America. These test sites all consist of locations where solar panels are installed and connected to the power grid, but primarily serve the needs of specific buildings. The experience gained in these studies indicate that modern PV have very high reliability. The cells making up the panel are stationary, and therefore they continue to generate a current as long as there is solar radiation or light hitting the panels. Failures occur within the array, however, due to failures in the inverter, or wiring [38]. Inverter and wiring failures were quite common in the early test systems due to lack of experience with the technology.

Such inexperience resulted in mistakes being made in inverter/panel matching, and in the installation process itself. However, once the initial problems were repaired, the systems have worked quite successfully.

Much of the available literature detailing experiences with grid connected PV provides details on the availability and failures of PV panels [8, 38-43]. Obtaining a generalized forced outage rate for PV panels from this data can be done by assessing the hours of operation versus the hours where the system has failed. In some instances availability was defined as the number of hours of operation when compared to the hours of daylight, which means that weather patterns contribute to the "down time" of the system. Because weather problems do not contribute to a FOR based on component failures, these systems were not included in developing a generalized FOR. In addition, systems which had been operational for only a short period of time were excluded from the calculations, as were systems installed prior to 1988. The reason for the latter two exclusions is due to the wear in period of the system, which usually has a higher failure rate than the long term system operation, and older systems are less reliable than modern systems due to improved quality control for array production and installation. As the specific type of PV cell makeup is not being examined in this work, Table 3.3 shows the FOR for various systems in the literature. The two best and two worst systems were eliminated from the data.

check wind mach data

Table 3.3: General Photovoltaic Forced Outage Rates

System [Reference]	Operational Time (Hours)	Failed Time (Hours)	FOR
1 [8]	26170	110	0%
2 [8]	34650	390	1%
3 [8]	34800	240	1%
4 [8]	34392	648	2%
5 [8]	33977	1063	3%
6 [40]	4968	300	6%
7 [38]	13009	131	1%
8 [38]	20980	920	4%
9 [38]	11751	225	2%
10 [38]	8672	88	1%
Total	223369	4115	2%

0 – 6%

3.3 Adding PV to the RBTS

3.3.1 Solar Simulation Years

Due to the computational time involved in determining 100 years of simulated solar radiation and PV array output, the first PV simulations completed examined the effect of reducing the number of simulation years. Simulations were completed using a typical meteorological year, and 10, 20, ... 100 years of unique, simulated PV output, which were then used as inputs into SGRASS. In each simulation, 1 MW of solar power was added to the RBTS. The stopping criteria used in these simulations was the same as that used for the conventional system analysis. Figure 3.3 shows that the variation in LOLE was less than 0.5% between 1 and 100 simulation years. From a numerical standpoint, the LOLE changed from a maximum of 0.928 hours/year to a minimum of 0.927 hours per year. The difference between these maximum and minimum values is well below the stopping criteria tolerance. It was therefore determined that subsequent simulations would only utilize the simulated array output for a typical meteorological year at the given location. Appendix C details the errors associated with reducing the simulation years when greater amounts of PV are added.

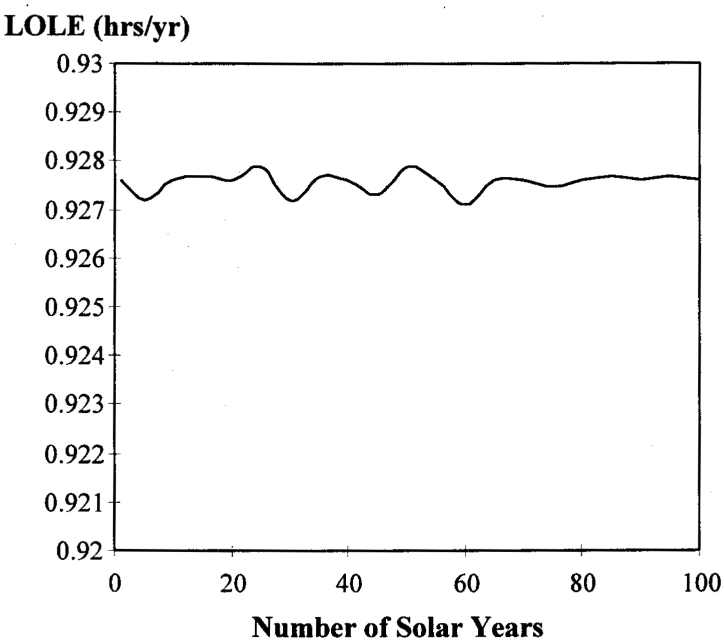

Figure 3.3 - Changing Loss of Load Expectation with Varying Number of Solar Years

3.3.2 Limiting Characteristics

The Monte Carlo simulation conducted using SGRASS takes 6800 simulation years to reach the desired accuracy. During this period, the LOLE varied considerably, based on the specific characteristics of the particular simulation year, and how that year affected all the simulations completed to that point. Figure 3.4 shows how the LOLE moves towards a limiting value as the simulation years increase, for a system with 1 MW of added solar energy.

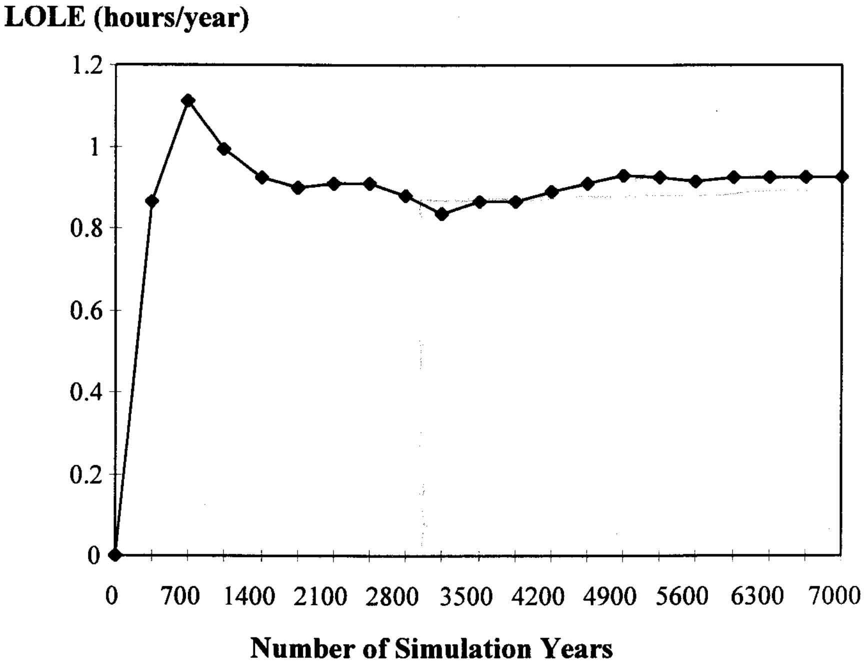

Figure 3.4 - Variation in the LOLE with the Number of Simulation Years

3.4 Summary of Parameters and Datum

From the initial analysis, the datum for this thesis have been determined. The reliability of PV have been assessed against the basic RBTS parameters found in Table 3.1, and against the RBTS with 1 MW of added conventional generation having a FOR of 2%. The PV panels and inverters remained unchanged throughout the study, because the issue being investigated is the reliability of PV in general, as opposed to the reliability of specific solar panels and inverters. Based on the experiences of utilities with installed solar power, the PV and inverter combination have a FOR of 2%, based on a MTTF of 4380 hours, and a MTTR of 90 hours. Studies conducted to examine the load carrying capability and capacity credit of solar power injections into a conventional generating capacity system using the above data are described in the following chapters.

4 SOLAR AVAILABILITY

4.1 Load Following Characteristics

4.1.1 Demand Side Management

Solar energy is often seen more as a demand side management tool than a source of generating capacity because peak sunlight hours are often the same hours that the utility's load peaks. The correlation between load and sunlight are particularly strong in latitudes close to the equator where the load is driven by air conditioning. In such locales, a solar panel connected directly to the air conditioning load is able to reduce the reliance on power supplied by the grid. In this manner, solar energy is seen by some to be equivalent to new lighting technologies, variable speed drives on motors, and improved insulation [44]. Unlike the energy reduction technologies, however, solar energy does nothing to improve the building's overall usage of energy. Instead, it simply reduces the energy requirements from the grid.

Utility companies have sponsored the installation of photovoltaic panels in certain areas in order to reduce the load peaks that occur on the hottest, sunniest days, rather than installing new distribution lines rated for a higher capacity [44]. However, until recently, these connections were not able to return energy to the grid after the local load had been supplied. Thus, any excess energy generated either had to be stored in batteries, or lost. The difficulty that utilities saw in allowing the energy to be supplied back to the grid was two fold. First, they weren't sure if the power meters and distribution lines could handle the two directional flow of electricity. Secondly, the utilities needed to ensure the safety of the people who work on the power lines. If the supply back to the grid is not curtailed in the event of a power failure or line outage, the workers may find themselves dealing with live lines, which creates a significant hazard. This second concern has been addressed by the development of fault protection in the inverters, which prevents the flow of electricity to the grid if the grid is down [2]. The concern with the back flow of power has resulted in the installation of different meters in some locations, along with testing of lines to ensure that they can handle two-directional flows.

4.1.2 Saskatchewan Load Following

4.1.2.1 Saskatchewan Characteristics

Saskatchewan is situated between the 49th and 60th parallels, just west of the center of Canada. It is a land locked, agriculturally based province. Agriculture has flourished here due to the amount of sunlight present during the year. There are very few times where there is a long stretch without sunshine. The province undergoes extreme variations in temperature and weather conditions, as each winter there are periods of time when the temperature can fall to below -40°C, while in the summer, the temperatures can reach highs above 40°C. The unique part about the temperature extremes in this province is that the coldest winter days and the hottest summer days are usually blessed with an abundance of sunshine, which indicates that there should be strong load following characteristics associated with photovoltaic energy.

The utility company in Saskatchewan is currently a winter peaking utility, but has been coming closer to a dual peak utility over the past 10 years with the increase in air conditioning loads, and the improved efficiency of homes, which decreases the winter peaks [45]. Due to the winter peaking nature of this utility, and the small number of sunlight hours which occur in the winter, it was thought that the correlation between load and available solar energy would be small. However, as the consumer demand moves towards a dual peak, problems with system maintenance may end up occurring and the potential for solar energy use increases. In the past, northern utilities have tended to use the lower demand for power occurring in the summer months to perform scheduled preventive maintenance, resulting in generating stations being taken off line or being derated. With the increasing summer load, the window for maintenance is becoming smaller, which may necessitate the addition of new generating stations in order to schedule the required maintenance.

4.1.2.2 Saskatchewan Load Following

The solar array output was simulated for five locations in Saskatchewan to develop an appreciation for the possible utilization of solar energy in this province. Comparing the output from each location to the load profile of the utility reveals a strong correlation between load and solar array output. Figures 4.1 and 4.2 show the correlation between load and photovoltaic output for a city in the southern area of the province, Regina, and for a northern town, Uranium City. The figures detail the solar array output for a typical meteorological year on a representative day near the middle of the month, compared to the typical load that occurs at the same time. There appears to be great potential for load reduction through the use of PV energy in this province, as indicated by the peaks of the PV output and the load profile. This is also evident in the winter months when the hours and amount of sunshine is quite low.

