PROBABILISTIC APPROACH TO ASSESS THE PERFORMANCE OF INTEGRATED RENEWABLE ENERGY SYSTEMS USING MARKOV MODELS

By

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LIST OF ACRONYMS

GD	System in good state
BD	System in bad State
UP	IRES is up or operational
DN	IRES is down or inoperable
ISO	System is Isolated for repair
IRES	Integrated Renewable Energy System
BIO	Biogas Facility
WECS	Wind Electric Conversion System
PV	Photovoltaic System
ES	Electrical Energy Storage
HYDRO	Hydro Energy System
LWH	Low Water Head
HWH	High Water Head

NOMENCLATURE

PRIMARY MODEL

λ_{12} Failure rate from state-1, IRES (Operational) to state-2, BIO (Bad)

λ_{13} Failure rate from state-1, IRES (Operational) to state-3, WECS (Bad)

λ_{14} Failure rate from state-1, IRES (Operational) to State-4, PV (Bad)

λ_{15} Failure rate from state-1, IRES (Operational) to state-5, ES (Bad)

λ_{16} Failure rate from state-1, IRES (Operational) to state-6, HYDRO (Bad)

μ_{21} Repair rate from state-2, BIO (Bad) to state-1, IRES (Operational)

μ_{31} Repair rate from state-3, WECS (Bad) to state-1, IRES (Operational)

μ_{41} Repair rate from state-4, PV (Bad) to state-1, IRES (Operational)

μ_{51} Repair rate from state-5, ES (Bad) to state-1, IRES (Operational)

μ_{61} Repair rate from state-6, HYDRO (Bad) to state-1, IRES (Operational)

SECONDARY MODEL

λ_B Failure rate of BIO going bad when IRES is UP

λ_{IB} Failure rate of IRES going down (due to the failure of all other constituent energy resources) with BIO under isolation

μ_B Repair rate of putting BIO operational

μ_{IB} Repair rate of putting IRES back to operation with BIO under isolation

ω_B Isolation rate of BIO when IRES is UP

ω'_B Isolation rate of BIO when IRES is DOWN

λ_{CCB} Common cause failure for BIO going bad and IRES going down

λ_E Failure rate of ES going bad when IRES is UP

λ_{IE} Failure rate of IRES going down (due to the failure of all other constituent energy resources) with ES under isolation

μ_E Repair rate of putting ES operational

μ_{IE} Repair rate of putting IRES back to operation with ES under isolation

ω_E Isolation rate of ES when IRES is UP

ω'_E Isolation rate of ES when IRES is DOWN

λ_{CCE} Common cause failure for ES going bad and IRES going down

λ_{PV} Failure rate of PV system going bad (due to the presence of cloud cover) when IRES is UP

λ_{IPV} Failure rate of IRES going down (due to the failure of all other constituent energy resources) with PV under isolation

λ_{CLPV} Failure rate of PV system going bad in the presence of cloud cover

λ_{NCLPV} Failure rate of PV system going bad in the absence of cloud cover

ξ_{CLPV} Rate of PV system going back to operational state after cloud cover disappearance

μ_{PV} Repair rate of putting PV system operational

μ_{IPV} Repair rate of putting IRES back to operation with PV under isolation

ω'_{PV} Isolation rate of PV system when IRES is DOWN

ω_{CLPV} Isolation rate of PV system (bad) in the presence of cloud cover

ω_{NCLPV} Isolation rate of PV system (bad) in the absence of cloud cover

λ_{CCPV} Common cause failure for PV system going bad and IRES going down

λ_W Failure rate of WECS going bad (due to the absence of wind) when IRES is UP

λ_{IW} Failure rate of IRES going down (due to the failure of all other constituent energy resources) with WECS under isolation

λ_{WW} Failure rate of WECS going bad in the presence of wind

λ_{NWW} Failure rate of WECS going bad in the absence of wind

ξ_{NWW} Rate of WECS going back to operational state after wind occurrence

μ_W Repair rate of putting WECS operational

μ_{IW} Repair rate of putting IRES back to operation with WECS under isolation

ω'_W Isolation rate of WECS when IRES is DOWN

ω_{WW} Isolation rate of WECS (bad) in the presence of wind

ω_{NWW} Isolation rate of WECS (bad) in the absence of wind

λ_{CCW} Common cause failure for WECS going bad and IRES going Down

λ_H Failure rate of HYDRO going bad (due to LWH) when IRES is UP

λ_{IH} Failure rate of IRES going down (due to the failure of all other constituent energy resources) with HYDRO under isolation

λ_{LWH} Failure rate of HYDRO going bad due to LWH

λ_{HWH} Failure rate of HYDRO going bad even with HWH

ξ_{LWH} Rate of HYDRO going back to operational state due to the increase in water head

μ_H Repair rate of putting HYDRO operational

μ_{IH} Repair rate of putting IRES back to operation with HYDRO under isolation

ω'_H Isolation rate of HYDRO when IRES is DOWN

ω_{HWH} Isolation rate of HYDRO (bad) with HWH

ω_{LWH} Isolation rate of HYDRO (bad) with LWH

λ_{CCH} Common cause failure for HYDRO going bad and IRES going down

CHAPTER 1

INTRODUCTION

1.1 Background

"Energy is essential to our society to ensure our quality of life and to underpin all other elements of our economy"- Stanley Bull [1].

Recent developments in the industrial sectors of developing countries are forcing the issue of the global availability of conventional energy resources in the near future. Developing countries have very little conventional fossil fuel and other resources of their own to meet the energy demand and it becomes mandatory for them to import this energy at the expense of their meager foreign exchange reserves [4].

Awareness of the environmental impacts of conventional energy production, greenhouse gas emissions, natural habitat disturbances, global warming, etc have paved the way for increased interest in the field of renewable energy. Renewable energy technologies are fast becoming a judicious alternative to fossil fuel and other conventional energy resources utilization in meeting global energy demands.

The energy derived from different renewable resources such as insolation (incident solar radiation) or sunlight, wind, water and biomass have a variety of applications and each one is suited to satisfy a specific energy need(s). For example, these resources can be used to produce electricity for a home, heat for cooking and fuels for transportation. These resources are spread throughout the world fairly evenly and they offer better long-range benefits as compared to conventional (non-renewable) energy sources. They generate little or no waste and most of them are pollution-free. The main drawback of these energy sources is that their abundance is tempered by their diluteness, intermittent and stochastic nature [5].

An integrated approach was proposed by Ramakumar, et. Al., in 1981 for collectively harnessing the variety of renewable resources available. This approach proposes to integrate the benefits of utilizing different renewable resources at the users' end. In a way, it is mainly aimed at catering to the needs of rural people in remote areas of developing countries in an economical way [5].

Due to the intermittent nature of the available renewable resources, it becomes very necessary to model and assess the performance of the system and its components in order to effectively operate it. This thesis approaches the issue using Markov models.

1.2 Role of Renewable Energy in Rural Development

Rural areas contribute to a third of the world's population of six (plus) billion people in 2004. These areas are without electricity as they are considered uneconomic and infeasible to supply power from national grids. They also do not have access to commercial energy resources such as coal, oil, and natural gas. However, renewable energy technologies have made significant progress and they have, in the long-run, have excellent potential proven to be a viable means of supplying energy to remote rural rural areas and contribute to their development.

The role of renewable energy to develop and electrify remote rural areas has been discussed for more than four decades in national and international conventions. Although various attempts were made to materialize this idea, there has only been a snail-like growth in this area. Due to the intermittent nature of renewable energy resources, developing countries are not making effective pursuits to satisfy their energy needs in rural areas.

The availability of energy in remote parts of developing countries is extremely decisive for improving productivity, creating workplaces and upgrading living conditions. Undoubtedly, the long term sustainable option to satisfy these energy needs will be to utilize the locally available renewable resources thereby averting global economic and environmental impacts [9]. The initial higher investments in such technologies are justifiable as even small amounts of this energy can be of considerable benefit in the rural areas [8].

Although utilization of renewable energy resources will prove vital for the development of rural areas, the "ideal marriage" between rural electrification and renewables has not yet been formalized due to various reasons. Inadequate understanding of rural needs is attributed as one of the reasons for the failure of renewable energy in rural areas. The farmers and villagers expect services and not products. The gap between the expectation of villagers and fulfillment of their needs will be bridged only by integrated use of different renewable resources in an appropriate manner.

Off-grid rural electrification necessitates a combination of two or more technologies such as PV- solar thermal, PV-wind, wind-biomass, PV-wind-biomass and micro hydro-wind coupled with sufficient energy storage capability to ensure a continuity of supply of electricity. An example of such integration is a village power system (hybrid) in Mexico that utilizes a combination of PV, Wind power and diesel to generate electricity with batteries for storage for continuous supply. PV arrays power the daytime of Xcalak village, while stronger winds at night is used after sunset. If the area becomes windless and cloudy for quite a few days, the backup power is supplied by the diesel generators.

The system, when went online, powered around "80 homes, four restaurants and a 20-room hotel" [10]. While the national and local government funded the acquisition of hybrid systems, the villagers paid for the maintenance and operation of the system. The increased generating capacity and load were accommodated by the local utility by upgrading the wiring throughout the village.

1.3 Objective of the Study

The basic objective of this study is to develop simple models for different renewable energy technologies and combine them to study the performance of an Integrated Renewable Energy System (IRES). It will be accomplished through the development of simple (binary) Markov model for different renewable energy technologies that can be used in performance and reliability assessment. The overall model will thus be simple enough to work with.

Another important objective of this study is to stress the need for meteorological data in the area of reliability studies. The models, when applied to real world scenarios will prove extremely beneficial in assessing the technical and economic performance of renewable energy systems.

Other objectives include the delineation of major areas where more research is needed with respect to distributed generation and alternative energy systems. Further studies could involve reliability models not only based on Markov models, but also other models such as fault trees, reliability block diagrams, etc.

This study is a part of a larger study within the Oklahoma State University – Engineering Energy laboratory and the PSO/Albrecht Naeter Professorship in the School of Electrical and Computer Engineering.

1.4 Organization of the Thesis

This section is intended to provide the reader, a glimpse of the various topics covered in different chapters.

Chapter 2 Literature Survey introduces the reader to the energy requirements in rural areas followed by the available renewable energy resources and technologies. The concepts behind reliability quantifiers and assessment are introduced in the latter part of this chapter.

Chapter 3 Integrated Renewable Energy Systems (IRES) starts by emphasizing the need for the integration of various renewable resources available in rural areas followed by proper resource-need matching and the design of such a system. This is followed by the description and operation of one such system. The need for performance assessment is discussed in the latter paragraphs.

Chapter 4 Assessment of the performance of IRES using Markov models presents the models used in this thesis. Hierarchical Markov modeling technique in which states are established based on primary failures, secondary failures, etc. is employed.

The approach used in this thesis actually contemplates the use of four forms of renewable resources/technologies namely Biogas (BIO), Photovoltaic (PV), Wind Electric Conversion Systems (WECS) and Hydro Energy source (HYDRO).

Markov models are developed for each of these sources considering the IRES to be a fully redundant system (initially). A fully redundant system is similar to a parallel system that goes "down" only when all its constituent systems go inoperable. In other words, redundant systems are designed to support operation in a derated mode. As storage is extremely important due to intermittent nature of the sources, a fifth model based on energy storage is also discussed.

The concluding part of the chapter proposes the methods used for combining all these models and their use in performance assessment.

Chapter 5 Discussion of Results provides the reader with the results based on a binary model to describe the behavior of all the major components constituting the IRES.

Chapter 6 Summary and Concluding Remarks summarizes this work, develops some concluding remarks and outlines scope for future studies.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

About two Billion people living in remote rural areas of developing countries in Sub-Saharan Africa, South Asia, etc. have no access to electricity and the available commercial energy supplies are not sufficient to satisfy their basic energy requirements. These areas depend almost entirely on local sources of solar energy such as insolation, firewood and other forms of biomass for their day-to-day energy needs. Lack of suitable resources and the increasing difficulties involved in their collection are leading to poverty, hardships and even starvation. Moreover, absence of basic energy resources and the associated job depletion contribute to an increase in the migration tide towards urban areas. Availability and accessibility to energy sources are extremely important and contribute to the economic and social development of rural areas of developing countries [16].

Sustainability of energy supply and utilization in rural areas can be achieved only by a conscious development of renewable energy technologies, conservation of depletable resources, decentralization of rural energy development, management of local resources by rural community, etc [16].

The energy requirements in rural areas are classified into basic needs and extended needs. Some of the basic needs are lighting, cooking, health & sanitation, water, communications, cold storage, agriculture etc. Extended needs include transportation and small-scale industries.

2.2 Renewable Energy Resources and Technologies

This section discusses different renewable energy resources and technologies with an emphasis on renewable energy diffusion in rural areas. There are a variety of technologies available to tap the locally available resources with less environmental impacts. Most of the renewable energy comes either directly or indirectly from the Sun. A brief overview of different manifestations of Sun's energy and its utilization will be discussed in the following paragraphs.

2.2.1 Bio energy

Biomass is the generalized term used to refer to all organic matter on earth produced by photosynthesis, humans and animals. The sun serves as the primary source for all these resources with the biomass acting as a chemical energy store. Recently, more advanced technologies have sprung up for extracting this energy and processing into useable forms of power or heat. It may be regarded as the only form of energy, usefully exploited by humans, that is still the main source of more than half of the world's population for their domestic energy needs [17].

Biomass resources are renewable as they originate from organic matter. They also produce carbon dioxide when burned, a major greenhouse gas like fossil fuels do. But the net greenhouse gas emission is zero as long as the trees and grasses are replenished. Thus utilization of bioenergy is environmentally benign as compared to fossil fuels.

The sources of biomass can be herbaceous crops, woody crops, agricultural crops, aquatic crops, agricultural crop residues, forestry residues, municipal waste, animal wastes, human waste, landfill gas, etc.

Future energy scenarios predict extensive use of woody biomass in terms of magnitude. Between 1997 and 2020, the use of Combustible Renewables and Waste (CRW including fuel wood, charcoal, crop residues and animal wastes) is projected to increase in almost every region of the world. This has led to increased global awareness of the alarming rate of deforestation and depletion of the resource base for firewood. In developing countries (DC), efforts are being made to make efficient use of available biomass resources. Use of biogas stoves is encouraged in the rural areas of many DC's such as India, China, Brazil, etc. in an effort to achieve better efficiency as compared to conventional direct combustion (of biomass) practices. Biogas can be produced by anaerobic digestion of animal wastes and crop residues.

Technological advances in the field of biomass around the world have led to the development of many biogas digesters, landfill biogas and its use to generate electricity, biomass gasification, production of biofuels (an alternative fuel for diesel generators), direct efficient biomass combustion and others. Researchers in this field forecast a significant improvement in the techniques employed for generating electricity, heat and fuels from biomass. In the future, bioenergy will be produced more efficiently and at lesser costs.

2.2.2 Solar (energy) Radiation

The incident solar radiation on the surface of the earth (insolation) is one of the major sources of energy in rural areas of developing countries. It is estimated that global energy needs can be satisfied by the utilization of even a small fraction of this insolation.

It is estimated that even with a low conversion efficiency of 4%, insolation on 1% of the per capita land area in India is sufficient to satisfy all the energy needs [6]. But this is limited by its dilute nature and the high cost involved in conversion to usable form.

Direct conversion of sun's energy to electricity is carried out by Photovoltaic (PV) systems. These technologies are extremely reliable, renewable and environmentally safe for supplying power that is vital to millions of households and communities in the developing world [17]. PV modules can light individual homes and can also be linked to run communication equipment in schools, and operate large-scale water pumps in remote areas. For remote rural areas, where access to basic energy services is limited, PV can cost-effectively help in providing much-needed services.

PV helps in the conservation of local resources and it is sure to become a major factor in the global energy supply in the near future [17]. These systems are especially suited to developing nations for individual and small community applications. They are modular, require very little maintenance, and can be easily transported, installed and conveniently expanded.

In developing countries, PV finds a variety of applications in community lighting, household appliances, refrigeration, battery charging, water pumping, etc. They can be operated in the stand-alone mode (off-grid) or may be connected to the grid.

