OPTIMIZATION AND DESIGN OF STAND-ALONE INTEGRATED RENEWABLE ENERGY SYSTEMS

By

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OPTIMIZATION AND DESIGN OF STAND-ALONE INTEGRATED

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NOMENCLATURE

a	Cost of hardware utilizing a given renewable energy resource
a_α	Ratio of Cost of hardware associated with α^{th} resource to a
a_{ij}	Cost in dollars per kWh when i^{th} resource is used for j^{th} task
A_1	Area under the power duration curve for 'C' (see Figure 29)
A_2	Area under the power duration curve for 'C' (see Figure 29)
A_a	PV array area
A_c	Solar cell area exposed
AP(0)	Atmospheric pressure at sea level
AP(Z)	Atmospheric pressure at altitude z above sea
b	Energy storage cost
c	Instantaneous power input to storage
C	The random variable power input to storage
C(t)	Power input to storage at time t
CA	Total annual cost
CC	Total capital cost of the system
c_1	Special value of c
C_p	Aeroturbine power coefficient

C_{ij}	That part of CA which corresponds to i^{th} resource - j^{th} task combination
CC_0	Initial cost of the system
CC_1	Special value of CC
d_i	Diversity factor for the tasks supplied by the i^{th} resource, $(d_i \geq 1)$
dE_B	The corresponding incremental decrease (increase) in the installed capacity of the Energy storage system required to maintain the same LPSP
dP_r	The incremental increase (decrease) in the installed system power output required for maintaining the same LPSP
D	Rotor diameter
D_e	Daily energy need
e	Electron charge
E_B	The installed capacity of the storage system
E_i	Total energy derived per year from the i^{th} resource for all the tasks (reckoned at point A of Figure 26)
E_g	Total energy derived from biogas
E_m	Minimum acceptable energy storage level
E_R	Maximum energy storage capacity
E_{B0}	Chosen value of E_B
$E_{B1}, E_{B2}, E_{B3}, E_{B4}$	Special values of E_B
E_{Bmin}	Minimum value of E_B allowed
E_{Bmax}	Maximum value of E_B allowed
E_{ij}	That part of E_i used for the j^{th} task
E_{imax}	Maximum available energy from i^{th} resource

$E(t)$	Energy stored at time t
$f(X)$	Probability density function for X
$f_C(c)$	Probability density function for C
$f_{I_{CC}}(I_{CC})$	Probability density function for I_{CC}
$f_{KK}(kk)$	Probability density function for kk
$f_L(l)$	Probability density function for L
$f_P(p)$	Probability density function for P
$f_{pe}(p_{ew})$	Probability density function for $p_{ew}(p_{ew} \neq 0)$
$f_{PA}(p_{ew})$	Probability density function for p_{ew} (for all values including zero)
$f_{ps}(p_s)$	Probability density function for p_s ($p_s \neq 0$)
$f_S(s)$	Probability density function for S
$f_{SA}(p_s)$	Probability density function for p_s (all values including zero)
$f_V(V_w)$	Probability density function for V_w ($V_C \leq V_w \leq V_F$)
$f_W(V_w)$	Probability density function for V_w (all values)
$f_W(w)$	Probability density function for W
$F_C(c)$	Probability distribution function for C
$F_{Pe}(p_{ew})$	Probability distribution function for $p_{ew}(p_{ew} \neq 0)$
$F_{PA}(p_{ew})$	Probability distribution function for p_{ew} (all values including zero)
$F_{PS}(p_s)$	Probability distribution function for $p_s(p_s \neq 0)$
F_{S1}	Probability of having non-zero insolation
$F_{SA}(P_s)$	Probability distribution function for p_s (all values including zero)
$F_W(V_F)$	Probability of wind speed less than or equal to V_F
$F_W(V_C)$	Probability of wind speed less than or equal to V_C

$F_w(V_w)$	Probability distribution for V_w
F_{w1}	Probability of wind speeds being between V_c and V_F
g	Acceleration due to gravity (9.81 m/s^2)
G_1	Constant defined in Equation (2.2.1.5)
G_2	Constant defined in Equation (2.2.1.6)
g(y)	Probability density function for Y
h	Mean head of water
i	Index representing the resource
I	Current in solar cell
IRES	Integrated Renewable Energy System
I_{CC}	Insolation under cloudy conditions
I_{CS}	Clear sky radiation
I_{Cmax}	Maximum I_{CC}
I_{ex}	Extraterestrial radiation = 1.35 kW/m^2
I_{max}	Maximum I_{CS}
I_o	Saturation current of solar cell
I_S	Short circuit current of solar cell
I(t)	Solar radiation intensity at time t
j	Index representing the task
J	Jacobian
k	Boltzman Constant
k_i	Effective load (plant) factor for the i^{th} resource
k_{ij}	Load factor for the i^{th} resource - j^{th} task combination
k_p	Packing factor
kk	Portion of sky covered by cloud ($0 \leq kk \leq 1$)
l	Instantaneous load
L_m	Minimum electrical load demand

L_M	Maximum electrical load demand
$LPSP_1$, $LPSP_2$, $LPSP_3$	Special values of LPSP
$L(t)$	Load demand at time t
m_{ij}	Fraction of the capital cost needed per year for the operation and maintenance of the i^{th} resource-j^{th} task combination
$m(0, \alpha_{SA})$	Air mass at sea level
$m(Z, \alpha_{sa})$	Air mass at altitude Z above sea
$m_{min}(0, \alpha_{SA})$	Minimum air mass at sea level
$m_{min}(Z, \alpha_{SA})$	Minimum air mass at altitude Z above sea
M	Number of resources considered
M_1	Number of resources considered for electricity generation using probabilistic approach
M'	Number of resources with upper bound for availability, $M' \leq M$
n_{ij}	Lifetime in years for the hardware involved in the i^{th} resource-j^{th} task combination
N	Number of tasks considered
p	Instantenous power output of the system
pdf	Probability density function
PDF	Probability distribution function
p_{ew}	WECS output power
p_i	Maximum rate of energy use expected of the i^{th} resource
p_{ai}	Available power rating for the i^{th} resource
p_{ij}	Maximum power required for handling the share of the j^{th} task supplied by the i^{th} resource

P_{oj}	Maximum output power required for the j^{th} task
p_s	SEC output power
$p[E_m]$	Probability of E(t) being larger than E_m
$p[E(T) < E_m; t < T]$	Probability of E(t) being less than E_m during the study period T
P_{kW}	Electric output power of hydroturbine
P_{ij}	Capital cost of the hardware involved in the i^{th} resource-j^{th} task combination
P_m	Mechanical output power of aeroturbine
P_r	Installed rated power of the system
P_{ro}	Chosen value of P_r
P_{rmin}	Minimum value of P_r
P_{rmax}	Maximum value of P_r
P_{rn}	Normalized WECS rating
$P_{r\alpha}$	Rating of device utilizing α^{th} resource
P_R	Rated output of WECS
P_{R1}	Output power of the WECS at the rated wind speed
P_S	Output power of SEC
P_{smax}	Maximum value of P_s
P(t)	Power output of the system at time t
Q	Water flow
r	Annual interest rate
R_o	Load impedance
R_i	Energy equivalent of the i^{th} resource
R_j	Junction impedance
R_U	Random variable uniformly distributed between zero and one

s	Instantaneous power output of PV array
S	The random variable, power output of PV array
SEC	Solar Electric Conversion System
Ssmin	Allowable equivalent continuous power depletion from the energy storage
$S(t)$	Output power of PV array at time t
t	Time
T	Study period
T_e	Temperature in degrees kelvin
$T_{cr,ij}$	Charge rate for the i^{th} resource-j^{th} task combination
u	Variable of integration
$U(X)$	Function of random variable X
U_j	Total output energy required for j^{th} task
U_{ij}	That part of U_j drawn from the i^{th} resource
V_C	Cut-in wind speed of WECS
V_F	Furling wind speed of WECS
V_g	Volume of biogas
V_j	Junction voltage
V_R	Rated wind speed of WECS
V_w	Wind speed
V_α	Mean hourly wind speed during the α^{th} hour
w	Instantaneous power output of WECS
W	Random variable, power output of WECS
WECS	Wind Electric Conversion System
W_d	Number of days of storage
$W(t)$	Power output of WECS at time t
$W(Y)$	Function of random variable Y

$W'(Y)$	Derivative of $W(Y)$ with respect to Y
x	Variable used in Equation (2.1.1.5)
x_i	Measure of the i^{th} resource required
X	Random variable
x_{ij}	That part of x_i required for j^{th} task
x_{imax}	Maximum value of x_i available
X_1	Intersection point of cost function and P_r - E_B curve for $LPSP_1$
X_{Aj}	Portion of resource A used for performance of task j
X_{Bj}	Portion of resource B used for performance of task j
X_{Cj}	Portion of resource C used for performance of task j
X_{Dj}	Portion of resource D used for performance of task j
y_α	Total hourly insolation for the α^{th} hour
Y	Random variable
Y_1	Intersection point of cost function and P_r - E_B curve for $LPSP_1$
Z	Altitude above sea
Z_1	Optimum point on P_r - E_B curve for $LPSP_1$
α	Index of summation
α_B	Scale parameter for Beta distribution
α_{SA}	Solar altitude angle
α_W	Scale parameter for Weibull distribution
β_B	Shape parameter for Beta distribution
β_W	Shape parameter for Weibull distribution
$\Gamma(x)$	Gamma function
η_{ij}	(U_{ij}/E_{ij}) from point A to point B in Figure 26
η_H	Combined efficiency of microhydro unit

η_p	Mean efficiency of PV array
η_{SC}	Efficiency of solar cell
η_t	Mean efficiency of solar thermal collector
η_w	Mean efficiency of aeroturbines
μ_B	Mean of recorded insolation
μ_W	Mean of recorded wind speed
Π	3.14 radians
ρ_o	Air density
ρ_w	Water density
σ_B	Variance of recorded insolation
σ_W	Variance of recorded wind speed

CHAPTER I

INTRODUCTION

1.1 Development and Utilization of Renewable Energy Resources

Energy resources that are renewed on a short term (daily, weekly, monthly, or annual) basis are designated as renewable energy resources. Almost all the renewable energy resources considered for utilization at the present time trace back to the Sun. Wind energy, solar radiation and heat, falling water, and biomass are different manifestations of solar energy and they have received most of the attention. They are fairly evenly distributed around the world, are plentiful [1], and free. However, these resources are dilute and conversion to usable forms require capital-intensive hardware.

Wind is the movement of air caused by the uneven heating of the earth's atmosphere and the associated temperature gradients. Wind energy has been used, in some form or other, for centuries to satisfy different energy needs of human beings. However, it was not until the turn of the 19th century that wind power was used for electricity generation as well as for supplying rotating shaft power. Denmark, France, Germany, and the United Kingdom are some of the European countries which initiated the early works in this area [2-7]. This interest was mainly due to the fuel shortage caused by the First and Second World Wars.

Solar radiation is the emission of photons from the Sun. One of the ways these photons can be utilized is by means of the photoelectric effect which is the primary effect of photons on solids [8]. This effect was discovered by H. Hertz in 1887. The generation of a potential when the region in or near the built-in potential barrier of a semiconductor is ionized by radiation is known as the photovoltaic effect. Photovoltaic effect was known long before its feasibility for direct energy conversion was illustrated by Chapin, Fuller, and Pearson [9]. Recently, the concept of utilizing solar radiation for electricity generation using solid-state power plants has gained momentum [10-12]. The recent interest is primarily due to the decreasing cost of photovoltaic devices, coupled with increasing conversion efficiencies.

Solar heat is due to thermal agitation of matter initiated by the absorption of solar radiation. The Sun has been used as a source of heat for a long time. For example, solar heat has been used, and still is, in many countries by farmers to dry their crops [13-15]. Solar energy has been used for space heating and cooling since the fifth century B.C., when the Greeks developed the basic principles to be used in solar architectural designs. Recently, the concept of utilizing the Sun as a source of energy for heating purposes has also been gaining momentum [16,17].

Falling water is a term used to denote the potential energy of water stored at an elevation. It is a renewable source of energy made available through the hydrologic cycle operated by the Sun's energy. Potential energy of water has made major contributions to the development of human beings. Watermills were among the first engines invented to assist humans [18]. Waterwheels have been used for milling, pumping, and other functions since 300 B.C. Watermills are still used in many countries to provide economical, low-level mechanical power [19]. With the invention of the dynamo in the 19th century, water turbines were used to generate electricity as well as rotating shaft power. Its potential as a source of energy for electricity generation was improved significantly with the development of high-voltage transmission lines.

All land and water plants, their wastes or by-products, and the wastes and by-products produced by their transformation are collectively labeled as biomass. The primary source of biomass production is the photosynthesis process by which plants capture sunlight and convert it to biomass [20]. The fact that a flammable gas will be produced if biomass is allowed to rot under certain conditions has been known for centuries. The first reported application of biogas was in Exeter, England in 1895, where the gas obtained by allowing manure to decompose in a carefully designed septic tank was used for street lighting. Countries such as India, China, Taiwan, Philippines, and Korea have been leading the development of this resource in recent times [21, 22]. Common feedstocks for a biogas digester are crop residues, animal wastes, and urban wastes. Use of these wastes for biogas generation not only provides a cheap source of energy but also reduces the health hazard posed by these wastes. The residue obtained after the production of gas constitutes an excellent fertilizer.

1.2 Literature Survey

There is a new awareness of the advantages of utilizing renewable energy sources such as solar radiation, solar heat, wind, biomass, and falling water. This is a consequence of the realization of the limitations of conventional energy sources (oil, coal, and natural gas), ever increasing demands being placed on the finite resources of the world [23], and the adverse effects of utilizing conventional energy resources on the environment. But, there is one basic problem inherent to most of the renewable energy sources and that is their intermittent and highly variable nature. The problem caused by the intermittency of these resources can be partially overcome by adding energy storage and reconversion facilities [24-26], and/or by using the strengths of one source of energy to overcome the weakness of the other.

One problem associated with most of the methods used for the design and analysis of systems utilizing renewable energy resources is the lack of a direct relationship between the system power output and the storage system capacity [27, 28]. For example, Karmeli, et al. [29] have developed a linear programming approach for finding an optimal combination of thermal and water storage for a solar pump. However, the random nature of load and insolation were neglected and average insolation values were used instead; load was divided into two periods - a day time load and a night time load. Also, most of the approaches currently available for design and analysis of systems utilizing renewable resources concentrate either on the economic feasibility of the system or on system reliability [30, 31]. For example, Slesser [32] uses the energy pay back approach and compares systems utilizing solar energy with systems utilizing fossil fuels from an economic point of view. Saif El Rahman [33] has defined a new performance index which can be used to assess the economic competitiveness of solar energy with other resources.

Ofry and Braunstein [34] have presented a design method using hour-by-hour simulation of a Solar Electric Conversion System (SEC). Following this, one can calculate the SEC rating and the required energy storage capacity that would satisfy the energy needs at a given level of reliability. The approach minimizes the total capital cost while arriving at the final design values and it is based on employing Loss of Power Supply Probability (LPSP) as the key system parameter. LPSP is a function of the amount of energy stored in the energy storage system, which, in turn, characterizes the overall status of the system very well because it is a function of system output, rated capacity of the storage system as well as load demand. This approach bridges the gaps mentioned earlier. Ofry's approach requires the availability and processing of a large amount of data. Bucciarelli [35] has presented another approach for designing a stand-alone SEC. It uses a one step Markov process [36] and treats the energy production and storage as a random walk in the energy storage domain. In order to use this approach the designer requires the following information: a) variance of the daily recorded insolation, and b) an estimate of the mean of the daily energy input to the storage. This approach also utilizes LPSP as the key system variable. However, it does not require detailed recorded data as in Ofry's approach. Farghal, et. al. [37] use linear programming to calculate a first approximation of the design and then use an LPSP based approach to find the combination of storage capacity and the SEC rating that satisfies the required reliability constraints and minimizes the cost.

A system utilizing more than one renewable energy resource as input to satisfy a variety of energy needs is called an "IRES", an acronym which stands for "Integrated Renewable Energy System". A number of energy centers utilizing one or more of the renewable energy resources mentioned have been established around the world in order to demonstrate the feasibility of harnessing renewable energy resources [38, 39]. Recently, the concept of utilizing different manifestations of solar energy in an integrated fashion has been gaining momentum world-wide [40-44].

Two approaches have been proposed for the utilization of several manifestations of solar energy in tandem. In the first approach, one form of energy is selected as the form which is to be made available to the consumers. All the available resources are then converted to this form for storage and supply to the consumers. The second approach advocates the matching of resources, devices, and needs a priori and achieves the integration of benefits at the user's end [45]. One of the fundamental technical problems facing the designers of IRES is to match the varying energy and power requirements of the loads with the mostly stochastic characteristics of the resources in an appropriate manner. However, the suitability or appropriateness of an IRES depends on many technical and socioeconomic factors [46, 47] which are highly site specific and country specific. Most earlier attempts at the design of an IRES simply consisted of independent (decoupled) design of individual components and subsystems. Reddy and Subramanian [48] have proposed a mathematical formulation of the IRES in an attempt to optimize its design. The stated objective was to find the optimum way of using a resource to satisfy a particular energy need by employing a specific device, subject to a set of constraints on resource availabilities and energy and power requirements of the loads. Optimum ratings of components of the IRES that would satisfy the energy needs and the given constraints are those that minimize the chosen performance index. However, this approach is too involved and it is almost impossible to obtain even reasonable estimates for all the variables, factors, and parameters needed. Because of its complex nature it has not yet advanced far beyond the formulation stage.

Almost all the attempts at designing an IRES up to this time have relied on detailed recorded data. Though the design results obtained by this procedures are accurate for the site in question, they require the availability and processing of large amounts of recorded data which are not readily available for many sites.

1.3 Problem Statement

The goal of the problem under study is to design an IRES to satisfy a given set of energy requirements by utilizing different renewable energy resources in an optimal manner as defined. The system is assumed to be "stand-alone", and energy storage is used as needed to supply the load at a predetermined level of reliability. An objective function, which could be either total capital cost or total cost per year, is minimized in arriving at optimum designs. In the case of total annual cost, cost of capital as well as operation and maintenance costs must be included. The resources under consideration are:

1. Biomass
2. Solar
    a. Heat
    b. Radiation
3. Wind
4. Falling water (natural or human-made over-head storage)

The energy needs are classified into four groups as follows:

1. Medium-Grade thermal energy (100° to 300° C)
2. Low-Grade thermal energy (less than 100° C)
3. Rotating shaft
    a. fixed
    b. mobile
4. Electricity (ac and dc)

The design procedure must take into account the stochastic characteristics of the resources under consideration as well as the probabilistic nature of the load demand. Resources such as wind and solar radiation are highly variable and site-specific. They have instantaneous, minute-by-minute, hourly, diurnal, interanual, and seasonal variations. On the other hand water resources are primarily seasonal in nature and biomass availability is fairly predictable. Both deterministic and probabilistic design procedures are to be explored and they have the following common elements:

1. Categorize the needs
2. Catalog the resources
3. Consider the stochastic nature of resources and load
4. Find the ratings of different devices and size of energy storage that will minimize the chosen performance index.

1.4 Method of Study

In order to design a stand-alone IRES it is necessary to develop an understanding of the operation of the components involved as well as the interactions between them. The steps taken towards achieving this goal are enumerated below.

(i) Develop both deterministic and probabilistic models as appropriate, for each of the renewable energy resources under consideration.

(ii) Employ these models to study the performance of components and subsystems utilizing these resources in conjunction with energy storage and a suitable load model. This step will include a study of the influence of changes in key system parameters on the operation of the components and subsystems.

(iii) Develop a deterministic formulation for optimizing the design of an IRES. Consider typical examples and perform some sensitivity analysis.

(iv) Develop a probabilistic approach for the design of an IRES and formulate a computer program for executing the design. Consider a few realistic examples.

The results of this research work will be presented in the form of mathematical models, tables, families of curves, and a computer program "IRES". Further, these results are analyzed and some useful conclusions are drawn which could be of assistance in designing an IRES. This work will also pave the way for future studies.

1.5 Organization of the Thesis

Chapter II discusses the mathematical models (both probabilistic and deterministic as appropriate) used for characterizing the various renewable energy resource (wind, solar, biomass, and falling water) and energy conversion devices employed.

Chapter III focuses on the concept of an integrated renewable energy system, and discusses the terminology used. The various approaches used for integrating different renewable energy resources are discussed in this chapter. Also, possible design objectives are outlined.

Chapter IV develops a deterministic model for an IRES, and a design approach based on this is presented. The approach utilizes linear programming to minimize the total annual cost of operating an IRES.

Chapter V develops a probabilistic approach to the design of an IRES. The approach utilizes LPSP as the key system parameter and aims at minimizing the initial total capital investment.

Chapter VI presents a collection of design examples using both deterministic and probabilistic approaches. The results are compared and discussed.

Chapter VII summarizes the dissertation, draws some conclusions and discusses the strengths and limitations of this work. Also, some suggestions for future studies are outlined.

CHAPTER II

RESOURCE, DEVICE, AND LOAD MODELS

This chapter presents and discusses mathematical models (both deterministic and probabilistic as appropriate) used for characterizing the various renewable energy resources (wind, solar, biomass, falling water) and some of the energy conversion devices employed to harness them.

2.1 Resource Models

Over the past decade, many attempts have been made to model stochastic energy resources such as wind and solar radiation as well as other renewable energy resources. [49-54]. However, not much use has been made of these models in designing systems that utilize these renewable energy resources. Instead, the designers have often relied on detailed recorded data [55]. The resulting calculations and designs are fairly accurate, but the procedure used requires the availability and processing of large amounts of detailed data which are not readily available for many sites.

This chapter discusses both probabilistic and deterministic models as appropriate for describing the characteristics of various renewable energy resources and some of the commonly used energy conversion devices employed to harness these resources.

2.1.1 Wind

Wind is highly variable and site specific [56]. It has minute-by-minute, hourly, daily, monthly, and seasonal variations. Continuous plots of wind speed and its direction as a function of time are required if complete information on the nature of the wind regime at any given site is to be obtained. Figure 1 illustrates typical plots of wind speed for a site in Albuquerque, New Mexico. However, such detailed information is not readily available for many sites, and designers of wind energy systems typically have to rely on far less information.

The most commonly available data are hourly wind speed and direction measurements. Different probabilistic models have been suggested for modeling wind speed distributions. [57, 58]. However, the Weibull distribution has found considerable acceptance [59, 60], primarily because of the possibility of adjusting the shape and scale of the distribution by manipulating the shape (β_w) and scale (α_w) parameters. This would allow for modeling a wide range of data. The density and distribution functions for wind speeds are expressed as follows.

$$f_w(V_w) = \left(\frac{\beta_w}{\alpha_w}\right)\left(\frac{V_w}{\alpha_w}\right)^{\beta_w - 1} \exp\left[-\left(\frac{V_w}{\alpha_w}\right)^{\beta_w}\right] \tag{2.1.1.1}$$

$$F_w(V_w) = 1 - \exp\left[-\left(\frac{V_w}{\alpha_w}\right)^{\beta_w}\right] \tag{2.1.1.2}$$

The scale (α_w) and shape (β_w) parameters can be obtained from mean (μ_w) and variance (σ_w) of recorded wind speed [61] by using the following equations.

$$\mu_w = \alpha_w \, \Gamma\left(1 + \frac{1}{\beta_w}\right) \tag{2.1.1.3}$$

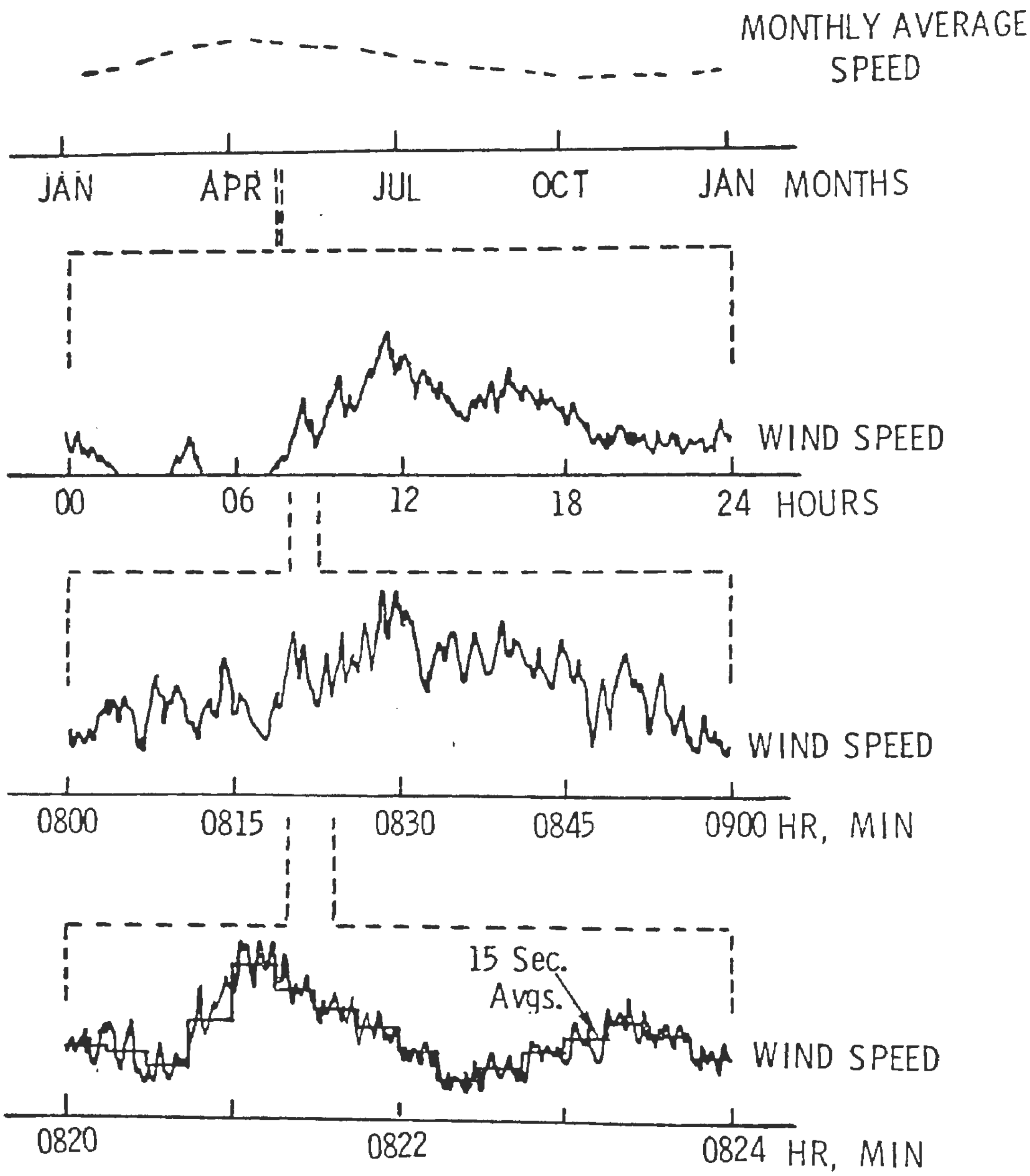


Figure 1. Wind Speed Records on Expanding Time Scales

$$\left(\frac{\sigma_W}{\mu_W}\right)^2 = \frac{\Gamma(1 + \frac{2}{\beta_W})}{\Gamma^2(1 + \frac{1}{\beta_W})} - 1 \qquad (2.1.1.4)$$

where

$$\Gamma(x) = \int_0^\infty u^{x-1} e^{-u} du \qquad (2.1.1.5)$$

This is the model that will be used in this study.

2.1.2 Insolation

Solar radiation is highly variable and it also has minute-by-minute, hourly, daily, monthly and seasonal variations. Continuous plots of insolation as a function of time are required if complete information on the characteristics of the insolation at any given site is to be obtained. Figure 2 illustrates typical plots of insolation for a site in New Mexico. However, such detailed information is not readily available for many sites, and designers of solar energy systems typically have to rely on far less information.

The simplest method for modeling insolation (I_{cc}) on a horizontal surface is to calculate the clear sky radiation (I_{cs}) and multiply [62] that by the random variable (1 - kk), where kk is a random variable representing the portion of the sky covered by cloud ($0 \leq kk \leq 1$).

$$I_{cc} = I_{cs}\,(1 - kk) \qquad (2.1.2.1)$$

Clear sky radiation on a horizontal surface is independent of kk and can be computed using Equation (2.1.2.2) [63].

$$I_{cs} = 0.5\, I_{ex}[\exp(-0.65m(Z, \alpha_{SA})) + \exp(-0.095m\,(Z, \alpha_{SA}))] \qquad (2.1.2.2)$$

where

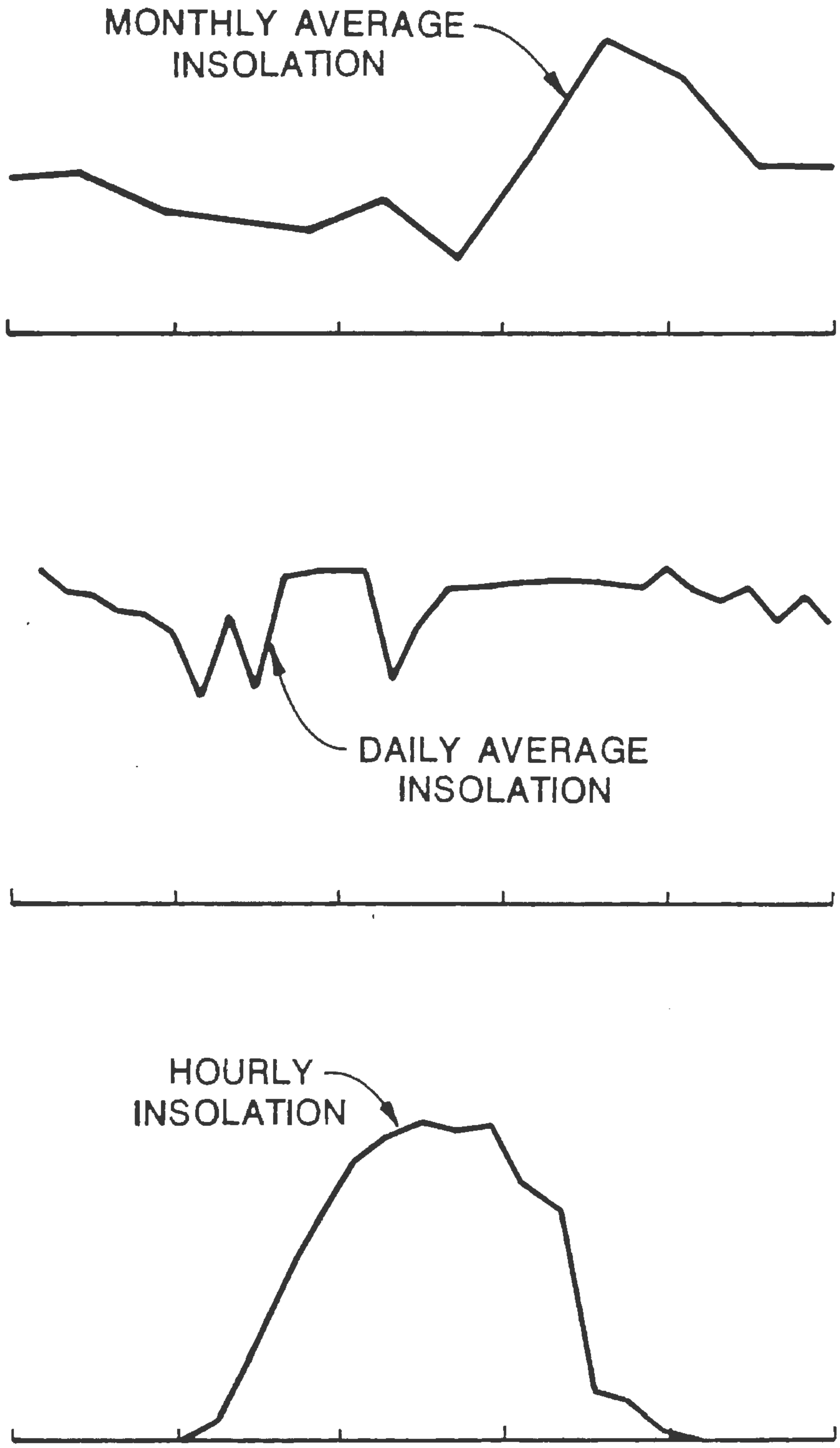


Figure 2. Insolation Records on Expanding Time Scale

$$m(Z, \alpha_{SA}) = m(0, \alpha_{SA}) \frac{AP(Z)}{AP(0)} \quad (2.1.2.3)$$

$$m(0, \alpha_{SA}) = [1229 + (614 \text{ Sin } \alpha_{SA})^2]^{1/2} - 614 \text{ Sin } (\alpha_{SA}) \quad (2.1.2.4)$$

Figure 3 illustrates the nature of the daily variation of clear sky radiation recorded using a recorder mounted on a fixed horizontal surface. But, the maximum amount of insolation is collected when the incidence angle is zero. In other words maximum insolation is collected when the aperture points directly towards the Sun [64]. The angle of incidence can be made zero at all times if the aperture has two degrees of freedom to track the sun as it moves. Figure 4 shows the insolation received by a surface with two degrees of freedom [65]. As can be seen the insolation is almost constant for most of the day, and is equal to the maximum radiation received by the horizontal surface. Therefore, Equation (2.1.2.1) can be modified to Eqution (2.1.2.5) for a two axis tracking system. This modified equation is valid during most of the sunshine hours.

$$I_{cc} = I_{max} (1 - kk) \quad (2.1.2.5)$$

Using Equation (2.1.2.2) it can be shown that

$$I_{max}=0.5 \; I_{ex}[\exp(-0.65m_{min}(Z, \alpha_{SA}))+\exp(-0.095m_{min}(Z, \alpha_{SA}))] \quad (2.1.2.6)$$

where

$$m_{min}(Z, \alpha_{SA}) = \frac{AP(Z)}{AP(0)} m_{min}(0, \alpha_{SA}) \quad (2.1.2.7)$$

But from Equation (2.1.2.4)

$$m_{min}(0, \alpha_{SA}) = 1 \quad (2.1.2.8)$$

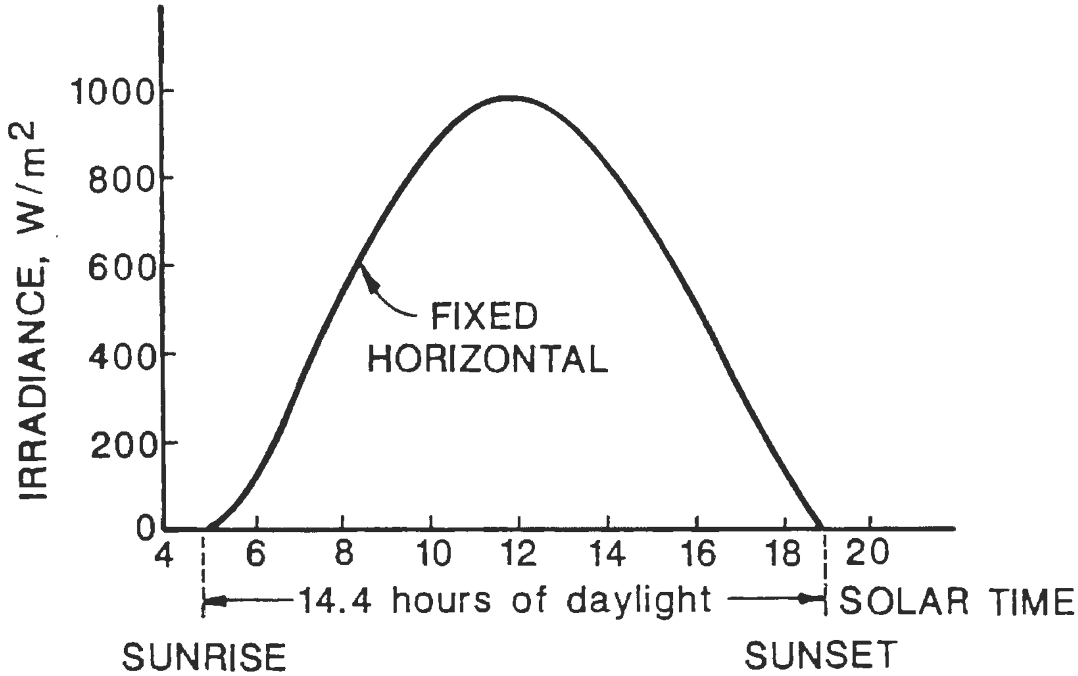


Figure 3. Irradiance Measured on a Fixed Horizontal Surface

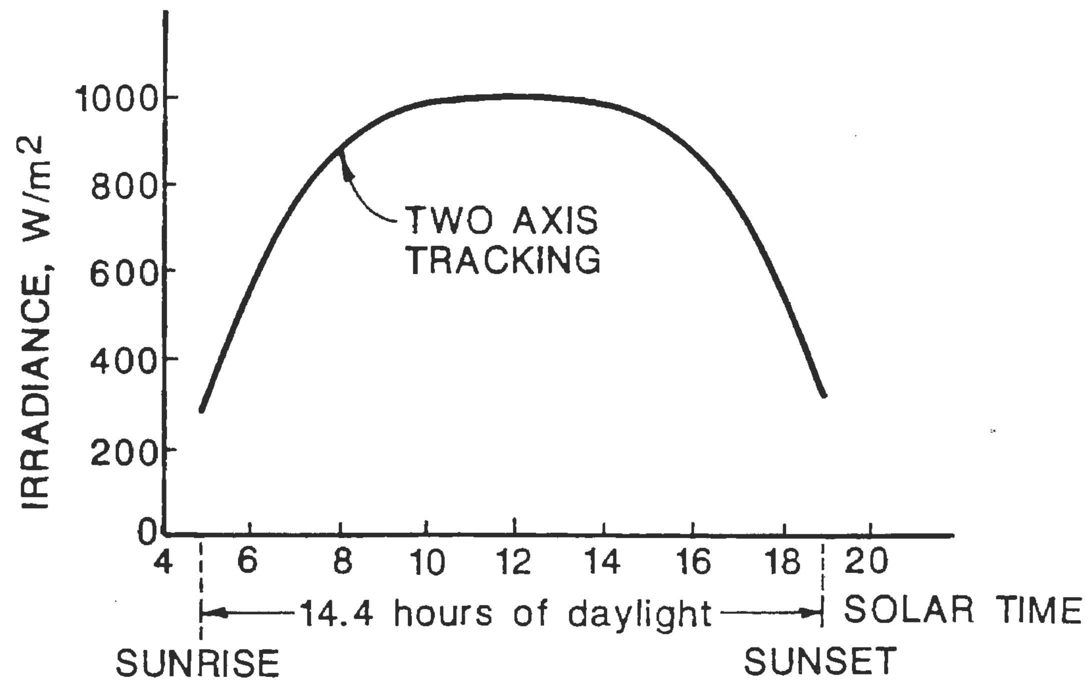


Figure 4. Irradiance Measured on a Surface with two Axis Tracking

therefore

$$I_{CC} = 0.5\ I_{ex}[\exp(-0.65\ \frac{AP(Z)}{AP(0)} + \exp(-0.095\ \frac{AP(Z)}{AP(0)})]\ (1 - kk) \qquad (2.1.2.9)$$

or

$$I_{CC} = I_{Cmax}(1 - kk) \qquad (2.1.2.10)$$

It has been shown that the cloud cover at a site can be described in terms of a continuous random variable with a Beta distribution [66]. The corresponding density function is defined in terms of a scale parameter α_B and a shape parameter β_B [67] which can be obtained from the mean and variance of recorded data [68].

$$f_{KK}\ (kk) = \begin{cases} \frac{\Gamma(\alpha_B + \beta_B)}{\Gamma(\alpha_B)\Gamma(\beta_B)}\ (1 - kk)^{\beta_B - 1}\ kk^{\alpha_B - 1} & 0 \le kk \le 1 \\ 0 & \text{otherwise} \end{cases} \qquad (2.1.2.11)$$

where

$$\Gamma(x) = \int_0^{\infty} u^{x-1} e^{-u} du \qquad (2.1.2.12)$$

$$\alpha_B = \mu_B[\frac{\mu_B\ (1 - \mu_B)}{\sigma_B^2} - 1] \qquad (2.1.2.13)$$

$$\beta_B = (1 - \mu_B)[\frac{\mu_B\ (1 - \mu_B)}{\sigma_B^2} - 1] \qquad (2.1.2.14)$$

The pdf of insolation can now be obtained by combining Equations (2.1.2.10) and (2.1.2.11) using the well known theorem given below [69].

Theorem: Suppose that X is a continuous random variable with probability density function f(X). Let Y = U(x) define a one-to-one correspondence between the values of X and Y so that equation $Y = U(X)$ can be uniquely solved for X in terms of Y, say $X = W(Y)$. Then the probability density function of Y is

$$g\ (Y) = f[W(Y)]\ |J|,$$

where $J = W'(Y)$ and is called the Jacobian of the transformation.

The pdf of solar radiation derived using the theorem noted above is given below.

$$f_{I_{CC}}(I_{CC}) = \begin{cases} \dfrac{1}{I_{Cmax}} \dfrac{\Gamma(\alpha_B + \beta_B)}{\Gamma(\alpha_B)\ \Gamma(\beta_B)} \left(1 - \dfrac{I_{CC}}{I_{Cmax}}\right)^{\alpha_B - 1} \left(\dfrac{I_{CC}}{I_{Cmax}}\right)^{\beta_B - 1} & 0 \leq I_{CC} \leq I_{Cmax} \\ 0 & \text{otherwise} \end{cases} \quad (2.1.2.15)$$

This is the model used in this study.

2.1.3 Other Resources

Other renewable energy resources such as biomass and falling water can be successfully modeled in terms of their average values over the study period because their characteristics are not as variable as in the case of wind speed or insolation. For example, total energy available per cubic meter of water is function of the height at which it is stored and using the average rainfall the total energy available can be calculated. Equation (2.1.3.1) gives the potential energy per cubic meter of water stored at a height of h meters.

$$R_4 = gh/3600 \qquad (2.1.3.1)$$

If the water resource is a river or stream, then using historical data the average amounts of water available during different seasons can be estimated [70].