4.1.2.3 RBTS Load Following

The simulations that are described in this thesis utilize a generalized load model that does not necessarily reflect the Saskatchewan situation. It is evident from Figures 4.1 and 4.2 that photovoltaic output closely follows the Saskatchewan load. The studies described in this thesis, however, were performed using the RBTS load profile, which has different peaking characteristics than that of the province's load profile. Figures 4.3 and 4.4 show that there is a strong correlation between the load and PV output, even for the generalized RBTS load model.

4.2 Solar Energy in Saskatchewan

4.2.1 Introduction

As noted earlier, Saskatchewan is a large, agriculturally based province. There is a large amount of open space, and communities are spread over long distances. The communities and farm yards are serviced by the utility company. It is, however, expensive to provide lines to each and every application for which electricity is needed on a farm. At current prices, it is cheaper to install PV panels to supply energy to a remote location than it is to extend the power line by 500m [39].

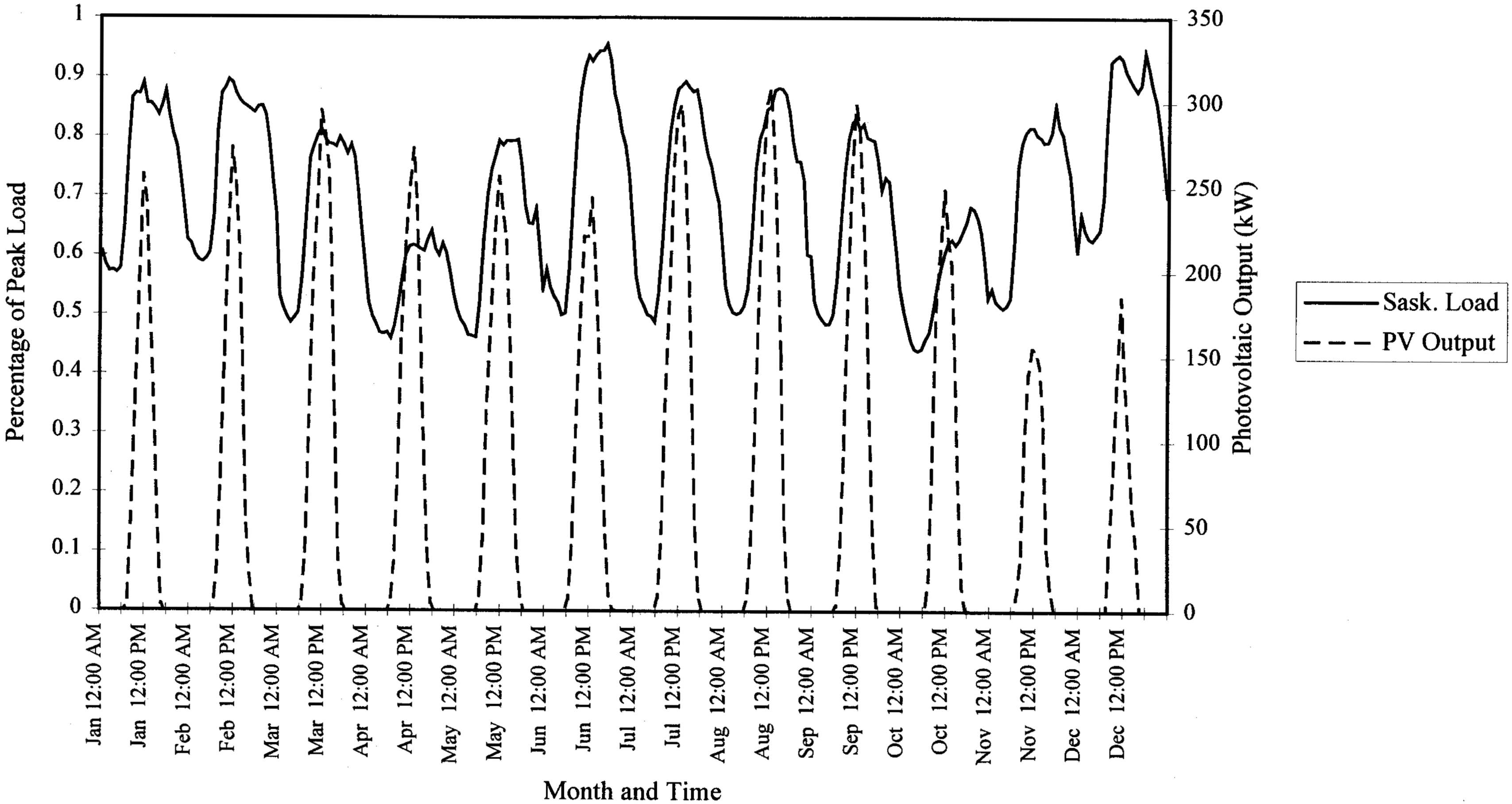

Figure 4.1 - Photovoltaic Array Output in Regina Superimposed on a Typical Saskatchewan Load Profile

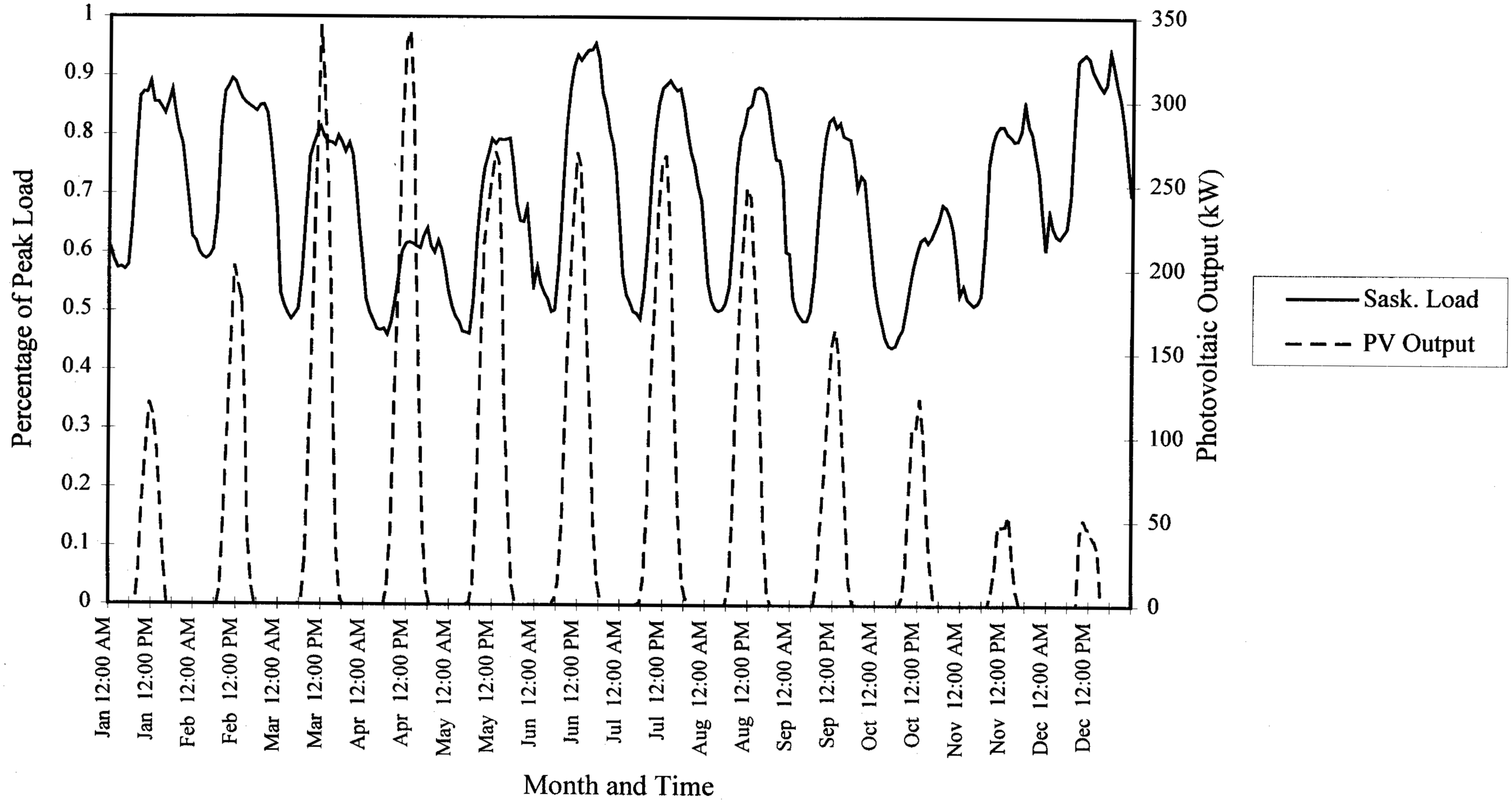

Figure 4.2 - Photovoltaic Array Output in Uranium City Superimposed on a Typical Saskatchewan Load Profile