2.2.3 Wind energy

Wind energy is a manifestation of solar energy and is the result of moving air due to uneven heating of the earth's surface. Energy in moving air (wind) can be easily converted to electrical or mechanical energy based on the needs. Wind electric conversion is considered to be the most cost-effective and fastest growing generation

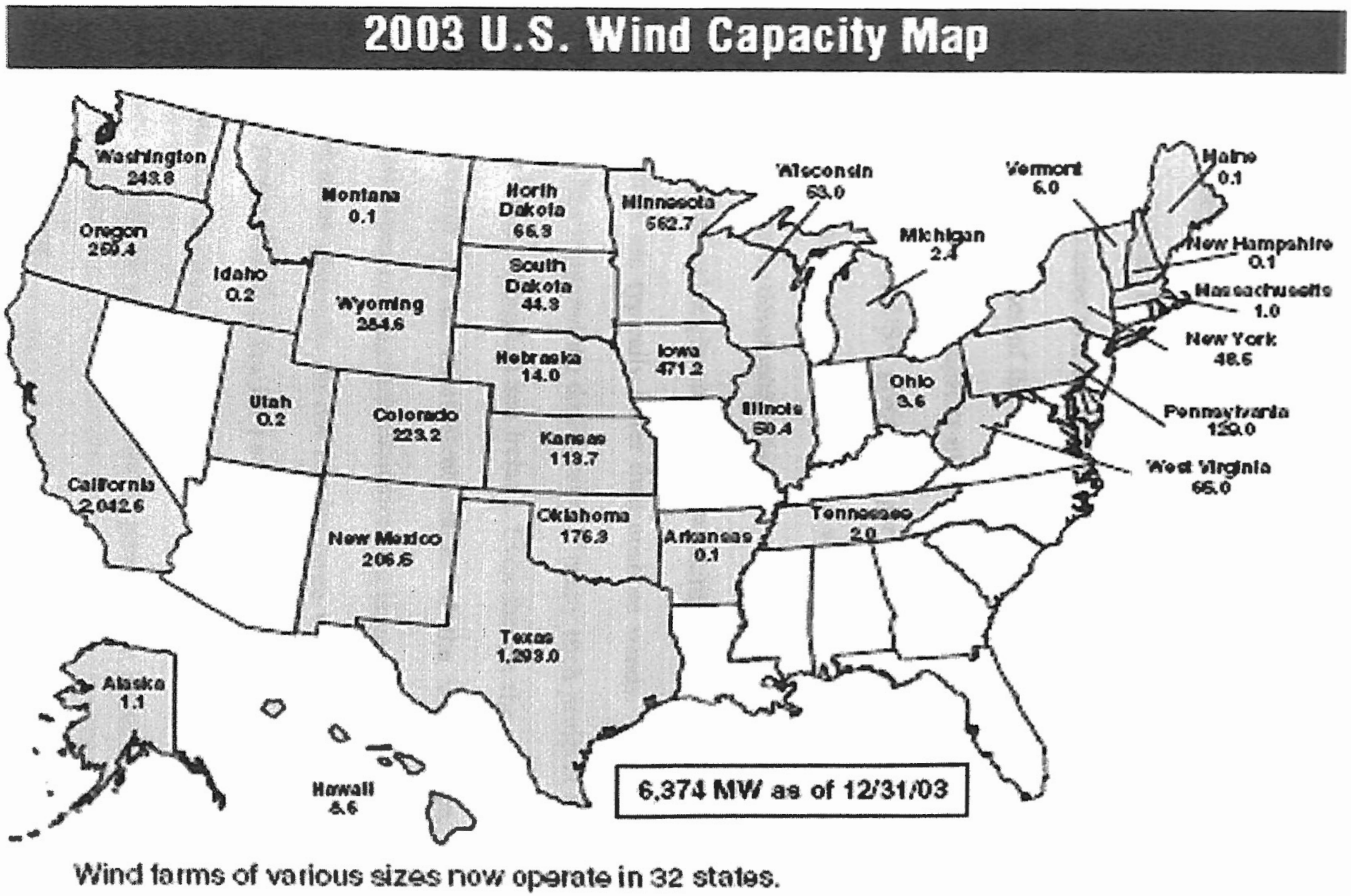

Figure.1. US Wind Capacity Map for the year 2003

technology with an average global growth rate of 35 % per year and a growth rate of more than 30% in the US in the year 2003 [21]. This is mainly attributed to the high quality output at a comparatively low cost coupled with the environmentally safe nature of this energy source. This has further led to the development of many wind projects around the world to cater to a wide range of applications. By the year 2003, more than 3 million homes in 32 states of the USA have been powered by wind turbines of various sizes with a total generating capacity of 6374 MW [21]. This phenomenon is illustrated in the wind power map of USA given in Figure 1 [21]. Global annual energy production from wind turbines is constantly increasing with more wind projects being deployed in developed as well as in developing countries.

Researchers and engineers are now working on developing offshore wind energy as offshore winds are typically faster than onshore winds. The high energy content of offshore wind has triggered the deployment of many such projects in Denmark, Sweden, Germany, the United Kingdom and Ireland. Even though the output of a wind turbine is entirely dependent on the intermittent nature of the wind input, advancements in forecasting can overcome this basic limitation to a large extent [17].

Rural areas generally do not require large wind turbines producing substantial amounts of power. Small (a few kW) units are appropriate due to their flexibility to work off-grid and their ability to satisfy a variety of rural energy applications. These windmills can be used to generate and store electricity, pump water, grind cereals, etc.

2.2.4 Hydro energy

Hydro energy is also a manifestation of solar energy. Energy that is harnessed from flowing water to satisfy electrical and mechanical loads is generally referred to as

Hydro energy. Hydro resources are abundant throughout the world except in parts of Africa and the Middle East. They are sparsely exploited due to lack of capital investments in developing countries. The amount of energy generated will be extremely high in many parts of the developing world if suitable infrastructure is available for harnessing and transporting this energy.

Moving water can be used to produce energy in a variety of ways. The most common way, "run-of-the-river" systems, are used for micro hydro systems which are used for small scale hydro projects in remote areas as they do not require large reservoirs [17]. A portion of the water from the river is diverted to a pipeline, channel or a penstock (pressurized pipeline) at the other end of which is a waterwheel or a turbine. This motion can be used to pump water or even power a generator or an alternator to generate electricity [17].

Hydro power can be classified based on the size namely Large (greater than 100 MW to feed a large electric grid), Medium (15-100 MW typically feeding a grid), Small (1-15 MW), Mini (between 100 KW and 1 MW typically used as stand-alone systems occasionally fed to a grid) and Micro-Hydro (from a few hundred watts to 100 KW typically used in small rural communities in remote areas that are off-grid). The last two categories are the most popular in rural areas of developing countries [17].

2.2.5 Energy storage

The intermittent and dilute nature of renewable resources necessitates the need for a proper energy storage and re-conversion system. Secondary batteries are the most widely accepted means of storage used globally. The options available are Lead-Acid and Nickel-Cadmium. Lead-acid batteries are probably the cheapest and easiest form of storage and are used for most lighting applications in remote areas. If a suitable terrain is available, pumped hydro is the most cost effective means of energy storage.

Extensive research in energy storage has paved the way for the development of new forms of energy storage such as flywheels, hydrogen, compressed air energy storage, super-capacitors, etc.

2.3 Reliability Quantifiers

"Reliability is the probability of a device (or system) performing its purpose adequately for the period of time intended under the operating conditions specified" [24]

Reliability is considered to be an inherent characteristic of a system or a product. Assessment of reliability is extremely useful in a design process. Thus it becomes mandatory for any company or organization to make reliability evaluation and feedback as an important part of the design process. In recent years, the qualitative process of assessing performance is slowly replaced by quantitative analyses due to the availability of statistical data and techniques. These evaluation techniques, in addition to providing a group of performance indices, also predict the expected failure rate of a system, its causes, consequences, etc [24].

Models to assess reliability are often based on carefully collected failure data. Based on these, future predictions are made in terms of probabilities. Primary advantages of this process are [24]:

- Useful comparison of alternative system designs, reinforcements and expansion plans
- Prediction of the expected behavior of the system
- Adequate performance assessment of systems that are stochastic in nature

Reliability is a term closely associated with probability because "probability theory" is one tool available to an engineer to utilize his/her knowledge of the system for the prediction of its likely behavior in the future. Typically, the engineer would be able to predict the following indices based on his knowledge of its past performance:

- *Expected number of failures that might occur in a time period*
- *Average time between failures*
- *Average down time of a system or a device*
- *Expected loss in revenue due to failure*
- *Expected loss of output due to failure*

These indices can be calculated by appropriate application of reliability and probability theories [24].

Assessment of reliability involves the use of certain quantifiers depending on the system under study. These quantifiers are discussed next.

Generation

Loss Of Load Probability (LOLP)

It is defined as the probability or risk that the load exceeds the available generation capacity for a certain mix of generation and load. The basic calculation involves the comparison of total generation against the annual peak load [18].

Loss Of Load Expectancy (LOLE)

It is simply the amount of load that is lost (not supplied) due to a lack of generation, calculated over short time intervals. The LOLE can be calculated from daily peak loads or hourly peak loads over a year [18].

Transmission

Expected Load Loss (ELL)

The load that is expected to be lost due to lack of transmission capacity is ELL. It is generally expressed in MW [18].

Distribution

System Average Interruption Frequency Index (SAIFI)

It is the average interruption frequency per customer. It is the ratio of the total number of customer interruptions to total number of customers [18].

System Average Interruption Duration Index (SAIDI)

It is the average duration of interruption for a customer. It is calculated as the ratio of the total customer interruption duration to the total number of customers [18].

Average Service Availability Index (ASAI)

It is the average time the system is available for service. It is calculated as the ratio of availability (for a customer) to the hours of demand [18].

Average Energy Not Supplied (AENS) Index

It is the average amount of energy not supplied to the customer [18].

For the sake of brevity, only terms like availability and unavailability will be used in this thesis. Availability is the probability that the load will be supplied at the arbitrary chosen time. This is close to the LOLP. Unavailability is one minus availability.

2.4 Reliability Assessment

Reliability assessment of engineering systems is not unique as a "single all-purpose" reliability model does not exist. It depends on the assumptions and problems associated with a particular system [24]. The fundamental advantage of reliability analysis is the need for a complete understanding of the engineering implications of the system. A valid reliability model can be derived and an appropriate evaluation technique can be chosen only after a thorough knowledge of the system.

Reliability models generally support the design of a system and are usually applied to set/interpret system requirements, predict reliability of different configurations, identify weak points in the system and encourage cost-effective tradeoffs. Two types of reliability evaluation techniques are possible. They are analytical and simulation. Analytical techniques typically represent the system by means of mathematical models and assess the performance of this model through numerical solutions whereas simulation techniques evaluate the reliability indices by means of simulation of the actual process and behavior of the system. Some of the many reliability models available are [20]:

Parts Count Models

These models are typically used to estimate the reliability of non-redundant components or systems. The fundamental assumption with this type of model is that a single failure will cause the system to fail. The parts count model can also be used in a redundant system for failure estimation of individual components [20].

Combinatorial models

These models are applied to simple systems with perfect spare components. It includes reliability block diagrams, fault trees, success trees, etc. These models suffer from limitations as they cannot model repairable components/systems.

Reliability block diagrams are very easy to use in the process of system reliability evaluation. It is one of the oldest and most commonly used reliability models.

Fault Trees are basically used in the safety analysis of a system. It shows combinations of component failures that might result in a system failure, when compared to the reliability block diagram which is dependent on successes.

Network models are typically applied in the area of communication networks consisting of many individual links. The individual communication links are assumed to be either operational or failed.

Markov Models

Markov models consider different system states with possible transitions between them. They overcome the basic disadvantage of the reliability block diagram approach of not including repairs. The fundamental assumption for a Markov model is that the system is memory-less i.e. the state transitions are based mainly on the present state and not on the past. These models generally employ state transition diagrams, which is a pictorial representation of system states, transition between states and transition rates. Because of its simplicity and applicability, Markov models have found widespread applications not only in reliability assessment but also in other fields.

CHAPTER 3

INTEGRATED RENEWABLE ENERGY SYSTEMS –IRES

3.1 Introduction

An Integrated Renewable Energy System (IRES) utilizes two or more renewable energy resources, conversion technologies, and end-use technologies to supply a variety of energy and other needs in remote areas [3]. These systems are typically operated in the stand-alone mode and could more than 2 million remote villages around the world with no grid connection [2, 3]. The available renewable energy in a particular area can be utilized to satisfy the energy and other needs in different ways. For example, heat from solar energy can be used to satisfy the drying and water heating requirements, wind energy could be utilized to pump water using wind-driven water pumps, available biomass resource can be converted to biogas and used for cooking purposes, and so on. The resources can also be utilized to satisfy certain needs such as cold storage, lighting, communication and some industrial loads.

3.2 Need for an IRES

Locally available renewable energy resources such as solar radiation and wind are adequate to supply the energy needs of remote rural areas. Unfortunately, the diluteness and intermittency of these resources pose serious concerns for their utilization [5]. The difficulties also arise due to the low efficiency of some of the energy conversion devices.

Several measures have been suggested to overcome these difficulties by employing energy storage and re-conversion facilities or by utilizing the strength of one resource to overcome the weakness of the other [3, 13]. For instance, average insolation is high during summer when the average wind speed is low. On the contrary, the average wind speed is high during winter when the insolation is low. This point to the need for the integration of different resources for reducing the variations in the overall output, thereby minimizing the amount of storage needed.

The principal goal in designing an IRES is to energize the rural areas with suitable forms of energy necessary to satisfy the different energy and other requirements and also provide a base for storage and utilization of energy for agricultural and industrial developments in future. In remote areas, integration of different renewable energy source is vital, where there may be an abundance of some resources and dearth of some others.

Employment of such integrated systems helps in improving the quality of life in remote rural areas by energizing them in a cost-effective way. Deployment of IRES will lead to a subsequent growth in job opportunities in developed as well as developing countries. Also, utilization of renewable resources is "environmentally benign" and even small quantities of energy will prove to be beneficial in remote areas which are not connected to the grid [13].

3.3 Design of IRES

Design of IRES involves finding the ratings of the different energy conversion and energy storage devices that are necessary to supply all the energy and other needs. As the IRES has multiple inputs and outputs, both of which has temporal variations, the site-specific, stochastic nature of wind and insolation and the predictable biomass, hydro, etc.

should all be taken into account appropriately [3,5,13].

The first and foremost goal of the design procedure is to find the sizes and ratings of the various energy conversion and storage devices that are essential to provide energy to different loads in remote rural areas. In addition, energy supplies must be provided at minimal cost and pre-designated reliability levels. As the initial capital investment for IRES is large and different resource inputs are mostly free, care should be taken to design a system that is cost-effective and efficient [3]. Also, the need for transportation, reconversion and transmission of energy should be minimized.

Design of IRES is highly influenced by the intermittent and location-dependent renewable resources such as solar radiation and wind. Biomass and water flow have seasonal variations that are typically predictable. Based on the locale, the loads may or may not be predictable. These factors necessitate the design of IRES with educated and balanced compromises [13, 14]. Figure.2 shows one of the many possible IRES designs possible for harnessing the locally available renewable resources.

Since the ultimate goal of IRES is integration of benefits at the user's end, designers are faced with the fundamental problem of matching the highly stochastic resources with the need based on energy and power requirements in rural areas. Suitability of IRES to satisfy needs is highly country and site-specific and it also depends on many socio-economic and technical factors. Thus the design procedure should include the basic step of identification of goals and definitions of some optimal conditions [13].

IRES design process can either be deterministic or probabilistic [19]. The process may include the following elements:

1 Resource matching and allocation based on the nature of needs

2 Stochastic nature of renewable resources and load demand

3 Choice of proper energy storage devices that will minimize performance index such as loss of load probability and determination of ratings for the energy conversion and storage devices

3.4 IRES Description & Operation

To utilize the locally available renewable resources, two basic approaches had been proposed [11, 12]. The first approach employs conversion of all forms of energy into one form, typically electrical, to supply all the needs of end-users. Such *Hybrid Systems* have been installed and operated in many developing countries. This approach is generally inefficient and expensive enough to hamper the economy of developing countries. The second approach which involves careful resource-need matching and conversion of the energy sources into more than one form in an appropriate manner is referred to as the *Integrated System.* This type of system, though economical, may not satisfy all the needs adequately. IRES makes a balanced mix of both of these approaches such that it is cost-effective and efficient.

An Integrated Renewable Energy System (IRES) may consist of water turbines, solar thermal collectors, wind electric conversion systems, photovoltaic arrays, anaerobic digesters, biogas driven engine-generator sets and energy storage/reconversion systems in one or more possible combinations to satisfy different energy and other needs [3]. This approach is highly likely to lead to an "economically viable option" for satisfying the energy and other needs of remote villages in developing countries [1]. It is mainly based on matching the needs and the resources a-priori to maximize end-use efficiency and minimize cost. These systems can also be operated in conjunction with conventional

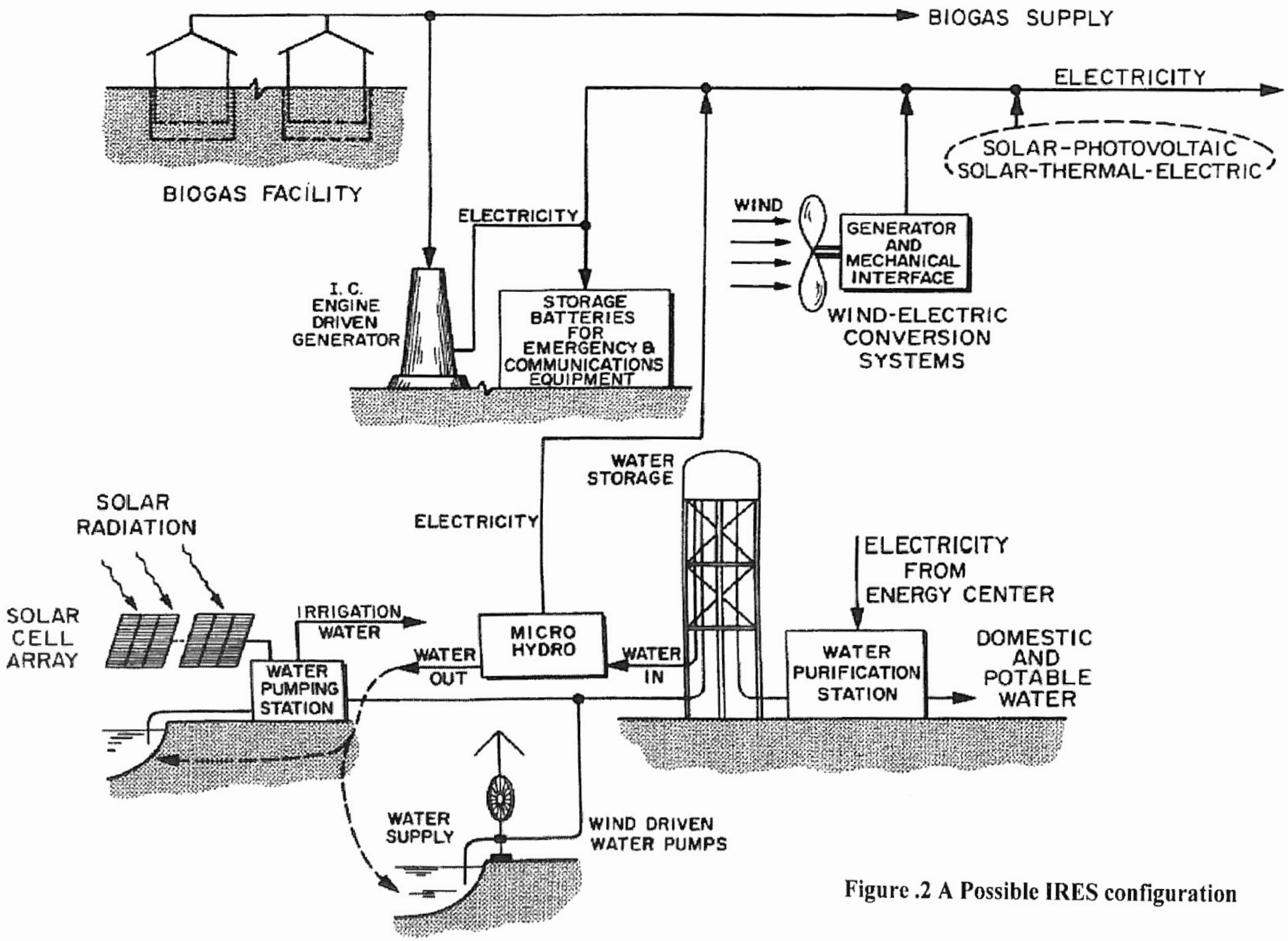

Figure .2 A Possible IRES configuration

energy systems and electric grid (if available) based on the needs and circumstances [4].