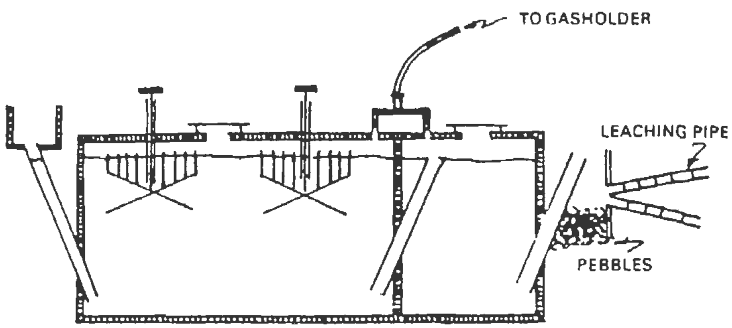
Anaerobic digestion of biomass is a process by which complex organic substances are broken down to produce biogas [71]. Biogas is simply a mixture of methane and a few other gases such as hydrogen sulfide. Information on the construction of plants converting biomass to biogas is readily available. In general, the plant consists of a tank where feedstock and water are mixed and allowed to ferment in the absence of oxygen (see Figure 5). The biogas is usually collected at the top of the tank and the solid residue is removed from the buttom. Common feedstock used for a biogas digester are crop residues, animal wastes, and urban wastes. The total energy available can be calculated for any site using volume of biogas produced and energy per unit volume of biogas as given by Equation (2.1.3.2).

$$E_g = V_g R_1 \qquad (2.1.3.1)$$

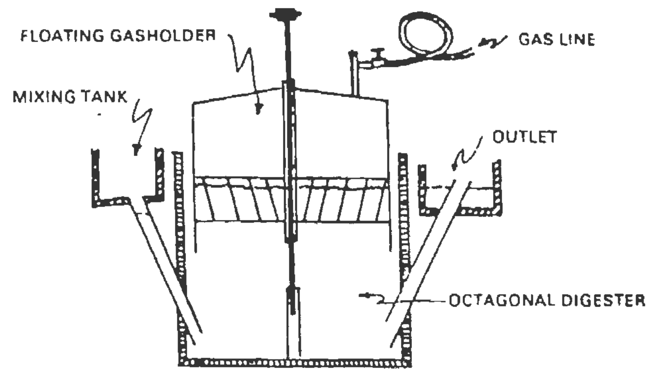
The total volume of the biogas produced depends on the amount and type of material used as feedback as well as the ratio of water to feedstock (see Figure 6). It also depends on the period of digestion and the temperature in the digester (see Figure 7). It should be noted that wastes from similar sources could produce different quantities of gas either under different operating conditions or because of differences in the characteristics of solid wastes used.

2.2 Energy Conversion Device Models

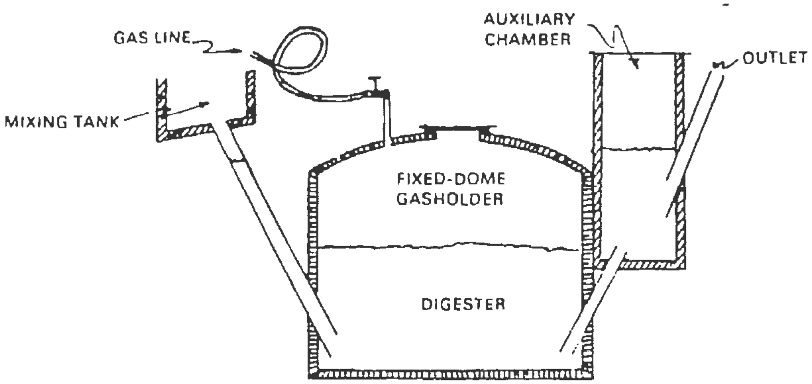
This section discusses some of the commonly used energy conversion



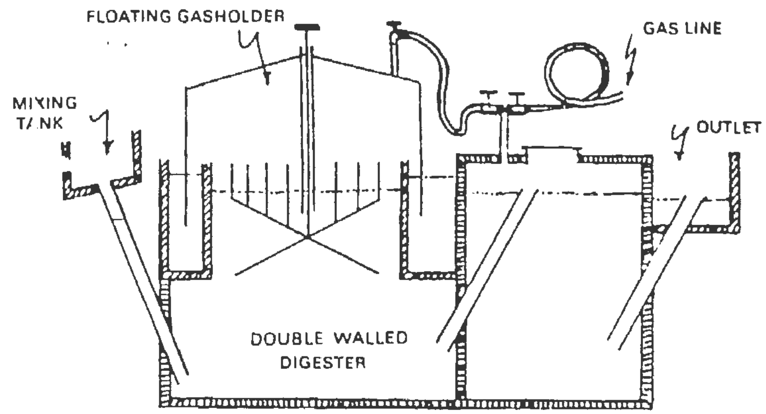
CONTINUOUS-FED DIGESTER FOR SLAUGHTERHOUSES
(MARAMBA-TAGANAS)



VERTICAL, CONTINUOUS-FED BIOGAS PLANT
(MAYA FARMS-INDIA)



FIXED-DOME CONTINUOUS-FED BIOGAS PLANT
(MAYA FARMS-CHINA)



DOUBLE-WALLED CONTINUOUS-FED BIOGAS PLANT
(MAYA FARMS-TAIWAN)

Figure 5. Typical Biogas Plants

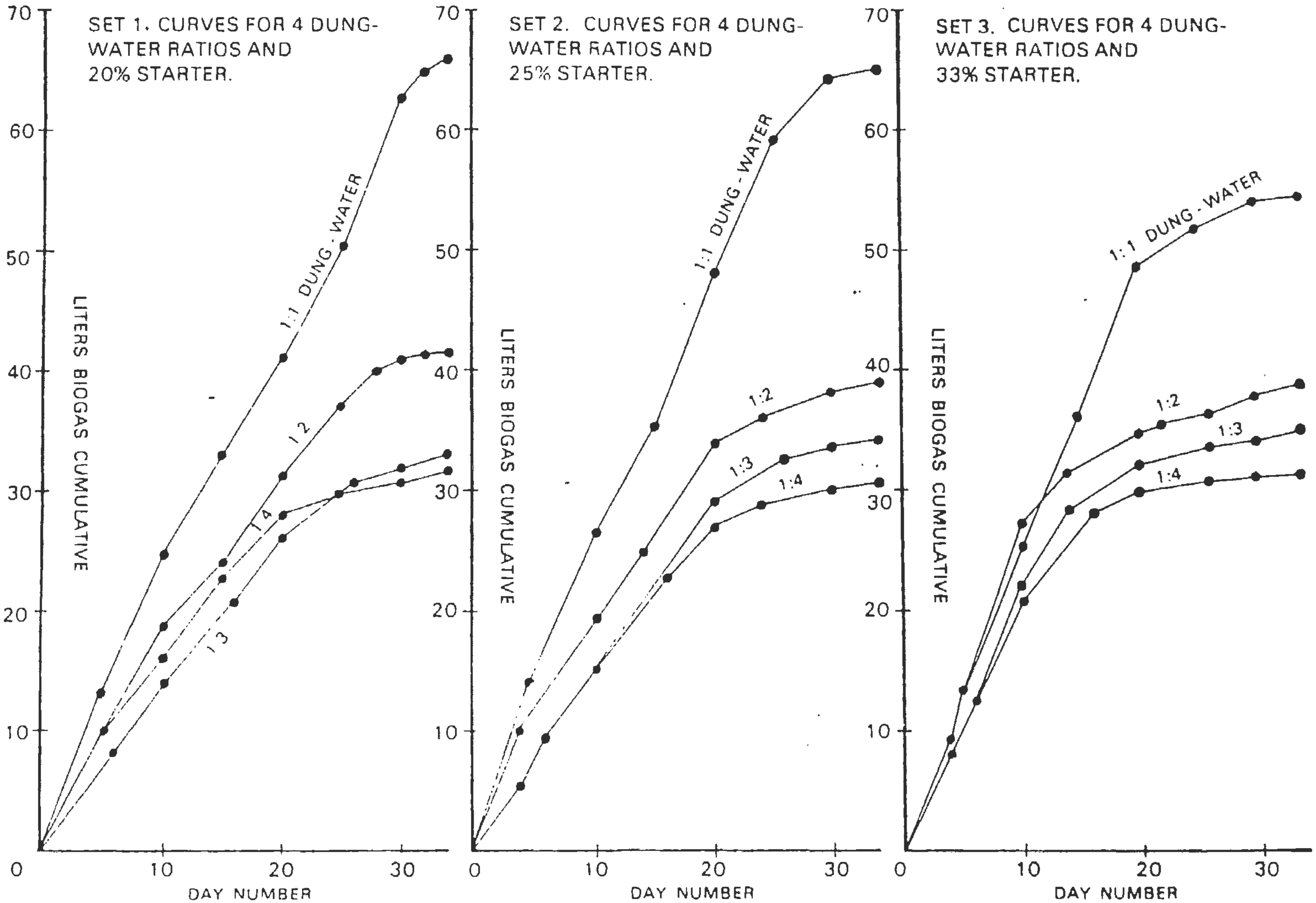


Figure 6. Variation of Volume of Biogas Produced with Different Feedstocks and Water to Manure Ratio

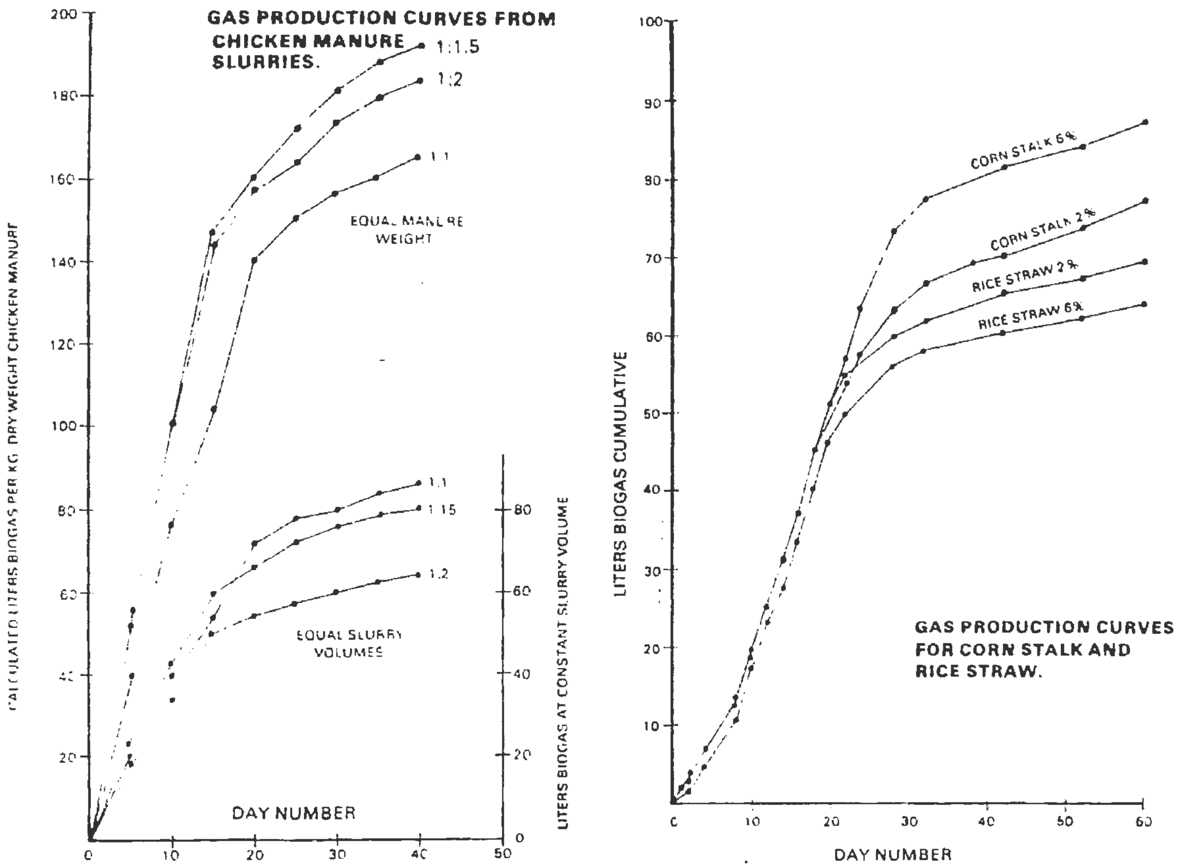


Figure 6. (Continued)

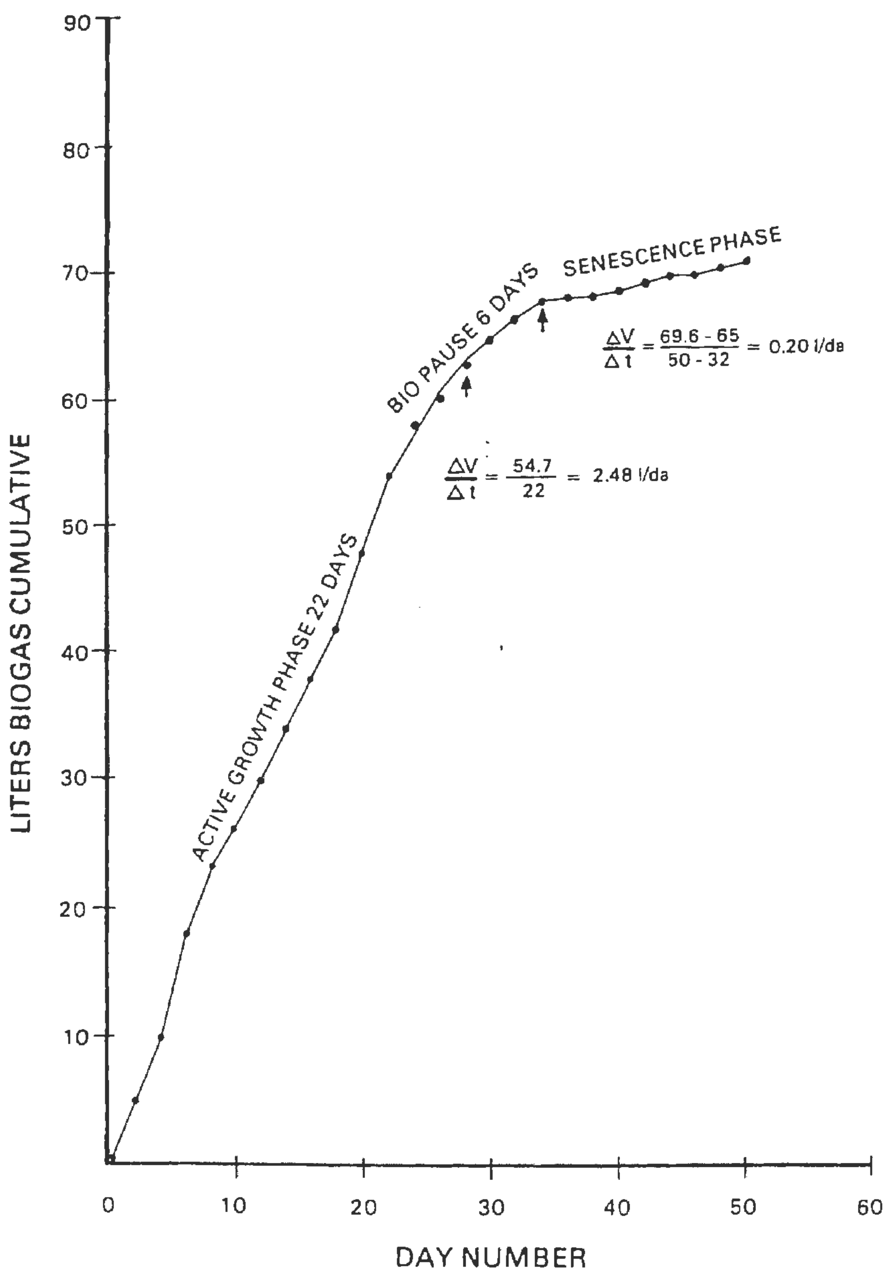


Figure 7. Variation of Vlume of Biogas Produced with Fermentation Time

devices for harnessing renewable energy resources in terms of the mathematical models used to describe their characteristics.

2.2.1 Wind Energy Conversion System

The mechanical power output, P_m, of an aeroturbine with a rotor diameter D is given by

$$P_m = 0.5 \rho_0 C_p (V_w)^3 \pi \frac{D}{4}^2 \qquad (2.2.1.1)$$

where C_p is the power coefficient of the aeroturbine, ρ_0 is the air density, and V_w is the incident wind speed. The coefficient C_p is a function of the tip speed to wind speed ratio λ, commonly known as the tip speed ratio. Typical variations of C_p with λ are shown in Figure 8 [72] for different types of aeroturbines. The power output of a wind electric conversion system (WECS) will, in addition, depend on the efficiencies of the mechanical interface and the electrical generator, and also on the manner in which the turbine is operated -- constant-speed or nearly-constant-speed or variable-speed. Figure 9 shows the theoretical power output characteristics for a typical large [$\geq$ 100 kW) constant-speed (or nearly-constant speed) wind electric conversion system [73]. However, it has been shown that [74] the actual, meaning measured, power output characteristic of a typical wind turbine can be approximated in terms of two straight line segments as shown in Figure 10.

As mentioned before the wind speed at a site can be considered as a continuous random variable with a Weibull distribution. The density function for wind speed between the cut-in (V_C) and furling (V_F) values can be expressed as follows.

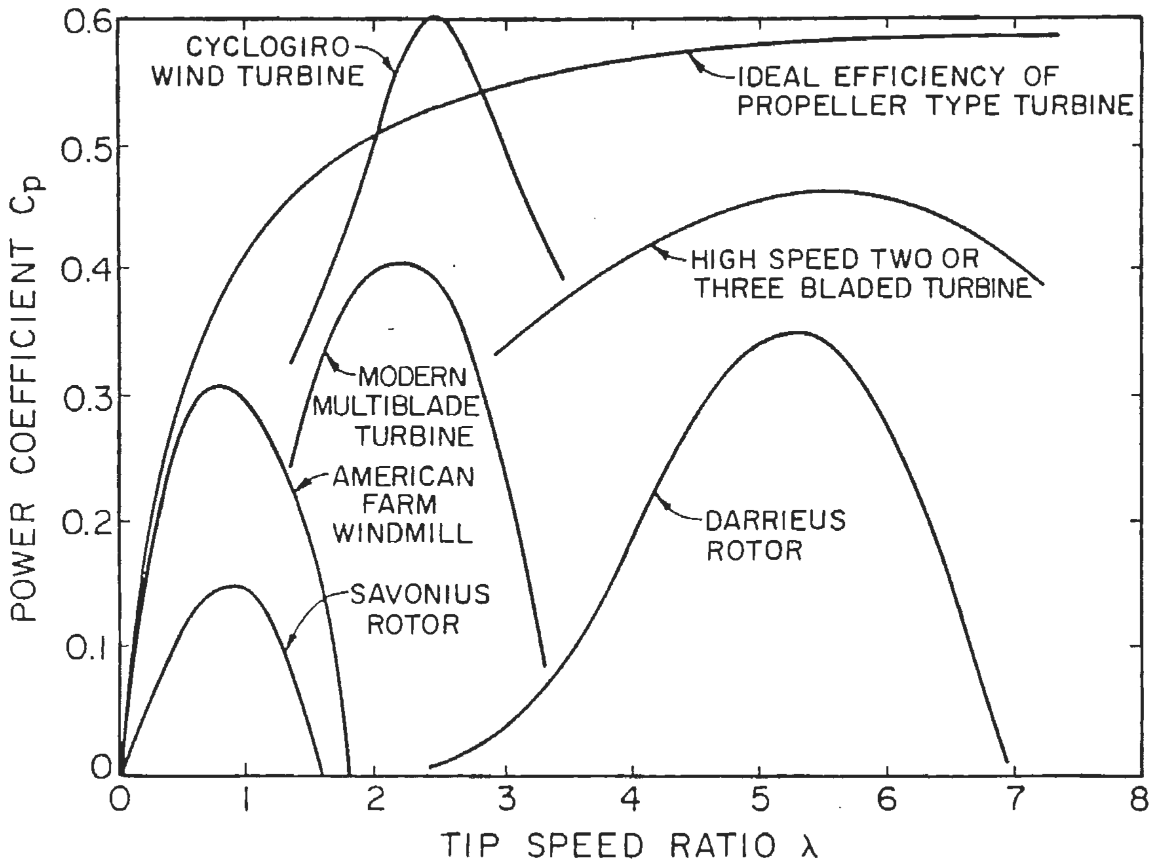


Figure 8. C_p Versus λ Characteristics of Aeroturbines

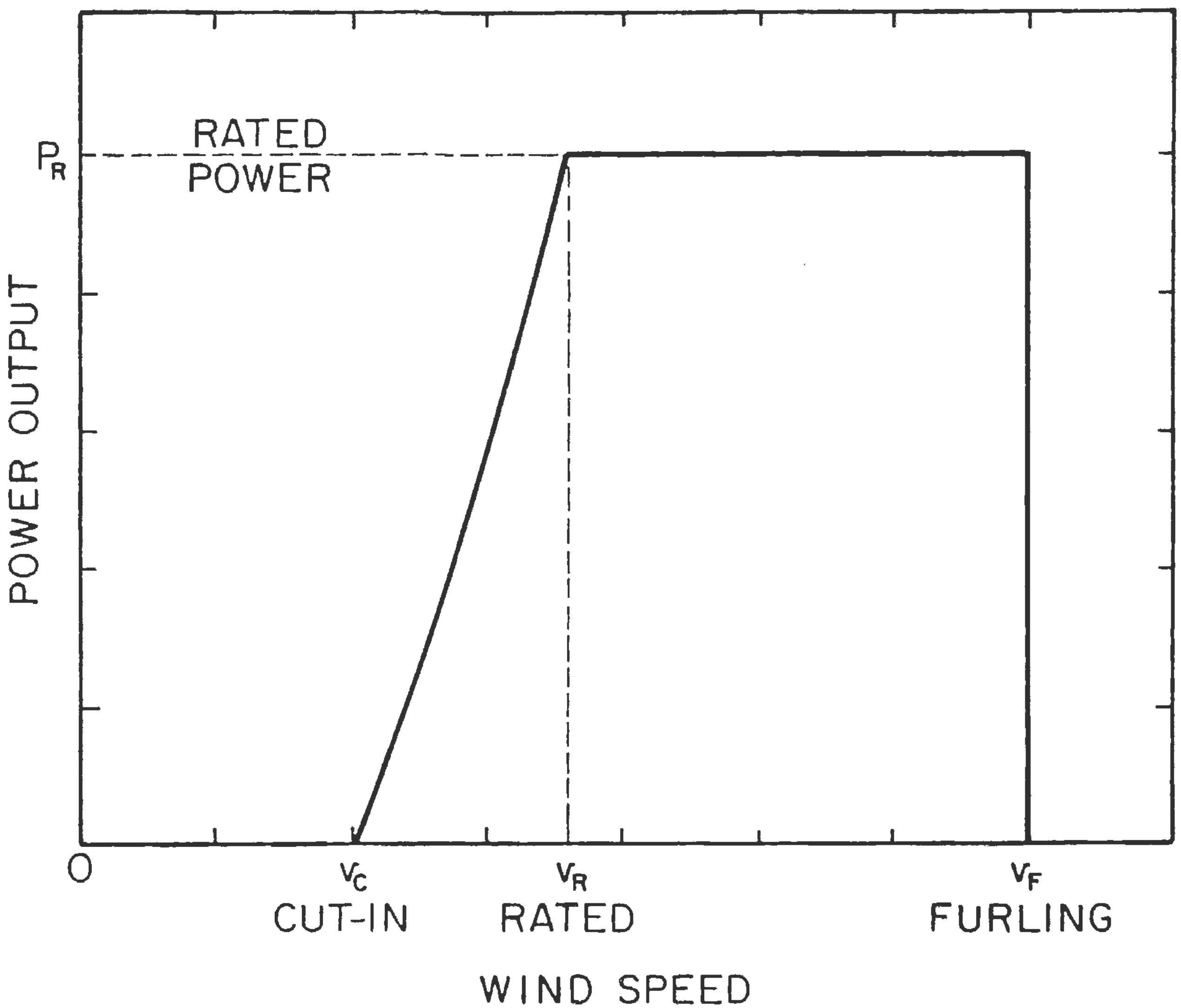


Figure 9. Typical Electrical Output Characteristic of a Large WECS Operating in the Constant (or Nearly-Constant) Speed Mode

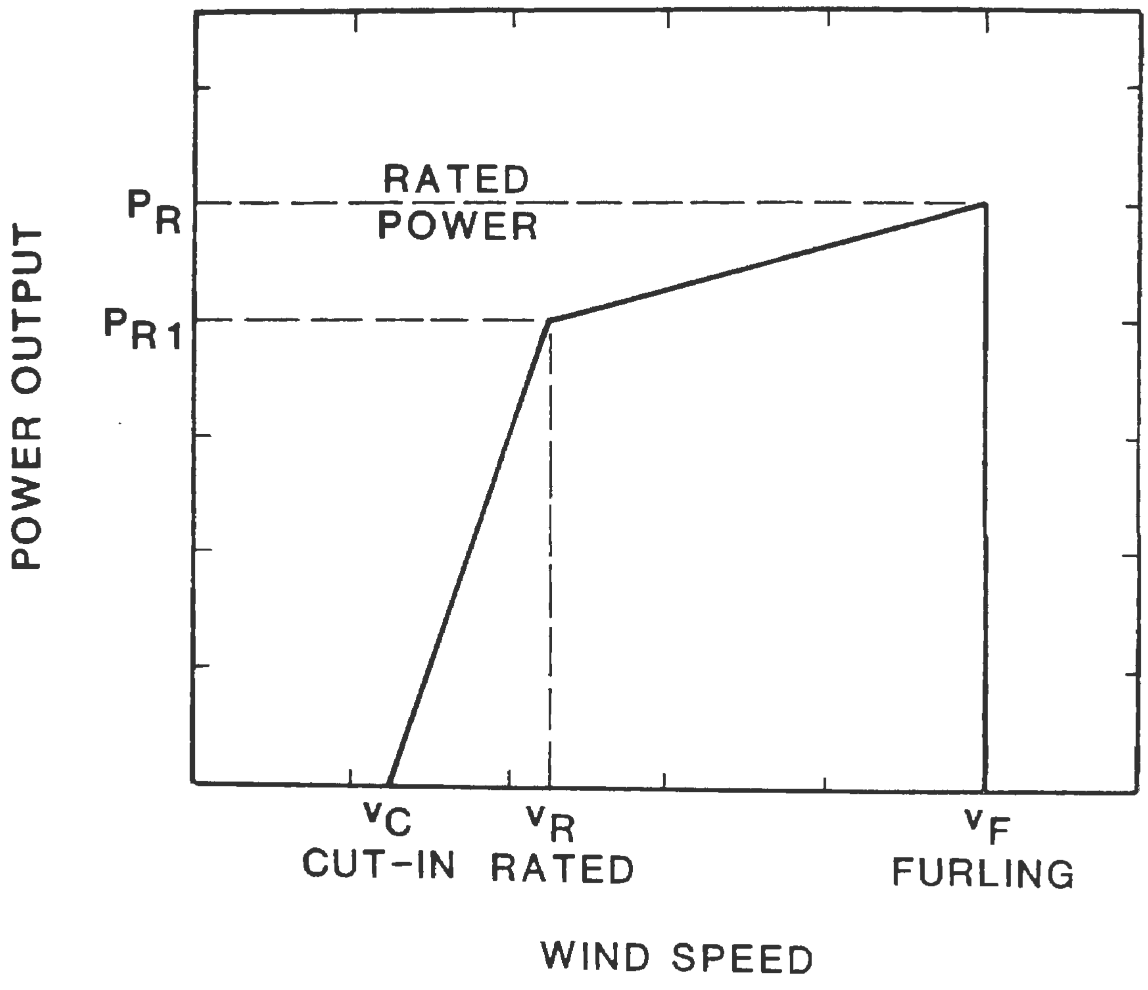


Figure 10. Approximation to Observed Power Output Characteristics of a WECS

$$f_V(V_w) = f_w(V_w | V_C \leq V_w \leq V_F) = \begin{cases} \dfrac{f_w(V_w)}{F_w(V_F) - F_w(V_C)} & \\ 0 & \text{otherwise} \end{cases} \tag{2.2.1.2}$$

where $f_w(V_w)$ and $F_w(V_w)$ represent the Weibull density and distribution function respectively. Considering only the wind speeds resulting in non-zero outputs ($V_C < V_w < V_F$) the density function $f_{Pe}(p_{ew})$ for the random variable P_{ew}, the power output of the WECS, is derived by combining equations (2.2.1.2) and the characteristics shown in Figure 10. The result is given below.

$$f_{Pe}(P_{ew}) = \begin{cases} \dfrac{(V_R - V_C)\ \beta_w}{P_{R1}\ \alpha_w^{\beta_w}} \dfrac{\left(V_C + (V_R - V_C)\dfrac{p_{ew}}{P_{R1}}\right)^{\beta_w - 1}}{F_{w1}} \times & \\ \quad \exp\left[-\left(\dfrac{V_C + (V_R - V_C)\dfrac{p_{ew}}{P_{R1}}}{\alpha_w}\right)^{\beta_w}\right] & 0 \leq p_{ew} \leq P_{R1} \\ \dfrac{\beta_w (p_{ew} - G_2)^{\beta_w - 1}}{(\alpha_w G_1)^{\beta_w}\ F_{w1}} \exp\left[-\left(\dfrac{p_{ew} - G_2}{\alpha_w G_1}\right)^{\beta_w}\right] & P_{R1} \leq p_{ew} \leq P_R \\ 0 & \text{otherwise} \end{cases} \tag{2.2.1.3}$$

where

$$F_{W1} = F_w(V_F) - F_w(V_C) \tag{2.2.1.4}$$

$$G_1 = \frac{P_R - P_{R1}}{V_F - V_R} \tag{2.2.1.5}$$

$$G_2 = \frac{V_F\ P_{R1} - V_R P_R}{V_F - V_R} \tag{2.2.1.6}$$

However, what is desired is the density function F_{PA} (p_{ew}) that is applicable for all wind speeds and power outputs, including the zero value. The power output will be zero if the wind speed is either below V_C or above V_F. Therefore, the actual distribution function F_{PA} (p_{ew}) can be written as

$$F_{PA}\ (p_{ew}) = F_{w1}\ F_{Pe}\ (p_{ew}) + (1 - F_{w1}) \qquad (2.2.1.7)$$

in which F_{w1} is the fraction of the time during the study period that wind speed is between cut-in and cut-out and $F_{pe}(p_{ew})$ is the distribution function corresponding to the density function f_{pe} (p_{ew}). The plot of $F_{PA}(p_{ew})$ will have a jump at zero output, the height of which is equal to the fraction of the time (equal to $1 - F_{w1}$) the output is zero. Corresponding to this, the actual density function f_{PA} (p_{ew}) will have an impulse of magnitude $(1 - F_{w1})$ at zero. This is the model used for this study.

2.2.2 Solar Photovoltaic Energy Conversion System (SEC)

The Photovoltaic (or solar) cell can be modeled in terms of a constant-current source delivering a current I_s, a nonlinear junction impedance R_j, and the load resistance R_o [75] as shown in Figure 11. Several idealizing assumptions have been made to arrive at this simple equivalent circuit. The most important assumptions are: (i) cell series resistance is negligibly small, and (ii) cell shunt resistance is very large. When a photovoltaic cell is illuminated, the photovoltaic effect causes a current I to flow through the load.

$$I = I_s - I_o[\exp(\frac{eV_j}{kT_e}) - 1] \qquad (2.2.2.1)$$

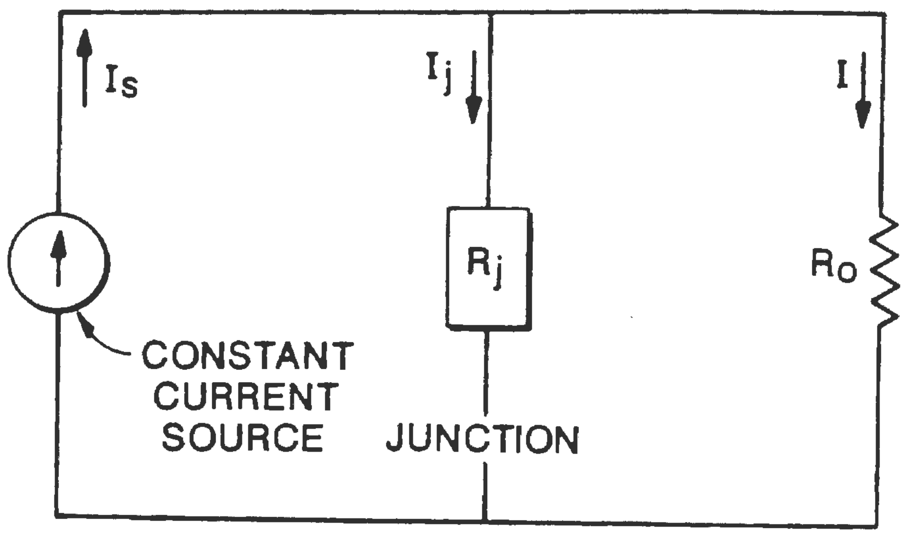


Figure 11. Simplified Equivalent Circuit of an Illuminated Photovoltaic Cell

where I_S is the source current - - the current that would flow through a short circuit ($R_o = 0$), I_o is the saturation or dark current, V_j is the voltage across the junction, k is the Boltzmann constant, and T_e is the temperature in degrees Kelvin. Figure 12 illustrates the I-V characteristics of a photovoltaic cell for different levels of incident radiation. The power output of a solar array, P_S, at any given time can be calculated using

$$P_S = A_a\ k_P\ I_{CC}\ \eta_{SC} \tag{2.2.2.2}$$

or

$$P_S = A_C\ \eta_{sc}\ I_{CC} \tag{2.2.2.3}$$

where

$$A_C = A_a\ k_P \tag{2.2.2.4}$$

$$I_{CC} = I_{Cmax}\ (1 - kk) \tag{2.2.2.5}$$

By combining Equations (2.2.2.3) and (2.2.2.5) we get

$$P_S = A_C\ \eta_{sc}\ I_{Cmax}(1 - kk) \tag{2.2.2.6}$$

For design purposes, the performance of a photovoltaic module can be characterized in terms of a constant average efficiency of 10% [76]. Figure 13 illustrates the output characteristics of a typical photovoltaic module. Using this value of average efficiency for the module, Equation (2.2.2.6) becomes

$$P_S = 0.1\ A_C\ I_{Cmax}\ (1 - kk) \tag{2.2.2.7}$$

or

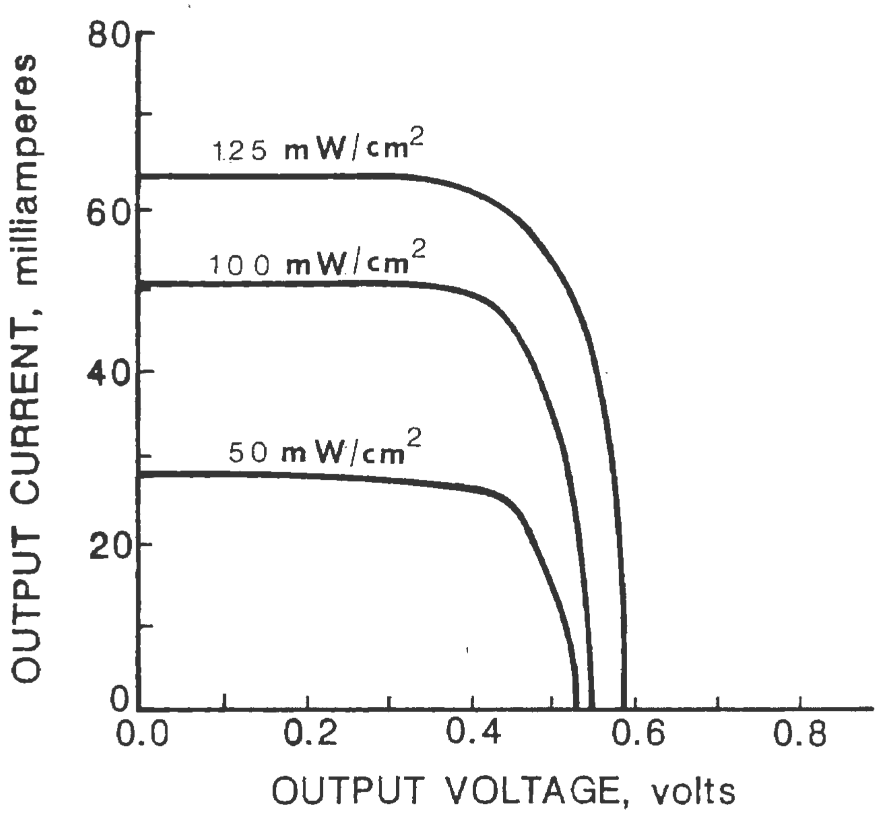


Figure 12. Typical Voltage-Current Characteristics for a Silicon P-on-n Cell

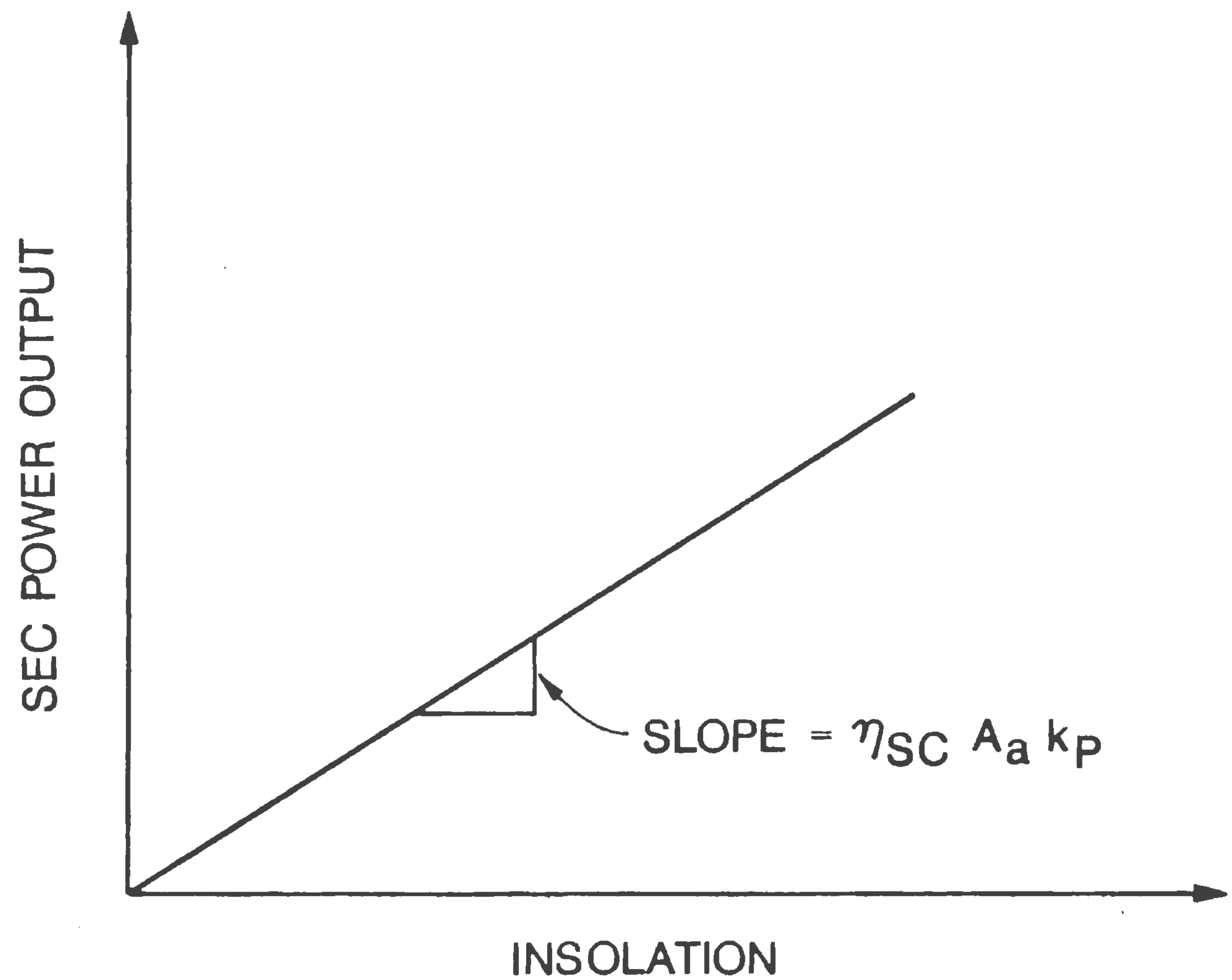


Figure 13. Assumed SEC Output Power Characteristic

$$P_S = P_{Smax}(1 - kk) \tag{2.2.2.8}$$

where P_{Smax} = maximum output power under clear sky condition.

As mentioned before, kk can be represented by a continous random variable with Beta distribution. Considering only the non-zero output, the pdf for the output of a PV array output can be obtained by transforming the pdf of the random variable I_{CC} using Equation (2.2.2.8) and the well known theorem given before. The result is given below.

$$f_{PS}(p_S) = \begin{cases} \dfrac{1}{P_{Smax}} \dfrac{\Gamma(\alpha_B + \beta_B)}{\Gamma(\alpha_B)\,\Gamma(\beta_B)} \left(1 - \dfrac{p_S}{P_{Smax}}\right)^{\alpha_B - 1} \left(\dfrac{p_S}{P_{Smax}}\right)^{\beta_B - 1} & 0 \leq p_S \leq P_{Smax} \\ 0 & \text{otherwise} \end{cases} \tag{2.2.2.9}$$

However, what is desired is the density function $f_{SA}\ (p_S)$ that is applicable for the entire range of possible output including zero. The power output will be zero if the sky is completely covered or during night times. Therefore, the actual distribution function $F_{SA}\ (p_S)$ can be written as

$$F_{SA}\ (p_S) = F_{S1}\ F_{PS}\ (p_S) + (1 - F_{S1}) \tag{2.2.2.10}$$

where F_{S1} is the fraction of time during the study period the output power is not zero and $F_{PS}\ (p_S)$ is the distribution function corresponding to the density function $f_{PS}\ (p_S)$.

The plot of $F_{SA}\ (p_S)$ will have a non-zero, finite, value at $p_S = 0$, the magnitude of which is equal to the fraction of time, $(1 - F_{S1})$, during which the output is zero. Corresponding to this, the actual density function $f_{SA}\ (p_S)$ will have an impulse of magnitude $(1 - F_{S1})$ at zero. This is the model used in this study.

2.2.3 Other Devices

In the previous sections probabilistic models describing the output characteristics of devices utilizing wind and solar radiation were developed. In this section deterministic models describing the output of devices utilizing other renewable energy resources are considered.

Some of these devices such as gas-burners used for burning biogas and solar collectors used for water heating, etc. can simply be represented in terms of their average efficiencies. This is justified because these devices will constitute only a minor part of the overall IRES and detailed models may not be necessary. Others, such as microhydro units, require a somewhat more complex expression. The electric output power of a hydroturbine, P_{kW}, in terms of combined turbine-generator efficiency η_H, water flow Q, h net head, density of water ρ_w, and acceleration due to gravity g is given by [77]

$$P_{kW} = \frac{\rho_w g Q h \ \eta_H}{1000} \tag{2.2.3.1}$$

2.3 Load Models

As mentioned before, the energy required by the loads can be classified into four groups based on the type and quality of the energy needs as follows:

1. Medium-grade thermal energy (100° - 300°C)

   This need is primarily for cooking and small-scale industries.