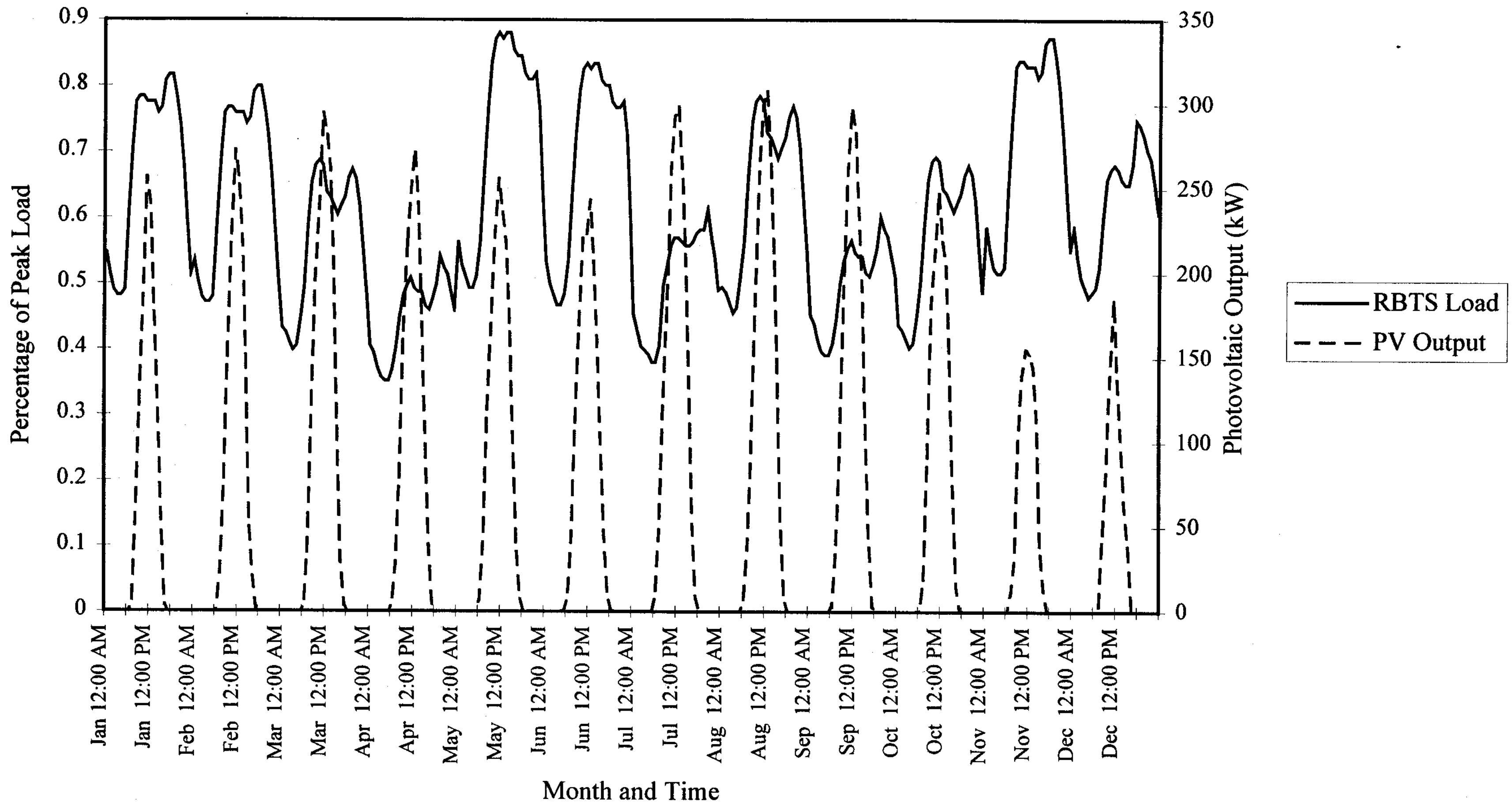

Figure 4.3 - Photovoltaic Array Output in Regina Superimposed on the RBTS Load Profile

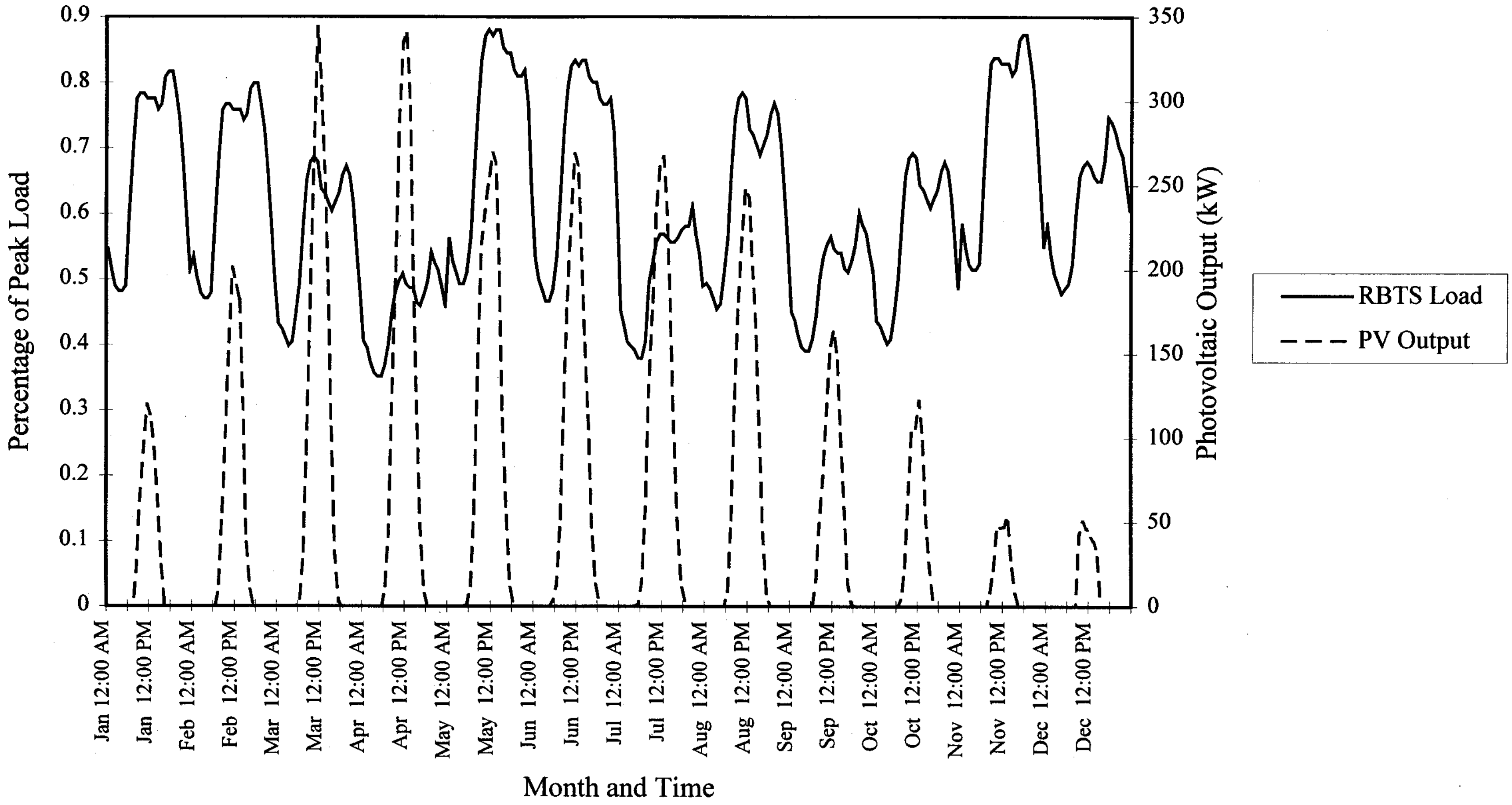

Figure 4.4 - Photovoltaic Array Output in Uranium City Superimposed on the RBTS Load Profile

Due to this expense, many people in the farming community are opting for non-conventional generation in locations where there is little need for continual supply, or where there is built-in storage. Two areas that have been well serviced by photovoltaic power generation are pumping and fence electrification. These experiences provide an understanding of the potential for solar energy use in this province, both on and off grid.

4.2.2 Current Applications of Photovoltaic Energy in Saskatchewan

4.2.2.1 Solar Water Pumping

Most farms in Saskatchewan have their own wells to supply water for the house, and often have dugouts to supply water to livestock. In both instances, pumping is necessary to bring the water to its intended use. If the location of the well or the dugout is a long way from the grid, or the power available at the house, other means, such as diesel generators, wind turbines or photovoltaic panels, are used to bring the water to the location where it will be used. In the case of utilizing wind or photovoltaics, a storage reservoir is employed to ensure the availability of the water in times where the sun is not shining, or the wind is not blowing. Due to the minimal cost and maintenance involved in utilizing PV and wind energy to pump the water, these technologies are becoming more common than diesel generators [46]. In addition, there is no charge for fuel once the system is established, which reduces the farm operating costs.

Properly sized wind and PV systems have been quite successful for water pumping, and are being utilized by more and more farmers. With wind power, it is a return to the system used to pump water before rural electrification. More farmers are now choosing PV arrays to pump their water, as the cost of the panels is generally lower than that of a wind turbine, and the arrays used are designed to pump water with only a small amount of available radiation [46]. Users of solar pumping systems find that the systems are pumping water almost every day of the year, even when it is raining outside.

4.2.2.2 Solar Electric Fences

Another aspect of farming is ensuring that livestock stays inside the intended pastures. Cattle, horses, goats, and other large animals are often able to get through the fences built around the pasture perimeter, so farmers have taken to electrifying their fences to ensure the animals stay inside. The interesting thing about electric fences is that the electricity does not need to continually flow because once the animals realize the fence is "hot" they tend to stay away from it. This makes solar energy a very viable option for powering fences, because there is no requirement for continuous electrification. In some cases, batteries are employed to provide some electrification at night, as well as during the day. Since the amount of energy required to make the fence a barrier for animals is minimal, small (50W) solar arrays and battery back up are all that is required [46].

4.2.2.3 Other Solar Uses in Saskatchewan

In addition to pumping and electrifying fences, solar energy is used to power specific components of many houses, including air conditioning units, or with battery storage, the entire power use of the house. However, any excess power generated can not currently be sold back to the grid. Due to this problem, solar thermal energy tends to be used more extensively than PV generation [47]. In particular, passive solar heating is used in many houses, both in urban and rural areas to reduce the heat loads required in the winter months, while in the summer, large overhangs or awnings are used to prevent the house from heating up too much. Active solar heating of water for domestic hot water use, and for heating swimming pool water is also employed in many parts of the province. For outdoor pools, which only operate in the summer months, solar heating is used quite regularly.

4.2.3 Reliability Indices for Grid Connected Solar Energy in Saskatchewan

Although PV are used throughout this province in off grid applications, there has been very little work done in determining how PV will work if connected to the grid. However, with the strong correlation between the load and the solar array profile, it is expected that the opportunity for solar energy to add generating capacity should be strong. It will take a shift in perspective for the local utility to incorporate PV energy into the grid, and to consider solar energy as a generation source rather than a demand side management tool.

In order to begin to appreciate the potential of PV, the solar energy profiles for five Saskatchewan sites were simulated using SGRASS to add 1 MW of PV capacity to the RBTS. The results of these simulations, in the form of LOLE and LOEE indices are shown in Table 4.1. The difference in reliability between each case is very small, due to the small amount of solar energy added (less than 0.5% of the energy generated is from PV). In fact, the LOLE values do not change between sites, and are within 1% of the LOLE obtained when adding 1 MW of conventional energy to the RBTS (0.932 hrs/yr $\sigma = 3.79$). The differences noted are in the LOEE where the energy supplied by the PV system to the grid has an impact.

Table 4.1: Generation Adequacy with 1 MW of Installed Photovoltaics In Saskatchewan

Location	Average Annual Energy To the Grid (MWh)	LOLE (hrs/yr)	LOEE (MWh/yr)
Estevan	540	0.928 $\sigma = 3.78$	9.014 $\sigma = 51.55$
Regina	547	0.928 $\sigma = 3.78$	9.008 $\sigma = 51.52$
Saskatoon	544	0.928 $\sigma = 3.78$	9.024 $\sigma = 51.59$
Swift Current	544	0.928 $\sigma = 3.78$	9.011 $\sigma = 51.56$
Uranium City	435	0.928 $\sigma = 3.78$	9.036 $\sigma = 51.65$

The loss of load expectation is basically the same in each of the five solar assisted cases and for the conventional system analysis. This is not too surprising when you consider that very little generation was added to the system. The smallest unit in the RBTS is 5MW and therefore, the addition of 1 MW of capacity, either conventional of solar, simply has a load modifying effect in the system. Another factor contributing to the lack of variation in the LOLE is that the stopping criterion used in the simulations was a difference in consecutive LOLE less than 0.05 hrs/yr.