In remote areas of developing countries, there may be abundance of some resources coupled with the absence of some others. In these areas, renewable energy systems can carve a niche provided there is sufficient data on these renewable resources. The designer/engineer may often have to rely highly on qualitative information provided by the local populace such as highly sunny, windy, prevalent clouds, etc. Relevant parameters needed to characterize and model insolation, prevalence of cloud cover, wind, etc. can be found only by using proper instrumentation. However, educated and experienced guesses are necessary for system design. The IRES design procedure involves a knowledge base that can handle all the resources in the presence of proper (or assumed) information [2].

Energy needs in rural areas of developing countries are very difficult to estimate. They can be facilitated by detailed discussions with the village community and after a thorough analysis of the prevalent energy resources and life patterns in that area. Introduction of IRES in remote areas will certainly alter the energy consumption patterns and the best estimates of the altered patterns are the ones that serve as guides to design, implement and operate such systems.

3.5 Need for Performance Assessment

Improvement in the standard of living of people living in very remote areas can be achieved only by judicious production and utilization of available renewable resources. Even though the flow of renewable energy to earth is about three orders of magnitude higher than the global energy demand, it is highly difficult to harness these sources into usable forms of energy [15]. Although growth rates of wind energy and to some extent photovoltaic are quite high (about 30% annually for wind), their contribution to the global energy mix is still meager (less than 2%) [15].

The need for performance assessment arises from the fact that improvement can be systematically made only when the designer is aware of the strengths and weaknesses of the system. Because of the huge initial investments needed and the uncertainty involved in the availabilities of the resources, appropriate models and analyses are necessary to assess the performance and indicate targets for improvement. The goal of this study is to propose Markov models and their simplified versions as a first step in this process.

CHAPTER 4

ASSESSMENT OF THE PERFORMANCE OF IRES USING MARKOV MODELS

4.1 Introduction

In this chapter, a probabilistic approach for assessing the performance of IRES is presented. Markov models are used to perform this task of performance assessment considering the IRES to be memory-less i.e. future states of a system are independent of the past except the immediately preceding one. The Markovian approach is explained first followed by the hierarchical markov model comprising of primary and secondary models.

4.2 Markovian Approach

Markovian approach is extremely useful for modeling IRES because of its non-hereditary nature. In other words, the future is independent of the past, and depends only on the present state and the associated rates of departure. This property has been used to model IRES in terms of primary and secondary models. Anderson and Agarwal [22] proposed this type of approach, which has been applied to model IRES in this work.

4.3 Assumptions

The assumptions used to develop a hierarchical Markov model for IRES are:

1. Failure, repair and isolation rates are constant
2. Repair of a system restores it to as good as new
3. Common cause failures can occur
4. The probability of more than one change occurring simultaneously within a subsystem (except for common cause failures) is neglected as small
5. All failures are mutually independent
6. IRES is down only when all the constituent components are totally inoperable
7. PV system is virtually of no use in the presence of dense cloud cover, even though the system as such is good
8. WECS is virtually of no use in the absence of wind, even though the system as such is good
9. HYDRO is virtually of no use during low water head conditions, even though the system as such is good
10. The isolation of individual components within a system under repair are neglected
11. A system is in a failure state when the need is not satisfied or when there is no effective output

4.4 Hierarchical Markov Modeling Technique

4.4.1 Primary Model

The primary model of IRES is given in Figure. 3. It mainly consists of IRES being in UP or operational state with the constituent energy systems going bad or inoperable in different states. The constituent energy systems are Biogas facility (BIO), Electrical energy Storage (ES), Photovoltaic system (PV), Wind Electric Conversion System

(WECS) and Hydro Energy System (HYDRO). State-1 corresponds to IRES with all the constituent energy systems in operational state. State-2 indicates BIO failing to satisfy the need with all the other energy systems being in operational state. State-3 represents ES going bad (failing to satisfy the need) with all the other energy systems in good condition. State-4 represents PV going bad with all the other constituent energy systems in operational state. State-5 represents WECS going bad with all the other systems operational. State-6 represents HYDRO going inoperable with the other systems being functional.

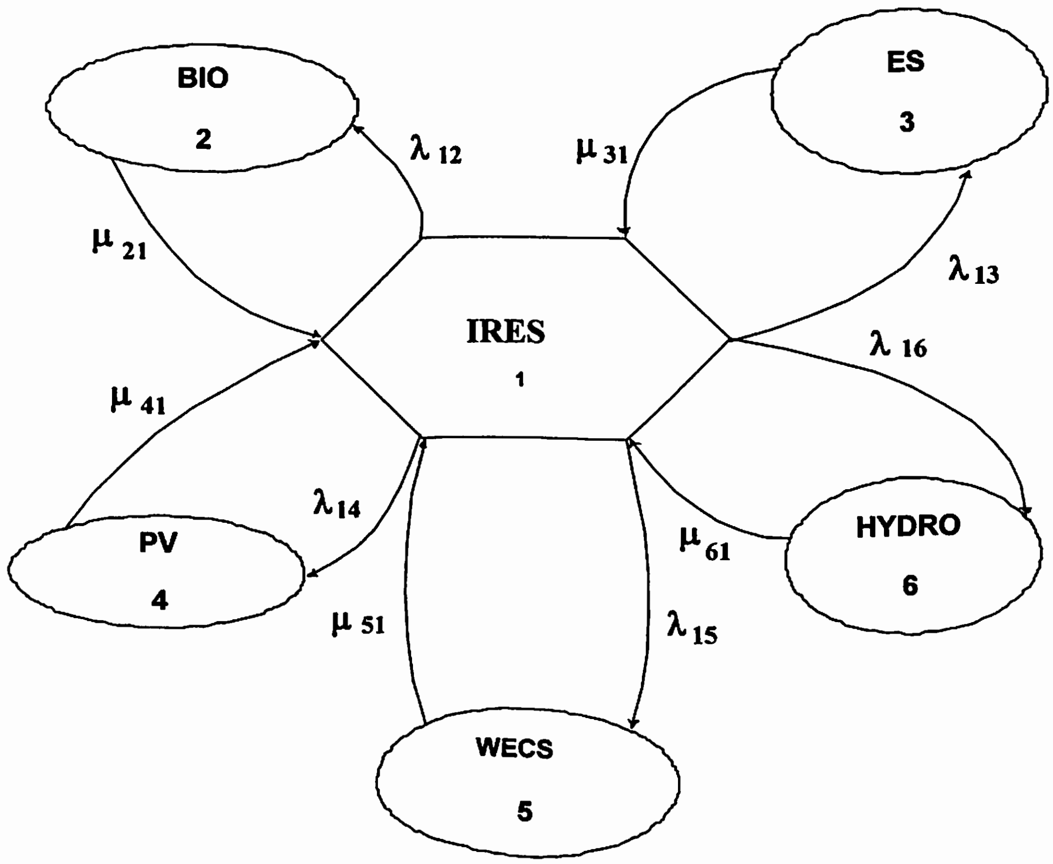

Figure.3 Primary Model for IRES

4.4.2 Secondary Models

In secondary models, failure of each energy system is studied individually and performance measures are obtained for each energy system separately

A. BIO MODEL

Referring to Figure.4, state B2 represents BIO failing to satisfy the energy needs such as cooking, irrigation, and lighting. Failure could be due to problems in the biogas digester or in the various equipments using biogas. Cooking is hindered by the failure of biogas stoves, whereas other failures may be due to the failure of biogas fueled engines or generators. Figure.4 illustrates the secondary model in which BIO is bad or inoperable.

1 State B1 represents normal operation with all the energy systems including BIO in operational state.

2 When BIO goes bad or inoperable, it transitions to state B2 briefly

3 The BIO is isolated in state B3 for repair and after repair it transitions back to state B1

4 When BIO is isolated for repair, there is a chance for all the other constituent energy systems to become inoperable at the same time. When this happens, it transitions to state B4 with IRES going down and BIO under isolation

5 When all the other systems are repaired and put back to operation with BIO under isolation , the system transitions back to state B3

6 There is a chance for common cause failure during which IRES (all the other energy systems) and BIO becomes inoperable simultaneously. Due to this, there is a transition from state B1 to state B5

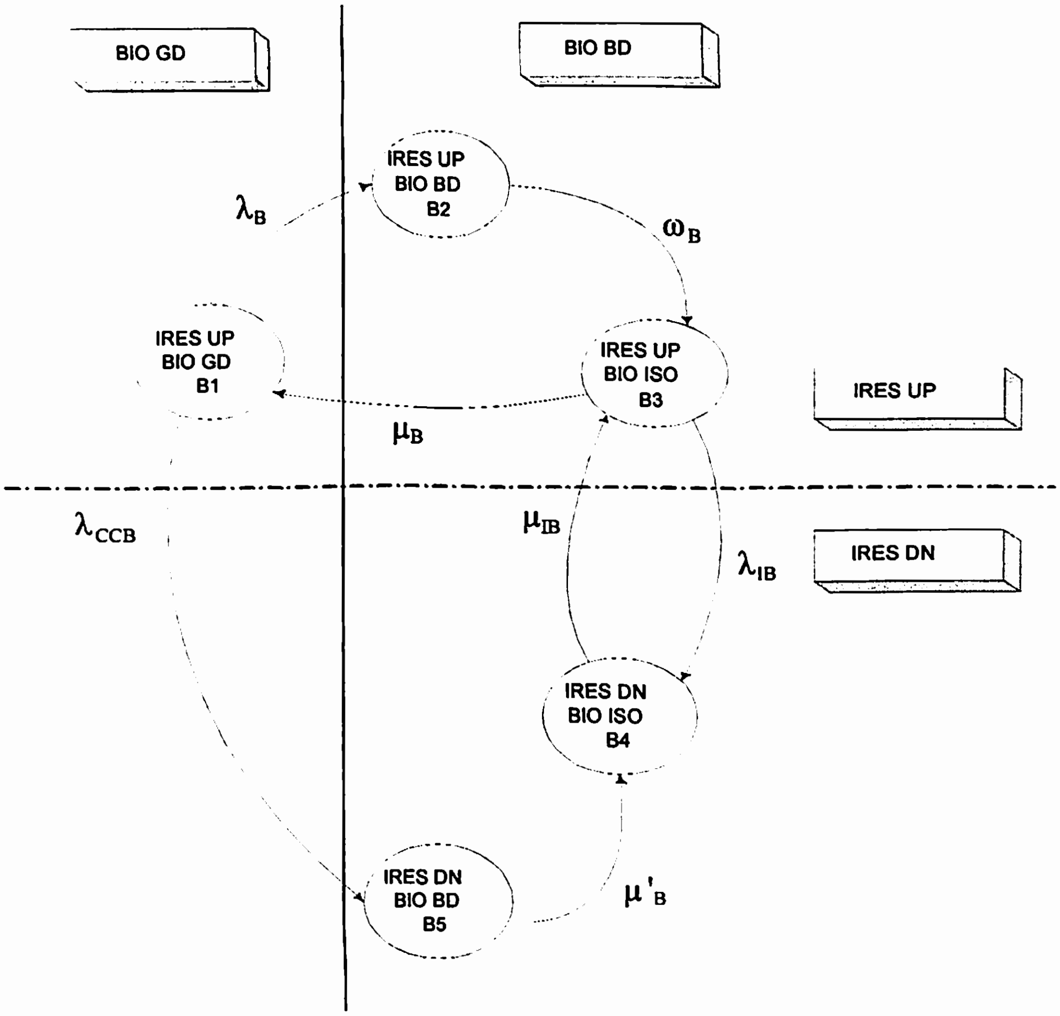

Figure.4 BIO Model

7 BIO being bad in state B5,when isolated, transitions to B4

The BIO model is solved using the frequency balance approach. The corresponding frequency balance equations are tabulated in Table I

The steady state probabilities are computed by solving the equations listed in Table I with the inclusion of $\sum_{i=1}^{5} P_{Bi} = 1$. Upon solving, we have

$$P_{B1} = \frac{\mu_B \mu_{IB} \omega_B \omega'_B}{D_B} \quad \text{.............................. (4-1)}$$

TABLE I

FREQUENCY BALANCE EQUATIONS FOR BIO MODEL

States	Rate in = Rate out
B1	$\mu_B P_{B3} = (\lambda_B + \lambda_{CCB}) P_{B1}$
B2	$\lambda_B P_{B1} = \omega_B P_{B2}$
B3	$\mu_{IB} P_{B4} + \omega_B P_{B2} = (\mu_B + \lambda_{IB}) P_{B3}$
B4	$\lambda_{IB} P_{B3} + \omega'_B P_{B5} = \mu_{IB} P_{B4}$
B5	$\lambda_{CCB} P_{B1} = \omega'_B P_{B5}$

where
$$D_B = \begin{bmatrix} \mu_B \mu_{IB} \omega_B \omega'_B + \lambda_B \mu_B \mu_{IB} \omega'_B + (\lambda_B + \lambda_{CCB}) \mu_{IB} \omega_B \omega'_B + \\ (\lambda_{IB}(\lambda_B + \lambda_{CCB}) + \lambda_{CCB}\mu_B) \omega_B \omega'_B + \lambda_{CCB} \mu_B \mu_{IB} \omega_B \end{bmatrix}$$

$$P_{B5} = \left[\frac{\lambda_{CCB}}{\omega'_B}\right] P_{B1} \quad \text{.......... (4-2)}$$

$$P_{B4} = \left[\frac{\lambda_{IB}(\lambda_B + \lambda_{CCB}) + \lambda_{CCB}\mu_B}{\mu_B \mu_{IB}}\right] P_{B1} \quad \text{.......... (4-3)}$$

$$P_{B3} = \left[\frac{\lambda_B + \lambda_{CCB}}{\mu_B}\right] P_{B1} \quad \text{.......... (4-4)}$$

$$P_{B2} = \left[\frac{\lambda_B}{\omega_B}\right] P_{B1} \quad \text{.......... (4-5)}$$

The above probabilities are obtained for the secondary model of BIO transitioning between GD and BD. It is possible to merge the states into a simple binary model of two states namely BIO GD and BIO BD.

From the binary equivalent shown in Figure.5

Availability of the binary system, $P_{GD} = P_{B1}$ .... (4-6)

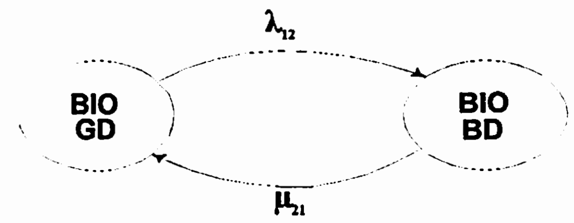

Figure.5 Equivalent binary model for BIO

Unavailability of the binary system,

$$P_{BD} = P_{B2} + P_{B3} + P_{B4} + P_{B5} \qquad (4\text{-}7)$$

μ_{21} is the repair rate of BIO in the primary model (see Figure.3). In order to calculate μ_{21}, we apply frequency balance approach to the merged binary model. Therefore

$$\mu_{21} P_{BD} = \lambda_{12} P_{GD} \qquad (4\text{-}8)$$

$$f_{BD} = P_{BD} \mu_{21} \qquad (4\text{-}9)$$

As there is a direct linkage between the two merged states, the frequency of the merged state is actually equal to the frequencies of the states merged, minus mutual encounters (transitions back and forth) [23]

$$f_{BD} = (f_2 + f_3 + f_4 + f_5) - (\lambda_{IB} P_{B3} + \mu_{IB} P_{B4} + \mu_B P_{B3})$$

$$= f_2 + f_5 \qquad (4\text{-}10)$$

$$= \omega_B P_{B2} + \omega'_B P_{B5}$$

$$= (\lambda_B + \lambda_{CCB}) P_{B1} \quad \text{(from Table.1)} \qquad (4\text{-}11)$$

$$P_{BD} \mu_{21} = P_{GD} \lambda_{12} \quad \text{(from Figure.5)} \qquad (4\text{-}12)$$

After simplification, we get

$$\mu_{21} = \frac{\lambda_{12} \omega_B \mu_B \mu_{IB} \omega'_B}{D_B - \mu_B \mu_{IB} \omega_B \omega'_B} \qquad (4\text{-}13)$$

$$\lambda_{12} = \lambda_B + \lambda_{CCB} \qquad (4\text{-}14)$$

Mean Time To Failure:

$$MTTF\ for\ BIO(GD) = \left(\frac{1}{\lambda_{12}}\right) \quad \text{.......... (4-15)}$$

Mean Time To Repair:

$$MTTR\ for\ BIO(BD) = \left(\frac{1}{\mu_{21}}\right) \quad \text{.......... (4-16)}$$

Cycle Time:

Cycle time for BIO (GD) = Cycle time for BIO (BD)

$$= \frac{1}{\lambda_{12}} + \frac{1}{\mu_{21}}$$

$$= \left(\frac{\lambda_{12} + \mu_{21}}{\lambda_{12}\mu_{21}}\right) \quad \text{.......... (4-17)}$$

B. ES MODEL

Referring to Figure.6, state E2 represents the failure of ES with all the other energy systems of IRES being operational. As this model is very similar in structure to the BIO model, the results are just provided below without detailing all the steps.