2. Rotating mechanical shaft power

   This form of energy is required for

a) pumping water

b) small-scale industries

c) agricultural operations

d) transportation (mobile rotating shaft)

3. Electricity

a) ac electricity

This is needed for domestic and community lighting and for supplying ac motor

b) dc electricity

This form is used for charging storage batteries for emergency lighting, educational, communication, health-related activities, and for supplying dc motors.

4. Low-grade thermal energy (less than 100° C)

This form is needed for water and space heating, crop drying as well as process heat for small-scale industries.

Both probabilistic and deterministic models for load demand are discussed next.

2.3.1 Electricity

Typical electricity demands have temporal variations between a maximum, L_M, and a minimum, L_m, value and in general can be represented by a continuous random variable. For the purpose of this study, a simple load model with uniform distribution is used. Figure 14 shows the probability density function and distribution function employed. The corresponding load duration curve is illustrated in Figure 15. Practical load duration curves can be reasonably idealized to correspond to the one used here [78,79].

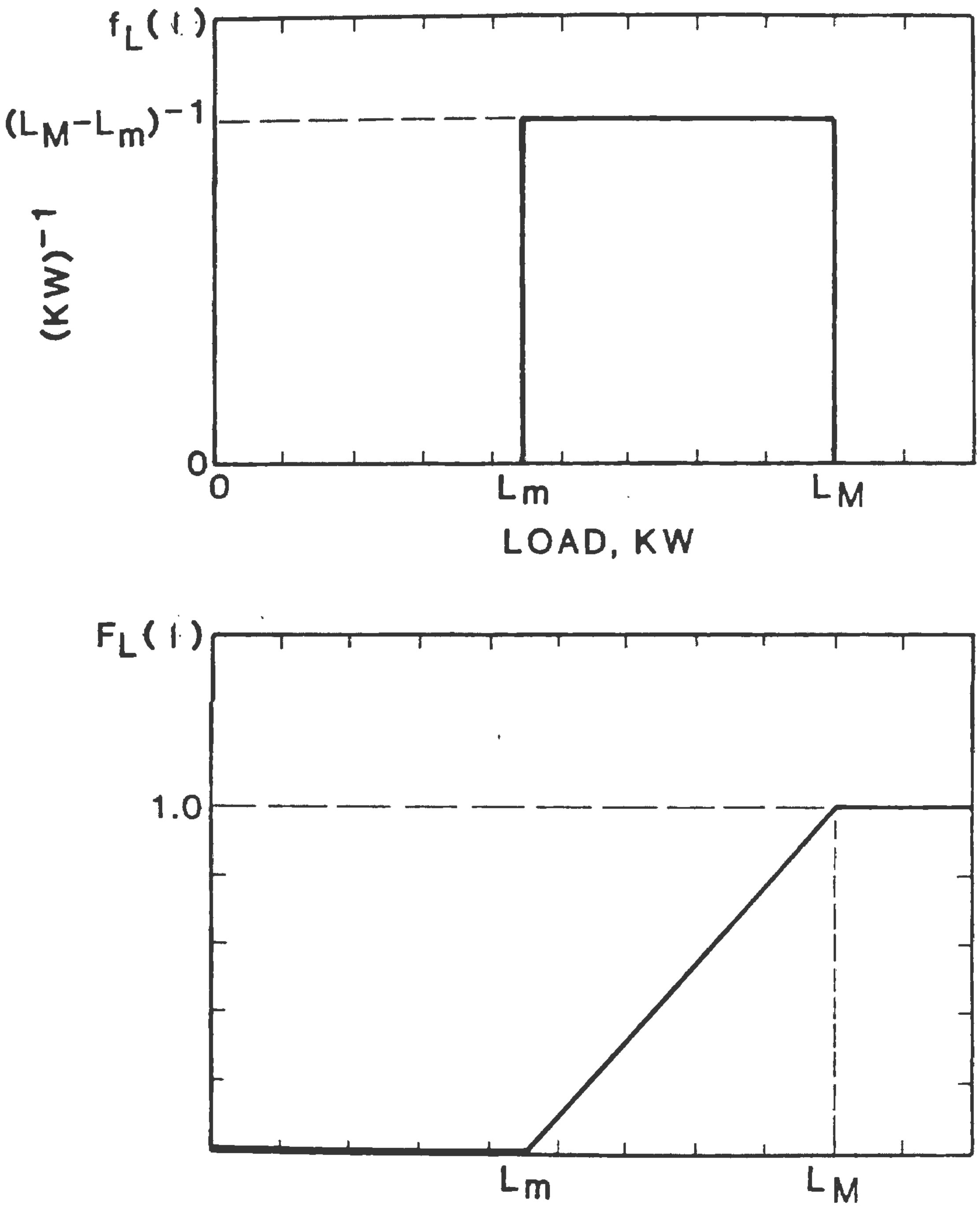


Figure 14. Assumed Electrical Load Model

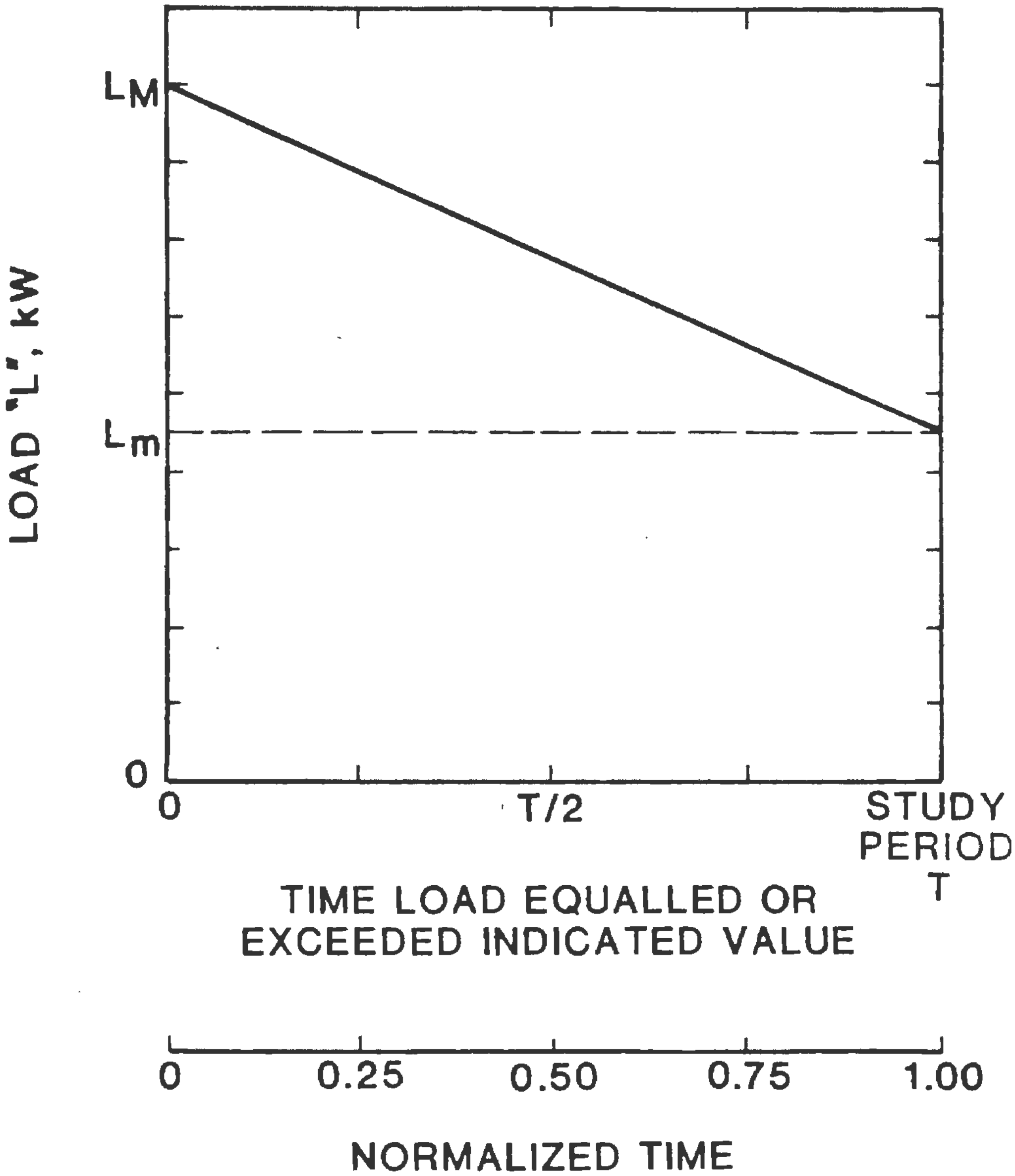


Figure 15. Assumed Electrical Load Duration Curve

2.3.2 Other Loads

The approaches used to arrive at the total energy needs of each of the remaining three groups require a certain amount of aggregation and approximation. For example, all the loads requiring rotating shaft power (water pumping, agricultural operation, etc.) are aggregated as one load. Similar procedure is employed for other demands as well.

In order to arrive at the total energy needs in each group, average load requirements are used and as such they are the same for the entire study period. The energy required per capita or task is estimated and the total amount of energy required by each group is then found by multiplying these numbers by the population and the number of tasks to be performed during the study period. In practice, load requirements will vary from season to season and the design procedure must be applied during different seasons, the resulting designs compared, and an overall compromise design might have to be evolved.

Models (both deterministic and probabilistic as appropriate) used for describing the characteristics of renewable energy resources, devices employed for harnessing them, and different loads were presented in this chapter. It was shown that the output of a WECS can best be represented by a continuous random variable with Weibull distribution. Also, it was concluded that the output of SEC can best be approximated by a continuous random variable with Beta distribtuion. In both cases, pdf will have to have an impulse corresponding to zero output. It was also shown that electricity demand can be approximated by a continuous random varible which is uniformly distributed between a maximum and a minimum value. Total energy available from the other renewable energy resources such as falling water and biomass was shown to be a function of the site, height of the storage tank in the case of hydroturbine units, and the type of feedstock used in the case of biogas units.

CHAPTER III

INTEGRATED RENEWABLE ENERGY SYSTEM(IRES)

In this chapter the concept of an Integrated Renewable Energy System (IRES), is defined and two different approaches used for integrating different renewable energy resources are discussed. Also, the terminology used and definitions of some of the important terms are presented.

3.1 Definitions and Terminology

The amount of energy available in the form of renewable resources such as wind or solar radiation is sufficiently large to make a significant contribution to the overall supply of energy [80]. However, there are several difficulties associated with the harnessing of these resources. Some of these difficulties are due to the diluteness of the resources and the consequent low overall efficiencies of devices used for conversion of these resources into useful energy forms. Some of the more serious of these difficulties are due to the highly variable nature of some of these resources such as wind and insolation [81]. The problems caused by the intermittency of these resources can be partially overcome either by adding energy storage and reconversion facilities, or by using the strengths of one source of energy to overcome the weakness of the other. For example, during summer the middle and high northern latitudes receive more insolation; however the average wind speed is higher in winter [82]. Table I presents the average monthly insolation available on a horizontal surface, and horizontal wind flow at 10 meters above ground for ten northeastern U.S. locations [83, 84]. Values corresponding to months of maximum and minimum energy availability are underscored. As expected, solar availability is greatest in summer and is at its lowest during winter. On the other hand, wind availability is greatest in winter and is at its lowest during summer. It is obvious that by combining different resources the variations in the overall output can be reduced and, in turn, the need for storage can be minimized [85].

A system utilizing more than one renewable energy resource is called an "IRES", an acronym which stands for "Integrated Renewable Energy System". A typical IRES will consist of two or more of the following: wind energy conversion system (WECS), solar photovoltaic energy conversion system (SEC), microhydro, biogas digester, solar thermal system, and some means of storing energy. This list is not meant to be exhaustive and as new devices are developed, they can also be included. Figure 16 illustrates one possible combination of devices and their interconnections suitable for utilizing different renewable energy resources in an integrated manner. In such a system each different manifestation of solar energy will have a role to play in order to (see Reference 45)

a) provide the most appropriate and cost effective form of energy needed by each task,
b) minimize the need for transportation and transmission of energy, and
c) protect the environment and improve the quality of life.

TABLE I

AVERAGE MONTHLY HORIZONTAL GLOBAL INSOLATION AND HORIZONTAL WIND FLOW AT 10m HEIGHT

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Albany, NY	S	1.44	2.17	3.11	4.21	4.95	5.46	5.44	4.73	3.69	2.58	1.44	1.12
	W	3.84	4.08	4.56	3.84	2.40	1.92	1.68	1.44	1.68	2.16	2.64	3.84
Binghamton, NY	S	1.22	1.82	2.72	3.92	4.72	5.30	5.23	4.49	3.57	2.46	1.31	0.94
	W	3.84	3.84	3.84	3.60	2.40	1.68	1.44	1.44	1.68	2.40	2.88	3.84
Boston, MA	S	1.50	2.24	3.21	4.18	5.11	5.73	5.52	4.69	3.97	2.81	1.59	1.27
	W	7.44	7.44	6.72	5.76	4.56	3.12	2.88	2.88	3.12	4.08	5.04	7.20
Buffalo, NY	S	1.10	1.72	2.80	4.15	5.04	5.69	5.60	4.77	3.63	2.47	1.27	0.89
	W	8.64	7.20	6.00	5.52	3.60	3.36	2.88	2.40	2.64	3.84	4.80	6.00
Burlington, VT	S	1.22	1.91	2.97	4.09	4.97	5.45	5.43	4.65	3.54	2.34	1.18	0.89
	W	2.64	2.40	2.64	2.40	2.16	1.68	1.68	1.20	1.68	2.16	2.40	2.64
Caribou, ME	S	1.32	2.28	3.58	4.46	4.98	5.54	5.56	4.73	3.48	2.17	1.16	0.98
	W	5.52	6.48	6.96	4.80	4.56	3.60	2.64	2.40	3.12	3.84	4.32	4.80
New York City	S	1.73	2.51	3.53	4.60	5.33	5.69	5.63	5.00	4.04	3.00	1.87	1.44
	W	5.76	6.00	5.28	4.56	3.60	2.88	2.40	2.40	2.88	3.36	4.32	5.76
Philadelphia, PA	S	1.75	2.51	3.50	4.52	5.24	5.71	5.55	4.97	4.04	3.02	1.95	1.48
	W	4.08	4.32	4.32	3.84	2.64	1.92	1.44	1.68	1.92	2.40	2.88	3.60
Pittsburgh, PA	S	1.34	1.97	2.97	4.15	5.05	5.53	5.33	4.77	3.81	2.82	1.59	1.09
	W	3.84	3.84	3.60	3.36	2.40	1.68	1.44	1.20	1.44	2.16	2.88	3.60
Washington, DC	S	1.80	2.57	3.55	4.60	5.42	6.00	5.73	5.10	4.23	3.17	2.05	1.52
	W	3.36	3.60	3.60	3.36	1.92	1.68	1.44	1.20	1.44	2.16	2.40	2.88

S = Solar
W = Wind

Underlined values are months of maximum or minimum energy availability.

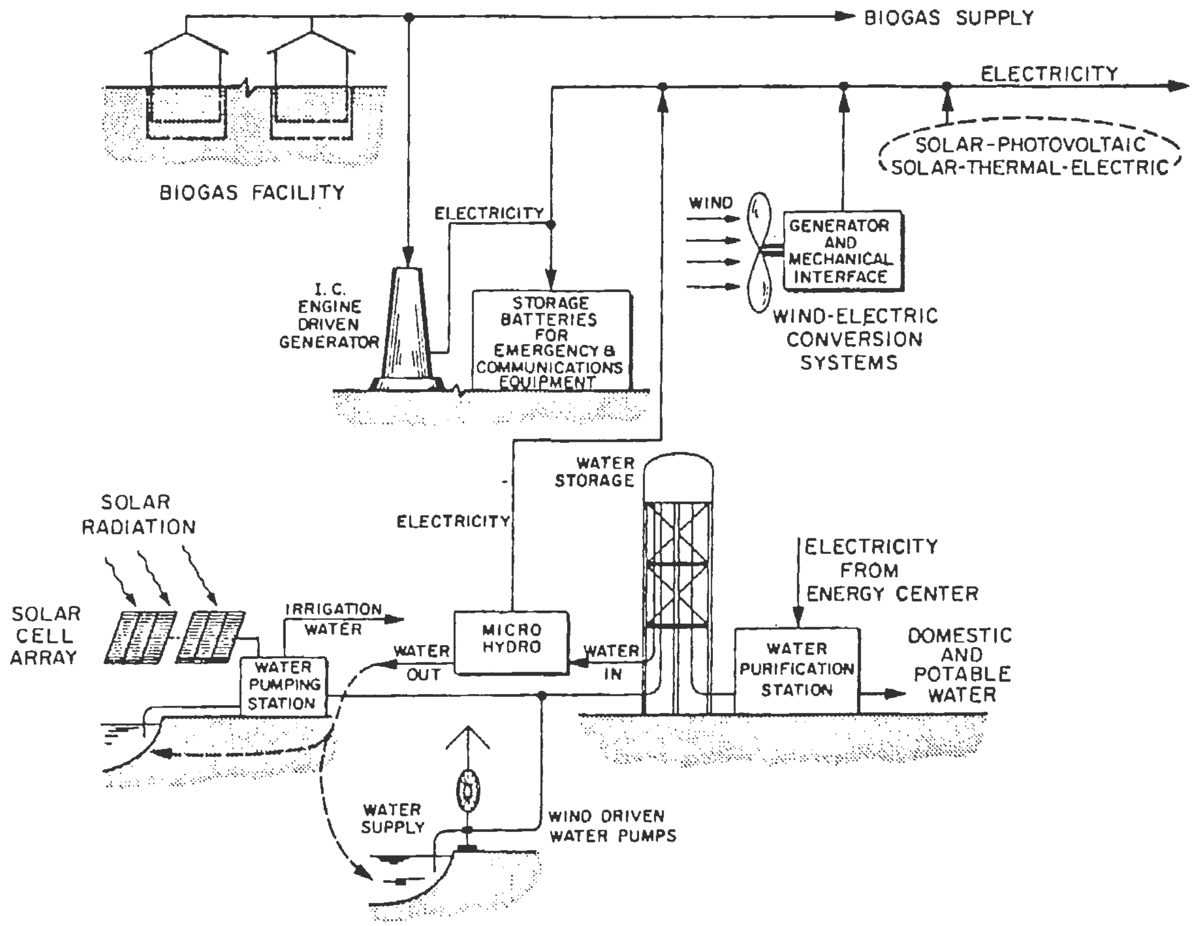


Figure 16. Schematic of an Energy System to Harness Renewable Energy Sources in an Integrated Fashion

A typical IRES utilizes a mixture of energy sources to perform a variety of tasks. This mixture of resources can consist of only primary sources or a combination of primary and intermediate sources which are obtained either from primary sources or from other intermediate sources. Primary sources are those which are inputs to the IRES and intermediate sources are those produced at various stages inside the system from primary sources. Examples of primary sources are wind, insolation, biomass, etc., and examples of intermediate sources are biogas, electricity, rotating mechanical shaft, etc.

3.2 Approaches to Integration

Recently, the concept of utilizing different manifestations of solar energy in an integrated fashion has been gaining momentum worldwide [86, 87]. Both cascaded and tandem approaches have been proposed for the integrated utilization of several renewable resources (see Reference 46).

In the cascaded approach, the primary sources are utilized to satisfy some of the energy needs and the intermediate sources such as heat obtained because of these processes are used to satisfy some of the remaining needs. For example, in a concentrating solar energy system, the dilute solar radiation (primary source) can be concentrated first for use in generating electricity by a point-focus solar-thermal-electric system. The rejected medium-grade thermal energy can be used for refrigeration, and finally the low-grade heat rejected by the cooling system can be used for water heating, space heating, etc. Figure 17 illustrates a schematic of this approach.

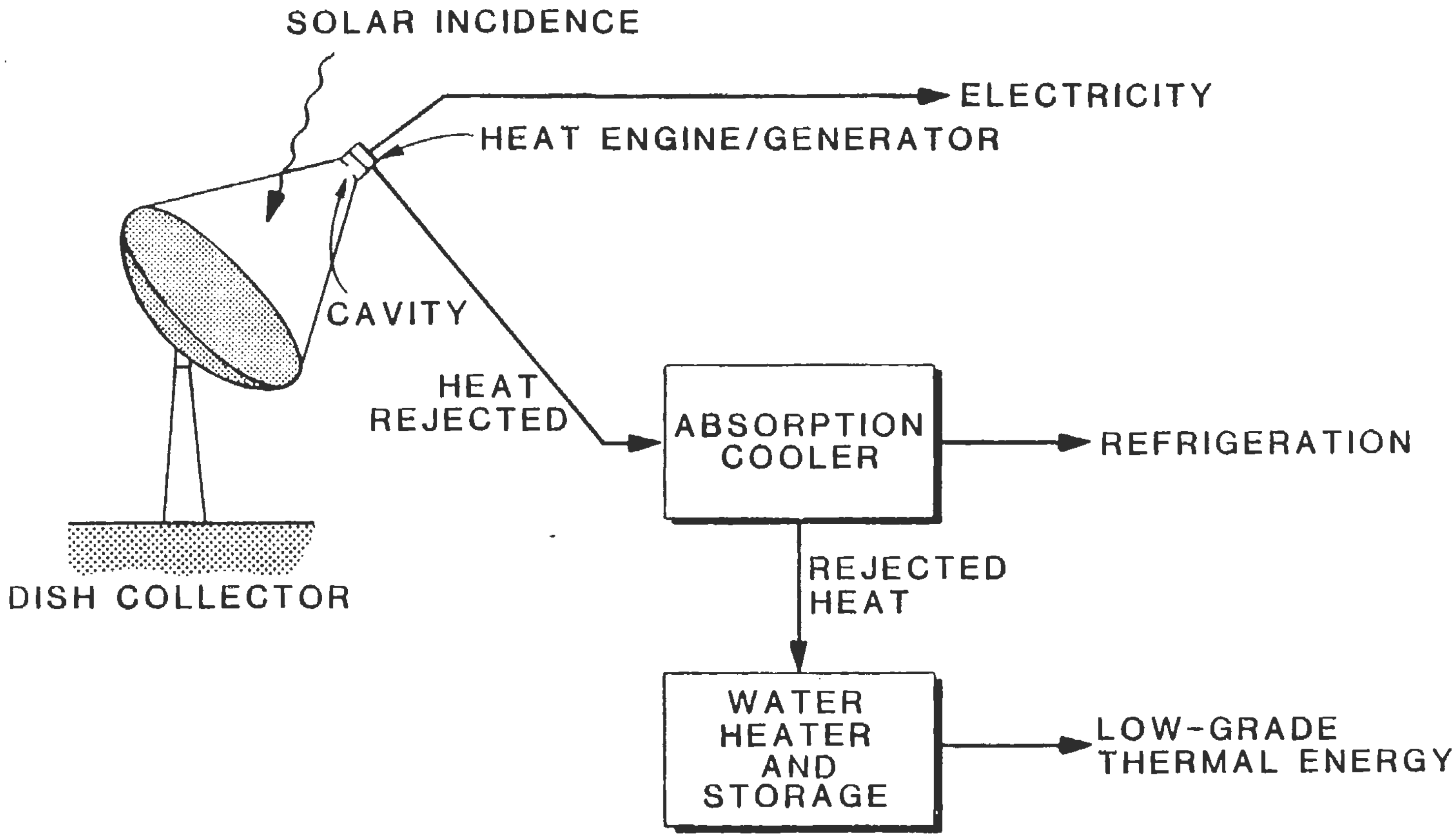


Figure 17. Schematic of a Cascaded Solar Energy System

Two approaches have been proposed [88] for the utilization of several manifestations of solar energy in tandem. In the first approach, one form of energy (typically electrical) is selected as the form which is to be made available to the consumers. All the available resources are then converted into this form for storage and supply to the consumers. The second approach advocates the matching of resources, devices, and needs a priori and achieves the integration of benefits at the user's end. In the latter, the objective is to minimize the cost and maximize the overall efficiency of utilization of the energy resources.

For example, instead of converting wind energy into rotary mechanical energy and then to electricity to be used for pumping water by means of an electric pump, the rotary mechanical energy can be used directly for pumping water. Biogas derived from anaerobic fermentation of biomass can be directly used for cooking instead of converting it into electricity (by means of a biogas-fueled-engine driven generator) and then distributing it to consumers for use in electric stoves. There are many ways to integrate different energy resources. For example, solar radiation and wind energy can be integrated in potential energy form using the scheme shown in Figure 18. Figures 19 and 20 illustrate possible schemes for integrating wind and solar radiation in the form of low-grade thermal energy and electrochemical energy respectively.

By employing a string of energy conversion and utilization devices, almost any energy need can be satisfied by any energy source. However, a word of caution is in order. Not all possibilities are attractive from the economic view point. Figures 21 through 25 show, in conceptual block diagram form, possibilities for supplying medium-grade thermal

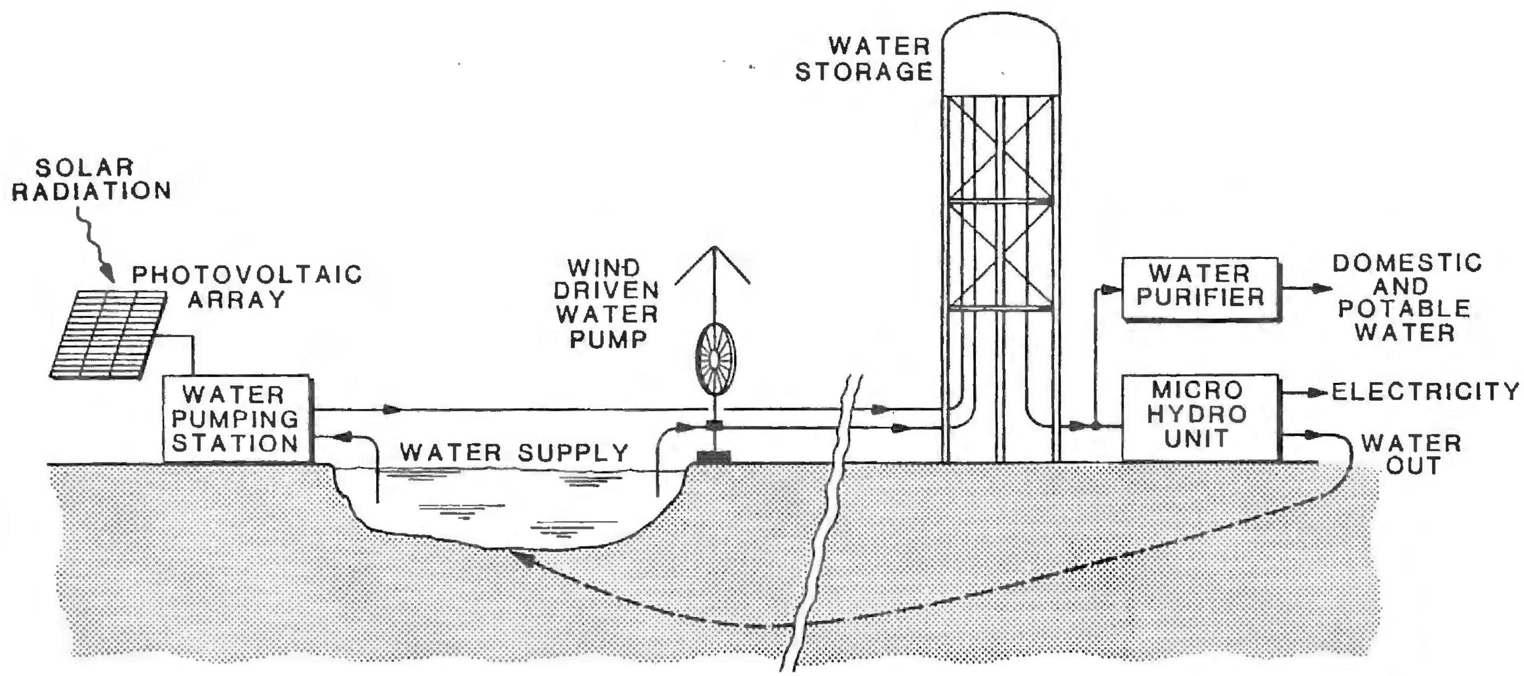


Figure 18. A Scheme to Integrate Solar Radiation and Wind Energy as Potential Energy

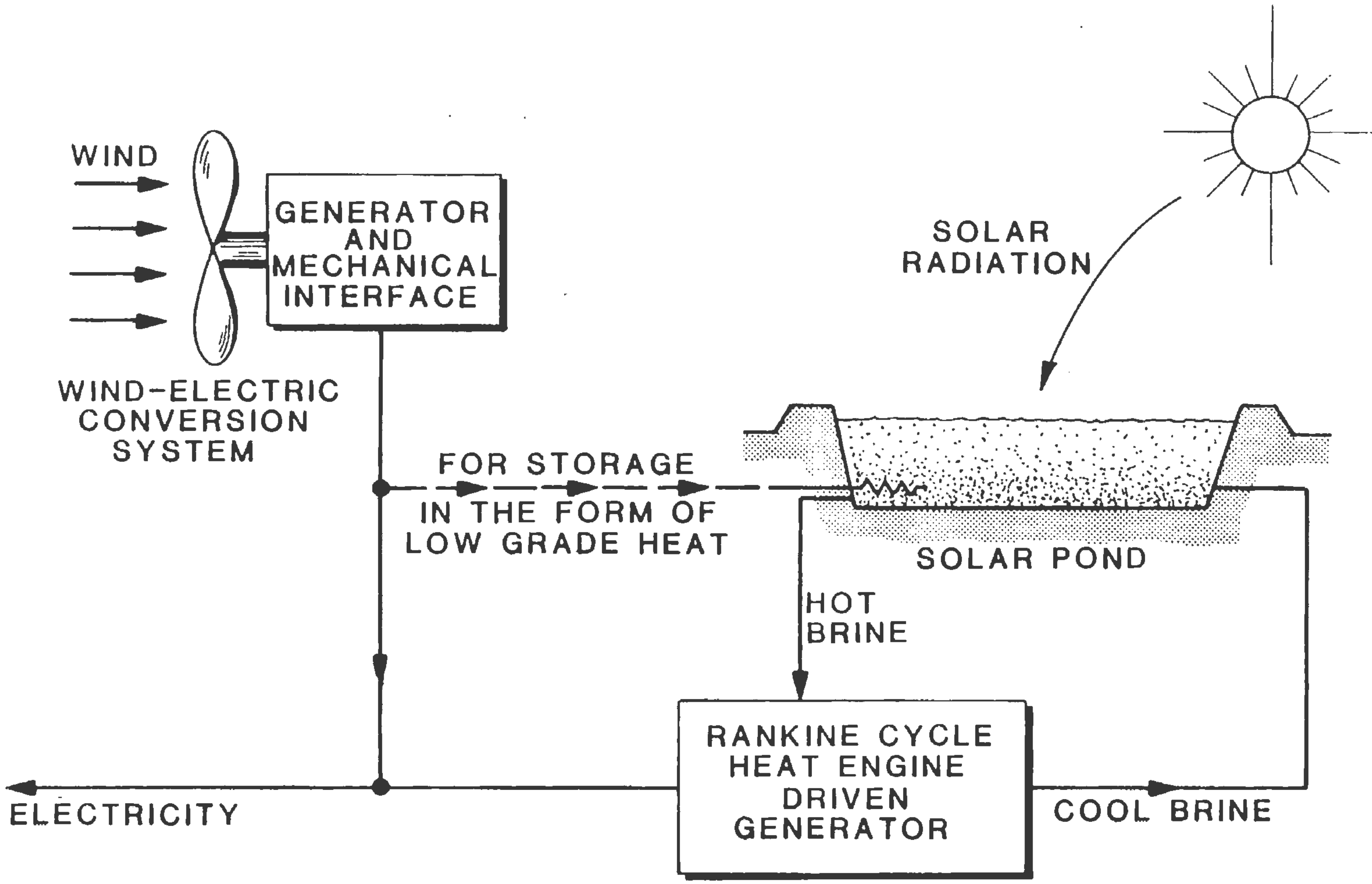


Figure 19. Integration of Solar Radiation and Wind Energy as Low-Grade Thermal Energy

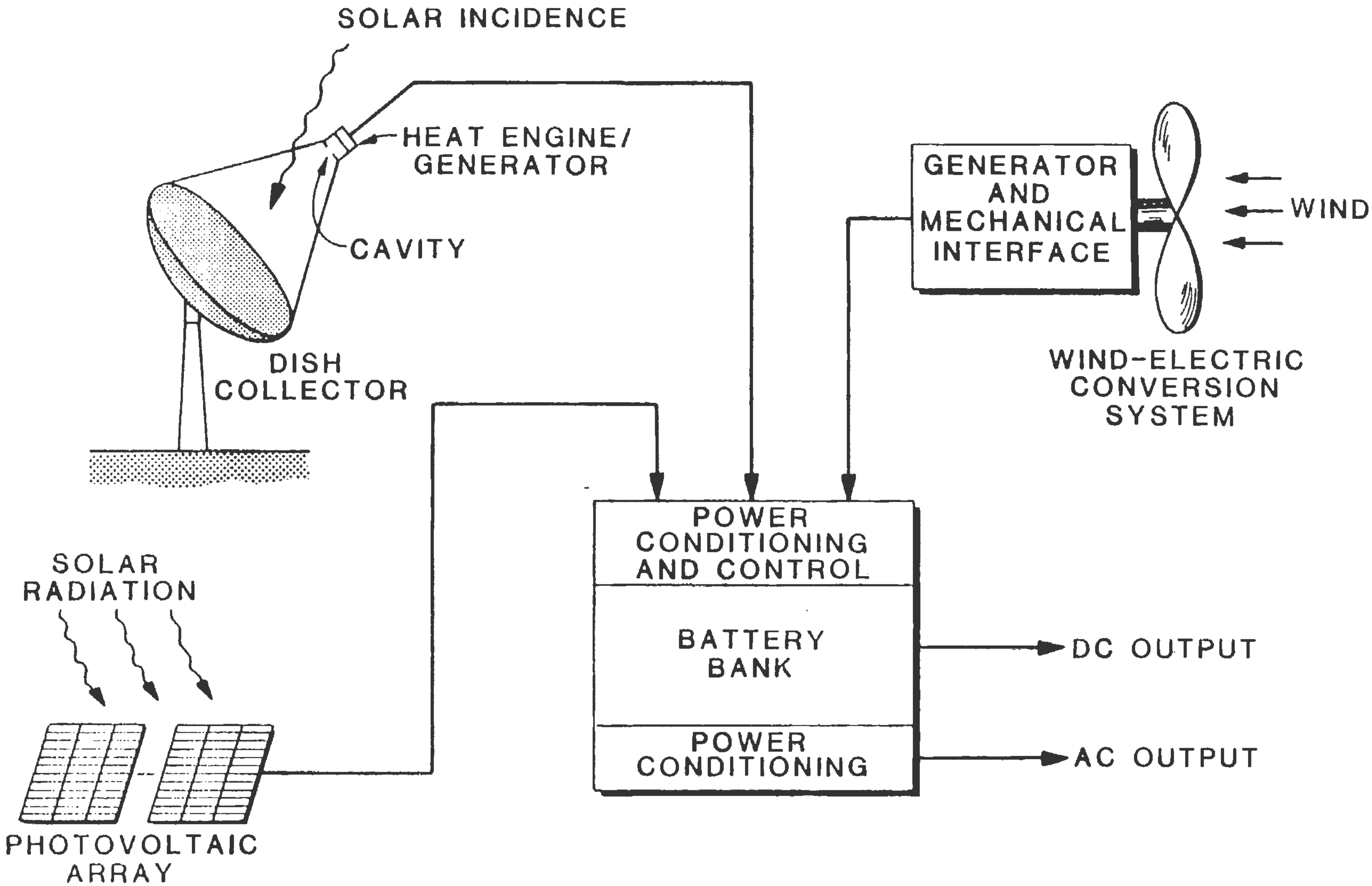


Figure 20. Integration of Solar Radiation and Wind Energy in Electrochemical Form

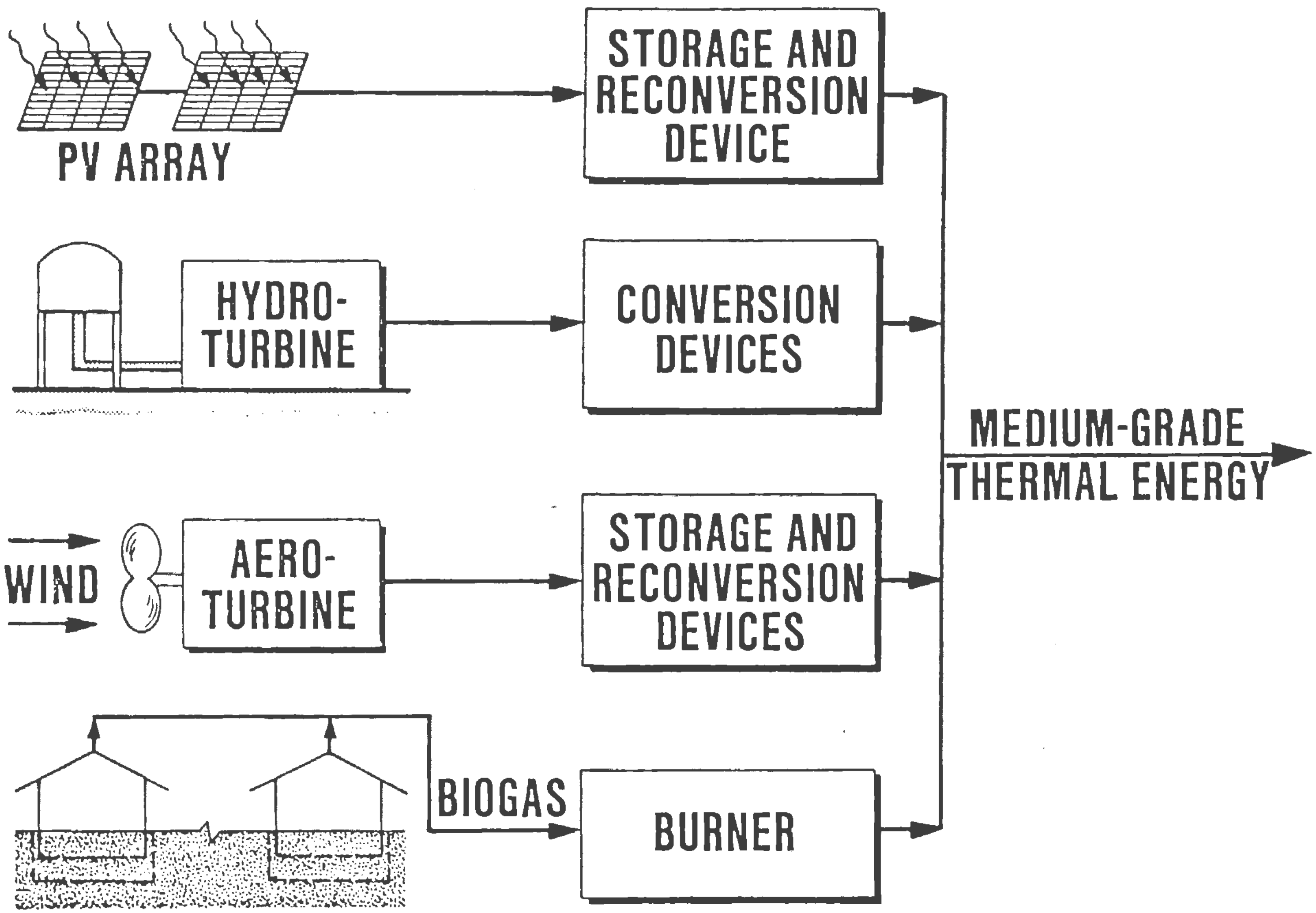


Figure 21. A Scheme to Integrate Renewable Energy Resources to Supply Medium-Grade Thermal Energy

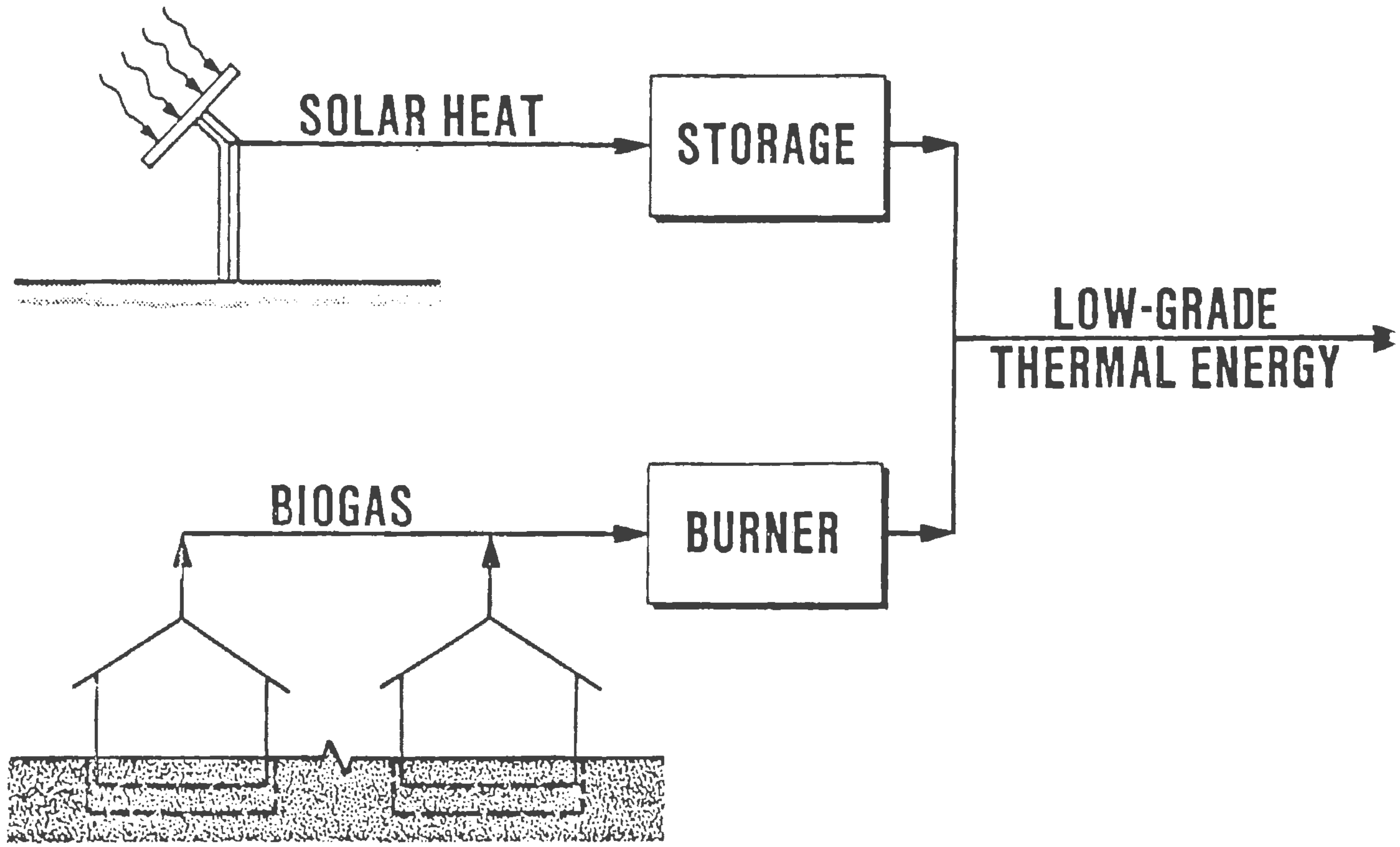


Figure 22. A Scheme to Integrate Renewable Energy Resources to Supply Low-Grade Thermal Energy