This stopping criterion was selected based on the computation time involved in the simulation.

There is one noticeable difference in the loss of energy expectation values in Table 4.1. Significantly less energy is supplied to the grid for the Uranium City data site than for the other four sites. In the Uranium City location, more load goes unserved because there is less "extra" energy added to the system. In essence, the number of failures stays the same, but the amount of load affected by the failures increases.

5 RELIABILITY OF GENERATING SYSTEMS CONTAINING PHOTOVOLTAICS

5.1 Introduction

North American utilities are facing increasing pressure from their customers to examine and utilize alternative forms of energy, such as photovoltaics. In some areas of the United States, the customers are even willing to pay higher power rates to help offset the cost of installing photovoltaic energy on the power grid [23]. The difficulty found with PV power is that most utilities see it simply as a demand side management tool, rather than as generation, and very little analysis has taken place to show how PV affects the grid. The previous chapter shows that PV follows the load quite closely, not only in southern summer peaking utilities, but also in northern areas such as Saskatchewan. It follows that there will be reliability improvements to the grid system with the installation of PV, both in terms of load carrying capability and in capacity credits.

5.2 Load Carrying Capability

5.2.1 Introduction to Load Carrying Capability

Customer load levels are constantly increasing, due to the expanding population and increasing plug loads, despite efforts being made in demand side management and energy conservation. From the utility side, the increasing load requires added generating capacity, or an acceptance of a lower system reliability. If PV generation is chosen to supplement the generation, it should allow the utility to carry a higher load than without added generation. Due to the load following characteristics of PV, the peak load that can be carried will be higher with PV than without, while maintaining the same reliability levels. As discussed earlier in this thesis, the benefits of adding PV, rather than conventional generation include reduced pollution and increased customer satisfaction.

In order to determine the load carrying capability of solar energy, the maximum load for the RBTS was varied between 175 and 195 MW, in increments of 5 MW. The system was simulated without photovoltaic energy and then with 1 and 2 MW of photovoltaic energy. The solar data for Saskatoon was selected for the PV location as it has the median amount of solar energy when compared with the other Saskatchewan sites considered.

5.2.2 Load Carrying Capability Based on LOLE

Figure 5.1 shows the LOLE as a function of the peak load for 1 MW of added PV. Using a criterion LOLE value of 1.067 hrs/yr, as indicated by the horizontal line, 1 MW of solar energy can handle just under an additional 0.9 MW of load, which is slightly less than the rated output of the PV system. (1.067 hrs/yr is the LOLE for the basic RBTS, with a load of 185 MW.) Figure 5.2 shows that, for 2 MW of solar, the increase in load carrying capability is just over 1.5 MW.

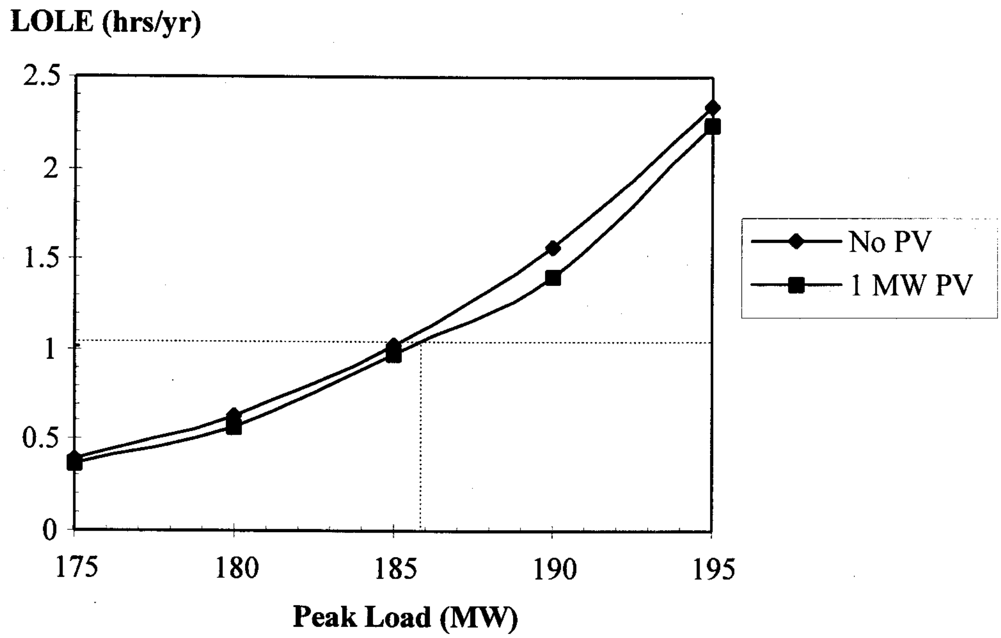

Figure 5.1 - Peak Load Carrying Capability with the Addition of 1 MW of Photovoltaic Energy, Based on LOLE

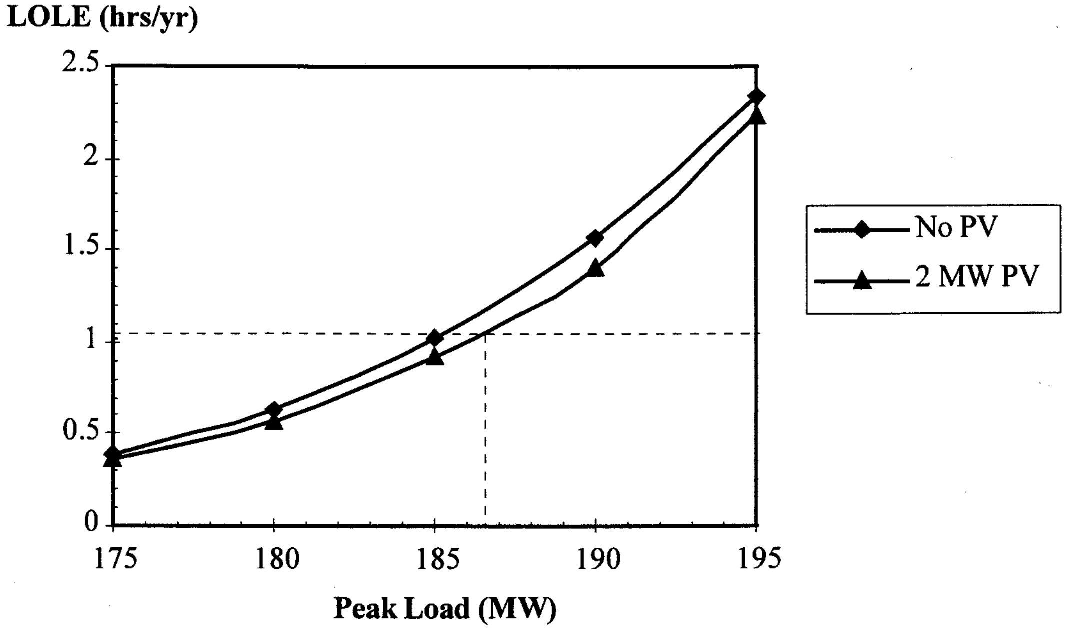

Figure 5.2 - Peak Load Carrying Capability with the Addition of 2 MW of Photovoltaic Energy, Based on LOLE

5.2.3 Load Carrying Capability based on LOEE

Figures 5.1 and 5.2 illustrate the increase in load carrying capability based on the LOLE. As noted in Chapter 4, LOLE is not necessarily the most suitable parameter to assess PV, because the actual amount of energy available at any given time is dependent upon the amount of solar radiation hitting the PV panels. Thus, the LOEE may give a different perspective on how the load carrying capability of the system is affected by the addition of PV generation. Figures 5.3 and 5.4, respectively, show the increase in the LOEE based on 1 and 2 MW of installed PV. Using the LOEE parameter, the load carrying capability due to 1 MW of PV energy is 0.9 MW of load, as was the case for the LOLE. With 2 MW of installed PV, the load carrying capability only increases to 1.1 MW, which is significantly lower than the 1.5 MW obtained using the LOLE.

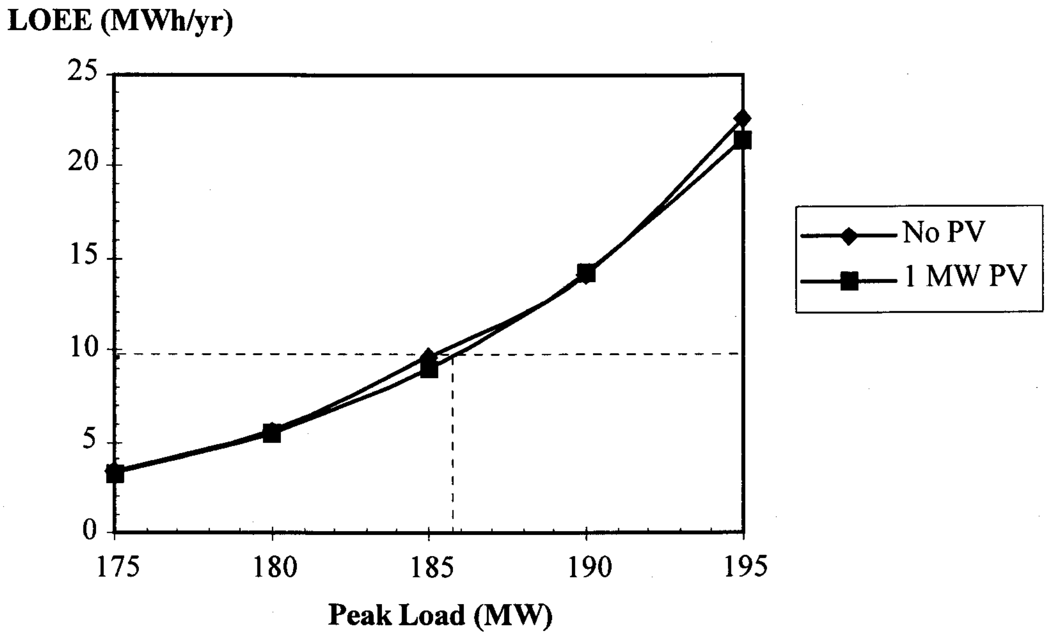

Figure 5.3 - Peak Load Carrying Capability with the Addition of 1 MW of PV Energy, Based on LOEE