The steady state probabilities associated with the ES model are

$$P_{E1} = \frac{\mu_E \mu_{IE} \omega_E \omega'_E}{D_E} \quad \text{.......... (4-18)}$$

where $D_E = \begin{bmatrix} \mu_E \mu_{IE} \omega_E \omega'_E + \lambda_E \mu_E \mu_{IE} \omega'_E + (\lambda_E + \lambda_{CCE})\mu_{IE} \omega_E \omega'_E + \\ (\lambda_{IE}(\lambda_E + \lambda_{CCE}) + \lambda_{CCE}\mu_E)\omega_E \omega'_E + \lambda_{CCE}\mu_E \mu_{IE} \omega_E \end{bmatrix}$

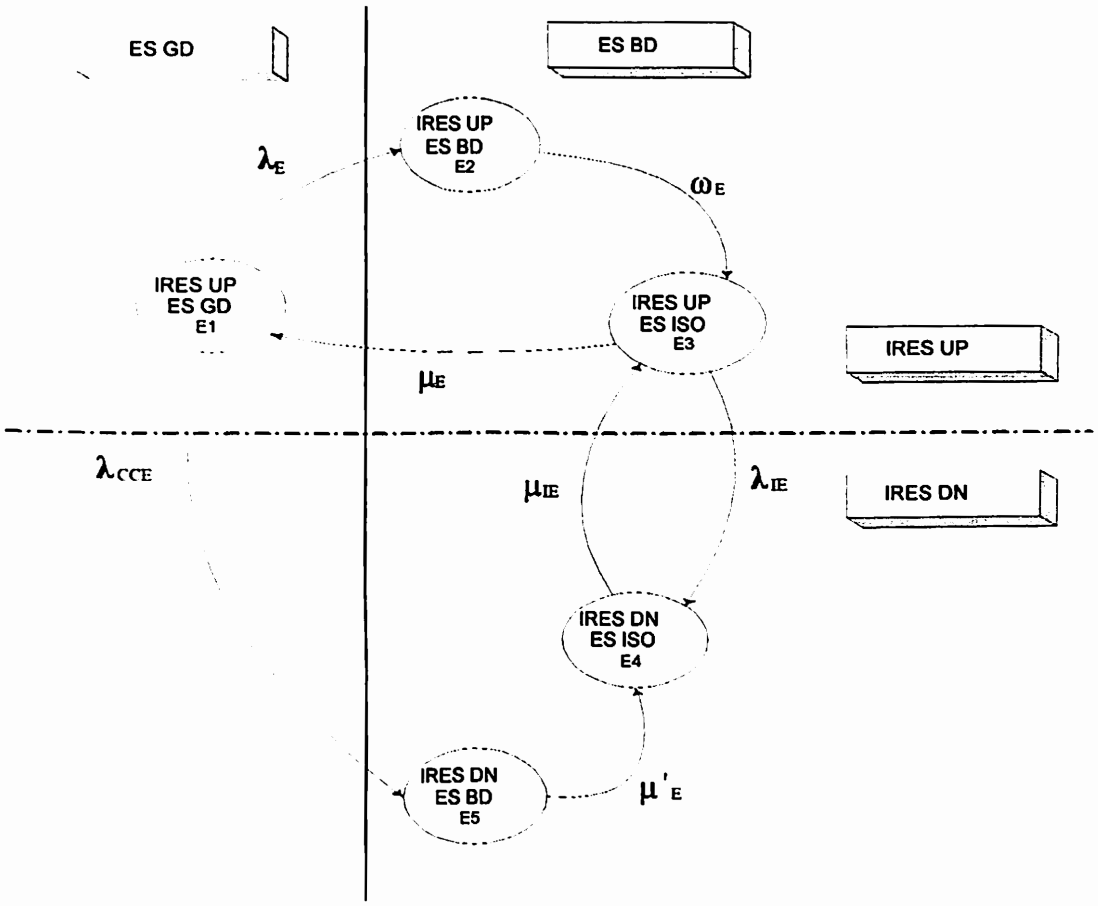

Figure.6 ES Model

$$P_{E5} = \left[\frac{\lambda_{CCE}}{\omega'_E}\right] P_{E1} \quad \text{.......... (4-19)}$$

$$P_{E4} = \left[\frac{\lambda_{IE}(\lambda_E + \lambda_{CCE}) + \lambda_{CCE}\mu_E}{\mu_E \mu_{IE}}\right] P_{E1} \quad \text{.......... (4-20)}$$

$$P_{E3} = \left[\frac{\lambda_E + \lambda_{CCE}}{\mu_E}\right] P_{E1} \quad \text{.......... (4-21)}$$

$$P_{E2} = \left[\frac{\lambda_E}{\omega_E}\right] P_{E1} \quad \text{.......... (4-22)}$$

From the binary model shown in Figure.7

The repair rate from ES (GD) to ES (BD) is

$$\mu_{31} = \frac{\lambda_{13}\omega_E \mu_E \mu_{IE} \omega'_E}{D_E - \mu_E \mu_{IE} \omega_E \omega'_E} \quad \text{...} (4\text{-}23)$$

The failure rate from ES (GD) to ES (BD)

$$\lambda_{13} = \lambda_E + \lambda_{CCE} \quad \text{..} (4\text{-}24)$$

Mean Time To Failure:

$$MTTF \ for \ ES\,(GD) = \left(\frac{1}{\lambda_{13}}\right)$$

$$\text{..} (4\text{-}25)$$

Mean Time To Repair:

$$MTTR \ for \ ES(BD) = \left(\frac{1}{\mu_{31}}\right)$$

$$\text{..} (4\text{-}26)$$

Cycle Time:

Cycle time for ES (GD) = Cycle time for ES (BD)

$$= \frac{1}{\lambda_{13}} + \frac{1}{\mu_{31}}$$

$$= \left(\frac{\lambda_{13} + \mu_{31}}{\lambda_{13}\mu_{31}}\right) \quad \text{..} (4\text{-}27)$$

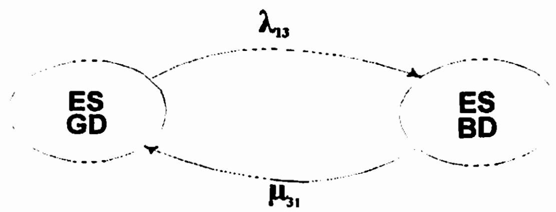

Figure.7 Equivalent binary model for ES

C. PV MODEL

Referring to Figure.8, states P3, P4 and P5 represent PV going bad or inoperable with all the other systems of IRES operational. The term bad denotes the failure of PV to satisfy the energy need or there is no effective output from PV due to cloud cover or other environmental factors. In this model, we consider the presence of cloud cover as the major contributor to the failure of PV to contribute energy even though the system, as such, is good. The probabilities of failure due to other environmental factors are so small that it can be neglected. Water supply and lighting are affected by the failure of PV driven water pumps and solar thermal collectors. The proposed PV model is illustrated in Figure.8.

1 State P1 represents normal operation with all the energy systems including PV in operational state. Even though the PV system is operational in state P1, it transitions to state P2, due to the presence of cloud cover. As soon as the cloud cover disappears, the system transitions back to state P1

2 The system transitions to state P3 from state P1, when PV goes bad and also there is a cloud cover

3 The system enters state P4 from state P1, when PV goes bad and there is no cloud cover.

4 The states P3 and P4 transition to state P5, where PV is isolated for repair. The isolated PV is repaired and the system reverts to state P1

5 When PV is isolated for repair, there is a chance for all the other constituent energy systems to go bad at the same time. When this happens, it transitions to state P6 with IRES going down and PV under isolation

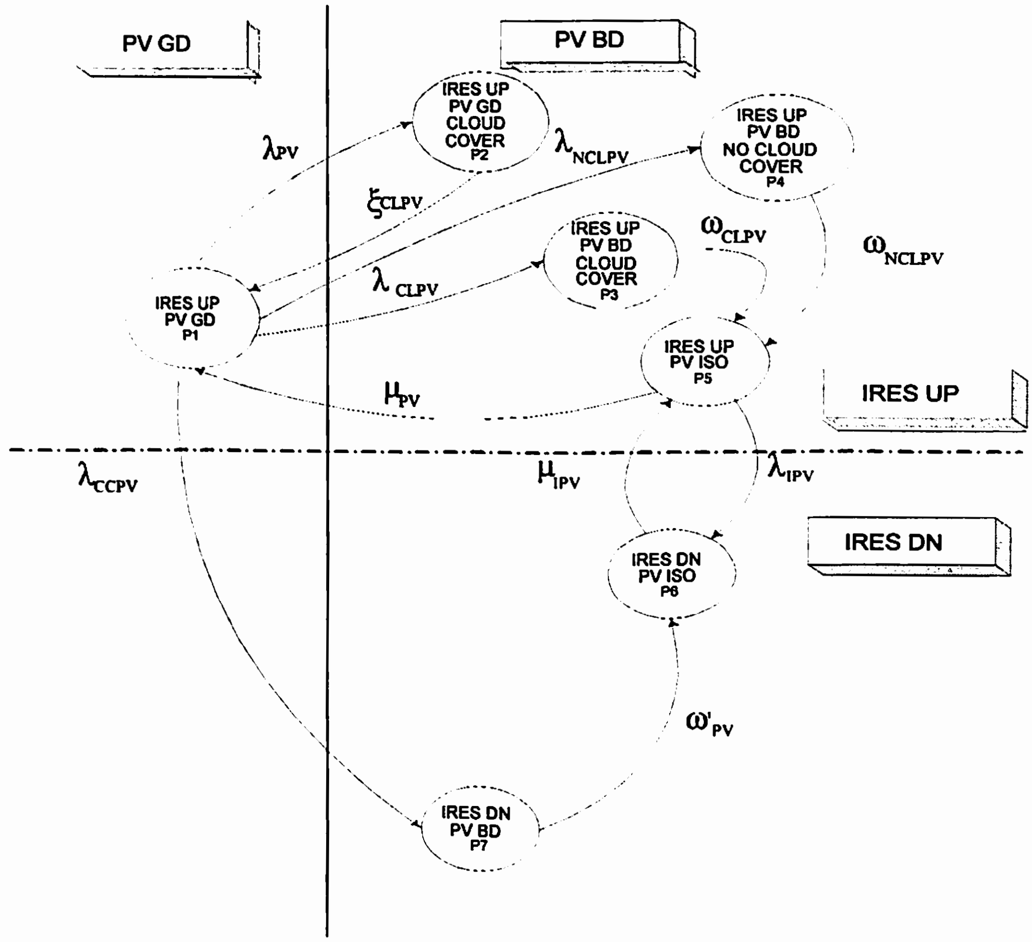

Figure.8 PV Model

6 When all the other systems are repaired and put back to operation with PV under isolation , the system transitions back to state P5

7 When PV and all other systems in the IRES go bad due to a common cause failure, it transitions to state P7

8 The PV being bad in state P7,when isolated, transitions to P6

TABLE II

FREQUENCY BALANCE EQUATIONS FOR PV MODEL

States	Rate in = Rate out
P1	$\mu_{PV}P_{P5} + \xi_{CLPV} = (\lambda_{NCLPV} + \lambda_{CLPV} + \lambda_{PV} + \lambda_{CCPV})P_{P1}$
P2	$\lambda_{PV}P_{P1} = \xi_{CLPV}P_{P2}$
P3	$\lambda_{CLPV}P_{P1} = \omega_{CL}P_{P3}$
P4	$\lambda_{NCLPV}P_{P1} = \omega_{NCL}P_{P4}$
P5	$\omega_{CL}P_{P3} + \mu_{IPP6} + \omega_{NCLPV}P_{P4} = (\lambda_{IPV} + \mu_{PV})P_{P5}$
P6	$\omega'_{PV}P_{P7} + \lambda_{IPV}P_{P5} = \mu_{IPV}P_{P6}$
P7	$\lambda_{CCPV}P_{P1} = \omega'_{PV}P_{P7}$

The PV model is solved using the frequency balance approach. The corresponding equations are listed in Table II

The steady state probabilities are computed from the above table by solving the frequency balance equations along with $\sum_{i=1}^{5} P_{Pi} = 1$ .The results are given below

$$P_{P1} = \frac{\xi_{CLPV} \cdot \mu_{IPV} \cdot \mu_{PV} \cdot \omega_{CLPV} \cdot \omega_{NCLPV} \cdot \omega'_{PV}}{D_{PV}} \quad \text{.................................} (4\text{-}28)$$

$$P_{P2} = \left(\frac{\lambda_{PV}}{\xi_{CLPV}}\right)P_{P1} \quad \text{...} (4\text{-}29)$$

$$P_{P3} = \left(\frac{\lambda_{CLPV}}{\omega_{CLPV}}\right)P_{P1} \quad \text{...} (4\text{-}30)$$

$$P_{P4} = \left(\frac{\lambda_{NCLPV}}{\omega_{NCLPV}}\right)P_{P1} \quad \text{...} (4\text{-}31)$$

$$P_{P5} = \left(\frac{\lambda_{NCLPV} + \lambda_{CLPV} + \lambda_{CCPV}}{\mu_{PV}} \right) P_{P1} \quad \text{.......... (4-32)}$$

$$P_{P6} = \left(\frac{\lambda_{CCPV} \cdot \mu_{PV} + \lambda_{IPV} \left(\lambda_{NCLPV} + \lambda_{CLPV} + \lambda_{CCPV} \right)}{\mu_{PV} \cdot \mu_{IPV}} \right) P_{P1} \quad \text{.......... (4-33)}$$

$$P_{P7} = \left(\frac{\lambda_{CCPV}}{\omega'_{PV}} \right) P_{P1} \quad \text{.......... (4-34)}$$

$$\begin{aligned}
D_{PV} = {} & \xi_{CLPV} \cdot \mu_{IPV} \cdot \omega_{PV} \cdot \omega_{CLPV} \cdot \omega_{NCLPV} + \\
& \lambda_{PV} \cdot \mu_{IPV} \cdot \mu_{PV} \cdot \omega_{CLPV} \cdot \omega_{NCLPV} \cdot \omega'_{PV} + \\
& \lambda_{CLPV} \cdot \xi_{CLPV} \cdot \mu_{IPV} \cdot \mu_{PV} \cdot \omega_{NCLPV} \cdot \omega'_{PV} + \\
& \lambda_{NCLPV} \cdot \xi_{CLPV} \cdot \mu_{IPV} \cdot \mu_{PV} \cdot \omega_{CLPV} \cdot \omega'_{PV} + \\
& (\lambda_{NCLPV} + \lambda_{CLPV} + \lambda_{CCPV}) \cdot \xi_{CLPV} \cdot \mu_{IPV} \cdot \omega_{CLPV} \cdot \omega_{NCLPV} \cdot \omega'_{PV} + \\
& (\lambda_{CCPV} \cdot \mu_{PV} + \lambda_{IPV} (\lambda_{NCLPV} + \lambda_{CLPV} + \lambda_{CCPV})) \cdot \xi_{CLPV} \cdot \omega_{CLPV} \cdot \omega_{NCLPV} \cdot \omega'_{PV} + \\
& \lambda_{CCPV} \cdot \xi_{CLPV} \cdot \mu_{IPV} \cdot \mu_{PV} \cdot \omega_{CLPV} \cdot \omega_{NCLPV}
\end{aligned}$$

For the binary equivalent shown in Figure.9

Availability of the binary system,

$$P_{GD} = P_{P1} \quad \text{.......... (4-35)}$$

Unavailability of the binary system,

$$P_{BD} = P_{P2} + P_{P3} + P_{P4} + P_{P5} + P_{P6} + P_{P7} \quad \text{.......... (4-36)}$$

μ_{41} is the repair rate of PV in the primary model. The frequency balance approach is used to calculate μ_{41}. Therefore

$$\mu_{41} P_{BD} = \lambda_{14} P_{GD} \quad \text{.......... (4-37)}$$

$$f_{BD} = P_{BD} \mu_{41} \quad \text{.......... (4-38)}$$

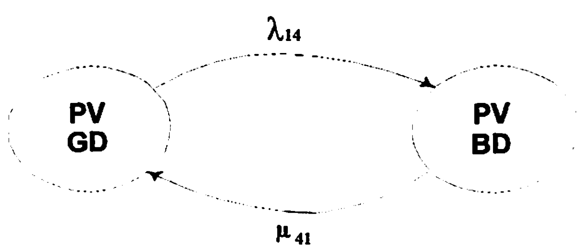

Figure.9 Equivalent binary model for PV

The frequency of the merged state is given by

$$f_{BD} = (f_2 + f_3 + f_4 + f_5 + f_6 + f_7) - [\mu_{IPV} P_{P6} + \lambda_{IPV} P_{P5} + \mu_{PV} P_{P5}]$$

$$= f_2 + f_3 + f_4 + f_7 \quad \text{.......... (4-39)}$$

$$= \xi_{CLPV} \cdot P_{P2} + \omega_{CLPV} \cdot P_{P3} + \omega_{NCLPV} \cdot P_{P4} + \omega'_{PV} \cdot P_{P7}$$

$$P_{BD} \cdot \mu_{41} = \lambda_{14} P_{GD} \quad \text{(from Figure.9)} \quad \text{.......... (4-40)}$$

The repair rate from PV (BD) to PV (GD) is given by

$$\mu_{41} = \left(\frac{\lambda_{PV} + \lambda_{NCLPV} + \lambda_{CLPV} + \lambda_{CCPV}}{D_{PV} - K_{PV}} \right) K_{PV} \quad \text{.......... (4-41)}$$

where $K_{PV} = \xi_{CLPV} \cdot \mu_{IPV} \cdot \mu_{PV} \cdot \omega_{CLPV} \cdot \omega_{NCLPV} \cdot \omega'_{PV}$

The failure rate from PV (GD) to PV (BD) is

$$\lambda_{14} = \lambda_{PV} + \lambda_{NCLPV} + \lambda_{CLPV} + \lambda_{CCPV} \quad \text{.......... (4-42)}$$

Mean Time To Failure (MTTF)

$$MTTF \ for \ PV \ (GD) = \left(\frac{1}{\lambda_{14}} \right) \quad \text{.......... (4-43)}$$

Mean Time To Repair (MTTR)

$$MTTR \ for \ PV \ (BD) = \left(\frac{1}{\mu_{41}} \right) \quad \text{.......... (4-44)}$$

Cycle Time:

Cycle time for PV (GD) = Cycle time for PV (BD)

$$= \frac{1}{\lambda_{14}} + \frac{1}{\mu_{41}}$$

$$= \left(\frac{\lambda_{14} + \mu_{41}}{\lambda_{14} \mu_{41}} \right) \quad \text{.......... (4-45)}$$

D. WECS MODEL

Referring to Figure.10, states W3, W4 and W5 represent WECS going bad due to different reasons with all the other energy systems of IRES operational. The WECS going bad implies that there is no effective output due to the absence of wind or equipment failure and it fails to satisfy the energy need. The main facilities affected due to the failure of wind driven mechanical pumps and wind electric conversion systems are irrigation and lighting. The WECS model is illustrated in Figure.10.