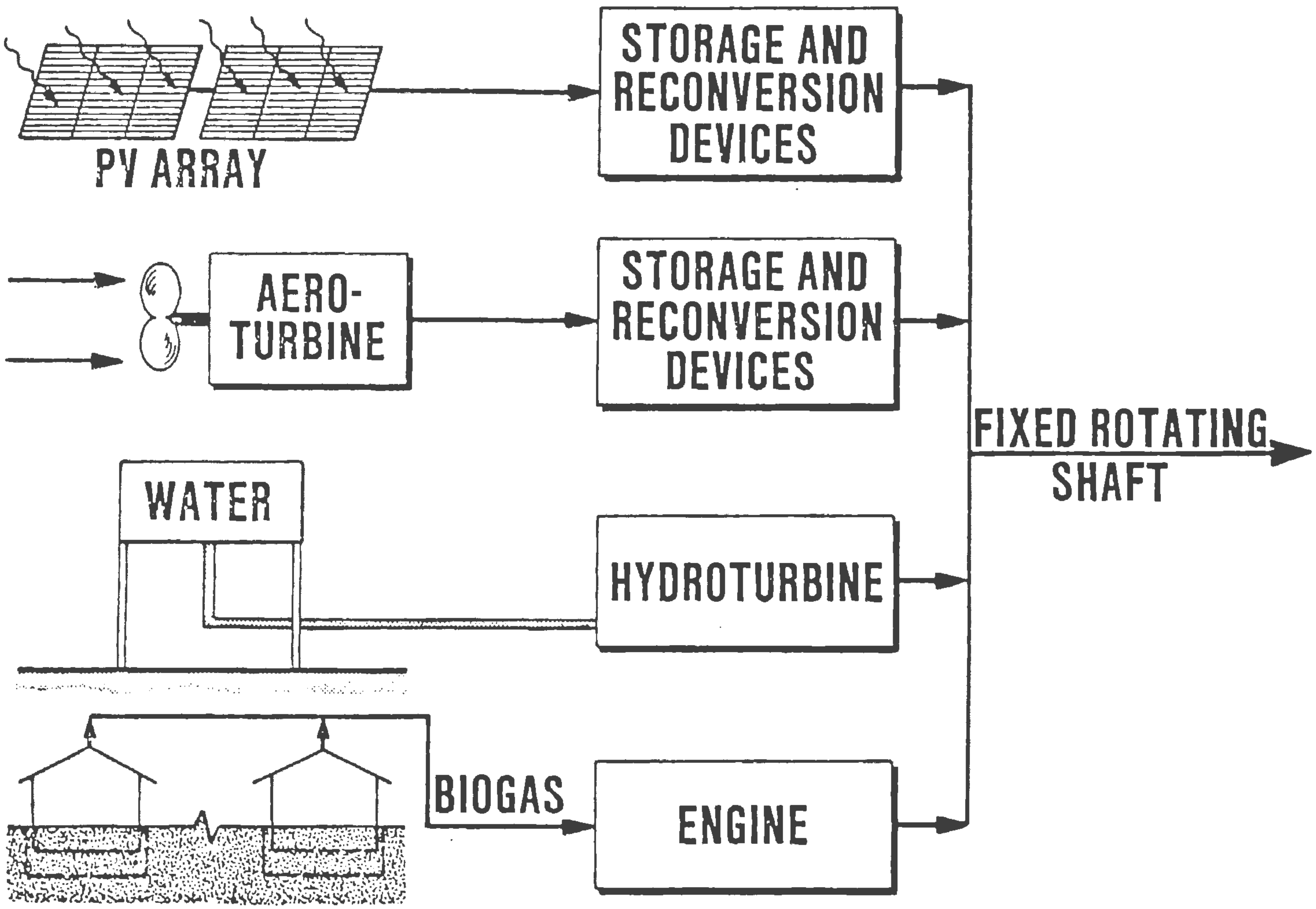


Figure 23. Integration of Renewable Energy Resources to Supply Fixed Rotating Shaft Power

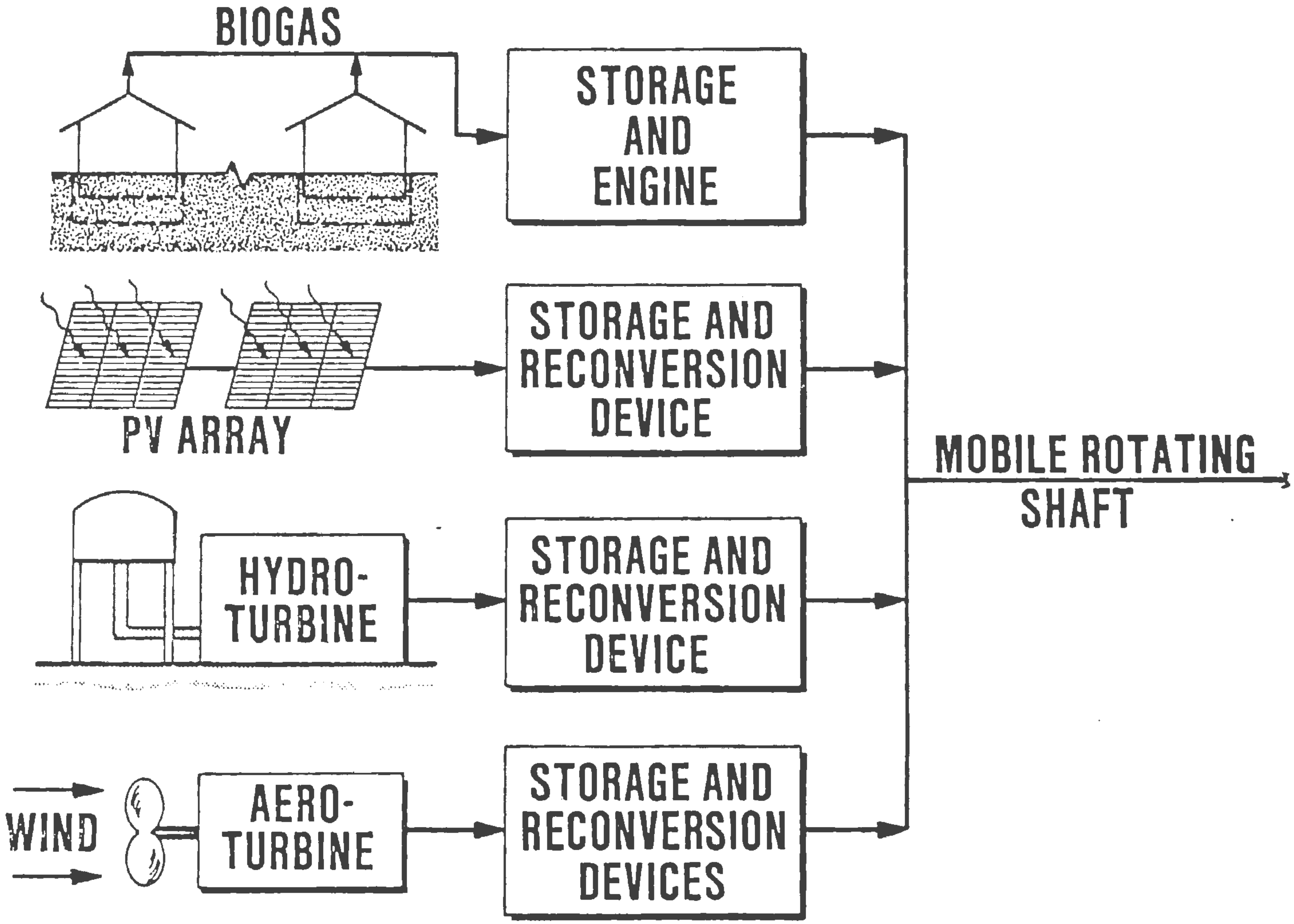


Figure 24. A Scheme to Integrate Renewable Energy Resources to Supply Mobile Rotating Shaft Power

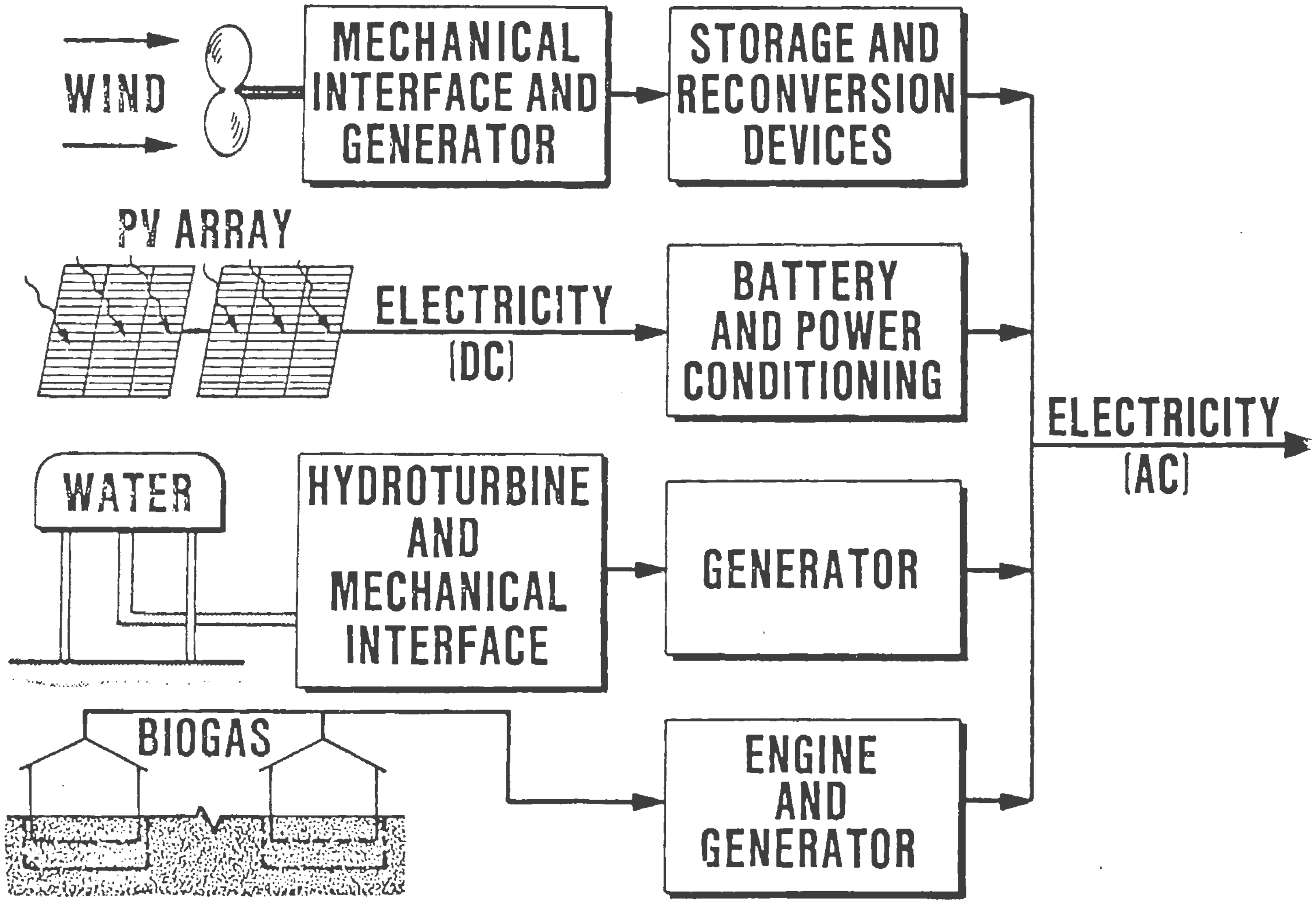


Figure 25. Integration of Renewable Energy Resources in Electrical Form

energy, low-grade thermal energy, fixed rotating shaft power, mobile rotating shaft power, and electricity demand respectively using different renewable energy resources.

3.3 Design of Integrated Renewable Energy Systems

There is a new drive towards utilizing renewable energy sources such as solar radiation, solar heat, wind, biomass, and falling water. This drive is motivated by realization of the limitations of non-renewable energy resources and by the environmental impacts of their uncontrolled use. One of the fundamental technical problems facing the designers of an IRES is to match the varying energy and power requirements of the loads with the mostly stochastic characteristics of the resources [89, 90] in an appropriate manner. However, the suitability or appropriateness of an IRES depends on many technical and socio-economic factors [91] which are highly site specific and country specific. Therefore, the first step in the process of designing an IRES is to identify the goals and define what is optimal or appropriate. Technical, economic, and more importantly, social aspects of the introduction of an IRES should be carefully analyzed before making specific choices.

The goal is to design an IRES to satisfy a set of energy requirements by utilizing different renewable energy resources. The system is assumed to be "stand-alone," and energy storage is used as needed to supply the load at a predetermined level of reliability. An objective function, which could be either total capital cost or total cost per year, can be minimized to arrive at optimum designs. In the case of total annual cost, cost of capital as well as operation and maintenance costs must be included. The resources under consideration are

1. biomass
2. solar
    a. heat
    b. radiation
3. wind
4. falling water (natural or human-made storage)

The energy needs are classified into four groups as follows:

1. medium-grade thermal energy (100^{o} to 300^{o} C)
2. low-grade thermal energy (less than 100^{o} C)
3. rotating shaft
    a. fixed
    b. mobile
4. electricity

The design procedure must take into account the stochastic characteristics of the resources under consideration as well as the probabilistic nature of the load demand. Resources such as wind solar radiation are highly variable and site-specific. They have instantaneous, minute-by-minute, hourly, diurnal, interannual, and seasonal variations. On the other hand, water resources are primarily seasonal and biomass (especially animal wastes) availability is fairly predictable.

The design procedure can be either deterministic [92] or probabilistic [93] and it must have the following elements.

1. Categorization of the needs
2. Cataloging of the resources
3. Consideration of the stochastic nature of resources and load

4. Finding the ratings of different energy conversion and utilization devices and the size of energy storage component that will minimize the chosen performance index.

To reiterate, an IRES utilizes different manifestations of solar energy in cascade or tandem to satisfy a set of energy needs. Two different approaches are available for utilizing different renewable resources in tandem. In the first approach all the resources are converted into a chosen form to be made available to the consumers. The second approach advocates the matching of resources and needs to achieve economy, efficiency, and the integration of benefits at the user's end. Also, the key steps in the process of designing an IRES were presented and discussed. The rest of this dissertation focuses on the modeling and design of tandem IRES that integrate the benefits at the user's end. Both deterministic and probabilistic techniques are considered.

CHAPTER IV

DETERMINISTIC APPROACH TO THE DESIGN OF INTEGRATED RENEWABLE ENERGY SYSTEMS

In this chapter a deterministic approach for designing an IRES is presented. The approach utilizes linear programming to minimize the total annual cost of operating the system. The objective and the problem to be considered are described first, then the mathematical formulation of the problem and the design approach based on this formulation are presented.

4.1 Problem Description and Objective

The basic objective is to supply some of the important energy needs by harnessing locally available renewable energy resources. The design of the system should minimize the total annual cost of operating the system, subject to constraints on resource availabilities and load demand.

The renewable energy resources available are:

1. Biomass
2. Solar radiation
3. Wind energy
4. Potential energy of water
5. Solar heat

6. Other resources such as geothermal, ocean thermal, tidal, and wave energies are extremely site-specific and as such are not considered. However, they can be included in the design if the appropriate parameters applicable to these resources are available.

Energy needs can generally be grouped into different tasks, depending on the type and quality of the energy required.

1. Medium-grade thermal energy (100^{o} - 300^{o} C)
   Medium-grade thermal energy is needed primarily for cooking and possibly for heating needs of small-scale industries.
2. Low-grade thermal energy (less than 100^{o} C)
   Low-grade thermal energy is used for domestic water heating, space heating, and process heat for small-scale industries.
3. Rotating mechanical shaft power
   Rotating shaft power is needed for small scale industries and/or of transportation purposes.
4. ac electricity
   Electricity in ac form is primarily used for lighting and supplying ac motors.
5. dc electricity
   dc electricity is primarily used for charging the batteries.

Theoretically, by employing a string of energy conversion hardwares, any resource can be used to satisfy the energy needs of any task in the list given above. However, some of the resource-task combinations are obviously not practical (either too expensive or too low in overall efficiency) and can be eliminated from further consideration. Thus in the general case of M resources and N tasks, the number of resource-task combinations to be considered will be far less than the product "MN". Table II lists the paths between resources and tasks that are judged to be feasible at the present time from economic and technical view points. As different and improved hardware becomes available, this list can be modified to reflect the new matchings. As mentioned earlier, when several renewable energy resources are used in tandem to supply a number of energy needs, two basic options are available for integrated system design.

a. Convert all the resources into one convenient form for storage and supply to all needs.

b. Use each resource in a way that is most convenient and efficient from the resource - task combination view point.

The deterministic design approach discussed here follows the second approach. The problem formulation that follows uses the partitioning of the components and devices as shown in Figure 26.

4.2 Problem Formulation

Consider the i^{th} resource being used to satisfy, in part or fully, the energy needs of the j^{th} task. Let the capital cost P_{ij} of the hardware involved be expressed in dollars per kW, with the kW rating being computed at the output of the energy conversion plants (point A in Figure 26). The cost C_{ij} in dollars per year for this resource - task combination can then be expressed as [94]

$$C_{ij} = \frac{T_{cr,ij} \, P_{ij} \, E_{ij}}{8760 \, k_{ij}} \tag{4.2.1}$$

where

$$T_{cr,ij} = \frac{r(1 + r)^{n_{ij}}}{(1 + r)^{n_{ij}} - 1} + m_{ij} \tag{4.2.2}$$

TABLE II

LIST OF RESOURCES, DEVICES, AND TASKS

Resources	Devices and Tasks
1. Biomass--Anaerobic Fermentation--Biogas	Burner - medium temperature heating, primarily for cooking
	Biogas fueled engine - mechanical rotating shaft power
	Biogas fueled engine driven generator, electricity generation
	Heater - low temperature heating, water heating, and space heating
2. Solar radiation, PV Array	dc motor - mechanical rotating shaft power
	Power conditioner - ac electricity
	Controller - dc electricity for batteries
3. Wind energy, Aeroturbine	Water pump - mechanical rotating shaft power for pumping water
	Generator - electrical energy generator
4. Water Head	Water turbines - mechanical rotating shaft power
	Water turbine driven generator (micro or mini hydro) - electrical energy generation
5. Solar heat, Collectors	Solar cooker - medium temperature heating for cooking
	Heat exchanger - low temperature water heating and space heating
	Heat engine - mechanical rotating shaft power
	Heat engine driven generator - electrical energy generation

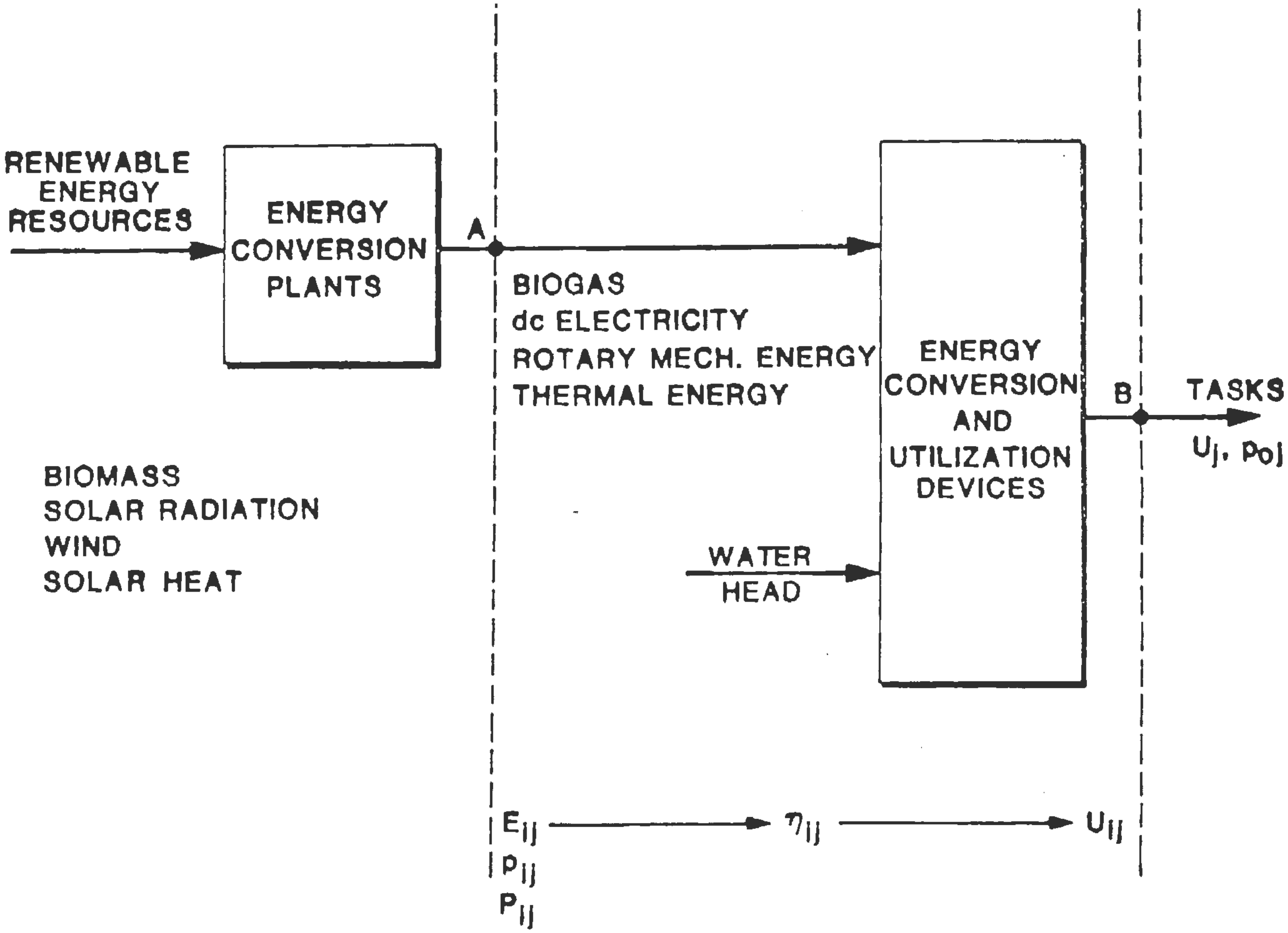


Figure 26. Schematic of the System for Problem Formulation

Summing over M resources and N tasks, the total cost CA in dollars per year becomes

$$CA = \sum_{i=1}^{M} \sum_{j=1}^{N} C_{ij} \tag{4.2.3}$$

In Equation (4.2.3), many terms in the double summation could be missing since the resource-task combinations are usually preselected based on several technical and economic considerations.

For design purposes, it is convenient to express energy supplied by resource i to satisfy demand j (E_{ij}) in terms of quantity of resource i required for performance of task j (x_{ij}) and energy equivalent of resource i (R_i) as follows.

$$E_{ij} = R_i \, x_{ij} \tag{4.2.4}$$

Combining Equations (4.2.1), (4.2.3), and (4.2.4), the total cost per year for satisfying all the energy needs becomes

$$CA = \left\{ \sum_{i=1}^{M} R_i \quad \sum_{j=1}^{N} a_{ij} \, x_{ij} \right\} \tag{4.2.5}$$

where

$$a_{ij} = \frac{T_{cr,ij} \, P_{ij}}{8760 \, k_{ij}} \tag{4.2.6}$$

The design approach focuses on minimizing CA, subject to the set of equality and inequality constraints listed below.

1. The sum of the energies supplied by the M resources for the j^{th} task should be equal to the total energy U_j required for the j^{th} task.

$$U_j = \sum_{i=1}^{M} R_i \quad {}_{ij} \, x_{ij}, \quad j=1,2,\ldots,N \tag{4.2.7}$$

2. The total quantity of some of the M resources is limited due to availability or other considerations. Therefore, the total amount of a particular resource consumed or used for various tasks should be less than or equal to the corresponding maximum available value. For the i^{th} resource, if E_{imax} is the maximum available, then

$$E_{imax} \geq \sum_{j=1}^{N} R_i \, x_{ij} \tag{4.2.8}$$

Since $E_{imax} = R_i \, x_{imax}$, Equation (4.2.8) can be written as

$$x_{imax} \geq \sum_{j=1}^{N} x_{ij}, \quad i = 1,2,\ldots,M', \quad (M' \leq M) \tag{4.2.9}$$

The range of i in Equation (4.2.9) takes into account the possibility that for some of the resource there may be no upper bound for x_i.

3. Obviously, all the x_{ij} values must be non-negative.

$$x_{ij} \geq 0 \quad \text{for } \begin{array}{l} i = 1,2,\ldots,M \\ j = 1,2,\ldots,N \end{array} \tag{4.2.10}$$

4. In addition to satisfying the total energy requirements of each task, the constraints imposed by the rate of energy use (power) should also be considered. For the i^{th} resource, if p_{ij} is the maximum power required for handling the share of the j^{th} task supplied by the i^{th} resource, then the maximum rate of energy use expected of the i^{th} resource, p_i, is

$$p_i = \frac{1}{d_i} \sum_{j=1}^{N} p_{ij}, \quad i = 1,2,\ldots,M \tag{4.2.11}$$

In Equation (4.2.11) d_i is the diversity for the tasks supplied by the i^{th} resource and it is greater than or equal to one.

$$d_i = \frac{\text{Sum of individual maximum demands}}{\text{Net maximum demand}} \tag{4.2.12}$$

If the total energy derived per year from the i^{th} resource for all the tasks is E_i, and if k_i is the effective load (or plant) factor experienced, then the available power rating p_{ai} in kW can be expressed as

$$p_{ai} = \frac{E_i}{8760\ k_i}\ ,\ i=1,2,\ldots,M \tag{4.2.13}$$

The power constraint of interest is

$$p_i \leq p_{ai},\ i = 1,2,\ldots,M \tag{4.2.14}$$

Moreover,

$$E_i = \sum_{j=1}^{N} E_{ij} = R_i \sum_{j=1}^{N} x_{ij} \tag{4.2.15}$$

$$p_{ij} = \frac{E_{ij}}{8760\ k_{ij}} = \frac{R_i\ x_{ij}}{8760\ k_{ij}} \tag{4.2.16}$$

Therefore the power constraint (see Equation [4.2.14]) becomes

$$\frac{1}{k_i} \sum_{j=1}^{N} x_{ij} - \frac{1}{d_i} \sum_{j=1}^{N} \frac{x_{ij}}{k_{ij}} \geq 0,\ i=1,2,\ldots,M \tag{4.2.17}$$

Determination of k_{ij} presents a special problem. Based on its definition and physical significance, one can write

$$k_{ij} = \frac{E_{ij}}{8760\ p_{ij}} = \frac{U_{ij}}{8760\quad {}_{ij}\ p_{ij}} \tag{4.2.18}$$

In Equation (4.2.18), p_{ij} and U_{ij} are not known a priori. However, the total energy requirement U_j and the maximum rate of energy consumption (maximum power required) p_{oj} for the j^{th} task must be known or estimated before proceeding with the design. If one assumes that the ratio of peak to average power rating required for a task (or a part thereof) does not depend on which resource supplies the power, k_{ij} can be estimated as follows:

$$k_{ij} = \frac{U_j}{8760 \; p_{oj}} \tag{4.2.19}$$

The design problem thus becomes an optimization problem, stated as follows:

Minimize the annual cost function CA, where

$$CA = \sum_{i=1}^{M} R_i \sum_{j=1}^{N} a_{ij} \, x_{ij} \tag{4.2.20}$$

Subject to the constraints

$$\sum_{i=1}^{M} R_i \, \eta_{ij} \, x_{ij} = U_j, \qquad j=1,2,\ldots,N \tag{4.2.21}$$

$$\sum_{j=1}^{N} x_{ij} \leq x_{imax}, \quad i = 1,2,\ldots,M' \;\; (M' \leq M) \tag{4.2.22}$$

$$\frac{1}{k_i} \sum_{j=1}^{N} x_{ij} - \frac{1}{d_i} \sum_{j=1}^{N} \frac{x_{ij}}{k_{ij}} \leq 0, \qquad i=1,2,\ldots,M \tag{4.2.23}$$

$$x_{ij} \geq 0 \qquad \text{for all } i \text{ and } j \tag{4.2.24}$$

Since the objective function and all the constraints are linear, this is a linear programming problem and can be solved by the simplex method [95].

4.3 Design Approach

The components of an integrated renewable energy system can be split into two groups -- (i) energy conversion plants and (ii) energy conversion and utilization devices as illustrated earlier in Figure 26. Biomass, solar radiation, wind, and solar heat are considered as inputs to the energy conversion plants. The outputs of the plants (at point A in Figure 26) are in the form of the biogas, dc electricity, rotary mechanical energy, and thermal energy. These energy forms, together with water head (potential energy of water), constitute the inputs to an array of energy conversion and utilization devices employed to accomplish the required tasks.

The design of the system involves finding the quantities of the various resources required per year and the sizes of collection devices that minimize the total (cost of capital and operation and maintenance charges) cost per year. The values to be found are:

x_1 = total volume of biogas in m^3 per year

x_2 = PV array area in m^2

x_3 = swept area of wind turbines in m^2

x_4 = volume of water in m^3 per year

x_5 = solar thermal collector area in m^2

Each of the resources listed above may be used for more than one task. Thus x_{ij} will be the portion of x_i used (or allotted or required) to perform its share of the j^{th} task. Therefore

$$x_i = \sum_{j=1}^{N} x_{ij} \tag{4.3.1}$$

The energy equivalent of the various resources are calculated using a set of factors denoted as R_i. For example,

$$E_i = R_i \, x_i \tag{4.3.2}$$

and

$$E_{ij} = R_i \, x_{ij} \tag{4.3.3}$$

The specific R_i factors used in the formulation of the design problem are listed below:

i = 1 R_1 is the energy equivalent of biogas in kWh per cubic meter

i = 2 R_2 is the annual dc electrical energy output of the PV array in kWh per square meter

i = 3 R_3 is the annual rotating mechanical shaft energy output of wind turbines in kWh per square meter of swept area

i = 4 R_4 is the potential energy of stored water in kWh per cubic meter

i = 5 R_5 is the annual thermal energy collected by solar-thermal collectors in kWh per square meter.

In particular

$$R_2 = \eta_p \sum_{\alpha=1}^{8760} y_\alpha \tag{4.3.4}$$

$$R_3 = \eta_w \sum_{\alpha=1}^{8760} v_\alpha^3 \tag{4.3.5}$$

$$R_4 = \frac{gh}{3600} \tag{4.3.6}$$

$$R_5 = \eta_t \sum_{\alpha=1}^{8760} y_\alpha \tag{4.3.7}$$

An example design based on this approach is given in Chapter VI. To summarize, a deterministic approach for designing an IRES utilizing renewable resources such as biomass, wind, solar radiation, and falling water has been presented. The system is to satisfy a variety of energy needs. The approach utilizes linear programming to minimize the total annual cost of operating the system subject to a set of constraints imposed by load characteristics as well as resource availability and characteristics.

CHAPTER V

PROBABILISTIC APPROACH TO THE DESIGN OF INTEGRATED RENEWABLE ENERGY SYSTEM

In this chapter a probabilistic approach for designing an IRES is presented. The approach utilizes the Loss of Power Supply Probability (LPSP) as the key system parameter and minimizes the initial total capital investment. Loss of power supply probability is defined first and different methods of evaluating LPSP are presented. This is followed by a discussion of the LPSP based design approach.

5.1 Loss of Power Supply Probability

Systems utilizing renewable energy resources are typically operated with energy storage devices such as batteries, water storage, etc. to smooth out the variable output of the system in a stand-alone situation. Whenever the combined system cannot meet the load demand, loss of power supply occurs. The probability of this event happening is a good measure of system's performance [96].

With the passage of time, as the energy storage system interacts with the IRES and load exchanging energy back and forth, the amount of energy stored, $E(t)$, constantly changes with time [97]. The variable $E(t)$ characterizes the overall status of the system very well, because it is a function of the system output, rated capacity of the storage system, as well as the load demand. The state of charge is also used as a decision variable for the control of overcharge and overdischarge. Overcharge may occur when high input levels and/or low power demands exist. In this case, if the state of the charge in the storage system exceeds a set maximum value (E_R), the control system will intervene and the charging process is stopped [98]. The case of overdischarge may occur if low input levels and/or high power demands exist. In this case, if the state of charge decreases below a set minimum value E_m (which can be zero but not negative), the control system intervenes and disconnects the load (see Reference 90). This action may be necessary to prolong the life of the energy storage device [99]. Figure 27 illustrates the nature of charge as a function of time. Each point on this curve yields the time period during which the state of charge equalled or exceeded a given value. Figure 28 is obtained by normalizing the time axis of Figure 27 with respect to the study period T and then exchanging both axis. Each point on the curve in Figure 28 gives the probability of existence of a charge equal or larger than the one determined by the corresponding point on the charge axis during the study period.

Based on the above discussion, the Loss of Power Supply Probability (LPSP) can be defined as follows:

> The probability of the state of charge at any accumulative time t (within the study period T) being less than or equal to the minimum permissible level, E_m.

Therefore the loss of power supply probability is

$$LPSP = p[E(t) \leq E_m; \ t < T] \qquad (5.1.1)$$

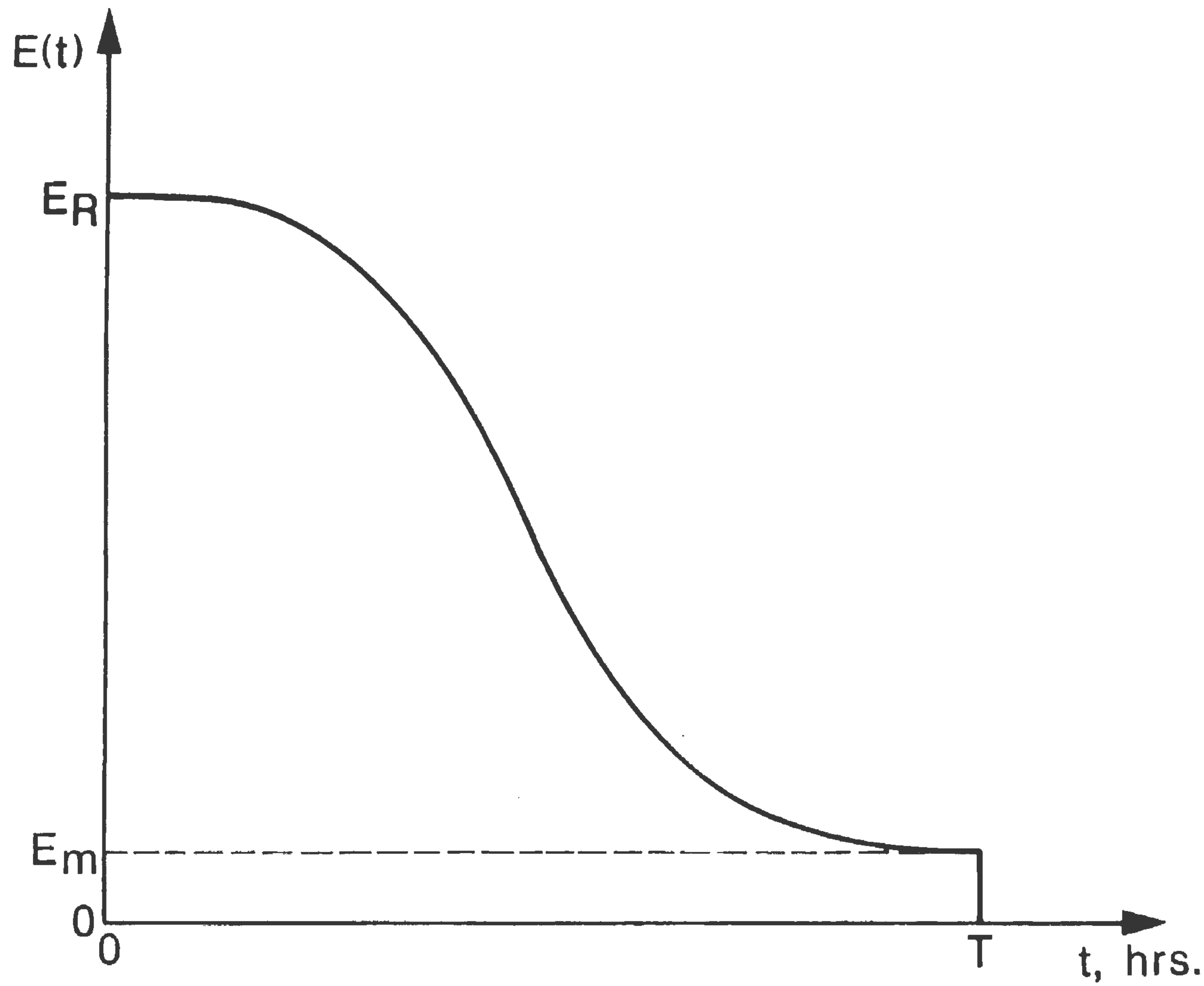


Figure 27. Variation of Stored Charge as a Function of Time

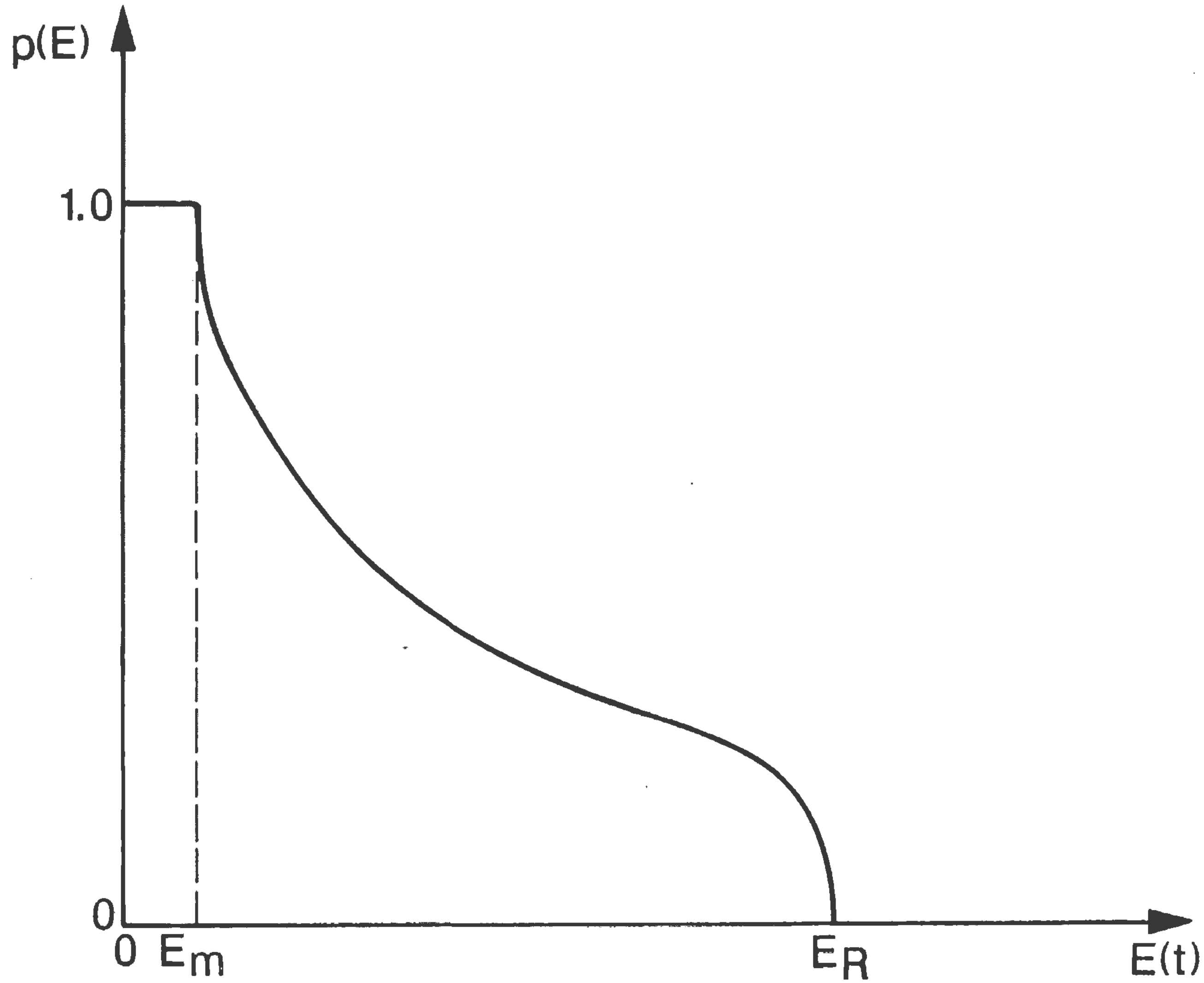


Figure 28. Normalized Complementary Distribution Function for the Stored Charge

or

$$LPSP = 1 - p(E_m) \tag{5.1.2}$$

where $p(E_m)$ is the probability that the charge is greater than E_m, and $[1 - p(E_m)]$ is the probability that the charge is less than or equal to E_m.

In the discussion of the LPSP method, it is assumed that the entire output of the IRES is processed through the appropriate interface and is stored in the energy storage and reconversion system from which the load is supplied on demand. Hence, power input to storage, $C(t)$, at any instant of time is the difference between the total output power of the system, $P(t)$, and the load demand, $L(t)$.

$$C(t) = P(t) - L(t) \tag{5.1.3}$$

Since the system output varies between zero and P_R, and the load varies between L_m and L_M, the power input $C(t)$ to the storage will vary between $(-L_M)$ for periods of no generation and maximum demand to $(P_R - L_m)$ for periods of maximum generation and minimum demand. If $L(t)$ and $P(t)$ are assumed to be constant for a specific time frame, then $C(t)$ is also equal to the energy input to the storage during this time. Negative values of $C(t)$ denote energy extraction from the storage system.