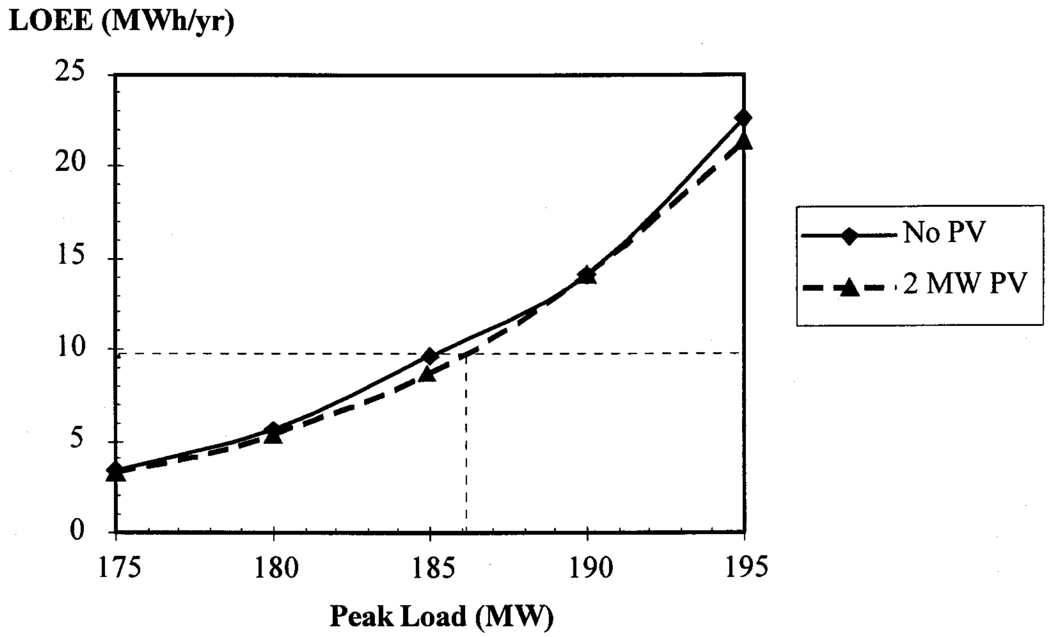

Figure 5.4 - Peak Load Carrying Capability with the Addition of 2 MW of PV Energy, Based on LOEE

5.3 Capacity Credit

5.3.1 Introduction

The previous section illustrates the peak load carrying capability for PV additions to the system. An important extension to this concept is the determination of a capacity credit that can be applied to a PV installation. The capacity credit is the amount of PV power that must be installed to provide the equivalent reliability associated with adding one megawatt of conventional generation. In these simulations, the conventional generation was added as a single unit, while the PV arrays were added in 1 MW increments. Two data sites, Saskatoon and Uranium City, were selected to illustrate the variations in the PV capacity credit.

5.3.2 Capacity Credit Based On LOLE

The loss of load expectation improves linearly with each added megawatt of PV generation, as can be seen in Figure 5.5. With small injections of solar power, up to 0.5% of the total generation, the capacity credit is approximately 1:1. As the

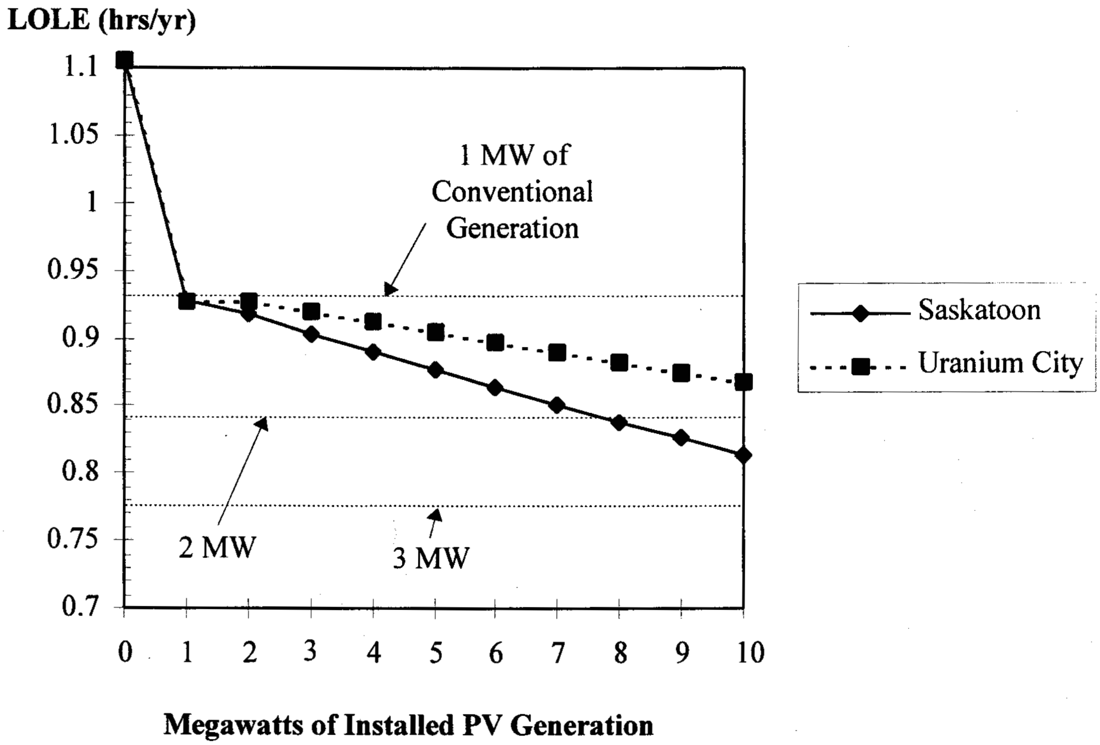

Figure 5.5 - LOLE for Varying Amounts of PV Added to the RBTS

amount of required generation increases, the capacity credit for solar power decreases. The amount of decrease depends on the location of the PV array. At the Saskatoon site, it drops to around 1:4 when PV makes up just under 1% of the total generation, while it drops below 1:10 for the Uranium City data location. Section 5.4 shows that the ratios become even higher as more capacity is required.

5.3.3 Capacity Credit Based On LOEE

The results are somewhat less favourable when the capacity credit is based on the LOEE index rather than the LOLE. Figure 5.6 shows that the LOEE improves almost linearly with increasing amounts of PV. At low levels of PV generation, i.e. less than 0.5% of the total system generation, it takes three megawatts of PV power, located in Saskatoon, to obtain the equivalent LOEE of 1 MW of conventional energy, giving approximately a 1:3 capacity credit. The credit drops to around 1:7 when the PV location is moved north to Uranium City.

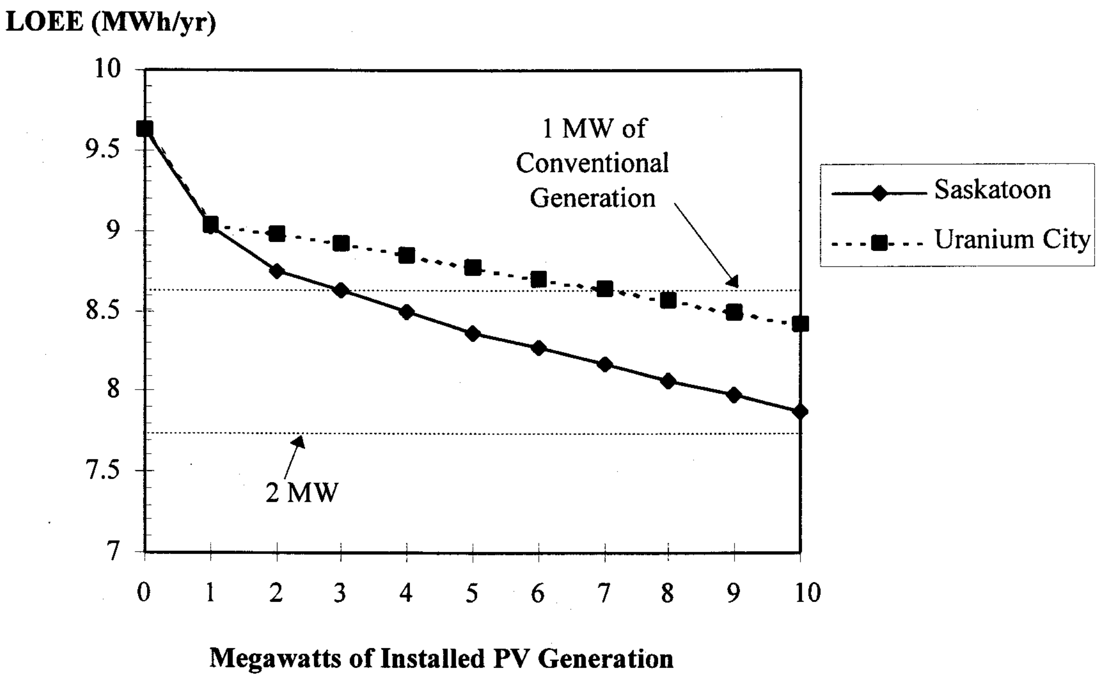

Figure 5.6 - LOEE for Varying Amounts of PV Added to the RBTS

The reason for this increase in required generation is due to the nature of PV generation, where an installation of 1 MW can provide 0 to 1 MW of power to the grid at any given time. When the conventional generation can not meet all the load, the added PV may still provide some energy, but not the full 1 MW of power that would be expected from an operational 1 MW conventional unit. As the amount of required generating capacity increases, the capacity credit decreases. More than 10 MW of PV are needed to provide the equivalent reliability associated with a 2 MW conventional unit.

5.3.4 Capacity Credit Variation

With increasing requirements for generating capacity, PV can be called upon to meet some of these needs. Figures 5.5 and 5.6 show that when the need for generation increases, the ability of PV to fill that need is reduced. This is due to a number of factors, including the dependent nature of the PV arrays used in these studies. Since all of the PV are assumed to be located in a single site, a weather disturbance in the area affects each of the panels, as opposed to widely distributed PV where the weather is virtually independent at each site.

The other notable feature of Figures 5.5 and 5.6 is that the Uranium City location requires greater PV installations than PV located at the Saskatoon data site, to achieve the same LOLE and LOEE levels. The basic reason for this is that Uranium City gets very few hours of sunshine in the winter months. Although the PV output still follows the load quite closely (as seen in Figures 4.2 and 4.4) the actual amount of power generated by the arrays is quite low from November through March. The implication of this is that much more PV would be required to obtain equivalent outputs, and consequently, reliability.

5.4 Replacing Base Load Generation with PV Generation

5.4.1 Analysis

When PV generation is added to the RBTS, PV has a capacity credit ranging from about 1:1 to less than 1:10 as the PV penetration increases. If PV arrays are installed to replace a generating unit that has been permanently removed from the system, the amount of PV generation required increases considerably. Studies were conducted with 5, 10 and 15 MW of PV capacity replacing a 5 MW conventional unit in the RBTS. Larger PV additions were not simulated due to the computation time involved, which runs at approximately one day per MW of PV. The effect of PV additions were simulated for both the Saskatoon and Uranium City data, to illustrate the differences between central and more northern locations.

The RBTS, before the 5 MW unit was removed, has an LOLE of 1.067 hrs/yr and an LOEE of 10.33 MWh/yr. The PV generation that was added using the Saskatoon and Uranium City solar data does not adequately replace the removed conventional unit, as can be seen in Table 5.1. This was expected, due to the capacity credit evaluation which indicated that more than 10 MW of solar generation would be required to replace 2 MW of conventional generation. The capacity credit evaluation also showed that larger amounts of PV are required as more generation is needed.