1 State W1 represents the normal operation of WECS with all other energy systems of IRES operational

2 Even though, WECS is operational in state W1, it transitions to state W2 due to the absence of wind. As soon as wind resumes, the system transitions back to state W1

3 From state W1, the system transitions to state W4, when WECS goes bad and there is no wind

4 From state W1, the system transitions to state W3, when WECS goes bad in the presence of wind

5 From state W3 and state W4, the system transitions to state W5, where WECS is isolated for repair. As soon as WECS is repaired , the system transitions back to state W1

6 When WECS is isolated for repair, there is a chance for all the other constituent energy systems to go bad at the same time. When this happens, it transitions to state W6 with IRES going down with WECS under isolation

7 When all other systems are repaired and put back to operation, with WECS under

isolation, the system transition back to state W5

8 There is a chance for common cause failure by which WECS and all other energy systems go bad at the same time. This transition takes place from state W1 to state W7

9 The WECS being bad in state W7, when isolated, transitions to state W6

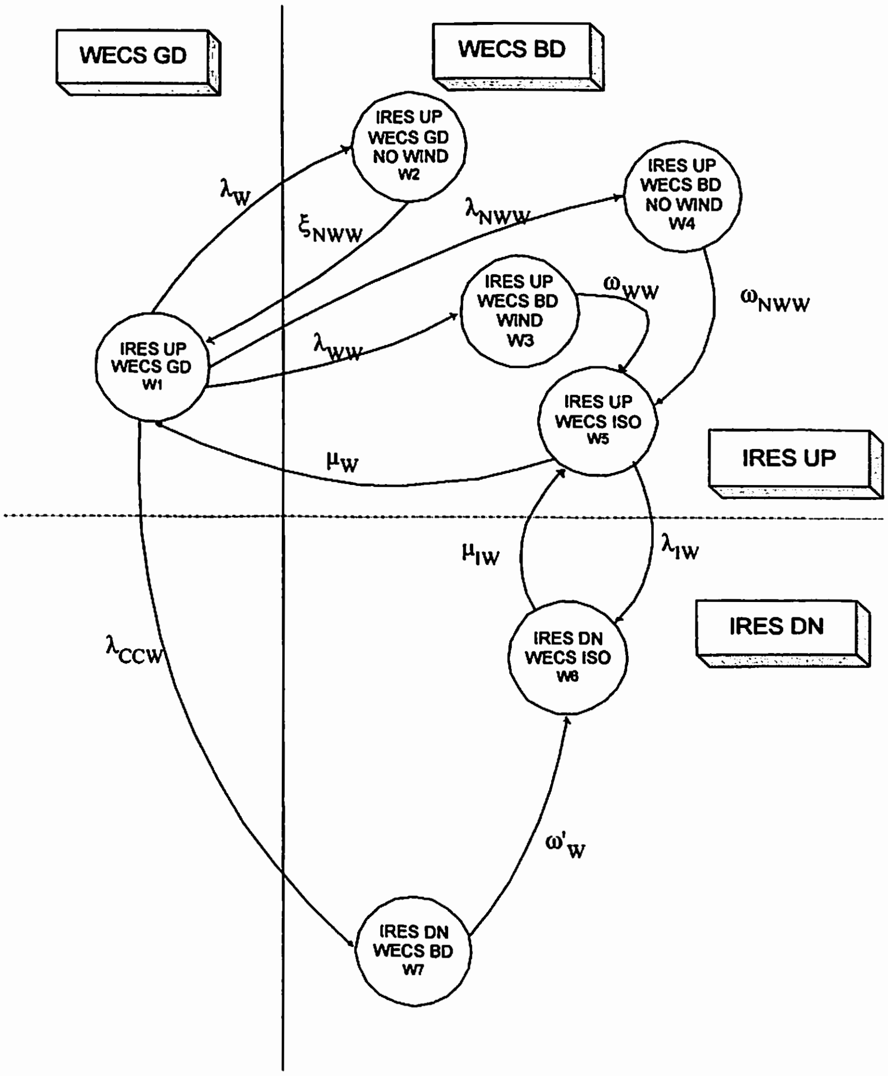

Figure.10 WECS Model

Analysis of the model in Figure.10 is done as before by employing the frequency balance approach. The steady state probabilities are found by solving frequency balance equations along with $\sum_{i=1}^{5} P_{W_i} = 1$ .The results are given below :

$$P_{W1} = \frac{\xi_{NWW} \cdot \mu_{IW} \cdot \mu_W \cdot \omega_{WW} \cdot \omega_{NWW} \cdot \omega'_W}{D_W} \qquad \text{(4-46)}$$

$$P_{W2} = \left(\frac{\lambda_W}{\xi_{NWW}}\right) P_{W1} \qquad \text{(4-47)}$$

$$P_{W3} = \left(\frac{\lambda_{WW}}{\omega_{WW}}\right) P_{W1} \qquad \text{(4-48)}$$

$$P_{W4} = \left(\frac{\lambda_{NWW}}{\omega_{NWW}}\right) P_{W1} \qquad \text{(4-49)}$$

$$P_{W5} = \left(\frac{\lambda_{NWW} + \lambda_{WW} + \lambda_{CCW}}{\mu_W}\right) P_{W1} \qquad \text{(4-50)}$$

$$P_{W6} = \left(\frac{\lambda_{CCW} \cdot \mu_W + \lambda_{IW}(\lambda_{NWW} + \lambda_{WW} + \lambda_{CCW})}{\mu_W \cdot \mu_{IW}}\right) P_{W1} \qquad \text{(4-51)}$$

$$P_{W7} = \left(\frac{\lambda_{CCW}}{\omega'_W}\right) P_{W1} \qquad \text{(4-52)}$$

$$\begin{aligned}
D_W = {} & \xi_{NWW} \cdot \mu_{IW} \cdot \omega_W \cdot \omega_{WW} \cdot \omega_{NWW} + \\
& \lambda_W \cdot \mu_{IW} \cdot \mu_W \cdot \omega_{WW} \cdot \omega_{NWW} \cdot \omega'_W + \\
& \lambda_{WW} \cdot \xi_{NWW} \cdot \mu_{IW} \cdot \mu_W \cdot \omega_{NWW} \cdot \omega'_W + \\
& \lambda_{NWW} \cdot \xi_{NWW} \cdot \mu_{IW} \cdot \mu_W \cdot \omega_{WW} \cdot \omega'_W + \\
& (\lambda_{NWW} + \lambda_{WW} + \lambda_{CCW}) \cdot \xi_{NWW} \cdot \mu_{IW} \cdot \omega_{WW} \cdot \omega_{NWW} \cdot \omega'_{WW} + \\
& (\lambda_{CCW}\, \mu_W + \lambda_{IW}(\lambda_{NWW} + \lambda_{WW} + \lambda_{CCW})) \cdot \xi_{NWW} \cdot \omega_{WW} \cdot \omega_{NWW} \cdot \omega'_{WW} + \\
& \lambda_{CCW} \cdot \xi_{NWW} \cdot \mu_{IW} \cdot \mu_W \cdot \omega_{WW} \cdot \omega_{NWW}
\end{aligned}$$

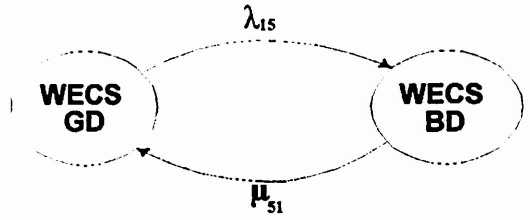

Figure.11 Equivalent binary model for WECS

From Figure.11,

The repair rate from W (GD) to W (BD) is

$$\mu_{51} = \left(\frac{\lambda_W + \lambda_{NWW} + \lambda_{WW} + \lambda_{CCW}}{D_W - K_W} \right) K_W \qquad \text{(4-53)}$$

where $K_W = \xi_{NWW} \cdot \mu_{IW} \cdot \mu_W \cdot \omega_{WW} \cdot \omega_{NWW} \cdot \omega'_W$

The failure rate from WECS (GD) to WECS (BD)

$$\lambda_{15} = \lambda_W + \lambda_{NWW} + \lambda_{WW} + \lambda_{CCW} \qquad \text{(4-54)}$$

Mean Time To Failure (MTTF):

$$MTTF \ for \ WECS \ (GD) = \left(\frac{1}{\lambda_{15}} \right) \qquad \text{(4-55)}$$

Mean Time To Repair (MTTR)

$$MTTR \ for \ WECS(BD) = \left(\frac{1}{\mu_{51}} \right) \qquad \text{(4-56)}$$

Cycle Time:

Cycle time for WECS (GD) = Cycle time for WECS (BD)

$$= \frac{1}{\lambda_{15}} + \frac{1}{\mu_{51}}$$

$$= \left(\frac{\lambda_{15} + \mu_{51}}{\lambda_{15}\mu_{51}} \right) \qquad \text{(4-57)}$$

E. HYDRO MODEL

Referring to Figure.12, states H3, H4 and H5 represent HYDRO going bad with all the other components of IRES operational. The term bad denotes the failure of HYDRO to satisfy the energy need or there is no effective output from HYDRO due to low water head (LWH) or equipment problems. Due to low water head, irrigation and water supply (domestic and potable) are affected badly. The HYDRO model is illustrated in Figure.12.

1 State H1 denotes the operational nature of HYDRO along with all the other systems of IRES in the good state

2 There is a transition from state H1 to state H2, as there is no output due to LWH conditions. As soon as the water head rises, the system transitions back to state H1

3 The system transitions to state H4, when HYDRO system goes bad, coupled with a LWH condition

4 The system transitions to state H3, when HYDRO system goes bad, coupled with a HWH condition

5 From states H3 and H4, the system transitions to state H5, where the HYDRO is isolated for repair. The system transitions back to state H1 when HYDRO is repaired

6 When HYDRO is isolated for repair, there is a chance for all the other constituent energy systems to go bad at the same time. When this happens, it transitions to state H6 with IRES going down and HYDRO under isolation

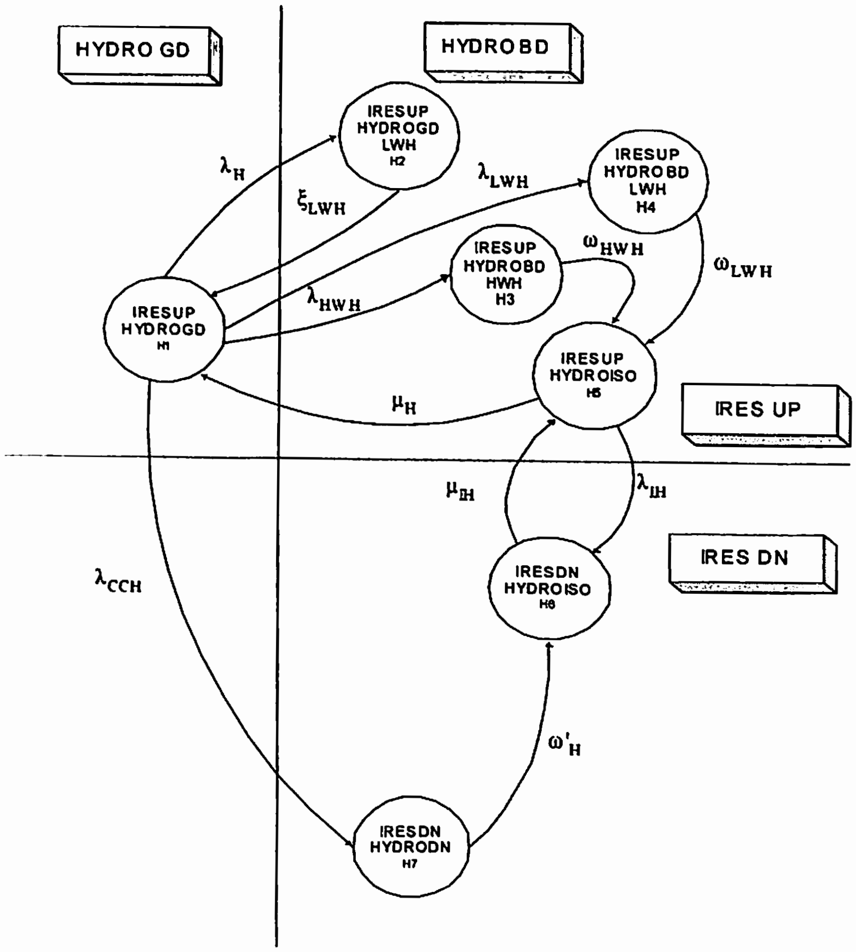

Figure.12 HYDRO Model

7 When all other systems are repaired and put back to operation with HYDRO under isolation, the system transitions back to state H5

8 The common cause failure of HYDRO coupled with the other energy systems of IRES going down leads to a transition from state H1 to state H7

9 The HYDRO being bad in state H7,when isolated, transitions to state H6

The steady state probabilities for the above model are

$$P_{H1} = \frac{\xi_{LWH} \cdot \mu_{IH} \cdot \mu_H \cdot \omega_{HWH} \cdot \omega_{LWH} \cdot \omega'_H}{D_H} \quad \text{........................ (4-58)}$$

$$P_{H2} = \left(\frac{\lambda_H}{\xi_{LWH}} \right) P_{H1} \quad \text{.......... (4-59)}$$

$$P_{H3} = \left(\frac{\lambda_{HWH}}{\omega_{HWH}} \right) P_{H1} \quad \text{.......... (4-60)}$$

$$P_{H4} = \left(\frac{\lambda_{LWH}}{\omega_{LWH}} \right) P_{H1} \quad \text{.......... (4-61)}$$

$$P_{H5} = \left(\frac{\lambda_{LWH} + \lambda_{HWH} + \lambda_{CCH}}{\mu_H} \right) P_{H1} \quad \text{.......... (4-62)}$$

$$P_{H6} = \left(\frac{\lambda_{CCH} \cdot \mu_H + \lambda_{IH} \left(\lambda_{LWH} + \lambda_{HWH} + \lambda_{CCH} \right)}{\mu_H \cdot \mu_{IH}} \right) P_{H1} \quad \text{.......... (4-63)}$$

$$P_{H7} = \left(\frac{\lambda_{CCH}}{\omega'_H} \right) P_{H1} \quad \text{.......... (4-64)}$$

$$\begin{aligned}
D_H = {} & \xi_{LWH} \cdot \mu_{IH} \cdot \omega_H \cdot \omega_{HWH} \cdot \omega_{LWH} + \\
& \lambda_H \cdot \mu_{IH} \cdot \mu_H \cdot \omega_{HWH} \cdot \omega_{LWH} \cdot \omega'_H + \\
& \lambda_{HWH} \cdot \xi_{LWH} \cdot \mu_{IH} \cdot \mu_H \cdot \omega_{LWH} \cdot \omega'_H + \\
& \lambda_{LWH} \cdot \xi_{LWH} \cdot \mu_{IIH} \cdot \mu_H \cdot \omega_{HWH} \cdot \omega'_H + \\
& \left(\lambda_{LWH} + \lambda_{HWH} + \lambda_{CCH} \right) \cdot \xi_{LWH} \cdot \mu_{IH} \cdot \omega_{HWH} \cdot \omega_{LWH} \cdot \omega'_{HWH} + \\
& \left(\lambda_{CCH} \cdot \mu_H + \lambda_{IH} \left(\lambda_{LWH} + \lambda_{HWH} + \lambda_{CCH} \right) \right) \cdot \xi_{LWH} \cdot \omega_{HWH} \cdot \omega_{LWH} \cdot \omega'_{HWH} + \\
& \lambda_{CCH} \cdot \xi_{LWH} \cdot \mu_{IH} \cdot \mu_{HWH} \cdot \omega_{HWH} \cdot \omega_{LWH}
\end{aligned}$$

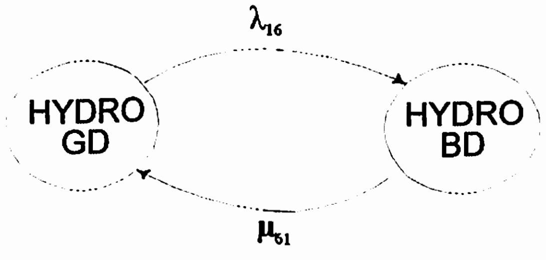

Figure.13 Equivalent binary model for HYDRO

From the equivalent binary model in Figure.13,

The repair rate from HYDRO (GD) to HYDRO (BD) is

$$\mu_{61} = \left(\frac{\lambda_H + \lambda_{LWH} + \lambda_{HWH} + \lambda_{CCH}}{D_H - K_H} \right) K_H \quad \text{(4-65)}$$

where $K_H = \xi_{LWH} \cdot \mu_{IH} \cdot \mu_H \cdot \omega_{HWH} \cdot \omega_{LWH} \cdot \omega'_H$

The failure rate from HYDRO (GD) to HYDRO (BD)

$$\lambda_{61} = \lambda_H + \lambda_{LWH} + \lambda_{HWH} + \lambda_{CCH} \quad \text{(4-66)}$$

Mean Time To Failure:

$$MTTF \ for \ HYDRO(GD) = \left(\frac{1}{\lambda_{16}} \right) \quad \text{(4-67)}$$

Mean Time To Repair

$$MTTR \ for \ HYDRO(BD) = \left(\frac{1}{\mu_{61}} \right) \quad \text{(4-68)}$$

Cycle Time:

Cycle time for HYDRO (GD) = Cycle time for HYDRO (BD)

$$= \frac{1}{\lambda_{16}} + \frac{1}{\mu_{61}}$$

$$= \left(\frac{\lambda_{16} + \mu_{61}}{\lambda_{16}\mu_{61}} \right) \quad \text{(4-69)}$$

4.5 Summary

This chapter has presented a framework to assess the performance of IRES using the Markov approach. The different performance parameters can be found by plugging in the suitable values for the various departure rates. It may be necessary to make educated and experienced guesses to glean the departure rates from real life operating data.