Assuming $P(t)$ and $L(t)$ are statistically independent random variables, the probability density function (pdf) $f_C(c)$ for the random variable $C(t)$ can be obtained by convolving the pdf's $f_P(p)$ and $f_L(l)$ of $P(t)$ and $L(t)$ respectively [100, 101].

$$f_C(c) = \int_{-\infty}^{+\infty} f_L(-l) f_P(c-l) dl = \int_{-\infty}^{+\infty} f_P(p) f_L(p-c) dp \tag{5.1.4}$$

Assuming $P(t)$ is equal to the sum of the output power of wind energy conversion system, $W(t)$, and the output power of the photovoltaic array, $S(t)$, both in electrical form,

$$P(t) = W(t) + S(t) \tag{5.1.5}$$

then

$$f_P(p) = \int_{-\infty}^{+\infty} f_S(s) f_W(p - s) ds = \int_{-\infty}^{+\infty} f_S(p - w) f_W(w) dw \tag{5.1.6}$$

where

$f_S(s)$ = pdf of photovoltaic array output

$f_W(w)$ = pdf of WECS output

Equation (5.1.6) assumes that $W(t)$ and $S(t)$ are statistically independent.

If detailed recorded data describing characteristics of each energy resource is available, the output power, $P(t)$, of the IRES can be computed using equations describing the output characteristics of each device utilized (see Chapter II). The power input to storage, $C(t)$, at time t is then calculated using Equation (5.1.3). As discussed previously, before if $L(t)$ and $P(t)$ are assumed to be constant over an hour, then $C(t)$ is also equal to the energy input to the storage system during this hour. The amount of energy in storage, $E(t)$, at the end of each hour is obtained by adding, algebraically, $C(t)$ to the amount of stored energy at the start of the hour. To simulate actual operating conditions, every time the value of $E(t)$ falls below E_m, it is restored to E_m after a failure of the power supply has been recorded and simulation is continued. Every time $E(t)$ exceeds E_R, it is brought back to E_R before proceeding further. This is commonly known as "dumping", and it is due to generation above and beyond energy demand when the storage system is charged to its full capacity. Following the steps outlined here, the number of times loss of power supply occurred (when $E(t)$ goes below E_m) is counted and expressed as a fraction of the study period in hours. This is the numerical value of the loss of power supply probability.

In the absence of detailed recorded data, the key to the computation of the LPSP is contained in the power duration curve for the random variable C, shown in Figure [29]. As mentioned before power input to the storage, C, varies between $(-L_m)$ and $(P_R - L_m)$. The area A_2 above $C = 0$ is proportional to the energy input to the storage during the study period T and the area A_1 below $C = 0$ is a measure of the energy output from the storage during the same period. Therefore, if a value c_1 can be found such that

$$A_1 - A_2 = (\text{Ssmin})T \tag{5.1.7}$$

where (Ssmin)T is the allowable energy depletion from the storage system, then the LPSP value can be calculated using the probability density function $f_C(c)$ of C [102].

$$\text{LPSP} = \int_{-L_M}^{-c_1} f_C(c)dc \tag{5.1.8}$$

It should be noted that Ssmin is the allowable equivalent continuous power output from the storage system during the study period.

$$\text{Ssmin} = \frac{E_R - E_m}{T} \tag{5.1.9}$$

The value of c_1 is found by trial and error using the following relationship involving the probability distribution function (PDF) $F_C(c)$.

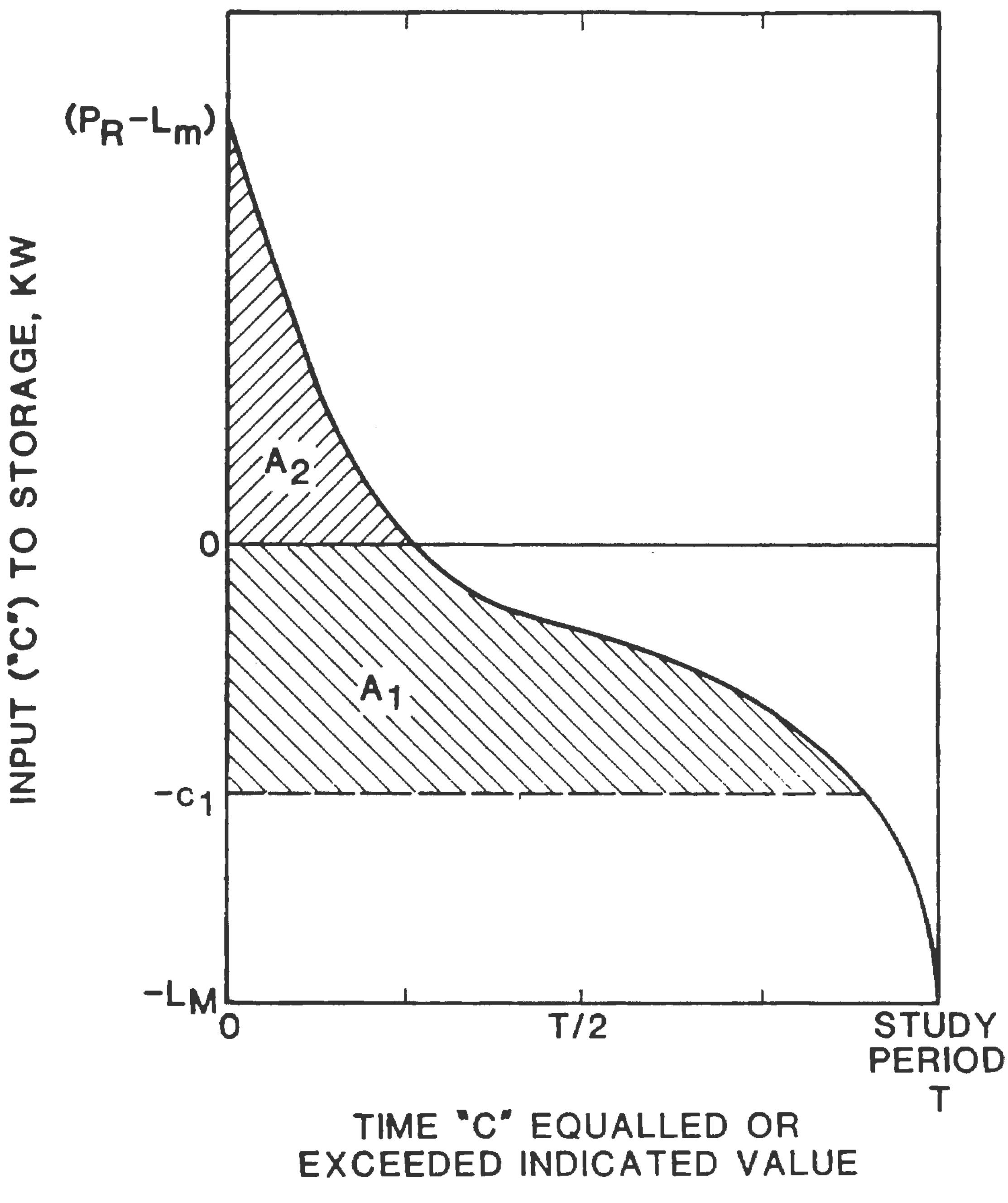


Figure 29. Power Duration Curve for "C"

$$(P_R - L_m) - \int_0^{P_R - L_m} F_C(c)dc + \text{Ssmin} = c_1 - \int_{-c_1}^{0} F_C(c)dc \qquad (5.1.10)$$

The validity of Equation (5.1.10) can be seen by multiplying both sides of the equation by T, the duration of the study period.

5.2 Design Approach and Methodology

The performance of any energy system is evaluated by its ability to satisfy the energy demand. The energy system is said to have experienced a breach if load is not supplied on demand. The probability of such an event happening (LPSP) can be taken as a numerical measure of the quality of the energy system. The objective of the designer is to decrease this measure to the lowest possible value, subject to constraints such as cost and availability of components. It is practically impossible to design a system with an LPSP of zero, especially when one considers the probabilities of failures of the various components constituting the system. One possible solution is to neglect the failure of components and focus only on the variations in the resources and in the load. The probability of a breach under this assumption is what has been called the LPSP. By selecting a small enough LPSP, one can design a stand-alone IRES that has reasonably good performance in spite of the fact that failure of components have not been accounted for.

Next, the design approach based on the key system parameter LPSP used to arrive at the final design values which satisfy the stated objective is presented by means of an example. Consider a simple system (see Figure 30) consisting of a photovoltaic array and a battery bank. The objective is to arrive at the ratings of the SEC, P_r, and the energy storage system, E_B, to achieve a given LPSP at the lowest possible

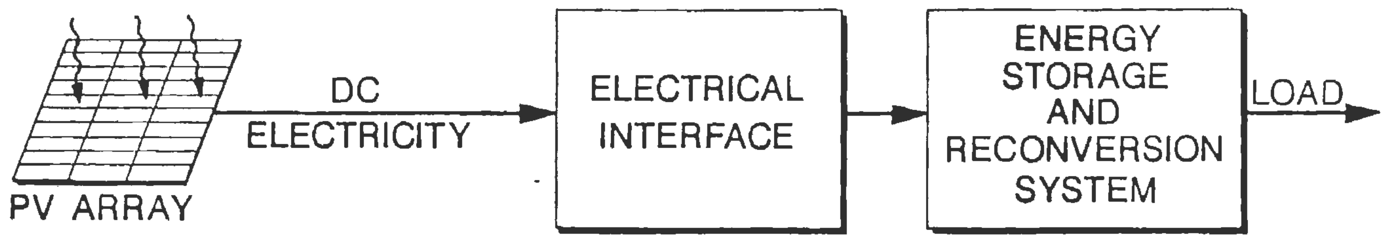


Figure 30. Block Diagram of the System Under Study

initial cost for a given site and load demand. The total capital cost of a SEC with energy storage can be expressed in terms of system rating and an initial fixed cost as follows.

$$CC = CC_0 + a\ P_r + b\ E_B \tag{5.2.1}$$

As P_r and E_B vary, the locus of points corresponding to a fixed total cost will be a straight line in the P_r - E_B plane with a slope of (-b/a). Moreover, a family of parallel straight lines is obtained corresponding to different values of CC. As CC increases (decreases), the intercept with the ordinate (P_r axis) increases (decreases), thus moving the straight line to the right (left). As mentioned before, the design objective is to select P_r and E_B such that CC is minimized for a chosen LPSP. The cost of system and LPSP calculations are made for various alternatives, including all reasonable combinations of SEC power output rating and the storage capacity of the storage system within a given range:

$$E_{Bmin} < E_B < E_{Bmax}$$

$$P_{rmin} < P_r < P_{rmax}$$

Since both P_r and E_B change in well defined steps, the number of possible combinations which must be evaluated is finite. Figure 31 displays the general nature of LPSP as a function of SEC rating for different values of energy storage capacity (E_B). It must be noted that the value of LPSP approaches zero for increasing values of P_r and theoretically it can be zero. This would mean that the energy supply is assured with no break during the study period. An examination of Figure 31 reveals that there are several possible combinations of P_r and E_B

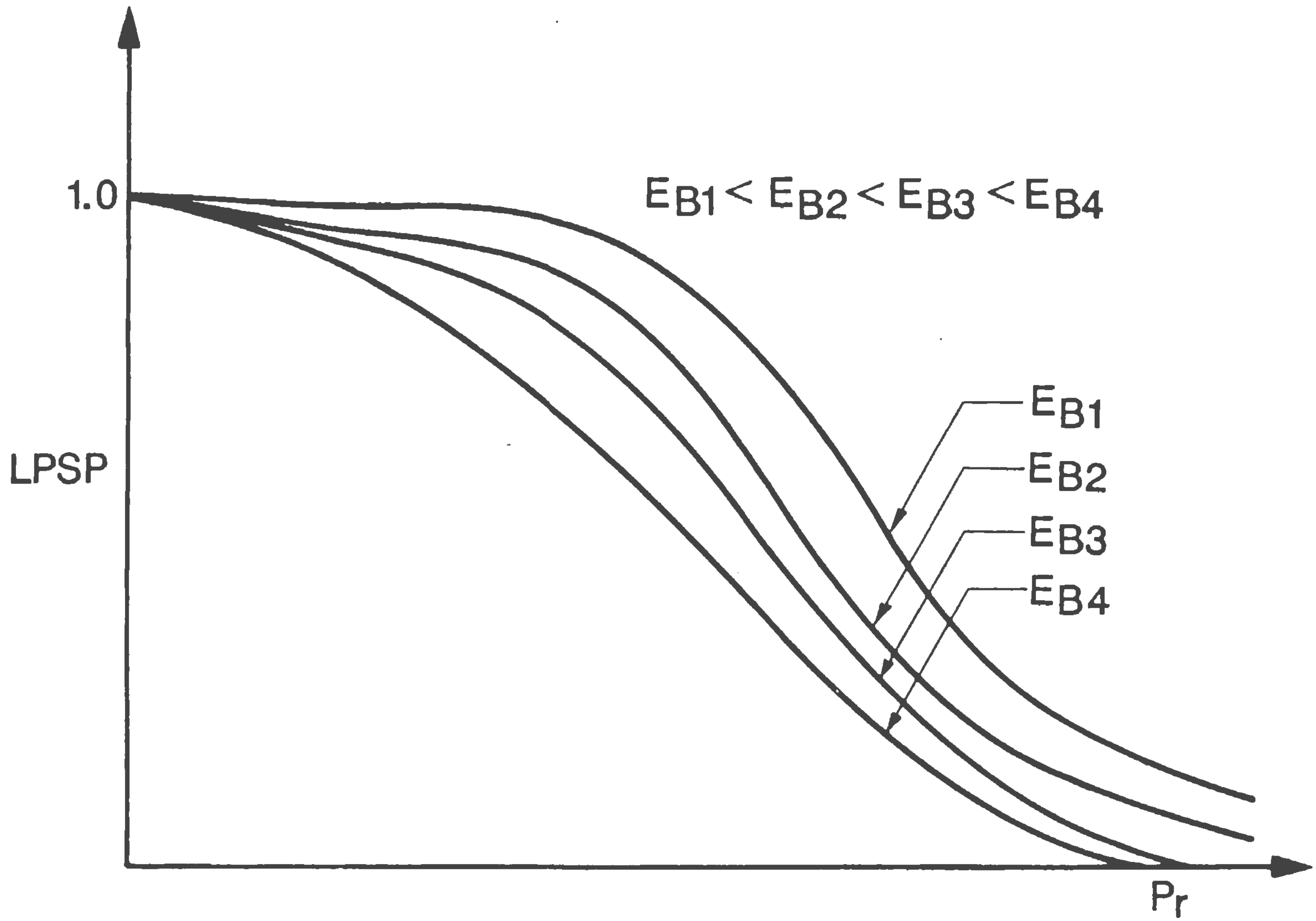


Figure 31. LPSP as a Function of P_r with E_B as a Parameter

that could result in a given value of LPSP.

Before solving the problem analytically, a graphical solution will be presented. Figure 32 illustrated P_r as a function of E_B with LPSP as the parameter. As mentioned before, the cost function [see Equation (5.2.1)] is a straight line in P_r - E_B plane, with a slope given by (-b/a). This line will intersect the P_r and E_B axis at (CC - CC_o)/a and (CC - CC_o)/b respectively. The size of the SEC and the size of the required storage capacity for a given total cost CC_1, and with a chosen LPSP value, say LPSP = $LPSP_1$, can be obtained by finding the points at which the straight line corresponding to the total cost function CC_1 intersects the curve of P_r versus E_B for the chosen $LPSP_1$. The two curves mentioned will typically have two intersection points X_1 and Y_1 (see Figure 33) but neither of them corresponds to an optimum solution. In order to find the system parameters corresponding to minimum cost, a straight line that not only has the slope (-b/a) but also is tangential to the $LPSP_1$ curve must be found (see Figure 33). This is equivalent to finding a point Z_1, on the P_r versus E_B curve for a given LPSP (equal to $LPSP_1$) at which the slope of the curve and the slope of the straight line are the same. In other words

$$dp_r/dE_B = -b/a \tag{5.2.2}$$

where

dP_r = The incremental increase (decrease) in the installed SEC power output required for maintaining the same LPSP (kW)

dE_B = The corresponding incremental decrease (increase) in the installed capacity of the energy storage system required to maintain the same LPSP (kWh)

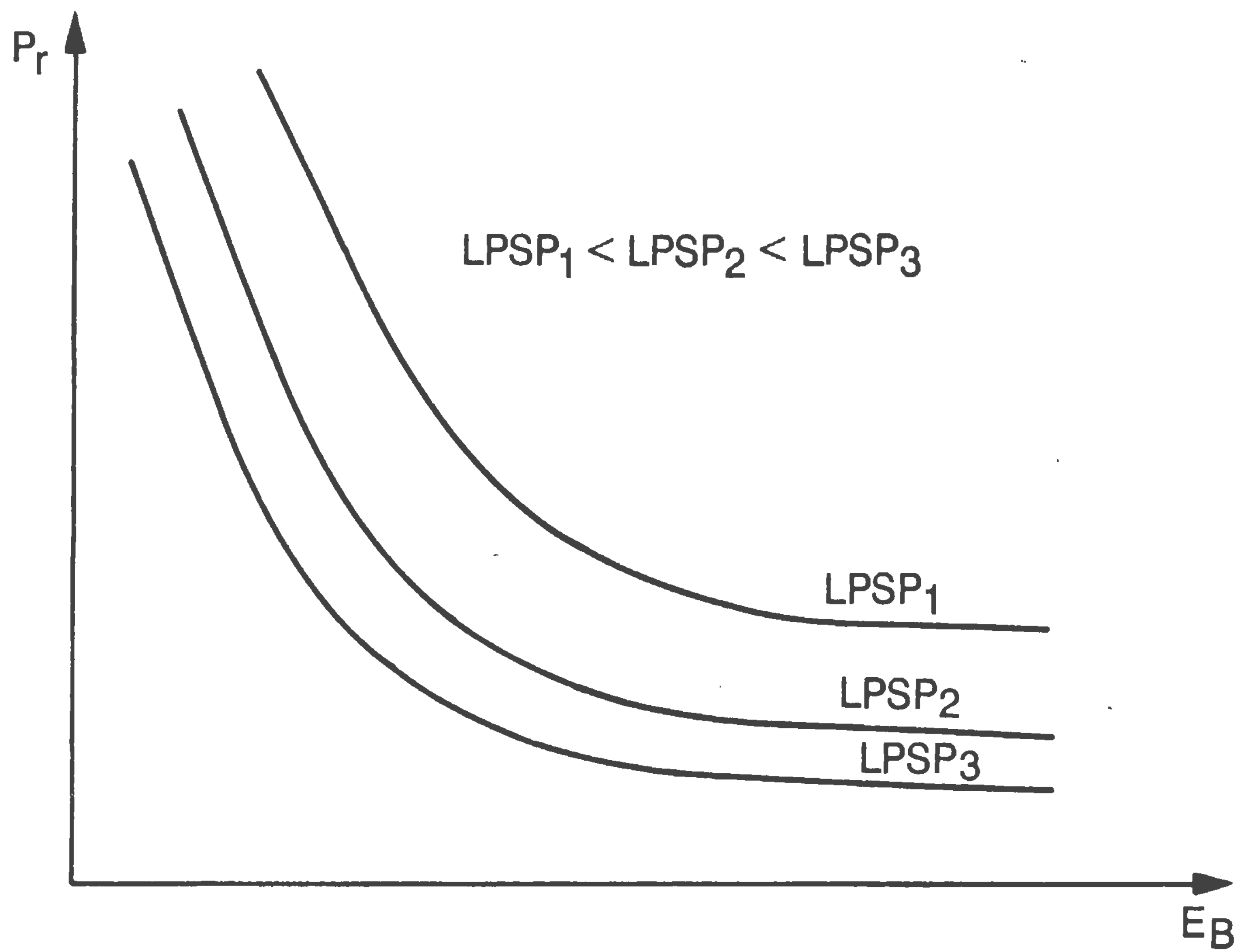


Figure 32. P_r as a Function of E_B with LPSP as a Parameter

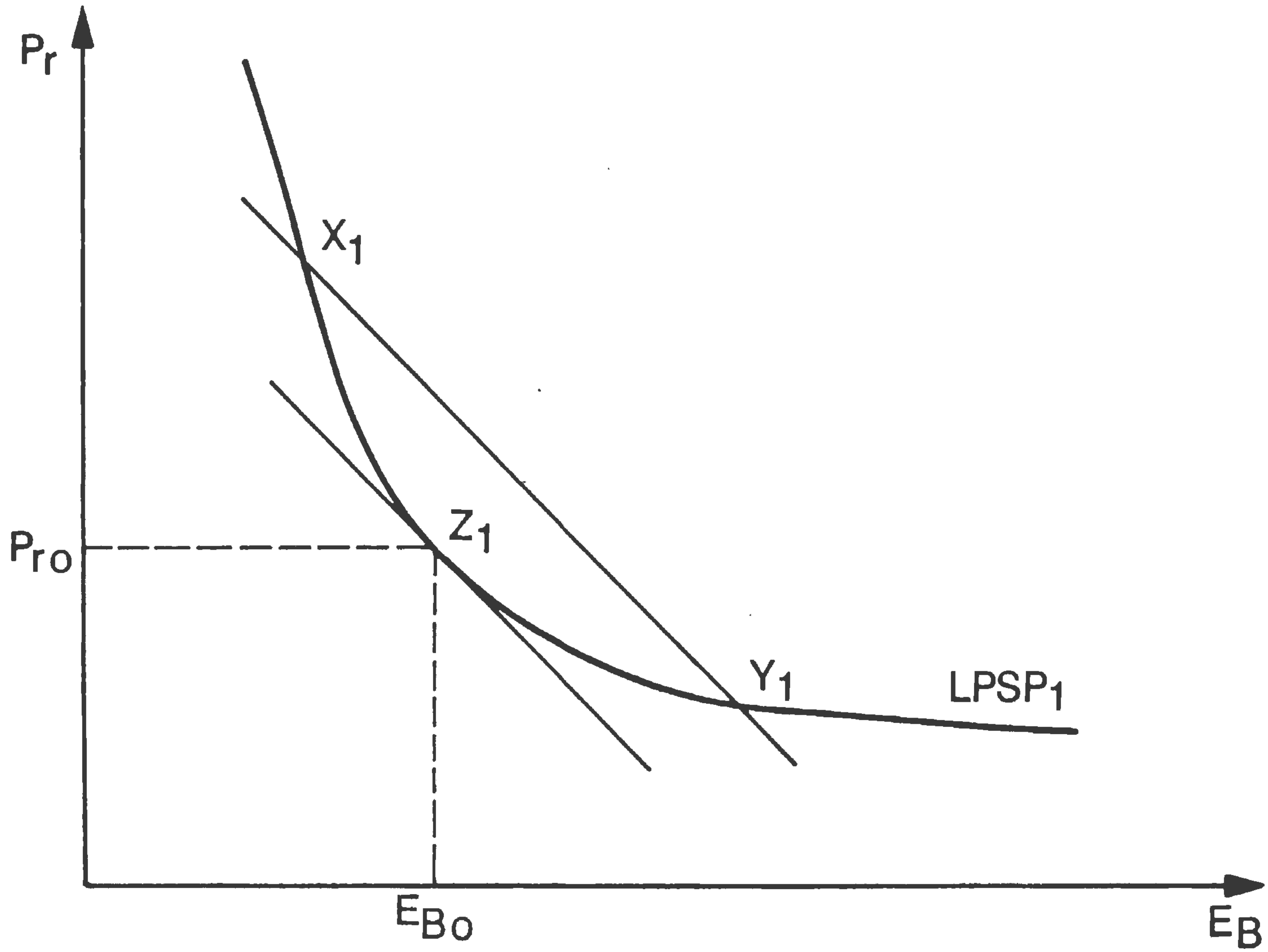


Figure 33. Graphical Method for Obtaining an Optimum Solution

The design parameters can now be found from Figure 33 the required SEC rating is P_{ro} kW and size of energy storage is E_{Bo} kWh.

Next a probabilistic approach for the design of an IRES based on LPSP is presented. The first step in the design procedure is to categorize and prioritize the needs. The next step is to start with the resource that requires the least amount of capital investment to satisfy the top-priority need, use it to exhaustion, then consider the remaining resource in the order of increasing capital requirements until all the needs are satisfied at the specified reliability level. Unless there is an abundance of the particular resource that requires the least amount of capital investment, as the design proceeds, one will reach a point at which several resources will have to be used to satisfy the needs. It is at this stage that the LPSP method is employed to determine the size of different devices required to satisfy the design criteria. In order to use the LPSP approach the rating of the system [P_r in Equation (5.2.1)] is computed using Equation (5.2.3).

$$P_r = \sum_{\alpha=1}^{M_1} a_\alpha P_{r\alpha} \tag{5.2.3}$$

where a_α is the ratio of the cost of the hardware associated with the α^{th} resource to the SEC cost. Obviously, the a_α associated with SEC will be equal to one. Equation (5.2.1) is then transformed into Equation (5.2.4) if more than one resource is to be considered.

$$CC = CC_o + a \sum_{\alpha=1}^{M1} a_\alpha P_{r\alpha} + bE_B \tag{5.2.4}$$

Then using the LPSP based design approach discussed, the graphical approach, system rating P_r [see Equation (5.2.3)] can be found and the individual system ratings are then selected based on other constraints such as the amount of energy available from different resources, amount of resource available, and constraints imposed by the chosen site.

5.3 IRES Program

The overall design approach described in this chapter is coded as a computer program named IRES. The design approach classifies the energy needs into four groups as follows:

1. Medium-grade thermal energy - primarily for cooking
2. Low-grade thermal energy - mostly for water and space heating
3. Rotating shaft:
   a) Fixed - for water pumping, small-scale industries, and the like
   b) Mobile - for transportation and agricultural uses
4. Electricity - for lighting, educational and communication devices, and for other uses as required.

Four renewable energy resources are considered:

A. Biomass

B. Solar

C. Wind

D. Falling water

The program is set up in five stages as illustrated in the flow chart of Figure 34. The first stage reads in information on the characteristics and availability of the various resources and needs, and converts all of them into a common unit basis (namely kWh). In the second stage, as much (or all) of the medium-grade thermal energy requirements as possible are satisfied by biomass (specifically biogas obtained by anaerobic fermentation). As the design proceeds to the third stage,

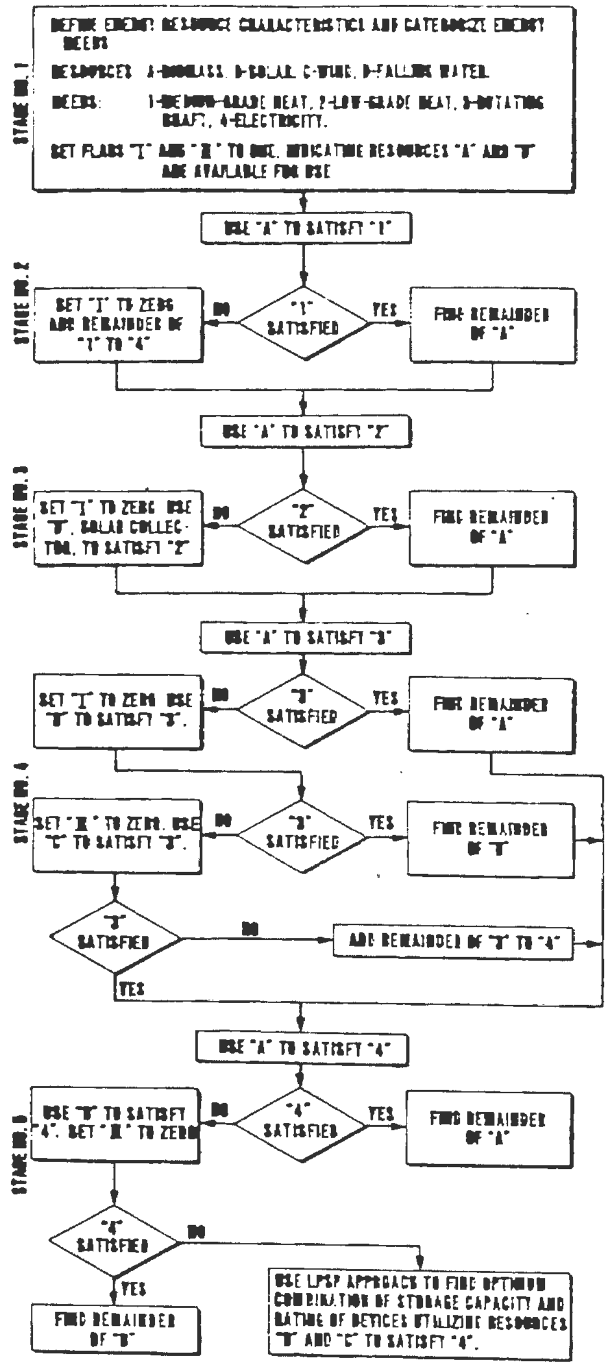


Figure 34. "IRES" Flow Chart

low-grade thermal energy requirements are considered. They are satisfied by biogas (if any of it is still available) and by solar-thermal collectors. In the fourth stage, rotating shaft energy demand is satisfied by a combination of biogas-driven engine (if any biogas is still available), falling water, and wind energy systems. If any of the needs considered in stages 2, 3, and 4 were not fully met by the earmarked resources, the unfulfilled portions are added (with suitable conversion factors) to the electrical energy requirements. The electrical energy requirements are considered in the last stage. Depending on the availability, it will be satisfied by biogas-driven engine-generator sets, microhydro, wind-electric, and solar-electric (photovoltaic) systems operating in conjunction with energy storage devices. Typically, by the time the design procedure reaches the fifth stage, only wind-electric and solar-electric options in conjunction with energy storage are expected to be available. The apportionment of the load between these two resources and the determination of the size of energy storage components are done by the LPSP approach [103].

To summarize, a probabilistic approach utilizing the key system parameter LPSP for designing an IRES utilizing renewable energy resources such as solar radiation, biomass, wind, and falling water is presented. The system is to satisfy a variety of energy needs. The LPSP value is evaluated using either recorded data or the pdf of load and output power of different components of the IRES. The approach utilizes LPSP as the key system parameter and minimizes the total capital cost of the system while maintaining a given level of reliability.

CHAPTER VI

CASE STUDIES AND EXAMPLES

In this chapter example designs of several stand-alone energy systems with energy storage utilizing one or more of the renewable resources are considered. Both probabilistic and deterministic approaches are used in the designs presented.

6.1 Design of a Stand-Alone Photovoltaic Solar Electric Conversion (SEC) System

Design of a stand-alone SEC with energy storage for supplying electricity to remote communications centers is considered for demonstrating the usefulness of the LPSP based design approach outlined before.

In this example, actual recorded insolation data for a site in New Mexico are used to calculate LPSP. A simplified block diagram of the system under study is shown in Figure 35. The output of the SEC, in the form of dc electricity, is processed through the electrical interface and is stored in the energy storage and reconversion system from which the load is supplied on demand. The output of the SEC depends on the availability of insolation as well as factors such as energy conversion efficiency of the photovoltaic cells and the cell area exposed. For design purposes the output of the system at any given time t can be

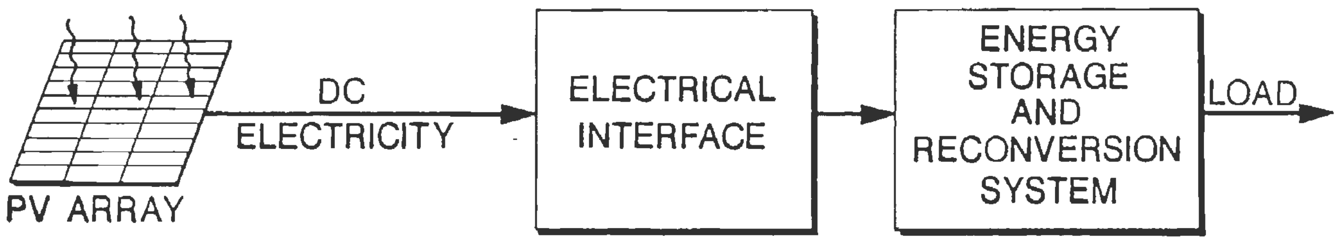


Figure 35. Block Diagram of the System Under Study

approximated as a linear function of the insolation as given by Equation (6.1.1).

$$P(t) = \eta_{sc} A_a k_p I(t) \tag{6.1.1}$$

The average efficiency of photovoltaic modules available at present can be assumed to be 10% (see Reference 76). The daily load demand is assumed to be a random variable, uniformly distributed between a maximum value (L_M) and a minimum value (L_m). Figures 36, 37, and 38 show the probability density function, probability distribution function, and the load duration curve corresponding this load model. This has been shown to be a good approximation for the daily load demand (see Reference 79). Using this model, hourly load values L(t) can be obtained by generating a uniformly-distributed random number R_U, between zero and one, and by using it in the equation given below.

$$L(t) = L_m + (L_M - L_m)R_U \tag{6.1.2}$$

The maximum and minimum load demands (including the inefficiencies involved in the charging and discharging of storage) were assumed to be 3 kW and 1 kW respectively [104].

Using hourly recorded insolation data and Equation (6.1.1) the LPSP can be calculated as discussed in Chapter V (see section 5.1).

The objective is to arrive at the ratings of the SEC and the energy storage system to achieve a given LPSP at the lowest possible capital cost for a given site and load demand. The total capital cost can be expressed in terms of system rating and an initial fixed cost as follows.

$$CC = CC_o + a\ P_r + b\ E_B \tag{6.1.3}$$

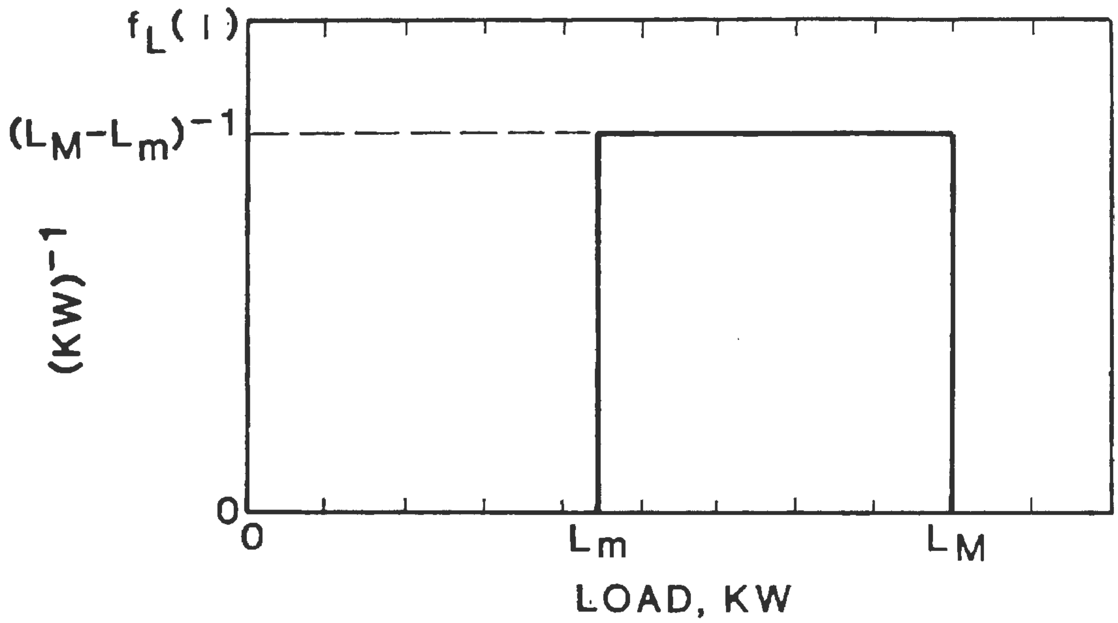


Figure 36. Probability Density Function for the Assumed Load Model

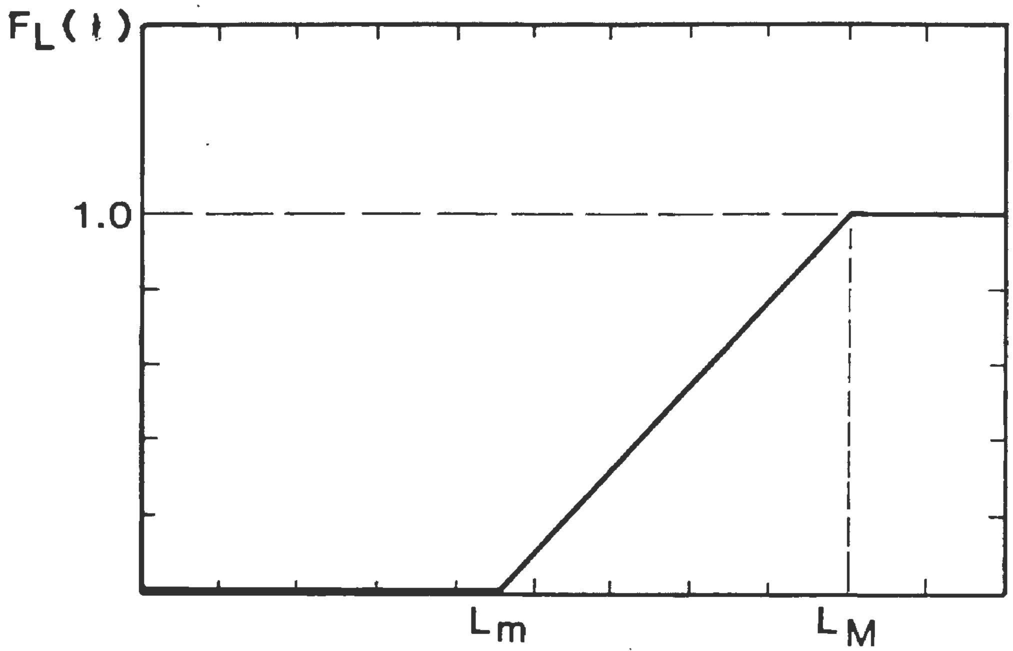


Figure 37. Probability Distribution Function for the Assumed Load Model

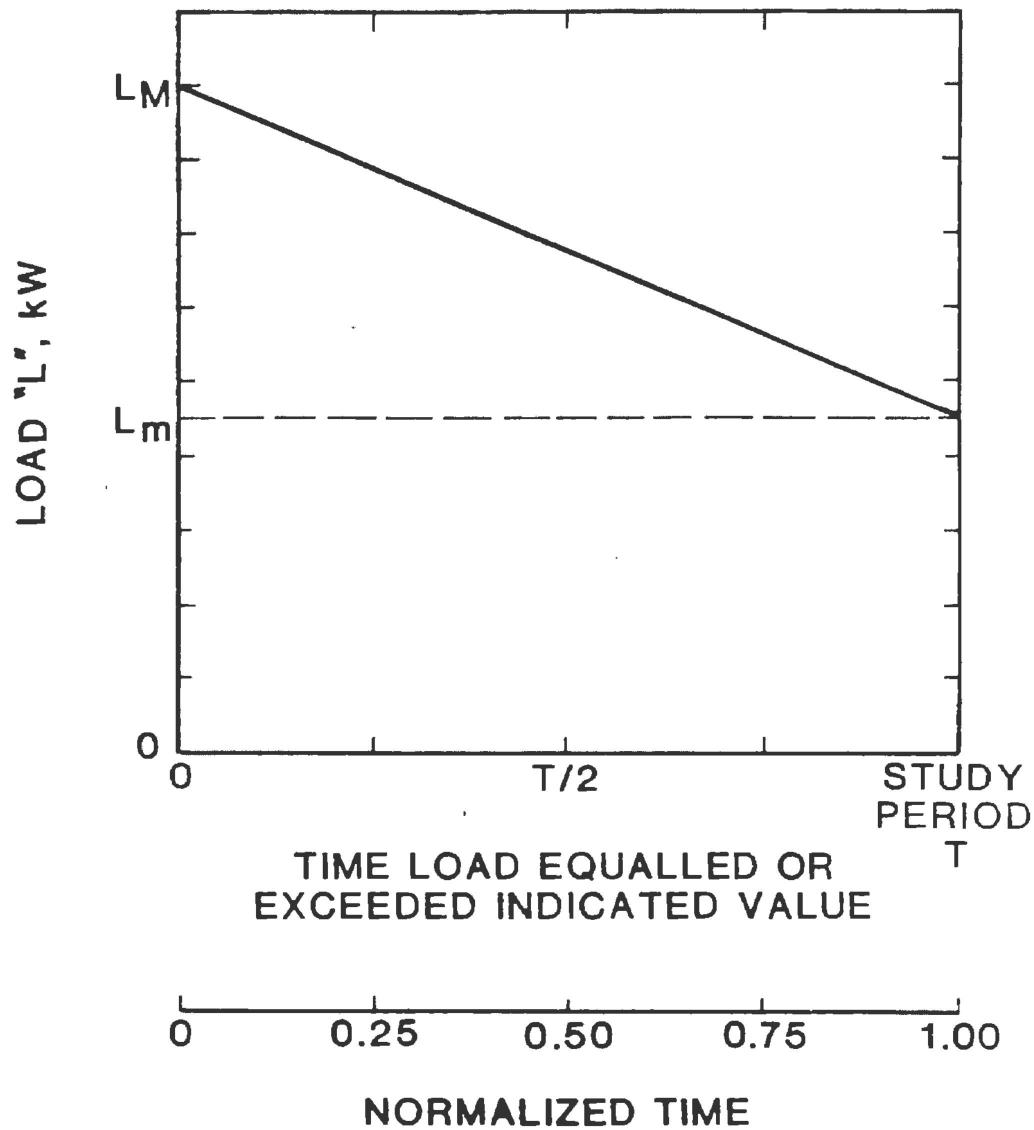


Figure 38. Load Duration Curve for the Assumed Load Model

The energy storage system is assumed to be fully charged at the beginning of the study period and is allowed to deplete to no less than 50% of its rated capacity. Figure 39 illustrates the variation of PV array area with storage capacity for LPSP values of 0.001 and 0.003. As can be seen, there are many possible combinations of array area (SEC rating) and storage capacity that would result in a system with a reliability of 99.9% (LPSP = 0.001) or 99.7% (LPSP = 0.003). Using the LPSP design approach, optimum combinations of array area and storage capacity were found. For example, for a cell cost of 5 \$/peak watt and a storage cost of 120 \$/kWh, optimum design values obtained are (see Figure 39) given below

array area = 173 m^2

storage capacity = 240 kWh

As expected, optimum size of storage and array area are inversely related to their individual cost figures. Figure 39 illustrates this relationship. For example, as cell cost increases from 5\$/peak watt to 7 \$/peak watt the design procedure automatically yields a smaller array area with an associated increase in storage capacity. The reverse is true if cell cost is decreased. In addition, with an increase in the allowable LPSP value, the cost of the system can be decreased.