Table 5.1 - Reliability of the RBTS with 5 MW of Generation Removed, and PV Generation Added

PV Data Location	PV Addition (MW)	LOLE (hrs/yr)	LOEE (MWh/yr)
Saskatoon	5	1.461	13.30
Saskatoon	10	1.438	13.15
Saskatoon	15	1.407	13.03
Uranium City	5	1.481	13.77
Uranium City	10	1.449	13.49
Uranium City	15	1.418	13.21

Table 5.1 indicates that 15 MW of PV is insufficient to obtain equivalent reliability indices to the RBTS. Linear extrapolation was used to assess the ability of PV generation to take over the role of the 5 MW base load unit removed from the RBTS. This type of extrapolation was chosen based on the capacity credit simulations completed in Section 5.3, which indicated that the LOLE and LOEE decrease almost linearly with each additional megawatt of PV generation added to the RBTS, for the Saskatoon and Uranium City data sites. In Section 5.5 it is shown that

the actual relationship between the points is quadratic, with a slight concave upwards turn. Thus, the results from the linear extrapolation will provide a slightly pessimistic view..

5.4.2 Base Load Replacement Using LOLE

Figure 5.7 shows that the Saskatoon and Uranium City data sites both require around the same amount of PV generation to achieve the basic RBTS LOLE of 1.067 hrs/yr. For the Saskatoon data, around 72.5 MW of PV is required, while 74.5 MW is required if the Uranium City data is used. These levels are in the 1:15 capacity credit range, when 2% of the generation is supplied by PV, which is less than half that of the LOLE capacity credit of approximately 1:4 for the Saskatoon data and around 1:6 for Uranium City data when only 1% of the generation is supplied by PV, shown in Figure 5.5. One of the reasons for this decrease in capacity credit can be attributed to the fact that this particular study examines the system reliability with PV taking over base load generation, rather than working to improve the reliability of the basic remove

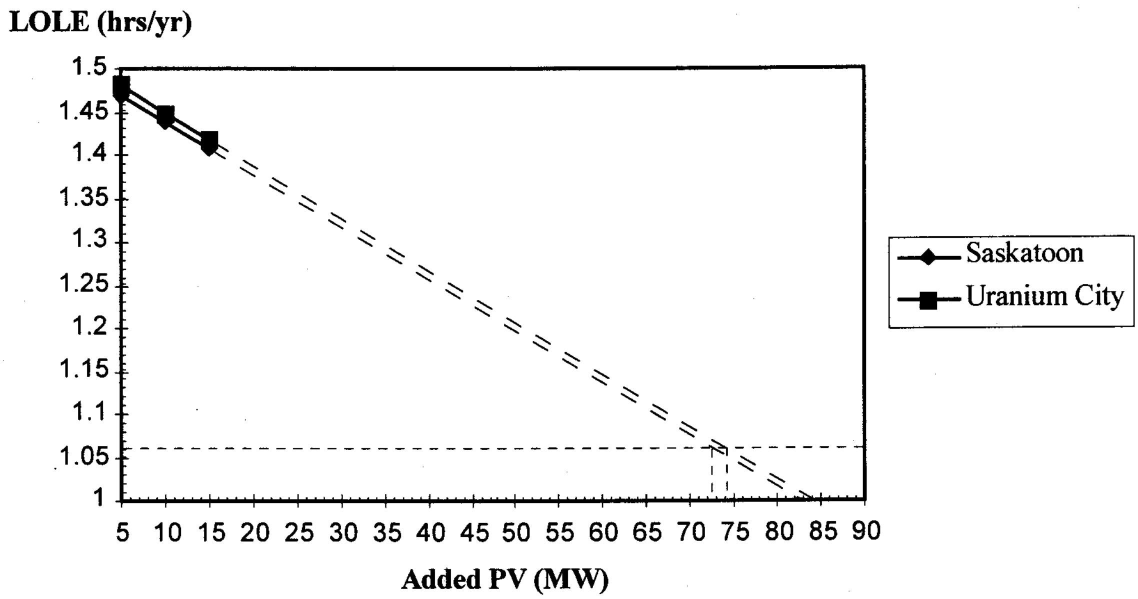

Figure 5.7 - PV Required to Obtain an Equivalent LOLE to the Basic RBTS when a 5 MW Generating Unit is Removed

RBTS. Another part of the decrease may be due to the fact that 5 MW of conventional generation are being replaced, rather than only 2 MW in the studies completed in Section 5.3.

5.4.3 Base Load Replacement Using LOEE

Figure 5.8 shows the extrapolation in which 56 MW of PV are required to obtain an LOEE of 10.33 MWh/yr using the Saskatoon data, while 65 MW of PV are required using the Uranium City data. These amounts of PV generation are lower than those that were required to replace the 5 MW base load generating unit when LOLE was used as the reliability index. In the previous studies, dealing with load carrying capability and capacity credit, the opposite was true. The difference occurs because the slope obtained when increasing generation using the LOEE index is greater than the slope of the line for the LOLE index. Thus, the incremental generation required to obtain improved LOLE is greater than the incremental generation required to achieve improved LOEE. When large amounts of PV are added to the system, as in these studies, the LOLE indicates a more pessimistic reliability than the LOEE.

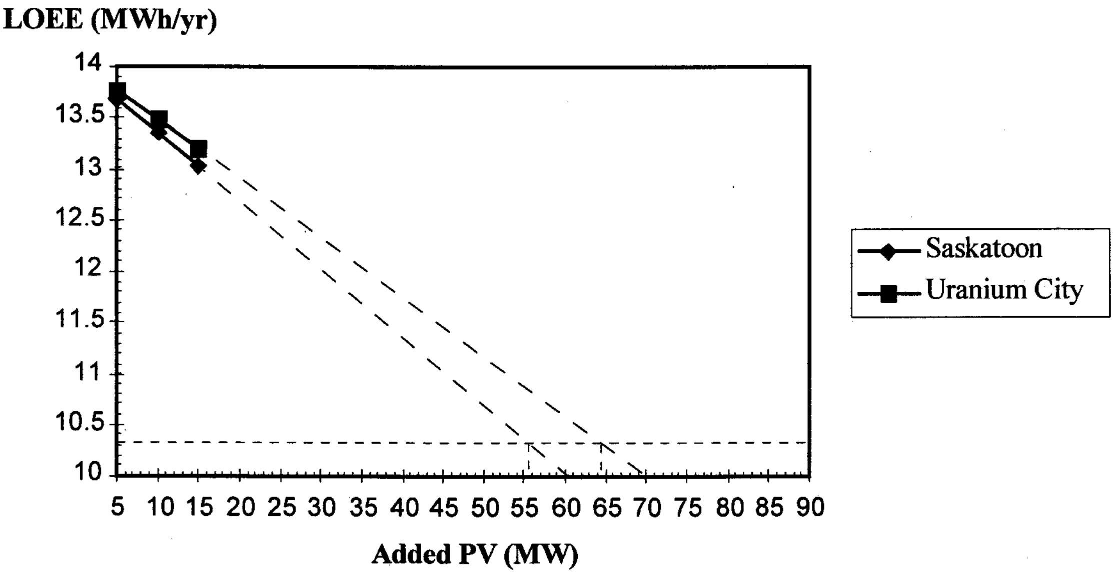

Figure 5.8 - PV Required to Obtain an Equivalent LOEE to the Basic RBTS when a 5 MW Generating Unit is Removed

5.5 Analytical Formula for Reliability Analysis of Grid Connected PV Arrays

5.5.1 Formula Development

The computation time involved in determining the reliability of a generating system containing PV energy is in the order of 1 day per MW of PV added to the system, using a Pentium 133 MHz computer. For large PV additions, this time is too large to be practical. An analytical calculation to provide reliability estimates is therefore desirable, particularly for preliminary PV investigations.

The LOEE obtained by adding varying sizes of PV arrays for the Saskatoon and Uranium City data sites were analyzed to determine a formula which can be used to calculate the LOEE for any size of photovoltaic array addition. Figure 5.9 shows the points used in determining the formula, when compared to the size of the added array. Due to the large variations in LOEE for each array size, depending on the data site, the formula needs to account for both the PV location, and the size of the installed array.

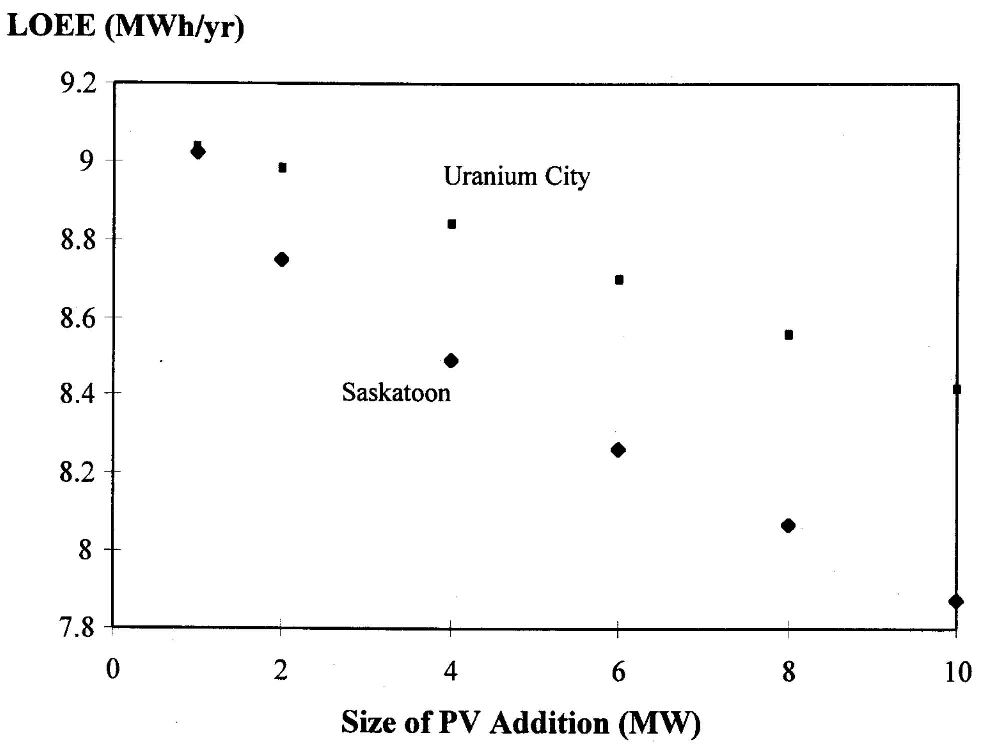

Figure 5.9 - LOEE for Adding Varying Amounts of PV for 2 Different Saskatchewan Data Locations

Figure 5.9 indicates that a formula based on PV array size will not satisfy all locations, and therefore another basis needs to be found that incorporates both the PV size and the solar data for the PV location. The studies described in Chapter 4 indicated that there is a trend for the LOEE to improve with increasing annual array energy supplied to the grid. This is particularly noticeable in Table 4.1 where greater PV outputs in the Saskatoon, Swift Current, Estevan and Regina data locations result in a better LOEE than for the lower PV output obtained using the Uranium City data site. By utilizing the average annual output from 1 MW of PV generation, along with the size of the PV installation, it is possible to develop a practical formula.