Assumption No. 6 (page 27) implies that the IRES goes inoperable (down) only when all the constituent components (subsystems) are inoperable. This is an extremely conservative assumption that can be justified only if any one of the subsystems can fully keep the IRES operational. This is unrealistic and will involve very high expenditure since it will be equivalent to having multiple(s) redundancy.

The other extreme case is to assume that failure of any one of the subsystems will result in IRES being down. In other words, all the subsystems must be up and running for the IRES to be successful. For this case, all the subsystems can be merged into a equivalent IRES down state and an equivalent binary model can be derived as shown in Figure.14.

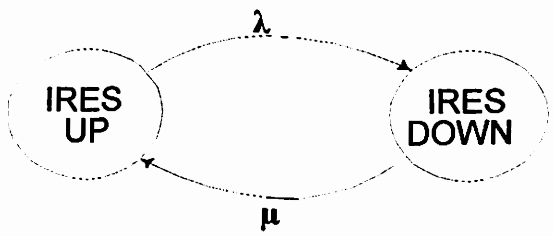

Figure.14 Equivalent Binary Model for IRES

The equivalent failure rate, λ is given by

$$\lambda = \lambda_{12} + \lambda_{13} + \lambda_{14} + \lambda_{15} + \lambda_{16} \quad \text{(4-70)}$$

Equivalent repair rate μ (for a series system) is given by

$$\mu \;=\; \lambda \,/\, \text{Total Downtime} \quad \text{..........................} \; (4\text{-}71)$$

$$\text{Total Downtime} \cong \sum_i \lambda_i r_i = \left[\frac{\lambda_{12}}{\mu_{21}} + \frac{\lambda_{13}}{\mu_{31}} + \frac{\lambda_{14}}{\mu_{41}} + \frac{\lambda_{15}}{\mu_{51}} + \frac{\lambda_{16}}{\mu_{61}}\right]$$

These two rates can be used to compute the Mean Time To Failure (MTTF), Mean Time To Repair (MTTR) and the Cycle time for the IRES.

In practice, depending on resource availabilities and location of the IRES, it will take the failure of more than one of the subsystems to cause a total system shut down. Once these subsystems are identified, they can be aggregated to form an "IRES DOWN" state and the rest of the subsystems can be aggregated into an "IRES UP" state. This will lead to a different equivalent binary model for IRES.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Introduction

In this chapter, representative binary models are derived for the different subsystems based on typical available data. The data used in this section are extracted from the online database of the National Renewable Energy Laboratory (NREL) in Golden, Colorado, US Geological Survey (USGS), and the Energy Information Administration (EIA). HOMER, a software developed by NREL is used for some data manipulation and simulation to obtain results suitable for IRES model.

5.2 BIO Model

Binary model for BIO is shown in Figure 5. This model has two possible states, namely GD for good and BD for bad. In a rural area, the amount of biomass is mostly determined by the amount of animal waste available which, in turn, is dependent upon the number of animals present in that area. Therefore it is assumed that BIO system failures are primarily due to technical or maintenance problems and not due to a lack of resource availability.

As mentioned earlier, the BIO system may fail due to problems in the digester, filtration system or some other technical problem such as poisoning of the bacteria involved. If we assume that the BIO system fails once in two months (i.e. once in 60 days) due to the reasons mentioned above, then

$$\lambda_{12} = \left[\frac{1}{60}\right] \text{ day}^{-1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5\text{-}1)$$

Therefore, from Equation (4-15) & (5-1),

Mean Time to Failure for BIO = 60 days

Similarly, assuming an average restoration/repair time to be 5 days, we obtain

$$\mu_{21} = \left[\frac{1}{5}\right] \text{day}^{-1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5\text{-}2)$$

From Equation (4-16) & (5-2),

Mean time to Repair = 5 days

From Equation (4-17),

Cycle time for BIO (GD) = Cycle time for BIO (BD)

$$= \left(\frac{\lambda_{12} + \mu_{21}}{\lambda_{12}\mu_{21}}\right)$$

= 65 days

5.3 ES Model

Binary equivalent of ES model is shown in Figure.7. The two aggregated states of the ES model are GD for good and BD for bad. Battery energy storage is considered for discussion purposes (as an example for ES). The GD and BD states are decided based on the charge and discharge of the battery. The down and restoration rates are given by λ_{13} and μ_{31} respectively.

Capacity versus discharge current characteristic for a typical (Trojan L16P) battery is shown in Figure.15. It can be seen that as discharge current increases, the capacity decreases nearly linearly.

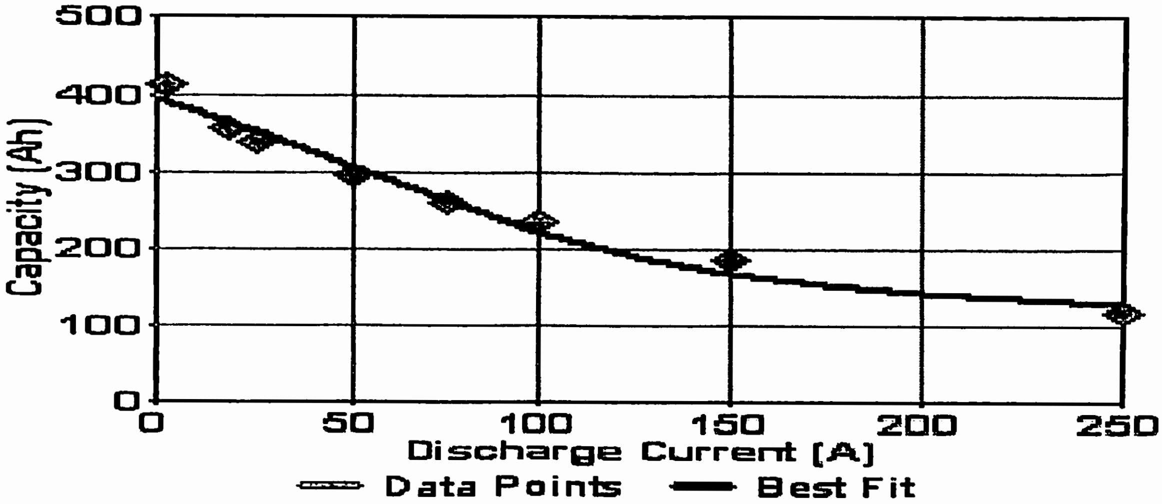

Figure.15 Capacity Vs discharge current curve for Trojan L16P battery

Nominal Capacity of the Trojan L16P battery = 360 Ah

Assuming a cyclical operation with a 50 % discharge,

Average output capacity for Trojan L16P battery = 180 Ah

Assuming a discharge rate of 60 A,

Discharge time (assuming 50 % discharge) = $\left[\frac{180Ah}{60A}\right]$ = 3 hours

Thus, failure rate of the battery,

$$\lambda_{13} = 8 \text{ days}^{-1}$$

The charge current rate for Trojan L16P = 18 A

Charging back to full nominal capacity will require (180 /80) or 10 hours

Therefore, repair rate (to charge),

$$\mu_{31} = 2.4 \text{ days}^{-1}$$

From Equation 4-25,

Mean Time To Failure = 0.125 days

From Equation 4-26,

Mean Time To Repair = 0.416 days

From Equation 4-27,

Cycle Time = 0.541 days

5.4 PV Model

This model considers the intermittent nature of solar energy. As discussed before, PV model will also be based on a simple binary equivalent shown in Figure.9. An off-grid house in Montana is used for analyses purposes. This data are extracted and fine tuned from the database of HOMER (NREL software) which provides with clearness index and daily solar radiation. As per the requirements of IRES, this data are suitably applied.

TABLE III

SOLAR RESOURCE DATA FOR AN OFF-GRID HOUSE IN MONTANA, USA

Month	Clearness Index	Average Daily Solar Radiation
		(kW/m2)
January	0.488	0.058
February	0.538	0.097
March	0.559	0.152
April	0.545	0.203
May	0.530	0.238
June	0.595	0.286
July	0.618	0.287
August	0.616	0.246
September	0.621	0.190
October	0.560	0.115
November	0.518	0.068
December	0.500	0.051
Annual Average (kW/m2)= 0.165		

Table III provides the values of clearness index (absence of cloud cover) and the daily solar radiation. These values can be used to decide whether the PV system is GD or BD.

The annual average daily solar radiation from Table III = 0.165 kW/m^2

Figure.16 is the pictorial representation of the data listed in Table III.

Assuming 50% of the annual average (i.e. 0.0825 kW/m2) as the threshold for deciding whether the system is GD or BD, it can be seen that the PV system is virtually BD for the entire months of January, November and December (a total of 92 days out of 365).

Probability of PV system residing in BD state (Unavailability)

$$= \left[\frac{\lambda_{14}}{\lambda_{14} + \mu_{41}}\right] = \left[\frac{92}{365}\right] = 0.2520$$

Probability of PV system in GD state (Availability) = 1 - 0.2520 = 0.7479

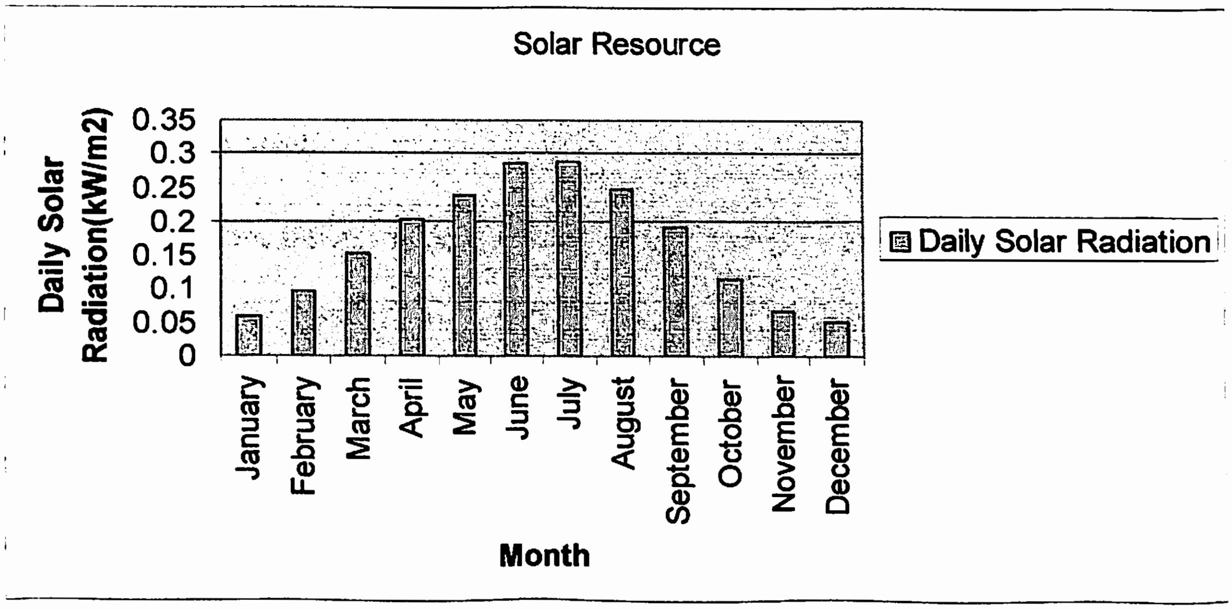

Figure.16. Solar resource for a year at the off-grid location in Montana, USA

After simplification,

$$\left[\frac{\lambda_{14}}{\mu_{41}}\right] = 0.3369 \Rightarrow \lambda_{14} = 0.3369.\ \mu_{41}$$

From the average monthly data,

The rate μ_{31} for transition from PV (BD) to PV (GD) = 0.020 $days^{-1}$ *

Using λ_{14}= 0.3369. μ_{41},

$$\lambda_{14} = 0.0067\ days^{-1}$$

Using Equations 4-43, 4-44, & 4-45

Mean time to transition from PV (GD) to PV (BD) = 148 days

Mean time to transition from PV (BD) to PV (GD) = 50 days

Cycle Time for PV = 198 days.

These values are based on monthly averages. There can be variations between days in a month which are discussed in Appendix B.

5.4 WECS Model

The equivalent binary model for WECS is given in Figure 11. There are two states-namely WECS (GD) and WECS (BD). As for the PV model, the same off-grid location in Montana is considered for discussion. Table IV shows the wind resource at the specified location with the corresponding power output. The power in wind is calculated using the formulae in Appendix A.

* Average restoration/recovery time based on daily solar radiation for January (30days), November (60days) and December (60 days) = 120/3 = 50 days

TABLE IV

WIND RESOURCE DATA FOR AN OFF-GRID HOUSE IN MONTANA, USA

Month	Wind Speed (m/s)	Average Power in wind
		kW/m2
January	7.400	0.248
February	6.700	0.184
March	7.108	0.219
April	5.700	0.113
May	6.100	0.139
June	4.600	0.059
July	4.200	0.045
August	4.900	0.072
September	4.900	0.072
October	5.400	0.096
November	5.200	0.086
December	6.800	0.192
Annual Average (kW/m2) = 0.127		

Figure.17 shows the average power output in wind for different months in a year. A threshold value of 0.063 kW/m^2 (50 % of annual average) is assumed. This value is used as the limiting factor for deciding whether the system is GD or BD.

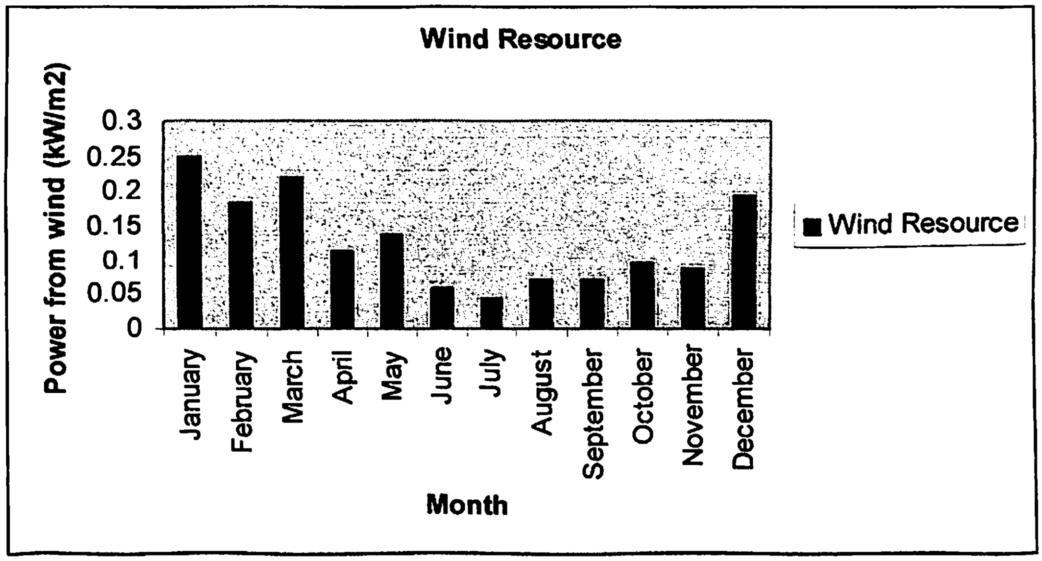

Figure.17.Wind power output for a year for the off-grid location in Montana, USA

The WECS will essentially be in BD state for the selected location for a duration of 2 months (June, July) in a year (61 days out of 365).