6.2 Design of a Stand-Alone Wind Electric Conversion System (WECS)

The design of a stand-alone WECS with energy storage to supply a given load is considered as the next example of the application of the probabilistic approach outlined in the previous chapter. The system

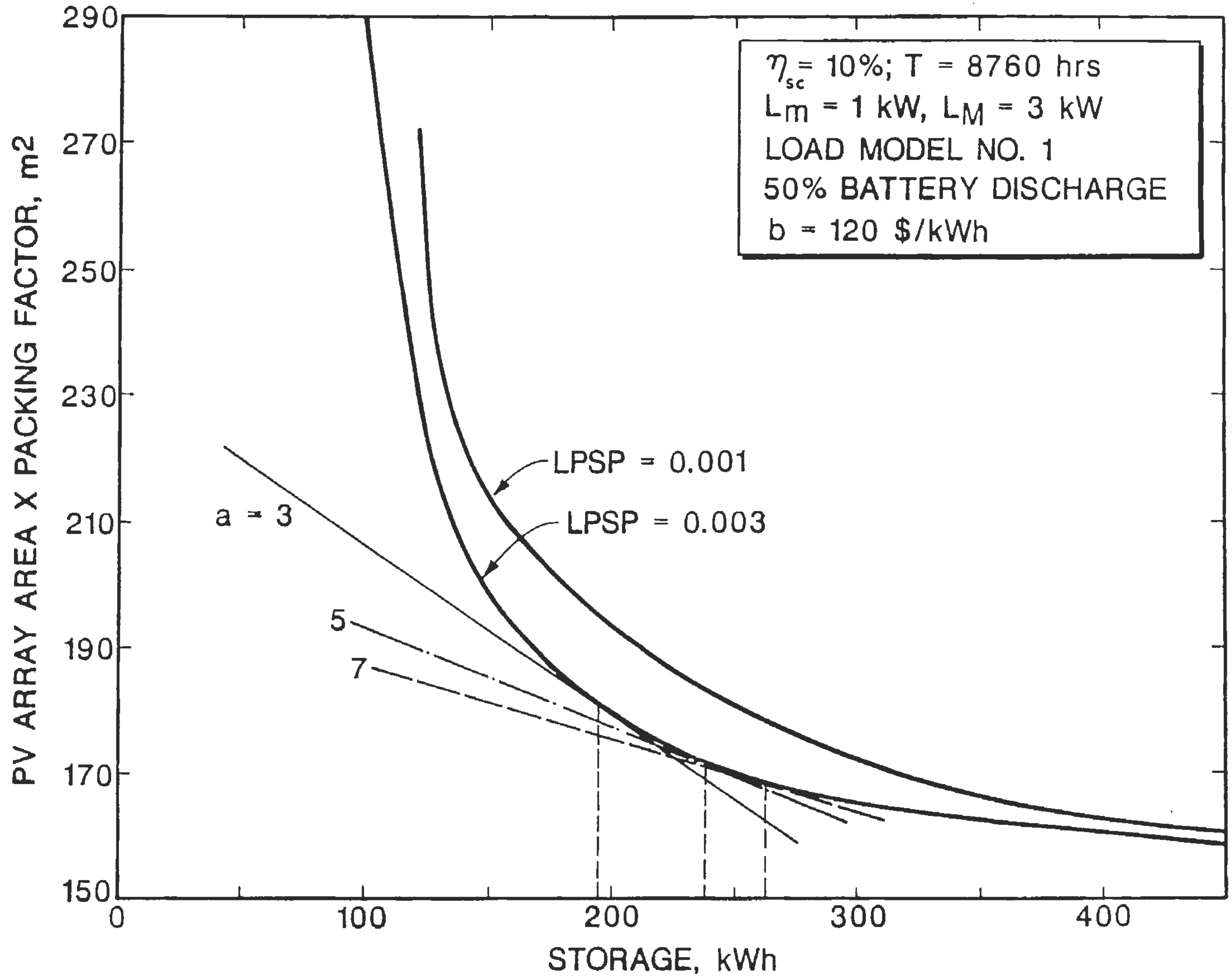


Figure 39. Relationship Between SEC Rating, Storage Capacity, and LPSP

under study is shown in block diagram form in Figure 40. The electrical output of the WECS is processed through the electrical interface and is stored in the energy storage and reconversion system from which the load is supplied on demand.

The output of the WECS depends on wind speed, aerodynamic characteristics of the aeroturbine, blade pitch angle, and generator efficiency. Typically, a WECS is designed to start delivering power when the wind speed reaches the cut-in value V_C, with the output increasing with wind speed up to the rated value P_R corresponding to the rated wind speed V_R. The output is maintained at P_R by means of blade pitch control for wind speeds beyond V_R up to the cut-out wind speed V_F. The unit is shut down for higher wind speeds for safety reasons. However, it has been observed (see Reference 74) that the actual (measured) power output characteristic of a typical large constant-speed WECS can be approximated by two straight line segments as illustrated in Figure 41. This is the model that is used here.

The load demand is assumed to be a random variable, uniformly distributed between a maximum load demand, L_M, of 60 kW and minimum load demand, L_m, of 20 kW. Figures 36, 37, and 38 show the probability density function, probability distribution function, and the load duration curve corresponding to this load model. Practical load duration curves can be reasonably idealized to correspond to the one shown here (see Reference 78). The energy storage system is assumed to be fully charged at the beginning of the study period and is allowed to deplete to no less than 50% of its rated capacity.

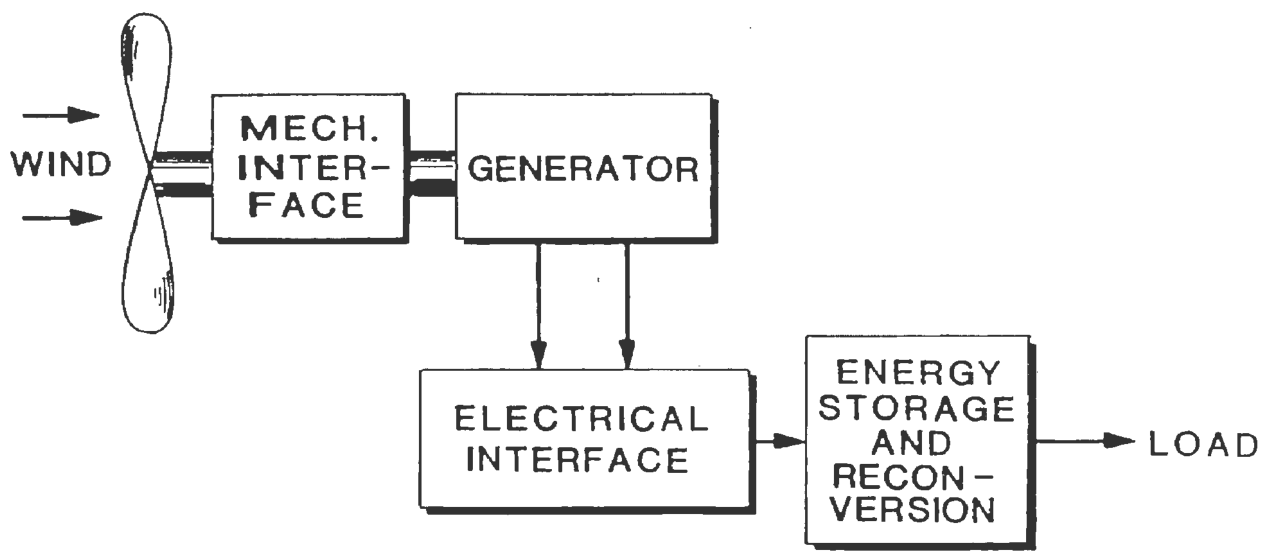


Figure 40. Block Diagram of the System Under Study

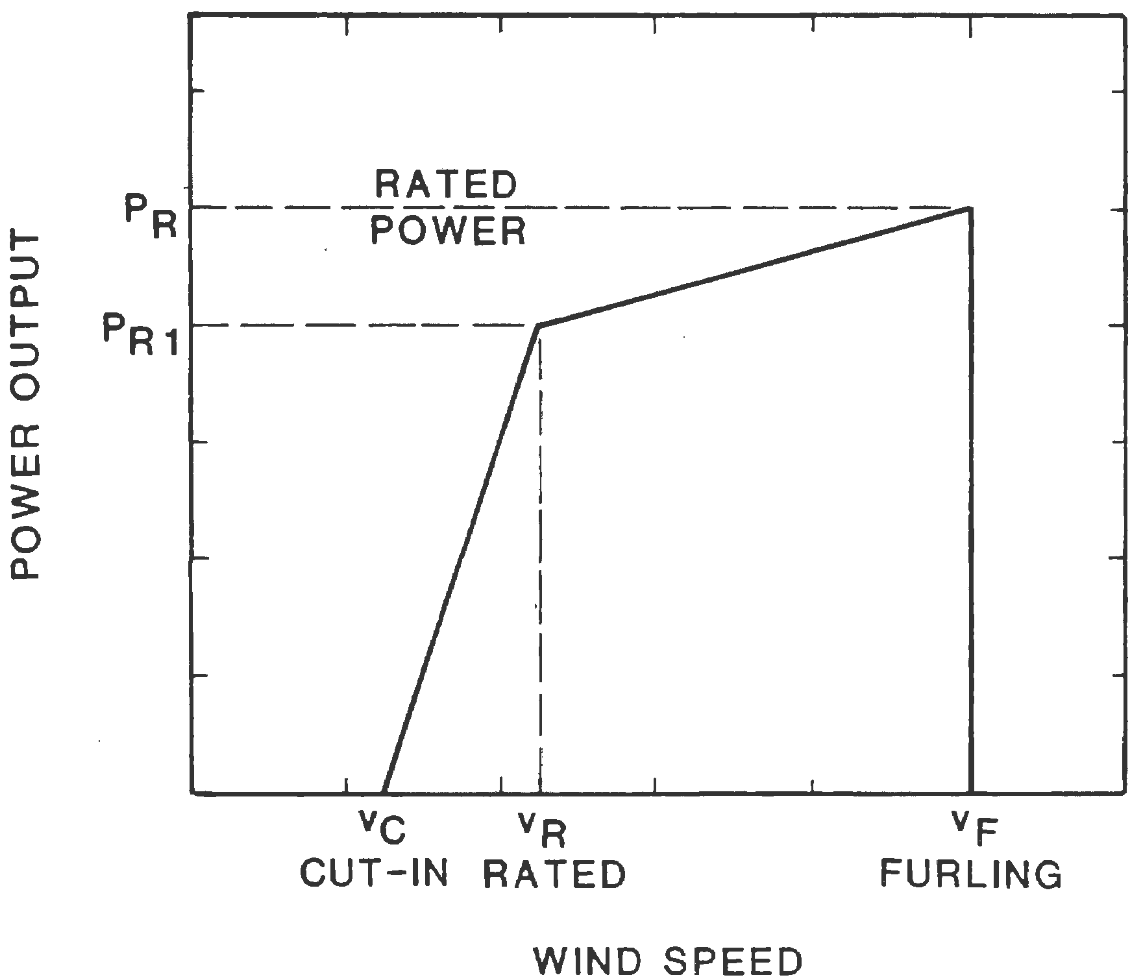


Figure 41. Assumed WECS Output Model

6.2.1 Design Employing Probability Density Function of Wind Speed

In this example the pdf of wind speed (see Chapter II) is utilized in the calculation of LPSP values. The WECS site will be assumed to have a good wind regime ($\alpha_w = 8.94$, $\beta_w = 4.0$) and the entire output of the wind system will be processed through storage to supply the load on demand. The load is assumed to be uniformly distributed between a maximum value (L_M) and a minimum value (L_m). The total capital cost of the system can be expressed as before as

$$CC = CC_o + a\, P_r + b\, E_B \tag{6.2.1.1}$$

Defining the normalized WECS rating P_{rn} and the number of days of storage W_d as

$$P_{rn} = P_r/L_M \tag{6.2.1.2}$$

$$W_d = E_B/D_e \tag{6.2.1.3}$$

in which L_M is the maximum load demand and D_e is the daily energy required by the load, Equation (6.2.1.1) can be rewritten in terms of normalized quantities.

$$CC = CC_o + (a\, L_M)\, P_{rn} + (b\, D_e)\, W_d \tag{6.2.1.4}$$

As P_{rn} and W_d vary, the locus of points corresponding to a fixed total cost will be a straight line in the P_{rn} - W_d plane with a slope of $-(b\, D_e/a\, L_M)$. The fixed cost CC_o in Equation (6.2.1.1) is taken as ten percent of the total cost. Figure 42 illustrates the variation of P_{rn} with W_d for LPSP values of 0.001 and 0.003. Assuming a WECS cost [105]

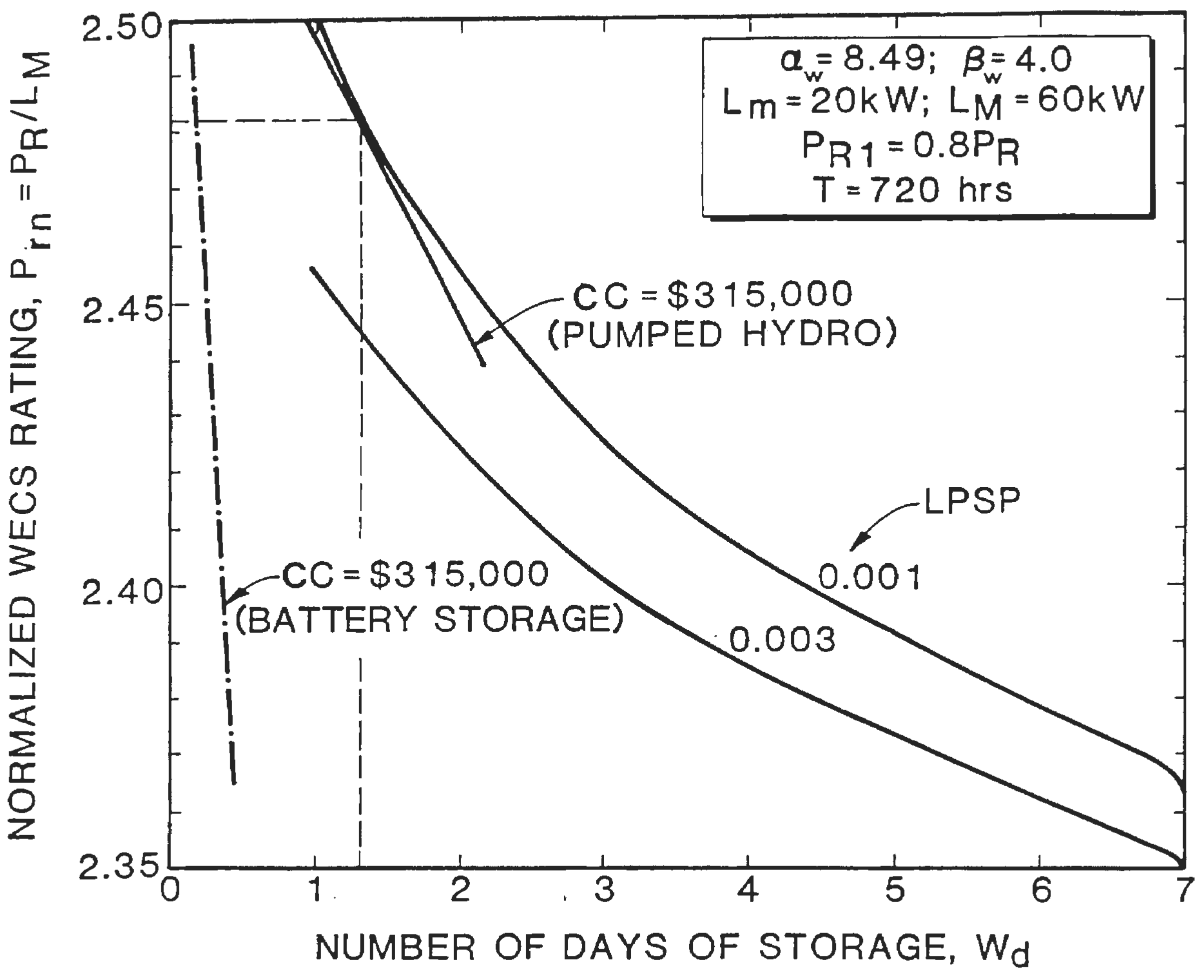


Figure 42. Illustrating the Design of the Example System Using pdf of Wind Speed

of \$1850/kW and pumped hydro storage cost [106] of \$6/kWh, the slope of the cost is

$$-(6 \times 960)/(1850 \times 60) = -0.052$$

for a design LPSP value of 0.001, the procedure yields (see Figure 42) $P_{rn} = 2.482$ and $W_d = 1.3$. The corresponding total cost is obtained as follows

$$CC = 0.1CC + 1850 \times 60 \times 2.482 + 6 \times 960 \times 1.3$$

or

$$CC = \$315{,}000$$

With electrochemical (battery) storage and the associated cost [107] of \$50/kWh, the slope of the cost line becomes -0.432. The cost line corresponding to CC = \$315,000 is also shown in Figure 42. It is obvious that this line has to shift significantly to the right before it can become tangential to the P_{rn} versus W_d curve corresponding to the design LPSP of 0.001. This means that the total cost must be considerably higher if battery storage is to be employed. The resulting W_d will be smaller and the corresponding P_{rn} will be larger as compared to the design with pumped hydro storage. It can be seen that as WECS cost decreases (or storage cost increases), the design procedure automatically yields a higher P_{rn} value with an associated decrease in W_d. The reverse is true if WECS cost increases (or storage cost decreases). In addition, with an increase in the allowable LPSP value, the cost of the system can be decreased for the optimum design.

6.2.2 Design Based on Recorded Values of Wind Data

In this example mean hourly wind speed values collected by the research group at the University of Hawaii at Manoa and a given electrical load model are used to evaluate LPSP values. The WECS site will be assumed to be in a good wind regime and the entire output of the WECS will be processed through storage. As before, the load is assumed to be uniformly distributed (see Figures 36-38) between a maximum (L_M) value and a minimum (L_m) value. The load is supplied from storage on demand. The WECS power output characteristic is approximated in terms of two straight line segments as before.

The objective is to arrive at the ratings of the WECS and the energy storage system to achieve a given LPSP at the lowest possible cost for a given site and load demand. The total capital cost is expressed as

$$CC = CC_0 + a\ P_r + b\ E_B \qquad (6.2.2.1)$$

As P_r and E_B vary, the locus of points corresponding to a fixed total cost will be a straight line in the P_r - E_B plane with a slope of (-b/a). The fixed cost CC_0 is taken as ten percent of the total cost. Figure 43 illustrates the variation of P_r with E_B for LPSP values of 0.001 and 0.003. Assuming a WECS cost of \$1850/kW and pumped hydro storage cost of \$6/kWh, the slope of the cost line is -(6/1850). With a design LPSP value of 0.001, the procedure (see section 6.1) yields (see Figure 43) a WECS rating of 62 kW and a storage capacity of 3600 kWh. The corresponding total cost is obtained as follows

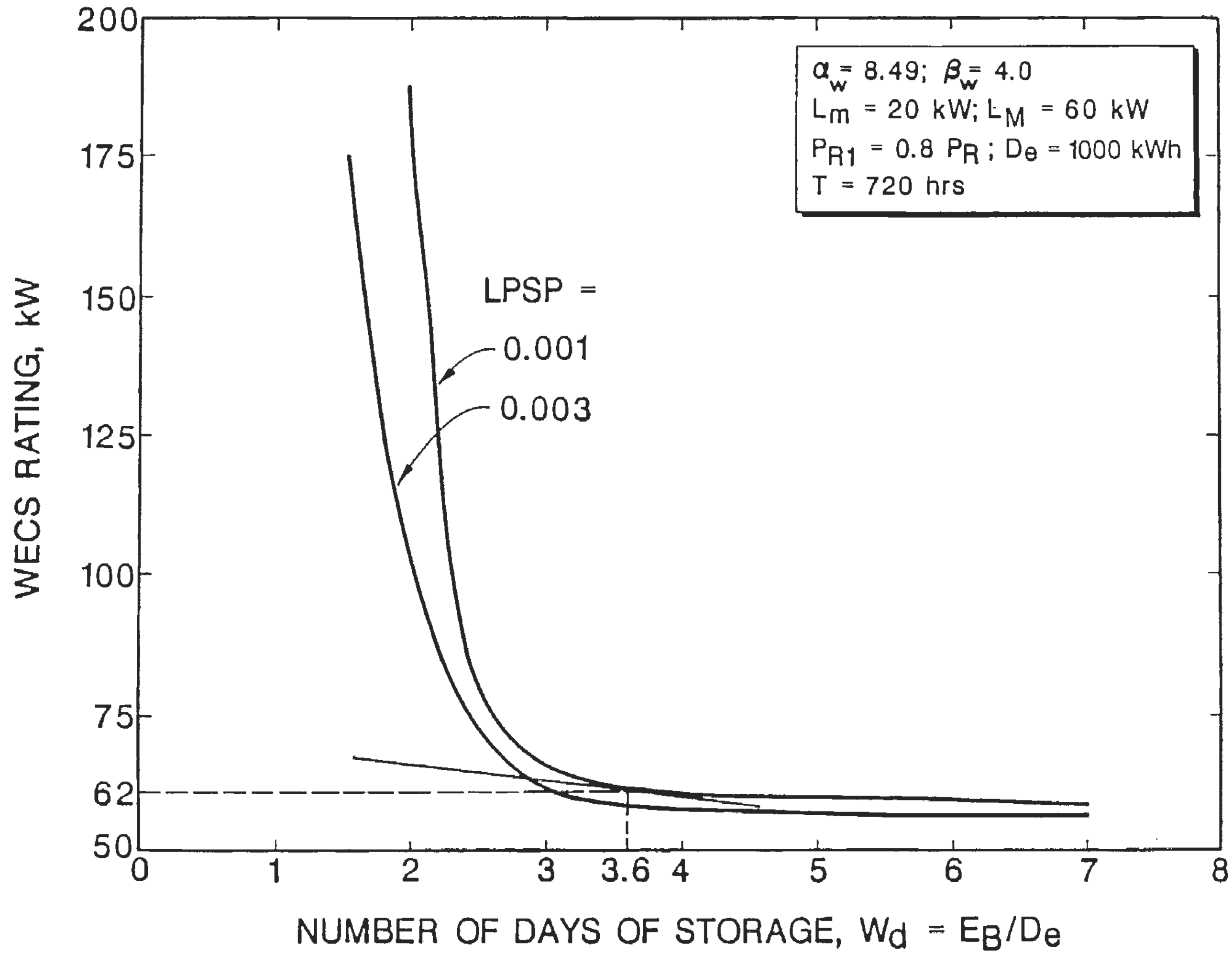


Figure 43. Illustrating the Design of the Example System Using Recorded Wind Speed

$$CC = 0.1\ CC + 1850 \times P_r + 6 \times E_B \quad (6.2.2.2)$$

or

$$CC = \$151{,}444$$

It can be seen that as WECS cost decreases (or storage cost increases), the design procedure automatically yields a higher P_r value with an associated decrease in E_B. The reverse is true if WECS cost increases (or storage cost decreases). In addition, with an increase in the allowable LPSP value, the cost of the system can be decreased for the optimum design. The total swept area required for wind turbines can be satisfied in a number of ways -- a few large units or a large number of smaller units. One has to consider economic and availability constraints before deciding on the actual hardware to be used.

6.3 Design of a Stand-Alone Integrated Renewable Energy System (IRES)

In this section the design of an IRES supplying the energy needs of a typical village situated in a remote rural area is considered for demonstrating the usefulness of the design approaches and the formulations presented in the previous chapters. The main purpose of the example is to illustrate the design methodology. The specific values chosen and the assumptions made are subject to wide variations depending on a variety of local conditions.

The village is assumed to have a population of 700 in 120 households and 450 heads of cattle. Most of the people are engaged in agriculture related activities and there are some small-scale industries. An adequate water supply is assumed (though it has to be pumped from a depth of about 5 to 10 meters) for irrigation, biogas production, and also for domestic and potable water supply.

In this example, annual average load requirements are used and as such they are the same for all seasons for one year. In practice, load requirements will vary from season to season and the design procedure might have to be applied during different seasons, the resulting designs compared, and an overall compromise system might have to be arrived at.

6.3.1 Deterministic Approach

The methodology of designing an IRES employing linear programming approach is applied to the typical village mentioned above. Four resources and four tasks are considered in this example. In arriving at the energy required for different tasks, a certain amount of aggregation has been done -- for example, all the loads requiring rotating shaft power (water pumping, small-scale industries, agricultural operations, transportation, etc.) are aggregated together as one task. The specific resources and tasks are listed below.

Resources: i = 1 Biogas
2 Insolation/photovoltaics
3 Wind
4 Water head

Tasks: j = 1 Medium-temperature heating, primarily for cooking
2 Rotating mechanical shaft power
3 ac electricity
4 dc electricity energy for battery charging

Next, using the information on hand, maximum quantity of each resource available over a desired period of time and its energy equivalent are calculated. Assuming an average yield of 10 kg of wet dung collected per animal per day, to be mixed with water in the proportion (volume) of 4:5, the amount of biogas available per day is estimated to be 280 cubic meters and the water required for biogas production per day is about 6 cubic meters. Therefore,

$$x_{1max} = 280 \times 365 = 102{,}200 \text{ m}^3$$

Estimated domestic water consumption is 0.13 m^3 per person per day. Thus, an overhead tank of 200 m^3 capacity can store the water required for two days. If one half of this water is available per year for electricity generation in a pump-hydro mode then,

$$x_{4max} = 100 \times 365 = 36{,}500 \text{ m}^3$$

For this example design, no upper limit is specified for x_2 (PV array area) and x_3 (swept area of wind turbines).

The energy equivalent of biogas can be obtained from the energy density per unit volume as

$$R_1 = 5.55 \text{ kWh/m}^3$$

If the annual total insolation is 2030 kWh/m^2 and if the average conversion efficiency is 10%, we have

$$R_2 = 203 \text{ kWh/m}^2 \text{ per year}$$

Assuming an annual mean wind speed of 3.7 m/s,

$$R_3 = 2 \times (10)^{-4} \times 8760 \times (3.7)^3 = 89 \text{ kWh/m}^2 \text{ per year}$$

For a mean water head of 10 m and $g = 9.81\ m/s^2$,

$$R_4 = (gh)/3600 = 0.027\ kWh/m^3$$

The assumed efficiency values (η_{ij}) for the preselected resource-task combinations are given in Table III, and the assumed energy and power requirements are given in Table IV. The total energy required is equal to 459,900 kWh/year. The k_{ij} values are calculated using the following equation.

$$k_{ij} = \frac{U_j}{8760\ P_{oj}} \tag{6.3.1.1}$$

Table V gives the values obtained using Equation (6.3.1.1). The effective plant (load) factor k_i and the diversity factor d_i assumed for the four resources are given in Table VI. Table VII gives the total cost values in \$/kW assumed to be associated with the i^{th} resource-j^{th} task combination. The per-unit interest rate used in evaluating the annual cost is 0.1. The system is assumed to have a lifetime of twenty years. Also, it is assumed that five percent of the capital cost is needed annually for the operation and maintenance of the hardware involved ($m_{ij} = 0.05$).

Using the formulation given in Chapter IV, the linear programming problem was solved by employing the IBM MPSX simulation package. The resulting design values are listed below.

x_{11} = volume of biogas needed per year for cooking

= 76,727 cubic meters

x_{13} = volume of biogas needed per year for electricity generation

= 25,473 cubic meters

x_{22} = PV array area for rotating shaft power

TABLE III

ASSUMED EFFICIENCIES ASSOCIATED WITH THE PRE-SELECTED RESOURCE-TASK COMBINATION FOR THE DETERIMINISTIC DESIGN APPROACH

Task / Resource	1	2	3	4
1	0.6	-	0.27	-
2	-	0.4	0.9	0.6
3	-	0.5	0.8	-
4	-	-	0.6	-

TABLE IV

ASSUMED ENERGY AND POWER REQUIREMENTS FOR THE DESIGN EXAMPLE

Task No. (j)		Energy kWh/year (U_j)	Maximum Output Power kw (p_{oj})
1		255,500	100
2		146,000	80
3		54,750	30
4		3,650	2
	Total	459,900	

TABLE V

CALCULATED LOAD FACTORS FOR THE i^{th} RESOURCE-j^{th} TASK COMBINATION

i \ j	1	2	3	4
1	0.29	-	0.21	-
2	-	0.21	0.21	0.21
3	-	0.21	0.21	-
4	-	-	0.21	-

TABLE VI

ASSUMED EFFECTIVE LOAD AND DIVERSITY FACTORS

Resource "i"	1	2	3	4
k_i	0.3	0.22	0.21	0.21
d_i	1.4	1.2	1.2	1.0

TABLE VII

COST ASSOCIATED WITH UTILIZING THE i^{th} RESOURCE FOR THE j^{th} TASK

i \ j	1	2	3	4
1	80	-	600	-
2	-	10,000	9,000	9,000
3	-	5,000	5,250	-
4	-	-	1,500	-

= 0 square meters

x_{23} = PV array area for electricity generation

= 0 square meters

x_{24} = PV array area for battery charging

= 30 square meters

x_{32} = wind turbines swept area for rotating shaft power

= 3291 square meters

x_{33} = wind turbines swept area for electricity generation

= 225 square meters

x_{43} = amount of water used per year for electricity generation (Micro-hydro)

= 36,500.00 cubic meters

Total cost per year $\cong$ \$158,000.00

Based on the economic factors assumed, this corresponds to an initial capital cost of nearly one million dollars. The total swept area required for wind turbines can be satisfied in a number of ways -- a few large units or a large number of smaller units. One has to consider economic and availability constraints before deciding on the actual hardware to be used. Similar arguments apply for the other components of the plant as well.

6.3.2 Probabilistic Approach (Using The IRES Program)

In this section the methodology of designing an IRES employing LPSP approach is applied to the village considered in section 6.3.1. The computer program (see Chapter V) developed, IRES, based on this approach is used to arrive at the final design values. Therefore, the preselected resource-task combinations will be slightly different from the ones used in the previous example. Four resources and three tasks are considered in this example. In arriving at the energy required for different tasks, a certain amount of aggregation is necessary -- for example, all the loads requiring medium-grade thermal energy (cooking, small-scale industries, etc.) are aggregated as one task. The specific resources and tasks considered are listed below.

Resources:

A. Biomass

B. Solar

C. Wind

D. Falling water

Tasks:

1. Medium-Temperature heating, primarily for cooking
2. Rotating mechanical shaft power
3. Electricity

The assumed efficiency values for the preselected resource-task combinations are given in Table VIII. Assumed energy and power requirements are given in Table IX. Total energy required is equal to 462,820 kWh/year. Using the information available and the values calculated (see section 6.3.1) for resource availabilities and energy equivalent of each resource as input to the IRES program (see Chapter V), the following design values were obtained.

x_{A1} = volume of biogas needed per year for medium-grade heat

= 76,727 cubic meters

TABLE VIII

ASSUMED EFFICIENCIES ASSOCIATED WITH THE PRE-SELECTED RESOURCE-TASK COMBINATIONS FOR THE PROBABILISTIC DESIGN APPROACH

Task Resource	1	2	3
A	0.6	0.4	-
B	-	-	0.09
C	-	0.5	-
D	-	0.5	-

TABLE IX

ASSUMED ENERGY AND POWER REQUIREMENTS FOR THE DESIGN EXAMPLE

Task No.	Energy kWh/year	Maximum Ouptut Power ,kw	Minimum Output Power, kw
1	255,500.0	100.0	0
2	146,000.0	80.0	0
3	61,320.0	12	2

Total 462,820 kWh/year

x_{A2} = volume of biogas needed per year for rotating shaft power

= 25,473 cubic meters

x_{B2} = PV array area for rotating shaft power

= 0 square meters

x_{B3} = PV array area for electricity generation

= 380 square meters

x_{C2} = wind turbines swept area for rotating shaft power

= 2005 square meters

x_{C3} = WECS rating for electricity generation

= 250 kW

x_{D2} = amount of water used per year for rotating shaft power

= 36,500.00 cubic meters

Based on the assumed economic factors, such as cost per kW of each component, this corresponds to total capital cost of nearly 1.3 million dollars. The WECS and SEC ratings were obtained using the LPSP approach. Figure 44 illustrates the variation of P_r and E_B for LPSP values of 0.001 and 0.003. Assuming a WECS cost of \$3000/kW, SEC cost of \$5000/kW, and storage (battery) cost of \$250/kWh the slope of the cost line (see Equation 5.2.4) is (-0.05). For a design LPSP of 0.001 (99.9% reliability) the procedure yields (see Figure 44) P_r = 188 kW and E_B = 395 kWh.

The requirements of biogas plant or wind turbine swept area can be met either by a single centralized plant or by a number of smaller decentralized plants. This will also improve the availability because of the redundancy achieved. For example, it may be more convenient to have two or four biogas plants instead of one large unit. Similarly, water pumping requirements can be met by a number of pumps placed in

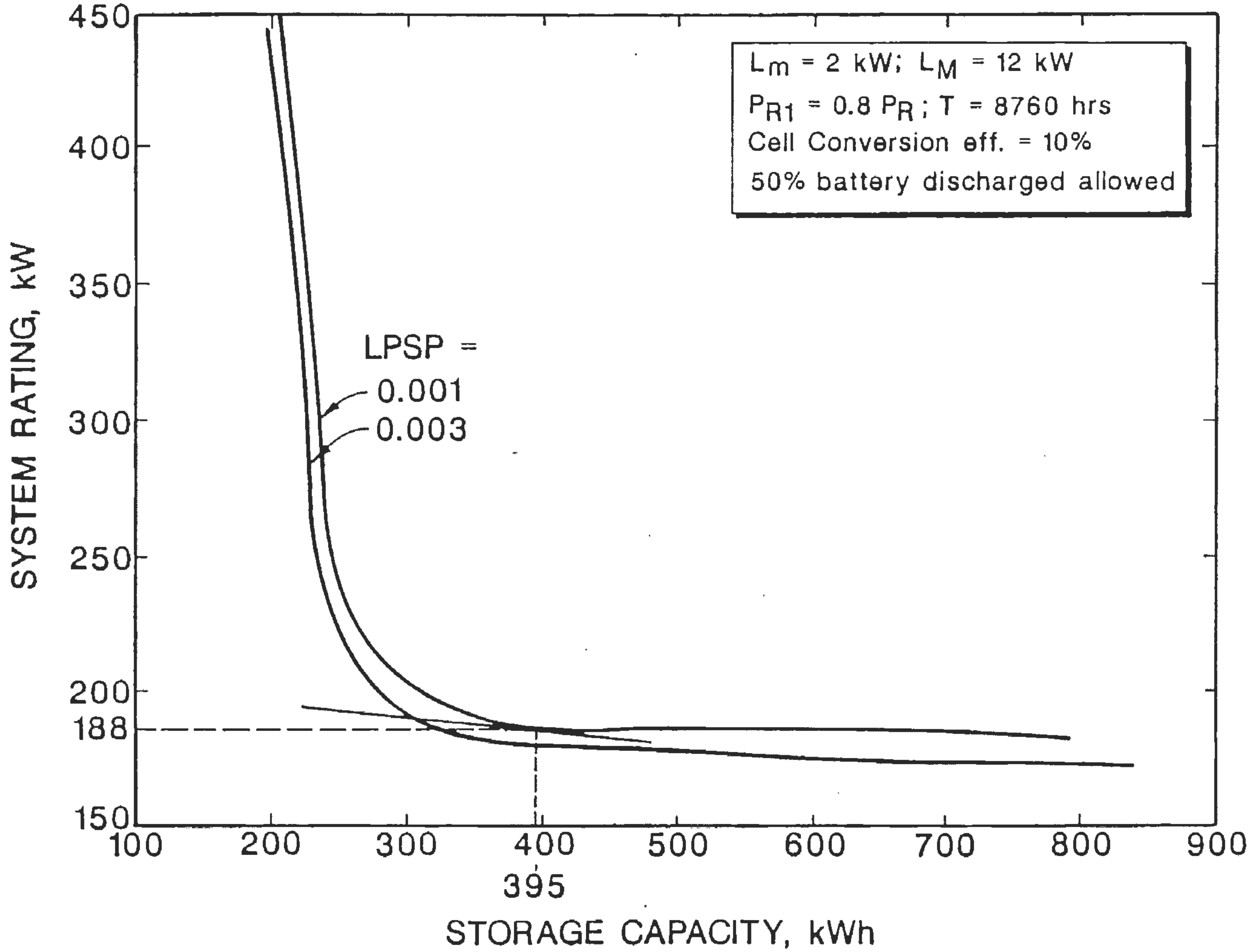


Figure 44. Relationship Between System Rating, Storage, Capacity, and LPSP (Obtained Using IRES Program)

convenient locations. It is necessary to consider economic and availability constraints and use engineering judgement before deciding on the actual hardware to be used.

6.4 Sensitivity Analysis and Design Comparisons

Considering the design results presented above as the base case, it is of interest to study the sensitivity of various design values to changes in key parameters. First the sensitivity of the IRES design is investigated using the deterministic approach.

Since the cost of PV arrays has shown a definite downward trend in the recent past, design calculations were made using linear programming approach for different sets of cost values of PV, keeping all the other parameters constant. The results are tabulated in Table X. Only those results that correspond to major shifts in the design values are given. It is seen that as the cost of PV arrays decrease, at first electricity generation by wind shifts to PV/power conditioner combination and a further decrease shifts rotating shaft power also from wind system to PV. Because of the specific resource-task combinations selected, all the other design values stay the same. The total cost per year and the average energy cost decrease as expected.

Depending on the terrain, wind regimes could differ widely even within a small geographical area such as a village. Since energy in wind is proportional to the cube of wind speed, the cost ($/kW) of wind energy systems is highly sensitive to the nature of the wind regime and, in turn, to the site selected. To study the effect of this on the overall system design, calculations were made for three different mean wind speeds, keeping all the other parameters the same as the base

TABLE X

DESIGN VALUES FOR VARYING PV COSTS

Cost of PV - Water pump system, \$/kw	10,000	7,000	4,000
Cost of PV array - Power conditioner, \$/kw	9,000	6,000	3,000
Cost of PV array and Controls for battery charging, \$/kw	9,000	6,000	3,000
Design Values			
x_{11} in Cubic meters	45,772	45,772	45,772
x_{13} in Cubic meters	8,978	8,978	8,978
x_{22} in square meters	0	0	0
x_{23} in square meters	0	164	164
x_{24} in square meters	28	28	28
x_{32} in square meters	2332	2332	0
x_{33} in square meters	494	0	0
x_{43} in cubic meters	36,500.00	36,500.00	36,500.00
Total cost per year, \$	120,737	119,006	93,431

case. The results are summarized (only the values that change are listed) in Table XI. With better wind regimes, the aeroturbine swept areas required for rotating shaft power and electricity generation go down because of the higher values of energy collected per unit area. The total cost goes down also and obviously no shifts to PV occur.

The present cost of PV is quite high and locating wind systems in better wind regimes results in a substantial decrease in the average energy cost. However, while the cost of PV is decreasing rapidly, the cost of wind energy systems are not expected to show any significant decrease in the foreseeable future. The PV cost figures that will result in a shift from wind to PV are expected to occur in the near future (before 1990). Further cost reductions will make PV very attractive for developing country applications unless the wind regimes are exceptionally good during most of the year.

For mean wind speeds of 4.5 and 5.5 m/s, PV system costs were reduced in steps of $1,000 until a shift from wind to PV occurred for electricity generation. In both instances, the shift occurred for the same value of PV system costs. The results are shown in Table XII.

Next the effect of changes in key system parameters on the design results obtained using the probabilistic approach are studied. Using LPSP based design approach and recorded insolation data, design calculations were carried out for different sets of PV and energy storage system costs, keeping all the other parameters constant. The results are tabulated in Table XIII. As expected, optimum size of storage and array area are inversely related to their individual cost figures. It can be seen that as the cost of PV arrays increases (decreases) or cost of storage system decreases (increases), the rating of PV system

TABLE XI

DESIGN VALUES FOR VARYING MEAN WIND SPEEDS

Mean wind speed at the site, m/s (mph)	3.5 (7.8)	4.5 (10.06)	5.5 (12.3)
Estimated Cost of aeroturbine-pump in $/kw	5500	3500	2750
Estimated cost of wind-electric system, $/kw	5750	3750	3000
Design values:			
x_{32} in square meters	2332	1097	601
x_{33} in square meters	494	232	127
Total cost per year, $	120,737	80,489	65,395

TABLE XII

DESIGN VALUES WHEN A SHIFT OCCURS FROM WIND TO PV FOR ELECTRICITY GENERATION

Cost of PV water pumping system = \$4,000.00 per kw		
Cost of PV array-power conditioner for ac output = \$3,000.00 per kw		
Cost of PV array and controls for battery charging = \$3,000.00 per kw		
Mean wind speed, m/s	4.5	5.5
Design values:		
x_{11}, cubic meters	45772	45772
x_{13}, cubic meters	8978	8978
x_{22}, square meters	0	0
x_{23}, square meters	164	164
x_{24}, square meters	28	28
x_{32}, square meters	1097	601
x_{33}, square meters	0	0
x_{43}, cubic meters	36,500.00	36,500.00
Total cost per year, \$	74,154	61,595

TABLE XIII

DESIGN VALUES FOR VARYING PV AND STORAGE COSTS

b ($/kwh)	a ($/peak watt)	$A_a \times k_p = m^2$ E_B = kwh
100	5	$A_a \times k_p = 170$ $E_B = 250.00$
	7	$A_a \times k_p = 168$ $E_B = 270.00$
120	5	$A_a \times k_p = 172$ $E_B = 240.00$
	7	$A_a \times k_p = 168$ $E_B = 265.00$
160	5	$A_a \times k_p = 175$ $E_B = 220.00$
	7	$A_a \times k_p = 170$ $E_B = 250.00$
600	5	$A_a \times k_p = 208$ $E_B = 140.00$
	7	$A_a \times k_p = 201$ $E_B = 150.00$

decreases (increases) and capacity of the storage system increases (decreases).

Depending on the terrain, wind regimes could differ widely within a small geographical area. To study the effect of this on the overall system design, simulation was performed for two typical wind regimes, designated as good ($\alpha_W = 8.94$, $\beta_W = 4.0$) and bad ($\alpha_W = 5.2$, $\beta_W = 2.36$), to cover the wide spectrum of possible wind regimes. LPSP values were calculated using the pdf of wind speed. Figures 45 and 46 show typical plots of LPSP versus energy storage capacity for good and bad wind regimes. Based on a number of simulation runs, it was found that the LPSP was much more sensitive to the amount of energy generated during the study period than to the size of the energy storage system. This emphasizes the need for proper sitting of the WECS. Deficiencies in the quality of the WECS site cannot be easily compensated for by the inclusion of energy storage. The rated speed of the WECS is another parameter that requires careful consideration. Figures 47 and 48 show the dependence of LPSP, evaluated using the pdf of wind speed, on V_R for good and bad wind regimes. As expected, the LPSP increases with increasing values of the rated speed V_R.