The first step in the formula development process involved utilizing least squares analysis to assess the best representation of LOEE for both the Saskatoon and Uranium City locations, based solely on the size of the solar installation. The resulting formulae (Equations 5.1 and 5.2) are quadratic, due to the slight curve at low levels of installed PV. The equations for the Saskatoon and Uranium City sites are:

$$LOEE_{STOON} = C_{S1} - C_{S2}S + C_{S3}S^2 \tag{5.1}$$

$$LOEE_{UC} = C_{U1} - C_{U2}S - C_{U3}S^2 \tag{5.2}$$

where

S is the size of the solar installation, in MW

C_{S1} = 9.1599 MWh/yr

C_{S2} = 0.1894 MWh/MW·yr

C_{S3} = 0.0063 MWh/MW^2·yr

C_{U1} = 9.1065 MWh/yr

C_{U2} = 0.0634 MWh/MW·yr

C_{U3} = -0.0005 MWh/MW^2·yr.

The constants were determined using least squares analysis.

In order to develop a generalized formula, the constants in Equations 5.1 and 5.2 should reflect the annual energy output from a 1 MW PV installation in each location. As there are only two points to work with for each constant, a line was calculated to relate the second and third constants with the annual energy output. The first constant in the generalized formula was taken to be the average of C_{S1} and C_{U1}. The resulting formula is given by Equation 5.3:

$$LOEE = C_1 - (C_{2a}E - C_{2b})S + (C_{3a}E - C_{3b})S^2 \qquad (5.3)$$

where

E = annual PV array output from a 1 MW installation, in MWh

C_1 = 9.1332 MWh/yr

C_{2a} = 0.00115 1/MW·yr

C_{2b} = 0.4381 MWh/MW·yr

C_{3a} = 6.21 X 10^{-5} 1/ MW^2·yr

C_{3b} = 0.0275 MWh/MW^2·yr.

Figure 5.10 shows the results using Equation 5.3, as compared with the simulated values for both the Saskatoon and Uranium City sites. It should be noted that when the RBTS is modified by changing the load or generation models the formula is unable to adjust. In these situations, C_1 should be set equal to the LOEE of the system before PV is added, rather than using the set constant of 9.1332 MWh/yr. The complete formula development is given in Appendix D.

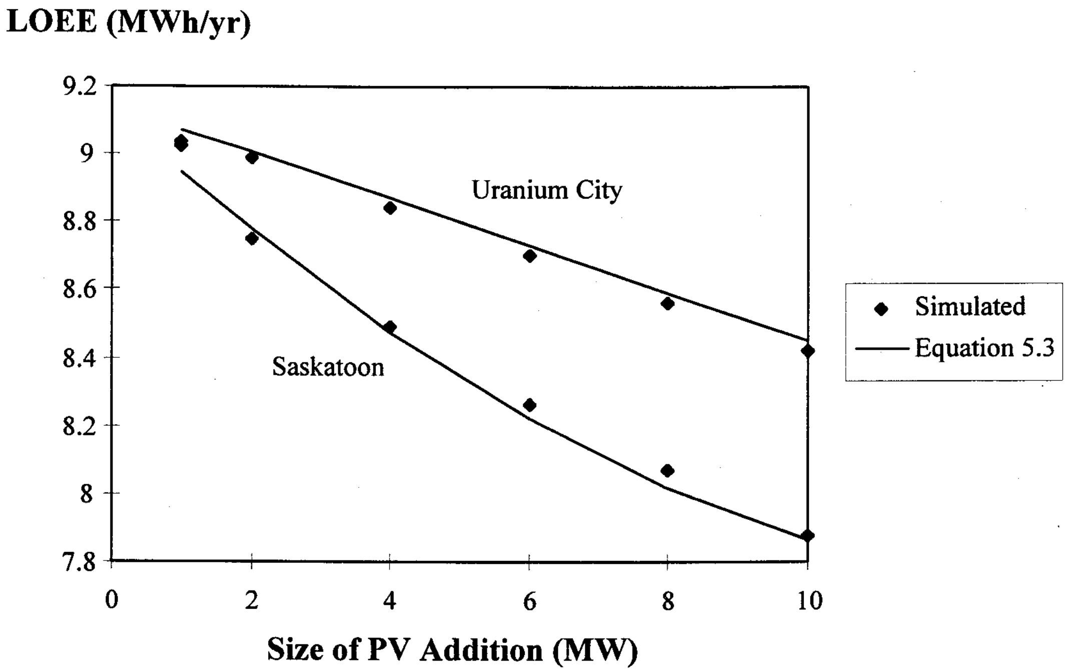

Figure 5.10 - Comparison of the Formula Output to the LOEE Values Simulated Through SGRASS

5.5.2 Formula Accuracy

Equation 5.3 can be used to determine the LOEE when PV arrays are added to the RBTS. Assessment of the accuracy of this formula can be done by comparing the simulated and calculated LOEE for the simulations that have already been examined in earlier sections of this chapter. A simple percentage error was calculated to determine how well the formula describes the simulation. The simulated values were used as the base value in calculating the error.

Table 5.2 details the accuracy of Equation 5.3 in determining the LOEE when PV generation is added to the RBTS. In addition to the five Saskatchewan solar data sites, two sites in the US were also analyzed to compare the formula to areas which have higher solar availability. As can be seen, the error between the simulated and calculated results is less than 3%, and less than 1% for all the Saskatchewan locations.

Table 5.2 - Formula Accuracy For PV Arrays Added to the Basic RBTS

Solar Data Location (in Sask. unless noted)	Size of PV Installation (MW)	Annual PV Energy for a 1 MW Array (MWh/yr)	Simulated LOEE (MWh/yr)	Calculated LOEE (MWh/yr)	Percent Error (%)
Estevan	1	540	9.014	8.954	0.67
Honolulu, USA	1	569	8.981	8.923	0.64
Phoenix, USA	1	782	8.966	8.690	3.08
Regina	1	547	9.008	8.947	0.69
Saskatoon	1	544	9.024	8.950	0.82
Swift Current	1	544	9.011	8.950	0.67
Uranium City	1	435	9.036	9.069	0.37
Saskatoon	2	544	8.747	8.779	0.36
Saskatoon	5	544	8.363	8.342	0.25
Saskatoon	10	544	7.875	7.866	0.11
Uranium City	2	435	8.987	9.004	0.19
Uranium City	5	435	8.775	8.803	0.32
Uranium City	10	435	8.423	8.448	0.29

As noted earlier, in situations where the RBTS is modified, the constant C_1 in Equation 5.3 should be set equal to the LOEE for the system before any PV is added. Using this modification, Equation 5.3 can be evaluated for the simulations that were conducted on load carrying capability and when PV was used to replace a base load generating unit. Table 5.3 shows the comparison when the conventional generation level is changed, as conducted for load carrying capability in Section 5.2. The variation between the simulated and calculated LOEE is less than 5% in all cases, with the greatest errors occurring when the reliability is low due to a high peak load.

When a generating unit is removed from the RBTS, as done in Section 5.4, the modified Equation 5.3 still provides a reasonable reliability estimate. Table 5.4 shows the difference between the simulated and calculated values. The greatest percent errors occur when the reliability is lowest, as was also noted in the load carrying capability study shown in Table 5.3. In addition, the calculated LOEE indices are always higher than the simulated LOEE indices, indicating that the formula gives slightly pessimistic results. Thus, the formula will indicate that the PV generation is less reliable than could actually be expected when PV is used to replace base load generation. Overall, the greatest difference between the simulated and calculated LOEE in Table 5.4 is under 8%, and in general, the errors seen in this case are higher than in previous cases.

Table 5.3 - Formula Accuracy for Saskatoon PV Array Data added to the RBTS with Changing Peak Load

Peak Load (MW)	Size of PV Installation (MW)	Simulated LOEE (MWh/yr)	Calculated LOEE (MWh/yr)	Percent Error (%)
175	1	3.281	3.305	0.74
175	2	3.260	3.135	3.84
180	1	5.394	5.452	1.08
180	2	5.355	5.281	1.37
190	1	14.17	13.96	1.44
190	2	14.06	13.79	1.88
195	1	21.50	22.41	4.26
195	2	21.32	22.24	4.34

Table 5.4 - Formula Accuracy for PV Arrays Added to the RBTS with a 5 MW Conventional Unit Removed

Location	Size of PV Installation (MW)	Annual PV Energy for a 1 MW Array (MWh/yr)	Simulated LOEE (MWh/yr)	Calculated LOEE (MWh/yr)	Percent Error (%)
Phoenix	5	782	13.30	13.34	0.34
Saskatoon	5	544	13.67	14.35	4.92
Saskatoon	10	544	13.35	13.87	3.87
Saskatoon	15	544	13.03	13.71	5.18
Uranium City	5	435	13.77	14.81	7.56
Uranium City	10	435	13.49	14.45	7.15
Uranium City	15	435	13.21	14.07	6.53

5.5.3 Formula Use

It should be noted that Equation 5.3 was developed specifically for small additions of PV generation to the RBTS. This is not a general formula, applicable to all power systems. Other systems should be simulated fully and an appropriate formula developed for each case.

6 CONCLUSIONS AND FUTURE WORK

Conclusions

The analysis on the RBTS described in this thesis shows that for small amounts of grid connected PV, (less than 0.5% of the total installed capacity of the generating system) there is very little difference in the impact on system reliability between the simulated Saskatchewan sites. This is due partially to the load following characteristics of PV power and partially due to the small amounts of intermittent generation used in the simulation. It is further evident that with larger solar energy installations, the sites with the best load following ability and the greatest amount of annual solar energy will contribute the most to improved reliability. Of the five Saskatchewan sites simulated, Regina was the best site to install PV arrays, followed closely by Swift Current, Estevan and Saskatoon. There was very little difference between the sites, except for Uranium City, which had considerably lower system reliability for the larger PV installations.

The determination of a capacity credit for PV energy when attached to a power system will enable a utility to consider PV generation as actual generating capacity rather than a load reduction technology. The actual capacity credit is highly variable, and depends on the reliability index used, the penetration level of PV into the grid, and the solar data location. In a system with high reliability, such as the original RBTS, PV arrays have a capacity credit ranging from 1:1 to 1:5 and lower. If however, the reliability of the entire system is much lower, as is the case when a 5 MW base load unit is removed from the RBTS, PV generation does not provide a good replacement.

When a PV array is called upon to replace base load capacity rather than provide supplementary energy, there is increased reliance on the PV generation. In such cases, the variable nature of the output from the PV array is unable to accommodate the increased demand. In addition, the studies described in this thesis assume that all the PV energy is located at a single site, which creates dependence in the PV output as cloud cover in the area will affect all the installed arrays. This would not be the case if the PV arrays were dispersed throughout the system.