Probability of WECS residing in BD state (Unavailability)

$$= \left[\frac{\lambda_{15}}{\lambda_{15}+\mu_{51}}\right] = \left[\frac{61}{365}\right] = 0.1671$$

Probability of WECS being in GD state (Availability) = 1- 0.1671 = 0.8328

After simplification,

$$\left[\frac{\lambda_{15}}{\mu_{51}}\right] = 0.2006 \Rightarrow \lambda_{15} = 0.2006.\ \mu_{51}$$

From the average monthly power output data,

The repair rate μ_{51} for WECS (BD) to WECS (GD) = 0.022 $days^{-1}$ *

Using λ_{15}= 0.2006. μ_{51},

$$\lambda_{15} = 0.0041\ days^{-1}$$

Using Equations 4-55, 4-56, & 4-57

Mean Time To Failure (MTTF) from WECS (GD) to WECS (BD) = 226 days

Mean Time To Repair (MTTR) from WECS (BD) to WECS (GD) = 45 days

Cycle Time for WECS = 271 days.

5.5 HYDRO Model

Development of the HYDRO model will also be based on a binary equivalent given in Figure.13. The data for the micro-hydro system at Montana, USA are given in Table V. The power from stream flow is calculated using the formulae given in Appendix A.

* Based on average restoration/ recovery time of power output for the months of June (60 days) and July (30 days) = 90/2= 45 days

TABLE V

HYDRO RESOURCE FOR BOULDER CREEK, MONTANA, USA

Month	**Average Daily Stream Flow**	**Hydro Power (from stream flow)**
	(L/s)	(kW)
January	14.90	1.11
February	15.70	1.17
March	13.50	1.00
April	18.00	1.34
May	52.20	3.90
June	128.30	9.59
July	34.50	2.57
August	15.20	1.14
September	12.20	0.91
October	15.30	1.14
November	16.30	1.21
December	14.90	1.11
Annual Average (kW) = 2.27		

HYDRO being in GD or BD states is dependent upon the amount of power generated by the micro-hydro system.

Assuming a threshold of 1.13 kW (50% of Annual average), HYDRO system at this location is BD for four months (January, March, September, and December) in a year (a total of 123 days out of 365 days).

The graph corresponding to Table V is given in Figure.18.

Probability of HYDRO residing in BD state (Unavailability)

$$= \left[\frac{\lambda_{16}}{\lambda_{16} + \mu_{61}}\right] = \left[\frac{123}{365}\right] = 0.3369$$

Probability of HYDRO in GD state (availability) = 1- 0.3369 = 0.6631

After simplification,

$$\left[\frac{\lambda_{16}}{\mu_{61}}\right] = 0.5080 \Rightarrow \lambda_{16} = 0.5080.\ \mu_{61}$$

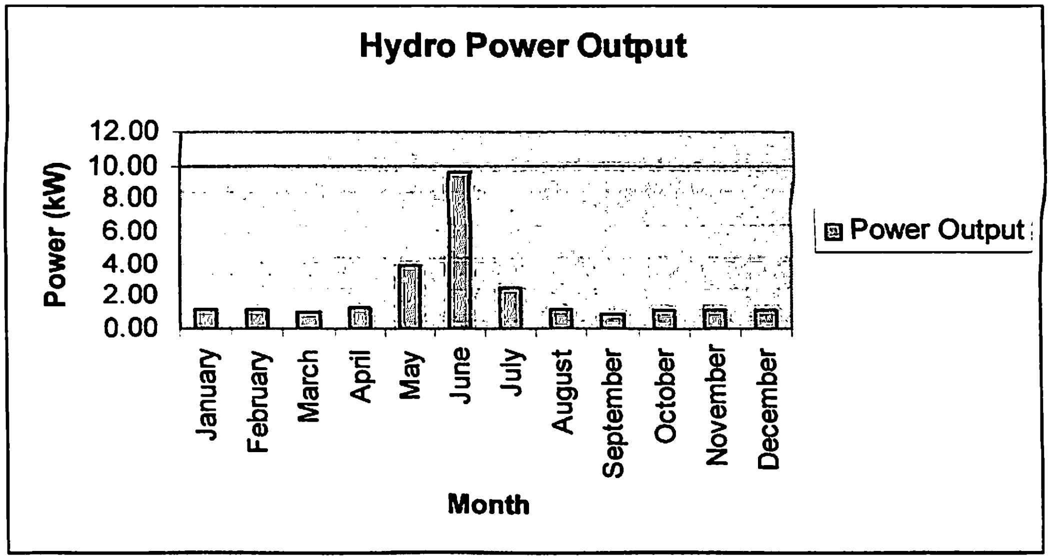

Figure.18. Hydro power output for a year for Boulder Creek, Montana, USA

From the average monthly power output data,

The repair rate μ_{61} for HYDRO (BD) to HYDRO (GD) = 0.026 $days^{-1}$ *

Using λ_{16}= 0.5080. μ_{61},

$$\lambda_{16} = 0.0133 \text{ days}^{-1}$$

Using Equations 4-67, 4-68, & 4-69

Mean Time To Failure (MTTF) from HYDRO (GD) to HYDRO (BD) = 75 days

Mean Time To Repair (MTTR) from HYDRO (BD) to HYDRO (GD) = 38 days

Cycle Time for HYDRO = 113 days.

* Based on the average restoration/recovery time for the months of Jan (30 days), March (30 days), September (30 days) and December (60 days) =150/4= 37.5 days = 38 (approx.)

5.6 Summary and Discussion

As discussed in Section 4.5, this model is based on a conservative assumption of a fully redundant system (i.e. presence of even one subsystem can fully keep the IRES operational). This assumption will involve high expenditure and it is extremely difficult to justify such a system in reality. Based on the resource availabilities, needs and location of the IRES, failure of more than one subsystem can cause a total shutdown of IRES. An aggregated binary model can be developed with "IRES DOWN" (aggregation of the subsystems whose collective failure might lead to system shutdown) and "IRES UP" (the rest of the subsystems in the operational state). This assumption will lead to a different binary equivalent for IRES as it is dependent entirely on the type and location of a subsystem(s) that fail. For example, in a scenario that demands both BIO and ES to be operational, failure of PV, HYDRO and WECS will not lead to system failure. On the contrary, combined failure of BIO and ES might lead to total shutdown of IRES even though all the other subsystems are functional. More scenarios are possible based on the resource, needs, and location of the system.

The binary equivalent shown in Figure.14 is based on the assumption (another extreme case) that failure of even one of the subsystems of IRES may lead to a total system shutdown. For this assumption, all the subsystem down states are merged into an "IRES DOWN" state.

The following results are obtained after applying the above assumption to the model.

From Equation 4-70,

$\lambda = 8.040 \text{ days}^{-1}$

Thus, MTTF for the total shutdown of IRES = 0.124 days (2.98 hours)

From Equation 4-71,

$\mu = 1.803 \text{ days}^{-1}$

MTTR from IRES (Down) to IRES (Up) = 0.554 days (13.3 hours)

Cycle time for IRES = 0.678 days (16.28 hours)

Mean time to transition from IRES (Up) to IRES (Down) is very low because of the extreme assumption that the IRES goes "down" with failure of even a single subsystem. This assumption corresponds to a series system whose success depends on the success of all the subsystems/components. For a series system, the components need not be topologically or physically in series but only that all of the subsystems/components must succeed for the system to succeed. In other words, it gives a lower bound for reliability whereas the parallel configuration gives an upper bound for reliability.

For the example selected, MTTF for ES is 3 hours and that makes the IRES go down also. This is extremely unrealistic as the IRES can survive the failure of more than one subsystem. In reality, it is necessary to identify all the proper combinations of subsystems which, when failed together, will lead to a total system shutdown. Analysis of such combinations will lead to a realistic performance assessment.

The discussion above points to the need for considerable future work in the area of performance assessment of IRES. It requires a long list of transition rates and performance measures that should be gleaned from real-life operating data (which are rare at the present time) or should be estimated based on reasonable grounds.

CHAPTER 6

SUMMARY AND CONCLUDING REMARKS

6.1 Summary and Concluding Remarks

An Integrated Renewable Energy System (IRES) utilizes two or more energy resource to supply a variety of energy and other needs in remote rural areas. Many energy conversion and storage devices are integrated into IRES in one of many possible combinations to meet the needs.

One of the many challenges faced by the designers of IRES is to assess the performance and supply energy at minimum possible cost with a quality demanded by end-users. Performance assessment is greatly dependent upon the temporal nature of different renewable energy resources and needs. The objective of this study was to develop and formulate a mathematical model for the analysis and quantification of an IRES using Markov modeling techniques.

Resources such as solar radiation and wind are highly stochastic and location-specific. They have variations that may be instantaneous, hourly, daily, monthly, annual, etc. Resources such as biomass and running water have predictable and seasonal variations. The approach described in this thesis considers all these aspects and proposes a framework to assess the performance based on mean residence times in various states, frequencies of encountering different operating states, availabilities of the subsystems constituting the IRES and an overall measure of effectiveness of the IRES in meeting the needs and objectives for which it is designed and operated.

Formulation of a Markov model could be based on the assumption that all the subsystems are logically in series (meaning that all them should be "up" for the IRES to be "up") or on the assumption that it is a fully redundant system meaning that the IRES can be fully operational even with the presence of a single subsystem. Both of these are extreme cases and do not reflect the real world situation since the overall system can succeed even with two or more subsystems being down. The numerical example presented assumes a series configuration. In reality, based on resource availabilities, needs and location of the IRES, failure of more than one subsystem can be tolerated and the IRES could be successful. Such cases should be properly identified for a location to carry out a performance assessment.

Obviously, many of the details of the proposed model could be refined and fine-tuned as more knowledge is gained on this subject. In practice, by resorting to balanced and educated compromises, performance of IRES can be assessed effectively. The necessary first step in this process has been developed and documented.

6.2 Scope for Future work

Further work on performance assessment of IRES is needed in the following areas:

1) Identification of the subsystems (or combinations thereof) vital for the operation of IRES
2) In addition to the two extreme cases mentioned above, approaches need to be developed assuming IRES to be a series-parallel system

3) Additional components/subsystems can be incorporated to satisfy even more energy needs in the study to simulate real-time application in remote rural areas

4) Failure models of subsystems of IRES (such as technical, environmental, social factors, etc) should be identified and quantified.

Further work on the identification of combinations of subsystems that are vital for the operation of IRES is a very good step towards performance assessment. For example, in a scenario that demands both BIO and ES to be operational, failure of PV, HYDRO and WECS may not lead to overall system failure. On the contrary, combined failure of BIO and ES might lead to total shutdown of IRES even though all the other subsystems are functional. Proper identification of BIO and ES as "vital" in the preliminary phase of assessing performance will prove extremely beneficial. Data on combined failure of BIO and ES should be collected to consider this specific case.

The Markov model developed in Chapter 4 can be refined assuming the IRES to be a series-parallel system. This assumption will be more realistic than the two extreme cases (series and parallel) mentioned.

Additional energy conversion and energy storage technologies based on other renewable energy resources can be included in the overall assessment as they become technically and economically viable. To be more realistic, all needs –electricity, water, cooking biogas, etc., must be taken into account for discussion based on the availability of data.

The approach discussed in this study considered a generalized failure (or down state) due to technical, lack of resource availability, environmental, social factors, etc. Each factor can be dealt with in detail and a separate Markov model can be developed incorporating different types of failures. Also, a computer program can be developed to analyze the detailed model and different scenarios based on importance of subsystem, failures, etc. Obviously, usefulness of the results obtained will depend on the quality of the data used to arrive at the various parameters of the model.

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APPENDIX A

CALCULATION OF POWER OUTPUT

Wind Power (kW)

Power in Wind, $P = \frac{1}{2} * \rho * v^3$

where

ρ (rho) = the density of dry air = 1.225 kg/m^3 (kilograms per cubic meter, at average atmospheric pressure at sea level at 15° C).

v = wind speed in m/s (meters per second)

Hydro Power (kW)

Hydro Power (from stream flow),

$$P = Q * g * H$$

where

Q = Stream flow in L/s (liters per second)

g = Acceleration due to gravity= 9.81 m/s^2 (meters per square second)

H = Available Head = 25 feet = 7.62 m for the selected location at Montana, USA

APPENDIX B

CALCULATION OF DAILY VARIATIONS WITHIN A MONTH

Calculation of daily variations within a month was carried out using HOMER, software developed by National Renewable Energy Laboratory, Golden, Colorado.

I. PV model

Daily variations of the solar resource for the off-grid location in Montana are given in Figure.19.

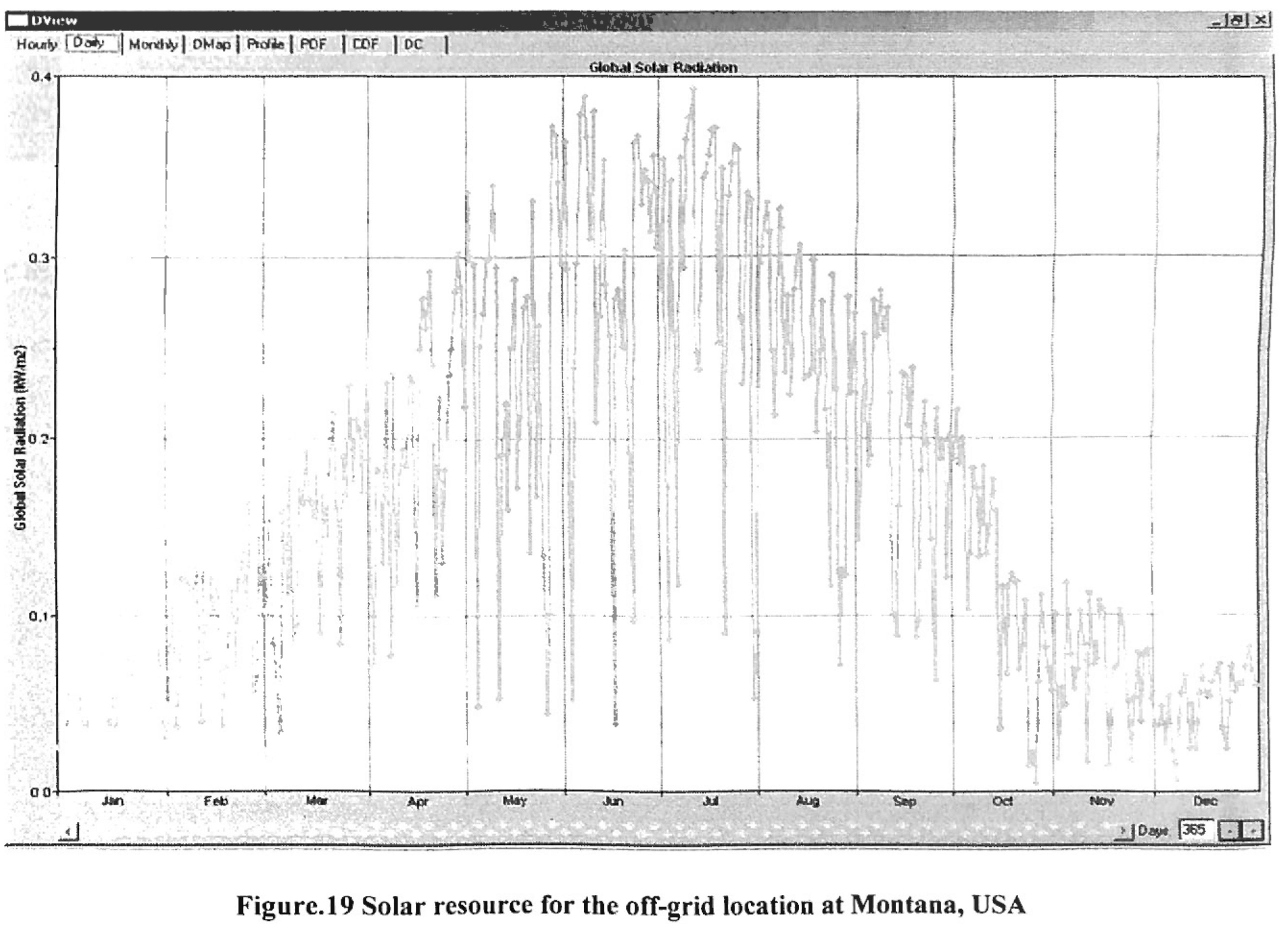

Figure.19 Solar resource for the off-grid location at Montana, USA

For this location, as mentioned before, the solar radiation is less than the annual average for the months of January, November and December. These months are considered for further analyses to find the recovery time (time for restoration of solar radiation above annual average). The following figures show the daily variations of solar radiation within the months of January, November and December.