Mean hourly wind speeds collected by a research group at the University of Hawaii at Manoa are used to study the effects of cut-in wind speed and size of energy storage system on the overall system design. Three typical and distinct wind regimes were selected to cover the wide spectrum of wind regimes possible, and they are labeled as A, B, and C. Qualitatively, the wind regimes A, B, and C can be classified as very good, good, and poor, respectively.

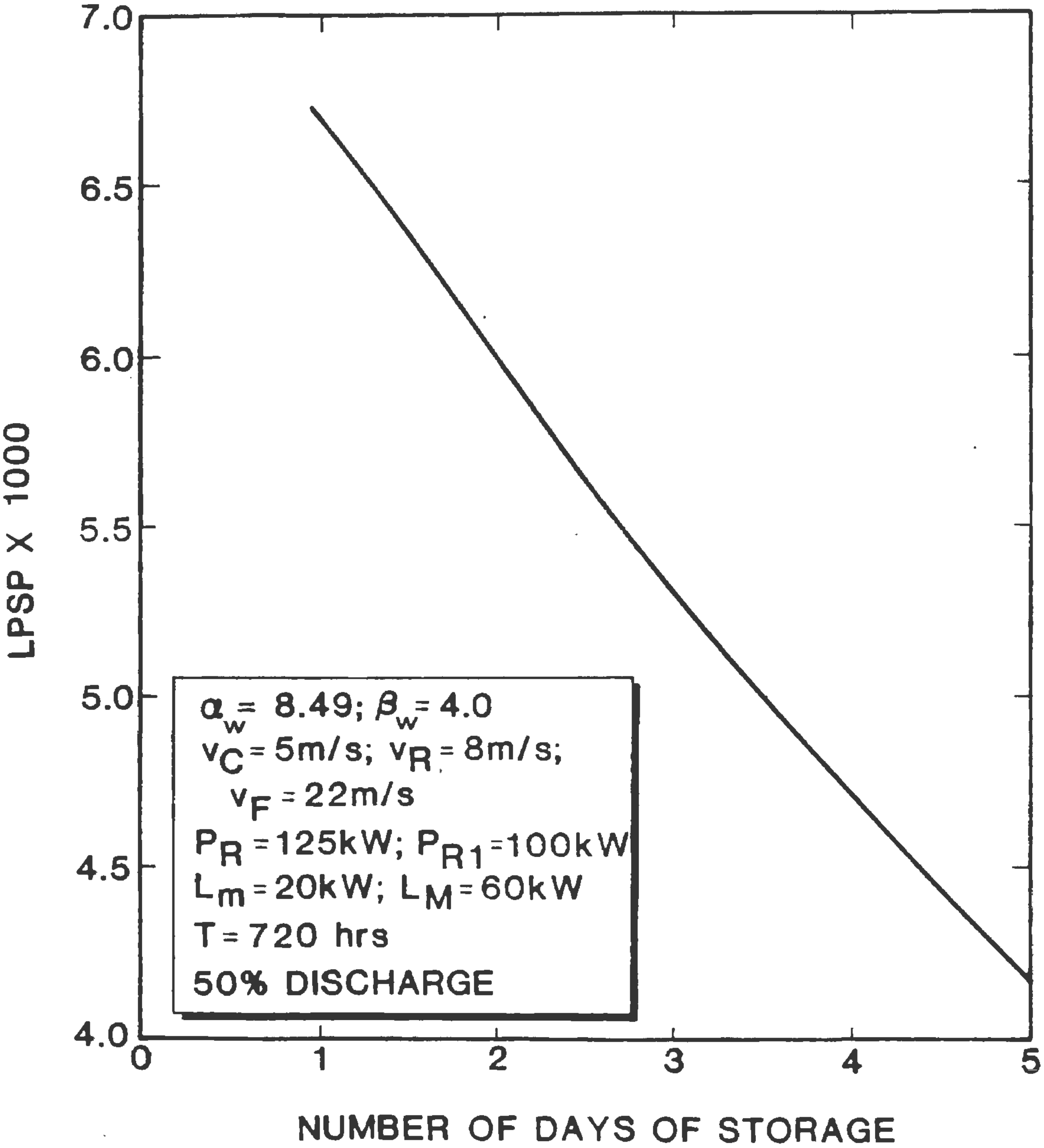


Figure 45. Variation of LPSP With Energy Storage Capacity (Good Wind Regime), Obtained Using pdf of Wind Speed

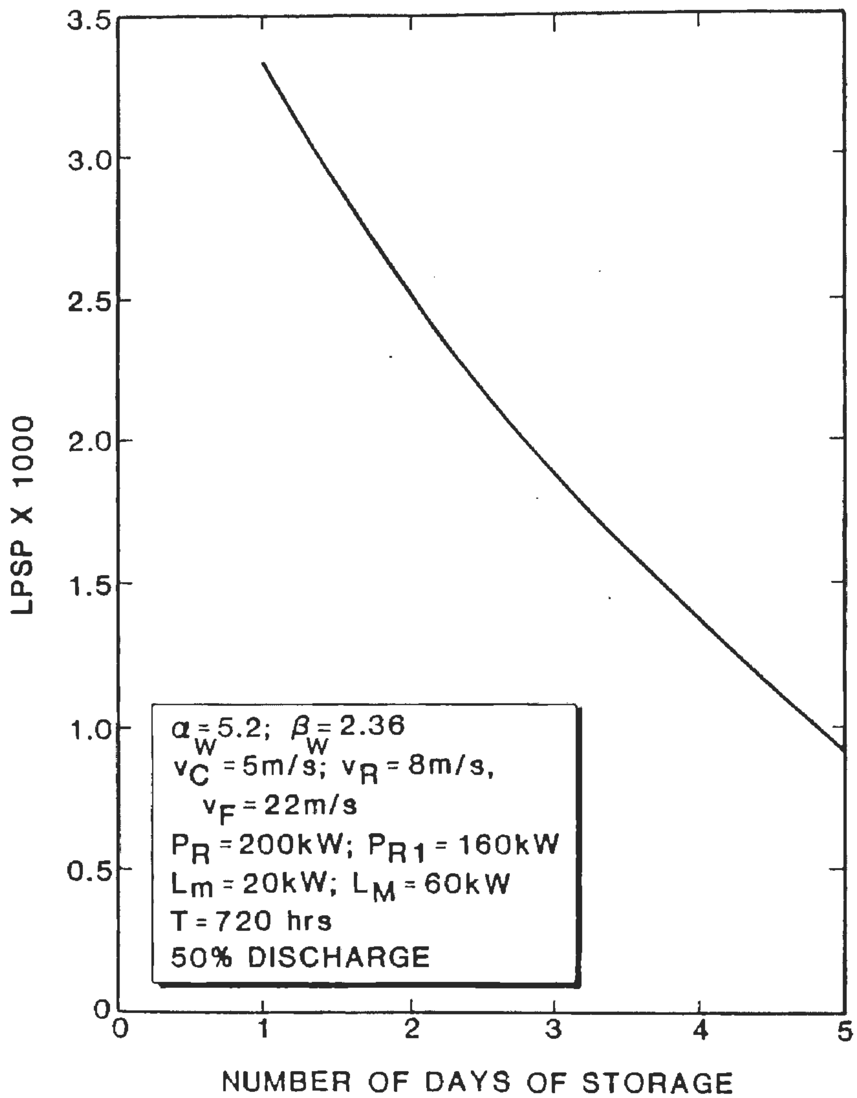


Figure 46. Variation of LPSP With Energy Storage Capacity (Bad Wind Regime), Obtained Using pdf of Wind Speed

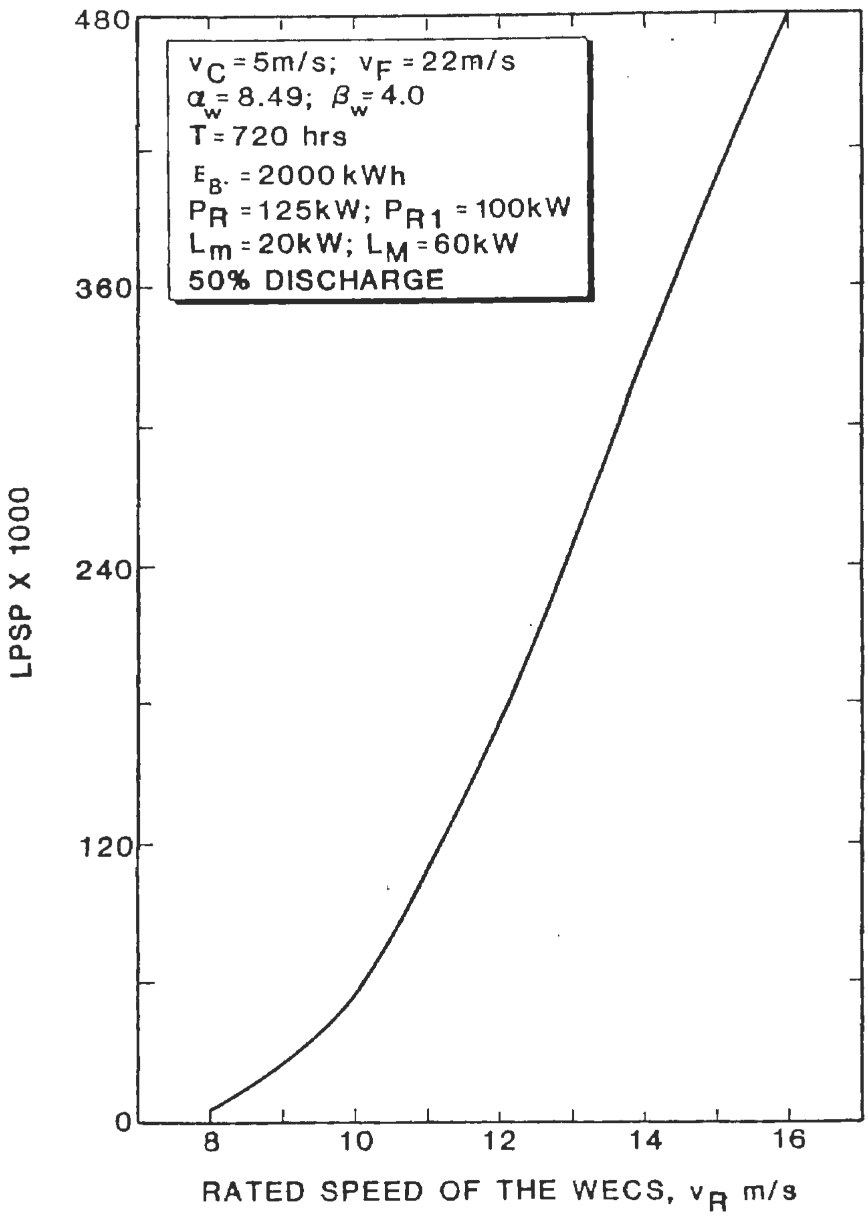


Figure 47. Illustrating the Dependence of LPSP on Rated Wind Speed of a WECS (Good Wind Regime), Obtained Using pdf of Wind Speed

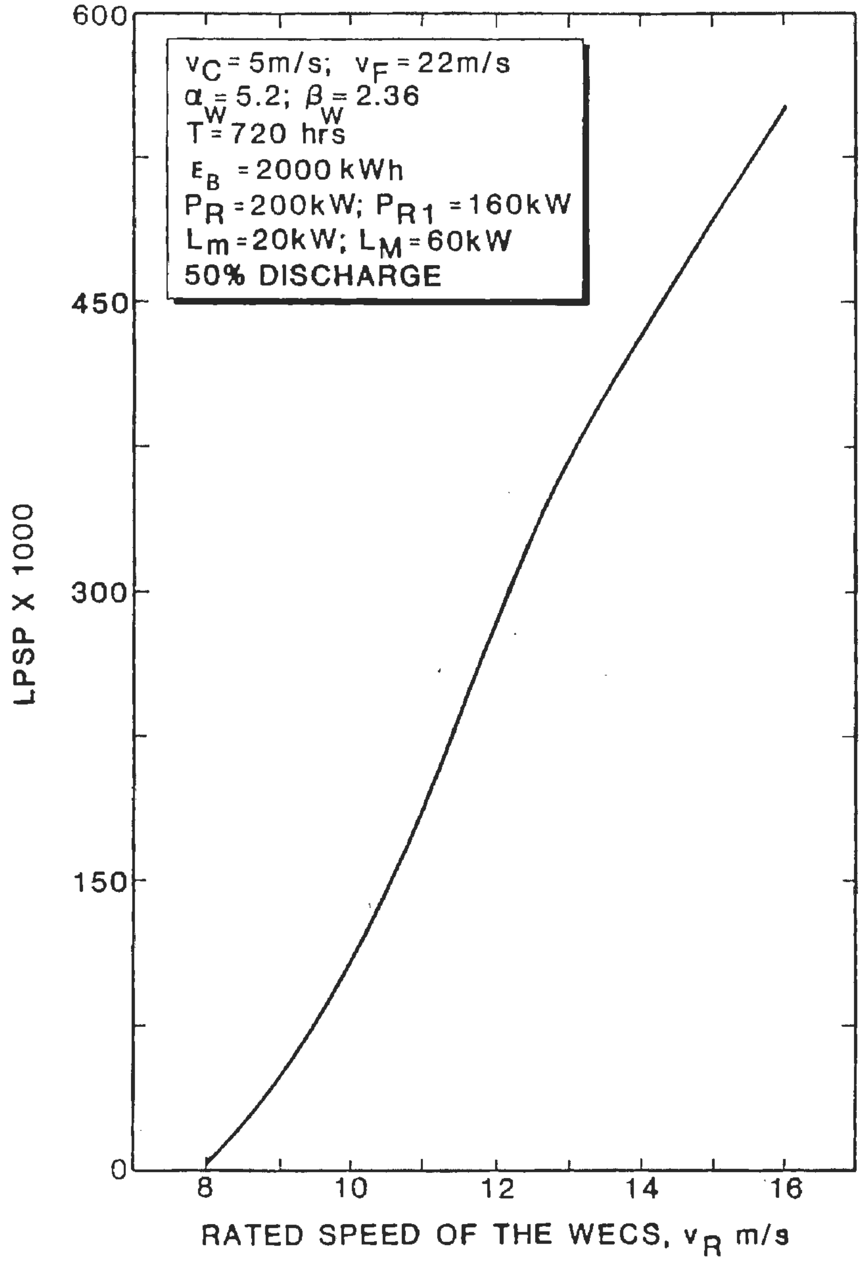


Figure 48. Illustrating the Dependence of LPSP on Rated Wind Speed of a WECS (Bad Wind Regime), Obtained Using pdf of Wind Speed

The influence of cut-in wind speed on the performance of WECS with energy storage is shown in Figures 49, 50, and 51 for wind regimes A, B, and C respectively. It can be seen that, for a fixed size of energy storage and for a given load, a desired level of reliability (meaning LPSP value) can be achieved by different combinations of cut-in speed and rated output power. Systems designed for lower cut-in speeds or higher rated powers will cost more, though the rate of increase will be different for the two options. Therefore, the cost of different combinations of V_C and P_R must be considered before selecting the most economical design. As expected, LPSP decreases for increases in P_R and for lower V_C values. These reductions are much sharper for the very good (A) and poor (C) wind regimes. Moreover, the dependence of LPSP on P_R is stronger with lower values of cut-in speeds.

Figures 52, 53, and 54 illustrate the relationship between LPSP, size of energy storage, and cut-in speed for a fixed P_R and for a given load. Dramatic reductions in LPSP values are achieved by increasing the size of energy storage system in the case of wind regimes A and B. However, the same is not true when the wind regime is poor (regime C). In other words, it is very difficult (and expensive) to compensate for major deficiencies in the wind regime by the addition of energy storage. It will be far better to explore other alternatives such as lowering V_C or increasing P_R.

Finally, the designs discussed in sections 6.3.1 and 6.3.2 are compared. Both designs are arrived at satisfying the energy needs of a village. However, one uses the deterministic approach and the other uses the probabilistic approach.

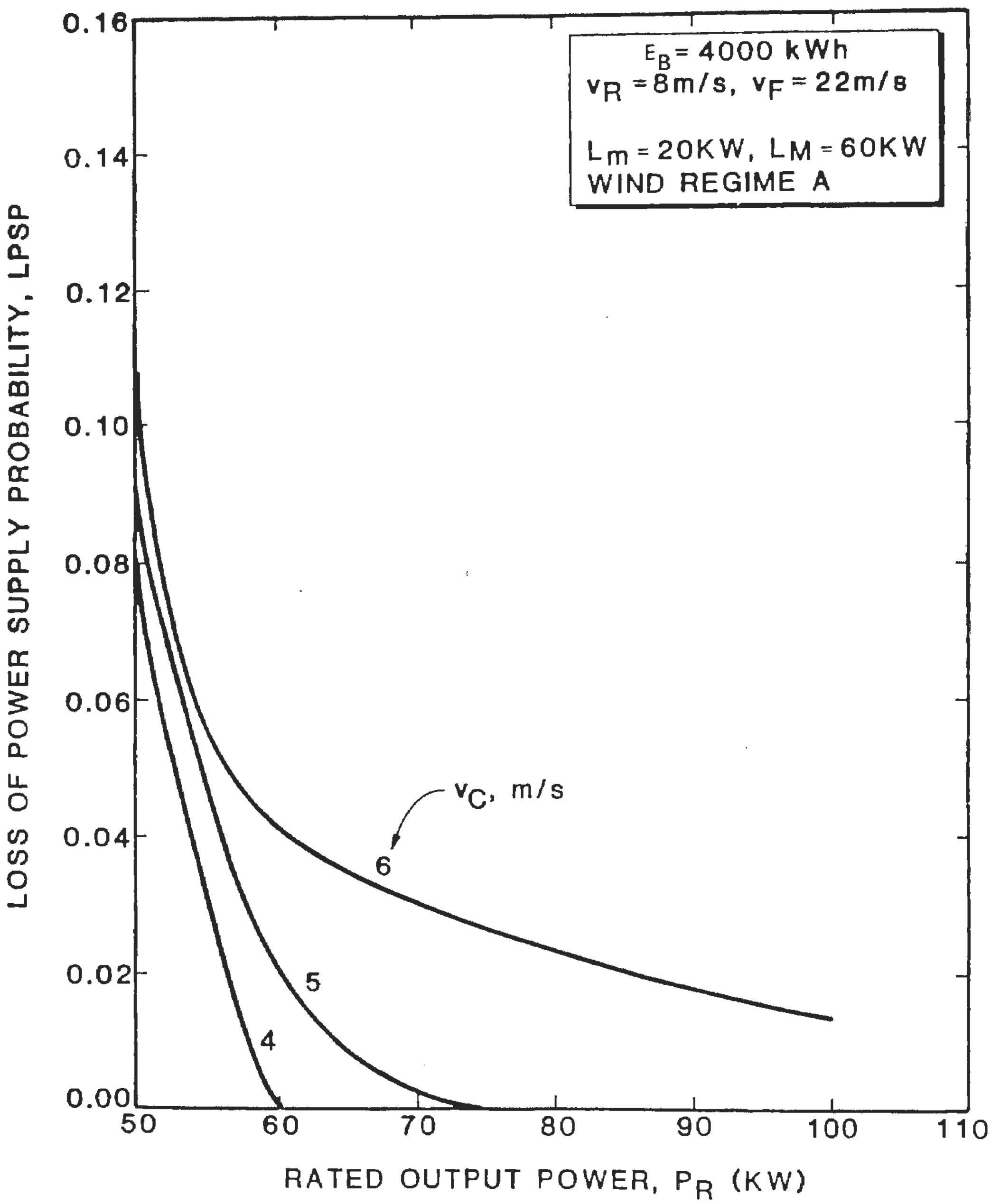


Figure 49. Influence of WECS Rating and Cut-In Speed on LPSP (Regime A), Obtained Using Recorded Wind Speed

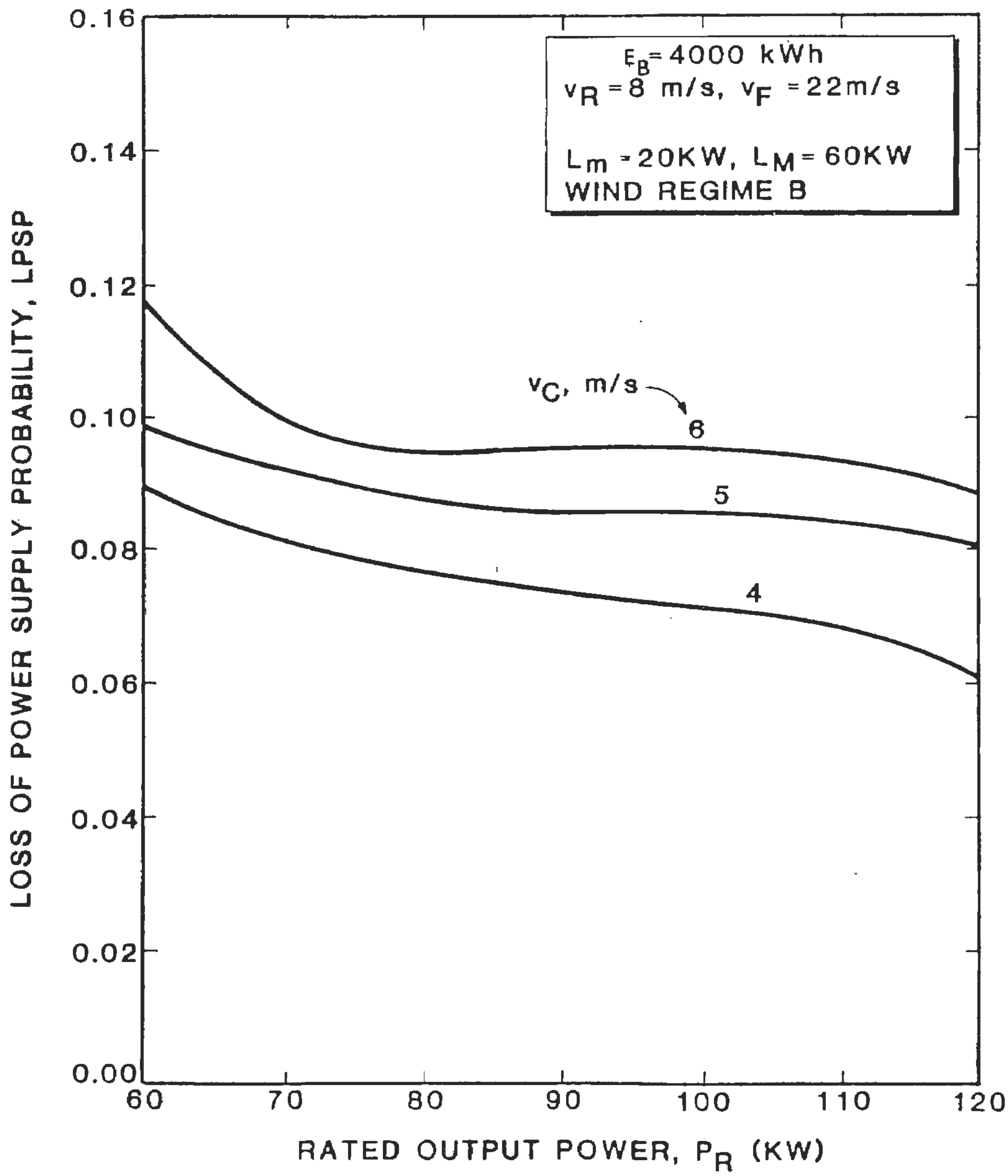


Figure 50. Influence of WECS Rating and Cut-In Speed on LPSP (Regime B), Obtained Using Recorded Wind Speed

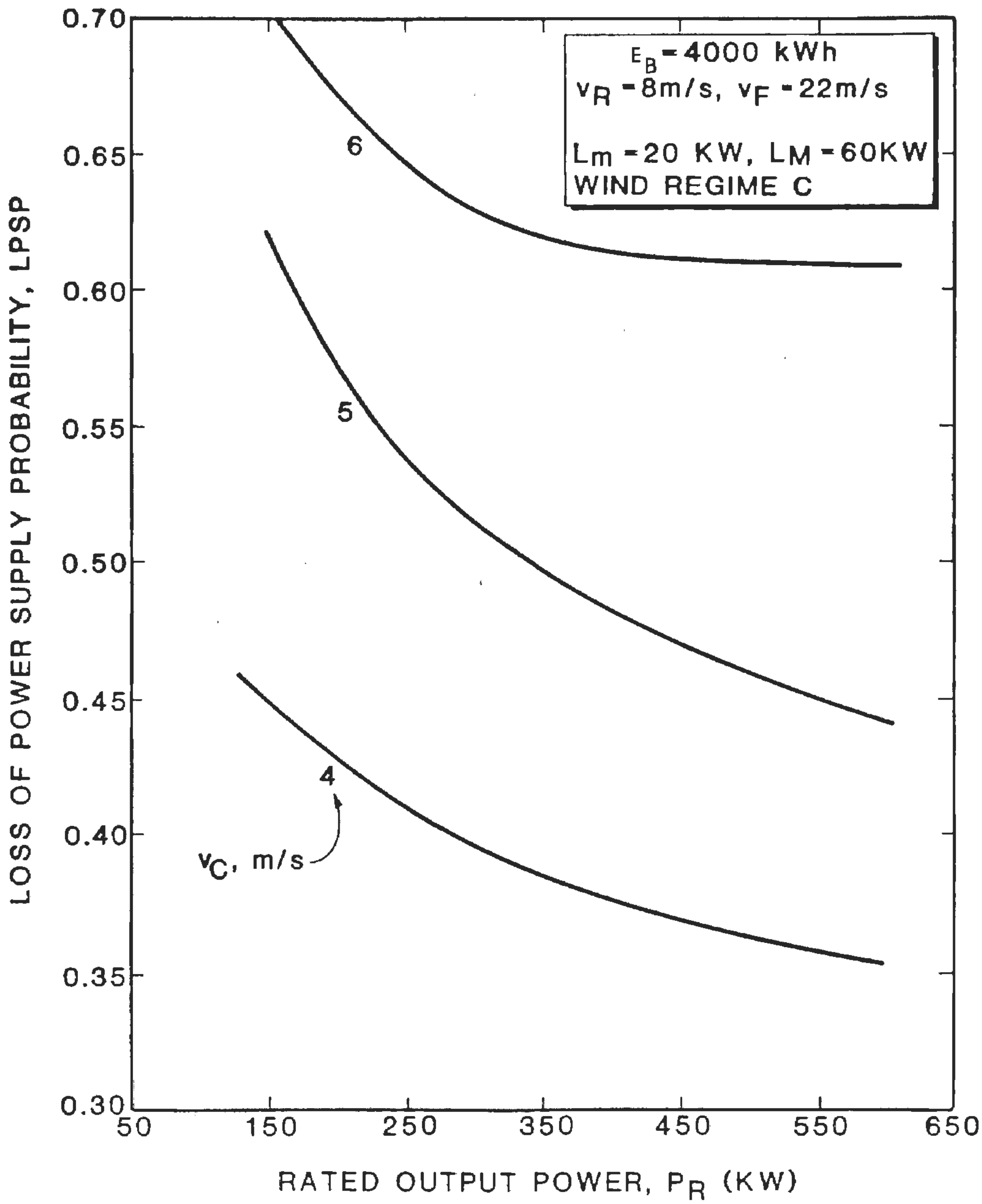


Figure 51. Influence of WECS Rating and Cut-In Speed on LPSP (Regime C), Obtained Using Recorded Wind Speed

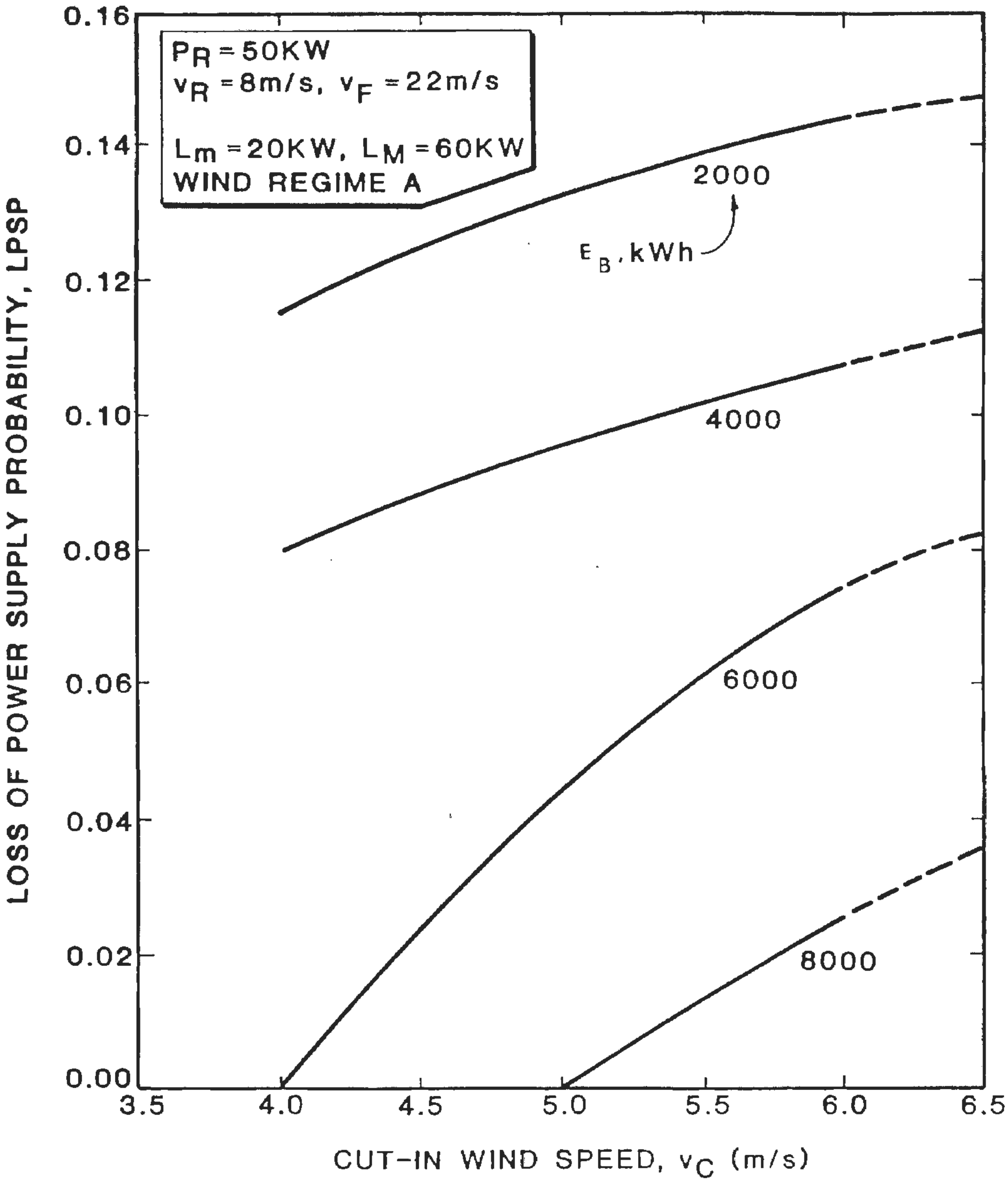


Figure 52. LPSP vs. Cut-In Speed for Different Storage Capacities (Regime A), Obtained Using Recorded Wind Speed

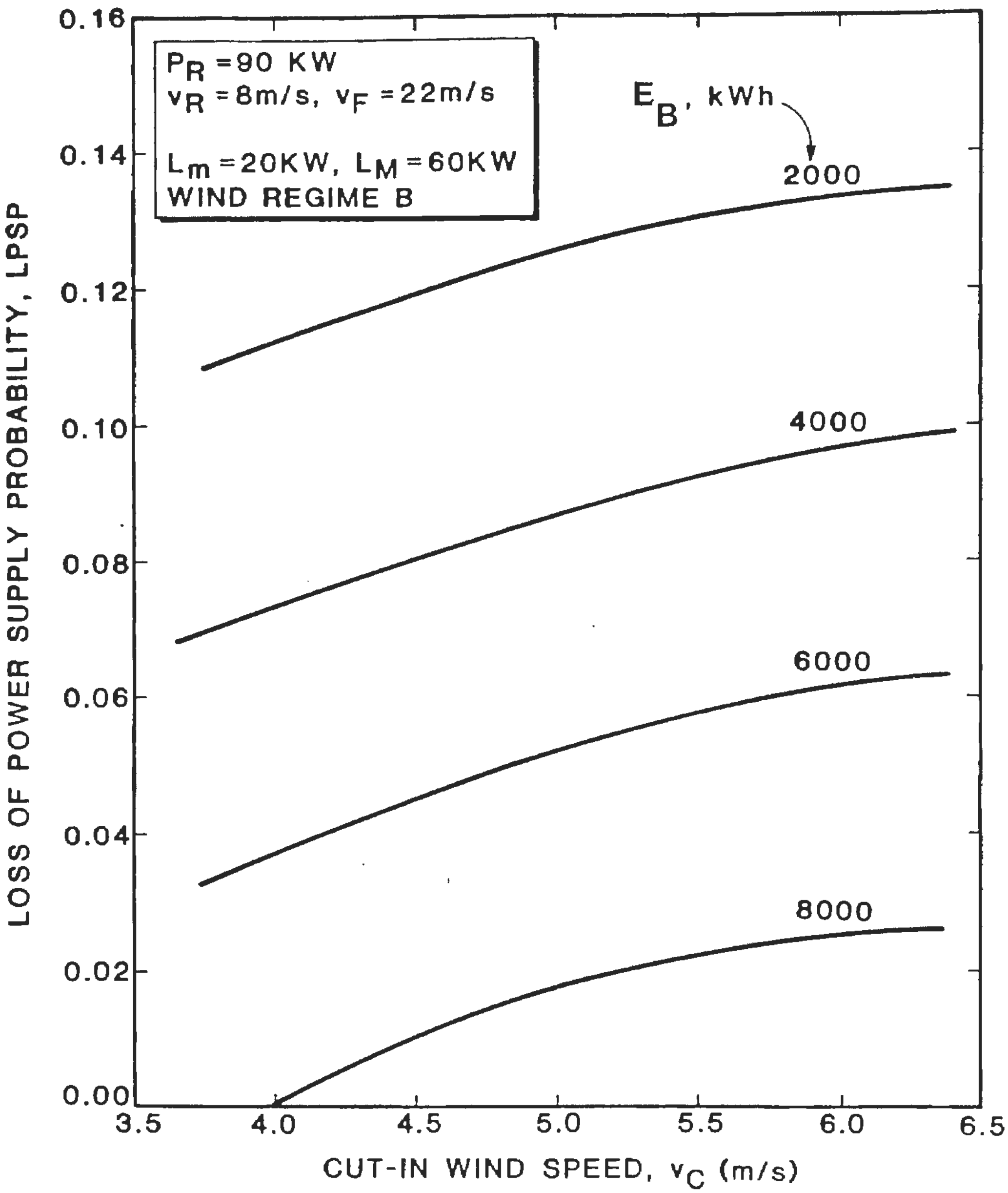


Figure 53. LPSP vs. Cut-In Speed for Different Storage Capacities (Regime B), Obtained Using Recorded Wind Speed

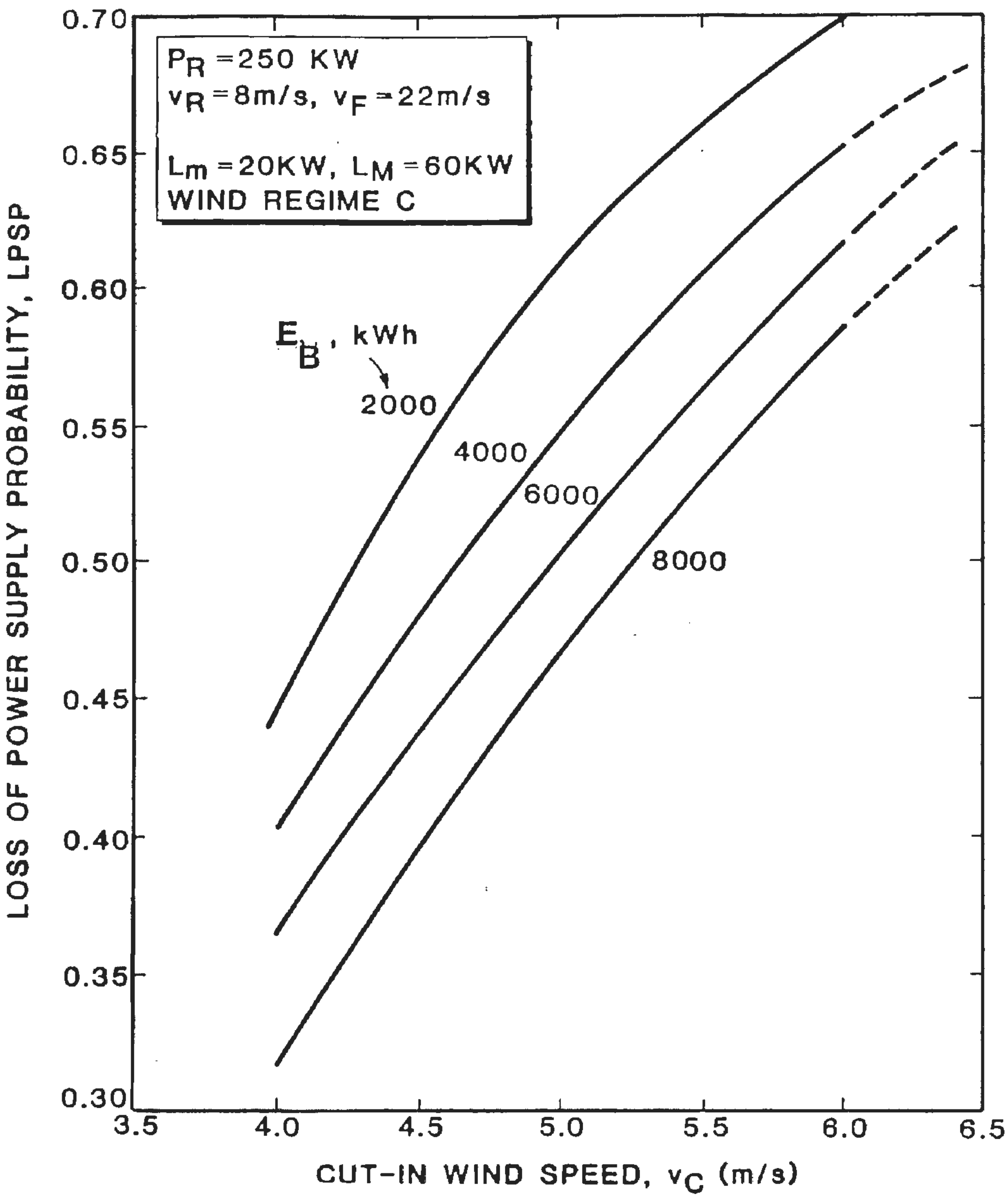


Figure 54. LPSP vs. Cut-In Speed for Different Storage Capacities (Regime C), Obtained Using Wind Speed

As can be seen, both approaches utilize biogas to exhaustion before another resource is utilized. But, due to the different resource-task combinations selected, biogas is not used to satisfy the same energy needs by both approaches. In the linear programming approach biogas is used to satisfy medium-grade heat and electricity requirements. But in the probabilistic approach, biogas is used to satisfy medium-grade heat and rotating shaft demand. Obviously, this will change the ratings of other components as well as the cost associated with the IRES.

Both approaches utilize potential energy of falling water before either solar energy or wind energy is used. However, because of the preselected resources-task combinations, each approach uses this resource to satisfy a different energy need.

Solar energy is used by both approaches for generating electricity. Wind energy is utilized by both approaches for generating electricity and rotating shaft power. But, because of slight variations in load demand contributed by the selected of different resource-task combinations, the component ratings calculated by each approach differ.

To summarize, several design examples illustrating both the deterministic approach and the probabilistic approach were presented in this chapter. It was shown that the final design values depend not only on the desired reliability level (meaning LPSP value), the total capital investment, and annual operating cost, but also on system parameters such as cut-in wind speed of a wind turbine, cost of different components, and the resource availability (site selected).

CHAPTER VII

SUMMARY AND CONCLUSIONS

7.1 Summary of Results and Concluding Remarks

A system utilizing more than one renewable energy resource to supply a variety of energy and other needs is called an Integrated Renewable Energy System (IRES). A typical IRES will utilize two or more of the renewable energy resources (wind, solar radiation and heat, biomass, falling water, etc.) in order to satisfy the energy and other needs of a community.

One of the fundamental technical problems facing the designer of an IRES is to match the varying energy and power requirements of the loads with the mostly stochastic characteristics of the resources in an appropriate manner. The objective of this study was to formulate a mathematical model, and use it to develop a systematic approach to the design of an IRES.

The design procedure must take into account the stochastic characteristics of the resources under consideration as well as the probabilistic nature of the load demand. Resources such as wind and solar radiation are highly variable and site-specific. They have instantaneous, minute-by-minute, hourly, diurnal, interannual, and seasonal variations. On the other hand, water resources are primarily seasonal and biomass availability is fairly predictable.

Two basic design approaches--one deterministic and the other probabilistic--have been presented. They both have the following common elements.

1. Categorize the needs
2. Catalog the resources
3. Consider the variable nature of resources and load
4. Find the ratings of different devices and size of energy storage that will minimize the chosen performance index

In the deterministic approach, average values (computed over the study period) of resources and load variables such as wind speed, insolation, electrical energy demand, etc. were used. The approach employed a linear programming technique for the design of integrated renewable energy systems. The technique was based on minimizing an objective function of total annual cost, subject to a set of energy and power constraints related to resource availabilities and load requirements. The mathematical formulation presented is simple, useful, and is easily applicable for the design of a stand-alone IRES. The data required, assumptions involved, and the design procedure were clearly documented. Also, the methodology has been illustrated by means of a numerical example.

The formulation is quite general and is applicable for almost any resource-task combination. However, this approach is only one of several possibilities for optimizing the design. Obviously, the optimum values obtained for the various quantities very much depend on the values chosen for the different parameters, which may vary widely depending on local conditions, and the objective function employed. The design procedure can accommodate these variations and therefore can be effectively employed for designing such systems under a wide variety of conditions. In practice, the load requirements and the resource availabilities will have seasonal variations. Hence trial designs have to be investigated for different seasons and the final design will have to be a judicious combination of the different designs obtained.

The inherent variability of the resources under consideration and the ensuing variations in all the other quantities involved suggested a probabilistic approach as an alternative to the linear programming approach. In the probabilistic approach, a combination of deterministic and probabilistic models, as appropriate, were used to model the energy resources and load demand. The probabilistic models were in the form of probability density and distribution functions.

In this approach Loss of Power Supply Probability (LPSP) was used to summarize and quantify the overall behavior of a stand-alone system with energy storage supplying a load. The LPSP-based design method, in conjunction with a judicious ordering (prioritizing) of the energy needs and resources, was suggested to design an IRES. The technique was based on minimizing an objective function of total capital cost while maintaining a given (assumed) level of reliability.