Another measure of how well PV interacts with the conventional power grid is through the determination of load carrying capability. It was found that as more PV is added to the system in the same location, the incremental load carrying capability of each megawatt of installed PV decreases. With small amounts of PV additions (< 0.5%) the added PV provides very close to its rated capacity in load carrying capability. The addition of 1 MW of PV to the system provided 0.9 MW of increased load carrying capability, while 2 MW of PV provided only a 1.5 MW increase, based on LOLE, or 1.1 MW if the LOEE is used.

A formula was developed to calculate the loss of energy expectation when PV energy is added to the RBTS or to a modified RBTS, based on the studies conducted on capacity credit, load carrying capability and the replacement of base load generation. The formula is related to the size of the array installation, and the amount of energy that could be expected from a 1 MW solar array installed in that location over a one year period. The resulting formula is:

$$LOEE = C - (0.00115E - 0.4382)S + (0.0000621E - 0.027496)S^2$$

where C = 9.1332 MWh/yr when the basic RBTS is used and C is equal to the initial LOEE for the modified RBTS, E is the average annual energy from a 1 MW PV array in the same location, and S is the size of the installation. The formula was found to be accurate to within 8% for all the simulations described in this thesis. It is important to note that the formula was developed for the RBTS and is not applicable to other systems.

For large installations, PV does not have favourable reliability characteristics and it can be concluded that, due to its intermittent nature, PV generation is not suitable for serving base load requirements. Given that small injections of PV generally provide good reliability, locating PV within the distribution system to supply localized load should prove to be a more suitable application. In addition to the favourable reliability characteristics of smaller, more localized installations, the effects of isolated, unfavorable weather will have less impact on overall PV generation. Due to the strong load following characteristics of PV, distributed installations should also be able to effectively generate power to meet the peak loads in outlying regions.

Future Work

The work described in this thesis are some possible first steps in examining the reliability of grid connected photovoltaic energy. Future areas of study will become more complex, encompassing further reliability studies and should examine the issue of the role of PV in sustainability.

The determination of load carrying capability and capacity credit were conducted on a small test system known as the RBTS. Further studies should be done to determine if the levels simulated for the RBTS hold true for other test systems such as the IEEE Reliability Test System, or models of actual generating systems. In addition, the PV array data should be simulated for several locations at the same time in order to assess the effects of localized cloud cover.

One of the benefits of solar energy noted in the literature [2, 5, 35, 38, 44] is that it can reduce the strain on the transmission and distribution systems of a utility grid, particularly when the PV arrays are distributed throughout the system and placed in close proximity to the loads. Reliability analysis should therefore be conducted at HLII and HLIII in order to assess the overall utility benefit of PV generation.

In addition to the reliability of grid connected PV, the issue of sustainability should be examined. Human beings have, throughout history, impacted the earth's environment, as do all animals in one form or another. However, since the industrial revolution, human impact has resulted in damage to humans, and the other animals and plants which share this earth. The issue of sustainability is one of enabling humans to use the earth without causing extreme damage through pollution and altering the landscape. This issue is not addressed in this thesis, but is one in which

PV power generation may play a pivotal role. The global impact of PV generation, and all other renewable and alternative energies needs to be explored so that humans can begin to live a sustainable existence.

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APPENDIX A - PHOTOVOLTAIC PANEL CHARACTERISTICS

From the WATSUN Component Library:

Siemens M55 Monocrystalline Panel

Slope of the Array		60^{o}
Reference Array Operating Temperature		$25^{o}C$
Reference MPP Voltage		17.4 V
Reference MPP Current		3.05 A
Reference Open Circuit Voltage		21.7 V
Reference Short Circuit Current		3.4 A
Array Lead in Resistance		0.06 Ω
Array Wind Speed Correction Factor		1.0
Solar Cell Absorptance		0.90
Front Panel	Emissivity	0.95
	Transmittance (visible)	0.95
	Transmittance (infrared)	0.90
Back Panel	Emissivity	0.90

Incidence Angle Modifiers (vertical):

Angle (degrees)	Akt Value
0	1
30	1
45	0.97
60	0.877
90	0

APPENDIX B - INVERTER CHARACTERISTICS

From the WATSUN Component Library:

Pacific Inverter, PI-3000 Single Phase, 60 Hz, 240V, 3kW output

Nominal Input Power Rating ....3300 W

Half Hour Surge Input Power ....115% of Nominal

Maximum Input Power ....120% of Nominal

Inverter Cut-off Output Power ....3 W

Parasitic Standby Power Losses ....0 W

Maximum Power Point Tracking

Power Tracking Window	Minimum	42 V (dc)
	Maximum	53 V (dc)

DC Power Input (%)	Inverter Efficiency (%)
0	0
10	69
15	77
20	82
25	88
30	90
40	91
50	91
60	92
100	92

APPENDIX C - SOLAR SIMULATION YEARS

Chapter 3, Section 3.3.1 shows that only one year of solar data is required to obtain reasonable accuracy in the LOLE and LOEE values. The potential problem with this simplification, when larger amounts of solar energy are added to the RBTS, is that the effect of random variations in PV output from year to year are not accounted for. The Saskatoon data location was simulated for 1, 50 and 100 years of solar data, with 10 MW of solar energy added to the RBTS to establish the validity of utilizing a single year of solar data. The results are shown in Table C1.

Table C1 - The Effect of Varying the Number of Solar Simulation Years for a 10 MW Photovoltaic Array

Number of Simulation Years	LOLE (hrs/yr)	LOEE (MWh/yr)
1	0.813 $\sigma = 3.27$	7.87 $\sigma = 47.6$
50	0.813 $\sigma = 3.27$	7.86 $\sigma = 47.5$
100	0.813 $\sigma = 3.27$	7.86 $\sigma = 47.5$

Table C1 indicates that for the simulations completed in this thesis, the effect of the number of years of simulate solar data has very little impact on the results.

APPENDIX D - FORMULA DEVELOPMENT

D1 Least Squares Analysis for Equation 5.1

Table D1 - Values for Least Squares Analysis of Equation 5.1

X	X^2	X^3	X^4	X^5	X^6
544	295936	1.61E+08	8.76E+10	4.76E+13	2.59E+16
1088	1183744	1.29E+09	1.40E+12	1.52E+15	1.66E+18
2176	4734976	1.03E+10	2.24E+13	4.88E+16	1.06E+20
3264	10653696	3.48E+10	1.14E+14	3.70E+17	1.21E+21
4352	18939904	8.24E+10	3.59E+14	1.56E+18	6.79E+21
5440	29593600	1.61E+11	8.76E+14	4.76E+18	2.59E+22
16864	65401856	2.90E+11	1.37E+15	6.75E+18	3.40E+22

Y	Y^2	X Y	X^2 Y	X^3 Y	X^2 Y^2
9.02	81.4	4909	2.67E+06	1.45E+09	2.41E+07
8.75	76.5	9517	1.04E+07	1.13E+10	9.06E+07
8.49	72.1	18477	4.02E+07	8.75E+10	3.41E+08
8.27	68.3	26979	8.81E+07	2.87E+11	7.28E+08
8.07	65.1	35121	1.53E+08	6.65E+11	1.23E+09
7.87	62.0	42837	2.33E+08	1.27E+12	1.84E+09
50.47	425.5	137840	5.27E+08	2.32E+12	4.25E+09

Resulting Systems of Equations:

Linear:

6	b0	+	16864	b1	=	50.472
16864	b0	+	6.5E+07	b1	=	137840

b0 = 9.03982
b1 = -0.00022

Quadratic:

6	b0	+	16864	b1	+	7E+07	b2	=	50.4722
16864	b0	+	6.5E+07	b1	+	3E+11	b2	=	137840
7E+07	b0	+	2.9E+11	b1	+	1E+15	b2	=	5.3E+08

b0 = 9.15981
b1 = -0.00035
b2 = 2.1E-08

Third Order:

6	b0	+	16864	b1	+	7E+07	b2	+	2.9E+11	b3	=	50.472
16864	b0	+	6.5E+07	b1	+	3E+11	b2	+	1.4E+15	b3	=	137840
7E+07	b0	+	2.9E+11	b1	+	1E+15	b2	+	6.7E+18	b3	=	5E+08
3E+11	b0	+	1.4E+15	b1	+	7E+18	b2	+	3.4E+22	b3	=	2E+12

b0 = 9.27794
b1 = -0.00056
b2 = 1.1E-07
b3 = -9.4E-12

D2 Least Squares Analysis for Equation 5.2

Table D2 - Values for Least Squares Analysis of Equation 5.2

X	X^2	X^3	X^4	X^5	X^6
435	189051	8.22E+07	3.57E+10	1.55E+13	6.76E+15
870	756204	6.58E+08	5.72E+11	4.97E+14	4.32E+17
1739	3024817	5.26E+09	9.15E+12	1.59E+16	2.77E+19
2609	6805837	1.78E+10	4.63E+13	1.21E+17	3.15E+20
3478	12099267	4.21E+10	1.46E+14	5.09E+17	1.77E+21
4348	18905104	8.22E+10	3.57E+14	1.55E+18	6.76E+21
13479	41780280	1.48E+11	5.60E+14	2.20E+18	8.87E+21

Y	Y^2	X Y	X^2 Y	X^3 Y	X^2 Y^2
9.04	81.7	3929	1.71E+06	7.43E+08	1.54E+07
8.99	80.8	7815	6.80E+06	5.91E+09	6.11E+07
8.85	78.2	15384	2.68E+07	4.65E+10	2.37E+08
8.70	75.8	22709	5.92E+07	1.55E+11	5.16E+08
8.56	73.3	29788	1.04E+08	3.60E+11	8.87E+08
8.42	70.9	36622	1.59E+08	6.92E+11	1.34E+09
52.56	460.7	116246	3.57E+08	1.26E+12	3.06E+09

Resulting Systems of Equations:

Linear:

6	b0	+	13478.8	b1	=	52.559
13479	b0	+	4.2E+07	b1	=	116246

b0 = 9.11642
b1 = -0.00016

Quadratic:

6	b0	+	13478.8	b1	+	4E+07	b2	=	52.559
13479	b0	+	4.2E+07	b1	+	1E+11	b2	=	116246
4E+07	b0	+	1.5E+11	b1	+	6E+14	b2	=	3.6E+08

b0 = 9.10654
b1 = -0.00015
b2 = -2.7E-09

Third Order:

$$
\begin{aligned}
6\ b0 &+ 13478.8\ b1 + 4E{+}07\ b2 + 1.5E{+}11\ b3 = 52.559 \\
13479\ b0 &+ 4.2E{+}07\ b1 + 1E{+}11\ b2 + 5.6E{+}14\ b3 = 116246 \\
4E{+}07\ b0 &+ 1.5E{+}11\ b1 + 6E{+}14\ b2 + 2.2E{+}18\ b3 = 4E{+}08 \\
1E{+}11\ b0 &+ 5.6E{+}14\ b1 + 2E{+}18\ b2 + 8.9E{+}21\ b3 = 1E{+}12
\end{aligned}
$$

$$
\begin{aligned}
b0 &= 9.09114 \\
b1 &= -0.00011 \\
b2 &= -2E{-}08 \\
b3 &= 2.4E{-}12
\end{aligned}
$$