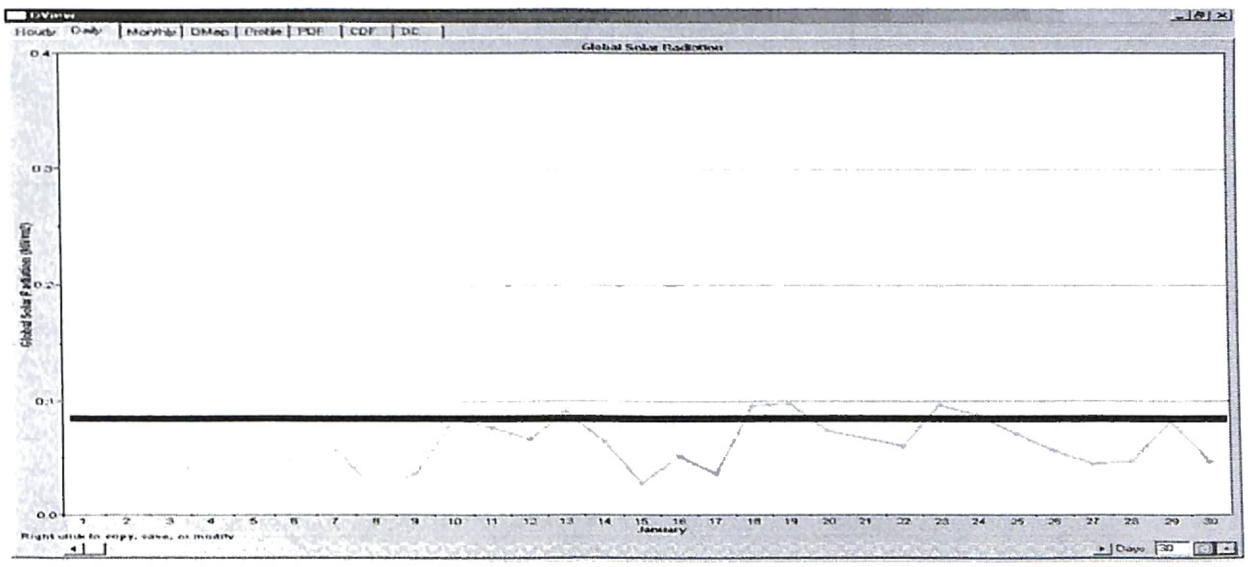

Figure.20 Daily variations of solar radiation for January

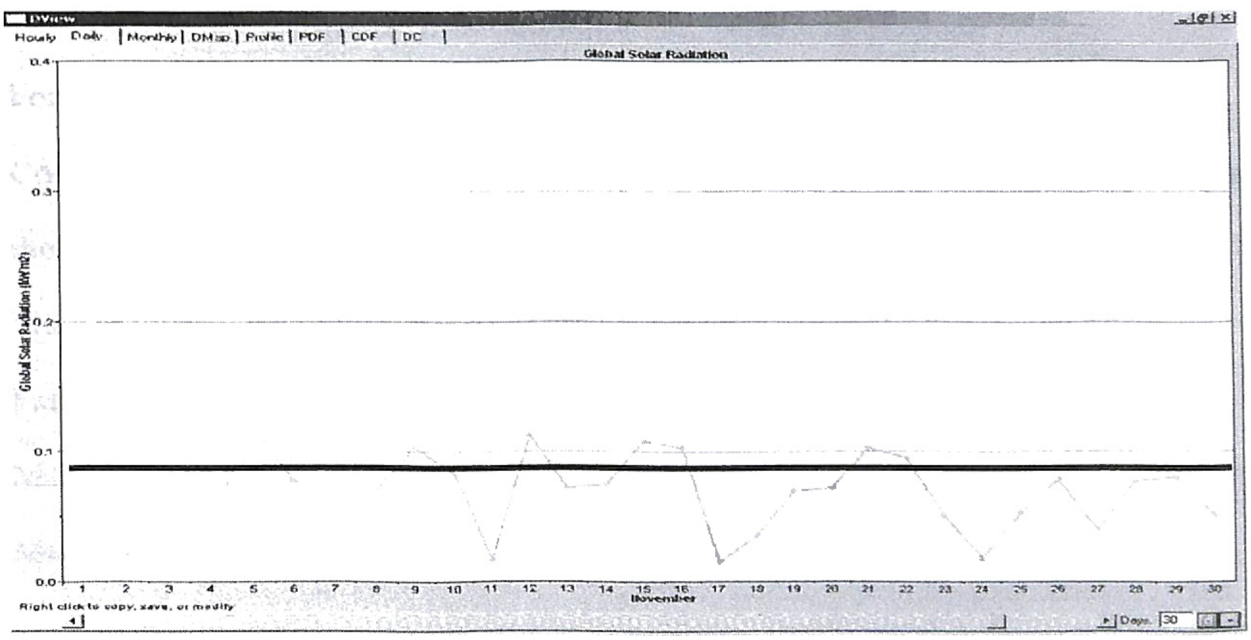

Figure.21 Daily variations of solar radiation for November

Assuming 50 % of annual average (i.e. 0.082 kw/m2), solar radiation in the month of January recovers to the threshold value every 4 days (on an average).

Mean time to transition from PV (BD) to PV (GD) = 4 days for January

For the month of November, it takes 4 days (on an average) to recover to the value of 0.082 kW/m2 (50% of annual average).

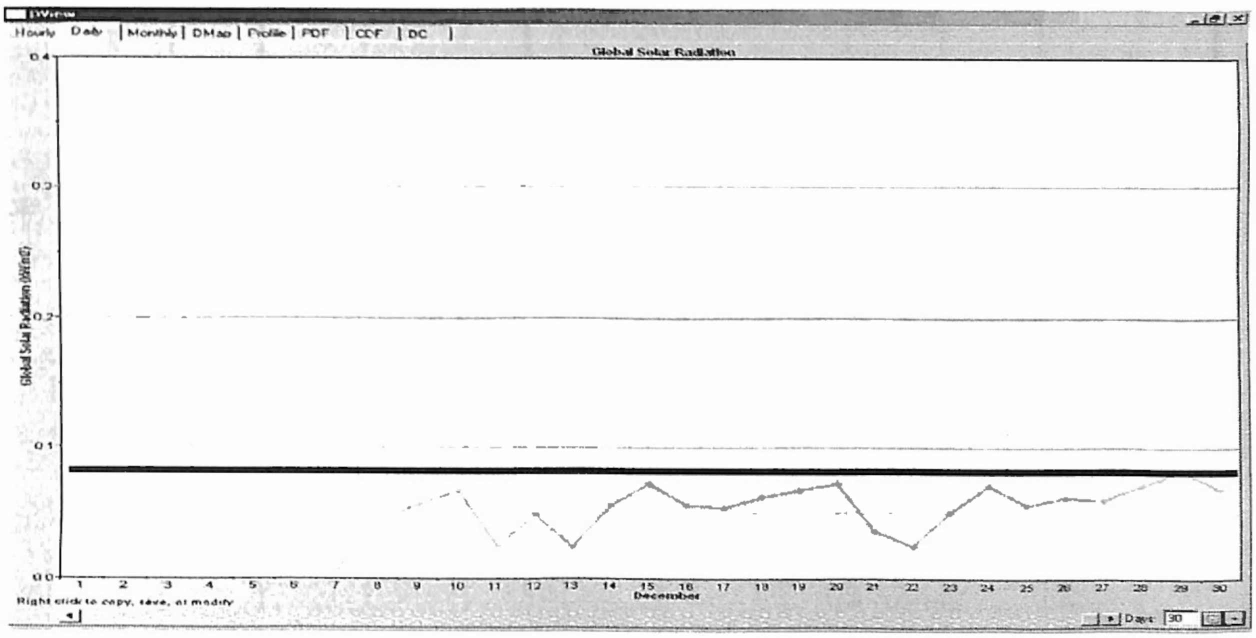

Figure.22 Daily variations of solar radiation for December

For December, the average solar radiation recovers after 10 days (approximately).

Considering these three months, mean time for the restoration of solar radiation to near the threshold value is around 6 days.

Thus recovery/ restoration rate $\mu_{41} = 1/6 = 0.166$ day^{-1}

Failure rate $\lambda_{14} = 0.3369.\ \mu_{41} = 0.0561$ day^{-1}

Mean time to transition from PV (GD) to PV (BD) = 18 days

Mean time to transition from PV (BD) to PV (GD) = 6 days

II. WECS model

Daily variations of wind resource for the location at Montana are given in Figure.23.

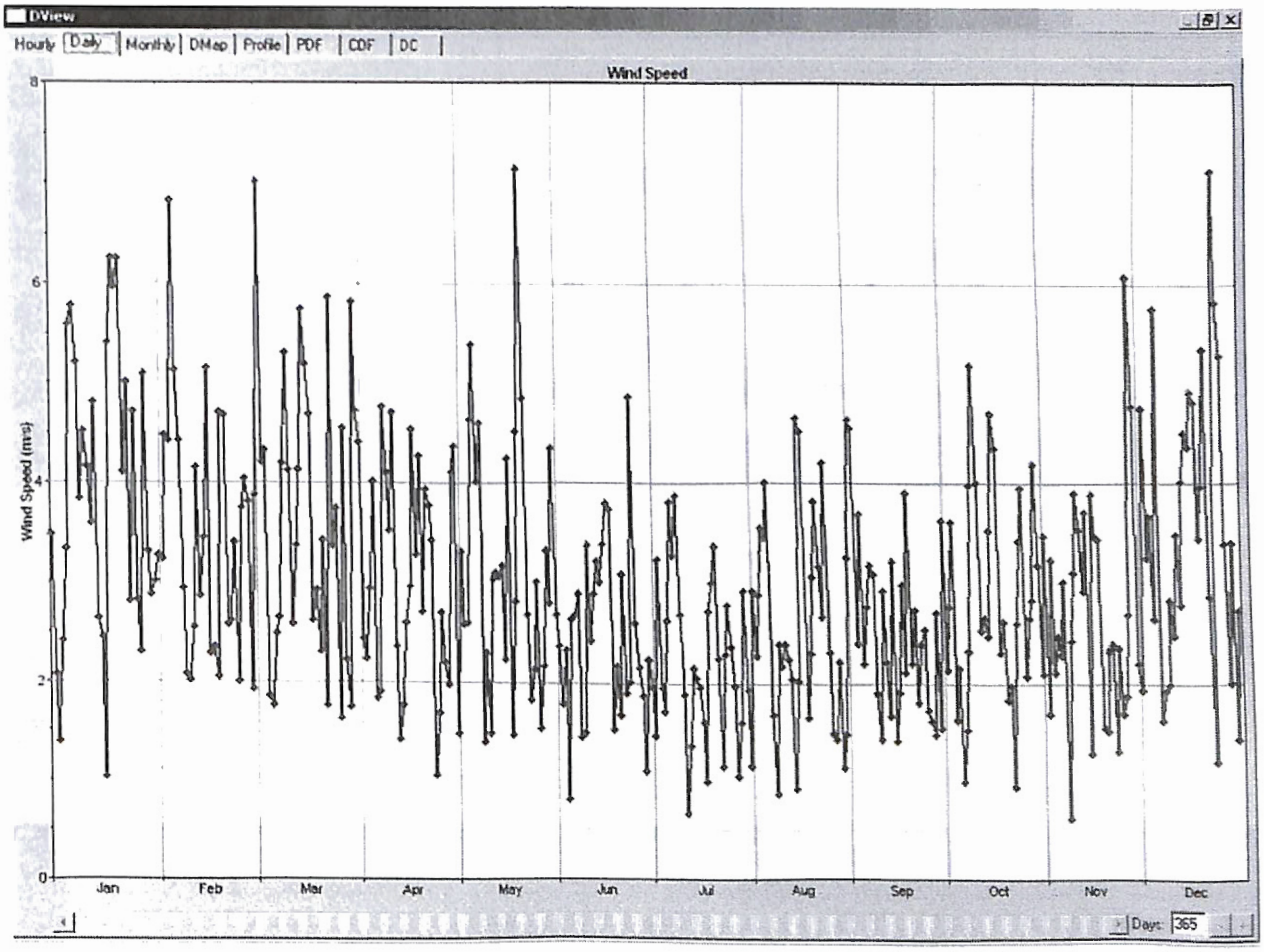

Figure.23 Daily variations of wind speed for the location at Montana, USA

Wind power output is less than annual average for the months of June and July. The rates of recovery for these months are calculated based on the daily variations within the month. The following figures illustrate the variation of wind speed for June and July.

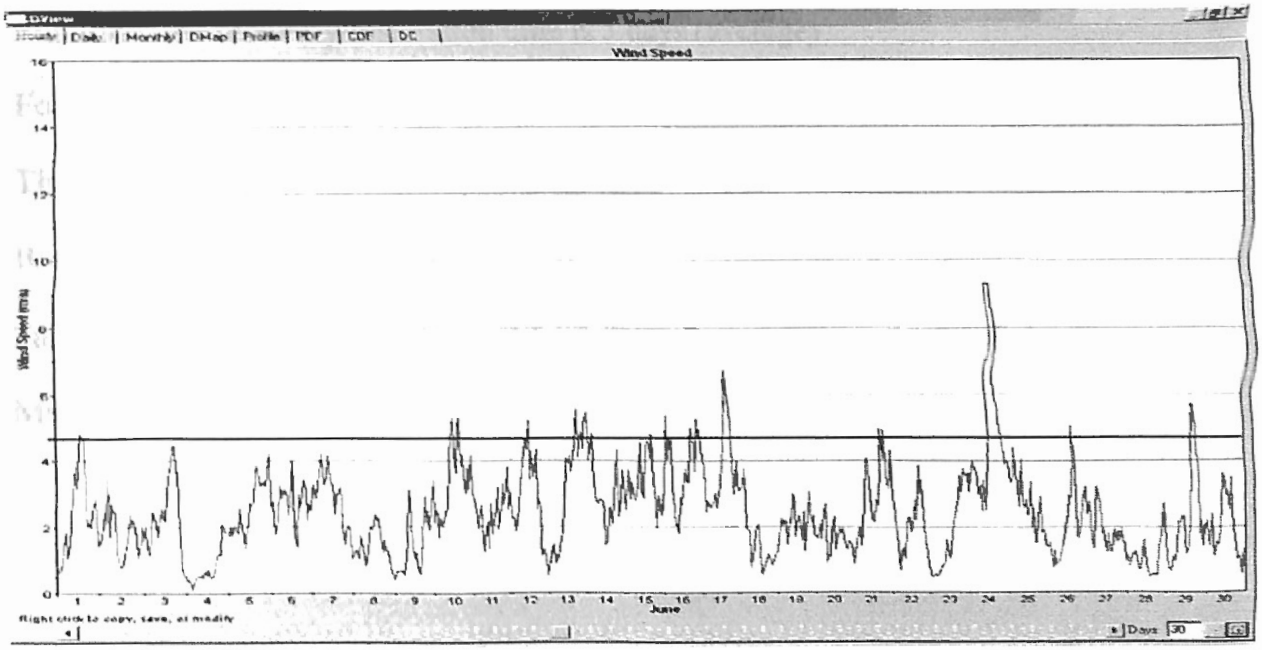

Figure.24 Wind speed variations for June at Montana, USA

Power in wind, $P = \frac{1}{2} * \rho * v^3$
P = 0.063 (50 % of annual average)
$\rho = 1.225\ kg/m^3$ – (Density of air at avg. atmospheric pressure at sea level at 15C)
Thus, Wind speed, v= 4.68 m/s

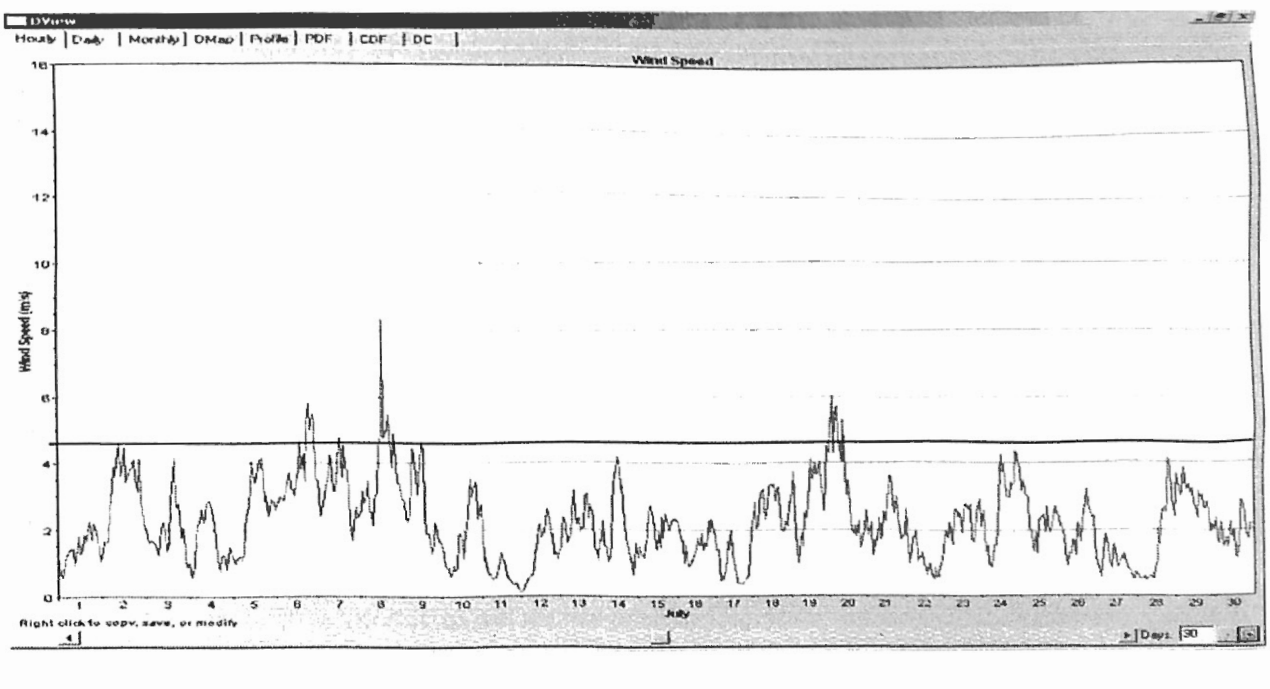

Figure.25 Wind speed variations for July at Montana, USA

For June, the recovery/restoration time is 3 days (average)

For July, it is 6 days (average)

Thus the mean time for restoration is 4.5 days = 5 days

Restoration rate, μ_{51} = 0.2 day $^{-1}$

Failure rate from WECS (GD) to WECS (BD), λ_{15} = 0.2006. μ_{51} = 0.040 day $^{-1}$

Mean time to transition from WECS (GD) to WECS (BD) = 25 days

VITA

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