The design procedure has been coded into a computer program called "IRES", included in the Appendix. It should be a very useful tool for designing an IRES. If the order of priorities are different from the ones assumed, the program is flexible enough to incorporate these changes. The LPSP-based design method as well as the probabilistic approach to design an IRES have been illustrated by means of several numerical examples.

Energy conversion device parameters such as cut-in or furling speed of the WECS will influence the optimum design values obtained. The design procedure can easily accommodate these variations and therefore can be useful for designing such systems under a wide variety of conditions. Seasonal variations in resource availabilities and load requirement will, as discussed earlier, require the calculation of trial designs for different seasons and the evaluation of a final design which will be a judicious combination of the different designs obtained. The computer program named IRES can be a very useful design tool.

Results of several simulations designed to study the influence of different parameters of the system on the final design values have been presented and discussed. Specifically, simulation results describing the dependence of the LPSP and final design values on wind regime, energy storage capacity, system parameters, and system cost of a WECS were documented and discussed. Also, the influence of certain key system parameters and component costs on the final design values obtained using the linear programming approach was studied. The results and discussion presented should be of useful to designers of integrated renewable energy systems.

The procedures described here can be applied to the design of an integrated renewable energy system for any community in any country. However, it is expected to be especially useful in designing rural energy centers based on renewable energy resources for energizing the remote rural areas of developing countires.

7.2 Scope for Further Work

Further work is indicated in several areas for both the deterministic and the porbabilistic approaches presented. Instead of using annual average values for the resources and loads, their seasonal variations should be considered in the deterministic design approach in a suitable manner. The energy and power requirements of different load demands should be studied in detail to develop appropriate models which can be used to obtain realistic values for some of the parameters such as load factor and diversity factor needed in the design calculations. Probabilistic concepts might have to be introduced to account for the way in which the system will operate.

The success of the deterministic design approach greatly depends on the proper and accurate field estimation of the various parameter values to be used in the computations. Further work is recommended on the establishment of procedures to accurately estimate the data required and in studying the sensitivity of the design to changes in key economic and technical parameters.

The possibility of having to discard (dump) the output power of some of the energy conversion components during the study period because of a combination of lack of demand and fully charged storage has not been included in the LPSP calculations utilizing the probability density function of different resources. Although it is felt that this should not be a significant factor for properly designed systems, only a comparison of results obtained by this approach and by using actual resource data (or a Monte Carlo simulation) can justify the validity of this statement.

The results presented are based on the assumptions that (i) load and resource availabilities are statistically independent, and (ii) the entire output of the system is processed through storage. Further work is necessary to consider the possibility of the system supplying the load directly during a portion of the time and to include any corelation that may exist between the availability of energy resources (wind, insolation, etc.) and load demand. Also, further work is indicated to include any correlation that may exist between different renewable energy resources.

The simple linear relationship used to compute the total capital cost may require modifications to include the changes in per-unit costs as the rating of components vary over a wide range. The basic steps in the design procedure appear to be applicable even with a modified expression for the total capital cost.

Some other aspects of stand-alone IRES with energy storage that require further study are the inclusion of the inefficiencies involved in the storage and reconversion of energy (currently accounted for by adjusting the load requirements); the selection of WECS operating parameters such as cut-in, rated, and furling speeds, and the value of P_{R1} (see Figure 10); consideration of the failure rates of the various components; and the selection of SEC operating conditions. Also, the load demands should be carfully studied to develop an improved load model. Further work is necessary to streamline the computer program to make it more efficient and user friendly.

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APPENDIX

```
C       ******************************
C       *                            *
C       *            IRES            *
C       *              .             *
C       ******************************
C
C
C       IRES is the acronym for 'Integrated Renewable Energy
C       Systems.'
C       This is IRES, a program to design integrated energy
C       systems to optimally utilize locally available
C       renewable energy sources in rural areas.
C       The renewable energy sources that will be considered are:
C       (i) Biomass, (ii)Wind, (iii)Insolation, and (iv)Falling water.
C       The energy needs that will be considered are classified
C       according to the quality of the energy required as follows.
C       1)Medium grade heat(150 to 300 degrees Celsius or
C       higher)
C       2)Low grade heat(less than 150 degrees Celsius)
C       3)Rotating shaft(fixed or mobile)
C       4)Electricity
C
C       The program consists of five stages. The function of each
C       stage is described below.
C
C
C       *****************************
C       *                           *
C       *        STAGE ONE          *
C       *        COMMENTS           *
C       *                           *
C       *****************************
C
C
C          This part of the IRES is used to input all the
C       information necessary for computations to be performed
C       later.  The input information consists of five sets:
C       1)Information about biomass
C
C          a)Amount and type of biomass available per day
C
C          b)Collection efficiencies
C
C
C          c)Volume of gas production expected per kg of
C            dry waste used
C
C          d)Expected specific energy of the biogas
C
C          e)Amount of water needed per kg of dry waste used
C
C       2)Information about wind
C
C          a)Weibull parameters for the wind distribution
C            for different seasons of the year
C
C          b)Mean wind speed
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C
C          c)Variance of the wind speed
C
C          d)Variability(high, low, medium)
C
C          e)Terrain related information
C
C       3)Insolation
C
C          a)Peak and mean(over 24 hours) daily insolation
C            levels during different seasons
C
C          b)Information on the nature and extent of cloud
C            cover expected
C
C          c)Longitude, latitude, and elevation of the location
C
C          d)Other relevant information(mean sunshine hours
C            per day; degree days; etc.)
C
C       4)Falling water
C
C          a)Total volume of water available during different
C           . seasons
C
C          b)Mean flow rate during different seasons
C
C          c)Per capita domestic and potable water consumption
C
C          d)Terrain related information(hills, valleys, lakes, etc.)
C
C          e)Other relevant information related to the
C            quality of the water
C
C       5)The daily needs to be satisfied(all energy values are in kWh)
C
C          a)Population statistics
C
C          b)Information on agricultural, livestock, small-scale
C            industrial, and other needs
C
C          c)Daily total medium-grade heat required
C
C          d)Daily total low-grade heat required
C
C          e)Daily total energy required in the form of
C            fixed rotating shaft
C
C          f)Daily total energy required in the form of
C            mobile rotating shaft
C
C          g)Daily total electricity required
C
C
C          The following variables are used in the first
C       stage of the IRES:
C
C         BCE      =  Efficiency of the internal combustion
C                     engine(in %)
C         BE       =  Efficiency of the burner(in %)
```

```
C        BM(I)    =  Amount of dry waste available for
C                    collection per day (kg)
C        CBM(I)   =  Collected biomass (kg)
C        CBMS(I)  =  Portion of collected biomass used (kg)
C        CE(I)    =  Collection efficiency of biomass(in %)
C        CWR      =  Daily water required per animal (m**3)
C        DER(K)   =  Daily per capita energy requirment (kWh)
C        DWC      =  Daily per capita water consumption for people (m**3)
C        EFW      =  Energy available in the form of potential
C                    energy stored in water (kWh)
C        EG       =  Efficiency of the generator(in %)
C        EME      =  Electrical motor efficiency(in %)
C        ESE      =  Electrical stove efficiency(in %)
C        EV(I)    =  Energy from biomass(of class I) collected (kWh)
C        EWT      =  Wind-to-mechanical efficiency of the wind
C                    turbine (in %)
C        GP(I)    =  Volume of gas produced per kg of waste (m**3)
C        HWR      =  Mean height of water level in the storage
C                    reservoir (m)
C        N        =  Number of different types of biomass resources
C                    available (dimensionless)
C        NC       =  Number of cattle in the village (dimensionless)
C        NP       =  Number of people in the village (dimensionless)
C        PE       =  Efficiency of the wind driven water pump (in %)
C        RCBM(I)  =  Portion of CBM(I) which is not used (kg)
C        REFW     =  Energy of falling water available for further
C                    use after fixed rotating shaft demand is
C                    satisfied (kWh)
C        REN      =  Remaining electrical demand to be met after
C                    all the biogas is utilized (kWh)
C        RFRS     =  Remaining fixed rotating shaft demand to be
C                    met after all the biogas is used (kWh)
C        RLGH     =  Remaining low grade heat requirments left to be
C                    satisfied after all the biogas is used (kWh)
C        RMGH     =  Remaining medium grade heat requirment to be
C                    met after all the biogas is used (kWh)
C        RMRS     =  Remaining mobile rotating shaft energy to be
C                    satisfied by electricity (kWh)
C        RREFW    =  Remaining energy obtainable from falling water
C                    after all the remaining electrical demand
C                    is satisfied (kWh)
C        RRFRS    =  Remaining fixed rotating shaft demand to be met
C                    by wind (kWh)
C        RREN     =  Remaining electricity needed after utilizing all
C                    the available biogas and falling water (kWh)
C        RTE(J)   =  Remaining energy obtainable from biogas after
C                    the (J+1)th stage (kWh)
C        RWA      =  Remaining water after the daily village need and
C                    biogas requirments are deducted (m**3)
C        SCA      =  Area of flat plate solar collector required to
C                    satisfy the remaining low grade heat (m**2)
C        SCE      =  collection efficiency of the flat plate
C                    solar collector (in %)
C        SH       =  Average daily insolation per unit area of the
C                    flat plate solar collector (kWh/m**2)
C        SSTE     =  Round trip efficiency of the storage system
C                    for low grade heat storage (in %)
C        STE(I)   =  Stored energy density in the gas produced
C                    from class I of biomass (kWh/m**3)
C        TE       =  Total energy available from the biogas produced(kWh)
```

```
C        TWA       =  Total water available at the site (m**3)
C        WPD       =  Average wind energy density (kWh/m**2)
C        WRW       =  Weight of water(in storage) used for energy
C                     production (kg)
C        WTA       =  Wind turbine area necessary for satisfying the
C                     remaining fixed rotating shaft demand (m**2)
C        WTE       =  Water turbine efficiency (in %)
C        WUB       =  Water necessary for the utilization of all the
C                     biomass collected (m**3)
C        WUBS      =  Water available after daily domestic and
C                     potable consumption is deducted (m**3)
C        WW(I)     =  Water volume required for gas production
C                     per kg of class I of biomass collected (m**3)
C
C
C         **************************
C         *                      . *
C         *       STAGE TWO        *
C         *       COMMENTS         *
C         *                        *
C         **************************
C
C         After all the data are received, the total volume
C      of biogas, considering the limitations imposed by water
C      and biomass availability, that can be produced(per day)
C      is calculated and stored for later use.
C          The amount of water left, after domestic and potable
C      consumption and what is used for biogas production, is
C      calculated and stored for later use.
C          The amount of medium grade heat required is compared
C      with the amount of medium grade heat obtainable by the
C      combustion of the biogas produced.  The excess biogas, if
C      any, will be computed and stored for later use.
C      If the biogas remaining is zero, a message will be
C      sent to the operator, and to the other stages.If the
C      medium grade heat requirment cannot be satisfied by
C      biogas alone, the calculated deficiency will be added
C      to the electricity need.
C          The following variables are used in this stage:
C      BE,BM(I),CBM(I),CBMS(I),CE(I),DER(1),DER(5),DWC,ESE,EV(I),
C      GP(I),NP,RCBM(I),RMGH,RTE(1),RWA,STE(I),TE,TWA,WUB,WUBS,
C      WW(I)
C
C
C       **************************
C       *                        *
C       *      STAGE THREE       *
C       *       COMMENTS         *
C       *                        *
C       **************************
C
C
C      In this stage the low grade heat requirment is satisfied.
C      First the remaining biogas, if any, will be burned to
C      satisfy the requirment.  If there is still some low
C      grade heat requirment left to be satisfied, then flat plate solar
C      collectors will be used to fill this need.
C      The following variables are used in this stage:
C
C      BE,DER(2),RLGH,RTE(1),RTE(2),SCA,SCE,SH,SSTE
```

```
C
C
C       **************************
C       *                        *
C       *      STAGE FOUR        *
C       *       COMMENTS         *
C       *                        *
C       **************************
C
C
C       In this stage the energy required in the form of
C       rotating shaft(fixed and/or mobile)will be satisfied
C       by biogas, falling water, and wind
C       The available biogas will be used in an internal
C       combustion engine to satisfy the mobile rotating shaft
C       requirment.  The remaining mobile shaft requirment will
C       be satisfied by electricity:
C       The energy required in the form of fixed rotating shaft
C       will be satisfied by biogas driven engine and/or by a
C       water turbine.  Wind driven water pumps will be used to
C       recirculate the water from the lower water level to the
C       storage tank at a higher level.
C       The following variables are used in this stage:
C       BCE,DER(3),DER(4),DER(5),EFW,EME,HWR,REFW,RFRS,RMRS,
C       RRFRS,RTE(2),RTE(3),RTE(4),RWA,WRW,WTA,WTE
C
C
C       **************************
C       *                        *
C       *      STAGE FIVE        *
C       *       COMMENTS         *
C       *                        *
C       **************************
C
C           In this stage of the program the total daily electricity
C       required will be satisfied by using the available resources
C       such as biogas, wind, insolation, and falling water(hydro).
C           Biogas would be used to satisfy as much of the load as
C       possible;  then falling water would be used(if there is any
C       available) to satisfy the remainder(if any).  If there is still any
C       demand left to be satisfied, then the optimum combination of wind,
C       insolation, and storage system will be used to satisfy the remainder.
C       An optimum combination of solar system and wind system is found
C       using the LPSP subroutine.
C       The following variables will be used in this stage:
C       DER(5),EG,REFW,REN,RREFW,RREN,RTE(4),RTE(5)
C
C
C
C
C       ***************************
C       *                         *
C       *       STAGE ONE         *
C       *        PROGRAM          *
C       *                         *
C       ***************************
C
C
C       Enter all the necessary information
C
```

```
C
      DOUBLE PRECISION BM(10),CE(10),WW(10),GP(10),STE(10),TWA,DWC,NP
     *,SH,SCE,HWR,DER(10),WUB,CBM(10),RWA,CBMS(10),WUBS,RCBM(10)
      DOUBLE PRECISION EV(10),TE,RMGH,RTE(10),RLGH,SCA,RMRS,RFRS,WRW,
     *EFW,RRFRS,REFW,WPD,EWT,WTA,WTE,PE,BE,BCE,EME,EG,REN,RREN,RREFW
      DOUBLE PRECISION SSTE,NC,CWR,ESE
      IN=5
      LP=6
C
C     Enter all information necessary for calculation of the
C     energy obtainable from the biomass
C
      N = 3
      Type *,'Enter the efficiency of the  electric stove (in %)'
      Read(IN,100)ESE
      Type *,'Enter the amount of dry human waste available to be
     * collected  (in kg/day)'
      Read(IN,100)BM(1)
 100  Format(D24.16)
      Type *,'Enter the amount of dry animal waste available to be
     * collected  (in kg/day)'
      Read(IN,100)BM(2)
      Type *,'Enter the amount of dry agricultural waste material
     * available to be collected ( in kg/day)'
      Read(IN,100)BM(3)
      Type *,'Enter the collection efficiency of the dry human waste
     *   (in %)'
      Read(IN,100)CE(1)
      Type *,'Enter the collection efficiency of the dry animal waste
     *   (in %)'
      Read(IN,100)CE(2)
      Type *,'Enter the collection efficiency of the dry agricutural
     * waste material  (in %)'
      Read(IN,100)CE(3)
      Type *,'Enter the volume of water required for biogas
     * production per kg of human waste (m**3)'
      Read(IN,100)WW(1)
      Type *,'Enter the volume of water required for biogas
     * production per kg of animal waste (m**3)'
      Read(IN,100)WW(2)
      Type *,'Enter the volume of water required for biogas
     * production per kg of agricultural waste material (m**3)'
      Read(IN,100)WW(3)
      Type *,'Enter the volume of gas produced
     * per kg of human waste (m**3)'
      Read(IN,100)GP(1)
      Type *,'Enter the volume of gas produced per
     * kg of animal waste (m**3)'
      Read(IN,100)GP(2)
      Type *,'Enter the volume of gas produced per
     * kg of agricultural waste material (m**3)'
      Read(IN,100)GP(3)
      Type *,'Enter the energy density of the biogas produced
     * from human waste (kWh/m**3)'
      Read(IN,100)STE(1)
      Type *,'Enter the energy density of the biogas produced
     * from animal waste  (kWh/m**3)'
      Read(IN,100)STE(2)
      Type *,'Enter the energy density of the biogas produced
     * from agricutural waste material  (kWh/m**3)'
```

```
      Read(IN,100)STE(3)
      Type *,'Enter the total volume of water available daily (m**3)'
      Read(IN,100)TWA
      Type *,'Enter the per capita daily domestic and potable water
     * consumption  (m**3)'
      Read(IN,100)DWC
      Type *,'Enter the number of people living in the village'
      Read(IN,100)NP
      Type *,'Enter the daily water requirment per head of
     * livestock (m**3)'
      Read(IN,100)CWR
      Type *,'Enter the number of cattle in the village'
      Read(IN,100)NC
C
C     Input the information required for calculating the
C     available low and medium grade heat, and rotating shaft energy
C     obtainable from other available sources.
C
C  1)Data on flat-plate solar collector
C
      Type *,'Enter the average daily insolation density (kWh/m**2)'
      Read(IN,100)SH
      Type *,'Enter the collection efficiency of the flat
     * plate solar collector  (in %)'
      Read(IN,100)SCE
C
C  2)Data on falling water(hydro)
C
      Type *,'Enter the average height(above the lower water level)
     * of water in the storage reservoir (m)'
      Read(IN,100)HWR
      Type *,'Enter the water turbine efficiency (in %)'
      Read(IN,100)WTE
      Type *,'Enter the available mean daily wind energy density
     *   (kWh/m**2)'
      Read(IN,100)WPD
      Type *,'Enter the wind-to-mechanical conversion efficiency
     * of the wind turbine (in %)'
      Read(IN,100)EWT
      Type *,'Enter the efficiency of the wind driven water pump (in %)'
      Read(IN,100)PE
      Type *,'Enter the efficiency of the biogas burner (in %)'
      Read(IN,100)BE
      Type *,'Enter the efficiency of the biogas driven internal
     * combustion engine  (in %)'
      Read(IN,100)BCE
      Type *,'Enter the electrical motor efficiency (in %)'
      Read(IN,100)EME
      Type *,'Enter the round trip efficiency of the low-grade
     * heat storage system  (in %)'
      Read(IN,100)SSTE
C
C     Input the information necessary for calculating the amount of
C     electrical energy that can be generated.
C
      Type *,'Enter efficiency of the electrical generator (in %)'
      Read(IN,100)EG
c
c this area is to be used for inputing the rest of the necessary
c information for stage five.
```

```
c
C
C     Input the per capita values of all the daily energy requirments
C
      Type *,'Enter the per capita medium grade heat energy required
     * per day  (kWh)'
      Read(IN,100)DER(1)
      DER(1)=DER(1)*NP
      Type *,'Enter the per capita low grade heat energy required
     * per day  (kWh)'
      Read(IN,100)DER(2)
      DER(2)=DER(2)*NP
      Type *,'Enter the per capita amount of energy required per
     * day in the form of a fixed rotating shaft  (kWh)'
      Read(IN,100)DER(3)
      DER(3)=DER(3)*NP
      Type *,'Enter the per capita amount of energy required per
     * day in the form of a mobile rotating shaft  (kWh)'
      Read(IN,100)DER(4)
      DER(4)=DER(4)*NP
      Type *,'Enter the per capita amount of energy required in
     * the form of electricity  (kWh)'
      Read(IN,100)DER(5)
      DER(5)=DER(5)*NP
      Type *,'Enter (1) to get a printout of the intermediate results'
      Read(IN,101)ICHECK
  101 Format(I1)
      Type *,'Enter (1) if a copy of the input data is required'
      Read(IN,101)IDEBUG
C
C     ***********************
C     *                     *
C     *      STAGE TWO      *
C     *       PROGRAM       *
C     *                     *
C     ***********************
C
C
C     Calculate the energy obtainable (in the form of biogas)
C     from biomass.
C
C   1) Calculate the amount of biogas produced, and the
C      volume of water required for the fermentation process.
C
      WUB=0.0
      DO I=1,N
      CBM(I)=(BM(I)*CE(I))/1.0D2
      WUB=WUB+CBM(I)*WW(I)
      Write(99,1)I,CBM(I)
    1 Format(1H0,'Collected biomass(',I2,')=',1X,D24.16)
      END DO
      Write(99,2)WUB
    2 Format(1H0,'volume of water required for utilization
     * of all the available biomass=',D24.16)
C
C    Check to see whether enough water is available.
C
      WUBS=TWA-DWC*NP-CWR*NC
      IF(WUBS.LE.0.0)Then
      Write(99,30)
```

```
30    Format(1H0,'NO water is left after satisfying the daily water
     * consumption(people and cattle) to be used for biogas production')
      WUBS=0.0
      DO I=1,N
      CBMS(I)=0.0
      END DO
      Else
      RWA=WUBS-WUB
      IF(RWA.GE.0.0)Then
      DO I=1,N
      CBMS(I)=CBM(I)
      END DO
      Else
      RWA=0.0
      IF(WUBS.LE.CBM(3)*WW(3))Then
      CBMS(3)=WUBS/WW(3)
      CBMS(2)=0.0
      CBMS(1)=0.0
      Else
      CBMS(3)=CBM(3)
      WUBS=WUBS-CBM(3)*WW(3)
      IF(WUBS.LE.CBM(2)*WW(2))Then
      CBMS(2)=WUBS/WW(2)
      CBMS(1)=0.0
      Else
      CBMS(2)=CBM(2)
      CBMS(1)=(WUBS-CBM(2)*WW(2))/WW(1)
      END IF
      END IF
      END IF
      END IF
      DO I=1,N
3     Format(1H0,'Portion of collected biomass used for biogas
     * production=',D24.16)
      RCBM(I)=CBM(I)-CBMS(I)
      Write(99,31)RCBM(I)
31    Format(1H0,'Portion of the collected biomass which was not
     * used=',D24.16)
      Write(99,3)CBMS(I)
      END DO
      IF(ICHECK.EQ.1)Write(99,32)RWA
32    Format(1H0,'Water available for other uses after the daily
     * village consumption and biogas production requirments have
     * been deducted=',D24.16)
C
C     Calculate the energy available in the form of biogas
C
      TE=0.0
      DO I=1,N
      EV(I)=CBMS(I)*STE(I)*GP(I)
      TE=TE+EV(I)
      IF(ICHECK.EQ.1)Write(99,4)I,EV(I)
4     Format(1H0,'Energy from class (',I2,') of biomas=',D24.16)
      END DO
      Write(99,33)TE
33    Format(1H0,'Total energy available in the form of biogas=',D24.16)
C
C     Check to see if all the medium grade heat requirments can be
C     satisfied by biogas. If not use electricity to satisfy
C     the remainder.
```

```
C
      RMGH=DER(1)-(TE*BE)/1.0D2
      IF(RMGH)40,41,42
 40   RTE(1)=TE-DER(1)/(BE/1.0D2)
      IF(ICHECK.EQ.1)Write(99,44)RTE(1)
44    Format(1H0,'Amount of biogas available for later use after all
     * the medium grade heat requirments have been satisfied=',D24.16)
      GO TO 43
41    Write(99,45)
45    Format(1H0,'All the biogas was utilized to satisfy the
     * medium grade heat requirments')
      RTE(1)=0.0
      GO TO 43
42    Write(99,46)RMGH
46    Format(1H0,'Amount of medium grade heat energy to be satisfied
     * with electricity=',D24.16)
      RTE(1)=0.0
      Write(99,45)
      DER(5)=DER(5)+ (RMGH / ESE) * 1.D2
43    Continue
C
C
C     ************************
C     *                      *
C     *      STAGE THREE     *
C     *        PROGRAM       *
C     *                      *
C     ************************
C
C
C     Satisfy the low grade heat requirments with biogas,
C     if available;  use flat plate solar collectors to satisfy
C     the remainder(if any).
C
C    1) Use biogas
C
      RLGH=DER(2)-(RTE(1)*BE)/1.0D2
      IF(RLGH)47,48,49
47    RTE(2)=RTE(1)-DER(2)/(BE/1.0D2)
      IF(ICHECK.EQ.1)Write(99,5)RTE(2)
5     Format(1H0,'Amount of energy in the form of biogas left
     * after medium and low grade heat energy requirments
     * are satisfied=',D24.16)
      GO TO 64
48    Write(99,45)
      RTE(2)=0.0
      GO TO 64
C
C   2)Use flat plate solar collectors
C
49    SCA=RLGH/((SH*SCE*SSTE)/1.0D4)
      Write(99,50)SCA
50    Format(1H0,'Area of flat plate solar collectors needed to
     * satisfy the remaining low grade heat required=',D24.16)
      RTE(2)=0.0
64    Continue
C
C     ************************
C     *                      *
C     *      STAGE FOUR      *
```

```
C       *          PROGRAM          *
C       *                           *
C       *************************
C
C       Satisfy energy requirments in the form of mobile rotating
C       shaft by
C
C           1)Biogas
C           2)Electricity
C
C   1) Use biogas
C
        RMRS=DER(4)-RTE(2)*(BCE/1.0D2)
        IF(RMRS)51,52,53
 51     RTE(3)=RTE(2)-DER(4)/(BCE/1.0D2)
        IF(ICHECK.EQ.1)Write(99,6)RTE(3)
 6      Format(1H0,'Amount of energy in the form of biogas remaining
       * after medium grade heat, low grade heat, and mobile rotating
       * shaft requirments are satisfied=',D24.16)
        GO TO 28
 52     RTE(3)=0.0
        Write(99,45)
        GO TO 28
 53     DER(5)=DER(5)+RMRS/(EME/1.0D2)
        Write(99,54)RMRS
 54     Format(1H0,'Amount of energy in the form of mobile rotating
       * shaft to be satisfied using electricity=',D24.16)
        RTE(3)=0.0
 28     Continue
C
C       Satisfy fixed rotating shaft energy requirments by using
C
C            1)Biogas
C            2)Falling water
C            3)Wind
C
C   1) Use biogas
C
        RFRS=DER(3)-RTE(3)*(BCE/1.0D2)
        IF(RFRS)55,56,57
 55     RTE(4)=RTE(3)-DER(3)/(BCE/1.0D2)
        IF(ICHECK.EQ.1)Write(99,7)RTE(4)
 7      Format(1H0,'Amount of energy in the form of biogas remaining
       * after satisfying medium grade heat, low grade heat, mobile
       * rotating shaft, and fixed rotating shaft requirments='D24.16)
        GO TO 29
 56     RTE(4)=0 0
        Write(99,45)
        GO TO 29
C
C       Use falling water
C       WRW=VOL*Density*g      (g=9.824)
C
 57     WRW=RWA*(1.0D3)*(0.9824D1)
        RTE(4)=0.0
        EFW=WRW*HWR*WTE/1.0D2
        RRFRS=RFRS-EFW
        IF(RRFRS)58,59,60
 58     REFW=EFW-RFRS
        IF(ICHECK.EQ.1)Write(99,61)REFW
```

```
61     Format(1H0,'Energy available in the form of falling water after
      * medium and low grade heat, and rotating shaft requirments
      * are satisfied=',D24.16)
       GO TO 29
59     Write(LP,62)
       REFW=0.0
62     Format(1H0,'All the energy available in the form of falling
      * water has been utilized.')
       GO TO 29
60     REFW=0.0
       WTA=RRFRS/(WPD*EWT*PE*WTE/1.0D6)
       Write(99,63)WTA
63     Format(1H0,'Wind turbine area needed to satisfy the remainder
      * of the fixed rotating shaft requirments=',D24.16)
29     Continue
C
C      ***********************
C      *                     *
C      *     STAGE FIVE      *
C      *      PROGRAM        *
C      *                     *
C      ***********************
C
C
C
C
C
       REN = DER(5) - RTE(4) * EG / 1.D2
       IF(REN) 70,71,72
70     RTE(5) = RTE(4) - DER(5) / (EG / 1.D2)
       WRITE(LP,73) RTE(5)
       WRITE(99,73) RTE(5)
73     FORMAT(1H0,'The portion of biogas energy which is not used = ',
      *D24.16)
       GO TO 75
71     RTE(5) = 0.D0
       WRITE(LP,74)
       WRITE(99,74)
74     FORMAT(1H0,' Entire biogas is used and the entire demand is met')
       GO TO 75
72     RREN = REN - REFW
       IF (RREN) 76,77,78
76     RREFW = REFW - REN
       WRITE(LP,79)RREFW
       WRITE(99,79)RREFW
79     FORMAT(1H0,'The amount of potential energy from water available =',
      *d24.16)
       GO TO 75
77     RREFW = 0.D0
       WRITE(LP,80)
       WRITE(99,80)
80     FORMAT(1H0,'All the potential energy from water is used and
      * all the energy needs have been satisfied')
       GO TO 75
C
C      Satisfy the electricity demand using WECS and SEC
C
78     RREFW = 0.D0
       WRITE(LP,81)
       WRITE(99,81)

81     FORMAT(1H0,'All the potential energy from water is used')
       CALL LPSP(RREN)
75     STOP
       END
```

```
      SUBROUTINE LPSP(REN)
C  THIS SUBROUTINE WILL FIND THE MAXIMUM ELECTRICITY
C  DEMAND.  THE MINIMUM ELECTRICITY DEMAND IS ASSUMED
C  TO BE THE SAME AS THE ORIGINAL ELECTRICITY DEMAND.

      DOUBLE PRECISION REN,LMIN,LMAX,T
      INTEGER IN,LP
C
C     LMAX = 2 * REN / T - LMIN
C
      TYPE *,'Enter the input and output devices (IN,LP)'
      READ(5,*)IN
      TYPE *,'Enter the minimum daily load demand'
      READ(IN,1)LMIN
1     FORMAT(D14.6)
      T = 24.0D0
      LMAX = (2.D0 / T) * REN - LMIN
      WRITE(LP,2)LMIN,LMAX
2     FORMAT(1H0,' Lmin = ',D14.6,2x,'Lmax = ',D14.6)
      call alldumpr(lmin,lmax)
      RETURN
      END
```

```
      subroutine alldumpr(lmin,lmax)
C     This program uses recorded wind and insolation data and
C generated load data, for calculating LPSP.  The load is
C assumed to be uniformly distributed between Lmax and Lmin.
C
C This program is based on Ofry'S approach.  Output of the
C WECS is assumed to be realted to wind speed as follows:
C
C       P = (V - Vc)/(Vr - Vc)*Pr1        Vc < V < Vr
C       P = (Pr - Pr1)/(Vf - Vr)*V + (Vf * Pr1 - Vr*Pr)/(Vf - Vr) Vr<V<Vf
C
C       where
C               P    = WECS power output
C               Pr   = rated output of the WECS
C               Pr1  = switching point
C               V    = wind speed
C               Vf   = cut out speed
C               Vr   = rated speed
C               Vc   = cut-in speed
C
C Output of the SEC, P1, is assumed to be related to insolation
C as follows:
C
C       P1 = eff * area * PF * I
C
C       where
C               P1    = SEC power output
C               eff   = conversion efficiency
C               PF    = packing factor
C               area  = array area
C               I     = insolation
C
C     NOTE: IN THIS PROGRAM AREA REFERS TO (PF * AREA).
C
C     NOTE: THIS PROGRAM CONSIDERS THE NEED FOR DUMPING ENERGY
C WHEN THE STORAGE IS FULL, AND RESTORES TO MINIMUM STORED
C CHARGE REQUIRED AFTER EACH FAILURE.
C
C     *************************
C     *                       *
C     *  Initialize variables *
C     *                       *
C     *************************
C
C
      CHARACTER*80 INFILE,OUTFILE,INFILES
      REAL MTH$RANDOM
      INTEGER IN,LP,IREPEAT,ISEED,ihour,ICHECK
      REAL MAXCMAX,MINCMAX,CMAX,DCMAX,MAXPR,MINPR,PR,PR1
      REAL DPR,MAXSW,MINSW,SW,DSW,MAXPER,MINPER,DPER
      REAL PER,MINLMIN,MAXLMIN,LMIN,DLMIN,MAXLMAX,MINLMAX
      REAL LMAX,DLMAX,VC,MAXVC,MINVC,DVC,VR,DVR,MAXVR,MINVR
      REAL VF,DVF,MINVF,MAXVF,L,P1,INSOL(8760)
      REAL CMIN,HOUR,V(8760),DISCHARGE,CHARGE,FAIL
      REAL DN,LPSP,RANDNO(8760),load(8760),lpspl
      REAL MAXAREA,MINAREA,AREA,DAREA,MAXEFF,MINEFF,EFF,DEFF
C
```

```
C       Set all initial values of arrays to zero
C
20      do i=1,8760
           INSOL(I)   = 0.
           randno(i)  = 0.
           V(i)       = 0.
           load(i)    = 0.
        end do
C
C       SET SEED NUMBER FOR RANDOM NUMBER GENERATOR
C
C
        ISEED = 385
C
C
C       SPECIFY THE INPUT/OUTPUT DEVICES
C
C
        TYPE *,'ENTER "IN" AND "LP"'
        READ(5,*)IN,LP
C
C
C       SPECIFY INPUT AND OUTPUT FILES
C
C
        TYPE *,'ENTER NAME OF THE INPUT FILE CONTAINING THE WIND SPEED'
        READ(IN,1)INFILE
        TYPE *,'ENTER NAME OF THE INPUT FILE CONTAINING THE INSOLATION'
        READ(IN,1)INFILES
        TYPE *,'ENTER NAME OF THE OUTPUT FILE'
        READ(IN,1)OUTFILE
C
C
C READ THE NECESSARY DATA
C
C
        type *,'enter the maximum LPSP desired (LPSP1)'
        read(in,*)lpsp1
        TYPE *,'ENTER MIN AND MAX VALUES OF VC'
        READ(IN,*)MINVC,MAXVC
        TYPE *,'ENTER NUMBER OF POINTS IN THE INTERVAL'
        READ(IN,*)DN
        DVC =(MAXVC - MINVC)/DN
        TYPE *,'ENTER MIN AND MAX VALUES OF VF'
        READ(IN,*)MINVF,MAXVF
        TYPE *,'ENTER NUMBER OF POINTS IN THE INTERVAL'
        READ(IN,*)DN
        DVF =(MAXVF - MINVF)/DN
        TYPE *,'ENTER MIN AND MAX VALUES OF VR'
        READ(IN,*)MINVR,MAXVR
        TYPE *,'ENTER NUMBER OF POINTS IN THE INTERVAL'
        READ(IN,*)DN
        DVR =(MAXVR - MINVR)/DN
        TYPE *,'ENTER MIN AND MAX VALUES OF SW'
        READ(IN,*)MINSW,MAXSW
        TYPE *,'ENTER NUMBER OF POINTS IN THE INTERVAL'
        READ(IN,*)DN
        DSW =(MAXSW - MINSW)/DN
        TYPE *,'ENTER MIN AND MAX VALUES OF Cmax (STORAGE CAPACITY)'
        READ(IN,*)MINCMAX,MAXCMAX
```

```
      TYPE *,'ENTER NUMBER OF POINTS IN THIS INTERVAL'
      READ(IN,*)DN
      DCMAX = (MAXCMAX - MINCMAX)/DN
      TYPE *,'ENTER MIN AND MAX VALUES FOR SYSTEM RATING'
      READ(IN,*)MINPR,MAXPR
      TYPE *,'ENTER NUMBER OF POINTS IN THIS INTERVAL'
      READ(IN,*)DN
      DPR = (MAXPR - MINPR)/DN
      TYPE *,'ENTER MIN AND MAX VALUES OF COLLECTOR AREA'
      READ(IN,*)MINAREA,MAXAREA
      TYPE *,'ENTER THE NUMBER OF POINTS IN THIS INTERVAL'
      READ(IN,*)DN
      DAREA = (MAXAREA - MINAREA)/DN
      TYPE *,'ENTER MIN AND MAX VALUES OF COLLECTOR EFFICIENCY (IN %)'
      READ(IN,*)MINEFF,MAXEFF
      IF(MINEFF.GT.1)MINEFF= MINEFF/100.D0
      IF(MAXEFF.GT.1)MAXEFF = MAXEFF/100.D0
      TYPE *,'ENTER THE NUMBER OF POINTS IN THIS INTERVAL'
      READ(IN,*)DN
      DEFF = (MAXEFF -  MINEFF)/DN
      TYPE *,'ENTER MIN AND MAX VALUES OF PERCENT DISCHARGE ALLOWED
     * (in %)'
      READ(IN,*)MINPER,MAXPER
      TYPE *,'ENTER NUMBER OF POINTS IN THIS INTERVAL'
      READ(IN,*)DN
      DPER = (MAXPER - MINPER)/DN
      TYPE *,'ENTER MIN AND MAX VALUES OF MINIMUM LOAD'
      READ(IN,*)MINLMIN,MAXLMIN
      TYPE *,'ENTER NUMBER OF POINTS IN THIS INTERVAL'
      READ(IN,*)DN
      DLMIN = (MAXLMIN - MINLMIN)/DN
      TYPE *,'ENTER MIN AND MAX VALUES OF MAXIMUM LOAD'
      READ(IN,*)MINLMAX,MAXLMAX
      TYPE *,'ENTER NUMBER OF POINTS IN THIS INTERVAL'
      READ(IN,*)DN
      DLMAX = (MAXLMAX - MINLMAX)/DN
C
C
C     READ WIND SPEED VALUES
C
C
C
C     OPEN INPUT FILE
C
C
      OPEN(1,NAME=INFILE,FORM='FORMATTED',STATUS='OLD',READONLY)
      DO I=1, 8760
        READ(1,*,END = 10) V(I)
      END DO
10    CLOSE(1)
      ICHECK = i - 1
      OPEN(1,NAME=INFILES,FORM='FORMATTED',STATUS='OLD',READONLY)
      DO I=1, 8760
        READ(1,*,END = 21) INSOL(I)
      END DO
21    CLOSE(1)
      ihour = i - 1
      IF(ICHECK.LT.IHOUR)IHOUR=ICHECK
C
C
```

```
C        Generate random number to be used for generating load
C
C
         DO I=1,ihour
            RANDNO(I) = MTH$RANDOM(ISEED)
         END DO
         WRITE(6,*)I-1,' POINTS GENERATED'
         hour = float(ihour)
C
C        OPEN OUTPUT FILE
C
         OPEN(2,NAME=OUTFILE,FORM='FORMATTED',STATUS='NEW')
C
C
C
C        FIND LPSP
C
C
         LMIN = MINLMIN
         DO WHILE (LMIN .LE. MAXLMIN)
         LMAX = MINLMAX
         DO WHILE (LMAX .LE. MAXLMAX)
         L = LMAX - LMIN
C
C        generate load data
C
C
C        Uniformly distributed load
           do i=1,ihour
             load(i) = l*randno(i) + lmin
           end do
C
C   SET UP LOOP
C
         EFF = MINEFF
         DO WHILE (EFF .LE. MAXEFF)
         SW = MINSW
         DO WHILE (SW  .LE.  MAXSW)
         VC = MINVC
         DO WHILE (VC .LE. MAXVC)
         VF = MINVF
         DO WHILE (VF .LE. MAXVF)
         VR = MINVR
         DO WHILE (VR  LE. MAXVR)
         WRITE(2,4) VC,VR,VF
4        FORMAT(1X,5X,'VC = ',F10.3,5X,'VR = ',F10.3,5X,'VF = ',F10.3)
         PER = MINPER
         DO WHILE (PER  .LE.  MAXPER)
         WRITE(2,3)LMAX,LMIN,PER,EFF
3        FORMAT(3X,'Lmax = ',F6.2,2X,'Lmin = ',F6.2,2X,
     *   'PER = ',F7.3,5X,'CELL EFF. = ',F7.3)
         CMAX = MINCMAX
         DO WHILE (CMAX .LE. MAXCMAX)
         PR = MINPR
         DO WHILE (PR .LE. MAXPR)
         PR1 = PR * SW
         AREA = MINAREA
         DO WHILE (AREA .LE. MAXAREA)
         CHARGE = CMAX
         FAIL = 0.0
```

```
      IF(PER.LT.1.) PER = PER*100.
      CMIN = CMAX * PER/100.
C
C  CALCULATE DISCHARGE AND LPSP
C
      DO I=1,IHOUR
         IF (V(I).LE.VC.OR.V(I).GE.VF)P = 0.0
         IF (V(I).GT.VC.AND.V(I).LT.VR)THEN
           P = (V(I) - VC)/(VR - VC) * PR1
         END IF
         IF (V(I).GE.VR.AND.V(I).LT.VF)THEN
           P = (PR - PR1)/(VF - VR) *V(I) + (VF*PR1 - VR*PR)/
     * (VF -VR)
         END IF
         P1 = INSOL(I) * EFF * AREA
         DISCHARGE = P + P1 - LOAD(I)
         CHARGE = CHARGE + DISCHARGE
         IF(CHARGE.GT.CMAX)CHARGE = CMAX
         IF(CHARGE.LE.CMIN)then
              FAIL = FAIL + 1.
              charge = cmin
         end if
      END DO
      LPSP = FAIL/HOUR
      if(lpsp.le.lpsp1.and.lpsp.ge.0.0)WRITE(2,2)LPSP,PR,CMAX,AREA
      AREA = AREA + DAREA
      IF (DAREA.EQ.0.0)GO TO 22
      END DO
22    IF(DPR.EQ.0.0)GO TO 11
      PR = PR + DPR
      END DO
11    IF(DCMAX.EQ.0.0)GO TO 12
      CMAX = DCMAX + CMAX
      END DO
12    IF(DPER.EQ. 0.0)GO TO 13
      PER = PER + DPER
      END DO
13    IF(DVR .EQ. 0.0)GO TO 14
      VR = VR + DVR
      END DO
14    IF(DVF .EQ. 0.0)GO TO 15
      VF = VF + DVF
      END DO
15    IF(DVC.EQ.0.0)GO TO 16
      VC = VC + DVC
      END DO
16    IF(DSW .EQ. 0 0)GO TO 17
      SW = SW + DSW
      END DO
17    IF(DEFF.EQ.0.0)GO TO 23
      EFF = EFF + DEFF
      END DO
23    IF(DLMAX.EQ.0.0)GO TO 18
      LMAX = LMAX + DLMAX
      END DO
18    IF(DLMIN.EQ.0.0)GO TO 19
      LMIN = LMIN + DLMIN
      END DO
19    CLOSE(2)
```

```
      TYPE *,'ENTER "1" TO REPEAT'
      READ(IN,*)IREPEAT
      IF(IREPEAT.EQ.1) GO TO 20
C
C
C     FORMAT STATEMENTS
C
C
1     FORMAT(A80)
2     FORMAT(1H0,'LPSP = ',F10.7,2X,'PR = ',F9.2,2X,'Cmax = ',F9.2
     *,2X,'CELL AREA = ',F9.3)
C
C
C     STATEMENT NUMBERS USED
C
C     FORMAT 1-4
C     STATEMENTS 10 - 23
C
      STOP
      END
```

VITA

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